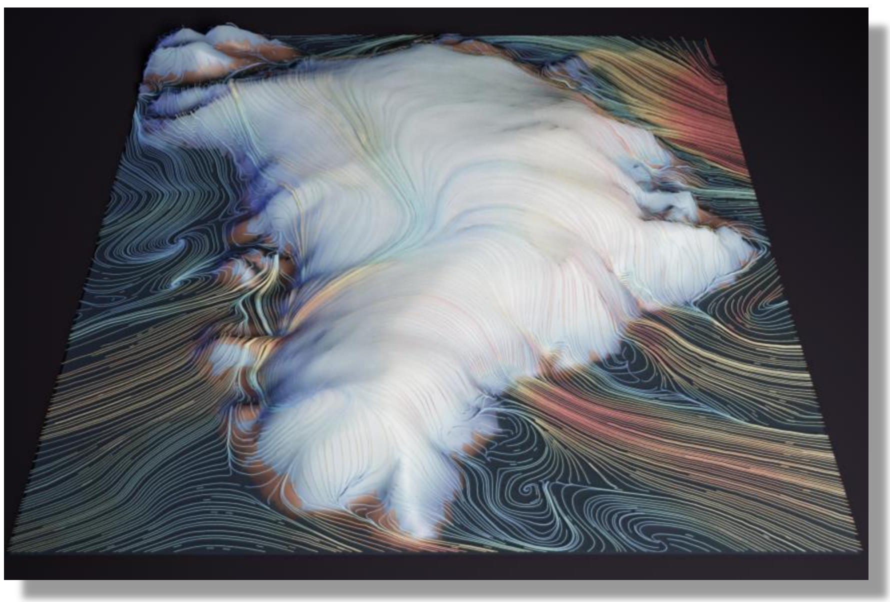
CESM

Community Earth System Model



CESM CSL Proposal Supplementary Material

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Period of Performance: 01 November 2020 – 31 October 2022

Total Request: 622.5 M Cheyenne (Equivalent) Core-Hours

Table of Contents

Cover image: Snapshot of the lowest model level streamlines, draped over the Greenland ice-sheet and colored by wind speed. Simulation was performed with a 1/8° refined grid over the island of Greenland using the variable-resolution configuration of the spectral-element atmospheric dynamical core in CESM2. Katabatic winds can be seen accelerating down the eastern slopes of the ice sheet. Visualization was developed by Matt Rehme (CISL) and Adam Herrington (CGD) of the National Center for Atmospheric Research, and was inspired by a visualization of winds over Antarctica by the Polar Meteorology Group at the Byrd Polar & Climate Research Center.

Acknowledgments

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This document contains the complete list of experiments, along with their core-hour and storage estimates, proposed by each CESM Working Group. In addition, details of the Community Projects are also provided.

Atmosphere Model Working Group (AMWG)

1. Broad Overview of Working Group and Research Plan

AMWG utilizes CSL resources primarily for the development of the CESM Community Atmosphere Model (CAM) and associated capabilities. This encompasses the advancement of both the representation of the unresolved physical processes in parameterization schemes and the dynamical core processes, including tracer transports. It also covers sensitivity experiments aimed at understanding many interactions among the represented physical and dynamical processes across climate regimes and multiple timescales.

In this allocation cycle, AMWG development activity will focus on the following broad areas: 1) deliver a unified atmospheric model that incorporates a well-resolved stratosphere as well as improved resolution of boundary layer turbulent processes; 2) examine new physics and their impacts on simulated climate; 3) produce scientifically-supported, regionally-refined model configurations for domains of interest in process studies, including the southeast Pacific stratus region and bordering topography; 4) continue with evaluation of new candidate atmospheric dynamical cores (dycores) – Model for Prediction Across Scales (MPAS) and Finite Volume cubed-sphere (FV3), noting that these are in addition to the Spectral Element (SE) dycore already in use; and 5) explore higher horizontal resolution in the context of a new vertical grid and potential physic modifications. Production activities will continue to explore physical processes in the CAM6 configuration.

2. Development Proposal (Y1: 21.0 M; Y2: 44.3 M; total 65.3 M core-hours)

D1. Vertical grid development (Y1 – 11.4 M; Y2 – 8.3 M): A key effort in this allocation will be to deliver a scientifically validated atmospheric model with a higher top as well as a well resolved stratosphere. We expect that this configuration will have around 85 levels (85L). In addition to this configuration, we will also deliver a *half-top* version possessing between 40 and 45 levels (45L) for more efficient tropospheric physics development. The 85L configuration will become the atmospheric component of the next coupled model version, CESM3, replacing CAM and WACCM (Whole Atmosphere Community Climate Model). We expect the 45L configuration to be in high demand by members of the current AMWG community for their development projects. Both 85L and 45L configurations will have to be fully vetted scientifically in coupled configurations. We plan to conduct full CMIP DECK (Coupled Model Intercomparison Project – Diagnostic, Evaluation, and Characterization of Klima) style integrations to accomplish this, including preindustrial control runs, 20th century simulations, as well as abrupt 4xCO2 and 1%CO2 increase scenarios. As a consequence, a significant portion of our allocation will be devoted to this effort.

We expect to focus on the development of both 45L and 85L configurations early in this allocation period. The principal tools for the initial step will be AMIP-style (Atmosphere Model Intercomparison Project), i.e., F-compset, simulations without an interactive ocean. Both boundary layer and free-tropospheric and stratospheric resolution will be modified. Some work on such increased resolution for the 85L / 80 km top configuration occurred under our current allocation. However, no work on planetary boundary layer (PBL) resolution has been done. 45L development has not begun. This development will require extensive testing of many possible configurations, including critical evaluations of high-latitude atmospheric variability which require ensembles of multiple multi-decade simulations. Therefore, we anticipate order 30 25-year-long simulations as a reasonable amount for the initial development of these configurations in Year 1.

In Year 2 we will focus on completing the characterization of the new vertical grids in coupled simulations. These will include extended preindustrial controls to allow confident determination of El Nino Southern Oscillation (ENSO) variability and other interannual-to-decadal variability in the new systems. In addition, we will perform a subset of the CMIP DECK suite as discussed above.

D2. New physics (Y1 – 1 M; Y2 – 1.4 M): We will also investigate new or modified PBL and convective physics parameterizations for CAM focusing on global CMIP class simulations. We expect this work to utilize the new 45L F-compset configuration.

D2.1 Cloud Layers Unified By Binormals (CLUBB) Prognostic momentum fluxes: The aspects of CAM simulated climate which have degraded between CESM1 and CESM2, including worse sea-level pressure and upper level wind biases, appear to be related to transport of momentum (drag). Momentum transport in CLUBB is the focus of recently funded NSF-NOAA Climate Process Team (CPT) effort. AMWG resources will be used to investigate new formulations of momentum transport in CLUBB using a combination of nudged and free-running AMIP simulations.

D2.2 Eddy-diffusivity Mass-Flux (EDMF) unified convection: A second NSF-NOAA CPT was funded to examine the impact of a new unified turbulence-convection parameterization framework. This new framework will enhance the representation of turbulence provided by CLUBB by implementing a mass-flux plume in the CLUBB infrastructure. AMWG will support this effort using a combination of nudged and free-running AMIP simulations.

D2.3 Convective Parameterization: Despite comprehensive updates of the physics, impactful parameterization development is still expected to occur within this allocation cycle. The Zhang and McFarlane (1995; ZM95) deep convection scheme is increasingly out of date and the community has committed to replacing this in the near future. This could take the form of a like-for-like replacement scheme. Efforts have included the Kain-Fritsch and variants of the Arakawa-Schubert schemes in the past, and university researchers have expressed interest in continuing this effort.

Additionally, simulations testing the UNICON scheme (Unified Convection; Park 2014) as well as the Grell-Freitas scheme (Grell and Freitas 2014) will be performed. Improvements to the MG2 (Gettelman and Morrison 2015) microphysics are also expected to become available during this allocation cycle.

D2.4 Stochastic Physics: By representing unresolved subgrid variability, stochastic parameterizations have the potential to reduce systematic model biases, e.g., by improving ENSO variability and precipitation bias and intensity (e.g., Berner et al. 2017). We will use the Stochastically Perturbed Physics Tendency (SPPT) scheme in AMIP and as well as coupled simulations to study which tendency perturbations lead to the improvement and how stochastic representations affect climate simulation in general. This information will be used to inform further parameterization development in CAM.

D3. Regionally refined (RR) process studies (Y1 – 1 M; Y2 – 12 M): The regional refinement capability of CAM Spectral Element dynamical core (CAM-SE) offers opportunities to investigate physical processes in key regions at high resolution. In Year 1 of this allocation, we will focus on exploratory calculations to define useful regionally refined domains for physics studies in Year 2. It is difficult to assign exact computational costs to such calculations. We will use a rough estimate of 60,000 core-hours per simulation year for these runs to accommodate a range of refinement levels, e.g., 25 km or 12 km, as well as a range of refined region areal fractions. We expect to use the 45L atmosphere-only configuration for the bulk of this work when available. In Year 1, we will design and perform initial tests of a number of new regional domains that include: i) Peruvian Stratus and Andes; ii) Maritime Continent; iii) Southern Ocean and Antarctic edge; and iv) Inter-Tropical Convergence Zone (ITCZ) upwelling. These complement the existing Continental US (CONUS) and Greenland Ice Sheet (GrIS) configurations which were developed with our current allocation. In Year 2 we will perform studies of model physics in these domains, focusing on a number of processes.

D3.1 Subgrid orographic effects: Subgrid orographic effects continue to be a topic of interest. PBL Turbulent Orographic Form Drag (TOFD; Beljaars et al. 2004) has been seen to play a significant role in mediating ice-sheet edge precipitation. In addition, we expect TOFD to play a significant role in simulations of low level PBL winds in the US Midwest. Significant mesoscale blocking by the Andes may also be an important component of the meteorological environment of the Peruvian Stratus and Stratocumulus zone.

D3.2 Microphysics: Cloud microphysical processes, especially mixed phase processes and cloud-aerosol interactions were seen to be key determinants of emerging CESM2 system behavior in CMIP6, including Equilibrium Climate Sensitivity (ECS) and the latter half of the 20th century warming. We will examine the behavior of CAM clouds in targeted regions such as the Southern Ocean and the Peruvian Stratus region to test parameter sensitivities as well as interactions with turbulence at a variety of resolutions.

D3.3 Convection: Convective process, especially convective organization are uniquely important and drive many of the persistent biases in global climate simulations. We will investigate the sensitivity of convective parameterizations to resolution as well as to physical parameters in the CONUS, Maritime Continent, and ITCZ domains.

D4. Process studies using LES (Y1 – 1 M; Y2 – 2 M): During this allocation cycle, AMWG requests time to conduct high-resolution process studies with dedicated limited area models involving the NCAR Pseudo-spectral Large Eddy Simulation framework (LES; Sullivan and Patton 2011). These activities will complement ongoing NCAR PBL reinvestment activities as well as contribute to CPT research using CAM. We will utilize the microphysical and complex terrain capabilities of LES to explore: 1) subgrid terrain effects on drag and momentum transfer; and 2) microphysics/turbulence/aerosol interactions in low-lying stratus clouds. These experiments will be designed in collaboration with Ned Patton (PBL re-investment lead). We are allocating 1 M core hours in year 1 to allow for exploration of experimental configurations. This is sufficient to perform 6-8 simulations in a 1024x512x256 domain, each lasting around 200,000 timesteps. In year 2, we will conduct a suite of LES research runs with varying terrain roughness and another suite varying aerosol levels in stratus clouds. The final design of these runs will be defined during Year 1. We allocate 2 M core hours for these experiments in anticipation of larger domains or an increased number of runs.

D5. Dynamical core testing and adoption (Y1 – 1.0 M; Y2 – 5.4 M): Three new dynamical cores (dycores) defined on quasi-isotropic grids (2 cubed-sphere and 1 Voronoi) are being or are planned to be integrated into the CESM: FV3 (loosely speaking a non-hydrostatic cubed-sphere version of FV), MPAS (loosely speaking a global version of Weather Research and Forecasting, WRF, model discretized on a Voronoi grid), and SE-CSLAM (Spectral-Element - Conservative Semi-Lagrangian Multi-tracer dynamical core with finite-volume transport).

Among the three dycores, the SE-CSLAM core is already well integrated in the CESM framework and has been vetted in prescribed sea surface temperature (SST), i.e., AMIP-style, simulations as well as in coupled configurations. Indeed, SE-CSLAM will be used for much of the vertical grid development and other tasks described in this proposal. So, the majority of our dycore adoption effort will focus on the two remaining dycores: FV3 and MPAS.

During our current allocation, excellent progress was made on integrating FV3 into the CESM infrastructure. Successful coupled simulations with FV3 were completed. With this allocation request, AMWG will ensure that FV3 is successfully coupled with the new proposed vertical grids discussed in D1.

MPAS is less mature within the CESM framework. We expect our efforts during Year 1 of this cycle to focus on integration and evaluation of MPAS in AMIP configurations. This effort will involve relatively short atmosphere-only simulations with the full CAM6 physics using the 85L vertical grid. We will focus on basic evaluation of model climate and attempt to characterize any dycore dependencies with respect to existing results with

SE-CSLAM and FV3. In Year 2, we expect this effort to proceed into coupled evaluations of MPAS using a preindustrial configuration.

D6. Advancing CAM high horizontal resolution climate (Y1 – 5.5 M; Y2 – 15.3 M): Climate simulations at high horizontal resolutions (ne120, ~25 km) continue to be of interest to the AMWG community. Our main objective with this allocation will be to deliver a well-tuned 25 km configuration using the 45L and 85L vertical grids. We will utilize short (5-year) atmosphere-only simulations to accomplish this goal. One focus of concern will to make an initial characterization of high-latitude variability in a model with both high-horizontal resolution and a well-resolved stratosphere. This will be undertaken in Year 2 via a small ensemble of climatological SST experiments.

3. Production Proposal (Y1: 8.9 M; Y2: 4.8 M; total 13.7 M core-hours)

P1. Perturbed Parameter Ensemble (PPE) (Y1 – 4.25 M; Y2 – 4.25 M): The CAM6 PPE aims to quantify sensitivity of critical climate metrics to parameter choices in CAM6 physics. This will include quantifying uncertainty in climate forcing, climate response to parameter choices, and identifying structural errors. We will develop an observationally constrained parameter set and uncertainty ranges for CAM6 parameters. We will also make a large data set available to the community with the latest big data access and analysis methods.

The goal is to conduct ~500 one-year nudged runs of standard resolution (1° horizontal, 32L vertical) CAM6 AMIP in 2 configurations: one with control climate and one with preindustrial aerosols. This will help determine uncertainty in climate forcing and control climate. We will then also conduct approximately 200 3-year simulations with both control climate and a perturbed climate (SST+4K and 2xCO2). This will be used to assess free running circulation changes and climate feedbacks. In total, this effort will entail 3400 simulation years in AMIP-style configurations.

P2. Perturbed parameter hindcast ensembles (Y1 – 1 M; Y2 – 0.5 M): This project aims to complement a subset of the boundary forced PPE (in P1) with a set of initialized CAM simulations. We will target specific phenomena known to be challenging for CAM6 to simulate based on past research and experience. This will include the Madden-Julian Oscillation, atmospheric high-pressure blocking, Midwest mesoscale convective systems, and atmospheric river events.

The goal is to understand how the fidelity in forecasting individual focused events depends on the parameter values as chosen in PPE. In particular, we will investigate whether specific climate dependencies map to forecast dependencies. The implication is that short term hindcasts could be used as a rapid assessment tool to diagnose structural climate sensitivities in CAM. The target is to perform individual 50-day simulations with a standard CAM6 configuration at 1° resolution, each of which would include a 20-day spin-up prior to a 30-day forecast for a total of 50 days. Ten ensembles would be used for each forecast event and for a subset of 30 parameter configurations from PPE in P1. There would be two forecast start dates: a date prior to the peak of the event and a date at the peak of the event, to test initiation and maintenance forecast skill. The total resources required in year 1 are 100 equivalent years of CAM6 at 1° and 32L. In year 2, when versions of CAM7 are available, with more final configurations in terms of resolution, dynamical core, and physics, a smaller subset of forecast configurations (estimated at 15) will be performed to compare performance with the standard CAM6 forecast set.

P3. Continued CAM6 climate investigation (Y1 – 1 M): The CMIP6 development process revealed interesting features in the climate of CESM2. Climate sensitivity as defined using the Gregory et al. (2004) method increased from 4K in CESM1 to ~5.3K in CESM2. In addition, it was found that minor changes in aerosol emissions data led to large differences in simulated 20th century warming. We will perform 150-year 4xCO2 experiments using key intermediate model versions between CESM1 and CESM2 to complete the analyses done with our current allocation.

P4. High-Mountain Asia (Y1 – 2.55 M): High Mountain Asia (HMA) encompasses the Himalayas, Karakoram, Hindu Kush, Pamir, Kunlun Shan, Tien Shan, Hengduan Shan, and Quilian Shan mountain ranges, and the highlands of the Tibetan Plateau. The mountain areas and highlands in this region are home for the largest ice and snow reserves outside the polar regions, sustain the seasonal water availability, and provide water resources that are vital for billions of people living in the mountainous regions and surrounding lowlands. The importance of the water resources illustrates the high vulnerability of this region to climate change, which most likely will affect the cryosphere and hydrology of HMA. The high vulnerability underlines the need for an improved understanding of how glaciers in HMA will evolve under future climatic conditions. The application of CESM in mountainous regions is, however, challenging due to the complexity of the mountainous terrain and the large heterogeneity in processes that occur over short horizontal distances. To improve the representation of cryospheric(-hydrological) processes like the glacier surface mass balance (SMB) or snow cover, a variable resolution CESM grid with a regional refinement up to 7 km over the HMA mountainous domains has already been developed. This variable resolution (VR) grid will be used to explore the historical model performance in simulating cryospheric-hydrological processes, such as SMB, and can eventually be used to assess the near-future evolution of glaciers in HMA.

A prior collaboration between AMWG and LIWG developed a VR grid in CAM with a 7 km regional refinement over the HMA region. This configuration costs about 85K core-hours per simulated year and resolves mountain ranges as high as 6 km above sea level. With our current allocation, we expect to perform a historical simulation with prescribed SST / sea-ice over the period 1979-1998, which will be completed before 31 October 2020. Here, we propose to extend this simulation by an additional 60 years, branching off the prior simulation and running through the present day and 38 years into the future (1999-2058) under a future emissions scenario. The simulations will be forced with prescribed SST / sea-ice from a coupled 1° simulations under the same future emissions scenario. The appropriate output will be saved to investigate forcing the Community Ice-Sheet Model (CISM) over the HMA domain, to better understand the response of HMA glaciers to climate change.

Experiment	Configuration	Resolution	No. of Runs	Years/Run	Core hours / simulation year	Total in M core hours	Data Volume (TB)	Priority A/B/C
Development								
Year 1								
D1 (85L Development)	FHIST/F2000(85L)	ne30	30	25	6640	4.98	75	A
D1 (45L Development)	FHIST/F2000(45L)	ne30	30	25	3515	2.64	60	A
D1 (85L piControl)	B1850	ne30	1	500	7640	3.82	15	A
D2.1(CLUBB-momentum)	FHIST/F2000(45L)	ne30	20	5	3515	0.35	2	A
D2.2(EDMF)	FHIST/F2000(45L)	ne30	20	5	3515	0.35	2	A
D2.3(Convection)	FHIST/F2000(45L)	ne30	10	5	3515	0.18	2	B
D2.4(Stochastic)	FHIST/F2000(45L)	ne30	7	5	3515	0.12	2	C
D3(Regional Refine exploratory)	FHIST/F2000(45L)	variable	9	2	60000	1.08	5	A
D4(LES/CRM)	LES and CRM	<3km	6	N/A	N/A	1.00	5	B
D5(FV3)	B1850(85L)	1 deg equiv	3	40	7640	0.92	5	B
D5(MPAS)	FHIST/F2000(85L)	1 deg equiv	10	1	6640	0.07	5	B
D6(High-Horz. Res)	FHIST/F2000(85L)	ne120	1	5	425000	2.13	50	B
D6(High-Horz. Res)	FHIST/F2000(45L)	ne120	3	5	225000	3.38	40	C
Total Dev. Year 1						**21.0**	**268**	
Year 2								
D1 (85L 20th Century)	B1850	ne30	1	150	7640	1.15	7	A
D1 (85L 4xCO2)	B1850	ne30	1	200	7640	1.53	8	A
D1 (85L 1%CO2)	B1850	ne30	1	150	7640	1.15	7	B
D1 (45L piControl)	B1850	ne30	1	500	4515	2.26	8	A
D1 (45L 20th Century)	B1850	ne30	1	150	4515	0.68	4	B
D1 (45L 4xCO2)	B1850	ne30	1	200	4515	0.90	4	B
D1 (45L 1%CO2)	B1850	ne30	1	150	4515	0.68	4	B
D2.1(CLUBB-momentum)	FHIST/F2000(45L)	ne30	20	5	3515	0.35	20	A
D2.2(EDMF)	FHIST/F2000(45L)	ne30	20	5	3515	0.35	20	A
D2.3(Convection)	FHIST/F2000(45L)	ne30	20	5	3515	0.35	20	B
D2.4(Stochastic)	FHIST/F2000(45L)	ne30	20	5	3515	0.35	20	C
D3.2(RR-Microphysics)	FHIST/F2000(45L)	variable	20	5	60000	6.00	40	A
D3.1(RR-Subgrid orographic drag)	FHIST/F2000(45L)	variable	10	5	60000	3.00	40	A
D3.3(RR-Convection)	FHIST/F2000(45L)	variable	10	5	60000	3.00	40	A

D4(LES/CRM)	LES and CRM	<3km	6 to 12	N/A	N/A	2.00	10	B
D5(MPAS)	B1850(85L)	1 deg equiv	5	40	7640	1.53	5	B
D5(FV3)	B1850(85L)	1 deg equiv	1	500	7640	3.82	5	B
D6(High-Horz. Res)	FHIST/F2000(85L)	ne120	2	10	425000	8.50	75	B
D6(High-Horz. Res)	FHIST/F2000(45L)	ne120	3	10	225000	6.75	50	B
Total Dev. Year 2						**44.3**	**387**	
Total Development						**65.3**	**655**	
Production								
Year 1								
P1(PPE)	FHIST/F2000	fv09	1700	1	2500	4.25	10	A
P2(PPE Hindcast)	FHIST/F2000	fv09	4	100	2500	1.00	4	A
P3(CESM2 sensitivity 4xCO2)	B1850	fv09	2	150	3500	1.05	10	B
P4(HMA)	FHIST/F2000	fv09	1	30	85000	2.55		A
Total Prod. Year 1						**8.85**	**24**	
Year 2								
P1(PPE)	FHIST/F2000	fv09	1700	1	2500	4.25	10	A
P2(PPE Hindcast)	FHIST/F2000	fv09	2	100	2500	0.50	2	A
Total Prod. Year 2						**4.75**	**12**	
Total Production						**13.7**	**36**	
Total Year 1						29.9	47	
Total Year 2						49.1	78	
Total all years						79.0	125	
Total Dev.+Prod.						79.0	125	
Variable mesh cost formula: C_var = A*(r^3)*C_1 + (1-A)*r*C_1 [units: CH/SY]								
A=fraction refined; r=refinement factor; C_1=cost of unrefined global configuration								
		A	r	C_1	C_var	C_var(45L)	C_var(85L)	
ne30		1	1	2500	2500	3516	6641	
ne30->ne120 CONUS		0.03	4	2500	14500	20391	38516	
ne30->ne240 CONUS		0.03	8	2500	57800	81281	153531	

ne30->ne120 Polar		0.167	4	2500	35050	49289	93102	
ne30->ne240 Polar		0.167	8	2500	230420	324028	612053	
ne30->ne120 MC		0.1	4	2500	25000	35156	66406	
ne120		1	4	2500	160000	225000	425000	
Default configurations for CESM2 using FV lat x lon dycore. These configurations use a large number of processors to increase throughput. This results in lower performance in terms of core-hours per simulation year than could be obtained with less "aggressive" PE layouts.								
F-case FV1x1				2500				
B-case FV1x1				3600				
Simpler model configurations								
Simpler models 1x1				1000				
New vertical grid configurations								
		32L B-case	32L F-case		B-case	F-case		
85-levels		3500	2500	85	7640.63	6640.63		
45-levels		3500	2500	45	4515.63	3515.62		

Biogeochemistry Working Group (BGCWG)

1. Broad Overview of Working Group and Research Plan

The goal of BGCWG is to produce a state-of-the-art Earth system model for the research community that includes terrestrial and marine ecosystem biogeochemistry. This model is used to explore ecosystem and biogeochemical dynamics and feedbacks in the Earth system under past, present, and future climates. Land and ocean ecosystems influence climate through a variety of biogeophysical and biogeochemical pathways. Interactions between climate and ecosystem processes, especially in response to human modification of ecosystems and atmospheric CO_2 growth, produce a rich array of climate forcings and feedbacks that amplify or diminish climate change.

2. Development Proposal (Y1: 5.2 M; Y2: 6.6 M; total 11.8 M core-hours)

a. Goals

Better understanding of ecosystem and biogeochemical dynamics and feedbacks with respect to a changing climate requires an expansion of current CESM land and ocean model capabilities. Biogeochemistry development is focused on:

- continued development of the Newton-Krylov fast spin-up technique;
- continued development of biogeochemical parameterizations;
- porting of Marine Biogeochemistry Library (MARBL) to Modular Ocean Model version 6 (MOM6);
- coupling across components and understanding interactions; and
- automated techniques for the optimization of model parameters.

b. Specific simulations and computational requirements

D.1 Newton-Krylov (NK): Evaluating the impact of biogeochemical and physical developments on the full depth carbon cycle currently requires lengthy experiments, which becomes impractical when multiple developments are being evaluated. Thus, we are allocating a portion of our computational request on the continued development of techniques to efficiently spin-up biogeochemical tracers. These techniques, based on NK solvers, are currently being applied successfully to ocean tracers with relatively simple dynamics (e.g., ideal age, abiotic natural radiocarbon, biogeochemical dissolved organic matter, and dissolved inorganic carbon), but have yet to be successfully extended to comprehensive biogeochemical tracer packages. These techniques would ease the evaluation of impacts of developments on ocean carbon uptake. Such a technique would also enable us to study long-term behavior of modifications to biogeochemical parameterizations. One view of how the NK solver works is that it is doing multiple short runs with perturbed initial conditions, and it optimizes for the combination of perturbations that reduce tracer drift. Therefore, computational time for the NK solver experiments consists of many short integrations. These experiments will utilize multiple model configurations, targeting both ocean models POP2 and MOM6.

D.2 MARBL development: Development of the ocean biogeochemistry library MARBL is ongoing, and we will dedicate some of our computational resources to support this. The exact nature of the runs needed for the development work is unknown, so we have requested allocation for numerous short runs.

D.3 MARBL MOM6 development: Additionally, we will continue the work of coupling MARBL to the MOM6 ocean model. We anticipate performing numerous short, test runs to vet the coupling of MARBL to MOM6, and fewer runs of longer duration to evaluate the results.

D.4 MARBL fisheries model coupling: BGCWG is engaged in an effort to couple a prognostic fisheries model to CESM. The fish model is called the Fisheries Size and Functional Type model (FEISTY); it is a temporally dynamic, spatially explicit, size-structured mechanistic model of forage, large pelagic, and demersal fish functional types and an unstructured pool of benthic invertebrate biomass. We are requesting development time to enable testing, tuning, and validation of FEISTY-MARBL configurations of CESM in an ocean – sea-ice configuration.

D.5 BGC coupling: A goal of CESM is to include enhanced coupling between the biogeochemistry parameterizations in different components of the coupled model. The upcoming release of version 6 of CICE will include a biogeochemistry model for the interior of the sea-ice column, extending the skeletal model present in version 5. We are devoting computational resources to explore the coupling of sea-ice biogeochemistry components to the biogeochemistry of the ocean model. We anticipate performing numerous short, test runs to vet the coupling, and fewer runs of longer duration to evaluate the results. We estimate the cost of this configuration as slightly more than the cost of the existing ocean – sea-ice ecosystem configuration.

D.6 Ocean BGC parameter optimization: In the past, parameters in ocean ecosystem model have been determined by evaluating parameter perturbation experiments, where the parameter values have been selected by expert judgment. As more processes have been added to the model, this manual process is becoming a weakness in the model development process. To mitigate this, we will explore the application of automated parameter optimization strategies to assist this process. The duration of the experiments in this work will be shorter or longer, depending on the timescales of the processes whose parameters are being optimized. This exercise will benefit from lessons learned from LMWG, which is pursuing a similar exercise with the Community Land Model (CLM).

3. Production Proposal (Y1: 9.8 M; Y2: 19.5 M; total 29.3 M core-hours)

a. Goals

Production runs address fully-coupled carbon cycle experiments and single component experiments with well-established models. We are requesting computing resources to address the following overarching production goals:

- examination of ocean ecosystems with resolved mesoscale eddies;
- additional carbon cycle sensitivity experiments; and
- evaluation of new biogeochemistry developments in a production context.

b. Specific simulations and computational requirements

P.1 High-resolution simulations with BGC: Several efforts are underway to apply CESM to questions related to the higher trophic levels of marine ecosystems and their sensitivity to climate variability and change. In this context, high-resolution integrations are extremely valuable, as the eddy-resolving / -permitting model includes more realistic spatiotemporal heterogeneity characteristic of ocean fields and has much greater skill in representing key current systems mediating important transport pathways. Our request aims to augment the high-resolution integrations started under the current CSL allocation, as well as support new, targeted experiments. These integrations will serve a very broad community of researchers and are of extremely high value. Indeed, there are only a handful of such runs available worldwide.

P.2 Idealized deforestation experiments: An active area of research in carbon cycle community is understanding how tropical deforestation affects a changing climate. The BGCWG is performing experiments to investigate the effects of idealized deforestation in 1% ramping CO2 experiments, with feedbacks between the carbon cycle and climate selectively turned off and on.

P.3 Sensitivity experiments: During previous CSL allocation periods, working group PIs have requested that particular sensitivity experiments that were not envisioned during the writing of the proposal be performed. We are including in this proposal time to accommodate such requests.

P.4 Hindcast simulations with MARBL-FEISTY: Once the MARBL-FEISTY coupling has been vetted, production ocean – sea-ice experiments with this configuration will be performed. These experiments involve multiple cycles of the forcing based on the Japanese Reanalysis Product (JRA55-do; Tsujino et al. 2018).

P.5 Land model evaluation: In coordination with LMWG, we are requesting time to evaluate how CLM, configured with parameter settings that arise from the LMWG parameter perturbation experiments, performs in the context of the coupled model.

Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in M of core-hours	Archived data volume per year (TB)	Total data volume (TB)	Priority (A/B/C)
Development, Year 1									
D1. Newton-Krylov POP-ECO	GECO+NK	T62_g17	200	5	800	0.8	0	0	A
D1. Newton-Krylov MOM	GMOM+NK	T62_g17	200	5	1200	1.2	0	0	B
D1. Newton-Krylov MOM-ECO	GMOMECO+NK	T62_g17	200	5	2400	2.4	0	0	A
D2. MARBL Dev	GECO	T62_g17	200	1	620	0.124	0	0	A
D3. MARBL-MOM Dev	GMOMECO	T62_g17	200	1	2200	0.44	0	0	A
D4. MARBL-FEISTY coupling	GECO+FEISTY	T62_g17	200	1	1000	0.2	0	0	C
Development Year 1 Total						5.164		0	
Development, Year 2									
D1. Newton-Krylov MOM-ECO	GMOMECO+NK	T62_g17	200	5	2400	2.4	0	0	A
D2. MARBL Dev	GECO	T62_g17	200	1	620	0.124	0	0	B
D3. MARBL-MOM Dev	GMOMECO	T62_g17	200	1	2200	0.44	0	0	A
D5. CICE-POP BGC coupling	GECO	T62_g17	100	5	700	0.35	0	0	C
D5. CICE-POP BGC coupling	GECO	T62_g17	10	50	700	0.35	0	0	C
D5. CICE-POP BGC coupling, JRA	GECO	T62_g17	10	61	700	0.427	0.05	30.5	C
D6. Ocean BGC Param Optim	GECO	T62_g17	200	10	620	1.24	0	0	C
D6. Ocean BGC Param Optim	GECO	T62_g17	20	100	620	1.24	0	0	C
Development Year 2 Total						6.571		30.5	

Development Total						11.735		30.5	
Production, Year 1									
P1.High-Res BGC POP	GECO	T62_t12	1	10	575000	5.75	4	40	A
P2. Idealized deforestation experiments	B	f09_g17	3	140	3500	1.47	0.1	42	B
P3. Misc. Sensitivity, 1850-2100	B	f09_g17	3	250	3500	2.625	0.1	75	C
Production Year 1 Total						9.845		157	
Production, Year 2									
P1.High-Res BGC POP	GECO	T62_t12	1	15	575000	8.625	4	60	A
P3. Misc. Sensitivity, 1850-2100	B	f09_g17	3	250	3500	2.625	0.1	75	C
P4. MARBL-FEISTY experiments	GECO+FEISTY	T62_g17	20	61	1000	1.22	0.05	61	B
P5. Coupled CLM PPE, 1850-2100	B	f09_g17	8	250	3500	7.0	0.1	200	B
Production Year 2 Total						19.47		396	
Production Total						29.315		553	

Chemistry Climate Working Group (ChCWG)

1. Broad Overview of Working Group and Research Plan

The goal of ChCWG is to continue development of the representation of chemistry and aerosols in CESM and to further our understanding of the interactions between gas-phase chemistry, aerosols, and climate, using multiple horizontal and vertical model resolutions. The scientific motivation for these developments is the need to understand present-day and future air quality for multiple scales, and to understand the role of climate change on tropospheric composition. The development and production simulations requested here will lead to improving the representation and chemical forecasts of tropospheric composition and air quality, and will allow us to participate in multi-model intercomparison activities.

The representation of tropospheric chemistry and aerosols continues to be developed and improved in CESM by ChCWG. Increasing horizontal resolution is a key factor in improving air quality simulations, so an important component of CAM-chem development is the testing and tuning of the CAM-SE model with chemistry and regional refinement, RR (CAM-SE-RR-chem). A configuration with horizontal resolution of approximately 14 km over the continental U.S. and approximately 1° for the rest of the globe has been developed, with corresponding resolution emissions and other input files, and is available as a component set in CESM2.2. This configuration has been labeled MUSICA-V0 (Multi-Scale Infrastructure for Chemistry and Aerosols, version 0; https://www2.acom.ucar.edu/sections/multi-scale-chemistry-modeling-musica). The first simulations are being analyzed and will be published this year, and simulations for additional years will be simulated for analysis of field campaigns and for producing real-time air quality forecasts. Additional refined regions (Europe, Asia, Australia) are desired by the community and will require testing. In addition, CAM-chem with the SE dycore and CSLAM will become the standard configuration and the impact of this dycore on tracer transports, chemistry, and aerosols continues to be evaluated. A number of chemistry and aerosol developments have been recently introduced in CESM, including a 5-mode Modal Aerosol Module (MAM5, adding a stratospheric sulfate coarse mode to MAM4), updated dust scheme, MOSAIC allowing for simulation of inorganic nitrate aerosols, and expanded chemistry schemes. In addition, a simpler chemistry mechanism suitable for climate simulations is being developed.

The capability for running daily to near-seasonal air quality forecasts will be developed in CAM-chem. We will continue the development of CAM-chem within the CESM and Data Assimilation Research Testbed (DART) multi-instances framework. The goal is to assimilate satellite observations from the day before, using CAM-Chem and DART to initialize a deterministic forecast of several days. We will assess the impact of the SE dycore on the chemical data assimilation performance.

The development of the new CESM workhorse model with a higher model top and vertical resolution will require moving CAM-chem to the same vertical grid. Several production simulations with CAM-chem using the new vertical resolution will be required to provide chemical fields for CESM, including the development and production of a simplified chemistry scheme.

2. Development Proposal (Y1: 4.5 M; Y2: 6.9 M; total 11.4 M core-hours)

a. Goals

The simulations listed below will assist in the ongoing improvement in the representation of tropospheric chemistry and aerosols in CESM (CAM-chem and Whole Atmosphere Community Climate Model, WACCM). New chemistry mechanisms, both more complex (for better representation of secondary pollutants and aerosols) and simpler (suitable for climate simulations) will be tested. In particular, a relatively simple chemistry scheme (with online oxidants that will be suitable for simulation of nitrate and secondary organic aerosols) for use in the new workhorse atmosphere model will be developed and evaluated against more detailed mechanisms. Testing of the TUV and FAST-J photolysis schemes, which take into account the attenuation by aerosols, will be performed. New aerosol schemes will be tested, including updated dust schemes, marine organic aerosols, formation of secondary organic aerosols, and the CARMA sectional aerosol scheme in the current code base. The combination of these new developments of the chemical mechanism, photolysis, and aerosols will be fully tested and evaluated. This development is tied closely to the work beginning in the development of MUSICA, and will include testing of RR grids over various parts of the globe, as well as globally uniform high-resolution simulations. The development of chemical data assimilation continues to be a priority and some resources are allocated for that work.

b. Specific simulations and computational requirements

D1. Chemistry, photolysis, and aerosol development: The development work will be performed primarily with CAM-chem-SE (ne30, approximately 1°), with the MOZART-TS1 chemistry scheme (default in CESM2, with 239 advected tracers), with CSLAM, and with the new default vertical levels of CESM (assumed here to be order 80L) which costs approximately 17,000 core-hours per simulation year. Development simulations will be run during both years of the proposal.

D2. MUSICA/CAM-chem-SE-RR development: New RR grids are desired by the community for air quality studies over Asia, Africa, Europe, and Australia, and we will perform test simulations in support of collaborative research. As these grids have not yet been created, we estimate the costs based on CAM-chem-SE-RR(CONUS) (ne0_ne30x8) configuration, presuming a comparable number of points will be in the new grids. With 32 model levels, these simulations cost 210,000 core-hours per simulation year. These simulations will be run during both years.

D3. High-resolution: We will also test running simulations with uniform higher resolution grids at approximately 0.5° and 0.25°, using the CAM-chem-SE(CSLAM) configuration. These simulations will allow further study of the impact of resolution on chemistry, beyond what has been examined with the RR configurations. The very brief simulations proposed here will be nudged to observed meteorology and will provide a preliminary assessment of the feasibility of running these configurations. The cost of these simulations is estimated by an 8x increase in cost (4x for number of grid points and 2x for the timestep) for each doubling of horizontal resolution.

D4. Data assimilation: The performance of the SE configuration of CAM-chem with chemical data assimilation in the DART framework has yet to be evaluated, and these CAM-chem-SE (ne30) simulations will be a start for that. Thirty ensemble members are required to account for variability in chemistry simulations.

3. Production Proposal (Y1: 5.7 M; Y2: 10.2 M; total 15.9 M core-hours)

a. Goals

Simulations of CAM-chem-SE(CSLAM) will be performed to study 40-year trends in atmospheric composition seen in observations. In addition, simulations will be performed in support of model intercomparison activities such as the Community Climate Model Initiative (CCMI) and World Meteorological Organization (WMO) ozone assessments. Daily chemical forecasts will be produced by running CAM-chem-SE-RR for 3-days each day to support community air quality research.

b. Specific simulations and computational requirements

P1. Reanalysis 1980-2020: CAM-chem, nudged to MERRA2 meteorology, simulation of 1980-2020 for trend analysis and comparison to satellite observations (e.g., MOPITT CO, MODIS AOD).

P2. Chemical forecasts with MUSICA-V0: The CAM-chem-SE-RR(CONUS) configuration will be run each day, nudged by GEOS-FP forecast meteorology, using real-time fire emissions, to provide state-of-the-science air quality forecasts for the U.S. These will be run similarly to current WACCM forecasts and the output provided to the community, for use as boundary conditions for regional air quality forecasts and for evaluation against operational forecasts and real-time observations. 3-day simulations will be run each day, in each year of the proposal.

P3. Chemistry-climate simulations: The workhorse model configuration of CAM-chem-SE(CSLAM), including MOSAIC aerosols, will be run for a standard set of simulations, to be provided to the community through the next phase of CCMI. These simulations include a preindustrial control for 100 years, and historical transient runs (1850-2015, 3 ensemble members) with both active and data ocean models. In addition, a specified-dynamics nudged simulation will be run (1980-2020). The cost of these simulations is estimated assuming a linear increase with the number of vertical levels (32 to ~80 levels). These simulations will be spread over the 2 years of the proposal.

Experi-ments	Configuration	Resolution, Levels	# runs	yrs/run	CPU-hr/ sim-yr	Total in M core-hours	Data Vol. (TB)	Priority
Development								
Year 1 Dev.								
D1	CAM-chem-TS1-SE	ne30pg3, L80	25	6	17,250	2.588	0	A
D2	CAM-chem-TS1-SE-RR	ne0np4CONUS. ne30x8, L32	3	1	210,000	0.630	0	A
D3a	CAM-chem-TS1-SE- 1deg	ne30pg3, L80	1	1	17,250	0.017	0	A
D3b	CAM-chem-TS1-SE- 0.5deg	ne60, L80	1	1	138,000	0.138	0	A
D3c	CAM-chem-TS1-SE- 0.25deg	ne120, L80	1	1	1,104,000	1.104	0	A
Total Year 1 Dev.						4.477	0	
Year 2 Dev.								
D1	CAM-chem-TS1-SE	ne30pg3, L80	10	5	17,250	0.863	0	A
D2	CAM-chem-TS1-SE-RR	ne0np4CONUS. ne30x8, L32	2	1	210,000	0.420	0	A
D4	CAM-chem-TS1-SE, with DART	ne30, 30 members, 32L	5	0.137	8,223,450	5.633	0	A
Total Year 2 Dev.						6.916	0	
Total Development						11.393	0	
Production								
Year 1 Prod.								
P1	CAM-chem-TS1-MOSAIC-SE, FCnudged	ne30pg3, L32	1	40	8,970	0.359	10	A
P2	CAM-chem-TS1-SE-RR, 3-day forecasts	ne0np4CONUS. ne30x8, L32	1	3	210,000	0.630	10	A
P3a	CAM-chem-TS1-MOSAIC-SE, BC1850	ne30_pg3, L80	1	100	28,000	2.800	5	A
P3b	CAM-chem-TS1-MOSAIC-SE, BCHIST	ne30_pg3, L80	1	70	28,000	1.960	20	A
Total Year 1 Prod.						5.749	45	
Year 2 Prod.								
P2	CAM-chem-TS1-SE-RR, 3-day forecasts	ne0np4CONUS. ne30x8, L32	1	3	210,000	0.630	10	A
P3b	CAM-chem-TS1-MOSAIC-SE, BCHIST (cont.)	ne30_pg3, L80	2	70	28,000	3.920	20	A

P3c	CAM-chem-TS1-MOSAIC-SE, FCHIST	ne30_pg3, L80	3	70	22,425	4.709	20	A
P3d	CAM-chem-TS1-MOSAIC-SE, FCnudged	ne30_pg3, L80	1	40	22,425	0.897	20	A
Total Year 2 Prod.						10.156	70	
Total Production						15905	115	
Total Yr 1						10,226	45	
Total Yr 2						17,072	70	
Total CHWG request						27,298	115	

Climate Variability and Change Working Group (CVCWG)

1. Broad Overview of Working Group and Research Plan

The goals of CVCWG are to understand and quantify contributions of natural and anthropogenically-forced patterns of climate variability and change in the 20th and 21st centuries and beyond by means of simulations with CESM and its component models. With these model simulations, researchers will be able to investigate mechanisms of climate variability and change, as well as detect and attribute past climate changes, and project and predict future changes. The CVCWG simulations are motivated by broad community interest and are widely used by the national and international research communities. The highest priority for the CVCWG simulations is given to runs that directly benefit the CESM community. CVCWG is a central element of the Department of Energy (DOE) - NCAR Cooperative Agreement and also provides an interface with national (e.g., U.S. National Assessment) and international (e.g., Intergovernmental Panel on Climate Change, IPCC) climate-change assessment activities. Additionally, because CVCWG does not lead model development but instead performs production runs and analyzes model simulations, it works with outside collaborators as well as across nearly all other CESM Working Groups. Based on input from the broader community as well as research goals within NCAR, the following priorities over the next two years have been determined.

With the forthcoming 100-member CESM2 large ensemble (CESM2-LENS), there are opportunities to augment this dataset to further our understanding of the influence of forcing scenarios on projected climate change. We will run a complementary 15-member ensemble with CESM2 under the SSP2-4.5 scenario, such that the climate change response to SSP2-4.5 can be directly compared to that under SSP3-7.0 (simulations already available through CESM2-LENS). In addition, we plan a long preindustrial control run and historical simulations with the newly configured *pencil* ocean model and a preindustrial control with prescribed time varying SSTs and a 10-member ensemble of Indian Ocean pacemaker experiments. This suite of simulations can be used to parse out the roles of ocean-atmosphere coupling, SST variability, deep ocean circulation, and mixed layer physics in the climate system. In CAM7, there will be a move toward a higher vertical resolution and a higher model top. While CAM7 development is still under way, the vertical grid configuration is close to being finalized. We will run a preindustrial control and idealized climate change scenarios with this new grid to allow a clean comparison with the lower resolution CESM2 to gain understanding of how this new grid configuration will impact climate variability and change. Targeted simulations are also proposed to investigate specific open questions in, and explore new methodologies for, climate variability and change such as tipping points in the Atlantic meridional overturning circulation (AMOC) in CESM2, tropical cyclone-ocean-storm track interactions, and the development of a machine learning tracking algorithm for mesoscale convective systems and other extremes. Finally, resources are devoted to two sets of regionally refined (RR) simulations that will be used to improve our understanding of the role of atmospheric resolution on the representation of climate variability and change. One is focused on the

North Atlantic and the other on the tropics and each of these will have a variety of applications.

2. Production Proposal (Y1: 20.1 M; Y2: 33.9 M; total 54.0 M core-hours)

a. Goals

The proposed simulations for this request can be roughly divided into three categories: 1. simulations that will be of broad use to the research community and complement the existing and forthcoming datasets that are being made available through CMIP6 and the CESM2-LENS; 2. targeted simulations to address specific topics in climate variability and change; and 3. exploratory simulations to gain understanding of how the representation of climate variability may be influenced by simulating the system at higher resolution than has previously been used on the timescales relevant for climate variability.

To complement the forthcoming 100-member CESM2-LENS suite run under SSP3-7.0 forcing, we will perform a 12-member ensemble under SSP2-4.5. These 12 members can be combined with the three that already exist through ScenarioMIP, to form a 15-member *medium ensemble* under this lower forcing scenario. This will allow researchers to quantify the uncertainties in future projected change due to the forcing scenario. To augment the existing coupled and uncoupled preindustrial control simulations, we will perform a preindustrial control with prescribed time varying SSTs taken from the coupled simulation, which will allow for investigations into the role of coupling and SST forced variability. Furthermore, in year 2, we will exploit the forthcoming *pencil* ocean model to perform a preindustrial control and a 10-member historical ensemble. This is a step up in complexity from a typical slab ocean model and represents the upper-ocean mixed layer with the same column physics as the full-depth ocean model, thereby allowing the column physics and mixed layer depths to respond and vary. These experiments will (a) allow us to explore this new configuration, and (b) provide complements to existing coupled and AMIP runs to explore the role of the deep ocean circulation versus mixed-layer physics in climate variability and change. To complement the existing CESM2 tropical Pacific pacemaker experiments, a 10-member ensemble of CESM2 Indian Ocean pacemaker experiments will be performed to allow researchers to investigate the influence of that region of the global climate system. The final suite of experiments that will be used to complement existing datasets as well as explore the impact of a major change to CAM in the transition from CAM6 to CAM7 will be a preindustrial control and idealized global warming scenarios with the improved vertical resolution and higher model top to be incorporated into CAM7. We will keep all other aspects of the model the same as CESM2, e.g., continue to use the FV dynamical core. This will allow for a clean examination of the impact of this major change to the model on climate variability and change and allow us to explore the impact of a realistic quasi-biennial oscillation (QBO) on climate variability and change. Finally, under this category of simulations of broad interest, we will perform a preindustrial control simulation with stochastic physics parameterizations turned on. There is interest in such a simulation from the CVCWG community to explore, in a controlled setting, the influence of stochastic physics parameterizations on features such as ENSO.

We propose to request resources to several targeted sets of experiments, including an investigation into tipping points in the climate system through sub-polar North Atlantic hosing experiments, an investigation into the influence of tropical cyclone (TC) induced SST anomalies on the North Pacific storm track, and a pair of RR CONUS simulations that will be used to develop a machine learning tracking algorithm for mesoscale convective systems and other extremes. Each of these projects will address important problems in climate variability and change.

Finally, we request a substantial portion of our resources in year 2 to RR CAM-SE simulations. While these are relatively resource intensive allowing for only a limited number of simulation years, they have the potential to be groundbreaking in terms of our understanding of the impact of resolution on the modelled representation of climate variability. A growing concern is the existence of a *signal-to-noise* paradox which has been found in the North Atlantic in initialized predictions on both seasonal and decadal timescales (e.g., Scaife et al. 2014; Athanasiadis et al. 2019; Smith et al. 2020). In brief, this paradox suggests that the real world is much more predictable than model simulations, i.e., it is responding much more strongly to slowly varying, predictable boundary conditions. This points toward our models missing important physics that allows them to respond to these boundary conditions. One potential candidate for this missing physics is resolution and very preliminary and somewhat speculative analysis suggests that resolutions higher than 0.25° are necessary to properly capture eddy-mean flow feedbacks in the North Atlantic (Scaife et al. 2019). If true, this will have major implications for our ability to simulate the climate system. We propose a CAM-SE simulation with RR to 1/8° over the North Atlantic to explore this issue. This simulation will run from 1950 to 2014 under historical forcings with prescribed observed historical SSTs to explore whether this resolution changes the nature of low frequency variability in the North Atlantic and eddy-mean flow feedbacks. The simulation can serve many other purposes such as exploration into the representation of TCs, polar lows, and atmospheric rivers at this high resolution. The second configuration to be explored will involve 0.25° RR in the tropics, focused on a band from 30°N to 30°S. The proposed experiment with this configuration will be used to examine features such as the Madden-Julian Oscillation (MJO) and extreme precipitation and it is also considered as a first step that we expect to expand to 1/8° resolution in the tropics, either in subsequent CVCWG CSL allocations or via other resources.

b. Specific simulations and computational requirements

The following projects are listed approximately in order of the year in which they are proposed, but aside from that they are in no particular order.

P1. <u>SSP2-4.5 medium ensemble:</u> An ensemble of coupled CESM2 simulations from 2014 to 2100 under the SSP2-4.5 forcing scenario, initialized from year 2014 of members of the CESM2-LENS. 12 members will be performed and combined with the 3 available through ScenarioMIP to form a 15-member ensemble. At the rate of 3500 core-hours per year for coupled CESM2, the cost of this ensemble will be 12 x 87 x 3500 = 3.66 M in year 1.

P2. Time Varying SST (TVSST) piControl: A 500-year CESM2 simulation with prescribed daily time varying SSTs taken from the coupled preindustrial control. At the rate of 2200 core-hours per year for prescribed SST CESM2, the cost of this ensemble will be 500 x 2200 = 1.1 M in year 1.

P3. 80L CESM2: Simulations using increased vertical resolution in the free troposphere and stratosphere and a raised model lid height (i.e., the free troposphere and stratosphere resolution of forthcoming CAM7). Current CESM2 vertical grid spacing in the free troposphere is ~1100 m and this new configuration will have 500 m. Current CESM2 model top height is ~40 km and this new configuration will have a model top of ~80 km. A coupled preindustrial control simulation of length 500 years will be performed to compare directly to the low vertical resolution CESM2 preindustrial control that is already available. In addition, an abrupt 4xCO2 simulation of length 500 years will be performed to compare with the existing corresponding simulation with low-top CESM2. All other aspects of the model (e.g., dynamical core and boundary layer resolution) will be kept the same as in previous simulations. The approximate cost of this 80L configuration is ~8500 core-hours per year. Total cost = (2 x 500 x 8500) = 8.5 million (4.25 M in year 1; 4.25 M in year 2).

P4. Mesoscale convective systems (MCS) tracking: Simulations with CAM-SE with RR down to 1/8° resolution over North America and 1° resolution elsewhere will be used to develop a tracking algorithm for MCSs and other weather extremes via machine learning. Two 15-year simulations will be performed. One under preindustrial conditions with prescribed climatological SSTs that are representative of that period and another under an idealized global warming scenario where the SSTs are warmed globally by 4K and atmospheric CO2 concentrations are quadrupled. These simulations will be used to train and test the detection algorithm, explore pre-cursors to such events, and examine the dynamics of these systems in present and future climates. We estimate that around 1/20th of the globe will be regionally refined in these simulations, placing the estimated cost of an uncoupled simulation at ~70 000 core-hours per year. The total cost of these experiments will, therefore, be 2 x 15 x 70 000 = 2.1 M in year 1.

P5. TC-Front-Stormtrack interactions: TC winds disrupt the upper-ocean stratification, bringing cold water up to the ocean surface and injecting warm water down into the ocean interior (Price 1981) with impacts on mid-latitude SSTs (Li and Sriver 2018), in particular along the Oyashio/Kuroshio front, which is critical for winter storm track activity in the Pacific. This set of experiments will explore how the SST anomalies induced by TC-ocean interactions can influence the North Pacific storm track during boreal winter. Two 20-member ensembles with prescribed SSTs of length 1 year will be performed with CAM-SE with RR down to 1/4° resolution over the Pacific and 1° resolution elsewhere. In one set of simulations, a seasonally varying climatology of SSTs will be prescribed. In another, the SSTs will be perturbed to include an SST anomaly induced by TC activity (already determined from a prior simulation). We estimate that this will involve regionally refining ~ 0.128 of the globe which leads to a cost of ~24 000 core-hours per year. Total cost: 2 x 20 x 24000 = 0.96 M in year 1.

P6. Hosing experiments: This targeted set of experiments will explore AMOC recovery under different freshwater hosing scenarios within CESM2. This will improve our understanding of potential tipping points in the system under climate change. Branching from the existing CESM2 preindustrial control, a 150-year simulation under preindustrial forcings will be performed but with moderate freshwater hosing of 0.3 Sv (1 Sv = 10^6 m^{-3}) imposed in the subpolar North Atlantic (experiment 1). Two experiments will be branched off experiment 1: in experiment 2, the hosing will be stopped after 20 years and the run continued without hosing for 100 years; in experiment 3, the hosing will be stopped after 50 years and continued for another 100 years with no hosing to assess whether AMOC recovers. Experiments 1, 2, and 3 will then be repeated with stronger and weaker hosing (0.5 Sv and 0.1 Sv, respectively). Furthermore, a realistic hosing scenario will be performed based on freshwater runoff from the Greenland ice-sheet model under SSP5-8.5 forcing. This simulation will be 85 years long. All experiments will be coupled CESM2 simulations at a cost of 3500 core-hours per year. Total cost = (3500 x 3 x (150 + 120 + 150)) + (3500 x 85) = 4.71 M (4.41M in year 1; 0.3 M in year 2).

P7. DAMIP simulations: CESM2 will be used to complete two ensembles of Tier 2 and Tier 3 DAMIP simulations to contribute to CMIP6. For the historical period, two 3-member ensembles from 1850 to 2020 will be completed. The histSOZ (3 members) and histCO2 (3 members) simulations use climatological 1850 forcings except for time evolving historical stratospheric ozone and time evolving CO2, respectively. In addition, 1 member from each of 6 future DAMIP scenarios will be run from 2020 through to 2100: ssp245GHG, ssp245SOZ, ssp245AER, ssp245VLC, ssp245CO2, and ssp245SOL. Historical cost = 6 x 171 x 3500 = 3.59 million. SSP cost = 6 x 80 x 3500 = 1.68 million. Total = 5.27 M (3.59 M in year 1; 1.68 M in year 2).

P8. Pencil model simulations: A suite of simulations will be performed with the newly developed pencil ocean model. This ocean model does not include deep or lateral ocean circulation, but incorporates one-dimensional vertical physics, including for ocean mixed layer as well as for representation of the ocean circulation associated with Ekman pumping in the mixed layer. This is, therefore, a much more advanced representation of the ocean mixed layer compared to a slab ocean model that has been used previously. The pencil model allows for time varying mixed layer depth. A 1000-year-long preindustrial control simulation will be performed that will be complementary to those already available. In addition, a 10-member ensemble of historical simulations from 1850 to 2014 will be performed to directly complement the coupled and prescribed SST historical simulations that have already been performed with CESM2. Comparison of the pencil model simulations with the fully coupled simulations will allow for exploration of the role of the deep ocean circulation in climate variability and change. An estimate of the cost of this configuration is around 2770 core-hours per year. Total cost of these simulations is (1000 x 2770) + (10 x 165 x 2770) = 7.34 M in year 2.

P9. RR North Atlantic AMIP simulation: A CAM-SE historical simulation with prescribed observed SSTs from 1950 to 2014. This will use RR down to 1/8° over the North Atlantic with 1° resolution elsewhere. We estimate that we will regionally refine around 0.11 of the globe, leading to a model cost of 140 000 core-hours per year. Total cost = 140 000 x 65 = 9.1 M in year 2.

P10. Stochastic physic piControl: A coupled preindustrial control simulation with CESM2 plus stochastic physics parameterizations. Approximating the cost as 3500 core-hours per year (i.e., similar to CESM2 without stochastic physics), a 1000-year preindustrial control will cost 1000 x 3500 = 3.5 M in year 2.

P11. Indian ocean pacemakers: A 10-member ensemble of CESM2 coupled simulations from 1880 to 2020 with SST anomalies in the Indian Ocean nudged toward observed. These will complement the existing CESM2 tropical Pacific Pacemakers and allow for exploration into the role of Indian Ocean SST variability on the global climate. 10 x 141 x 3500 = 4.9 M in year 2.

P12. RR Tropical belt: A RR CAM-SE AMIP (CAM6 physics) configuration designed to investigate tropical dynamics will be developed. This simulation will use RR down to 0.25° in the tropics from 30°S-30°N and 1° elsewhere. An historical AMIP simulation from 1979 to 2015 will be performed and will be used to develop and study algorithms for Atmospheric River detection, assess TC statistics, and study MJO dynamics, land atmosphere coupling and extreme precipitation. Estimating the cost of this RR configuration to be 76 000 core-hrs per year gives 1 x 37 x 76 000 = 2.81 M in year 2.

* denotes made available through the climate data gateway; core-hours highlighted in blue are Year 1, highlighted in pink are Year 2.

Experiment	Configuration	Resolution	# simulations	# years/simulation	core - hr/sim-yr	Total in M core-hours	Data Volume (TB)	Priority A/B/C
P1. SSP2-4.5*	CESM2-BGC (BSSP245)	f09_g17	12	87	3500	3.654	56.7	A
P2. TVSST*	CESM2-BGC (F1850)	f09_f09	1	500	2200	1.100	6.8	B
P3. 80L CESM2 (piControl)*	CESM2-BGC (B1850)	f09_g17	1	500	8500	4.250	50.4	A
P3 80L CESM2 (abrupt4xCO2)*	CESM2-BGC BCO2x4CMIP	f09_g17	1	500	8500	4.250	50.4	B
P4. MCS Tracking	CAM-SE	ne30_ne30 (with regional refinement to ne240 over North America)	2	15	70000	2.100	15.8	A

P5. TC-Front-Stormtrack interactions	CAM-SE	Ne30_ne30 (with regional refinement to ne120 over the Pacific	40	1	24000	0.960	15.2	A
P6. Hosing (1)	CESM2-BGC	f09_g17	3	150	3500	1.575	24.4	A
P6. Hosing (2)	CESM2-BGC	f09_g17	3	120	3500	1.260	19.6	A
P6. Hosing (3)	CESM2-BGC	f09_g17	3	150	3500	1.575	24.4	A
P6. Hosing (4)	CESM2-BGC	f09_g17	1	85	3500	0.298	4.6	B
P7. DAMIP historical*	CESM2-BGC	f09_g17	6	171	3500	3.591	80	A
P7. DAMIP Future (SSP's)*	CESM2-BGC	f09_g17	6	80	3500	1.680	30.9	C
P8. Pencil Model (piControl)*	CESM2-BGC (B1850)	f09_g17	1	1000	2770	2.770	54.3	A
P8. Pencil Model (historical)*	CESM2-BGC (BHIST)	f09_g17	10	165	2770	4.571	89.6	B
P9. RR Atlantic AMIP*	CAM-SE (FHIST)	Ne30_ne30 (with regional refinement to ne240 over the Atlantic)	1	65	140000	9.100	65.3	B
P10. Stochastic physics*	CESM2-BGC (B1850)	f09_g17	1	1000	3500	3.500	54.3	C
P11 Indian Ocean Pacemakers*	CESM2-BGC	f09_g17	10	141	3500	4.935	47	B
P12 RR tropics	CAM-SE	ne30_ne30 (with regional refinement to ne120 from 30°S to 30°N)	1	37	3500	2.812	49	B

Earth System Prediction Working Group (ESPWG)

1. Broad Overview of Working Group and Research Plan

ESPWG focuses on understanding the processes responsible for predictability on scales from subseasonal to decadal and filling a very much needed niche of providing the community a framework for performing and analyzing initialized predictions of the Earth system as well as serving as a community nexus for ESP research.

Experiments proposed by ESPWG focus on facilitating community efforts to understand the sources of predictability on timescales from subseasonal to decadal, and exploring the many uncertainties associated with ESP system design, such as land, ocean, atmosphere initialization, drift, bias, etc. Key science questions that the group will address are a. how and at what time scales do individual Earth system states (land, atmosphere, ocean, and sea-ice) affect predictability, and b. how do various aspects of prediction system design (such as ensemble size, initialization technique, and model structural characteristics, including resolution and physical parameterization) impact prediction skill.

In the next two years, the group's developmental efforts will focus on case study sensitivity tests to efficiently assess the impact on subseasonal to decadal skill of different choices for: initialization, model physics, ensemble size, and atmospheric vertical resolution. These efforts will include tests of initialization using data-constrained atmosphere and ocean states produced by ensemble data assimilation (DA) and work to optimize DA initialization in the presence of model biases. The proposed production simulations will focus on understanding predictability on seasonal to multi-year timescales using the new CESM2 model, as well as a detailed assessment of sources of predictability and the role of stochastic physics on the subseasonal timescale. The annual breakdown of our compute request (17.5 M in Year 1, 23.4 M in Year 2) is slightly overloaded up front, but we anticipate that some of the Year 1 work will bleed into Year 2.

2. Development Proposal (Y1: 7.1 M; Y2: 2.0 M; total 9.1 M core-hours)

D1. Anomaly Initialization Sensitivity Experiments (AISE): Case study experiments will be performed to test the potential benefits of anomaly initialization instead of full field initialization for seasonal to decadal prediction. Experiments will consist of initialized ensemble hindcasts using CESM1 or CESM2 in which one or more component models will be initialized with observation-based anomalies added to CESM climatology. The impact of initialization will be quantified by comparing anomaly-initialized hindcast signals with those in (uninitialized) historical large ensembles (CESM1-LENS or CESM2-LENS). For seasonal to multiyear timescales, SMYLE (see below) will be used as the baseline prediction dataset against which improvement can be assessed. For decadal timescales, CESM1 Decadal Prediction Large Ensemble (CESM1-DPLE) will be used as the baseline prediction dataset. The skill assessment will depend on the case study to be explored. Candidate case studies include (but are not limited to): 1. the abrupt mid-1990s warming of the Atlantic subpolar gyre; 2. the 2015 *cold blob* in the subpolar Atlantic; 3.

the 2014 North Pacific *warm blob*; and 4. the 1997/98 El Niño. The cost of such experiments will depend on multiple factors such as: model configuration (e.g., CESM1 or CESM2); simulation length (e.g., 1-year simulations to probe the 2015 cold blob; 10-year simulations to probe the mid-1990s warming); and ensemble size. As an example, a 10-member ensemble integrated for 2 years using CESM2 will cost 70,000 core-hours (3500x2x10). A 10-member ensemble integrated for 10 years using CESM1 will cost 230,000 core-hours (2300x10x10). We budget for roughly 13 CESM2 experiments and 5 CESM1 experiments. (2.06 M Year 1)

D2. Data Assimilation Case Studies (DACS): We propose several case studies to evaluate performance of data-constrained initial states in predictability experiments at subseasonal-to-decadal timescales. Each experiment will consist of an ensemble hindcast initialized by the posterior distribution of an ensemble DA procedure constrained by in-situ observations in both ocean-only and ocean and atmosphere (weakly coupled DA) simulations. Impacts of initialization will be assessed by comparison to uninitialized historical large ensembles (CESM2-LENS) as well as to full-field initialized (SMYLE) and anomaly-initialized hindcasts (Section D1). Case studies will target the 2015 North Atlantic *cold blob* and the 2014 North Pacific *warm blob*. Costs of experiments will depend on the number of ensemble members run (DA and prediction), DA domain (ocean-only vs. weakly coupled), DA type (Ensemble Adjustment Kalman Filter vs. Ensemble Optimal Interpolation), and run length, both in the DA period leading up to the start date and in the predicted interval. We budget for approximately 8 coupled ocean – sea-ice DA initialization experiments in Year 1 to test sensitivity to different DA durations before initialization, and 3 coupled DA experiments in Year 2. (1.5 M Year 1; 1.52 M Year 2)

D3. S2S Case Studies (S2S-CS): Subseasonal-to-seasonal (S2S) case study experiments for five extreme events linked to large-scale phenomena are proposed to test the impact of ensemble size, ocean initialization, and model parameter changes on prediction skill. The existing or proposed control hindcasts already contain 11 members. An additional 11 members will be run for the specific cases using the same setup as the control hindcasts. Additionally, five different configurations of ocean initialization, and model parameter changes will be tested for each case. The experiments will be performed for three start dates for each case to test the ability to predict the initiation and evolution of each event. Furthermore, the output for these events will be sufficient to drive regional models for dynamical downscaling purposes. The case studies will consist of five cases involving two TCs, flash drought, an atmospheric river, and a sudden stratospheric warming. (3.5 M Year 1)

D4. Atmosphere Vertical Resolution Sensitivity Experiments (AVeRSE): To explore the impact of atmospheric vertical resolution on system prediction skill, we will re-run multi-year and S2S prediction case studies (following the lead of tasks D1.AISE and D3.S2S-CS) with the only change being the use of a new CAM vertical grid (currently under development) that has increased vertical resolution in the boundary layer and throughout the free troposphere. These CESM2 prediction sensitivity experiments will be compared to baseline hindcast sets (CESM2-SMYLE and CESM2-S2S, respectively), uninitialized ensembles, and corresponding D1.AISE and D3.S2S-CS hindcasts. For multi-year case studies, we request for approximately 3 1-year simulations using 10 members (~280,000 core-hours) and for S2S case studies roughly 17 45-day hindcasts using 11 members (~220,000 core-hours), noting that the precise cost of CESM2 with enhanced atmosphere vertical grid is currently unknown. (0.5 M Year 2)

3. Production Proposal (Y1: 10.5 M; Y2: 21.4 M; total 31.9 M core-hours)

P1. Seasonal/Multi-Year Large Ensemble (SMYLE) Hindcasts: While the CESM1-DPLE continues to be an important data resource for ESPWG, there is a need for a new set of initialized, multi-year hindcasts using the new CESM2 model to entrain a broader group of scientists into ESPWG. Toward that goal, ESPWG proposes to begin building up a set of CESM2 initialized hindcasts that can bridge seasonal to multi-year to (eventually) decadal timescales. Our SMYLE production runs begin to work towards that ambitious goal by focusing on the multi-year timescale that has heretofore been relatively unexplored. SMYLE hindcasts will be initialized 4 times per year (November 1, February 1, May 1, August 1) for each year between 1970-2019 (50 x 4 = 200 start dates). The prediction simulations will run for 2 years, and each hindcast will use a 20-member ensemble. This experiment therefore entails 8,000 simulation years using the current, fully-coupled CESM2 version at nominal 1° resolution. At the rate of ~3,500 core-hours/sim-year, the computational cost of SMYLE is ~28 M core-hours. A CISL NSC award (Spring 2020) was granted that will partially cover the expense of this experiment (18 M core-hours on Cheyenne). To complete the set of hindcasts, an additional 10 M core-hours is needed. (10 M Year 1)

P1.1 SMYLE extension: An additional 9 M core-hours will allow ESPWG to extend SMYLE in one of several ways: 1. increase the ensemble size to improve detectability of predictable signals that are expected to be present but unrealistically weak; 2. extension of a subset of the hindcasts to probe predictability over longer time horizons, e.g., extension from 2-year to 5-year hindcasts for select start dates; or 3. expansion of the hindcast set backwards in time to include pre-1970 start dates or forward in time to include 2020-2022 initializations. The choice of how to extend SMYLE will depend on results obtained in the initial set and will be determined through working group discussion. (9 M Year 2)

P2. 2020/2021 S2S Hindcasts (S2S-2020): S2S hindcasts with weekly start dates, run length of 45 days using 11 ensemble members, have been carried out with default CESM2 for years 1999-2019 following the SubX protocol (Pegion et al. 2019) and will be provided soon as a community resource for exploring sources of predictability on the subseasonal timescale. We will extend these runs through September 2021 as initial conditions become available. These simulations will allow us to assess the prediction skill of CESM2 and explore mechanism of generation for recent weather extreme events. (0.45 M Year 1)

P3. 2021/2022 S2S Hindcasts (S2S-2021): Similar to task P2 (Year 1 of proposal), we will extend the S2S hindcasts run with CESM2 through September 2022. These simulations will allow for examining predictability of recent extreme weather events. (0.25 M Year 2)

P4. S2S Predictability Source Experiments (S2S-PSE): To isolate the role of land, ocean, and atmosphere on predictability on subseasonal time scales, sensitivity experiments will be carried out by replacing the observed initial state of the model with a climatological one for each one of the model components (land, ocean and sea-ice, atmosphere). S2S hindcasts will be run for the winter season November - March for years 1999-2019 and follow the methodology for the existing S2S hindcast set for a clean comparison. Three sets of experiments (each one with changes to either land, ocean and sea-ice, and atmosphere) will be performed, each one costing 2 M core-hours. (6 M Year 2)

P5. S2S with SPPT (S2S-SPPT): To examine the role of stochastic physics on subseasonal predictability, the S2S hindcast set with CESM2 will be rerun with the addition of Stochastically Perturbed Physics Tendency (SPPT) following the SubX protocol (Weekly starts, years 1999 to 2019, 11 ensemble members). The baseline set has already been carried out. These simulations will allow for a thorough evaluation of the influence of stochastic physics on predictability of precipitation, cold and warm weather outbreaks, and the MJO. (5 M Year 2)

P6. Decadal Predictability Source Experiments (DPSE): The CMIP6 Decadal Climate Prediction Project (DCPP) Component C2 experiments (Boer et al. 2016) call for a set of perturbed initialization hindcasts to probe the mechanisms associated with the mid-1990s abrupt warming in the subpolar North Atlantic (SPNA). ESPWG will undertake a limited set of C2 experiments using CESM1, with CESM1-DPLE (officially submitted to CMIP6) to be used as the control. Five hindcasts of CESM1-DPLE (1992-1996) will be redone using 10-member ensembles, with the only change being that the ocean initial conditions from CESM1-DPLE will be altered to have climatological ocean conditions in the SPNA. Comparison with the original CESM1-DPLE hindcasts will reveal the impact of anomalous SPNA conditions on decadal Atlantic predictability. (1.15 M Year 2)

Experiment	Configuration	Resolution	# simulations	# years/simulation	core-hr/sim-yr	Total in M core-hours	Data Vol/sim-year (TB)	Total Data Vol (TB)	Priority (A/B/C)
Development Year 1									
D1.AISE-CESM1	CESM1-BHIST	f09_g17	5	100	2300	1.15	0.035	N/A	A
D1.AISE-CESM2	CESM2-BHIST	f09_g17	13	20	3500	0.91	0.075	N/A	A
D2.DACS 1	CESM2-GIAF+DART	f09_g17	3	4,6,11 (21 total)	31244	0.66		N/A	A
D2.DACS 2	CESM2-BHIST	f09_g17	6	40	3500	0.84	0.075	N/A	A

D3.S2S-CS	CESM2-BHIST	f09_g17	825	45 days (0.123 yrs)	3500	3.5	0.015	1.5	A
Production Year 1									
P1.SMYLE	CESM2-BGC B20C/BSSP	f09_g17	72 out of 200	40	3500	10.0	0.035	280	A
P2. S2S-2020	CESM-BHIST	f09_g17	1001	45 days (0.123 yrs)	3500	0.45	0.015	2	A
Total Year 1						17.5 1		283. 5	
Development Year 2									
D2.DACS 1	CESM-BHIST+DAR T	f09_g17	3	3,5 (7 total)	15622 0	1.24	3	N/A	A
D2.DACS 2	CESM-BHIST	f09_g17	2	40	3500	0.28	0.075	N/A	A
D4.AVeRSE.SM Y	CESM2-BHIST	f09_g17	3	10	10500	0.28	0.075	N/A	B
D4.AVeRSE.S2 S	CESM2-BHIST	f09_g17	170	45 days (0.123 yrs)	10500	0.22	0.015	1	B
Production Year 2									
P1.1.SMYLEext	CESM2-BGC B20C/BSSP	f09_g17	2570	1	3500	9.0	0.035	90	B
P3. S2S-2021	CESM-BHIST	f09_g17	572	45 days (0.123 yrs)	3500	0.25	0.015	1	A
P4. S2S-PSE	CESM-BHIST	f09_g17	14520	45 days (0.123 yrs)	3500	6.0	0.015	27	A
P5. S2S-SPPT	CESM-BHIST	f09_g17	11440	45 days (0.123 yrs)	3500	5.0	0.015	20	A
P6. DPSE	CESM1-BHIST	f09_g17	5	100	2300	1.15	0.035	17.5	A
Total Year 2						23.4 2		156. 5	

Land Ice Working Group (LIWG)

1. Broad Overview of Working Group and Research Plan

The main objectives of LIWG during 2020–2022 are to develop new physics parameterizations in the Community Ice Sheet Model (CISM), to extend ice-sheet coupling to marine-based ice sheets in CESM2, and to carry out coupled ice-sheet and climate simulations with interactive Greenland, Antarctic, and paleo ice sheets. We aim to understand and simulate land-ice evolution on time scales of decades to millennia, and thus to provide scientifically sound estimates of future sea-level rise and associated uncertainties.

CISM development priorities include: i) subglacial hydrology based on the SHAKTI model (Sommers et al. 2018); ii) improved treatments of ice fracture and calving; and iii) new parameterizations and reduced-order ocean models to compute sub-ice-shelf melt rates. These developments will support coupled modeling of marine ice sheets, a major goal for CESM3. With planned software advances, we will be able to run CESM2 with multiple CISM domains (e.g., both Greenland and Antarctica), with two-way coupling between the ocean and ice-sheet models. (Previously, ice sheets have been interactively coupled to the land and atmosphere, but not the ocean.) High-priority coupled simulations include:

- Multi-century simulations of future Greenland deglaciation, to study ice-sheet stability and potential recovery;
- Paleoclimate simulations of Northern Hemisphere ice-sheet inception at the end of the Last Interglacial period, and of Greenland ice-sheet evolution during the Holocene;
- Studies of future Antarctic ice-sheet evolution and feedbacks with the atmosphere and ocean; and
- Simulations of glacier SMB in High Mountain Asia, using a new variable-resolution grid.

Some of these simulations will be new capabilities not only for CESM, but for Earth system models generally, and will enable high-profile science publications. Following the extensive participation of the LIWG in the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6), these simulations will also support LIWG contributions to ongoing intercomparison projects, including ISMIP, the Paleoclimate Model Intercomparison Project (PMIP), and the Marine Ice Sheet–Ocean Model Intercomparison Project (MISOMIP).

2. Development Proposal (Y1: 6.0 M; Y2: 9.0 M; total 15.0 M core-hours)

a. Goals

The development allocation will support new physics parameterizations in CISM (e.g., models of subglacial hydrology, calving, and hydrofracture); CISM development to allow the representation of mountain glaciers, particularly in High Mountain Asia; land-ice-relevant developments in CLM; and more complete coupling of CISM with POP (initially) and MOM6 (in a later stage). We will use part of the development allocation to test and carry out a variety of fully-coupled CESM simulations, with the aim of providing more realistic initial conditions and ice sheet–ocean interactions for simulations of future Greenland and Antarctic ice-sheet evolution. Also, we will test CISM applications to paleo ice sheets, including the large Northern Hemisphere ice sheets that advance and retreat during glacial cycles. These developments are prerequisites for several of the simulations in our production proposal.

b. Specific simulations and computational requirements

D1. Development of the Community Ice Sheet Model (2.8 M core-hours; year 1 and 2): We will improve the realism of CISM physics parameterizations for both standalone and coupled ice-sheet simulations. Specifically, we will implement the SHAKTI hydrology model (Sommers et al. 2018) with the goal of applying it to both Greenland and Antarctica. We will also implement new physics-based calving and hydrofracture parameterizations to improve marine-ice simulations and assess possible instabilities triggered by ice-shelf loss. We will test new parameterizations first in standalone CISM with idealized test cases, then for standalone Greenland and Antarctic simulations with data forcing, and finally in coupled CESM runs. CISM grid resolution will range from 2 to 8 km, with coarser resolutions for debugging and finer resolution for realistic spin-ups.

D2. Land-ice-relevant development in CLM (1.4 M core-hours; year 1 and 2): The ice-sheet SMB is computed in CLM (now part of the Community Terrestrial Systems Model, CTSM). Thus, coupled ice-sheet simulations require realistic snow and firn simulations in CLM. We will modify the SMB definition in CLM so that growth and melting of the snow column (in addition to ice growth and melting) will contribute to SMB passed to CISM. We will continue to improve the treatment of snow and firn, for example by implementing a blowing snow model, adding more sophisticated water percolation schemes, and revising the parameterization of meltwater refreezing in firn.

D3. Development to support coupled ice-sheet–ocean simulations (2.8 M core-hours; year 1 and 2): This work will support coupled simulations with ice-sheet–ocean interactions. We will develop and test new parameterizations and simple models that translate far-field ocean conditions (e.g., ocean temperature and salinity near the calving front) to basal melt rates in sub-ice-shelf cavities. In this way, we can better simulate mass changes in marine ice sheets in long-term simulations, and analyze regional and global feedbacks involving ocean circulation, biogeochemistry, and sea-ice. We will develop improved spin-up techniques that bring ice sheets into steady state not only with SMB received from CLM, but also with lateral and sub-shelf melting of marine ice. The ocean boundary conditions will be taken initially from POP, and later from the new MOM6 model, which can support ocean circulation beneath floating ice shelves. This development will support LIWG participation in the MISOMIP2 project.

D4. Simulation of Northern Hemisphere ice sheets in paleoclimate studies (2.8 million core hours, year 1 and 2): We have recently started using CISM to simulate paleo ice sheets, including the Laurentide and Eurasian ice sheets that covered high-latitude northern land masses during glacial periods. For the new allocation, we will run coupled simulations of Northern Hemisphere ice-sheet inception at the end of the Last Interglacial, along with ice-sheet retreat during the Holocene. We will first carry out standalone CISM simulations with data forcing to test new physical parameterizations (D1) and explore parameter space. These simulations require relatively high resolution (~4 km) and long duration (many millennia).

D5. Initializing the Greenland Ice Sheet for future simulations (1.6 M core-hours; year 1): In recent CESM2 simulations, the present-day Greenland Ice Sheet (GrIS) was initialized to be too large in extent and volume, complicating the analysis of future Greenland area and volume changes. We will work to improve the present-day Greenland volume, by adapting and extending the JG/BG accelerated spin-up technique developed by LIWG members (Löfverström et al. 2020) and by coupling outlet glaciers to the ocean. We will also test the impact of horizontal resolution (f19_g17 versus f09_g17) and evaluate the quality of the lower-resolution (~2°) simulations over Greenland.

D6. CISM development to support mountain glacier simulations (2.0 M core-hours; year 2): Using a new variable-resolution (VR) atmospheric grid, CESM is now being used to simulate the climate of High Mountain Asia (HMA) at resolutions as high as 7 km. One goal of VR simulations is to generate SMB output that is sufficiently accurate to force a high-resolution glacier model. We will therefore develop CISM to support simulations of mountain glaciers, forced with the SMB from VR simulations carried out in year 1 (P5). These CISM runs will require sub-km spatial resolution to resolve individual glaciers, as well as new techniques to estimate initial glacier thickness in data-sparse regions.

D7. Software engineering and new diagnostics (1.6 M core hours, year 1 and 2): This part of the allocation will cover standard software testing of developments to CISM, CLM, and the coupler, including running the CLM automated test suite. Also, with support from a newly funded NSF Cyberinfrastructure project, we will develop and test a diagnostic package for land-ice outputs in CESM. The goal will be to unify land-ice diagnostics with ongoing development of other CESM component packages that use the python framework.

3. Production Proposal (Y1: 9.0 M; Y2: 16.5 M; total 25.5 M core-hours)

a. Goals

Our production proposal focuses on simulating and understanding the interactions between ice sheets and the rest of the climate system. Our first goal is to use CESM2, coupled to CISM, to explore the long-term, centennial-scale response of the Greenland Ice Sheet to global warming, and to explore thresholds for ice-sheet collapse and recovery under different forcing scenarios. We will also carry out coupled runs that allow, for the first time in CESM, detailed study of ice-sheet interactions with the ocean. We will run multi-century simulations of the future evolution of both Greenland and Antarctica for a variety of forcing scenarios and model settings. Another focus will be coupled simulations of the past evolution of Greenland and other Northern Hemisphere ice sheets, e.g., at the end of the Last Interglacial and throughout the Holocene. Running with accelerated ice-sheet dynamics, and optionally at coarser atmospheric resolution (FV2), will enable multi-millennial simulations. We will also run high-resolution simulations of HMA climate and glacier dynamics, study the impact of changing ocean conditions on Greenland climate and SMB, and explore Antarctic elevation–mass balance feedbacks. Several production runs are joint projects with other working groups, including the AMWG, PCWG, and PaleoWG.

b. Specific simulations and computational requirements

P1. Greenland Ice Sheet beyond 2100 in CMIP6 scenarios (0.7 M core-hours; year 1): In the framework of ISMIP6, LIWG has run simulations of GrIS evolution to 2100 (Muntjewerf et al. 2020a) under the high-emission SSP5-8.5 forcing scenario. Using new output from extended (2100-2300) CESM2(WACCM6) experiments, our Greenland-focused runs can now be extended to 2300. This will be done initially for the SSP5-8.5 scenario. If the SSP5-8.5 extension is completed during the current allocation, we will run a 200-year extension for the moderate-emission SSP5-3.4 overshoot scenario.

P2. Long-term Greenland mass loss reversibility (3.15 M core-hours; year 1): The 2015 Paris Agreement aims to limit the global mean temperature increase to “well below” 2.0°C relative to preindustrial. Here, we are interested in (1) the long-term effect of such a scenario on Greenland mass balance and (2) the health of the firn layer in both the GrIS and the Antarctic Ice Sheet (AIS). For GrIS, it is believed that even a Paris-compatible scenario will set off a slow deglaciation, which possibly can be prevented or reversed due to ice-sheet inertia. We will study several new scenarios with peak greenhouse gas concentrations (GHGs) followed by carbon drawdown, using CESM-CISM with an interactive GrIS. We will focus on the impact of ice-sheet dynamics, freshwater, and firn retention thresholds. The requested allocation supports a 400-year CESM run (with CISM run asynchronously) to full deglaciation; two 150-year recovery runs; and a partly coupled 200-year run with fixed ice-sheet topography.

P3. Interglacial to glacial simulation of Northern Hemisphere ice sheets (3.0 M core-hours; year 1 and 2): Using CESM-CISM, we will simulate the later stages of the Last Interglacial period, the last glacial inception, and the transition to glacial conditions, covering years 120 ka to 112 ka with 5x acceleration of orbital and ice-sheet clocks. This simulation will bridge two previous coupled simulations, investigating (1) the deglaciation of GrIS during the warm phase of the Last Interglacial period, and (2) the last glacial inception and transition into glacial conditions. These simulations will use a high-resolution (4-km) Northern Hemisphere CISM grid and are of great interest to the paleoclimate and ice-sheet research communities. This project is co-sponsored with PaleoWG. The requested allocation will cover one-half of a 1600-year CESM run with asynchronous CISM (5 CISM years per CESM year).

P4. Greenland Ice Sheet through the Holocene (2.3 M core-hours; year 1 and 2): This project would build on a current CESM-CISM simulation of GrIS evolution from 9 ka to 6 ka, with natural vegetation updated using output from the BIOME4 model. We will continue this run through the period from 6 ka to 1850 CE. Paleo records show that GrIS retreated behind the present-day margin and subsequently readvanced during the Neoglacial or 'little ice age'. The timing and retreat rates vary spatially and do not coincide with the peak Holocene warming (4°C) at 11–8 ka estimated from ice core records, implying additional regional feedbacks and forcing. For example, the local ice caps and glaciers across Northern Greenland readvanced around 5 ka in response to reduced sea-ice cover and increased precipitation. The final ice sheet and climate state will be compared to the JG/BG spin-up (Löfverström et al. 2020) and could serve as a starting point for future GrIS simulations. This project is co-sponsored with PaleoWG. The requested allocation will cover one-half of a 1200-year CESM run with 5-to-1 asynchronous CISM.

P5. High-resolution simulations of HMA (2.55 M core-hours, year 1): HMA holds the largest ice and snow reserves outside the polar regions and provides vital water resources for billions of people living in the mountainous regions and surrounding lowlands. This region is highly vulnerable to climate change, which likely will affect HMA cryosphere and hydrology, but is challenging to study using at Earth system model scales. To improve the representation of complex mountainous terrain and small-scale heterogeneous processes, we will apply a variable-resolution (VR) atmospheric grid with regional refinement up to 7 km. Using this VR grid, we will run CESM (at a cost of 85 K core hours per simulated year) from 1999 until 2058, to evaluate historical model performance and assess the near-future evolution of HMA glaciers. The simulations will be forced with prescribed SST and sea-ice from a coupled 1° simulation under the same future emissions scenario. The appropriate output will be saved to investigate forcing of CISM over the HMA domain, to better understand the response of HMA glaciers to climate change (D6). This project is co-sponsored with the AMWG, and the requested allocation will cover one-half of a 60-year simulation.

P6. Ocean impacts on Greenland climate (2.1 M core-hours, year 2): This project will explore the response of the GrIS SMB to surface and oceanic perturbations including: 1. sea-ice-free ocean (i.e., sea-ice impacts on atmospheric circulation, precipitation phase, distribution and amount); 2. no meltwater retention in firn (i.e., impacts of impermeable ice slabs on runoff); 3. rapid darkening of bare-ice areas in the ice-sheet ablation zone (i.e., impacts of bacterial, algal and impurities deposition on melt); and 4. rapid darkening of firn (i.e., impacts of large-scale snow metamorphism on melt). The requested allocation will support four simulations of 150 years each.

P7. Feedback on an evolving Antarctic ice sheet in the climate system (1.7 M core-hours, year 2): The elevation–temperature feedback accompanying ice-sheet retreat is well known. In addition to this thermodynamic feedback, recent modeling studies suggest that the high elevation of AIS also acts as a dynamic barrier to moist and dry poleward energy transport. This may help explain the relative lack of warming over the Antarctic continent today, but could portend greater future warming as AIS melts and its surface elevation decreases (Singh and Polvani 2020). To understand whether these dynamic processes related to surface orography are, indeed, a positive feedback on surface warming, we will conduct a series of CESM1 and CESM2 experiments in which Antarctic surface elevation is decreased according to CISM projections of future West Antarctic Ice Sheet (WAIS) retreat. Three fully-coupled experiments, each 230 years long, will be branched from the equilibrated preindustrial control experiment for each model with the following configurations: i) abrupt CO_2-doubling with the AIS at its present-day elevation; ii) abrupt CO_2 doubling with full WAIS retreat; and iii) full WAIS retreat only (CO_2 held at preindustrial levels). This project is co-sponsored by PCWG and LIWG, with costs shared equally.

P8. Coupled CESM2-CISM with second-generation spin-up technique and inclusion of ocean forcing (3.7 M core-hours, year 2): The coupled GrIS simulations described by Muntjewerf (2020a; 2020b) have two major shortcomings: The spun-up preindustrial and contemporary ice sheet has a greater area and volume than the present-day ice sheet, and the model does not apply ocean thermal forcing to outlet glaciers. This project aims to improve the spin-up and ocean forcing while exploring long-term ice-sheet deglaciation for a high-emission scenario to 2500 and a low-emission scenario to 2300. Development and preliminary spin-up runs will be done during year 1 under D5. The requested allocation will include a spin-up of 200 CESM years (with asynchronous CISM), followed by a historical run (1850–2014) and two scenarios runs of 500 and 300 years, respectively.

P9. Multi-century simulations of Antarctic ice sheet evolution (6.3 M core-hours, year 2): Following successful CESM-CISM simulations with an interactive GrIS, we will extend two-way coupling to AIS, taking advantage of new CISM and coupler development (D1 and D3). The AIS will be spun-up to steady state under modern (1950) conditions, combining JG/BG spin-up techniques with additional tuning for ice shelves (Lipscomb et al. 2020). We will then run the coupled model forward for several centuries, under different combinations of GHG forcing (e.g., moderate vs. high emissions scenarios) and ice-sheet physics (e.g., with and without rapid ice-shelf retreat). These simulations will primarily use POP, in which the ice-sheet–ocean boundary is fixed and sub-ice-shelf ocean temperature is extrapolated from the calving front into ice-shelf cavities. A subset of runs could include MOM6, if available. To reduce the cost per run, we will run CAM at FV2 resolution, which has been shown to give an Antarctic SMB similar to FV1. The requested allocation will support an ensemble of 12 runs of 350 years each (1950–2300). The estimated storage for these runs is about 92 TB.

Experiment	Compset	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in M of core-hours	Long-term storage needed (TB)	Priority
Development								
Year 1								
D1: CISM development	CISM-only	Various	Many	Various	Various	1.00	0	A

D2: CLM development	I, IG	f09, gl4	Many	Various	Various	0.60	0	A
D3: Ice–ocean coupling	TG, BG	f09_g17, gl4, an4	Many	Various	Various	1.00	0	A
D4: N. Hemisphere paleo ice sheets	CISM-only, TG	nh4	Many	Various	Various	1.00	0	B
D5: Greenland ice sheet initialization	BG	f09_g17, f19_g17, gl4	Many	Various	3500 (FV1), 1500 (FV2)	1.60	0	A
D7: Software engineering and diagnostics	Various	Various	Many	Various	Various	0.80	0	A
Total year 1						6.00		
Year 2								
D1: CISM development	CISM-only	Various	Many	Various	Various	1.80	0	A
D2: CLM development	IG	f09, gl4	Many	Various	Various	0.80	0	B
D3: Ice–ocean coupling	TG, BG	f09_g17, gl4, an4	Many	Various	Various	1.80	0	A
D4: N. Hemisphere paleo ice sheets	CISM-only, TG	nh4	Many	Various	Various	1.80	0	A
D6: Mountain glaciers in CISM	CISM-only, TG	hma4	Many	Various	Various	2.00	0	A
D7: Software engineering and diagnostics	Various	Various	Many	Various	Various	0.80	0	A
Total year 2						9.00	0	
Production								
Year 1								
P1: GrIS, extended CMIP6 run	BG	f09_g17, gl4	1	200	3500	0.70	9.4	A
P2a: GrIS, long-term deglaciation	BG	f09_g17, gl4	1	400	3500	1.40	18.8	A
P2b: GrIS, long-term recovery	BG	f09_g17, gl4	2	150	3500	1.05	14	A
P2c: GrIS, partly coupled	BG	f09_g17, gl4	1	200	3500	0.70	9.4	B
P3: N. Hem. interglacial–glacial (with PaleoWG)	BG	f09_g17, nh4	1	400	3800	1.52	19	A
P4: GrIS through Holocene (with PaleoWG)	BG	f09_g17_gl4	1	300	3800	1.14	14	A
P5: High Mountain Asia (with AMWG)	FHIST	VR HMA, g17	1	30	85,000	2.50	5	A
Total year 1						9.01	89.6	
Year 2								
P3: N. Hem. interglacial–glacial (with PaleoWG)	BG	f09_g17, nh4	1	400	3800	1.52	19	A
P4: GrIS through Holocene (with PaleoWG)	BG	f09_g17, gl4	1	300	3800	1.14	14	A

P6: Ocean impacts on GrIS climate	BG	f09_g17, gl4	4	150	3500	2.10	28	B
P7a: Antarctic elevation feedbacks, CESM2 (with PCWG)	B	f09_g17	3	115	3500	1.20	15.5	A
P7b: Antarctic elevation feedbacks, CESM1 (with PCWG)	B	f09_g16	3	115	1500	0.52	15.5	B
P8a: GrIS evolution: new spin-up/forcing, ssp5-85 to 2500	BG	f09_g17, gl4	1	850	3500	2.98	40	A
P8b: GrIS evolution: new spin/forcing, ssp1-26 to 2300	BG	f09_g17, gl4	1	200	3500	0.70	9.4	B
P9: Future AIS evolution	BG	f19_g17, an2	12	350	1500	6.30	92.4	A
Total year 2						16.46	233.8	
Totals					Year 1	15.01	89.6	
					Year 2	25.46	233.8	
					Development	15.01	0.0	
					Production	25.46	323.4	

Land Model Working Group (LMWG)

1. Broad Overview of Working Group and Research Plan

The goals of LMWG are to advance the state-of-the-art in modeling Earth's land surface, its ecosystems, watersheds, and socioeconomic drivers of global environmental change, and to provide a comprehensive understanding of the interactions among physical, chemical, biological, and socioeconomic processes by which people and ecosystems affect, adapt to, and mitigate global environmental change. Land biogeophysical and biogeochemical processes are intimately linked and therefore it is not possible to separate land biogeophysics development from land biogeochemistry development. For this and previous allocation requests, land biogeochemistry model development has been included in the LMWG request.

LMWG continues to pursue an ambitious program of model development. In particular, there are several large development projects that are underway, including a multi-layer canopy scheme, a representative hillslope hydrology model, and the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) configuration of the Community Land Model (CLM). These projects will continue into this CSL request along with other development projects on water management and agriculture model development. In addition, LMWG in collaboration with land modeling scientists across NCAR continue to work towards unifying land modeling activities across NCAR within the Community Terrestrial Systems Model (of which CLM5 is the current climate configuration of the broader CTSM).

Parameter estimation/calibration and sensitivity assessment are increasingly important LMWG activities. Within this allocation request is support for an unprecedented parameter exploration of the full CLM. Simulations investigating the role of land processes and their role in climate variability and change in support of LMWG research are also requested.

2. Development Proposal (Y1: 7.0 M; Y2: 11.0 M; total 18.0 M core-hours)

a. Goals

We lump the requested resources for model development into several classes of integrations that would be completed during typical model development activities. For biogeochemistry model development, to permit a faithful comparison against observations, the model needs to be run from preindustrial time up to present day (~165 years) with transient land cover and nitrogen deposition. Time is requested for several CLM spin-up simulations, and many historical land-only simulations, which are conducted regularly as model advances are pulled into the code (D1, D2, D7, and D8). As we transition to CLM(FATES) as a default configuration of CLM, there will be an increased emphasis on CLM(FATES) global simulations. CLM(FATES) is currently substantially more expensive (8x) than CLM5(BGC). Research is underway to identify possible sources of computational performance improvements in FATES. In this request, CLM(FATES) spin-up and historical simulation time are requested (D5, D6, D11, and D12).

As the complexity of CLM has continued to increase, so has the depth of interactions within the model along with the number of model parameters. During the latter stages of CLM5 development, LMWG embarked on a new effort in global parameter estimation / calibration. Parameter optimization for a global land model is challenging due to the complexity of the model (especially with an active carbon cycle), the long response timescales of key carbon and water processes, and the large number of poorly constrained parameters. Running at low resolution, we have been able to run a set of ensembles at preindustrial and present-day CO_2 levels for about 25 key parameters. Using an emulator and assuming linearity, we have then demonstrated that PFT-specific optimization of these key parameters can reduce biases in key land fields such as LAI, GPP, NPP, LH, and albedo. LMWG continues to refine our methods and are assessing the impact of assumptions of linearity and are working towards a method that can address both the relatively short timescale processes (order 20 years, e.g., vegetation and water processes, D3) and longer timescale processes (order 100 years, e.g., those related to soil carbon and nitrogen processes, D9).

Additionally, implicitly embedded within our model development request are resources that LWMG will use for emerging model development efforts with external collaborators. Past experience suggests that collaborators come to us with useful model development projects that were not included in the original request but that are best tested and integrated on NCAR computer systems. We plan to accommodate reasonable requests for such use. Selected model development activities that we anticipate over the length of this allocation period are outlined below. Several smaller projects are not explicitly listed.

b. Specific model development projects

Length of integrations for development projects differs widely; long century-scale integrations are included in the proposal, but often shorter simulations are sufficient for certain projects.

D5, D6, D11, and D12. Ecosystem demography (FATES): The CLM FATES component has been merged into the trunk of the CLM code, and continues to be the subject of great interest from the scientific community. Developing CLM(FATES) as an optional default model configuration of CLM is a high LMWG priority.

D1, D2, D7, and D8. Crop and forest management: Crop management (no-till, nitrogen use, irrigation, crop selection, cover crops) and forest management (harvesting, site preparation, silvicultural treatments) are being developed for CLM.

D1, D2, D7, and D8. Hillslope hydrology: CLM is collaborating with CUAHSI on a funded NSF project to advance the representation of hydrological processes in earth system models (Clark et al. 2015). Initial work has focused on the introduction of within-grid cell hillslope hydrology and aspect controls that will enable the model to capture the stark differences in ecosystem and water cycle behavior in upland vs. lowland environments.

D1, D2, D7, and D8. Multi-layer canopy: Land surface models treat the plant canopy as a single "big leaf," or in the case of CLM as two big leaves that represent the sunlit and shaded fractions of the canopy. Considerable theoretical and observational studies show that the big-leaf approach fails to fully capture the non-linearity of radiative transfer with canopy depth and within-canopy gradients of leaf traits, temperature, humidity, etc. Multi-layer canopy models do represent these gradients and will be implemented and tested in CLM.

D1, D2, D7, and D8. MIMICS: Implement a vertically-resolved version of the MIcrobial-MIneral Carbon Stabilization (MIMICS) model into CLM(BGC).

D4 and D10. CAM-CLM testing: Milestone land development projects will be tested in CAM-CLM configurations to examine the impact on simulated weather and climate. Standard evaluation simulations are 30 years in length to ensure statistical robustness of results. Occasional shorter simulations are also needed.

3. Production Proposal (Y1: 13.0 M; Y2: 23.0 M; total 36.0 M core-hours)

a. Goals

With CMIP6 Land Model Intercomparison Project (LandMIP) simulations mostly complete, LMWG is shifting focus to two priority computing projects. The first project is an ambitious parameter sensitivity effort termed the CLM5 Perturbed Parameter Ensemble (CLM5PPE). The goal of this community project is to complete a comprehensive multi-faceted parameter uncertainty assessment of the full CLM5(BGC) model and to assess the impact of parameter uncertainty on emergent features of the model, including the long-term carbon and water trajectories under climate change. A second major emphasis is on the transition to CLM(FATES) as a default configuration option for CESM3. To this end, LMWG requests allocation to complete preindustrial control, historical, and SSP simulations with CESM2(CLM5-FATES) to assess the impact of a representation of state-of-the-art vegetation demography on the coupled system. The remainder of the allocation request supports other LMWG community research activities related to fire emissions, land-atmosphere interactions, urban climate, and hillslope hydrology as well as support for non-CMIP-related MIPs that are anticipated over the coming CSL allocation cycle. Based on prior experience, time is also requested for collaborative community projects that are suggested in the normal course of LMWG activities during the allocation cycle (P19, P20).

b. Specific simulations and computational requirements

P1, P2, P9, P10. MIPs (TRENDY, PLUMBER2): Historical period land-only carbon, hydrology, and surface energy budget MIPs. Years required differs by MIP and in some cases is not yet fully defined. Request represents total numbers or years and spin-ups required that past experience suggests is typically required.

P3, P4, P5, and P6. CLM5 Perturbed Parameter Ensemble: Prior efforts to assess CLM parametric uncertainty have been hampered by computational constraints or code limitations, necessarily limited to selected parameters related to specific processes. LMWG plans to conduct a comprehensive tiered exploration of parameter sensitivity and uncertainty under the CLM5PPE umbrella. We have identified 200+ model parameters across processes that control energy, water, carbon, and nitrogen interactions. Phase 1 of CLM5PPE involves one-at-a-time high and low parameter perturbations for all 200+ parameters on a sparse grid (~250 grid cells) that reasonably captures the main features of global high-resolution simulations. Each simulation will be checked for reasonableness (e.g., vegetation survivability rates). Each parameter perturbation will also be run with environmental perturbations (CO2, climate, N-deposition) that span historical and projected values. A set of 50 parameters are selected for further evaluation with the criteria for selection based on their importance in determining the mean, variability, and responses to environmental perturbations for a range of key land climate variables. Phase 2 uses these parameters to run a Latin hypercube sparse-grid 2500-member perturbed parameter ensemble, again repeated for each environmental perturbation. In Phase 3, ~150 best performing parameter sets will be used to run an ensemble of historical and projection period 2° resolution simulations to provide a realistic and comprehensive assessment of parametric uncertainty. Phase 4 involves CAM6-CLM5 time slice simulations with a 50-member subset of the best performing parameter sets. All data output from this project as well as the scripting infrastructure to automate parameter perturbations, generate large ensembles, and assess model performance, will be made available to facilitate further parameter exploration of this and future versions of CLM.

P7. <u>LS3MIP Tier 2:</u> Land-only simulations anomaly-forced with future climate projections (2015-2100).

P8 and P16. <u>Climate Process Teams (CPTs):</u> LMWG is participating in two NOAA CPTs that focus on land-atmosphere interactions. The first team, CLASP (Coupled Land-Atmosphere Subgrip Parameterization), focuses on passing and using subgrid flux and state information between CLM and CAM. The second team is focused on developing parameterizations to account for mountain shading, snow impurities, and canopy impurities on surface radiation properties. Allocation for a series of CAM-CLM simulations is requested to support these CPTs.

P11. <u>Fire emissions:</u> Coupled historical simulations in which human influence on fire is turned off (no human ignitions or fire suppression or deforestation fires) which will enable a full assessment of the historic influence of humans on fire and its impact on climate through emissions and changes in ecosystem functioning. These simulations are complementary to the Fire Emissions community project.

P12. <u>Urban climate: Climate change, sustainable urban development, and climate adaptation:</u> This project aims to improve the understanding of urban hydroclimatic change and building energy use in response to large-scale climate change and to advance the science of sustainable urban development and climate adaptation strategies by utilizing the newly-developed urban surface datasets and building energy model (Oleson and Feddema 2019). The project will simulate change of urban climates and building energy use in response to future SSP or RCP scenarios and test a set of novel infrastructure-based urban climate adaptation and sustainability strategies including new roof, green infrastructure, and urban energy infrastructure.

P12, P13, and P14. CESM2(CLM-FATES): In Year 2, LMWG requests allocation to repeat preindustrial control, historical ,and SSP simulations with the CLM5(FATES) version to evaluate the impact of state-of-the-art vegetation demography on climate and carbon cycle simulations. These simulations are critical towards understanding the potential of utilizing CLM(FATES) in CESM3.

P17 and P18. CLM5(FATES-Hillslope): Spin-up, historical, and projection period simulations with flagship version of CLM in which the FATES model is combined with hillslope model. These unprecedented simulations will be at the cutting edge of land modeling and will enable research into how lateral water redistribution as well as slope and aspect affect vegetation distribution and functioning under a changing climate.

Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in M of core-hours	Total data volume (TB)	Priority
Development								
Year 1						6.97	0	
D1: CLM Development	CLM5	1°	20	150	450	1.35	0	A
D2: CLM Spinup	CLM5	1°	5	500	200	0.50	0	A
D3: Parameter estimation	CLM5	4°	800	20	20	0.32	0	B
D4: CAM-CLM testing	CAM6-CLM(FATES)	1°	10	30	3000	0.90	0	B
D5: CLM(FATES) Development	CLM5(FATES)	2°	20	200	600	2.40	0	A
D6: CLM(FATES) Spinup	CLM5(FATES)	2°	5	500	600	1.50	0	A
Year 2						10.98	0	
D7: CLM Development	CLM5	1°	30	150	450	2.03	0	A
D8: CLM Spinup	CLM5	1°	5	1000	200	1.00	0	A
D9: Parameter estimation	CLM5	4°	500	100	20	1.00	0	B
D10: CAM-CLM testing	CAM6-CLM(FATES)	1°	5	30	3000	0.45	0	B
D11: CLM(FATES) Development	CLM5(FATES)	1°	20	200	1000	4.00	0	A
D12: CLM(FATES) Spinup	CLM5(FATES)	1°	5	500	1000	2.50	0	A
Production								

Year 1						12.94	19.68	
P1: MIPs (TRENDY, GSWP3)	CLM5	0.5°	5	165	820	0.68	1.44	B
P2: MIPs Spinup		0.5°	2	500	820	0.82	0	B
P3: CLM5 Perturbed Parameter	CLM5	Sparse	1000 0	100	4	4.00	3	A
P4: CLM5 Perturbed Parameter	CLM5	2°	150	250	75	2.81	5.63	A
P5: CLM5 Perturbed Parameter Spinup	CLM5	2°	150	100	75	1.13	0	A
P6: CAM-CLM Perturbed Parameters	CAM6-CLM5	2°	100	50	520	2.60	7.88	B
P7: LS3MIP Tier 2 Projection to 2100	CLM5	1°	4	85	450	0.15	0.15	B
P8: Climate Process Team	CAM6-CLM5	1°	5	50	3000	0.75	1.58	A
Year 2						22.97	102.03	
P9: MIPs (TRENDY, PLUMBER2)	CLM5	0.5°	4	165	820	0.54	1.15	B
P10: MIPs Spinup		0.5°	2	500	820	0.82	0	B
P11: No Human Fire Manage	CESM2	1°	5	165	3500	2.89	23.76	A
P12: Urban sustainable	CAM6-CLM5	1°	5	85	2400	1.02	2.68	A
P13: PI Control	CESM2(FATES)	1°	1	500	4000	2.00	14.4	A
P14: Historical	CESM2(FATES)	1°	5	165	4000	3.30	23.76	A
P15: SSP1-2.6, SSP3-7	CESM2(FATES)	1°	10	85	4000	3.40	24.48	B
P16: Climate Process Team	CAM6-CLM5	1°	5	50	3000	0.75	1.58	A
P17: CLM5(FATES-Hillslope)	CLM5(FATES-Hill)	1°	2	250	3000	1.50	1.74	B
P18: CLM5(FATES-Hillslope) Spin	CLM5(FATES-Hill)	1°	1	500	3000	1.50	0	B
P19: LMWG Collaboration reserve	CAM6-CLM5	1°	20	50	3000	3.00	6.3	B
P20: LMWG Collaboration reserve	CLM5	1°	20	250	450	2.25	2.18	B

Ocean Model Working Group (OMWG)

1. Broad Overview of Working Group and Research Plan

The primary goals of OMWG are to advance the capability and fidelity of the CESM ocean component in support of specific science objectives of the broader CESM community and to conduct curiosity driven research using CESM to advance our understanding of ocean processes, the role of the ocean in the Earth system, and its interactions with other Earth system components.

2. Development Proposal (Y1: 10.9 M; Y2: 15.3 M; total 26.2 M core-hours)

a. Goals

Many years of parameterization development in the Parallel Ocean Program version 2 (POP2) produced a CESM ocean component model that was world leading in physically based process representation and simulation fidelity. A primary objective of OMWG over the next allocation cycle will be to continue the process of bringing that experience and parameterization technology forward into the Modular Ocean Model version 6 (MOM6) framework with the understanding that differences in the fundamental formulation of the dynamical core will require a re-examination of many choices that were made over the last two decades of POP2 development. In particular, the Arbitrary-Lagrangian-Eulerian (ALE) vertical framework in MOM6 presents a number of challenges and opportunities to rethink process representation and parameterization choices. In addition to implications for implementation of parameterizations, the ALE coordinate provides considerably more latitude in representing the vertical structure of the ocean and bottom topography than was available with the geopotential vertical coordinate in POP2 and will require extensive experimentation to develop OMWG experience with this capability. Work planned for the allocation period in this category includes continued exploration of vertical coordinate and resolution options, the representation of terrestrial runoff (the Estuary Box Model), tidal and shear mixing parameterizations, Langmuir mixing driven by wind-waves as represented in Wave Watch3 and short-wave radiation absorption, all building on prior experience with POP2.

Simultaneously, we will be developing and assessing new parameterizations of oceanic processes focusing primarily on two issues. The first focus relates to ocean mesoscale eddies. There has been considerable progress in the development of lateral subgrid scale closures appropriate for both the eddy-parameterized and the eddy-permitting regimes over the last few years. Several alternatives are under development and investigation by members of OMWG using both deterministic and stochastic approaches. OMWG is closely tied to the NSF and NOAA funded Ocean Eddy Energetics Climate Process Team (CPT). We will contribute to that effort by evaluating the performance of eddy parameterizations developed in this CPT in our MOM6 workhorse model configuration relative to corresponding eddy-resolving simulations. One component of this line of research involves applying machine learning algorithms to eddy-resolving global ocean simulations to derive “mesoscale mixing emulators”. The second focus in new parameterization development is exchange between the surface mixed layer and the ocean interior. Research with the POP2 based CESM1 over the last several years has shown that there are significant deficiencies in the representation of this process, especially in the Southern Ocean, resulting in large biases in uptake of CO_2 and CFCs. Insights from process modeling studies with Large Eddy Simulation (LES) provide the best guidance for development of the surface boundary layer parameterization and coupling to wind waves. We are including a modest number of targeted LES simulations for that purpose.

In addition to development of the core MOM6-based ocean component model, resources are requested for development of ancillary capabilities in data assimilation and regional downscaling, the former continuing with POP2 for the time being, the later with MOM6.

While OMWG research is focused on formulation of the model dynamics and physical parameterizations, we will coordinate with BGCWG to systematically evaluate the fidelity of the MOM6 simulation of marine biogeochemical cycles. This is a valuable part of the ocean model development process because the behavior of these tracers often provides insight that is not available when examining dynamical tracers alone. In addition, throughout this development process we will work with BGCWG to transition the Newton-Krylov fast solver technology from POP to MOM6.

b. Specific simulations and computational requirements

D1. CESM3-MOM6 base model development: Our development process for MOM6 is one of continuous evaluation and assessment of both existing and new parameterizations through a hierarchy of forced ocean – sea-ice and fully-coupled integrations. The experimentation in the forced configurations is built around the CMIP6 Ocean Model Intercomparison Project (OMIP) JRA55-do forcing protocol (Tsujino et al. 2018), with the pace of experimentation set primarily by available human resources. We carry out a new short (one 61-year cycle of forcing) experiment every 2-3 weeks, a longer experiment (five cycles of forcing) every 6-8 weeks, followed by a fully coupled experiment every 4-6 months. Very short debugging and software quality testing experiments (1 year) are conducted continuously.

D2. Ocean parameterization development:

D2.1 CPT testing: One of NCAR's roles in the CPT is to code and test the new parameterizations that are developed therein. Several parameterization approaches, both deterministic and stochastic, are being developed and evaluated. These tests will be performed using our nominal 2/3° resolution, which individually are not very expensive. However, we expect that several tests will be required, and their evaluation will necessitate running over a full JRA55-do cycle.

D2.2 Machine learning with Mesoscale Eddy Kinetic Energy (MEKE) parameterization: A new machine-learning based approach to parameterizing the mesoscale eddy energy is being developed. OMWG members are collaborating with partners at University of Victoria and Cray-Hewlett Packard, to train a neural network using eddy statistics derived from high-resolution (0.1°) CESM-MOM6. Multi-decade integrations of the 0.1° CESM-MOM6 with high-frequency sampling are required to obtaining sufficient statistics for this training.

D2.3 LGM IDEmix: A joint study with PaleoWG will investigate the role of tidal mixing in driving diapycnal mixing during LGM. Part of this project involves coding and testing the IDEmix internal wave energy parameterization (Eden et al. 2014), for which we request a small allotment of this CSL proposal.

D2.4 LES: The development of improved vertical mixing schemes in the ocean component model of CESM and other community models will benefit from guidance and benchmarks provided by LES of the ocean surface boundary layer. At present, LES is used generally either in idealized parameter sensitivity studies, i.e., a range of similar runs with simple initial conditions and surface fluxes that can be parameterized in terms of a small set of non-dimensional parameters, or in highly-customized experiments with more realistic initial conditions and time-dependent forcing. This effort will contribute to developing the capacity to conduct the latter type of experiments more efficiently and on a production basis, and thus use such simulations to guide parameterization development.

D3. MOM6 regional and nested modeling: Coupled regional modeling capability is being introduced via the advent of CESM-MOM6 and the National Unified Operational Prediction Capability (NUOPC) coupler, and requires extensive testing to achieve research-grade functionality. The pioneer project for this effort is a study of the eastern tropical Pacific Ocean, with which we have already achieved a proof-of-concept simulation that is currently being run for research on coral larval dispersion. To make this capability accessible to other researchers, further refinement and testing of the regional modeling functionality will be necessary.

D4. Ocean and coupled data assimilation: Work in ocean and coupled data assimilation will explore ensemble filter and smoother approaches for the problems of initializing Earth system predictability and generating coupled climate state estimates. In addition to conventional ensemble Kalman approaches, we plan to investigate an iterative approach whereby small increments are computed using covariances generated from CESM2-LENS and added over the course of multiple repeated simulations. We also anticipate exploring assimilating time-averaged observations and investigating paths for reducing model bias. These approaches will be evaluated in ensemble forecast simulations in Year 2 focusing on case studies of predictability of extreme North Atlantic variability.

3. Production Proposal (Y1: 9.1 M; Y2: 18.6 M; total 27.7 M core-hours)

a. Goals

The primary goals for the production portion of the OMWG request are to contribute to international model assessment projects (OMIP) and to better understand the climate simulated by CESM, and to extend work begun in the previous allocation period related to AMOC variability. In response to interest within the university research community, members of OMWG are planning for provision of a “simplified” ocean model, analogous to aqua-planet atmosphere configurations. This would be targeted as both a training tool for students and new model users as well as a platform for process studies and parameterization development.

b. Specific simulations and computational requirements

P1. OMIP: OMWG contributed to a recent intercomparison of low-resolution (LR; nominal 1°) and high-resolution (HR; nominal 0.1°) CMIP6 OMIP2 simulations (Chassignet et al. 2020). This study highlighted the sensitivity of HR variability characteristics to the degree to which ocean surface velocities are taken into account in the calculation of surface stress. The CLIVAR Ocean Model Development Panel (OMDP) is expected to formalize a plan for multi-model HR sensitivity studies that will build on the Chassignet et al. (2020) results, in order to develop more rigid and well-founded guidelines for future HR OMIP intercomparisons. In order for OMWG to participate in this exploration of best-practices for forced ocean simulations at HR, we budget for one JRA55-do interannual forcing cycle (61-years) each of CESM2-POP and CESM-MOM6 at 0.1° resolution in the ocean – sea-ice coupled configuration.

The predecessor experiments to CMIP6-OMIP, designated CORE-II (Coordinated Ocean-ice Reference Experiments phase II) by the OMDP, included a forcing design referred to as “normal year” (NYF), a repeating synthetic year with synoptic timescale variability. The updated JRA55-do based forcing data protocol has chosen a variant of that design with a repeating actual year of forcing (RYF). We are budgeting for a 150-year simulation of HR CESM2-POP with the JRA55-do RYF forcing to serve as a reference for future HR forcing perturbation experiments (see WISHBONE below) and as a resource for attribution of free vs. forced oceanic variability by comparison with the JRA55-do interannually varying forcing experiments described above.

P2. WISHBONE: WISHBONE (Wider Impacts of Subpolar NortH Atlantic decadal variaBility on the OceaN and atmosphereE) is an international collaboration that is jointly funded by UK-NERC and US-NSF. The overarching objective of WISHBONE is to characterize the linkages between anomalous buoyancy forcing of the subpolar North Atlantic and impacts on the wider North Atlantic coupled system on decadal timescales, and to determine the oceanic and atmospheric processes that control those impacts. The work plan calls for a series of coupled ensemble experiments using CESM1 and CESM2 at workhorse (nominal 1°) component resolution. These experiments involve North Atlantic Oscillation (NAO)-related forcing, following the setup described in Kim et al. (2020), but explore 2 different forcing regions and 2 different model versions (for each of CESM1 and CESM2, 2 regions x 2 forcings x 10-members x 20-year simulations = 800 sim-years). The impact of coupling will be explored by repeating the experiments in a forced ocean – sea-ice configuration (8 experiments x 20-year simulations = 160 sim-years). Finally, some HR runs are planned to test the sensitivity of results to model horizontal resolution. The NAO-forcing experiments will be repeated at HR using uncoupled 0.1° CESM2-POP. This requires a spun-up (150-year) 0.1° RYF simulation described above to use as control, and twin 25-year branch experiments subject to idealized NAO+ and NAO- forcing.

P3. CESM simplified modeling suite: There is an emerging thrust to expand CESM's capability to include easily-configured, coupled idealized modeling. A simplified modeling toolkit is presently being developed to allow CESM users to set up non-standard model configurations with greatly reduced effort. A set of spun-up solutions for a small number of idealized fully-coupled configurations will be prepared under the proposed effort as part of the construction of this community resource.

P4. Arctic wave climate: There is preliminary evidence that wave fracture of sea ice in the marginal ice zone is a key coupling (Roach et al. 2018) which is missing from CESM. In order to achieve this coupling, a resolved floe size distribution is needed in the sea ice and waves must be propagating through and attenuated by the sea ice. Both of these features are available in prototype CESM2 versions, but the coupling presently assumes the same grid for sea ice and waves, which is expensive. We request resources to assess the performance of these new codes at CESM2 resolutions of 1° match grid between sea ice and waves and 0.1° grid matched resolution. Through these simulations, we plan to arrive at an approach viable for production runs that can capture this key interaction.

	Project Title	Model (POP, MOM6)	Configuration (C,G,B)	Resolution	# Runs	Sim Yrs /Run	Core Hrs / Sim Year	Total in M Core-hours	Data Volume (TB)/ Sim Year	Total Data Volume (TB)	Priority (A,B,C)
MOM6 Development											
	CESM3 (mini)	MOM6	B,G,C	0.66	200	1	1,500	0.30	0	0	A
	CESM3 (short)	MOM6	G	0.66	20	61	1082	1.32	0	0	A (10 runs), B (10 runs)
	CESM3 (short)	MOM6	G	0.66	13	61	1082	0.86	0.06	47.58	A (5 runs), B(8 runs)
	CESM3 (long)	MOM6	G	0.66	5	305	1082	1.65	0.06	91.5	A
	CESM3 fully-coupled	MOM6	B	0.66	2	100	4027	0.81	0.16	32	A
	ML Meke	MOM6	G	0.1	2	10	136,205	2.72	1.3	26	A
	Regional MOM6	MOM6	G	0.05	3	20	22,176	1.33	1	60	B
										0	
Ocean Parameterization Development										0	
	Ocean PBL	LES	numbers to right are per day	1 meter	2	30	15000	0.90	0	0	A
										0	
Data Assimimilation										0	
	DA	CESM2-POP	B	1	10	30	3500	1.05	0.075	22.5	A

Year 1 Development Total								10.94		279.6	
										0	
MOM6 Production										0	
	Simplified Coupled	MOM6	B	2	2	400	680	0.54	0.005	4	B
										0	
POP Production										0	
	JRA55-do RYF (monthly archive)	POP	G	0.1	1	50	48,000	2.40	0.13	6.5	A
	JRA55-do RYF (high-freq archive)	POP	G	0.1	1	50	48,000	2.40	0.52	26	A
	WISHBONE	CESM1-POP	B	1	40	20	2300	1.84	0.035	28	A (20 runs), B(20 runs)
	WISHBONE	CESM2-POP	B	1	20	20	3500	1.40	0.075	30	A(10 runs) ,B(10 runs)
	WISHBONE	CESM2-POP	G	1	8	20	160	0.03	0.028	4.48	A(4 runs), B(4 runs)
	Arctic Wave Climate	CESM2-POP-WW3	G	0.1	1	1	500,000	0.50	1.96	1.96	B
Year 1 Production Total								9.11		100.94	
Year 1 Total Storage										380.54	
Year 1 Total M								20.05			

PI	Project Title	Model (POP, MOM6)	Configuration (C,G,B)	Resolution	# Runs	Sim Yrs/ Run	Core Hrs / Sim Year	Total in M Core-hours	Data Volume (TB)/ Sim Year	Archival Data Volume (TB)	Priority (A,B,C)
MOM6 Development											
	CESM3 (mini)	MOM6	B,G,C	0.66	200	1	1,500.00	0.30	0	0	A
	CESM3 (short)	MOM6	G	0.66	10	61	1,082.00	0.66	0	0	A(5 runs), B(5 runs)
	CESM3 (short)	MOM6	G	0.66	5	61	1,082.00	0.33	0.06	18.3	A(3 runs), B(2 runs)
	CESM3 (long)	MOM6	G	0.66	5	305	1,082.00	1.65	0.06	91.5	A(3 runs), B(2 runs)
	CESM3 fully-coupled	MOM6	B	0.66	5	100	4,027.89	2.01	0.16	80	A(3 runs), B(2 runs)
	ML Meke	MOM6	G	0.1	4	10	136,205.00	5.45	1.3	52	A(2 runs). B(2 runs)
	Regional MOM6	MOM6	G	0.05	3	20	22,176.00	1.33	1	60	B

Ocean Parameterization Development										0	
	Ocean PBL	LES	numbers to right are per day	1 meter	4	30	15000	1.80	0	0	A(2 runs), B(2 runs)
										0	
Data Assimimilation										0	
	DA	CESM2-POP	B	1	10	30	3500	1.05	0.075	22.5	A
	DA/predictability	CESM2-POP	B	1	40	5	3500	0.70	0.075	15	A
Year 2 Development Total								15.28		339.3	
MOM6 Production											
	OMDP-OMIP	MOM6	G	0.1	1	61	136,250	8.31	1.96	119.56	B
	Simplified Coupled	MOM6	B	2	2	500	680	0.68	0.005	5	B
										0	
POP Production										0	
	JRA55-doRYF	CESM2-POP	G	0.1	1	50	48,000	2.40	0.52	26	A
	OMDP-OMIP	CESM2-POP	G	0.1	1	61	48,000	2.93	1.96	119.56	B
	WISHBONE	CESM2-POP	G	0.1	2	25	48,000	2.40	0.52	26	A
	WISHBONE	CESM2-POP	B	1	20	20	3500	1.40	0.075	30	A
	Arctic Wave Climate	CESM2-POP-WW3	G	0.1	1	1	500,000	0.50	1.96	1.96	B
Year 2 Production Total								18.62		328.08	
Year 2 Total Storage										667.38	
Year 2 Total in M Core-hours								33.90			

Paleoclimate Working Group (PaleoWG)

1. Broad Overview of Working Group and Research Plan

PaleoWG is a consortium of scientists engaged in modeling to understand Earth's past climates and provide a long-term perspective on climate system feedbacks and processes that underlie the transient nature of climate change. The PaleoWG members include participants from universities and laboratories, with interests that range from early Earth to the climate of the Common Era. Members conduct simulations for specific past climate states, designed to explore the relationships between climate forcings, such as variations in atmospheric greenhouse gases, the presence of large continental-scale ice sheets, solar variability and volcanic activity, and feedbacks and processes that control ECS and climate responses on a range of temporal and spatial scales. Assessing model simulations for these out-of-sample climate states against paleoclimate reconstructions based on geological and geochemical records is an important element of the PaleoWG activities.

The overall plan for this 2020-2022 CSL period focuses on the following research and development priorities:

- Enabling a suite of geotracers, especially water isotope tracers, in all components of CESM2, to be continued into the development stream of CESM3, for improved comparisons to paleoclimate and modern observations;
- Conducting a perturbed parameter ensemble using CAM6 to advance understanding of the state dependence of cloud feedback processes and the ECS in out-of-sample climates much different from present day;
- Testing the application of the lower resolution configuration of CESM2 with the interactively coupled dynamic CISM for use in multi-millennial paleoclimate simulations to provide a useable community tool for studying climate-ice sheet interactions and ice-sheet evolution;
- Conducting a suite of high-value high-resolution atmosphere paleoclimate simulations with water isotope tracers for process studies, leading to an advanced understanding of extreme phenomena under out-of-sample background climate conditions such as extreme warmth and large continental ice sheets;
- Providing multi-century long simulations for the community: two implemented with water and carbon isotope tracers, focused on paleoclimates of high interest: LGM and a warm interval in the mid-Pliocene. Additionally, an LGM simulation will be conducted using MOM6 as the ocean component in CESM2. These simulations will be the basis of many process studies and are of high value to the data assimilation and synthesis community;
- Conducting additional coupled simulations with the high-top WACCM: two additional transient simulations of the last millennium to allow an improved assessment of low-frequency climate variability, top-down influences of volcanic and solar forcing, and the development of last millennium volcanic forcing for lower cost CAM6 simulations; and time-slice simulations of a glacial and an extreme

warm climate, which will be the first simulations in the paleoclimate community to leverage the unique capabilities of the high-top atmosphere model;

- Conducting two multi-millennial long simulations with the interactive dynamic ice-sheet model in close collaboration with LIWG, to advance understanding of the Earth climate system during periods of major ice-sheet retreat and regrowth;
- Conducting simulations for intervals when records indicate the climate system experienced abrupt cold events thought to be forced by meltwater flushed to the high-latitude North Atlantic from melting ice sheets: a short centennial scale event during the early Holocene, and a millennial scale Heinrich stadial event 11, that occurred before the start of the last interglacial period. These simulations, combined with proxy data, will help to examine potential tipping points in the Earth system.

As with previous community simulations, these proposed simulations will be documented and archived at NCAR as a community resource.

2. Development Proposal (Y1: 11.2 M; Y2: 17.7 M; total 28.9 M core-hours)

a. Goals

The overall development goal is to provide the community with an expanded set of capabilities in CESM suitable for application to a wide range of paleoclimate research problems. To this end, the proposed CSL development resources will target a number of specific objectives.

To support the broader paleoclimate community, new configurations and capabilities of CESM2 will be implemented and tested through paleoclimate applications. A high priority is to continue to maintain and expand the water isotope tracing capability of CESM, which is essential for directly using the paleoclimate geochemical archive to inform paleoclimate simulations, as well as providing additional constraints on hydrological processes in modern climate. PaleoWG will test paleoclimate applications using MOM6, a new ocean component released as an option in CESM2.2, and targeted for CESM3. Coupled WACCM6 configurations will be tested for application to both high CO2 and glacial paleoclimate states. The capability of two-way coupling between climate and the dynamical ice-sheet model (CISM2) within CESM2 will be investigated for running multi-millennial simulations at a lower resolution (FV2_g17_gl4) with a focus on the transient ice sheet-climate interactions. High resolution atmosphere-land-only paleoclimate simulations will be run with the isotope-enabled CESM1.2 for improved comparisons to proxy data. In collaboration with AMWG, a perturbed parameter ensemble will be performed to explore the parameter space of CAM6 with a focus on the ability of CESM2 to simulate past cold and warm extreme climates. This exercise will help constrain model physical parameterizations using real-world data and improve the understanding of cloud feedback processes under different background climates.

b. Specific simulations and computational requirements

D1. Software development and testing of CESM2 for Paleoclimate applications (Year 1: 735 K core-hours, Year 2: 310K core-hours): Simulations will be carried out to test the application of CESM2 coupled to CISM2 with the f19_g17_gl4 grid. This configuration will provide the community a lower cost framework for running multi-millennial transient simulations for periods when ice-sheet climate interactions are essential. We will incorporate the capability to accelerate the orbital year by namelist parameters. Accelerating the orbital year by a modest factor of 5 has been shown to work well (Sommers et al. 2020) and makes CESM2-CISM2 coupled runs feasible for multi-millennial paleoclimate simulations. (f19_g17_gl4, 350 yrs x 2100 core-hours/yr = 735K core-hours, Year 1) Year 2 computer resources are requested to support continued developments of the water isotope tracer capabilities in CESM2, primarily to aid the implementation of water isotope tracers in the land model and to test the coupled framework in a preindustrial control simulation. The goal is to ensure that isotopic state and flux variables are being correctly exchanged between model components and that isotopic fractionation is correctly implemented. (f19_g17, 100 yrs x 3100 core-hours/yr = 310K core-hours, Year 2).

D2. High-resolution Paleoclimates with iCESM1.2- CAM5 (¼° resolution, 70 K x 3 x 50yrs =10.5 M core-hours, Year 1): High horizontal resolution has been shown to provide a better representation of hydrological cycle processes and would greatly improve comparison to proxy data, particularly sites with complex topography (Kopparla et al. 2013; Shields et al. 2016). Higher resolution also enables us to examine variability of weather and climate extremes, such as tropical cyclones and atmospheric rivers. These simulations will also be used for assessment of temperature and rainfall extremes under past out-of-sample climates. These simulations will build on available coupled time slice simulations of key periods in Earth's history at FV2x1. Four time periods across different climate states - PETM: high CO_2/extreme warmth, mid-Pliocene: CO_2 at 400 ppm, warm climate, LGM: low CO_2, cold climate, and the Preindustrial, will be chosen to evaluate process understanding of extreme phenomenon under different climate and boundary forcing. We will leverage off work already completed for the PETM and Preindustrial using FV 0.25° CAM5 without isotopes, extending these two runs to 50 years. The mid-Pliocene and LGM high-resolution simulations will also include isotopes and run for 50 years.

D3. CAM6 Perturbed Parameter Ensemble (SST-4K) (10 M core-hours, Year 2): Traditionally, the development and tuning of model physical parameterizations has been done with the aim to reproduce the present-day instrumental record (e.g., Gettelman et al. 2009). However, the historical record only provides a loose constraint on the model behavior under large external forcings (Zhu et al. 2020). We plan to collaborate with AMWG and expand the CAM6 Perturbed Parameter Ensemble (PPE) experiments by including a set of experiments with SST –4K. The goal is to investigate the state dependence of cloud feedbacks in the parameter space and make use of paleoclimate constraints to guide the choice of model parameters. Complementing the preindustrial

AMIP and SST +4K experiments that the AMWG is planning to perform, the SST –4K experiments will be conducted in a similar way. PPE experiments will be performed with the standard FAMIP configuration at the FV1 resolution. AMWG has selected a set of ~50 model parameters that are relevant for the cloud feedback. The Latin Hypercube Sampling method will be used to select model parameters in a single experiment, which typically is run for 10 years. To explore 50 model parameters, approximately 500 experiments are needed. The set of SST –4K experiments will cost ~10,000 K core-hours (~1900 core-hours/yr x 5000yrs).

D4. Coupled WACCM6 glacial and warm climates (BWma1850, f19_g17, 2x500yrsx3500/yr, 3.5 M core-hours, Year 2) Using the same middle atmosphere chemistry version of WACCM6, PaleoWG requests computer resources to set up and run coupled simulations of high interest to the paleoclimate community: LGM and the warm Eocene climate state. These simulations will use the f19_g17 resolution grid and boundary conditions developed for previous CESM simulations with CAM. These will be the first simulations in the paleoclimate community to leverage the unique capabilities of the high-top WACCM.

D5. Testing coupled CESM with MOM6 for paleoclimate (4030 core-hours/yr x 500 yrs, 2.015 M core-hours,Year 2): Computer resources are requested to set up, test, and run a coupled CESM2 paleoclimate simulation with MOM6 as the ocean component using the f09_t061 grid. This simulation, compared to the baseline CESM2 simulation with POP2, will help evaluate the impact of using a different ocean component and model physics on the climate response to paleoclimate boundary conditions and forcings much larger than occurred during the historical period. As MOM6 will be the standard ocean component for CESM3, this simulation will provide feedback to developers on its application to paleoclimates. The target is LGM, for which many boundary conditions and forcings need to be changed. For example, due to large continental scale ice sheets, sea level is ~120 m lower exposing continental shelves such as the Sunda shelf in Southeast Asia. The change in ocean volume increases global mean salinity by ~1 psu. These out-of-sample differences will be a severe challenge for the new configuration.

D6. Paleoclimate simulation with isotope-enabled-CESM2 (f19_g17, 2x300 yrs, 3150 hrs/yr, 1.89 M core-hours, Year 2): We request computing resources to test the water isotope-enabled CESM2 (iCESM2), in two simulations, a preindustrial control and a paleoclimate (e.g., LGM) at f19_g17 resolution. Estimated cost is about 1.5 times the cost of the standard CESM2 for that resolution. We will validate the simulations against available observations to investigate whether biases in water isotopes identified in iCESM1.2 have been improved due to improved model physics in CESM2. Moreover, we implemented a correction in iCESM1.2 to the isotopic water flux at the ocean surface to remove the drift in the system that is caused by the conservation issues in isotope-enabled CAM5 and CLM4. We will re-evaluate the conservation of isotopic water in iCESM2 and update the flux correction if necessary. Runs of multi-hundred years are necessary to evaluate the conservation of isotopic water in the entire system.

2. Production Proposal (Y1: 9.7 M; Y2: 16.3 M; total 26.0 M core-hours)

a. Goals

The overall production goals of PaleoWG focus on providing CESM paleoclimate simulations in support of community research into the fundamental questions of paleoclimate science by students, university researchers, and early career scientists globally. Our simulations provide the opportunity to test CESM in multiple configurations, and using new capabilities, for simulating out-of-sample climate states under various forcing conditions. Benchmarking the CESM against the paleoclimate records provides important information on its applications in future climate projections.

Production simulations proposed here will complement simulations completed using our current allocation with CESM2. These include two additional last millennium simulations with CESM2(WACCM6ma) to complete a 3-member ensemble. Two simulations will be performed using CESM2(CISM2) to investigate the transient interactions between the climate and an evolving dynamic ice sheet. The first will simulate the climate and ice-sheet evolution over a 6000-year-long period during the midHolocene when the Greenland Ice Sheet (GrIS) retreated then advanced into the little ice age. The second will simulate the evolution from the end of the last interglacial and the transition into the glacial conditions, complementing the ongoing Transient Last Interglacial simulation (Sommers et al. 2020). Both simulations will be conducted in close collaboration with LIWG and resources shared equally over both year 1 and 2. Two additional simulations will investigate high latitude tipping points and the transient response of ocean circulation and feedbacks in the climate system to freshwater additions to the North Atlantic from melting ice sheets.

b. Specific simulations and computational requirements

P1: GrIS evolution from the midHolocene through the last millennium, (1200 simulated yrs with 5 times acceleration of orbit and ice-sheet clock, f09_g17_gl4, 3800 core-hours/yr x 1200yrs=4.56 M core-hours, 56 TB, to be split with LIWG in years 1 and 2 evenly): This simulation would build off a transient simulation utilizing CESM2(CISM2) from 9 ka to 6 ka, including evolution of natural vegetation using the output from BIOME4, to be completed soon on the current PaleoWG CSL allocation. We will continue this simulation from 6 ka to 1850CE. During the mid-Holocene, GrIS underwent a retreat behind the present-day margin and a subsequent readvance during the Neoglacial or ‘little ice age’. Records suggest the timing and retreat rate vary spatially; does not coincide with the peak Holocene warming (4°C) estimated from ice cores records implying additional regional feedbacks and forcings. The final ice-sheet and climate state could be used as a starting point for future simulations of the ice sheet and be compared to the recent results of the BG/JG simulation (Löfverström et al. 2020).

P2: Evolution of Northern Hemisphere ice sheets from Last Interglacial to glacial, CESM2-CISM2, 120 ka to 112 ka, (f09_g17_nh4, 1600 yrs x 3800/yr = 6.08 M core-hours Total; 76 TB, split with LIWG and in years 1 and 2 evenly): A transient simulation over the latter stages of the last interglacial period, the last glacial inception, and transition into glacial conditions will be conducted (covering the period: 120 ka-112 ka, with 5x accelerated orbit and ice-sheet clock). This simulation will bridge two previous projects with CESM2(CISM2) to investigate i) the deglaciation of the GrIS during the warm phase of the last interglacial period (Sommers et al. 2020, in prep for JAMES), and ii) the last glacial inception and transition into glacial conditions (Löfverström et al; in prep for Nature). Simulations will utilize a high-resolution (nominal 4-km) Northern Hemisphere CISM2 grid, and will be of large interest to the paleoclimate and ice-sheet research communities.

P3: CMIP6 Tier 1, CESM2(WACCM6ma) past1000 ensemble members #2 and #3, (BWmaHIST, 1000yrsx3500/yr=7.0 M core-hours; Year 1): The past1000 experiment (850CE to 1850CE) is a Tier 1 CMIP6 PMIP4 simulation designed to investigate the climate response to transient natural forcings (volcanic aerosols, solar variability, greenhouse gas, and orbital) over the last millennium. The largest external radiative forcing over this period is the volcanic aerosol emissions. One ensemble member was completed with WACCM6 with middle atmosphere chemistry and prescribed volcanic emissions from the PMIP4 protocol in the current CSL allocation. PaleoWG will run two additional past1000 ensemble members with the same configuration and forcings, using the initial random noise perturbation method to differentiate members. Together, these simulations will provide valuable statistics on forced and internal climate variabilities on interannual to centennial scales, process studies on the "top-down" influences of solar and volcanic forcings, and assess the fingerprint of the regional forced response against a large proxy data set. With three ensemble members, a CAM6 volcanic forcing data set can be constructed, as was done for the CESM2(CAM6) CMIP6 simulations of the historical period, enabling last millennium simulations to be done with CESM2(CAM6) at a lower cost for the community.

P4: Transient Response to meltwater events, the 8.2kyr and Heinrich Stadial 11 events: About 8200 years ago, proxy-climate records suggest an abrupt cooling interval took place that lasted ~150 years. The cause of the abrupt cooling is hypothesized to be the slowing of AMOC in response to freshwater pulses to the surface ocean in high-latitude deep-water formation regions from the collapse of the remnant North American ice sheets and outburst from proglacial lakes. Evidence for this abrupt cooling is well-documented in multiple records, however less constrained is the magnitude, location, and duration of the freshwater pulse to the North Atlantic. We request computer resources to run three 400-year-long simulations with the fully-coupled CESM2 at 1° resolution to investigate the sensitivity to different meltwater input scenarios that bracket the range of uncertainty in the reconstructions. (3x400yrsx3500 core-hours/yr =4.2M core-hours, Year 2); Heinrich layers in the North Atlantic, containing high concentrations of ice-rafted debris, record multiple examples of prolonged iceberg discharge. Computer resources are requested for a simulation of the well-documented Heinrich Stadial Event 11, that took place near the start of the Last Interglacial (LIG) period and lasted a few thousand years representing about 80m of global mean sea level rise. This event has been proposed as an explanation for the overshoot of temperature and greenhouse gases recorded in Antarctic ice cores at the start of the LIG. It has also been hypothesized to be important for the collapse of the WAIS during the LIG. This hypothesis invokes the "seesaw" climate pattern to the H11 meltwater in the North Atlantic, leading to warm Circumpolar Deep Water onto the continental shelf and triggering WAIS retreat. (2100 core-hours/yr x 4000yrs, f19_g17; 8.4 M core-hours, Year 2). These simulations, in comparison to proxy data, will provide an understanding of the capability of CESM2 to simulate abrupt climate events in response to tipping points in the climate system.

P5: Isotope-enabled PlioMIP2 simulation, (1000yrs x 1000/yr=1 M core-hours, Year 2): Computer resources are requested to simulate the mid-Piacenzian warm period (mPWP) of the Pliocene (3.2 Million years ago) using boundary conditions from the Pliocene Model Intercomparison Project, phase 2 (PlioMIP2) with the isotope-enabled CESM1.2 model at the fv19_g17 resolution. Simulating the mPWP with the suite of water isotope tracers in all components will be key for linking the simulated physical state to geological archives. These measurements contain key information on changes of past hydrological cycle and sea level. Yet, interpretations of water isotope records are largely reliant on empirical correlations between measured isotopic values and climate quantities such as the surface temperature and precipitation amount and disregard possible non-stationarity of the relationships as well as other effects such as changes in moisture sources and transports. This simulation will have valuable use to the paleoclimate data assimilation and synthesis community (Tierney et al. 2019). Boundary and initial conditions for this simulation exist, as completed simulations have been run with the standard CESM1 and CESM2 version as part of PlioMIP2 (Feng et al. 2019). To ensure the isotopic equilibrium of the ocean, a total of 1000 simulation years are budgeted.

Experiment	Comp-set	Resolution	# Runs	Total # of model years	Core-hours /simulated Year	Total in M of core-hours	Long-term data volume (TB)	Pri-ority
Development								
Year 1								
D1a CESM2 - CISM Testing for Paleo	BG	f19_g17_gl4	Varies	350	2100	0.74	16	A
D2 High-Resolution Paleo	F	f02_f02	4	150	70000	10.50	80	A
Total Year 1						11.24	96	
Year2								
D1b: Isotope-enabled CESM2 Dev. And Test	B	f19_g17	Varies	100	3100	0.31	3	A
D3: Cold Climate Pert. Param. Study	F	f09_f09	50	5000	1900	10.00	33	A
D4: Coupled WACCM6 Paleo	BWma	f19_g17	2	1000	3500	3.50	38	A
D5: Coupled LGM w/MOM6	BMOM	f09_t061	1	500	4030	2.02	32	B

D6: iso-CESM2 paleoclimates	B	f19_g17	2	300	3150	1.89	18	A/B
Total Year 2						17.72	124	
Production								
Year 1								
P1a: Mid-Holocene GIS evolution	BG	f09_g17_gl4	1	300	3800	1.14	14	A
P2a: LIG to glacial NH Ice Sheet Evolution	BG	f09_g17_nh4	1	400	3800	1.52	19	A
P3: CEM2 WACCM6 Last Mill. #2, #3	BWmaHIST	f19_g17_nh4	2	2000	3500	7.00	76	A
Total Year 1						9.66	109	
Year 2								
P1b: Mid-Holcene GIS evolution	BG	f09_g17_gl4	1	300	3800	1.14	14	A
P2b:LIG to Glacial, NHIS evolution	BG	f09_g17_nh4	1	400	3800	1.52	19	A
P4a: Sensitivity to 8.2ka Meltwater scenarios	B	f09_g17	3	1200	3500	4.20	62	A
P4b: LIG H11 Meltwater event	B	f19_g17	1	4000	2100	8.40	120	A
P5: Mid Pliocene Warm Period with iCESM1.2	B	f19_g17	1	1000	1000	1.00	30	B
Total Year 2						16.26	245	
Totals					Year 1	20.90	205	
					Year 2	33.98	369	
					Development	28.96	220	
					Production	25.92	354	

Polar Climate Working Group (PCWG)

1. Broad Overview of Working Group and Research Plan

PCWG is a consortium of scientists who are interested in understanding and modeling Arctic and Antarctic climate and its relationship to global climate. To enable polar science within PCWG and the CESM project as a whole, we request computing resources for both polar-specific CESM parameterization development and for polar-specific CESM scientific research. We anticipate both publishable and frontier results will emerge from the diversity of activities we propose, and that these results will provide new understanding of polar climate processes.

2. Development Proposal (Y1: 3.0 M; Y2: 13.9 M; total 16.9 M core-hours)

a. Goals

Our overall development objective is to ensure that CESM has state-of-the-art abilities to simulate polar climate. We strongly encourage and use CSL resources to facilitate the use of cutting-edge observations and techniques by PCWG members towards our overall development goals. Here, we request resources to incorporate, test, and diagnose the influence of new polar-relevant physics and diagnostics into the sea ice model (CICE) used in CESM.

b. Specific simulations and computational requirements

D1. Implementing CICE6 within CESM2: Improvements to numerous aspects of the sea ice model within CESM will be developed and tested during the lifetime of this proposal. A large part of proposed development runs for the next allocation cycle will be dedicated to updating the version of the sea ice component from the CICE Consortium model CICE5 to CICE6. This new version of the CICE model will include a number of new physics developments as well as a column model component for the vertical thermodynamics, known as Icepack. The technical steps involve a new cap or driver to couple to the CESM and updating the Fortran namelist. We request 50 years of simulation for testing. Then we will need to verify the climate of CICE6 within the coupled model. To accomplish this, we will do a 100-year preindustrial simulation with CESM2 coupled to CICE6 and validate against the CMIP6 preindustrial control run. After CICE6 has been validated, we will focus efforts on coupling to MOM6. The first step will involve new coupling of heat, fresh water, and salt. Then, we will be working on dynamic coupling with the staggered grid formulation. This will require 100 years of simulation for testing and implementation.

D.2 Assessing new CICE6 physics options: CICE6 has a number of new physics options available that we will consider for CESM simulations. To assess these, simulations are proposed to investigate the impacts of the new physical parameterizations available in CICE6 on the fully-coupled climate. Here, we will use 50 years for testing and do 100-year simulations with each new physics option. In the first year, we will aim to test the landfast sea ice parameterization of Lemieux et al. (2016). This parameterization allows for the grounding of thick sea ice in coastal regions. The other parameterization we anticipate validating within year one is the floe size distribution of Roach et al. (2018). This is a representation of sea ice floes of different sizes instead of a single size within each grid cell in the model. This has been shown to change the sea ice-ocean interactions and in particular the interaction with surface waves in the ocean. In addition to preindustrial control simulations, we will also perform several ensemble members of historical and SSP simulations to establish how this new physics affects sea ice related feedbacks in a transient climate state.

D3. New sea ice parameterizations

D3.1 Community developments: Over the lifetime of this computing allocation, we anticipate that numerous community sea ice model parameterizations will become available from PCWG members. Specific developments underway within the PCWG community include efforts to better model: Sea ice and wave interactions, snow on sea ice, ridging of sea ice, lateral melting of sea ice, among others. We anticipate that these developments and possibly others, will become available in the latter part of year 1 and in year 2 of the computing allocation. For each of these developments, we will implement parameterizations within CESM2 and explore the impacts on coupled climate behavior using preindustrial control simulations. We request 100 years of coupled runs for each parameterization for testing and implementation. This will allow us to make choices of the sea ice model configuration for CESM3.

D3.2 Biogeochemistry coupling: CICE6 incorporates a sea ice biogeochemistry component. In the initial phase of implementing CICE6 into CESM (Runs D3.1 and 3.2), this will be disabled. Starting in the latter part of year 1 of the computing allocation, we request resources to test this ice biogeochemistry within CESM. This will require new model infrastructure to couple the ice biogeochemistry to the ocean ecosystem model. It will also require extensive testing to ensure that the model is working properly. After performing test simulations (approximately 100 years of simulation required), we will perform a preindustrial control run (100 years) in which ice biogeochemistry is active and coupled to the ocean.

D3.3 Arakawa C-grid capability: MOM6, the ocean component for CESM3, uses an Arakawa C grid staggering of variables, whereas CICE6 is configured to run using an Arakawa B grid staggering. Because ice-ocean exchange occurs on a coupling grid, the models can run coupled in spite of the grid mismatch. However, there is a benefit to having both the ocean and sea ice model on the same grid. In particular, it allows for ice-ocean exchange to occur on the computed grid without averaging (and in doing so, losing information) to a coupling grid. To enable this, in year 2 of the computing allocation, we will implement an Arakawa C-grid capability within CICE6. This will require multiple test integrations and century-scale validation simulations.

D3.4 Stochastic parameterizations: Stochastic parameterizations allow for uncertainty in parameterized processes to be explicitly included and have shown promise for atmospheric modeling (Berner et al. 2017). A number of efforts are planned to use machine learning to build stochastic parameterizations of sea ice processes. These include efforts focused on a parameterization for the strength of the ice and efforts focused on snow and sea ice heterogeneity and its influence on the conduction of heat through the ice pack (and subsequently on ice growth rates). We anticipate that in year 2 of this allocation request, these parameterizations will be ready for testing within CESM. As such, we request resources for implementation, testing, and climate simulation analysis.

D4. Exploring high resolution (HR): HR experiments (with an ocean and sea ice model at a 0.1° resolution) performed with CESM have used older versions of the sea ice modeling system. Anticipated advances in sea ice parameterizations, such as land-fast ice treatments, wave-ice interactions, and sea ice biogeochemistry will be incorporated into CESM under this allocation. Given this, there is a need to assess sea ice simulations in HR configurations with this new physics. We propose to perform tests of a HR (0.1°) ice-ocean hindcast with active biogeochemistry for the 2000-2018 time period to test the influence of new sea ice physics. These will be branched from existing simulations that are currently underway and are running from 1958-2018. These will be performed in year 2 of the allocation and take advantage of new developments incorporated during year 1.

3. Production Proposal (Y1: 12.0 M; Y2: 11.6 M; total 23.6 M core-hours)

a. Goals

The overarching PCWG production goal is to enable important and topical polar science research using CESM. This includes experiments of value to a large number of researchers that are related to polar prediction, integrating models and observations to enhance process understanding, understanding the response of sea ice to a variety of forcings, and understanding coupled system interactions and feedbacks at both poles. The proposed experiments make use of the CESM2 configuration, including CESM2 tuned ice albedo experiments (Kay et al., in prep) that were performed by PCWG under the current allocation. This will allow for the diagnoses of important climate processes relative to the large number of simulations available for the CESM2-LENS and also enhanced understanding of new interactions within CESM2.

b. Specific simulations and computational requirements

P1. Polar prediction research: With large scale reductions in Arctic sea ice and extreme variations in Antarctic sea ice cover over the historical record, there is a need to better understand the predictability of sea ice and polar climate conditions on seasonal to interannual timescales.

P1.1 Perfect model experiments: To explore the predictability of polar climate conditions, we propose “perfect model” prediction experiments in which CESM is used to predict itself. This allows for the determination of the inherent predictability in the system given a near-perfect knowledge of initial conditions. Given that previous work has suggested predictability barriers associated with the timing of initialization

(Bushuk et al. 2020; DuVivier et al. 2020), we will explore the initialization-month dependence of ice and polar climate predictability in perfect model experiments by performing annual forecasts initialized on the first day of each month. This will include 12 sets of simulations with 15 ensemble members in each experiment and performed for 3 possible initial states. This will amount to a total of 540 years of simulation.

P1.2 Sea ice reanalysis: Additionally, with new capabilities in the assimilation of sea ice properties using DART coupled with CICE, we are now in a position to test the capacity to perform sea ice reanalyses for the historical record. We will perform CICE simulations in which three different sea ice variables are assimilated using DART. These will be performed for the 2001-2020 time period and time is requested to perform tests of the system (40 years) and then perform two sets of reanalyses with different ice model configuration for a 20-year period with 30 ensemble members in each. Ultimately this will create a global sea ice reanalysis of major variables that is complete in time and space and with quantified uncertainties. To perform these experiments will require 80 years of total simulation of with CICE coupled to DART.

P1.3 Impact of atmosphere-ocean coupling frequency on sea ice predictability: Comparison of sea ice evolution between CESM2 and older CESM1 suggests that the newer model has less persistence and predictability (Singh et al. 2020). Indeed, sea ice in global climate models generally appears to have greater diagnostic predictability than in observations, suggesting that there may be biases in model physics that overestimate persistence (Blanchard-Wrigglesworth and Bushuk 2019). One difference between CESM2 and CESM1 that may give rise to greater sea ice predictability in the latter is the atmosphere-ocean coupling frequency: atmosphere-ocean coupling in the CESM1 occurs once per day, while it occurs once per hour in the CESM2. More frequent coupling allows stochastic atmospheric noise, i.e., weather to impact the ocean at shorter intervals, which may contribute to decreased sea ice predictability. To test this hypothesis, we propose to run a 300-yr simulation of CESM2 in which the coupling frequency is decreased to once per day, as it is in CESM1. We will compare sea ice predictability, ocean state persistence, and ocean-ice interactions in this experimental run with the CESM2 control simulation to understand the impact of ocean-atmosphere coupling frequency on sea ice.

P2. Integrating models and observations: Over the past 40 years, satellite observations have provided comprehensive spatial and temporal data about the state of the high latitude climate system, particularly that of sea ice and snow-covered regions. However, it is also clear that observations from satellites, which are obtained through complex retrieval algorithms that interpret (active or passive) electromagnetic signals, cannot readily be compared to output from global climate models. To compare model results with satellite observations, satellite simulators are run within the model to produce the equivalent of satellite observations. The Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP), for example, has been developed to produce satellite-comparable cloud fields in global climate models, which can then be compared directly to satellite observations (e.g., Kay et al. 2016b). However, the current generation of simulators do not include the full range of satellite observational products, particularly those that are important for the study of the high latitudes. The following projects are intended to develop these simulators such that satellite observations in the far-infrared and of surface melt onset using surface brightness temperatures can be directly compared to that from CESM simulations.

P2.1 COSP2 Simulator Development: Observations of far-infrared (> 15 micron) emissions will soon be available from NASA (PREFIRE mission) and ESA (FORUM) satellites. These measurements are particularly crucial for resolving cold radiative temperatures, including those that prevail over the polar regions for much of the year. The current generation COSP, however, does not include functionality for simulating such far-infrared emissions measurements from cloud tops and the surface. To develop such a simulator, we propose to run ten 10-year test cases using the atmosphere-only CESM2 version.

P2.2 Surface Brightness Temperature Simulator: Melt season onset is an important indicator of the sea ice seasonal cycle. Passive microwave satellite data can be used to infer melt season onset over the satellite era (1979 to present; Markus et al. 2009). However, such satellite data relies on brightness temperature to infer melt, which differs from the direct calculation of surface melt made in global climate models. To compare melt onset observations with that in global climate models, we propose to complete development of an in-model simulator of brightness temperatures, which will require approximately 150 years of fully-coupled CESM2 simulations.

P3. Interactions between winds and sea ice: Previous work has indicated that wind variations have large impacts on sea ice variability in both hemispheres (e.g., Ding et al. 2017; Holland et al. 2017) and that changing sea ice also influences the strength of polar surface winds (Mioduszewski et al. 2018). We propose a number of experiments to better understand these interactions and their implications for sea ice and polar climate variability and change over time.

P3.1 Nudged wind experiments: To assess the influence of historical winds on sea ice conditions, we will perform coupled model simulations in which the wind field is nudged to the 20th century observationally-based ERA-20C reanalysis data. This configuration allows the model to be constrained by the observed atmospheric circulation state while still allowing feedbacks to the atmosphere. We will perform ten ensemble members for the 1901-2010 period with this configuration. These experiments will allow us to understand the ocean and sea ice responses to imposed observed winds during the past 110 years.

P3.2 Surface wind sensitivity to ice conditions: Previous work has indicated that in response to reductions in Arctic sea ice, stronger surface winds occur (Mioduszewski et al. 2018). This result is consistent across climate models and strongly linked to the sea ice conditions. A primary hypothesis for this behavior is that it results from changes in the surface roughness and in particular, the fact that open water is a smoother surface than sea ice. To test this hypothesis, we propose experiments in which the sea ice roughness is set equal to that of the ocean waters. A 100-year preindustrial simulation will be performed to assess the impact in a control climate, and transient simulations with changing climate conditions will also be performed to assess compared to the CESM2-LENS integrations. This will include a single historical ensemble member and three future scenario members. These simulations will allow us to quantify the influence of changes in the surface roughness in polar regions on wind changes over the 20th and 21st centuries.

P4. Response of polar climate to external forcings: Arctic surface climate has an amplified response to greenhouse gas forcings relative to the globe given strong positive feedbacks in the regions. In contrast, the Southern Ocean surface climate can have a muted response due to ocean processes. However, the polar influence of various external forcings can vary depending on numerous factors and there is a need to explore how various external forcings impact the poles. Here, we propose experiments to explore the influence of specific external forcings on the Arctic and Antarctic climate system.

P4.1 Arctic response to ozone depleting substances: Previous work (Polvani et al. 2020) has shown that ozone depleting substances can impact Arctic climate through their radiative forcing effects. We will further explore this in CESM2 runs to quantify how much ozone depleting substances have contributed to Arctic warming and sea ice loss since the 1950s. This will include simulations of CESM2 from 1955-2014 in which ozone depleting substances are fixed at 1955 values. Ten ensemble members will be performed to enable us to quantify the forced signal. Comparison CESM2-LENS will allow us to diagnose the impacts of changing ozone depleting substances on Arctic warming and sea ice loss.

P4.2 Polar climate response to external forcings: In historical simulations, external forcings such as those from volcanic emissions or biomass burning, are prescribed based on observed records. However, when observations are not available (including for preindustrial control and future scenario runs), synthetic external forcings are used. Work that is underway suggests that the choices made in devising these forcings can have implications for the transient polar climate response. We will explore this further by performing simulations to test the sensitivity to external forcings used when observational constraints are not available. This will include tests of the sensitivity to volcanic and other emissions. We request 250 years of preindustrial control simulations, and 5 ensemble members for the 1850-2050 period to test different forcing choices.

P5. Antarctic sea ice, the Southern Ocean, and climate: The Antarctic climate system evolves through a complex interplay between the atmosphere, the Southern Ocean, sea ice, and the Antarctic Ice Sheet (AIS). The following series of proposed experiments aims to better understand the processes that drive the evolution of this coupled system over the historical period and into the next several centuries.

P5.1 Antarctic sea ice resilience to retreat: Over the satellite era, Antarctic sea ice has proven remarkably resilient to retreat, despite rising atmospheric greenhouse gas concentrations and increasing global surface temperatures. This stands in contrast to the Arctic, which has experienced marked retreat in summer sea ice area over the same time period. Some recent modeling results hint that long time scale internal variability in the ocean may be an important factor in this apparent resilience of Antarctic sea ice to external forcing (Zhang et al 2019; Singh and Polvani 2020). At the same time, other studies suggest Southern Ocean temperatures equatorward of the ice edge have little impact on sea ice evolution (Zhang et al. 2020; Singh et al. 2016). We propose a series of model experiments to understand this apparent sensitivity of Antarctic sea ice to ocean temperatures under the ice pack, and whether moderating these temperatures, or decreasing the sensitivity of sea ice to these temperatures, may make Antarctic sea ice more resilient in models and, therefore, more comparable to the real world. A first set of 5 historical CESM2 ensemble members (1950 to 2020) will be run in which the ocean-to-ice heat exchange coefficient is decreased, modeling reduced sensitivity of the ice pack to underlying mixed layer temperatures. A second set of 5 historical ensemble members will be run in which the ocean temperatures under the ice pack are nudged to those that are observed, modeling evolution of Antarctic sea ice in the event that the ocean mixed layer under sea ice only warms modestly, i.e., less rapidly than it does in most free-running models.

P5.2 Antarctic surface orography-dependent feedbacks (collaboration between PCWG and LIWG): The elevation-temperature feedback accompanying ice-sheet retreat is relatively well known. In addition to this thermodynamic feedback, however, recent modelling studies suggest that the high elevation of AIS also acts as a dynamic barrier to moist and dry poleward energy transport processes (Steig et al. 2015; Singh and Polvani 2020). Such impacts of ice-sheet surface elevation on the dynamics may help explain the relative lack of warming over the Antarctic continent today, but may also portend even greater warming in the future as AIS melts and its surface elevation decreases (Singh and Polvani 2020). To understand whether these dynamic atmospheric processes related to surface orography are, indeed, a positive feedback on surface warming with realistic (rather than idealized) surface orography changes, we propose to conduct a series of CESM2 and CESM1 experiments in which Antarctic surface elevation is decreased according to CISM projections of future West Antarctic Ice Sheet (WAIS) collapse. A total of three fully-coupled experiments, each 230 years long, will be branched from the equilibrated preindustrial control experiment for each model with the following configurations: i) abrupt CO2-doubling with the AIS at its present-day elevation; ii) abrupt CO2-doubling with full WAIS retreat; and iii) full WAIS retreat only (CO2 held at pre-industrial levels). Differences in the CO2-doubling response between present-day elevation and WAIS retreat experiments will reveal whether lower surface orography is associated with amplified surface warming, indicating a positive feedback. Inter-model differences in the CO2-doubling responses will be a gauge of robustness. These simulations will be split with LIWG and so we are asking for half of the request for these runs here (with LIWG asking for the other half).

P5.3 Global climate impacts of Southern Ocean heat uptake: The subpolar Southern Ocean is a critical region for shuttling surface heat into the deep ocean as the global climate warms. From the perspectives of the atmosphere and upper ocean, heat uptake into the deep ocean acts as a *de facto* energy sink, which impacts large-scale energy transport and convergence in the coupled atmosphere-ocean system. Studies of this phenomenon with a slab ocean model suggest substantial dynamic impacts of Southern

Ocean heat uptake, particularly on ITCZ position (Hwang et al. 2017). However, slab ocean model results may greatly overstate the magnitude of such responses, as the lack of ocean dynamics does not permit changes in ocean heat transport, which tend to temper the atmospheric response (see, for example, Kay et al. 2016a; Singh et al. 2016). Through two CESM2 experiments, we aim to isolate the impact of ocean heat uptake on the global climate system in a fully-coupled setting. In the first experiment, subpolar ocean heat uptake in the preindustrial CESM2 will be enhanced by increasing cloud opacity over the Southern Ocean in winter, which will tend to increase downward longwave fluxes into the ocean surface and suppress (sensible and latent) turbulent fluxes. In the second (complementary) experiment, subpolar ocean heat uptake will be suppressed by decreasing Southern Ocean cloud opacity in winter. Differences in the large-scale dynamics in these runs, relative to the CESM2 preindustrial control experiment, will be used to ascertain the impact of Southern Ocean heat uptake on the Earth's climate system.

P5.4 Representing Antarctic ice shelf processes: Ocean models, like POP, do not include functionality for modeling the sizable cavities under floating ice shelves, such as the Ross and Ronne-Filchner shelves of the West Antarctic. The presence of these shelves, however, is thought to be essential for water mass transformation processes that impact ocean hydrography under the Antarctic ice pack (Foldvik et al. 1985; Nichols et al. 2003; Mahoney et al. 2011). To better represent such water mass transformation processes in CESM2, we propose a series of experiments in which heat and freshwater fluxes are injected into the water column at the Antarctic coast to mimic the creation of Ice Shelf Waters. The injections would be salinity- and heat-conserving to avoid spurious ocean drift. We propose to run 10 ensemble members, each 50 years, with different spatial patterns and magnitudes of these heat and freshwater fluxes. The evolution of Southern Ocean hydrography and sea ice will then be evaluated to achieve a process-level understanding of the impacts of ice shelf processes on the Antarctic climate system.

Development Runs

Experiment	Configuration	Resolution	# Runs	# Years	Cost per year	Total in M core-hours	Data Usage (TB)	Priority	When
D1	B1850	f09_g17	1	250	3543	0.89	7	A	Year 1
D2	B1850	f09_g17	2	150	3543	1.06	8	A	Year 1
D3.1	B1850	f09_g17	4	100	3543	1.42	11	A	50% Yr 1 50% Yr 2
D3.2	B1850	f09_g17	1	200	3543	0.71	5.5	B	50% Yr 1 50% Yr 2

D3.3	B1850	f09_g17	1	200	3543	0.71	5.5	A	Year 2
D3.4	B1850	f09_g17	2	250	3543	1.77	14	A	Year 2
D4	GIAF	TL319_t13	1	18	575,000	10.35	5	C	Year 2
Yearly Total						3.015 13.895	23.3 32.8		Year 1 Year 2
Net Total						16.91	56.1		

Production Runs

Experiment	Configuration	Resolution	Number of Runs	Number of Years	Core hours per year	Total in M core-hours	Data Usage (TB)	Priority	When
P1.1	BHIST	f09_g17	540	1	3432	1.85	30	B	Year 2
P1.2	CICE with DART	T62_g17	4	20	3000	0.24	0.4	A	50% Y1 50% Y2
P1.3	B1850	f09_g17	1	300	3543	1.06	16.5	B	Year1
P2.1	F	f09_f09	10	10	3000	0.30	5.5	A	Year 1
P2.2	BHIST	f09_g17	1	150	3432	0.51	8	A	Year 1
P3.1	BHIST	f09_g17	10	110	3432	3.78	60.5	A	Year 1
P3.2	B1850, BHIST, SSP3.70	f09_g17	1	505	3500	1.77	28	B	Year 1
P4.1	BHIST	f09_g17	10	60	3432	2.06	33	A	Year 1
P4.2	B1850 BHIST SSP3.70	f09_g17	1 5 5	250 165 35	3500	4.38	69	B	Year 2
P5.1	BHIST	f09_g17	10	70	3432	2.40	38.5	B	Year 1
P5.2 (PCWG & LIWG joint)	B1850 (CESM1 & CESM2)	f09_g17	3 CESM2 3 CESM1	115 115 (other 115 years requested under the LIWG)	3543 1500	1.74	38	C	Year 2
P5.3	B1850	f09_g17	2	250	3543	1.77	27.5	C	Year 2
P5.4	B1850	f09_g17	10	50	3543	1.77	27.5	C	Year 2

Yearly total						12.00 11.63	190.2 192.2		Year 1 Year 2
Net total						23.63	382.4		

Software Engineering Working Group (SEWG)

1. Broad Overview of Working Group and Research Plan

The role of SEWG is to coordinate the computational development of the CESM model components, oversee the evolving design of the CESM as new model components, new model grids, and new model physics are added to the system, and at the same time engineer the model system to obtain optimal throughput and efficiency. This continues to be particularly challenging as the number of model configurations, model complexity, and model resolutions are rapidly increasing. Numerous tests are carried out for each new CESM revision on all production platforms to ensure required functionality (such as exact restart capability), correct results (such as bit-for-bit reproducibility where it is expected), tracking of memory and performance metrics (to determine if these have changed relative to the previous revision), and other key production requirements (such as optimizing performance of new revisions, especially where new component science has been introduced). This testing also ensures the robustness of model infrastructure development, such as improvements to the model driver, coupler, tools, and scripts. Computing time is requested to carry out these important functions throughout the various CESM versions that will be generated, both in the CESM2 series and on the path towards CESM3. The NWSC supercomputing resources remain our primary resources for conducting this testing.

2. Development Proposal (Y1: 6.0 M; Y2: 9.0 M; total 15.0 M core-hours)

SEWG's computing usage is nearly all spent on regular, ongoing software testing. We expect full use of our entire allocation, because of the increasing computational cost of many of the CESM components, which in turn leads to an increased software testing cost. CAM will likely see a doubling of its testing costs due to the addition of new dynamical cores, higher vertical resolution, and more expensive chemistry. MOM is many times more expensive than POP, and for a while, testing will need to be done on both ocean models. CTSM will be moving to a default configuration that includes the Functionally Assembled Terrestrial Ecosystem Simulator (FATES), which currently increases computational cost by about a factor of 6, and is also expanding to support many additional configurations that need to be tested. To some extent, we can compensate for the additional computational cost by decreasing the simulation lengths of our tests and removing other redundancies – as well as working to improve the current high costs of the new components – but we will not be able to completely compensate for this increase in model costs. Moreover, testing of additional model functionalities and associated performance optimizations also increase demands on our allocation. In general, we will use our allocation for: i) software testing of individual CESM components; ii) software integration testing of CESM alpha, beta, and release versions; iii) software testing of new CESM infrastructure, including ESMF-based CMEPS / CDEPS; and iv) ESMF regression tests.

Whole Atmosphere Working Group (WAWG)

1. Broad Overview of Working Group and Research Plan

WAWG research plan promotes the development of a unified sun-to-earth modeling framework with WACCM and WACCM-X, a version of WACCM extended throughout the thermosphere, to 500 km. Production runs are also proposed for NCAR science as well as collaborations with the community.

The development proposal includes exploring higher vertical and horizontal resolution, both in the context of WACCM and WACCM-X. Resources are also requested to evaluate and tune SE versions of WACCM that include Regional Refinement.

On the production side, simulations will contribute to studies of the QBO and other high-vertical resolution simulations for basic research and for contributing to ongoing QBOi activities. Production will also include WACCM simulations of the Last Millennium (850-1850) with interactive volcanic aerosols derived from emissions, and studies of space climate with WACCM-X.

2. Development Proposal (Y1: 9.7 M; Y2: 12.5 M; total 22.2 M core-hours)

D1. High vertical resolution WACCM6: CESM2(WACCM6) has been run in a 110-level (110L) configuration. This produces a realistic QBO, consistent with that obtained using CESM1(WACCM5.4). The WACCM6-110L simulations have shown that using a vertical resolution (dz) of 500 m through at least 25 km altitude improves representation of slow Kelvin waves in the lower stratosphere, which are necessary to simulate a realistic QBO. We will pursue new scientific topics motivated by these findings. We will investigate the sensitivity of our QBO simulations to (a) vertical resolution finer than 500 m, and (b) expansion of the high-vertical resolution region to higher altitudes. The latter will explore the possibility that enhanced vertical resolution through the depth of the middle atmosphere improves not just the QBO, but the overall model climatology, including reduction of polar cold temperature biases.

We request time for 3 x 30 year runs to debug, tune, and document the climatology of the QBO at dz = 400 m. Running WACCM6-110L with specified chemistry (SC) costs about 10 K-hr per year of simulation. dz = 400 m configuration has 120 levels, so we prorate the cost of these simulations based on the number of levels, that is, by a factor of 120/110 = 1.1 (11 K-hr/yr). Storage is estimated at 0.44 TB/year for the 110L model with full chemistry. Because these are SC simulations, that number is reduced to 0.22 TB/yr for the 110L model, 0.24 TB/yr for the 120L.

D2, D3, and D4. Evaluation and tuning of WACCM-SE/SE-RR (Regionally Refined): This project proposes to evaluate and tune 1° and 1/8° RR WACCM-SE, a potential replacement for the FV dycore. The impacts of the new advection and damping schemes, as well as the interaction of the SE dycore with physics, need to be assessed and compared with existing FV simulations, reanalyses, and observations. We also need to assess the dynamics of convectively-generated gravity waves within the regional refinement: to improve their parameterization on the global grid, to develop a more scale-aware gravity wave scheme, and to develop a better understanding. WACCM-SE will be run at 1° resolution with both 70L and 110L with full troposphere-stratosphere-mesosphere-lower-thermosphere chemistry over the 1979-2014 historical period to assess the coupled circulation, chemistry, climate, and variability of the whole atmosphere to vertical resolution. Three-member ensembles will ensure adequate sampling of variability over the historical period. We will run 110L WACCM-SE-RR for 5 years of simulation time. This single member run will be used to assess and tune WACCM-SE-RR with an equatorial refinement from 5°S to 5°N. This simulation will resolve a large fraction of the convectively-generated gravity wave spectrum and can inform better and more scale-aware gravity wave momentum and transport parameterizations.

D5. Development of an Asian Summer Monsoon RR grid model: During the summer of 2021, a joint NSF and NASA two-aircraft campaign (ACCLIP) is planned. This campaign will measure air masses lofted by the Asian Summer Monsoon convection from the boundary layer and transported to the Western Pacific upper troposphere and lower stratosphere by sub-seasonal-scale eastward eddy shedding. The post-mission science will need a high horizontal (0.25°) and vertical (500 m) resolution chemical transport model. To meet the needs of ACCLIP, a SE RR version of SD WACCM will be used. The request is for a 3-year simulation.

D6, D7, and D8. WACCM-X development: Recently WACCM-X physics has been merged with CAM6 physics. The new development goal for the next two years is to transition WACCM-X dynamical core from FV to SE dycore. After finishing the initial modification of the SE dycore to take into consideration the major species dependence in the thermosphere, we will start testing and validation. We request time for WACCM-X-SE simulations under perpetual solar maximum, moderate, and minimum conditions (1 model year for each) at NE30 (~1°) horizontal resolution and ¼ scale height vertical resolution (130L). These results will be compared with WACCM-X-FV of comparable resolutions for validation. We will then develop and test WACCM-X-SE high resolution capabilities. Our target resolution is NE120 in the horizontal and 0.1 scale height in the vertical (300L). Our test will consist of 1 one-month run (January).

The propagation of small-scale waves depends upon the large scale, i.e., planetary scale, atmospheric flow. It is therefore necessary to constrain the larger scale flow to simulate the behavior of small-scale waves as realistically as possible. For the second year, we will develop the methods necessary to constrain the larger scale flow in high resolution WACCM-X-SE using external meteorological data from, for example, MERRA2 or WACCMX+DART. This will enable us to assess the capabilities of the high resolution WACCM-X-SE to simulate the behavior of small-scale waves during specific time periods. For this development, we will use WACCM-X-SE at NE120 and 300L resolution and run simulations for a winter with prominent SSW (2008-2009).

3. Production Proposal (Y1: 17.6 M; Y2: 14.6 M; total 32.2 M core-hours)

P1 and P2. Historical simulations with best QBO: Depending on the results of D1, we will conduct simulations of the historical period, 1980-2020, at the vertical resolution that produces the most realistic QBO when compared to observations. Assuming that this will be accomplished at dz = 400 m, we will complete WACCM6 atmosphere-only runs where high vertical resolution is used through 25 km and through 80 km. Runs with dz = 400 m resolution through 80 km require 210 levels, so the cost relative to WACCM6-110L is 1.9.

P3. PALEOSTRAT volcanic Last Millennium: A 1000-year WACCM6 simulation at 2° horizontal resolution will be carried out to evaluate the effect of aerosols, including volcanic injections, in the “last millennium” (LM; 850-1850). This simulation uses MAM adapted for the stratosphere to compute explicitly the evolution of aerosols based on a time-dependent volcanic injection data set. This run is required to evaluate the model's ability to reproduce the climate of the last millennium using interactive stratospheric aerosols and a database of SO2 injections from volcanic eruptions.

P4. Sensitivity studies of atmospheric optical depth (AOD) and surface climate in response to SO_2 injection: We will use CESM2(WACCM6), 70L, to carry out sensitivity studies of AOD and surface climate in response to SO_2 injections into the stratosphere to perturbations in model physics. Ten 5-year simulations (50 years) with SO_2 injections in the stratosphere will be carried out with changes to two parameters: tuning parameters in the gravity wave drag parameterization and small perturbations in the MAM3 aerosol distribution. These simulations will be branched from year 2035 of the SSP5-8.5 simulations that have already been carried out with CESM2(WACCM6) and SO_2 injections will be prescribed to reduce the global mean temperature by ~0.5°C. Stratospheric response, AOD, and residual circulation changes will be examined. Six of the simulations will be extended by 25 years to examine the sensitivity of surface impacts (temperature, precipitation, etc.) to small changes in model representation (160 years).

P5. WACCM6 110L no-QBO runs: We will investigate changes to stratospheric and tropospheric variability that result from QBO by performing a set of simulations without a QBO to complement simulations with a QBO that are already being carried out with CESM2-WACCM-110L. The QBO will be shut off by setting the efficiency of convectively generated gravity waves to zero, hence only impacting the tropical simulation. The request is for a single run for the 1981-2020 period.

P6. Simulations in support of 2022 WMO/UNEP Scientific Assessment of Ozone Depletion: Every four years the future evolution of stratospheric ozone is accessed with the state-of-the-art chemistry climate models. For the 2022 ozone assessment, the halogen recovery scenarios have not been defined. We ask for time to run one recovery scenario. The scenario will include a given SSP assumption for greenhouse gases (e.g., CO_2, CH_4, and N_2O) along with an assumption regarding the organic halogen’s evolution (e.g., CFCs, HCFCs, etc.). It will need an ensemble of 3-members for the 2015-2100 period using CESM2.2(WACCM6). Results from this assessment will be published in the 2022 WMO/UNEP Scientific Assessment of Ozone Depletion.

P7. Evaluation of halogen heterogeneous chemical processes in the lower stratosphere: New high vertical resolution CESM2(WACCM6) 110L model results will be compared to available satellite observations. We will use the satellite coordinate output option for this work. WACCM6 will be run in the specified dynamics mode and 'nudged' to NASA MERRA2 reanalysis. Two simulations will be conducted: 1) reference simulation with heterogeneous processes on sulfate aerosols, nitric acid trihydrate, and water-ice aerosols; and 2) no halogen heterogeneous simulation (on these aerosol types). Each simulation will start in 1980 and finish in 2020. This period was chosen for the purpose of examining inorganic halogen (e.g., HCl, ClO, and $ClONO_2$), nitrogen dioxide (NO_2), and nitric acid (HNO_3) observations from the SAGE, SAGEII, SAGE III-Meteor, SAGEIII-ISS, Aura MLS, ACE-FTS, and OSIRIS satellite instruments. These simulations will also be the reference simulations for the subgrid scale gravity impact on chemistry project (next CSL project).

P8. 2020/2021 S2S hindcasts with CESM2(WACCM): S2S hindcasts with weekly start dates between September and April, run lengths of 45 days, 11 ensemble members, have been carried out with CESM2(WACCM) for years 1999-2019. We will extend these runs through Sep 2021 as initial conditions become available. These simulations will allow for examining predictability of recent events relevant to the whole atmosphere.

P9 and P10. WACCM-X Production: Using WACCM-X-SE at resolution NE30/130L, we will perform historical SD runs for the period 2010-2020. The model output will be used for studying the whole atmosphere climatology, including the space environment. This will update our current model climatology, which is based on WACCM-X-FV.

Using high resolution WACCM-X-SE at resolution NE120/300L, we plan to make a northern winter run for 2018-2019 (DJ) with large-scale nudging. The model results will be compared with GOLD measurements.

Experiment	Configuration	Resolution, vertical levels	Number of runs	Number of years per run	core-hours per simulated year	Total in M core-hours	Total data volume (TB)	Priority
DEVELOPMENT								
Year 1								
D1 QBO in high vertical resolution (400 m) WACCM6	FWscHIST	f09_f09_mg17, 120L	3	30	11,000	0.99	22	A
D3 Evaluation and tuning of WACCM-SE	FW2000	ne30pg3_ne30pg3_mg17, 70L	3	36	33,000	3.56	3	A
D5 Development of an Asian Summer Monsoon Regionally Refined Grid Model	FWSD	ne30x8_ne30x8_mg17, 110L	1	3	1,000,000	3.00	6	A
D6 WACCM-X NE30/130L development	FX2000	ne30/130L	3	1	300,000	0.90	0.3	A

D7 WACCM-X-SE NE120/300L development	FX2000	ne120/300L	1	1/24	30,000,000	1.25	2	A
						9.70	33.3	
Year 2								
D2 Evaluation and tuning of WACCM-SE	FW2000	ne30pg3_ne30pg3_mg17, 110L	3	36	46,000	4.97	3	A
D4 Evaluation and tuning of WACCM-SE-RR	FW2000climo	ne30x8_ne30x8_mg17, 110L	1	5	1,000,000	5.00	16	A
D8 WACCM-X-SE NE120/L300 SSW development	FXHIST	ne120/300L	1	1/12	30,000,000	2.50	4	A
						12.47	23	
PRODUCTION								
Year 1								
P1 Historical Simulations high dz to 25 km	BWHIST	f09_f09_mg17, 210L	1	40	44,000.00	1.76	19	A
P3 PALEOSTRAT volcanic	BWmaHIST	f19_19_mg17, 70L	1	1000	3,500	3.50	45	A
P4 Response to SO2 injections	FWHIST	f09_f09_mg17, 70L	16	12.5	25,000	5.00	56	A
P6 Simulations for 2022 WMO/UNEP ozone assessment	BWHIST	f09_f09_mg17, 70L	3	85	25,000	6.38	112	A
P8 2020/2021 S2S Hindcasts	FWHIST	f09_f09_mg17, 70L	300	0.123	25,000	0.92	1	A
						17.56	233	
Year 2								
P2 Historical Simulations high dz to 80 km	BWHIST	f09_f09_mg17, 210L	1	40	83,600	3.34	33	A
P5 WACCM6-110L no-QBO	BWHIST	f09_f09_mg17, 110L	1	40	40,000	1.60	18	A
P7 Evaluation of Het Chemistry Process	FWSD	f09_f09_mg17, 110L	2	21	40,000	1.68	21	A
P9 WACCM-X-SE NE30/130L	FXSD	ne30, 130L	1	10	300,000	3.00	1	A
P10 WACCM-X-SE NE120/300L	FXHIST	ne30/300L	1	1/6	30,000,000	5.00	8	A
						14.62	81	
DEVELOPMENT TOTAL						22.17	56.3	
PRODUCTION TOTAL						32.18	314.0	
YEAR 1 TOTAL						27.26	266.3	

YEAR 2 TOTAL						27.09	104.0	
GRAND TOTAL						54.35		
STORAGE TOTAL							370.3	

Community Projects

C1. World-Avoided Mini-MIP (9.2 M core-hours)

Requested by: To support CESM's participation in the World-Avoided Mini-MIP organized by the U.S. Climate Modeling Summit with the U.S. modeling centers participating.

The purpose of these simulations is to identify the chemistry (including air quality and health) and climate impacts of the 1970 Clean Air Act, including its amendments. This is part of a coordinated effort between all the U.S. climate modeling centers, organized by the U.S. Climate Modeling Summit sponsored by the USGCRP's Interagency Group on Integrative Modeling. The simulations will require use of the CESM2(WACCM6) transient version at the nominal 1° horizontal resolution. In collaboration with S. Smith (PNNL), a set of emissions was created as perturbations from the CMIP6 emissions. These World-Avoided sensitivity simulations will be run for the 1970-2014 period. To identify robust signals, an ensemble size of 10 is recommended. We note that our existing CMIP6 CESM2(WACCM6) simulations will be used as control experiments. However, because there are only 3 members for this control, a separate effort led by A. Fiore, L. Polvani, and J.-F. Lamarque is generating an additional 7 members using a combination of micro and macro perturbations at no cost to this proposal to bring the total number of control ensemble members to 10. Therefore, the present request is only for the sensitivity simulations: 10 (members) x 45 (years) x 20,340 (cpu-hrs / year) = ~9.2 M hours. The estimated request for Campaign Storage is ~198 TB, based on ~0.44 TB of output per simulation year.

C2. Additional Single Forcing Experiments to Complement CESM2 Large Ensemble (14.1 M core-hours)

Requested by: CVCWG and community members

The forthcoming CESM2 100-member Large Ensemble (CESM2-LENS) will be a very widely used resource. These simulations are being performed in South Korea in collaboration with the Institute for Basic Science Center for Climate Physics in Busan. The scientific value of this new CESM2-LENS, which uses all forcings from SSP3-7.0, can be greatly increased if additional simulations can be used to further our understanding of its behavior. An important complement is *single forcing* simulations in which individual natural or anthropogenic forcings are imposed in isolation. If a complete suite of single forcing experiments can be performed, then they can be used to isolate the roles of individual forcings and their non-linear interactions in producing the overall climate changes seen in CESM2-LENS.

The relevant forcings to consider are: greenhouse gas forcing (GHG); industrially emitted aerosols (AER); biomass burning aerosols (BMB); Ozone (O3); volcanic eruptions (VOL); and solar (SOL). Based on experience from the CESM1 single forcing experiments, at least 15 members are necessary to tease out the forced response (even more members are needed when considering changes in extremes). We propose to run the following four single forcing ensembles for the 1850-2050 period using the CESM2(CAM6) configuration at the 1° resolution as in CESM2-LENS: (A) GHG-only; (B) AER-only; (C) BMB-only; and (D) O3 + VOL + SOL only. These simulations will allow for a clean isolation of the influence of these different forcings on CESM2-LENS. While experiment (D) includes multiple forcings, the distinct timing of their influence over the historical record should still allow their signal to be isolated.

Performing 15-member ensembles for each of these 4 single forcing sets would require a total of 60 201-year simulations. Fortunately, progress is already being made through an existing NCAR Strategic Capability (NSC) allocation (with lead PI Danabasoglu). The available NSC computational time will permit around 40 members of single forcing experiments. We, therefore, request additional resources to augment the 40 members running under the NSC resources with another 20 to bring our total to 60 members. The estimated cost of this request is: 20 (members) x 201 (years) x 3500 (cpu-hrs / year) = 14.1 M core hours. The estimated request for Campaign Storage is ~219 TB.

C3. Wildfires (17.0 M core-hours)

Requested by: ChCWG, LMWG, LIWG, and PCWG

This project will investigate how wildfires change in a warming climate and the impacts of fire variability and change on the climate system. This is a timely topic given events like the recent Australian and Siberian wildfires and the apparent sensitivity of the high latitude climate to the details of the biomass burning emissions in CESM2 historical and scenario simulations. The project will use two types of simulations: i) with prescribed variations in biomass burning emissions to test the sensitivity to those emissions, and ii) with biomass burning emissions produced prognostically by the fire model to investigate the simulation of changing fires and their impacts. The use of these different types of simulations will allow us to assess the direct influence of changes in fire emissions and to investigate feedbacks associated with changing fires. For future prescribed emissions, this project will leverage a large set of CLM parameter perturbation experiments to obtain a range of possible future fire emissions. In the case of interactive fire emissions, tuning and validation of the fire model within coupled runs will be required. Our proposed integrations will allow us to address a number of science questions that include: How and why are fires likely to change in a warming climate and what are the climate impacts? How does the choice of fire emissions in pre-industrial, historical, and future climate affect the simulation of climate variability and change and the quantification of internal variability? and How does variability and change in fire emissions affect air quality?

All the proposed simulations will be performed using either CESM2(CAM6) or CESM2(WACCM6) configurations at the nominal 1° horizontal resolution. The table below lists the simulations with the blue and green shadings denoting runs with prescribed emissions and with emissions simulated by the CLM fire model, respectively.

Exp	Config	# Runs	# Years	Cost per year	Total cost (M core-hours)	Total Storage (TB)	Purpose
PI Control with modified emissions	B	1	500	3500	1.75	27.5	To assess the impact of fire variability in a non-GHG forced climate state
Historical with modified fire emissions	B	5	165	3500	2.89	45.37	To assess the historical transient change to fire emission choices
SSP with modified fire emissions	B	5	85	3500	1.49	23.37	To assess the future transient change to fire emission choices
PI Control with fire-model produced emissions	B	1	300	3500	1.05	16.5	Tuning of model; assessing impact on the PI climate
WACCM PI Run with fire model produced emissions	BW	1	100	20340	2.03	15.0	Tuning of model; assessing impact on the PI climate
Historical with fire model produced emissions	B	5	165	3500	2.89	45.37	To assess changing fires, their impacts on emissions, and consequent climate impacts in the historical climate
Historical with fire model produce emissions	BW	1	165	20340	3.36	24.75	To assess changing fires, their impacts on emissions, and

							consequent climate impacts in the historical climate
SSP runs with fire model produced emissions	B	5	85	3500	1.49	23.37	To assess changing fires, their impacts on emissions, and consequent climate impacts in future climate scenarios
Total					16.95	221.23	

C4. Development and Evaluation of CESM2(WACCM6-MA) (7.0 M core-hours)

Requested by: WAWG, CVCWG, and Geoengineering Large Ensemble (GLENS) collaborators

CESM2(WACCM6) was developed and run for CMIP6 at 1° horizontal resolution with the FV dycore and with full chemical representation of the troposphere, stratosphere, mesosphere, and lower thermosphere (TSMLT1). In addition, a lower-cost version was developed at reduced, i.e., 2° horizontal resolution with more limited middle atmosphere (MA) chemistry, reducing model cost by a factor of ~8. This version also ran the CMIP6 DECK and historical simulations, and proved adequate for many climate applications, e.g., Last Millennium paleoclimate. In this request, we propose to develop and evaluate an intermediate-cost version, using MA chemistry at 1° resolution (FV1x1).

This MA version, WACCM6-MA, will retain features of WACCM6-TSMLT1 such as an interactive QBO and the regional predictability, while reducing cost by a factor of ~2.3 with respect to the full WACCM6. It will be comparable in features and cost to the version of CESM1(WACCM) that has been used extensively for stratospheric aerosol geoengineering research, including GLENS that was conducted in 2018. Considering both the research that led up to GLENS and subsequent analysis of GLENS simulations, CESM1(WACCM) has been used in at least 24 publications to date, involving researchers in multiple CESM working groups (WAWG, AMWG, CVCWG). The development of FV1x1 WACCM6-MA is motivated by a desire to continue this research using CESM2(WACCM6), and provide an intermediate-cost model version to the community for many climate applications that do not require full tropospheric chemistry but do require 1° horizontal resolution.

Development of FV1x1 WACCM6-MA is currently underway, with a fully-coupled preindustrial control (piControl) experiment to check and tune the radiative balance. We request computing time to perform 4 simulations required to evaluate the model's climate and establish baseline control simulations for additional studies. We will run one historical simulation (1850-2014), followed by two future scenarios: SSP2-4.5 and SSP5-8.5 (2015-2100). In addition, we will continue the piControl simulation for 250 years past the point from which the historical simulation branched, in order to assess any long-term climate drifts. In our request, we use 12 000 core-hours per simulation year based on our current simulation.

	# years of simulation	Core-hours in M	Data volume to be stored (TB)
piControl	250	3.00	40
Historical	165	1.98	27
SSP2-45	86	1.03	14
SSP5-85	86	1.03	14
Total	587	7.04	95

C5. Simulating the Climate of Greenland and Antarctic Ice Sheets Using VR-CESM (12.1 M core-hours)

Requested by: AMWG, CVCWG, LIWG, and PCWG

Recently completed simulations using the Arctic regionally refined grid in CESM2.2 have demonstrated substantial improvements to the simulated meteorology and climate of the Greenland Ice Sheet (GrIS) compared with the standard 1° grid in CESM. Higher horizontal resolution relieves longstanding biases through resolving the steep margins of GrIS, permitting realistic orographic precipitation and accurately representing narrow ablation zones. These improvements translate into a more realistic surface mass balance, positioning Variable Resolution CESM (VR-CESM) as a valuable tool for providing accurate projections of cryospheric contributions to sea level rise over the next centuries.

We request resources to simulate and understand processes controlling the evolution of both the Greenland and Antarctic ice sheets (AIS) using VR-CESM. In a collaboration between AMWG, CVCWG, LIWG, and PCWG, the Arctic grid is currently being coupled to the 1° POP ocean model and the 4 km CISM ice-sheet model. This configuration is unique for its ability to resolve complex interactions at high-resolution between sea-ice, ocean, ice sheets and the atmosphere, and is being spun-up to provide a dynamic representation of GrIS during the preindustrial period. For this proposal, we seek to continue this successful cross-WG collaboration through branching off the preindustrial simulation to run the fully-coupled Arctic grid configuration over the historical period (1850-2020), and into a future RCP-SSP scenario (2020-2200) for a total of 350 years. In addition to providing a cutting-edge projection of the contribution of GrIS to future global sea level, it also provides an opportunity to understand resolution dependent meteorological phenomena such as atmospheric rivers, polar lows, and katabatic winds, and how they fare against observations. The resources required for the Arctic simulation are 8.4 M core hours.

An additional 3.7 M core hours are requested for the purposes of developing and using an Antarctic grid. This application of VR-CESM to the Southern Hemisphere high latitudes will be the first of its kind, and will have a similar setup as the Arctic grid described above. The focus of the simulations will be to provide a high-resolution data set of contemporary (1979-2018) Antarctic snowfall and surface mass balance, which will be compared in detail with default CESM2 output and available in-situ and remote sensing observations. Additionally, we will study the impact of Southern Ocean conditions on Antarctic atmosphere, surface melt, and snowfall. For this purpose, resources for 4 40-year AMIP-style VR-CESM sensitivity simulations are requested. Here, ocean forcing will be offline ocean forcing, and the sea ice and sea surface temperature conditions around Antarctica will be varied.

Compset	Resolution	# of runs	# of years per run	Core-hours per year	Total in M core-hours	Disk volume (TB)
BHISTG	ne0ARCTICne30x4_g17 (1/4° refinement)	1	350	24000	8.40	20
FHIST	ne0ANTARCTICne30x4_ne0ANTARCTICne30x4_mt12 (1/4° refinement)	4	40	23000	3.68	5
TOTAL					12.1	25

C6. Emerging Science (7.5 M core-hours)

Requested by: The CESM Chief Scientist

During the course of our allocation cycles, several science topics naturally emerge that can be addressed using various CESM configurations. The topics in this category are usually time critical. They include, for example, climate impacts of reductions in emissions due to COVID-19 and deciphering impacts of details of how biomass burning emissions are constructed in CMIP6. Clearly, such topics are of broad community interest, with both national and international assessment implications. Therefore, it behooves CESM to respond to such emerging science topics in a timely fashion where a modest amount fo computer time can be allocated for these purposes. Furthermore, if additional computational resources would be necessary for coupled CESM3 simulations as discussed in our Summary Plan in the primary proposal, some resources would be provided from this allocation.

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