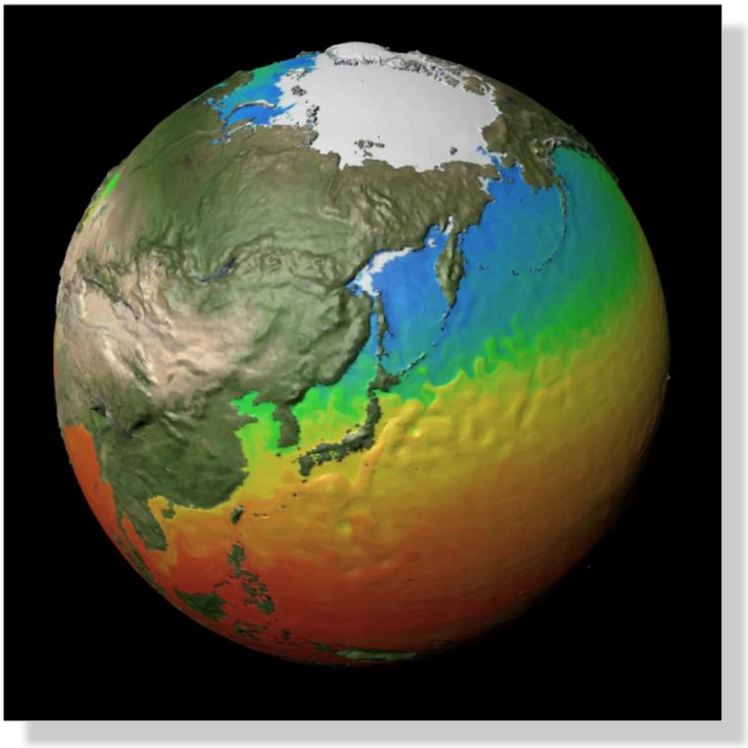
CESM

Community Earth System Model



CESM CSL Proposal Supplementary Material
PI: Gokhan Danabasoglu, CESM Chief Scientist
Period of Performance: 01 November 2018 – 31 October 2020
Total Request: 460 M Cheyenne Core-Hours

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

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Atmosphere Model Working Group (AMWG)

1. Broad Overview of Working Group and Research Plan

The 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 transport. It also covers sensitivity experiments aimed at understanding the many interactions among the represented physical and dynamical processes across climate regimes and multiple timescales.

The most recent version of CAM - CAM6 - was released as part of CESM2. CESM2 is a state-of-the-art Earth system model (ESM) with significantly improved (compared to CESM1) representations of aerosol processes, land surface interactions, coastal estuarine processes, ocean biogeochemistry, stratospheric chemistry, and dynamics among other things. In addition, CESM2 includes, for the first time, a fully prognostic model of the Greenland ice sheet. As the "sphere" that mediates the Earth's radiation budget and the only component which communicates with all other components in an ESM, the atmospheric model is the linchpin of the fully-coupled system. During the previous proposal period, CSL resources were used by AMWG scientists for exhaustive exploration, evaluation, and final adjustment of atmospheric physical parameterizations in the context of the fully-coupled system that is now being used in the CMIP6. This included development and testing of surface drag modifications to improve simulations of polar processes such as surface mass balance (SMB) over the Greenland Ice Sheet and air-sea interactions over the Labrador Sea - *the* key region for deep water formation in the World Ocean. AMWG researchers also used CSL resources to evaluate the impacts of detailed microphysical aerosol-cloud interactions (ACI) in CAM6. These ACIs may play the dominant role in determining the net response of the coupled system to the anthropogenic perturbations that have taken place during the last 150 years.

With the upcoming allocation, AMWG development activities will include: 1) Analyzing impacts of CAM6 physics schemes on current model behavior; 2) Refocusing on model resolution – both vertical and horizontal; 3) Evaluating new candidate atmospheric dynamical cores - MPAS and FV3; 4) Developing scientifically-supported regionally-refined model configurations for domains of interest such as the Continental U.S. (CONUS) and the west Pacific warm-pool; 5) Continuing physics developments including improvements to Cloud Layers Unified By Binormals (CLUBB) as well as exploring alternative convection, turbulence, and drag schemes; and 6) Exploring new frameworks for climate model evaluation including idealized configurations such as radiative-convective equilibrium and gray-radiation physics, cloud-locking capabilities, forecast configurations, nudging, and coupling with the Data Assimilation Research Testbed (DART) framework.

2. Development Proposal (32.8M core-hours)

D1. CAM6 climate investigation (Y1 - 2.8M; Y2 - 3.1M): 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 around 4°C in CESM1 to about 5.3°C in CESM2. In addition, it was found that minor changes in aerosol emissions data led to large differences in simulated 20th century warming by the model. We will conduct coupled as well as atmosphere-only simulations to investigate the origins of these sensitivities which likely result from coupled feedbacks operating at a variety of timescales. We therefore envision conducting suites of coupled simulations with perturbed physics parameters ranging in length from 20 to 300 years. These suites will include abrupt 4xCO_2 experiments, experiments with modified aerosol emissions, pre-industrial control simulations as well as transient 20th century simulations. We expect to focus on aerosol-cloud interactions as simulated by the Morrison-Gettelman v2 microphysics (MG2, Gettelman and Morrison 2015), but also expect to explore the representation of rain microphysics and cloud overlap in the model. Coupled sensitivity experiments will range from 50 to 150 years in length depending on set-up. We request resources for a total of 10 experiments of 100 years in length. Coupled sensitivity studies will be supplemented with atmosphere-only experiments to explore sensitivity to cloud and aerosol processes in a more constrained setting. These runs will range from a few years in length to complete AMIP (Atmosphere Model Intercomparison Project) style historical experiments.

While CAM6 climate is improved in most respects compared to that in CAM5, it nevertheless exhibits a number of simulation biases. Persistent biases include the existence of a double Inter-Tropical Convergence Zone (ITCZ) bias in tropical rainfall, warm-dry bias over summertime continents in mid-latitudes (e.g., US Midwest), excessive orographic precipitation, cold polar tropopause bias, and excessive high latitude surface wind stresses over ocean. A small but notable degradation in CAM6 performance is in its simulation of high-latitude sea level pressure. The origin of these biases will be investigated via perturbed physics sensitivity runs. Because these biases are present in atmosphere-only runs, we expect to address them using prescribed-SST, atmosphere-only configurations. To confidently eliminate impacts of internal variability especially in northern high-latitudes will require simulations of at least 20 years.

A persistent problem during recent CAM development activities has been the diverging climates as simulated by fully coupled and prescribed SST (AMIP) model configurations. AMIP simulations are historically a useful indicator of coupled model performance, particularly for global energy budget requirements of a balanced Earth system model. Many factors may come into play to explain discrepancies between configurations, e.g., surface component configuration, coupled feedbacks; and so, we propose to dedicate a set of coupled and AMIP experiments with CAM6 to determine the underlying causes.

These simulations are intended primarily to deepen our understanding of the CAM6 and CESM2 climate at the 100 km resolution utilized in the CMIP6 intercomparison. The findings from these experiments should help us to address model biases in future versions of CAM both at 100 km and higher resolutions. Resources to conduct a total of around 900 years of simulation with the FV_09x1.25 prescribed SST configuration is requested. Assuming a nominal simulation length of 20 years, we expect to perform 20 experiments in Year 1 and 25 in Year 2.

A nominal breakdown of these 45 experiments is as follows: 10 variations of MG2 microphysics; 5 variations of Zhang-McFarlane deep convection; 10 variations of CLUBB parameters, including those concerning momentum transport and cloud condensation; 10 variations of subgrid orographic parameters including anisotropy parameters as well as degrees of topographic smoothing. Selected configurations from the above will be explored further in climate sensitivity configurations including SST+4K (5 runs) and aerosol-indirect effect configurations using pre-industrial emissions in present day (5 runs).

D2. <u>CAM physics development (Y1 - 0.7M; Y2 - 3.7M):</u> CAM6 incorporated important changes to every physical process representation in the atmosphere with the exception of clear sky radiative transfer. The CLUBB scheme (Bogenschutz et al. 2013) completely replaced the parameterizations of planetary boundary layer (PBL) turbulence, shallow convection (ShCu), and the representation of subgrid cloud quantities (cloud macrophysics). Cloud and precipitation microphysics were significantly advanced with the introduction of MG2 which includes prognostic precipitation species as well as cloud condensates and improved representation of mixed-phase cloud processes. The parameterization of subgrid orographic drag carried by both mesoscale gravity waves (OGWD) and PBL eddies (Turbulent Orographic Form Drag, TOFD) was substantially modified. TOFD is now represented using the scheme of Beljaars et al. (2004) and OGWD now incorporates both topographic orientation and near-surface nonlinear effects (e.g., Scinocca and McFarlane 2000). The scheme of Zhang and McFarlane (1195; ZM95) is still used to parameterize deep convection in CAM6, but the implementation of ZM95 in CAM6 includes significant changes compared to that in CAM5.

The calculations discussed in this section, except for the refined mesh microphysics studies, will focus on the "work horse" climate resolution of ~100 km and the estimated computational resource requirements reflect this. Initial exploration of physics modifications will occur in short runs (< 5 years) primarily in Year 1, followed by longer runs (order 20 years) in Year 2 to better define climate impacts.

D2.1 <u>Convective parameterization:</u> Despite this comprehensive update of the physics, impactful parameterization development is still expected to occur within this CSL cycle. The 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 2013) will be performed. Improvements to the MG2 microphysics are also expected to become available during this CSL cycle.

D2.2 Subgrid orographic effects: Subgrid orographic effects continue to be a topic of interest. We expect to test improved numerical formulations of tendency terms from orographic drag as well as to explore coupling subgrid temperature and vertical velocity variance from orography to moist processes in the model. Experience with CAM6 suggests that his may be especially important for correct SMB simulations around steep ice-sheet edges.

D2.3. 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). More importantly, stochastic perturbations to parameters and variables can be used to identify model sensitivities and thus be used to efficiently inform deterministic parameterization schemes. For example, perturbing the physical tendencies of CAM4 in CCSM4 led to an improved ENSO variability (Berner et al. 2018), suggesting that the atmospheric and ocean component were too strongly coupled. 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. This information will be used to inform, e.g., the deep convection scheme, and represent the optimal spatio-temporal characteristics of the mesoscale convective momentum transport parameterization. A perturbation capability might also help in the analysis of the diverging climate problem between fully coupled and prescribed SST by representing the effects of unresolved subgrid-scale SST variability in AMIP simulations.

D2.4 Convective organization and momentum transport: The importance of convective organization on the global circulation has been recognized for more than three decades but parameterizations of these processes are missing from models. The current convective momentum transport representation in CAM6 does not account for mesoscale momentum transport and its inclusion could significantly alter precipitation patterns, surface wind stresses, the Madden Julian Oscillation (MJO), and potentially ENSO. A prototype of a mesoscale momentum transport parameterization (Moncrieff and Liu 2006) was implemented in CAM5 and showed promising results towards reducing precipitation and wind stress biases (Moncrieff et al. 2017). The effects of this parameterization will be investigated in CAM6 and the parameterization will be further developed to include more realistic relationships between vertical wind shear and momentum transport.

Furthermore, explicit representations of convective organization as previously demonstrated in Mapes and Neale (2011) and Park (2014) will be investigated as augmentations to current and potential future parameterizations, with a particular focus on tropical convectively coupled wave activity and U.S. warm season mesoscale convective systems.

D2.5. Microphysics – Refined mesh: In conjunction with collaborators in other parts of NCAR (RAL, MMM) and NASA, we are also advancing the parameterization of cloud microphysics with better treatment of the ice phase, and adding rimed ice (graupel or hail) to the cloud microphysics, as well as representing micro-physics parameter uncertainties. We would like to continue to develop and evaluate these new approaches and how they affect climate, particularly at high resolution, which can be tested in variable resolution meshes (e.g., 14 km refined mesh CAM-SE over CONUS).

D2.6. CLUBB development: Finally, we expect significant development of CLUBB to continue. CLUBB developers at University of Wisconsin have already developed an initial version of prognostic subgrid momentum transport via moments. In collaboration, we will also explore alternative PBL/ShCu parameterization schemes for CAM. This could range from block replacement of CLUBB to regime-based extensions to CLUBB perhaps following EDMF-like approach (Soares et al. 2004).

D3. Advancing CAM high-resolution climate (Y1 - 2.98M; Y2 - 12.2M): The focus for CAM6 development during the last CSL cycle was on delivering a model that performed well at a horizontal resolution of 100 km for the CMIP6. The vertical grid in CAM6 was also left essentially unchanged from that in CAM5 – namely a ~50 m near-surface layer with vertical grid spacing increasing linearly to around 1500 m above 850 hPa. During this development cycle we will devote significant resources to evaluating configurations with higher vertical and horizontal resolution.

D3.1 Vertical resolution: Improvements in climate variability with increased tropospheric and stratospheric vertical resolution were demonstrated with CAM5 (Richter et al. 2014). We plan to continue evaluating increased vertical resolution with CAM6. Previous efforts avoided adding levels in the atmospheric boundary layer due to sensitivities in the parameterized physics. Experiments that alter the lowest model level show pathologic behavior of both shallow and deep convection. Yet it is known that increased vertical resolution in the lowest few kilometers is needed for improved representation of surface-based inversion, shallow cloud layers, aerosol transport, and myriad of other processes. We plan to further evaluate the sensitivity to vertical resolution in the boundary layer, alter physics to be able to cope with these added levels (especially the deep convection scheme), and conduct tests with several potential candidates for a new vertical grid. These tests will include idealized configurations for initial testing, retrospective forecasts to evaluate changes in predictive skill on short timescales, and longer climate runs to evaluate the impacts on long-term climate and variability. In Year 1, we will focus on understanding the gross sensitivities of CAM6 physics to vertical resolution. This should be possible using short (< 5 years) runs. In Year 2, we will perform longer runs (order 20 years) to better understand climate impacts of enhanced vertical resolution.

D3.2 Horizontal resolution: We expect to target a global 25 km mesh using the CAM-SE (ne120; spectral element) dycore for our high horizontal resolution configuration. Initial evaluation of CAM6 at 25 km resolution has revealed deficiencies in tropical cyclone structure and other aspects of mesoscale organization. Understanding the nature of these deficiencies should be possible using relatively short runs (< 5 years) of the global ne120 configuration. We will focus on improving the performance of the ne120 configuration in Year 1. In Year 2 longer integrations (order 20 years) aimed at producing a reasonable climate at ne120 will be undertaken.

D4. Regionally refined capability (Y1 - 0.49M; Y2 - 3.4M): Regional refinement allows us to explore many aspects of high-resolution at a reasonable cost while preserving the possibility of two-way interactions between the refined region and the global circulation. We will continue to explore simulations at 25 km resolution in two regions of particular interest. We will develop regionally-refined CAM-SE configurations over CONUS as well as the Maritime Continent to explore the atmospheric dynamics of these important and problematic regions. This effort will focus on short simulations (5 years) to examine sensitivity of precipitation processes over CONUS to physics. In Year 2, we will extend this effort to include regionally refined simulations over the Maritime Continent.

D4.1. CONUS: The continental U.S. (CONUS) is of interest for obvious reasons. The central U.S. is among the most important food producing regions on earth. Yet precipitation in this region is poorly simulated in all configurations of CESM, including those with high horizontal resolution. Dry warm biases in summertime over the central U.S. are nearly universal in the CMIP5 ensemble. AMWG will collaborate with RAL investigators (R. Rasmussen) in a multi-pronged effort to understand the origins of this persistent and common model bias.

D4.2. Maritime continent: The Maritime Continent is another region where climate models perform poorly. The region is characterized by warm ocean, island terrain with elevations up to 5000 m, as well as geometrically-complex land-sea contrasts. Poorly resolved diurnal cycles of precipitation as well as excessive precipitation over high terrain are common features of model simulations in this region. It is likely that these deficiencies have a negative impact on simulations of intra-seasonal oscillations such as the MJO. In addition, other upscale effects of biases in the Maritime Continent are possible, including remote effects on mid-latitudes and effects on stratospheric tracer transport.

D5. Dynamical core testing and adoption (Y1 - 0.75M; Y2 - 1.8M): Three new dynamical cores 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 WRF discretized on a Voronoi grid), and SE-CSLAM (spectral-element dynamical core with finite-volume transport).

The SE-CSLAM core is relatively mature within the CESM framework and has been vetted in prescribed SST (AMIP) simulations. During this CSL cycle, AMWG will focus on fully integrating this dynamical core as the “work horse” configuration for climate simulation at 100 km. This is a high priority for AMWG. We expect to focus on coupled behavior of the SE dycore. Even the initial phase of such an evaluation requires relatively long integrations (~50 years). This will take place in Year 1. We will continue this development and assessment of SE in coupled mode in to Year 2 with longer integrations if required.

MPAS and FV3 are less mature within the CESM framework. We expect our efforts during this cycle to focus on initial integration and evaluation of these dynamical cores in CESM. This effort will involve relatively short (10 years) atmosphere-only simulations with the full CAM6 physics. We will focus on basic evaluation of model climate and attempt to characterize any dycore dependencies. We expect this effort to proceed in similar fashion in Years 1 and 2, but it is possible that as our understanding of MPAS and FV3 improves, we will begin a more intensive exploration of CAM climate, requiring longer runs.

D6. Alternative model development testbeds (Y1 - 0.25M; Y2 - 0.25M): We propose to evolve the CAPT (Cloud Associated Parameterization Testbed) retrospective forecast and nudging frameworks to be i) easier to run and ii) include a standardized set of simulations that can be routinely run with development versions of the model. To do this we will begin an investigation of alternative initialization strategies; in particular, we plan to evaluate whether a separate land spin up process can reduce the computational overhead of spinning up the land surface for each set of hindcasts. We will develop a standard configuration that will initiate daily 5-day forecasts over a specified time interval, probably of 2 years. That is equivalent to about 10 simulated years plus the cost of spin up, which may be several years (current method) to as little as a few days (using separate spun up land data set). These forecasts can be directly compared with observations to evaluate model skill on short time scales, potentially expediting the diagnosis of model errors and accelerating the development process at reduced computational cost (e.g., short time-scale errors identified in the forecasts could obviate the need for 30-year atmosphere-only or 100-year coupled simulations).

D7. Simpler models (Y1 - 0.1M; Y2 - 0.3M): Simpler models will be developed for use by the community (Polvani et al. 2017). Applications include research on climate and atmospheric dynamics as well as quick evaluation of dynamical cores. We will continue to develop a series of simpler model frameworks coupled to a variety of CAM dynamical cores. These will range from dry specified physics, e.g., Held-Suarez to aqua planet configurations with full physics. It is difficult to specify a single computational cost as simpler configurations span a range of complexity. As a conservative estimate, we project around 1000 processor hours per year as a nominal cost for a 1° equivalent simpler configuration. We request resources for approximately 100 years in Year 1 and 300 years in Year 2.

3. Production Proposal (5.6 M core-hours)

P1. Evolution of CAM6 (Y1 - 0.3M): AMIP simulations of ~30 years will be carried to reconstruct the evolution of CAM6 from CAM5 in order to understand the behavior of the new model. We will examine configurations with components of CAM6 replaced with their CAM5 equivalents. We expect to do 4 experiments swapping key elements of CAM6 physics: CLUBB to UW; MG2 to MG1; Beljaars+Aniso. OGW to TMS+Isotropic OGW; and changes in the ZM95 scheme. These simulations will be used in the preparation of CAM6 model description papers.

P2. Participation in Tier 2 of CFMIP (Y1- 1.2M; Y2- 2.2M): Resources are requested to participate in Tier 2 of the CFMIP (Cloud Feedback Model Intercomparison Project) which will be part of CMIP6. Participation in this MIP will advance the communities understanding of cloud processes in climate models. The protocol for CFMIP is complicated, requiring a variety of coupled and uncoupled runs of different lengths. Our resource request in the table below simply reflects the total of coupled (600 years) and uncoupled (519 years) simulations requested by CFMIP.

P3. Sub-seasonal to Seasonal Forecasting (Y1 - 1.8M): Subsesonal-to-seasonal (S2S) hindcasts for years 1999 - 2018 will be carried out following the Subseasonal Experiment (SubX) protocol. 10-member ensemble hindcasts will be initiated every Wednesday and run for 45 days. Atmosphere will be initialized using ERA-Interim reanalysis and random field perturbation method. The ocean and sea-ice initial conditions will come from a forced ocean – sea-ice simulation that employs an adjusted Japanese Reanalysis atmospheric state fields and fluxes (referred to as JRA55-do forcing) as surface boundary conditions. Land will be initialized using initialized conditions from simulations forced with 6-hourly precipitation, temperature, specific humidity, wind speed, lowest atmospheric level pressure, and incoming longwave and shortwave radiation from the Climate Research Unit - National Centers for Environmental Prediction joint dataset (CRU-NCEP). The same hindcast set has already been carried out with CESM1. Comparison of hindcasts with CESM2 to CESM1 will allow for the characterization in changes in model skill coming strictly from the new model physics in CESM2. In Year 1 of this allocation, we will conduct the Northern Hemisphere cold-season portion of the forecast ensemble, i.e., mid-October through February (around 20 weekly starts). This amounts to approximately 4000 total 45-day forecasts.

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Experiment	Configuration	Resolution	No. of Runs	Years / run	CH/SY	Total CH in thousands	Data Volume (Tb)	Priority A/B/C
Development								
Year 1								
D1	B1850	fv09	5	100	3600	1800	6.8	A
D1	FHIST/F2000	fv09	20	20	2500	1000	6.8	A
D2.1(conv)	FHIST/F2000	ne30	10	5	1700	85	0.8	B
D2.2(SGO)	FHIST/F2000	ne30	10	5	1700	85	0.2	B
D2.3(Stoch.)	FHIST/F2000	ne30	5	5	1700	42.5	0.8	B
D2.4(Conv. Org. / Mom. Trans.)	FHIST/F2000	ne30	5	5	1700	42.5	0.8	B
D2.5(micophys)	FHIST/F2000	ne30/ne240 CONUS	5	2	39304	393	0.2	B
D2.6(CLUBB)	FHIST/F2000	ne30	10	5	1700	85	1.8	A
D3.1(Vert.Res)	FHIST/F2000	ne30	15	5	3400	255	1.6	A
D3.2(Horz.Res)	FHIST/F2000	ne120	5	5	108800	2720	7.8	A
D4.1(RR CONUS)	FHIST/F2000	ne30/ne120 CONUS	10	5	9860	493	0.5	C
D4.2(RR Mar. Cont.)	FHIST/F2000	ne30/ne120 MC	0	0	17000	0.0	0.0	C
D5(SE)	B1850	ne30	3	50	2700	405	1.2	A
D5(MPAS)	FHIST/F2000	1 deg equiv	10	10	1700	170	5.5	B
D5(FV3)	FHIST/F2000	1 deg equiv	10	10	1700	170	5.5	B
D6(CAPT)	FHIST/F2000	fv09	25	2	2500	125	0.7	B
D6(Nudging)	FHIST/F2000	fv09	25	2	2500	125	0.7	B
D7	Simpler models	1 deg equiv	10	10	1000	100	5.5	B
Total Dev. Year 1						8100	47.5	
Year 2								
D1	B1850	fv09	5	100	3600	1800	6.8	B
D1	FHIST/F2000	fv09	25	20	2500	1250	6.8	B
D2.1(conv)	FHIST/F2000	ne30	10	20	1700	340	0.8	B

D2.2(SGO)	FHIST/F2000	ne30	10	20	1700	340	0.8	B
D2.3(Stoch.)	FHIST/F2000	ne30	10	20	1700	340	0.8	B
D2.4(Conv. Org. / Mom. Trans.)	FHIST/F2000	ne30	10	20	1700	340	0.8	B
D2.5(micophys)	FHIST/F2000	ne30/ne240 CONUS	5	8	39304	1570	0.2	B
D2.6(CLUBB)	FHIST/F2000	ne30	22	20	1700	748	1.8	A
D3.1(Vert.Res)	FHIST/F2000	ne30	20	20	3400	1360	1.6	B
D3.2(Horz.Res)	FHIST/F2000	ne120	5	20	108800	10900	31.0	A
D4.1(RR CONUS)	FHIST/F2000	ne30/ne120 CONUS	25	5	9860	1230	0.5	C
D4.2(RR Mar. Cont.)	FHIST/F2000	ne30/ne120 MC	25	5	17000	2130	0.5	B
D5(SE)	B1850	ne30	3	100	2700	810	1.2	A
D5(MPAS)	FHIST/F2000	1 deg equiv	30	10	1700	510	16.4	B
D5(FV3)	FHIST/F2000	1 deg equiv	30	10	1700	510	16.4	B
D6(CAPT)	FHIST/F2000	fv09	25	2	2500	125	0.7	B
D6(Nudging)	FHIST/F2000	fv09	25	2	2500	125	0.7	B
D7	simpler models	1 deg equiv	30	10	1000	300	5.5	B
Total Dev. Year 2						24700	93.3	
Total Development						32800	140.8	
Production								
Year 1								
P1(CAM6 Evol.)	FHIST/F2000	fv09	4	30	2500	300	1.6	A
P2(CFMIP)	FHIST/F2000	fv09	1	200	2500	500	2.7	B
P2(CFMIP)	B1850	fv09	1	200	3600	720	2.7	B
P3(Seasonal Frcst)	FHIST/F2000	fv09	4056	0.12328767	3600	1800	6.8	B
Total Prod. Year 1						3320	13.8	
Year 2								
P2(CFMIP)	FHIST/F2000	fv09	1	319	2500	798	1.6	B

P2(CFMIP)	B1850	fv09	1	400	3600	1440	5.4	B
Total Prod. Year 2						2240	7.0	
Total Production						5560	20.8	
Total Year 1						11400	61.3	
Total Year 2						26900	100.3	
Total all years						38400	161.6	
Total Dev.+Prod.						38400	161.6	
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			
ne30		1	1	1700	1700			
ne30->ne120 CONUS		0.03	4	1700	9860			
ne30->ne240 CONUS		0.03	8	1700	39304			
ne30->ne120 Polar		0.167	4	1700	23834			
ne30->ne240 Polar		0.167	8	1700	156685.6			
ne30->ne120 MC		0.1	4	1700	17000			
ne120		1	4	1700	108800			
Default configurations for CESM2 using FV latlon dycore. These configurations use a large number of processor to increase throughput. This results in lower performance in terms of CH/SY than could be obtained with less "aggressive" PE layouts								
F-case FV1x1				2500				
B-case FV1x1				3600				
Simpler model configurations								
Simpler models 1x1				1000				

Biogeochemistry Working Group (BGCWG)

1. Broad Overview of Working Group and Research Plan

The goal of the 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 will be 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. Biota also modulate regional patterns of climate change. Ecosystems are the focus of many carbon sequestration approaches for mitigating climate change, and are the central elements of potential climate impacts associated with food security, water resources, human health, and biodiversity. However, the magnitudes of these climate-ecosystem interactions are not well constrained, and are critical scientific unknowns affecting the skill of future climate projections.

At present only about half of anthropogenic carbon remains in the atmosphere to drive climate change; the remainder is removed in about equal amounts by the land biosphere and the oceans. While the magnitude of contemporary ocean uptake of anthropogenic carbon is constrained by observations to within 10%, the future uptake is uncertain. For example, while there is consensus that global warming will decrease the efficiency of ocean uptake, the magnitude of this effect is poorly constrained. A primary objective of the BGCWG is to estimate this future ocean uptake using CESM. Current research suggests that terrestrial ecosystems are at present a net carbon sink, but this conclusion masks considerable complexity and uncertainty with respect to future behavior. The availability of nitrogen, as well as other nutrients (e.g., phosphorus), alters the magnitude of the carbon cycle-climate feedback. Additional processes associated with ozone deposition and methane emission will alter the magnitude of the biogeochemical-climate feedbacks. Human activities from land use and land cover change play a very direct role in terrestrial ecosystem dynamics. The ambiguities in the mechanisms controlling the land carbon sink and their climate sensitivities translate into large uncertainties in future atmospheric CO_2 trajectories and climate change rates. Another primary objective of the BGCWG is to analyze these, and other, terrestrial feedbacks using CESM.

2. Development Proposal (13.3 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

- preliminary high-res experiments
- continued development of biogeochemical parameterizations
- porting of MARBL (Marine Biogeochemistry Library) to MOM
- coupling across components and understanding interactions
- automated techniques for the optimization of model parameters

b. Specific simulations and computational requirements

D1. Newton-Krylov: 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 Newton-Krylov (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. So computational time for the NK solver experiments consists of many short integrations.

D2. High-resolution POP BGC development: We plan to run a hindcast experiment forced with a new data set based on the Japanese Reanalysis Product JRA55-do with the existing ocean ecosystem model in a high-resolution, 0.1°, configuration of the Parallel Ocean Program (POP). The resources for this are being requested in the community allocation pool of this proposal. In order to prepare for that experiment, we are devoting computational resources to short preliminary vetting experiments in this configuration.

D3 and D4. MARBL: Ocean biogeochemistry development is ongoing and we will dedicate some of our computational resources to support this. We anticipate continued development of a size-spectra resolved configuration of MARBL (MARBL-SPECTRA) which costs more than the standard ecosystem configuration, and development of a reduced complexity configuration of MARBL (MARBL-NPD). The exact nature of the runs needed for the development work is unknown, so we have requested allocation for numerous short runs. The reduced complexity configuration is new work, and we anticipate using it to study biogeochemistry in a high-resolution, 0.1°, configuration of POP.

D5. MARBL development: The developments described above will be carried out within the MARBL framework that has been developed with previous CSL allocations. We are devoting computational resources to the continued base development of MARBL, anticipating a public release of version 1 of MARBL in the first year of the proposal. The computational resources for this work will be used for testing and evaluating model results in short runs.

D6. MARBL – MOM: Additionally, we will couple MARBL to the Modular Ocean Model version 6 (MOM6), the provisional ocean model for CESM3. We are estimating the computational cost of an ocean – sea-ice ecosystem configuration with MOM6 as 2.5 times the cost without the ecosystem, based on our experience of adding the ocean ecosystem to POP. 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.

D7. 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, the CESM sea-ice component, 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-ice ecosystem configuration.

D8 and D9. 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. In order 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. We are also devoting computational resources to the application of these strategies to optimize carbon cycle parameters in the land model.

3. Production Proposal (12.8 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: i) CMIP6 Tier 2 experiments, and ii) Additional carbon cycle sensitivity experiments.

b. Specific simulations and computational requirements

P1 and P2. C4MIP, CDRMIP, and OMIP: In order to participate fully in CMIP6, we will be performing Tier 2 experiments for C4MIP (Coupled Climate Carbon Cycle Model

Intercomparison Project), CDRMIP (Carbon Dioxide Removal Model Intercomparison Project), and OMIP (Ocean Model Intercomparison Project). The C4MIP Tier 2 experiments, collectively labeled P1, include additional CO_2 1% ramping experiments to evaluate carbon-climate feedbacks, and various CO_2 concentration driven and emissions sensitivity experiments, some carried out to year 2300. We are also augmenting some of the Tier 1 C4MIP experiments with more ensemble members, labeled P2, in order to have a rough assessment of model spread and to provide a better control for forcing sensitivity experiments.

P3. CDRMIP Tier 2 emissions-based future scenario experiments: An overshoot scenario, where CO_2 emissions are initially high and then are reduced, an afforestation-reforestation scenario, where CO_2 emissions are high, but land use is from a low emission scenario, and an ocean alkalinization scenario, where alkalinity is added to the ocean, which increases ocean uptake of CO_2.

P4. OMIP Tier 2 experiment: The biogeochemistry has been spun up, and the spinup to initialize this. The long spinup run is done with reduced frequency output. The listed duration is based on previous experience spinning up the biogeochemical tracers. This spinup will also be utilized to evaluate Newton-Krylov based spinup techniques described in the development portion of this proposal.

P5. Sensitivity experiments: We anticipate performing historical and future scenario sensitivity experiments with the coupled model related to land-use change and permafrost-climate feedbacks. Additionally, during previous CSL allocation periods, working group members 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.

P6. MARBL climate change: We also plan to evaluate how some of the new MARBL developments (e.g., MARBL-SPECTRA) respond to climate change. This will be done by running the new code in ocean – sea-ice experiments that are forced with output from coupled model historical and future scenario experiments, avoiding the cost of the fully coupled model. These sensitivity experiments will be run over the historical and future scenario time periods.

Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in thousands of core-hours	Total data volume (Tb)	Priority (A/B/C)
Development Year 1								
D1. Newton-Krylov	GECO+NK	T62_g17	50	5	800	200	11.3	A
D2. High-Res BGC POP dev	GECO	T62_t12	3	1	300000	900	2.7	A
D3. MARBL-SPECTRA	GECO-SPECTRA	T62_g17	50	10	1200	600	22.5	B
D4. MARBL-NPD	GECO-NPD	T62_g17	50	10	400	200	22.5	A
D5. BEC Dev	GECO	T62_g17	500	1	620	310	22.5	A
D6. MARBL-MOM	GMOMECO	T62_g17	50	5	2000	500	11.3	A
Development Year 1 Total						2710	92.8	
Development Year 2								
D1. Newton-Krylov	GECO+NK	T62_g17	50	5	800	200	11.3	A
D2. High-Res BGC POP dev	GECO	T62_t12	2	1	300000	600	1.8	A
D3. MARBL-SPECTRA	GECO-SPECTRA	T62_g17	50	10	1200	600	22.5	B
D4. MARBL-NPD	GECO-NPD	T62_g17	50	10	400	200	22.5	A
D4. MARBL-NPD	GECO-NPD	T62_t12	2	10	150000	3000	18.0	B
D5. BEC Dev	GECO	T62_g17	500	1	620	310	22.5	A
D6. MARBL-MOM	GMOMECO	T62_g17	50	5	2000	500	11.3	A
D6. MARBL-MOM	GMOMECO	T62_g17	10	50	2000	1000	22.5	B
D7. CICE-POP BGC coupling	GECO	T62_g17	100	5	700	350	22.5	A
D7. CICE-POP BGC coupling	GECO	T62_g17	10	50	700	350	22.5	B

D8. Ocean BGC Param Optim	GECO	T62_g17	200	10	620	1240	90.0	A
D8. Ocean BGC Param Optim	GECO	T62_g17	20	100	620	1240	90.0	B
D9. Land BGC Param Optim	I		1000	50	20	1000	1.0	A
Development Year 2 Total						10590	358.4	
Production Year 1								
P1. C4MIP Tier 2 1% runs	B	f09_g17	3	140	3500	1470	22.9	A
P1. C4MIP Tier 2 hist	B	f09_g17	1	165	3500	577.5	9.0	A
P2. C4MIP Tier1 SSPs, extra ens	B	f09_g17	2	85	3500	595	9.3	B
P4. OMIP Tier 2 spin-up	GECO	f09_g17	1	2000	620	1240	109.0	A
P4. OMIP Tier 2	GECO	f09_g17	1	310	620	192.2	16.9	A
P5. Misc. Sensitivity	B	f09_g17	1	250	3500	875	13.6	A
P6. MARBL climate change	GECO	T62_g17	1	250	620	155	11.3	B
Production Year 1 Total						5104.7	192.0	
Production Year 2								
P1. C4MIP Tier2 SSPs	B	f09_g17	2	85	3500	595	9.3	A

P1. C4MIP Tier2 SSPs, 2100-2300	B	f09_g17	1	200	3500	700	10.9	A
P3. CDRMIP Tier2 SSPs	B	f09_g17	2	85	3500	595	9.3	A
P3. CDRMIP Tier2 SSPs, 2100-2300	B	f09_g17	1	200	3500	700	10.9	B
P5. Misc. Sensitivity	B	f09_g17	5	250	3500	4375	68.1	A
P6. MARBL climate change	GECO	T62_g17	5	250	620	775	56.3	B
Production Year 2 Total						7740	164.8	

Chemistry Climate Working Group (CHWG)

1. Broad Overview of Working Group and Research Plan

The goal of the CHWG 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. The scientific motivation for these developments is the need to understand present-day and future air quality, and to understand the role of climate change on tropospheric composition. The development and production simulations requested here will lead to improving the representation of tropospheric composition and air quality.

The representation of tropospheric chemistry and aerosols continues to be developed and improved in CESM by the CHWG. Inorganic nitrate aerosols have been added within the framework of the Modal Aerosol Model (MAM4) using the MOSAIC (Model for Simulating Aerosol Interactions and Chemistry) treatment of aerosol thermodynamics, phase state and dynamic gas-particle mass transfer and heterogeneous chemistry. Increasing horizontal resolution is a key factor in improving air quality simulations, so an important component of CESM chemistry development is the testing and tuning of the CAM-SE (spectral element) configuration with regional refinement and comprehensive chemistry (CAM-SE-RR-Chem). Currently this configuration is being tested with the continental U.S. at 14 km x 14 km and approximately 1° for the rest of the globe. In addition, we are testing CSLAM (Conservative semi-Lagrangian Multi-tracer) in CAM-Chem and the impact of this transport scheme on tracer transport, chemistry, and aerosols. Biogenic emissions will also be updated, in collaboration with the University of California-Irvine, by updating MEGAN (Model of Emissions of Gases and Aerosols from Nature), already in the Community Land Model (CLM), to Version 3 which will account for drought and other stresses on the emissions. Simulations with CAM-Chem including CLM-MEGAN3 will be evaluated against field experiments, and performing analyses of the responses to weather and climate changes. The capability for running daily to near-seasonal air quality forecasts will be developed in CAM-Chem. We will finalize the development of CAM-Chem with the CESM and the Data Assimilation Research Testbed (DART) multi-instances framework, including the testing of the best configuration in terms of number of nodes per instances, which has not been tested for chemistry yet. The goal is to assimilate satellite observations from the day before using CAM-Chem/DART to initialize a deterministic forecast of several days.

2. Development Proposal (5.9 M core-hours)

a. Goals

The simulations listed below will assist in the ongoing improvement in the representation of tropospheric chemistry in CAM-Chem and WACCM (Whole Atmosphere Community Climate Model). A number of development activities are underway and will lead to improved simulations of tropospheric composition. A major effort will be to develop the capability of running the regionally refined version of CAM-SE with chemistry, which will support analysis of air quality (AQ) on a local scale, and allow for more critical model evaluation with observations from field experiments and surface AQ monitoring sites. Model improvements that were developed and tested in previous model versions, such as MOSAIC and inorganic nitrate aerosols, aerosol dry deposition, absorbing organic aerosol (brown carbon, BrC), and very short-lived (VSL) halogen chemistry, will be ported to CAM6-Chem and evaluated.

b. Specific simulations and computational requirements

D1. Chemistry, photolysis, aerosol development: Planned model developments require testing new schemes which include testing the implementation of a new photolysis scheme (online Troposphere Ultraviolet-Visible (TUV) model), different chemistry schemes including extended halogens, organic chemistry, improved aerosol descriptions: MOSAIC, CARMA (Community Aerosol and Radiation Model for Atmospheres), BrC, and the CSLAM transport scheme. Simulations at ~0.25° with SE dycore will also be tested. Those developments require 5- or 10-year simulations each and therefore sum up to about 50 years of CAM-Chem with various complexities. With increased model complexity we estimate the cost of each model simulation year to be order 10K core-hours.

D2. CAM-SE-RR-Chem development: The regionally refined version of CAM-SE with full tropospheric and stratospheric chemistry (CAM-SE-RR-Chem) will be tested and evaluated. The model grid is approximately 1° resolution (ne30_ne30) for most of the globe, with 28 km grid over the continental U.S. In particular, the use of high-resolution emissions, and the coupling to online biogenic emissions in CLM will be tested. A few simulations of 2-3 months, to compare with field campaign observations, will be required.

D3. CLM-MEGAN-v3 biogenic emissions testing: The MEGAN biogenic emissions (online in CLM) will be updated to MEGAN-V3. CAM-Chem at 1° resolution, with specified dynamics (5 years) and free-running climate (10 years) configurations, will be tested with new versions of MEGAN.

D6. CAM-SE-RR-Chem simulations for campaign analysis and forecasting: CAM-SE-RR-Chem will be run to perform analyses of aircraft experiments using different chemistry schemes. In addition, this configuration of the model will be tested for use in running air quality forecasts.

D5. Chemistry, photolysis, aerosol development: Continued development as described in D1. In addition, tests of a new aerosol dry deposition scheme, coupled to CLM, will be run and evaluated against observations. Five simulations of 10 years each will be required to test each new development step.

D6. CAM-SE-RR-Chem development: Testing and evaluation of regionally refined version of CAM-SE with full tropospheric and stratospheric chemistry will continue from D2. Simulations will span 2000 to 2014 (15 years) in order to overlap with a number of North American aircraft field campaigns and evaluate the model capability based on high resolution emissions from anthropogenic and biogenic (MEGAN) emissions. Model spin-up for the field campaigns will be done at the coarser resolution (ne30 with 28 km refined grid) as a continuous 15-year simulation. These results will provide initial conditions for short high-resolution (14 km in the refined grid) intercomparison runs (total of 5 years of simulations). Simulations with MOSAIC, including nitrate aerosols, will also be run for this period.

3. Production Proposal (6.4 M core-hours)

a. Goals

The CAM-SE-RR-Chem model is expected to be fully functional by Year 2 and a number of simulations are planned to exploit its use in the analysis of observations and studies of air quality. Updates to aerosol dry deposition and representation of brown carbon will be tested in CAM6-Chem. In addition, simulations with the expanded very short-lived (VSL) halogen chemistry will be performed for comparison to CMIP6 simulations. Operational-style short-term and seasonal forecasts of air quality will be run during both years of the proposal.

b. Specific simulations and computational requirements

P1. Nitrate and Brown Carbon climate evaluation: The climate impacts of nitrate and BrC aerosols will be evaluated through CAM6-Chem simulations, comparing runs with and without nitrate aerosols, and with and without BrC aerosols. This will require 3 simulations of 10 years each.

P2. Air Quality reanalysis: CAM-Chem, 1°, Specified Dynamics 2000-2018 (19 years) simulations with different vertical resolutions (32L and 56L) and 3 different fire emissions inventories will be run to study the impact of fire emissions uncertainty on air quality predictions and evaluate the model with numerous observations. High resolution time output (6-hr) will be provided for regional model boundary conditions. These simulations will also provide spin-up for chemical forecasts. Simulations with one fire inventory will be done at 32L and 56L, the other two fire inventories will be used in simulations with 32L (4 simulations of 19 years each).

P3. 3-day daily forecasts with data assimilation: Regional air quality forecast models depend on realistic boundary conditions. We will run CAM-Chem/DART, assimilating satellite retrievals of atmospheric composition (CO, O3, aerosols) to evaluate the capabilities of CESM to provide realistic chemical weather forecasts. These forecasts require a 30-member ensemble analysis for each day with DART assimilation, followed by a single 3-day simulation for the forecast.

P4. 10-day forecasts with WACCM: We will use WACCM with best meteorological and chemical initial conditions (from CAM-chem real-time analysis/forecast). The analysis will be used to initialize a 10-day forecast, either in a free running mode, or driven by the

NASA/GEOS5 forecast, depending on prior tests. 10-day forecasts run each day is equivalent to one 10-year simulation performed in Year 1.

P5. VSL Halogen simulations: The role of horizontal resolution on tropospheric transport and chemistry will be examined using the SD CESM2 (CAM6-Chem) model with VSL halogen chemistry (250 species). The VSL chemistry module will be migrated from CESM1 (CAM4-Chem) to CESM2 (CAM6-Chem) in Year 1. High resolution specified dynamics simulations (~0.5°) for years 2014-2016 will then be simulated for comparison with several aircraft campaigns that measured VSL halogen compounds (e.g., NSF/ORCAS and NSF/CONTRAST experiments).

P6. CESM2 (CAM-Chem-VSL): The role that VSL chlorine, bromine, and iodine species have on the ozone budget and climate from pre-industrial to present-day is not well understood. Using the model development and evaluation version completed in Year 1, CESM2 (CAM6-Chem-VSL) will be run at 1° (B-case, interactive ocean, 250 species). The simulation period will be from 1850 to 2015 (165 years). Comparisons will be made to the CMIP6 hindcast reference simulation(s).

P7. Field campaign analysis: Simulations for analysis of several recent tropospheric composition campaigns (KORUS-AQ, ATom, WE-CAN) will be performed with CAM-SE-RR-Chem for the 1-2 months of each field campaign. Sensitivity studies with different anthropogenic and fire emissions inventories will be run to find optimal simulations to match the observations, resulting in a total of 5 years of simulations.

P8. CAM-Chem: 3-5-day forecasts with data assimilation: Chemical forecasts will be continued as described for Year 1 (P3), using CAM6-chem/DART. Running 3-day forecasts each day is equivalent to three 1-year simulations, plus a 1-day 30-member ensemble each day for the analysis with assimilation.

P9. 10-day up to 6-week forecasts with WACCM: We will use WACCM with the best meteorological and chemical initial conditions (from CAM-Chem). The analysis will be used to initialize a 10-day forecast, either in free-running mode, or with specified dynamics from NASA/GEOS5 forecasts. Full tropospheric and stratospheric chemistry will be added to the on-going 6-week forecasts being run with CAM by Richter. Each day a 10-day forecast of WACCM (72 levels) with 10 ensemble members will be run.

Summary of Experiments

Experiment	Configuration	Resolution	# runs	Yrs/ run	CPU-hr/ sim-yr	Total 1000-CPU-hr	Data Vol (TB)	Priority
Development								
Year 1								
D1	CAM6-Chem, F	0.9x1.25, 32L	5	10	10000	500	10	A
D2	CAM-SE-RR-Chem	1deg/14km	3	0.2	100000	240	10	A
D3	CAM6-Chem, F	0.9x1.25, 32L	1	15	8000	120	5	B
D4	CAM-SE-RR-Chem	ne30/14km	1	2.5	400000	1000	2	
Total Year 1 Dev.						1860	27	
Year 2								
D5	CAM6-Chem, F	0.9x1.25, 32L	5	10	10000	500	10	A
D6a	CAM-SE-RR-Chem	ne30/28km	1	15	100000	1500	30	A
D6b	CAM-SE-RR-Chem	ne30/14km	1	5	400000	2000	30	B
Total Year 2 Dev						4000	70	
Total Development						5860	97	
Production								
Year 1								
P1	CAM6-Chem, F	0.9x1.25, 32L	3	10	8000	240	6	B
P2	CAM6-Chem, F	0.9x1.25, 32L	4	19	10000	690	15	A
P3	CAM6-Chem, F	0.9x1.25, 32L	33	1	8000	260	7	A
P4	WACCM, F	0.9x1.25, 72L	10	1	25000	250	10	A
P5	CAM6-Chem-VSL, F	0.5x0.6, 32L	1	3	70000	210	15	B
Total Year 1 Prod						1650	53	
Year 2								
P6	CAM6-Chem-VSL, B	0.9x1.25, 32L	1	165	9100	1500	33	B
P7	CAM-SE-RR-Chem	ne30/28km	1	5	100000	500	10	A
P8	CAM6-Chem, F	0.9x1.25, 32L	33	1	8000	260	10	A
P9	WACCM, B	0.9x1.25, 72L	10	10	25000	2500	10	A
Total Year 2 Prod						4760	63	
Total Production						6410	116	

Climate Variability and Change Working Group (CVCWG)

1. Broad Overview of Working Group and Research Plan

The goals of the 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 the CESM and its component models. With these model simulations, researchers will be able to investigate mechanisms of climate variability and change, as well as to detect and attribute past climate changes, and to 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. The main focus over the next two years will be simulations intended for submission to CMIP6, including numerous MIPs, lengthy control integrations with hierarchical configurations of CESM2, AMIP and *Pacemaker* style historical ensembles, and simulations for investigation into climate variability and extremes.

The CVCWG is a central element in the 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, since the 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 the other CESM Working Groups. In particular, for contribution to CMIP6, the CVCWG will work closely with the AMWG on CFMIP (Cloud Feedback Model Intercomparison Project), and outside collaborators on DAMIP (Detection and Attribution Model Intercomparison Project), Polar Amplification (PA) MIP, and ScenarioMIP.

2. Production Proposal (35.4 M core-hours)

a. Goals

As previously stated, one goal of the CVCWG over the next two years is to contribute simulations to CMIP6 and the associated MIPs mentioned above. In the writing of this request, we have assumed that a CESM general allocation of the CSL will be used for all Tier 1 required simulations for which the CESM will contribute (with the nominal 1° model version). For participation in Tier 1 of ScenarioMIP, only one simulation is required; however, our WG plans to contribute two more members to reduce uncertainty. The CVCWG also plans to contribute one member for each of the Tier 2 and 3 DAMIP simulations. We additionally plan to expand on the runs for CFMIP with aqua planet simulations to dig deeper into feedbacks. Currently, high resolution simulations with CESM2 involving the 0.25° atmosphere and the 0.1° ocean will not be conducted with the general allocation; therefore, the CVCWG has planned high-resolution simulations for

Year 2 of this allocation. We anticipate that the CESM high-resolution configuration will be available in the Fall of 2019.

We will also perform long pre-industrial control simulations and large ensembles of historical simulations with a hierarchy of model configurations as discussed above to explore and understand internally-generated patterns, time scales and mechanisms of climate variability and change. The model configurations will include the atmospheric model coupled to the land model (A-L model configuration) forced by a repeating seasonal cycle of sea surface temperatures (SSTs) and sea ice (taken from the CESM2 control) and the A-L model coupled to the full-depth ocean model (CESM2). This model hierarchy will enable researchers to quantify the contributions of internal atmospheric variability and full ocean physics to the various patterns and timescales of climate variability. The historical ensembles of simulations will also be conducted with a similar hierarchy of model configurations. In particular, the A-L model will be forced with the observed evolution of tropical and global SSTs, and the CESM2 model will be nudged to the observed evolution of SST anomalies in the eastern tropical Pacific (the so-called Pacemaker protocol), allowing air-sea interaction in the remainder of the global oceans. All of the above types of simulations have been conducted with CESM1, and are widely used not only by the CESM community, but nationally and internationally as well, and are therefore important to continue with the improved CESM2.

Another ongoing research area of the CVCWG is to gain an understanding of the interplay between external forcing and internal variability. A major mode of variability having a global impact is the Interdecadal Pacific Oscillation (IPO) for which a number of mechanisms have been proposed. A paper led by G. Meehl postulated that a build-up of off-equatorial heat content anomalies in the western tropical Pacific on decadal timescales could be triggered by an ENSO event to produce a phase transition of the IPO. We propose simulations to test this theory using year two of the CSL allocation. We are also investigating processes and mechanisms that characterize high impact events and how the events and driving mechanisms might change in the future. These events are of great significance to society with potential consequences to habitats, economics, and human life. Towards this effort, we have specific simulations planned to investigate tropical cyclones, precipitation and drought extremes, atmospheric rivers, and sea level rise.

b. Specific simulations and computational requirements

b.1 Simulations related to MIPs

P1. <u>DAMIP:</u> One member of all Tier 2 and 3 historical and future scenarios for DAMIP will be completed using CESM2. These include four historical scenarios (histSOZ, histSOL, histVCL, and histCO2) and four future scenarios (ssp245GHG, ssp245SOZ, ssp245AER, and ssp245NAT). We will conduct two additional ensemble members for these scenarios on a different machine, thus providing three ensemble members for all DAMIP Tier 1 and 2 categories. (4.2M core-hours; Year 1)

P2. ScenarioMIP: Two members will be added to three of the Tier 1 ScenarioMIP simulations (ssp5-8.5, ssp2-4.5, and ssp1-2.6). This creates an ensemble of three members. (1.8M core-hours; Year 1)

P3. PAMIP: Three Tier 2 experiments of the PAMIP. (The other two Tier 2 PAMIP experiments will use resources from the Polar Climate Working Group.) These three 100-year long experiments with CAM6/CLM are: "2.3 pa-futArcSIC" Arctic SIC (sea ice concentration) nudged to late 21st century conditions (from CESM2 at 2°C warming); "2.4 pa-piAntSIC" Antarctic SIC nudged to pre-industrial conditions (from CESM2 PI); and "2.5 pa-futAntSIC" Antarctic SIC nudged to late 21st century conditions (from CESM2 at 2°C warming). (1.0M core-hours; Year 1)

P4. CFMIP: The CESM2 aqua planet will be run in atmosphere / land-only mode using a slab ocean (Q-case) in a configuration consistent with CFMIP (FV dycore, CAM6 physics, nominal 1° resolution). This is in contrast to CFMIP which uses prescribed SST. The two sets of simulations can then be compared to examine feedbacks in the climate system. (0.65M core-hours; Year 2)

P5. DECK AMIP: We will conduct 10 members each of present day and future atmosphere-only (AMIP) simulations at the 0.25° resolution using CESM2, contributing to the high-resolution DECK and providing many more ensemble members than required by CMIP6. This will be conducted in collaboration with the AMWG. (1.8M core-hours; Year 2)

P6. DECK high-resolution: As a contribution to the high-resolution DECK simulations with the CESM2, we plan to contribute to a long pre-industrial control simulation (200 years). We anticipate using much of this run to conduct tuning and spinup. This will be conducted in collaboration with the AMWG. (1.6M core-hours; Year 2)

P7. High-resolution ocean-only: A long (200-year) control ocean – sea-ice -only simulation (G-case) forced with the data sets based on a new Japanese Reanalysis product (JRA55-do) with CESM2 at high spatial resolution (0.1°) will be conducted. We will run 60 years using normal year forcing and then an additional 140 years using the time-varying forcing. This simulation will be compared with the high-resolution simulation described in P5 to investigate differences in ocean mixing, heat transport and freshwater fluxes associated with tropical cyclones. (1.6M core-hours; Year 2)

b.2 Simulations related to climate variability and extremes

P8. FAMIP-TOGA (Tropical Ocean Global Atmosphere): A 10-member Tropical AMIP ensemble with CAM6/CLM6 using historical radiative forcing and specified observed time-evolving SSTs in the tropics and a repeating seasonal cycle outside of the tropics for the period 1880-present. This ensemble will enable researchers to isolate the role of tropical SST variability in global climate. (3.6M core-hours; Year 1).

P9. Pre-industrial control extension: A 300-year extension of the DECK 1000-year fully-coupled (CESM2) control run under 1850 radiative forcing conditions. This will allow for robust determination of the characteristics of internal variability in CESM2. (1.1M core-hours; Year 1).

P10. Pacemaker simulations: Pacemaker-type simulations will be conducted with the 1° CESM2 for the purpose of exploring the mechanisms important for the predictability and decadal skill of the IPO, particularly those mechanisms related to IPO transition. Proposed mechanisms investigated here are the influence of ENSO, the latitudinal extent of westerly wind anomalies, and on and off equatorial ocean heat content anomalies. We plan 6 ensemble sets made up of 10 members that are each 10 years in length. (2.1M core-hours; Year 2).

P11. CLM sensitivity experiments: In collaboration with the LMWG, We will conduct offline CLM (Community Land Model) simulations to investigate model hydrologic sensitivity and precipitation extremes. This set of runs will include a 30-year present day and 30-year future scenario with 9 additional perturbed future scenarios. This would significantly contribute to our understanding of the modeled parameter sensitivity related to precipitation extremes. (82.5K core-hours; Year 2)

P12. Freshwater hosing experiments: The Atlantic Meridional Overturning Circulation (AMOC) has a strong influence on sea level variability regionally. We plan to contribute a 200-year long, fully-coupled future simulation in which the future forcing is kept constant at year 2014 and freshwater is injected into the North Atlantic to mimic the impact of meltwater on the strength of the AMOC. We will then compare with one of the ScenarioMIP future scenarios to determine thermal versus haline impacts on AMOC and how it regionally impacts sea level change. (700K core-hours; Year 2)

P13. CAPT drought: We plan to use the coupled CAPT (Cloud Associated Parameterization Testbed) framework to identify sources of predictability for drought and mechanisms that lead to and maintain drought using the California drought of 2014-2016 as a case study. For this, we propose fully-coupled CESM2 simulations that are 6 months in length and initialized every few days (resulting in ~50 simulations per year). (262K core-hours; Year 2)

P14. CAPT Typhoon: A case study of Super-typhoon Haiyan will be constructed by performing hindcasts within the CAPT framework. This framework allows a unique method of determining what processes were responsible for this extreme event. The hindcast ensemble will consist of simulations in which the large-scale environment is altered (for example, by removing the Pacific Decadal Variability, PDV, that was present) to determine the influence of a particular feature or process on the typhoon formation. These will be two-week forecasts each with 20 members. (3K core-hours; Year 2).

P15. AMIP pre-industrial control: A 2000-year control run of the CAM6/CLM model under 1850 radiative forcing conditions. The SSTs and sea ice will consist of a repeating climatological seasonal cycle taken from the long fully-coupled CESM2 1850 control run. This run will provide crucial baseline statistics of the model's internally-generated atmospheric variability. (5.2M core-hours; Year 2).

P16. Tropical Pacific pacemaker: A 10-member "Tropical Pacific Pacemaker" ensemble with CESM2 using historical radiative forcing and time-evolving SST anomalies nudged to observations in the eastern tropical Pacific for the period 1880-present. This ensemble will provide crucial information on the role of observed tropical Pacific SST variability in global climate variability and change in a more realistic (e.g., coupled) setting than in P8 (although mean state biases in the tropical Pacific may introduce errors). In conjunction with P8, researchers will be able to assess the role of air-sea interaction in the remote atmospheric response to tropical Pacific SST variability. (4.8M core-hours; Year 2).

P17. FAMIP-TOGA DECK: A 10-member TOGA AMIP ensemble with CAM6/CLM6 using historical radiative forcing and specified time-evolving SSTs in the tropics and a repeating seasonal cycle outside of the tropics, taken from the first member of the CESM2 DECK historical ensemble for the period 1880-present. When compared with P16, this ensemble will reveal the effects of coupled model systematic errors on atmospheric model simulation. (3.6M core-hours; Year 1).

Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in thousands of core-hours	Total data volume (Tb)	Priority (A/B/C)
P1. DAMIP historical Tier 2/3 - histSOZ	CESM2-BGC B20C	f09_g17	1	171	3500	600	9.3	A
P1. DAMIP historical Tier 2/3 - histSOL	CESM2-BGC B20C	f09_g17	1	171	3500	600	9.3	A
P1. DAMIP historical Tier 2/3 - histVLC	CESM2-BGC B20C	f09_g17	1	171	3500	600	9.3	A
P1. DAMIP historical Tier 2/3 - histXO2	CESM2-BGC B20C	f09_g17	1	171	3500	600	9.3	A
P1. DAMIP future Tier 2/3 - BGC245GHG	CESM2-BGC BSSP	f09_g17	1	80	3500	275	4.4	A
P1. DAMIP future Tier 2/3 - BGC245SOZ	CESM2-BGC BSSP	f09_g17	1	80	3500	275	4.4	A
P1. DAMIP future Tier 2/3 - BGC245AER	CESM2-BGC BSSP	f09_g17	1	80	3500	275	4.4	A
P1. DAMIP future Tier 2/3 - BGC245NAT	CESM2-BGC BSSP	f09_g17	1	80	3500	275	4.4	A
P2. ScenarioMIP additional Tier 1 -ssp5-8.5	CESM2-BGC BSSP	f09_g17	2	85	3500	600	9.3	A

P2. ScenarioMIP additional Tier 1 -ssp2-4.5	CESM2-BGC BSSP	f09_g17	2	85	3500	600	9.3	A
P2. ScenarioMIP additional Tier 1 -ssp1-2.6	CESM2-BGC BSSP	f09_g17	2	85	3500	600	9.3	A
P3. Polar Amplification MIP Tier 2 -pa-futArcSIC	CESM2-BGC BSSP	f09_g17	1	100	3500	350	5.5	A
P3. Polar Amplification MIP Tier 2 -pa-piAntSIC	CESM2-BGC BSSP	f09_g17	1	100	3500	350	5.5	A
P3. Polar Amplification MIP Tier 2 -pa-futAntSIC	CESM2-BGC BSSP	f09_g17	1	100	3500	350	5.5	A
P8. FAMIP-TOGA	CESM2 FAMIP	f09_f09	10	138	2600	3,600	18.6	A
P9. B1850 Control Extension	CESM2-BGC B1850	f09_g17	1	300	3500	1,050	16.3	A
Year 1 Totals			**28**	**1857**	**55100**	**11000**	**134.1**	
P4. aquaplanet expansion on CFMIP	CESM2-aqua Q	f09_g17	5	50	2600	650	13.6	A
P5. DECK AMIP present day	CESM2-BGC 20C	ne120_ne120	10	30	6000	1800	93.0	A
P5. DECK AMIP future	CESM2-BGC BSSP	ne120_ne120	10	30	6000	1800	93.0	A
P6. DECK high resolution PI tuning	CESM2-BGC B1850	ne120_g16	1	200	8000	1600	128.0	B
P7. High resolution ocean-only	CESM2-BGC G	ne120_t12	1	200	8000	1600	228.4	B
P10. Pacemaker - IPO transition	CESM2-BGC B20C	f09_g17	60	10	3500	2100	32.7	A
P11. CLM sensitivity experiments -control	CESM2-BGC I	f09_f09	1	30	250	7.5	0.4	A
P11. CLM sensitivity experiments -future control and experiments	CESM2-BGC I	f09_f09	10	30	250	75	4.1	A
P12. fixed forcing future freshwater hosing	CESM2-BGC BSSP	f09_g17	1	200	3500	700	10.9	A
P13. CAPT drought predictability	CESM2-BGC B20C	f09_g17	200	0.5	3500	350	5.5	A
P14. CAPT hindcasts -Super-typhoon Haiyan	CESM2-BGC B20C	f09_g17	20	0.04 (2-week)	3500	3	1.0	A
P15. F-case Control	CESM2 FAMIP	f09_f09	1	2000	2600	5,200	27.0	A
P16. Pacemaker Tropical Pacific	CESM2-BGC B20C/BSSP	f09_g17	10	138	3500	4,830	75.2	A
P17. FAMIP-TOGA forced with DECK 1st Historical Member SST/ICE	CESM2 FAMIP	f09_f09	10	138	2600	3,600	18.6	A
Year 2 Totals			**341**	**3226.54**	**57300**	**24420.5**	**733.1**	

Land Ice Working Group (LIWG)

1. Broad Overview of Working Group and Research Plan

The primary objective of the LIWG in the timeframe of this proposal is to carry out pioneering simulations using the coupled ice-sheet/climate model consisting of the Community Ice Sheet Model version 2.1 (CISM2.1) in CESM2. This coupling will enable the LIWG to carry out the Tier 1 and Tier 2 coupled climate experiments of the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). Meanwhile, in-house development of new science capabilities will continue, with the focus expanding from the Greenland ice sheet to include Antarctic and paleo ice sheets.

ISMIP6 is an international effort whose goals are to estimate past and future sea level contributions from the Greenland and Antarctic ice sheets, along with associated uncertainty, and to investigate feedbacks due to dynamic coupling between ice sheet and climate models. During Year 1 of this proposal, we aim to run a full suite of stand-alone ice sheet and coupled ice sheet–climate experiments as specified in the ISMIP6 protocols. Papers analyzing the results will be submitted by the end of 2019, in time for consideration in the next IPCC (Intergovernmental Panel on Climate Change) assessment. During Year 2, production resources will be used for coupled CISM-CESM runs on time scales of a millennium or longer: for paleoclimate simulations of the last deglaciation and for multi-century future simulations of Greenland deglaciation. Development efforts will broaden to include coupled simulations on a variable-resolution grid to better capture the surface mass balance (SMB) of Greenland and West Antarctica. Other development runs will test new CISM capabilities to simulate marine ice sheets, with the long-term goal of supporting climate simulations with a dynamic Antarctic ice sheet in CESM3.

2. Development Proposal (5.3 M core-hours)

a. Goals

With an improved representation of the atmosphere, ice sheet surface conditions, and resulting ice sheet SMB in CESM2, the LIWG will continue to refine the simulation of ice sheet climate. We will expand the initial work of Van Kampenhout et al. (2018) with the variable-resolution CESM (VR-CESM), where the horizontal resolution of CESM is enhanced over ice sheets. Higher resolution improves ice sheet surface climate and precipitation and, in the long term, will render the use of elevation classes over ice sheets unnecessary when coupling the climate model (CESM) to the ice sheet model (CISM). We will set up, test, and analyze VR-CESM runs with higher resolution for Greenland and West Antarctica.

Meanwhile, CISM development will focus on increasingly high-resolution simulations of the Greenland, Antarctic, and paleo ice sheets. CESM2 supports interactive simulations with a dynamic Greenland ice sheet, but Antarctic simulations to date have been run only in standalone CISM. Near-term development will allow CESM to run with a dynamic Antarctic ice sheet, either on its own or combined with a Greenland or paleo-Northern

Hemisphere ice sheet. In the longer term, we aim to increase ice-sheet resolution to ~1 or 2 km.

b. Specific simulations and computational requirements

D1. CISM development for Greenland and Antarctica (1.2 M core-hours, Year 1&2, priority A): Currently, the default resolution for Greenland simulations in CESM is 4 km; similarly, stand-alone CISM Antarctic simulations are limited to 4 km. With algorithmic enhancements to CISM's velocity solvers, we can increase resolution to 2 km and possibly 1 km. Development resources will be used to test and debug these new algorithms. In addition, we will test ongoing improvements of physics parameterizations for basal sliding, iceberg calving, and sub-ice-shelf melting.

D2. One-way coupling of CISM and POP + plume model implementation (0.2 M core-hours, Year 1&2, priority A, B): We will implement and test a new regridding of ocean temperature and salinity fields to CISM to drive a melting parameterization based on a sub-ice-shelf plume model. Testing will be needed both in offline configurations (CISM only, forced by POP data) and in coupled configurations (combined POP and CISM).

D3. Allowing large ice sheet extent in the Northern Hemisphere during Last Glacial Maximum (0.2 M core-hours, Year 1, priority A): To date, CISM runs in CESM have been validated only for the Greenland ice sheet. Here, we aim to extend support to include the Laurentide, Greenland, and Eurasian ice sheets during glacial periods. These simulations would use output from fully coupled climate simulations from the Last Glacial Maximum.

D4. Software engineering tests (0.7 M core-hours, Year 1&2, priority A): This part of the proposal is designed to cover software testing of developments to CISM, CLM, and the coupler. Much of this use consists of running the CLM automated test suite.

D5 and D6. VR-CESM simulation development (2.7 M core-hours, Year 2, priority A): The stability of ice sheets and ice shelves is strongly dependent on the local SMB, which is computed in CLM in multiple elevation classes. In order to evaluate this subgrid parameterization in a changing climate, we will carry out experiments using a higher spatial resolution over the ice sheet regions. Previously, Van Kampenhout et al. (2018) have used VR-CESM at 28 km to model the Greenland Ice Sheet (GrIS) in the present-day climate. Here, we will expand on these first tests by setting up a new variable-resolution grid over the West Antarctic Ice Sheet (WAIS), with 28-km horizontal resolution over the region of interest and regular 0.9°x1.25° resolution over the rest of the globe. New simulations will be performed on both the GrIS and WAIS domains, forced by sea surface temperatures (SST) and sea ice extent from upcoming CESM2 historical and future simulations, in order to investigate simultaneously the effects of spatial resolution and varying ocean conditions and increasing atmospheric greenhouse gases on surface climate, precipitation, melt, and SMB. We will carry out four 95-year GrIS runs to explore different CMIP6 21st century scenarios. For WAIS, we will do a 30-year benchmark simulation (with observed SST and ice extent), followed by three runs with low, mid, and high sea ice extent and two with low and high SSTs.

D7. Firn model development (0.7 M core-hours, Year 2, priority A): The LIWG plans to continue development of polar snow and firn within CLM in collaboration with the LMWG. In particular, we will invest resources to complete the implementation of a blowing snow model; incorporate more sophisticated water percolation schemes; and revise the parameterization of refreezing of meltwater in firn. These new physics are believed to be important to a) reduce outstanding biases in the present-day climate, such as the general lack of an ablation zone in northern Greenland and b) achieve a more realistic sensitivity of runoff (and therefore SMB) to transient temperature forcings. We propose five 20-year runs to assess the climatological impact of the new parameterizations. The proposed runs are fully-coupled but may be replaced by nudged AMIP style runs if that technique is proven successful.

3. Production Proposal (10.7 M core-hours)

a. Goals

With the release of CESM2 and support for two-way ice–climate coupling, we will move toward production simulations with an interactive Greenland ice sheet in a variety of climate scenarios. These runs will form the LIWG contribution to ISMIP6, which includes three suites of experiments: i) standard CMIP6 experiments (DECK, historical, etc.) analyzed in terms of ice sheet forcing; ii) standalone ice sheet experiments based on CMIP6 model output from future climate scenarios; and iii) coupled climate/ice-sheet experiments to study ice sheet feedbacks. During Year 1 of this proposal, experiments in the last two categories will be carried out using LIWG computing resources. (Some Tier 1 experiments under (iii) are included in the CESM allocation for CMIP6.)

Production simulations during Year 2 will extend this work to paleo ice sheets and longer time scales. One set of experiments will focus on the recent Holocene deglaciation, when the Greenland ice sheet was retreating and remnants of the large Laurentide ice sheet were disappearing. Running at coarse atmosphere resolution (FV2) with accelerated ice sheet dynamics will allow multi-millennial simulations. Also, we will study the long-term evolution of the Greenland ice sheet under different climate scenarios, to identify thresholds for deglaciation.

b. Specific simulations and computational requirements

P1, P2, P3, and P4: The future of the Greenland ice sheet and associated climate feedbacks: CESM2 contribution to ISMIP6 coupled climate/ice-sheet experiments (3.9 M core-hours, Year 1, priority A, B): The goal of this work is to extend and support the Tier 1 ISMIP6 simulations and carry out a suite of Tier 2 simulations, using fully coupled CESM-CISM. These simulations will investigate processes of ice-climate interaction that delay or speed-up deglaciation, and will determine climate feedbacks associated with future Greenland ice sheet loss. We will extend the Tier 1 transient CO_2 simulation (1pctCO2to4x) by 150 years to get 500 years in total, and we will run a reference 500-year simulation without a dynamic ice sheet, in order to quantify feedbacks due to ice sheet changes. Also, we will carry out a 165-year historical run (1850-2014), followed by an extended 286-year scenario run (2015-2300) with high-end radiative forcing (ssp5-85).

P5. Future sea-level contribution from the Greenland and Antarctic ice sheets: CESM/CISM contribution to ISMIP6 standalone ice sheet experiments (0.3 M core-hours, Year 1, priority A): These experiments support the ISMIP6 goal of estimating sea level contributions from the Greenland and Antarctic ice sheets, based on output from CMIP6 future climate scenarios. We will use standalone CISM, configured and forced according to ISMIP6 protocols. About half the requested resources will be used for multi-millennial model spin-up, with the remainder used to run the requested future climate experiments and to assess parameter sensitivity.

P6, P7, and P8: Past as a key for the future: Greenland in the Holocene (4.0 M core-hours, Year 2, priority A, B): We will study the sensitivity of the Greenland ice sheet to the greenhouse-gas and insolation-driven warm climate of the Holocene, in collaboration with the PaleoWG. In this work, we are particularly interested in the final era of deglaciation of the Laurentide and marine-based Greenland ice sheets (12,000 to 5,000 BP), during which global sea level rose almost 60 m. We are interested in the ice sheets' geometry changes, retreat rates, sea level contribution, and impact on Northern Hemisphere climate. Because of the long simulation time (7,000 years), we will use a lower-resolution version of CESM (FV2), and/or an accelerated ice-sheet component (JG/BG), both of which will drastically reduce the overall computational cost. Besides a long-term transient simulation, we will analyze the sensitivity to the coupling frequency between climate and ice sheet components, as well as to the choice of various ice sheet parameters.

P9 and P10. Thresholds, sea level commitment, and reversibility: Using CESM2 for studying long-term Greenland Ice Sheet - climate interactions (2.5 M core-hours, Year 2, Priority A): The FV2 and JG/BG techniques will also be applied to future simulations, allowing us to extend the simulation time and look at long-term evolution of Greenland ice sheet deglaciation in various climate change scenarios. After running a 1000-year baseline experiment to simulate Greenland evolution to year 3000, we will carry out 5 shorter (300-year) runs to consider the effects of 5 alternative future greenhouse scenarios. This will allow us to quantify temperature thresholds for irreversible ice sheet loss, and total sea level commitment in each of the CMIP6 climate scenarios.

References

van Kampenhout, Rhoades, Zarzycki, Herrington, Sacks, Lenaerts, van den Broeke, 2018: Regional grid refinement in an Earth system model: Impacts on the simulated Greenland surface mass balance. *The Cryosphere* (in preparation).

Experiment	Compset	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in thousands of core-hours	Data Volume (Tb)	Priority
Development								
Year 1								
D1: CISM development	CISM-only	gl4, ar8, ar4	~1000	~200	~1	200	20.0	A
D2: POP-CISM 1-way coupled	CISM-only, T	gl4	~500	~200	~1	100	10.0	A
D3: CISM LGM N. Hemisphere	CISM-only, T	nh4	~100	~1000	~1	100	10.0	B
D4: Software engineering tests	T, I, IG, B, BG	f09_g16_gl4	~1000	~0.1	~3500	350	5.5	A
Year 2								
D1: CISM Greenland, Antarctica	CISM-only	gl4, gl2, an4, an2	~500	~200	~10	1000	10.0	A
D2: Plume model implementation	CISM-only	an4, an2	~50	~200	~10	100	1.0	B
D4: Software engineering tests	Various	Various	~1000	~0.1	~3500	350	1.0	A
D5: VR-CESM Greenland	F	Variable to 28 km	4	95	4300	1634	0.4	A
D6: VR-CESM West Antarctica	F	Variable to 28 km	6	30	6000	1080	0.2	A
D7: Firn model development	B	f09_g16_gl4	5	20	3500	350	5.5	B
Production								
Year 1								
P1: 1pctCO2to4x-withism, yr 351-500	BG	f09_g16_gl4	1	150	3500	525	8.2	A
P2: 1pctCO2to4x control, yr 1-500	B	f09_g16_gl4	1	500	3500	1750	27.3	B
P3: historical-withism, 1850-2014	BG	f09_g16_gl4	1	165	3500	577.5	9.0	A
P4: ssp5-85-withism, 2015-2300	BG	f09_g16_gl4	1	286	3500	1001	15.6	A

P5: ISMIP6 standalone ice sheet	CISM-only	gl4, gl2, an4, an2	~100	~300	~10	300	3.0	A
Year 2								
P6: Last deglaciation, 12 to 5 ka w/ cism accel	BG-FV2	f19_g16_nh4	1	1000	1000	1000	42.0	A
P7: Last deglac, increased cpl frequency	BG-FV2	f19_g16_nh4	5	400	1000	2000	84.0	A
P8: Last deglac, sensitivity	BG-FV2	f19_g16_nh4	5	200	1000	1000	42.0	B
P9: Long-term GrIS stability, baseline	BG-FV2	f19_g16_gl4	1	1000	1000	1000	42.0	A
P10: Long-term GrIS stability, thresholds	BG-FV2	f19_g16_gl4	5	300	1000	1500	63.0	A
Totals					***Year 1***	4903.5	108.6	
					Year 2	11014	291.1	
					Development	5264	63.6	
					Production	10653.5	336.1	

Land Model Working Group (LMWG)

1. Broad Overview of Working Group and Research Plan

The goals of the 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. A portion of the proposed terrestrial carbon cycle production work has been included in the BGCWG request.

The LMWG has pursued an ambitious program of model development, which culminated with the release of CLM5 in February 2018. Several additional large development projects have been progressing in parallel to CLM5 development including a multi-layer canopy scheme, a representative hillslope hydrology model, and the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) configuration of CLM. These projects will continue into the next CSL allocation cycle along with other development projects on water management and agriculture model development. Parameter estimation/calibration is an increasingly important feature of CLM development. In addition, the LMWG in collaboration with land modeling scientists across NCAR has begun work towards unifying land modeling activities across NCAR to form the Community Terrestrial Systems Model (of which CLM5 is the current climate configuration of the broader CTSM).

Land processes and their role in climate variability and change have gained significant expanded focus in CMIP6. Land-focused MIPs within CMIP6 include LUMIP (Land-use MIP), LS3MIP (Land surface, soil moisture, and snow MIP), and C4MIP (Coupled Climate Carbon Cycle MIP). Together, these MIPs address the main feedbacks and forcings from the land surface, and also include a benchmarking land-only MIP (LMIP, which is part of LS3MIP). CESM2 will participate in each of these MIPs, utilizing CLM5 in both coupled and land-only experiments.

2. Development Proposal (6.7 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 pre-industrial time up to present day (~165 years) with transient land cover and nitrogen deposition. Time is requested for several CLM spinup simulations.

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, the 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 pre-industrial 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. We continue 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 / water processes, D3) and longer timescale processes (order 100 years, e.g., those related to soil carbon and nitrogen processes, D8).

Selected model development activities that we anticipate over the length of the CSL allocation period are outlined below. Several smaller projects are not explicitly listed.

b. Specific model development projects

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

D1, D2, D6, and D7. 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, D6, and D7. 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, D6, and D7. Hillslope hydrology: CLM is collaborating with Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) on a funded NSF project to advance the representation of hydrological processes in ESMs. 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/water cycle behavior in upland versus lowland environments.

D4 and D9. 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 clarity of results. Occasional shorter simulations are also needed.

D5 and D10. 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. Many projects are funded to use and develop the CLM(FATES), including the Next-Generation Ecosystem Experiment (NGEE) in the tropics, which is planning to use CLM/E3SM-Land(FATES).

D11. CLM-DART: Creation of a model-data fusion framework in which a variety of remote sensing and ground-based ecosystem measurements made across a range of temporal and spatial scales to produce optimal solutions for model parameter values, states and fluxes. This framework will enable spatial extrapolation of observations and ecological forecasting. It draws upon multi-instance capability within CESM and a suite of specialized scripts to link CLM restart files to the Data Assimilation Research Testbed (DART). We will be: i) developing methodology for identifying and assimilating PFT-specific observations; ii) investigating and testing methodologies for optimally using “time-averaged” observations, such as annual measures of productivity or net primary productivity derived from tree rings; and iii) investigating and testing methodologies for parameter estimation within the DART framework. Length of required simulations differs widely based on specific development project. Standard length of 50 years included in the proposal.

3. Production Proposal (16.6 M core-hours)

a. Goals

The LMWG has strong participation in the CMIP6 “LandMIPs” including LUMIP, LS3MIP, and C4MIP. Together, these MIPs address the main feedbacks and forcings from the land surface, and also include a benchmarking land-only MIP, LMIP, which is part of LS3MIP. Allocation is requested for Tier 2 experiments in LUMIP and LS3MIP. In addition, CLM5 will participate in several planned additional MIPs including those focused on the carbon cycle (TRENDY), terrestrial hydrology (SOILWAT), and the surface energy budget (PLUMBER2). Within the working group, there is an expanded emphasis on human management of the terrestrial system and allocations are requested to support several community projects on crop and forest management, the role of land-atmosphere interactions in modulating land-use change impacts on climate, and urban-climate interactions. Hydrology and permafrost simulations, in support of funded projects, are also included in the request.

b. Specific simulations and computational requirements

P1, P2, P7, and P8. TRENDY, SOILWAT, 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 spinups required that past experience suggests is typically required.

P3 and P4. LUMIP: A set of 16 land-only historic simulations that assess the various impacts of land-management on the carbon, water, and energy fluxes. Additional ensemble members for coupled historical no land use and alternative land use future scenarios are also requested. Years 1850-2014.

P5 and P9. LS3MIP: Land-only simulations with alternative historical forcing datasets; land-only simulations anomaly-forced with future climate projections (2015-2300). Coupled simulations with prescribed soil moisture and prescribed snow to assess soil moisture/snow feedbacks. These are Tier 2 coupled experiments in LS3MIP, which includes additional ensemble members for the Tier 1 experiments as well as additional sensitivity experiments. Years 1980-2100.

P6 and P10: Land carbon stock trend uncertainty: Land-only simulations that assess how new model features such as a multi-layer canopy, ecosystem demography, and hillslope-hydrology affect the simulation of land carbon flux trend uncertainty. Crop and forest management simulations will also be included. 250 years, 1850-2100.

P11. Ecosystem dynamics: Simulations assessing trait filtering and sensitivity of terrestrial ecosystems to representation of plant diversity. In order to evaluate long timescale vegetation competition processes, 200-year long simulations are required.

Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in thousands of core-hours	Total data volume (Tb)	Priority
Development								
Year 1						1673	1.5	
D1: CLM Development	CLM5	1°	12	165	250	495	0.7	A
D2: CLM Spinup	CLM5	1°	2	500	250	250	0	A
D3: Parameter estimation	CLM5	4°	800	20	20	320	0.4	A
D4: CAM-CLM testing	CAM6-CLM5	1° (FV)	4	30	2400	288	0.1	B
D5: CLM(FATES) Development	CLM5(FATES)	2°	16	200	100	320	0.3	A
Year 2						5070	4.9	
D6: CLM Development	CLM5	1°	40	150	250	1500	2.2	A
D7: CLM Spinup	CLM5	1°	4	1000	250	1000	0	A

D8: Parameter estimation	CLM5	4°	500	100	20	1000	1.2	A
D9: CAM-CLM testing	CAM6-CLM5	1° (FV)	5	30	2400	360	0.2	B
D10: CLM(FATES) Development	CLM(ED)	2°	40	200	100	800	0.8	A
D11: CLM-DART	CLM	2°	50	100	82	410	0.5	C
Production								
Year 1						5323.7	63.1	
P1: MIPs (TRENDY, GSWP3)	CLM5	0.5°	4	165	820	541.2	5.0	B
P2: MIPs Spinup		0.5°	2	500	820	820	0	B
P3: LUMIP Tier 2 LU manage factorial	CLM5	1°	16	165	250	660	10.0	A
P4: LUMIP hist-noLu, ssp ensembles	CESM2	1°	6	125	3500	2625	40.5	A
P5: LS3MIP Tier 2 Projection to 2300	CLM5	1°	6	285	250	427.5	3.8	A
P6: Land carbon stock trend uncertainty	CLM5	1°	4	250	250	250	3.8	A
Year 2						11303	43.7	
P7: MIPs (TRENDY, PLUMBER2)	CLM5	0.5°	10	165	820	1353	25.0	B
P8: MIPs Spinup		0.5°	3	1000	820	2460	0	B
P9: LS3MIP Tier 2 Coupled	CESM2	1°	12	120	3500	5040	1.6	A
P10: Land carbon stock trend uncertainty	CLM5	1°	20	250	250	1250	9.5	A
P11: Future vegetation dynamics	CLM5(FATES)	1°	20	200	300	1200	7.6	B

Ocean Model Working Group (OMWG)

1. Broad Overview of Working Group and Research Plan

The primary goals of the 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 improve our understanding of ocean processes, the role of the ocean in the Earth system, and its interactions with other Earth system components.

The OMWG is in the midst of a major transition of the dynamical core of the CESM ocean component model, moving from the Parallel Ocean Program (POP) that has been used in CESM since CCSM version 2 through the present, to the Modular Ocean Model version 6 (MOM6). The motivation, process and justification for the decision to change ocean dynamical cores were described in the previous CESM CSL proposal and are documented on the CESM OMWG web pages. The choice of MOM6 as the new dynamical core was finalized shortly after the previous CSL proposal was submitted. During the later-half of the previous allocation cycle, work began in earnest in establishing a collaborative development arrangement with the MOM6 team at the Geophysical Fluid Dynamics Laboratory (GFDL), configuring a prototype version of MOM6 for CESM and developing the necessary infrastructure to couple MOM6 to the CESM framework. As of August 2018, this ground work is very near completion. A few remaining issues related to coupling of the ocean and sea ice components are being resolved. A large fraction of the resources requested for the coming proposal period are classified as *development* and to be dedicated to completing the porting of the physical parameterizations developed in POP to MOM6, exercising MOM6 in a variety of configurations within the CESM framework to establish a better understanding of its simulation biases and sensitivities, and to begin to exploit the new capabilities that are enabled by the MOM6 dynamical core. These include, for example, prognostic sea level change, higher vertical resolution near the sea surface, more accurate treatment of topography, and more flexible time stepping. New and ongoing parameterization development efforts are underway on several fronts and will be transitioned to the MOM6 framework. Additionally, the transition to MOM6 opens the opportunity to broaden the use of CESM within the oceanographic research community and to begin to provide capabilities to the CESM community that had been difficult or impossible with the POP based dynamical core including idealized geometry configurations, regional or nested configurations, and configurations at “eddy permitting” resolutions. An objective of the development work proposed here is to be able to release one or more versions of CESM with MOM6 as the ocean component prior to the release of CESM3. Efforts using the Data Assimilation Research Testbed (DART) with both moderate and high-resolution versions of CESM-POP will continue as a part of research in seasonal- to decadal prediction underway with CESM2.

While no further development of the POP ocean component is planned, the resources requested for production experiments will exploit the newly available POP-based CESM2. A set of experiments will investigate the origin of bi-stability of the CESM2 climate expressed as a proclivity for shut down of Labrador Sea convection and expansion of sea ice over the subpolar North Atlantic. A separate line of research will investigate the physical basis for the very weak ventilation of the deep Pacific Ocean that became a critical problem in the representation of the marine carbon cycle in CESM2. A high-resolution coupled ocean-sea-ice simulation with POP will be completed using the recently prepared ocean forcing data set based on the JRA-55 (Japanese Reanalysis) product with sampling sufficient to investigate eddy-mean-flow interaction. An extension of work begun in the previous allocation using CESM1 for investigations of Atlantic meridional overturning circulation (AMOC) is also requested.

2. Development Proposal (15.1 M core-hours)

a. Goals

Many years of parameterization development in POP produced a CESM ocean component model that was world leading in physically-based process representation and simulation fidelity. A primary objective of the OMWG over the next allocation cycle will be to bring that experience and parameterization technology forward into the 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 POP development. In particular, the Arbitrary-Lagrangian-Eulerian (ALE) vertical coordinate 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 POP and will require extensive experimentation to develop OMWG experience with this capability.

New parameterization development efforts planned for this allocation cycle focus primarily on two issues. The first is exchange between the surface mixed layer and the ocean interior. Research with the POP 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 (Large Eddy Simulation) are guiding new development of the surface boundary layer parameterization and coupling to wind waves. The second focus relates to ocean mesoscale eddies. There has been considerable progress in the development of lateral sub-grid 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 the OMWG using both deterministic and stochastic approaches and will be implemented in MOM6 and tested in both forced ocean-sea-ice and fully coupled simulations.

In response to interest within the university research community, members of the 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.

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.

While OMWG research is focused on formulation of the model dynamics and physical parameterizations, we will coordinate with the 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 the BGCWG to transition the Newton-Krylov fast solver technology from POP to MOM6.

b. Specific simulations and computational requirements

D1. <u>MOM6 base model development:</u> The highest priority of the OMWG over the next allocation cycle will be to develop a “workhorse” configuration of the MOM6 based ocean component model. The prototype we are currently working with has somewhat higher resolution (nominally 2/3°) than the most recent version of the POP based ocean component (nominally 1°), but is still in the “eddy-parameterized” regime. The higher horizontal resolution (2x as many grid points) and increased algorithmic complexity are reflected in higher cost (approximately 4x) relative to the standard resolution version of POP. The development plan is to iteratively bring in the full suite of parameterizations developed in POP with simulations in forced ocean – sea-ice, and fully coupled CESM configurations to establish the sensitivity and climate biases of the new model and an understanding of the behavior of familiar parameterizations in an unfamiliar dynamical core. As discussed above, new parameterization development is proceeding simultaneously for both diabatic (surface mixed layer) and adiabatic (mesoscale eddy) physics, and will be implemented in the MOM6 framework. A typical sequence of experiments for each step of this ongoing development would be one or more short (25-50 year) ocean – sea-ice (G-compset) experiments as validation and sanity checks, followed by a longer (100-300 year) experiment to evaluate climate impacts of the changes and longer-term climate drift. Parameterizations with more uncertain free parameters will require more than one pass through this iteration. Once a set of experiments have refined the choices for a class of physics (e.g., mesoscale eddy parameterization), a moderate length (100-300 year) fully coupled experiment (B-compset) will be carried out to assess interactions with other components and impact on the overall climate simulation. Forcing for G-compset experiments will come from the JRA-55 reanalysis-based ocean forcing data set developed with an international group of collaborators as part of the previous CSL allocation. The resource requirements for the MOM6-based CESM are based on measurements of the G-compset prototype version of MOM6 on Cheyenne. The resource requirement for the MOM6 B-compset are obtained by combining these measured ocean – sea-ice timings with data from standard POP based fully coupled experiments.

D2. MOM6 high resolution development: Heretofore, the OMWG has avoided the "eddy-permitting" ocean resolution regime (20-40 km horizontal grid spacing) in CESM due to the absence of physically based closures for partially resolved mesoscale eddies. Recent theoretical and process studies have pointed toward viable parameterizations in this regime and members of the OMWG are active in their development. We will work towards versions of CESM with ocean components in this regime (nominally 1/4°) that provide the advantage of better resolution of mean flow features (eastern boundary upwelling, western boundary currents, flow through narrow passages) as well as the emergence of intrinsic ocean variability, but with appropriate physically based closures for sub-grid scale mesoscale variability. The need for scale adaptive parameterizations is acute in this resolution regime. Both deterministic and stochastic modifications to the Gent-McWilliams closure will be developed and implemented in MOM6 for the eddy-permitting resolution. Notably, two of the parameterizations under consideration (QG-Leith and GM+E) couple the viscous and diffusive sub-grid closures, providing some of the first physically based closures for this regime. The GM+E closure may also be appropriate at the standard 2/3° resolution and will also be tested there. In addition, we will implement a version of MOM6 in the "eddy-resolving" regime (nominally 1/12°) both as a replacement for the successful 1/10° version of CESM-POP and as a basis for evaluating the eddy-permitting solutions. The same parameterization development targeted at surface boundary layer processes will also be tested at the higher resolutions. The development cycle is analogous to that described above for the standard resolution version of the model, but with the length of the experiments shortened to contain computational cost. The resource estimates for the higher resolution MOM6 experiments are derived by scaling the measured lower resolution estimates by the ratio of the number of grid points and anticipated time step length.

D3. MOM6 simple models: In response to interest and requests from the CESM user community, an effort to collaboratively develop one or more "simplified" configurations of the MOM6 ocean component is being planned by the OMWG. The simplifications would be at least geometric in nature with simplifications in physics to be determined, providing something akin to the popular aqua-planet atmosphere. The intention of such a configuration is that it is moderate in computational cost and that it can be easily modified by users, so the emphasis of the development will be on providing robust example configurations that can be run with either specified atmospheric forcing or coupled to a simplified version of CAM as an idealized Earth system model. The cost estimates for this part of the resource request are based on the same horizontal resolution as the standard resolution version of MOM6 described above (approximately 2/3°), but with somewhat reduced cost to reflect the intention of simplified physics. The focus for Year 1 will be development and testing of this set of canonical configurations, with longer science driven experiments in Year 2.

D4. MOM6 regional and nested modeling: While a number of efforts to provide coupling of the CESM ocean component to regional ocean models have been carried out over the last years, they have all been challenged by the complexity of coupling POP to a different ocean model (ROMS). A regional modeling capability in MOM6 is under development by university groups active in the OMWG, opening the opportunity to provide cleaner and more easily supported ocean downscaling capability for CESM in a single code base. Resources are requested for development of this capability in the current allocation cycle. Several downscaling experiments will be carried out. Two hindcast experiments driven by the JRA-55 forced global MOM6 simulations (D1 or D2) will be completed for the California Current System and the Northwest Atlantic Gulf Stream System, each with 1/12° resolution. The results of these downscaled simulations can be compared against the high-resolution global simulations described in D2. For each domain, a 3-member ensemble of downscaled climate time-slice experiments for the end of the 21st century will be carried out using forcing anomalies from CESM2 climate change experiments. We will also transition the ROMS-based Coral Triangle (far western tropical Pacific and Indonesian Seas) 5 km resolution configuration to MOM6 and carry out a simulation forced with output from the eddy-permitting JRA-55 forced experiment described in D2. The resource requests for these experiments are based on timing measurements of a stand-alone (i.e., not running under CESM infrastructure) California Current System configuration of MOM6 developed by the Rutgers University group.

D5. <u>Ocean and coupled data assimilation:</u> To advance data assimilation capabilities within the CESM and Data Assimilation Research Testbed (CESM-DART) framework in support of both the broader CESM community and several ongoing projects, resources are requested for finalization and testing of the “pause-resume” capabilities. This effort will initially focus on the POP-DART, i.e., ocean reanalysis only, but will later be implemented in the other CESM components. We will use both the nominal 1° horizontal resolution version of POP-DART and the high-resolution (1/10° horizontal resolution) version of POP-DART where we anticipate the cost reductions to be even more significant. We will perform many simulations ranging from a few days to a few months with both resolutions and our cost estimate based on measurements of the POP-DART system on Cheyenne is 500,000 hours.

3. <u>Production Proposal</u>

a. Goals

The primary goals for the production portion of the OMWG request are to better understand the climate simulated by CESM2 and to complete work begun in the previous allocation period related to AMOC variability. Notably, all of the experiments proposed under this production allocation will use existing versions of the model, though generally using non-standard options.

b. Specific simulations and computational requirements

P1. <u>Investigation of CESM2 ocean processes and stability:</u> Two significant issues involving ocean physics emerged in the development of CESM2 that remain unexplained and require further investigation. The first is the apparent bi-stability of the CESM2 climate with regards to Labrador Sea convection and sea ice coverage. The second is very weak ventilation of the deep Pacific basin by the Antarctic Bottom Water (AABW), leading to critical biases in biogeochemistry that required an ad-hoc fix to keep the solutions stable. These experiments are of interest to the PCWG and BGCWG as well as the OMWG, and of potential interest to other groups as the bi-stability concern has repeatedly presented itself during CESM2 development. A suite of POP G-compset experiments at 1° will be conducted to test the sensitivity of the water mass formation in the Labrador Sea and Antarctic shelf regions to factors including but not limited to the eddy mixing parameterization, overflow parameterization, ice-ocean drag coefficient, hosing with artificial freshwater input, and modified surface fluxes from the atmosphere to account for mesoscale wind features. Additional experiments will investigate the transport and transformation of AABW in the deep Pacific, exploring mesoscale eddy and deep diapycnal mixing options. A set of semi-prognostic G-compset experiments with geostrophic current nudging will be conducted to understand the contribution of advective transport of temperature and salinity to the shut-down of convection and freezing over of the Labrador Sea. Based on the above experiments, we will run 3 fully coupled simulations with three ensemble members each. These will be run 150 years to test the modifications to the ice and ocean models. It is necessary to run this minimum number of ensembles and years because during CESM2 development the bi-stability was found not to be a consistent system response and it could take up to 100 years to manifest. Deep Pacific ventilation issues can be investigated largely in the G-compset cases. Results from P2 will also be used in the analysis of this issue.

P2. High resolution POP with JRA55 forcing: Simulations with the 0.1° POP model, particularly with the inter-annually varying forcing data sets, have proven to be of high interest in the ocean research community, with the results supporting a number of PhD theses and published papers. We are requesting resources to complete an additional simulation of this type using updates to the sub-grid scale closure (QG-Leith) and using the new JRA55 based forcing. Note that the storage estimate for this experiment is based on 5-day rather than monthly sampling to allow for identification and tracking of mesoscale features.

P3. AMOC experiments: In the previous OMWG allocation, a set of experiments were conducted to examine the response of the AMOC to persistent North Atlantic Oscillation (NAO)-related forcing. These were 10-member ensembles of 10-year experiments. We are requesting resources to extend these ensembles for an additional 20 years to investigate the coupled freshwater feedbacks that develop on multi-decadal timescales. Note that these experiments will be conducted with CESM1.2

Experiment	Configuration	Resolution	# of Runs	Sim-Yrs / Run	Core-hrs / sim-Yr	Total (k-core-hr)	Data Vol / sim-yr (GB)	Total Data Vol (TB)	Priority
Development									
Year 1									
D1 MOM6 Base Model									
D1g short	G-MOM6	2/3°	8	50	800	320	17	6.8	A
D1g long	G-MOM6	2/3°	2	300	800	480	17	10.2	A
D1b	B-MOM6	2/3°	2	100	4150	830	57	11.4	A
D2 MOM6 High Resolution									
D2g 1/4	G-MOM6	1/4°	1	50	5400	270	121	6.1	B
D3 MOM6 Simple Model	C-MOM6	2/3°	8	20	750	120	10	1.6	A
D4 MOM6 Nested/Regional									
D4a CCS/NWA	C-M-REG	1/12°	1	50	1000	50	50	2.5	A
D5 Data Assimilation	POP-DART	0.1° & 1°				500		NA	B
Total Dev. Year 1						2570		38.6	
Year 2									
D1 MOM6 Base Model									
D1g short	G-MOM6	2/3°	8	50	800	320	17	6.8	A
D1g long	G-MOM6	2/3°	4	300	800	960	17	20.4	A
D1b	B-MOM6	2/3°	2	300	4150	2490	57	34.2	A
D2 MOM6 High Resolution									
D2g 1/4	G-MOM6	1/4°	6	50	5400	1620	121	36.3	A
D2g 1/12	G-MOM6	1/12°	1	50	51200	2560	1089	54.5	B
D2 b 1/4 : 1	B-MOM6	1/4° O : 1° A	2	50	8758	875.8	312	31.2	A
D2b 1/4 : 1/4	B-MOM6	1/4° O : 1/4° A	1	25	105408	2635.2	500	12.5	B
D3 MOM6 Simple Model	C-MOM6	2/3°	2	300	750	450	10	6.0	A
D4 MOM6 Nested/Regional									
D4a CCS/NWA	C-M-REG	1/12°	7	50	1000	350	50	17.5	A
D4b CT	C-M-REG	5 km	1	50	4000	200	200	10	A
Total Dev. Year 2						12461		229.4	
Total Dev.						15031			

Production									
Year 1									
P1 CESM2 Ocean Processes									
P1g	G-POP	1°	10	50	150	75	17	8.5	A
P1b	B-POP	1°	3	150	3543	1594.35	57	25.7	A
P2 High-Res POP	G-POP	0.1°	1	50	50000	2500	2200	110	B
P3 AMOC	B (CESM1)	1°	10	20	1640	328	57	11.4	B
Total Prod Year 1						4497.35		155.6	
Year 2									
P1 CESM2 Ocean Processes									
P1g	G-POP	1°	10	50	150	75	17	8.5	B
P1b	B-POP	1°	6	150	3543	3188.7	57	51.3	B
P3 AMOC/AMV	B (CESM1)	1°	10	20	1640	328	57	11.4	B
Total Prod Year 2						3591.7		71.2	
Total Production						8089.05			
Total OMWG Request Year 1						7067.35			
Total OMWG Request Year 2						16052.7			
Total OMWG Request Year1+2						23120.1			

Paleoclimate Working Group (PaleoWG)

1. Broad Overview of Working Group and Research Plan

The PaleoWG is a consortium of scientists interested in modeling and understanding past Earth climates, allowing a long-term perspective on Earth-system feedbacks. PaleoWG members include participants from universities and laboratories, with interests ranging from early Earth to the recent millennium. Individually and as a community, we conduct scientific modeling experiments to establish relationships between forcings and feedbacks for specific time periods, and to explore the transient nature of these responses. Comparing model results to observational data is an important component of the PaleoWG efforts. We also test model components developed by other CESM working groups in a paleoclimate context and develop new capabilities that allow better assessment of model simulations against data.

The PaleoWG simulations will utilize the FV 1°x1° version of CESM2 for several reasons. First, the protocols for PMIP (Paleoclimate Modeling Intercomparison Project) and DeepMIP require the CMIP6 *piControl* and *abrupt-4xCO*$_2$ simulations to be run by the modeling groups. These will be already completed as part of the CMIP6 DECK simulations being run at NCAR. Second, a finer ocean resolution of 1° has been shown to be necessary to simulate flow through narrow gateways. Third, the only low-resolution version of CESM2 will be the FV 2°x1° version, which is still under development. Simulations will be branched or initialized from previous simulations to reduce spinup time. Descriptions of the protocols for the CMIP6/PMIP4 Tier 2 and 3 and DeepMIP experiments can be found in the references.

2. Development Proposal (14.8 M core-hours)

a. Goals

The PaleoWG development goal is to provide the community with expanded capabilities in CESM for application to a wide range of paleoclimate research problems on multiple time scales and time periods. The working group develops and explores model parameterizations and capabilities to shed light on unanswered questions about past climates, and for out-of-sample testing and evaluation of the model parameterizations that are being used in projections of the future. That is, for forcing and boundary condition changes that are much larger than during the historical period. In this proposal, we include testing new configurations of CESM, such as the capability to simulate the inception and retreat of Greenland, North American, and Eurasian ice sheets with CISM2 (Community Ice Sheet Model version 2) coupled to CESM2, the sensitivity of the Last Millennium simulation to alternate forcings, the application of CESM2 to the high CO_2 early Eocene, and the extension of the PMIP4 simulations to include the water isotope implementation scheduled for CESM2.2.

b. Specific simulations and computational requirements

D1 and D5. DeepMIP simulations for early Eocene: The Early Eocene Climatic Optimum (EECO, ~53-51 Ma) is the period of greatest sustained (> 1 Myr) warmth within the last 65 million years. As well, the Paleocene-Eocene Thermal Maximum (56 Ma) has been suggested as an analog for rapid GHG-climate change. The Year 1 DeepMIP simulation will explore the capability of CESM2 under high CO_2 forcing (6 x pre-industrial) and will be compared to simulations with earlier versions of CCSM/CESM as well as assessed with a new synthesis of geological data sets. This simulation will be branched from a CESM1.2 simulation to reduce spinup time. An additional simulation will be branched off from the D1 simulation and run in Year 2 with 9 x pre-industrial CO_2 to bracket the uncertainty in proxy GHG estimates. CESM1.2 simulations have been shown to be stable at 3x, 6x, and 9x CO_2 (3.5M core-hours, Year 1; 1.75M core-hours, Year 2).

D2. Greenland inception in the late Pliocene: Coupled CESM2-CISM2 simulation will be completed to study the inception of the Greenland ice sheet in the M2 glaciation near the end of the Pliocene (ca. 3.3 Ma). A fully coupled simulation will be run, using a forcing protocol consistent with the M2 glaciation (including: orbital parameters, greenhouse gases, vegetation, and land-sea mask) but with ice-free conditions in Greenland and initialized from the CMIP6/PMIP4 Tier 1 Pliocene simulation. High frequency atmospheric data will be extracted that can subsequently be used to force ice sheet only and land-ice sheet sensitivity simulations. This simulation will complement a simulation of the inception of ice sheets over eastern Canada and northern Eurasia at the end of the Last Interglacial (116 ka). The latter is being completed on a NCAR Strategic Capability (NSC) computing allocation (1.8M core-hours, Year 2).

D3. Last Millennium with alternate forcing datasets: An additional Last Millennium + historical extension simulation will be completed to explore the uncertainties related to the external drivers. Without taking uncertainties in forcing into account, model-observation discrepancies might be wrongly attributed to model failures and/or systematic problems in proxy reconstructions (4.1M core-hours, Year 2).

D4. CMIP6/PMIP4 simulations with water isotopes: CESM2.2, expected to be released in early 2019, will include the capability of simulating water isotopes in all the model components. The CMIP6 Tier 1 paleoclimate simulations for the Mid-Holocene, Last Interglacial (LIG), and Mid-Pliocene warm period, targeted to be completed in the fall of 2018, will be extended with water isotopes enabled. The expectation is that the water isotopes will be included in the CMIP6 Tier 1 paleoclimate simulations for the Last Glacial Maximum and Last Millennium which will start in Spring 2019 (3.6M core-hours, Year 2).

3. Production Proposal (18.6 M core-hours)

a. Goals

The PaleoWG production goal is to provide benchmark simulations of past climates to the community. These simulations offer the opportunity to test CESM 2.1 for various forcing conditions, carry out detection and attribution studies, and improve confidence in its application for the future. The working group carries out experiments as part of international intercomparison projects – PMIP4 and ISMIP6 (Ice Sheet Model Intercomparison Project for CMIP6). Our proposed production simulations include the Tier 2 and 3 simulations, which have been proposed by these MIPs as a coordinated set of sensitivity experiments to complement and enhance understanding of the CMIP6 Tier 1 simulations. The CMIP6 Tier 1 paleoclimate simulations of PMIP4 – Last Millennium *past1000* [850-2014], Mid-Holocene *midHolocene* (6000 yrs ago), Last Glacial Maximum *lgm* (21,000 yrs ago), Last Interglacial *lig127k* (127,000 yrs ago), and Mid-Pliocene warm period *midPlioceneEoi400* (3.2 million yrs ago) will be completed under the CESM CMIP6 allocation.

b. Specific simulations and computational requirements

P1. Mid-Pliocene factorization simulations: Two additional Mid-Pliocene simulations will be completed to assess the relative contributions of changes in the CO_2, land ice, and land-sea mask/orography in explaining the global and regional Pliocene warmth. These simulations are Tier 2 simulations for PMIP4/CMIP6 and will branched from the CMIP6 Tier 1 simulation for the Mid-Pliocene (2.8M core-hours, Year 1).

P2. LIG transient simulation: The response of the climate and Greenland ice sheet (and its contribution to the LIG sea level highstand) has yet to be explored in a state-of-the-art, fully-coupled climate-ice sheet model forced with the transient orbital and GHG forcings. Starting from the *lig127k* PMIP4/CMIP6 Tier 1 simulation, we will run two transient simulations from 127 ka to 124 ka, with the orbital forcing accelerated by a factor of 10: one with the Greenland ice sheet prescribed as pre-industrial and one where the Greenland ice sheet evolves with two-way coupling to CISM. Surface Mass Balance (SMB) from the first simulation will be used in standalone CISM simulations to assess the height elevation-SMB feedbacks (2.1M core-hours, Year 1).

P3 and P5. Last Interglacial and Holocene vegetation sensitivity simulations: CESM2 does not include a predictive vegetation model. Rather the CESM2 Tier1 simulation for the mid-Holocene and Last Interglacial will be run with prescribed preindustrial land cover. Pollen and other macro-fossil evidence indicate that the boreal forest extended to the Arctic coast in Eurasia and a greening of the Sahara during these interglacials. Starting from their respective PMIP4/CMIP6 Tier 1 simulations, these Tier 2 PMIP4/CMIP6 CESM2 simulations will explore the sensitivity of high-latitude temperatures and tropical hydrology to these observed vegetation changes under the different orbital forcings (1.4M core-hours, Year 1; 1.4M core-hours Year 2).

P4. Sensitivity to the Heinrich-11 meltwater event during the early LIG: Geological records of iceberg discharge at the end of the penultimate glaciation indicate a large meltwater flux into the North Atlantic. The resulting bipolar warming of the Southern Ocean has implications for explaining the rapid warming and CO_2 rise recorded in the Antarctic ice cores as well as the possible role of the West Antarctic ice sheet in explaining the sea level rise in the early LIG. This Tier 2 PMIP4/CMIP6 simulation (*lig127k-H11*) will explore the climate responses in CESM2. The warming of the Southern Ocean will provide ocean temperatures that can be used to assess the sub-ice-shelf melting being developed by the LIWG. The prescribed meltwater flux is applied for 1000 years. The protocol states that the simulation should be run a minimum of 100 years after the end of the pulse and if possible even longer, preferably until the Atlantic meridional overturning circulation has recovered to its initial state. Previous freshwater hosing simulations for modern suggest that ~400 years for recovery is required (4.9M core-hours, Year 2).

P6. Early Holocene simulation: The maximum expression of Holocene orbitally-induced differences in top-of-atmosphere insolation forcing from present occurred during the early part of the Holocene, though unlike the LIG, the climate at this time was still affected by the presence of a relic Laurentide ice sheet. This CESM2 PMIP4/CMIP6 Tier 2 simulation (*hol9.5k)* will explore the similarities and differences of the climate responses between the two interglacials. This simulation will also provide the initial conditions for a Transient Holocene community simulation (2.45M core-hours, Year 2).

P7. LGM sensitivity simulations: Two additional Last Glacial Maximum simulations (*lgm-PI-ice* and *lgm-PI-ghg*) will be completed to assess the relative contributions of changes in the greenhouse gases and large continental ice sheets in explaining the regional patterns of cooling during the LGM. These simulations are Tier 2 simulations for PMIP4/CMIP6 (3.5M core hours, Year 2).

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Experiment	Compset	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in thousands of core-hours	Total data volume (Tb)	Priority
Year 1								
D1. DeepMIP *deepmip-stand-6xCO2*	B1850	f09_g17	1	1000	3500	3500	54.5	A
Year 1 Total - development						3500	54.5	
P1. Pliocene, CMIP6/PMIP4 Tier 2, *midPlioceneE400* *midPlioceneEo400*	B1850	f09_g17	2	400	3500	2800	21.8	A
P2. LIG transient	B1850 BG1850	f09_g17	1 1	300 300	3500 3500	1050 1050	21.8	A
		f09_g17_gl4					21.8	A
P3. LIG, CMIP6/PMIP4 Tier2, l*ig127k-veg*	B1850	f09_g17	1	400	3500	1400	21.8	A
Year 1 Total - production						6300	87.2	
Year 1 Total						9800	141.7	
D2 Late Pliocene Greenland inception	BG1850 T and IG	f09_g17_gl4	1 various	500 various	3500 various	1750 50	27.3	B
D3. Last Millennium with alternate forcing	B1850	f09_g17	1	1165	3500	4100	63.5	B
D4. Tier 1 with water isotopes	B1850 +isotopes	f09_g17	3	300	4000	3600	49.1	A
D5. DeepMIP *deepmip-stand-9xCO2*	B1850	f09_g17	1	500	3500	1750	27.3	A
Year 2 Total - development						11250	167.2	
P4. Last Interglacial, CMIP6/PMIP4 Tier2, *lig127k-H11*	B1850	f09_g17	1	1400	3500	4900	76.3	A

P5. Holocene, CMIP6/PMIP4 Tier2, *midHolocene-veg*	B1850	f09_g17	1	400	3500	1400	21.8	A
P6. Early Holocene, CMIP6/PMIP4 Tier2, *hol9.5k*	B1850	f09_g17	1	700	3500	2450	38.2	A
P7. LGM, CMIP6/PMIP4 Tier2, *lgm-PI-ice* *lgm-PI-ghg*	B1850	f09_g17	2	500	3500	3500	54.5	B
Year 2 Total - production						12250	190.8	
Year 2 Total						23500	358.0	

Polar Climate Working Group (PCWG)

1. Broad Overview of Working Group and Research Plan

The 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 the 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 be produced from the diversity of activities we propose, and that these results will provide new understanding of polar climate processes.

2. Development Proposal (6.2 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 (e.g., data assimilation, satellite simulators, high-resolution) by the PCWG members towards our overall development goal. Here, we request resources to incorporate new polar-relevant physics and diagnostics into the sea ice model (CICE) and atmospheric model (CAM) used in CESM.

b. Specific simulations and computational requirements

D1. Sea ice model developments: Improvements to numerous aspects of the sea ice model within CESM will be developed and tested during the lifetime of this proposal. This will include the analysis of a land-fast sea ice parameterization, development of improved treatments of snow on sea ice, analysis of biogeochemistry within sea ice, the testing of new sea ice dynamics formulations, improvements based on diagnostic evaluation of CMIP6 models, and development of coupling between sea ice and the ocean model for CESM3, among others. These improvements will be developed and tested in a variety of configurations, both stand alone and coupled models, to investigate the role of new physics within the sea ice system itself and on coupled interactions. More specifically:

- The impact of land-fast ice will be tested in the context of the CESM-LE (Large Ensemble) to enable the assessment of the role of this parameterization relative to internal variability. 45 years of pre-industrial control spin-up followed by 155 years 20th century simulation are requested.
- Improved snow model representation will be developed in ice-only (D compset) simulations with 6 simulations of 50 years each requested to test different parameterizations (i.e., snow aging, blowing snow, snow loss to leads) and parameter values within these parameterizations. Two additional coupled runs of 50 years each are requested to assess the influence of the best candidate snow representations as assessed from the D-runs on coupled interactions.

- To assess sea ice biogeochemistry, sea ice dynamic formulations, and other new community enhancements to the sea ice model (i.e., floe size distribution, new ridging scheme), we request 6 simulations of 50 years each of the coupled model with a slab ocean (E compset). This will allow for the testing of these new physics in a model that spins up quickly and with enough years of simulation to assess the influence on the climatology and variability.
- To develop and test coupling between sea ice and the MOM6 ocean model for development of CESM3, we request two 60-year simulations of the ice-ocean model (G compset). This will allow for testing and assessment of the coupling in the context of a cycle of atmospheric interannual forcing (1958-2015). Two simulations will allow for the assessment of different potential sea ice model formulations for use in CESM3.
- Improvements based on diagnostic evaluation of CMIP6 will focus on sources of error in sea ice variability by identifying emergent constraints across the CMIP6 model ensemble, particularly related to the role of ocean stratification. The influence of parameterizations in CESM2 will be explored using the f19_g17 resolution B compset for efficiency since our focus is on sea ice and upper ocean. We request resources to do many (8 requested) short integrations of ~30 years, long enough for the sea ice and upper ocean to adjust and enable the assessment of the influence of parameterizations on sea ice properties.

Additionally, ice-ocean coupled simulations at high resolution are proposed in order to test ice dynamics that is more appropriate for these resolutions. This includes 25 years of simulation in Year 1 and 20 years of simulation in Year 2, allowing for analysis of the influence on interannual variability and comparison to similar simulations undertaken by the OMWG.

Ultimately all of this work will lead to an improved model for CESM3, which will better simulate sea ice processes and feedbacks.

D2. Satellite Simulator development - Implementing satellite simulators to assess moist atmospheric processes: Joint with the AMWG, the PCWG proposes to evaluate and improve atmospheric model moist physics parameterizations with a specific emphasis on polar boundary layer, turbulence, clouds, and precipitation processes. We propose to use a CMIP-endorsed instrument simulator package COSP, which enables scale-aware and definition-aware comparisons between models and observations (Bodas-Salcedo et al. 2011, Kay et al. 2012). With the latest version of COSP released with CESM2 (COSP2), many new opportunities exist to expand diagnostics available within CESM. As such, computing resources are requested to develop new joint simulator diagnostics for clouds and precipitation based on CloudSat spaceborne radar observations and CALIPSO spaceborne lidar observations, to port diagnostics for opaque clouds (Guzman et al. 2017) and precipitation frequency (Kay et al. 2018) available in COSP1.4/CESM1 into COSP2.0/CESM2, and to use COSP to help motivate improvements in candidate atmospheric models proposed for CESM3. We request one 50-year simulation of the F-compset to develop new joint simulator diagnostics and a second 50-year simulation to port COSP1.4 diagnostics and use COSP to help motivate CESM3 improvements.

D3. Surface spectral emissivity: Recent work has indicated that spectrally resolving the surface emissivity in a climate model can improve the polar climate conditions. We propose to investigate this within the CESM2 by incorporating spectral surface emissivity values and consistent representation of surface physics in the model. Simulations will be assessed for improvements in polar climate conditions and feedbacks. We request resources for 8 simulations of 30 years in length within the CESM LE configuration. This will allow for the assessment of changes in the climate conditions relative to the robust characterization of internal variability available from the CESM-LE. This will inform model developments for CESM3.

3. Production Proposal (8.3 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, and understanding coupled system interactions and feedbacks. The proposed experiments make use of both the CESM-LE and CESM2 configurations. This will allow for the diagnoses of important climate processes relative to the large number of simulations available for the CESM-LE and also enhanced understanding of new interactions within CESM2.

b. Specific simulations and computational requirements

P1. Polar prediction research: With declines in Arctic sea ice, there is considerable interest in the predictability of sea ice and polar atmospheric conditions on seasonal to interannual timescales. Given this, we propose a number of CESM simulations to assess the importance of various aspects of model initialization and processes that influence predictability. These *perfect predictability* simulations will leverage the CESM-LE integrations for initial state information because of the large number of realizations available. Runs will thus use the CESM-LE configuration and include control simulations to obtain high frequency restart information for model initialization (one 130-year long simulation) and prediction ensemble integrations of two years in length that are initialized at different times of year, during different phases of climate variations, and during different aspects of modeled extreme events (for example just prior to a major ice loss event). We request 80 of the prediction ensemble simulations to allow for 8 sets of 10 ensemble members each in order to explore these different aspects of initialization. This will enable new understanding on the controls of polar predictability.

P2. Integrating models and observations: Recent research and community workshops have highlighted the need for a better integration of models and observations to enhance understanding. We propose a number of experiments that will explore this for both atmosphere and sea ice processes within CESM.

P2.1 Satellite simulators – atmosphere: Work is proposed to use satellite simulators to assess cloud and precipitation processes within CESM by leveraging a widely used satellite simulator package (COSP2.0) to assess the detectability of polar cloud and precipitation changes in a future climate. Simulations of an 1850 control run (100 years to obtain good statistics), 20th century historical run, and 21st century climate with COSP diagnostics will be performed to enable detection and attribution studies. As these runs are global, they will be of interest to a broad community studying moist atmospheric processes and also to space agencies that are planning for next-generation satellites recommended by the 2018 NASA Decadal Survey. Given that this will use the RCP8.5 forcing scenario, they will also enable direct comparisons to CESM1 simulations that have the same forcing. This will be of value to many researchers.

P2.2 Satellite simulator – sea ice: A satellite simulator for sea ice thickness will also be used to diagnose model biases relative to satellite products from NASA IceSAT (2003-2009) and IceBridge (2009-2018) missions. While this simulator is run offline, it requires frequent (hourly) model output and we propose to perform seven CESM2 CMIP6 historical ensembles with this output for 15-year periods to enable the simulator comparisons. This will allow for comparisons during the time of the IceSAT and IceBridge missions and a measure of the role of internal variability in the model. Post-processing of the model output will reduce the data volume. This work will provide the research community with a simulated ice thickness dataset that is directly comparable to satellite products for studies of variability and change.

P2.3 Field campaign guidance: Models can provide useful context for field campaigns by providing information on the internal variability and spatial representativeness of measurements. In association with the upcoming MOSAIC ice drift field campaign, we propose a single 20th century simulations based on the CESM-LE which has enhanced and higher frequency model output. By adding variables of subgridscale quantities at more frequent output we plan to disentangle mechanisms driving the large spread in sea ice extent and thickness that are possible during the melt season and may be experienced by MOSAIC. The use of the CESM-LE model configuration will enable comparisons to the internal variability that can be characterized using the large ensemble. This will be of value to the MOSAIC campaign and the many projects associated with that year-long field program.

P2.4 Data assimilation: Another mechanism to integrate models and observations is through the direct assimilation of observational data. This capability is now available for the CESM sea ice model and to compliment the sea ice simulator work, we will also perform experiments in which IceSAT2 and other observational data are directly assimilated into the sea ice model. This will use the D (sea ice/slab ocean model) compset and 40 years of simulation are requested to explore different aspects of the assimilation. This will inform sea ice forecasting work, provide insights on sea ice model biases, and provide further community investigations on sea ice variability and change.

P3. Understanding CESM2: A number of experiments are proposed to understand and further document the polar climate produced in CESM2. This includes sensitivity tests of the fully coupled model and ice-ocean simulations that will elucidate processes and feedbacks in the model and the source of model bias.

P3.1 Coupled sensitivity tests: We propose model simulations in which sea ice processes are varied and the coupled system response is assessed. This will include modifications to properties of the surface sea ice (albedo, ponding, snow distribution, snow fraction), among others to assess aspects of the surface albedo feedback. We request four simulations of 50 years each for this work. This will allow for investigation of several different sea ice properties and adequate time for model adjustment. The simulations will provide new insight on the relative importance of parameterization uncertainty in the model and how this modifies feedbacks and interactions.

P3.2 Ice-ocean sensitivity tests: Previous studies have found that there is a large spread in sea ice thickness distributions in coupled ocean-sea ice models (Chevallier et al. 2016), which may be potentially due to differences in prescribed atmospheric forcing. This forcing can be considerably different given that there is a large diversity in reanalysis data over the Arctic (Lindsay et al. 2014). This source of model uncertainty will be quantified by performed ice-ocean model simulations with a variety of different prescribed atmospheric forcing (for example, ERA-Interim and MERRA reanalysis). We request four simulations of 500 years in length. This will allow us to assess a number of different atmospheric forcing products and provide adequate years of simulation for the model to spin up. These simulations will also be useful for studies of ocean variability and the influence of forcing uncertainty in non-Arctic regions.

P4. Fresh water in the Arctic: Changes in the Arctic hydrological system can have far reaching impacts, for example on deep water formation in the North Atlantic. Fresh water tracer enabled simulations provide the ability to track different sources of freshwater, such as Pacific inflow, sea ice meltwater, and river runoff to the Arctic ocean. They also enable comparison with observations which can identify these different freshwater sources. To understand the changing Arctic ocean freshwater distribution, we propose to perform a high-resolution ice-ocean simulation with freshwater tracers. 30 years of simulation are requested. This run will be branched from an existing high-resolution simulation for the late 20th-early 21st century to enable comparison to observations. This will provide insight on the importance of model resolution for capturing ocean dynamics that modify the Arctic freshwater distribution.

P5. Coupled system interactions: Coupled feedbacks and interactions play an important role in polar climate variability and change. Here we propose a number of experiments to further elucidate various aspects of these interactions and their importance for the climate system.

P5.1 Arctic cyclones and sea ice: Recent work indicates that Arctic cyclones can have considerable impacts on sea ice. To further investigate this, we propose simulations designed to study Arctic cyclones, their influence on sea ice and what conditions cause cyclones to develop and amplify. These integrations will use CESM1 with the MPAS dynamical core in CAM5 with atmospheric grid refinement to allow higher resolution in the Arctic. We will employ nudging to control variables in the atmosphere and sea ice in isolated domains. We propose to run a series of deterministic experiments for classic and well-studied Arctic storms in the summers of 2006, 2012, and 2014. Integrations will be approximately 10 days long. Experiments will independently nudge the sea ice and atmosphere, also nudging will be isolated to specific regions to evaluate the role of heat and moisture sources and other observed features. To accommodate the multiple experiments, we request 48 total months of integration. In addition to new insights on cyclones and sea ice, this work will provide guidance on the use of atmospheric grid refinement for Arctic simulations.

P5.2 Importance of atmosphere-ice coupling: Because of strong coupled system interactions, the modeled parameter sensitivity is likely to change in the presence of coupling. Performing parameter sensitivity simulations with and without coupling between sea ice and the atmosphere can provide new insight on coupled interactions and feedbacks. Here we propose a set of one-degree resolution experiments to test the sea ice sensitivity to 5 parameters identified by Urrego-Blanco et al. (2016) in offline experiments in the CESM coupled and uncoupled configurations in order to better understand coupled feedbacks impacting the modeled sea ice state. These experiments will branch off the CESM2 DECK preindustrial control experiment. There will be 6 fully coupled simulations (1 control, 5 experiments) and 5 ice-ocean experiments forced with the atmospheric state from the control. Each simulation will be run 30 years, allowing the model to adjust to the parameter changes.

P5.3 Polar Amplification MIP (PA-MIP): The polar amplification model intercomparison project seeks to enhance understanding of polar amplification, including the relative importance of local and remote influences, and the global climate system response to changing sea ice. Here we propose to perform several of the Tier 2 simulations of the PA-MIP, including an experiment in which the global sea ice concentration is nudged to present-day conditions (experiment 2.1) and an experiment in which the Arctic sea ice concentration is nudged to late 21st century conditions (experiment 2.3). As discussed in the PA-MIP protocol, each experiment uses the fully coupled model and is 100 years in length. This will provide insight on the role of Arctic sea ice change in the simulation of polar amplification.

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Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year	Total in thousands of Cheyenne core-hours	Total data volume (Tb)	Priority (A/B/C)
Year 1								
D1 - CICE5 - Landfast Ice	B1850LENS, B20TRLENS	f09_g16	1	200.0	2200	440	10.9	B
D3 - Spectral Surface Emissivity	B1850LENS	f09_g16	8	30.0	2200	528	13.1	B
D1 - CICE6 - High Resolution	G	T62_t13	1	25.0	50000	1250	22.5	B
Year 2								
D1 - CICE6 - High Resolution	G	T62_t13	1	35.0	50000	1750	31.5	B
D1 - CICE6 improvements from CMIP6	B1850	f19_g17	8	30.0	1200	288	10.1	A
D1 - CICE6 Improved snow processes	D	T62_g17	6	50.0	40	12	13.5	A

D1 - CICE6 Improved snow processes	B1850	f09_g17	2	50.0	3500	350	5.5	A
D2 - COSP1.4 in CESM2	FAMIPCFCN with COSP	f09_f09	2	50.0	5000	500	1.4	A
D1 - CICE6 / MOM6	G	T62_g17	2	60.0	800	96	5.4	A
D1 - CICE6 / SOM	E1850	f09_g17	6	50.0	3500	1050	16.4	A
Year 1								
P1 - Prediction - initial state information	B20TRLENS	f09_g16	1	130.0	2200	575	7.1	A
P2.3 - MOSAiC ship tracks	B20TRLENS	f09_g16	1	155.0	2200	341	8.4	A
P5.1 - Coupled Interactions - cyclones	B1850LENS with MPAS regional refinement	A_g17	1	4.0	132000	528	10.0	B
P5.2 - Coupled Interactions	B1850	f09_g17	6	30.0	3500	630	9.8	A
P5.2 - Coupled Interactions	G	T62_g17	5	30.0	150	23	6.8	A
Year 2								
P1 - Prediction - perfect model experiments	B20TRLENS	f09_g17	80	2.0	2200	352	8.7	A
P2.2 - Satellite simulators, sea ice	B20TR	f09_g17	7	15.0	3500	368	5.7	A
P2.1 - Satellite simulators, precip and clouds	B1850 with COSP	f09_g17	1	100.0	5500	550	5.5	A
P2.1 - Satellite simulators, precip and clouds	B20TR with COSP	f09_g17	1	165.0	5500	908	9.0	A
P2.1 - Satellite simulators, precip and clouds	BRCP85 with COSP	f09_g17	1	85.0	5500	468	4.6	A
P2.4 - CICE Data Assimilation	D with DARt	T62_g17	1	40.0	7700	308	1.8	A
P3.1 - Understanding CESM2 - Sensitivity tests	B1850	f09_g17	4	50.0	3500	700	10.9	A

P3.2 - Understanding CESM2 - ice-ocean tests	GIAF	T62_g17	4	500.0	150	300	80.0	A
P4 - Fresh water tracers	GIAF	T62_t13	1	30.0	50000	1500	27.0	B
P5.3 - Polar amplification MIP	B1850	f09_g17	2	100.0	3500	700	10.9	A
		Total Cheyenne	Total volume					
		Thousand CH	Terabytes					
	D - year 1	2,218	46.5					
	D - year 2	4,046	83.8					
	P - year 1	2,097	42.1					
	P - year 2	6,153	164.1					
	Total Year 1	4,315	88.6					
	Total Year 2	10,199	247.9					
	Total	14,513	336.5					
	Total Development	6,264	130.3					
	Total Production	8,249	206.2					

Software Engineering Working Group (SEWG)

1. Broad Overview of Working Group and Research Plan

The role of the 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). In addition, this testing also ensures the robustness of the continuing and significant model infrastructure development, such as the improvements to changes to the model driver, coupler, tools, and scripts. Computing time is requested to carry out this important function throughout the various CESM versions that will be generated.

2. Development Proposal (12 M core-hours)

This request is needed ensure successful and robust periodic updates to the upcoming CMIP6 based CESM2.1.x release series and to incorporate new science into the following CESM2.2.x series which will be the first steps towards CESM3.

Whole Atmosphere Working Group (WAWG)

1. Broad Overview of Working Group and Research Plan

The WAWG research plan involves development designed to continue the move towards a unified sun-to-earth modeling (WACCM, Whole Atmosphere Community Climate Model) framework with high fidelity, and production runs for science and community projects. This involves continuing work on a number of development projects across NCAR laboratories and outside collaborators. The development request focuses on building a unified sun-to-earth modeling framework. This will include advancing the photolysis treatment, exploring higher vertical resolution, improving representation of gravity waves, and bringing WACCM-X, the solar weather model, up to the same climate model version as the rest of CESM. This will provide a framework for the simulation of space weather within CESM, thereby taking advantage of the explicit representation of the full processes in the lower atmosphere that are affecting the upper atmosphere. On the production side, simulations will contribute to ISA-MIP (Interactive Stratospheric Aerosol Model Intercomparison Project) for comparison of models with interactive stratospheric aerosols, GeoMIP (Geoengineering Model Intercomparison Project) for geoengineering studies, and QBOi for comparison of models with interactive quasi-biennial oscillations. 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 (16.2 M core-hours)

A. CESM Photolysis Development: The WACCM photolysis approach will be updated including a fast inline radiative transfer (RT) approach based on the Tropospheric Ultraviolet and Visible (TUV) Radiation Model. This is a line-by-line radiative transfer model that provides more accurate solutions for the radiative transfer (RT). With inline RT one can better represent clouds and aerosol impacts. We will do the development in 1.9x2.5 CESM1 (WACCM). The final tests will be with CESM2 (WACCM6). The goal is to provide a more detailed alternative and benchmark for the CESM radiation code, in particular for WACCM. Each simulation will start in 1980 and finish in 2017.

D1. CESM1 (SD-WACCM/MERRA2): We request time for 1 ensemble member of 38 years. We think these years and ensemble members are needed to compare to observations through the satellite era (1980-2017).

D2. CESM2.1 (SD-WACCM/MERRA2): We request time for 1 ensemble member of 38 years. We think these years and ensemble members are needed to compare to observations through the satellite era (1980-2017).

B. Evaluation of Halogen Heterogeneous Chemistry: Model calculations of key species will be compared to satellite observations. We will use the satellite coordinate output option for this work. We will run three CESM2.1 (SD-WACCM / MERRA2) – 1°

simulations: 1) reference simulation with heterogeneous processes only on sulfate aerosols (no water-ice chemistry, only on sulfate and NAT); 2) no halogen heterogeneous simulation (on water-ice, sulfate, and NAT); 3) same as 2), except with $BrONO_2 + H_2O$ included (on sulfate and NAT). Each simulation will start in 1980 and finish in 2017. This period was chosen for the purpose of examining nitrogen dioxide observations (NO2) from the NASA SAGE, SAGEII, SAGEIII-Meteor, SAGEIII-ISS, ACE-FTS, and OSIRIS satellite instruments.

D3. CESM2.1 (SD-WACCM/MERRA2): We request time for 3 ensemble members of 37 years each. These years are needed to compare to observations through the satellite era (1980-2017). Three ensemble members are needed to test sensitivities to individual chemical processes.

C. High Vertical Resolution WACCM6 tuning: In addition to a low horizontal resolution model, we also want to develop a high vertical resolution version of the model. This will be done in conjunction with the development of a high vertical resolution version of CAM6. It has been shown that to properly represent the stratospheric Quasi-Biennial Oscillation (QBO) it is necessary to increase the vertical resolution to about 500 m in the upper troposphere and lower stratosphere. This allows representation of low-frequency Kelvin waves and results in an apparently realistic apportioning of westerly forcing to resolved Kelvin waves and parameterized gravity waves, at least by comparison to recent very high-resolution simulations (e.g., Kawatani et al. 2010). A 110-level WACCM version (increased from the standard 70 levels) has been shown to provide a robust representation of the QBO (Garcia and Richter 2018), and we will use this experience as our target for high vertical resolution. For testing, we estimate a requirement of 100 years of WACCM-SC simulation and 50 years of WACCM, with an estimated cost of 1.4 times that of those models with the standard 70 levels. The configuration will be released to the community as a functional comp set for CESM2.1.

D4. WACCM-SC: We request time for 10 ensemble members of 20 years each. These runs are needed for tuning the high-resolution version of WACCM6 with specified chemistry.

D5. WACCM: We request time for 5 ensemble members of 10 years each. These runs are needed for tuning the high-resolution version of WACCM6 with full chemistry.

E. Gravity Wave (GW) Parameterization Development: Forcing of the middle atmosphere depends critically on the deposition of momentum from (parameterized) small-scale gravity waves. CESM2 (CAM6) adds some new physical schemes that affect gravity waves, such as a new surface drag scheme, a new orographic drag scheme with anisotropic topography, and even adjustments to the deep and shallow convective schemes. We will work on improving the gravity wave schemes and their interaction with the CAM6 physics.

In addition, a recent examination of the vertical diffusivity associated with dissipation of parameterized gravity waves has shown that the estimated effective diffusion coefficient is specific to the case where dissipation occurs via wave breaking, and produces incorrect results in the thermosphere, where dissipation occurs via molecular diffusion. We propose to update this aspect of the gravity wave parameterization and to test it by comparison with observations of temperature and minor constituent distributions in the upper mesosphere and lower thermosphere in WACCM (and throughout the thermosphere in WACCM-X).

D6. GW tuning for orographic scheme development: We request time for 8 ensemble members of 10 years each. These runs are needed for tuning of the orographic gravity wave parameterization in WACCM with specified chemistry.

D7. GW diffusivity development and climatology testing: We request time for 5 ensemble members of 10 years each. These runs are needed for development and testing of the gravity wave diffusivity parameterization in WACCM with specified chemistry.

D8. GW diffusivity development and climatology testing: We request time for 5 ensemble members of 10 years each. These runs are needed for development and testing of the gravity wave diffusivity parameterization in WACCM with full chemistry.

F. WACCM-X development: WACCM-X is the extension of WACCM up to the thermosphere (600-700 km) to be able to handle the connections between the sun and the earth: so-called space weather. A major goal of WACCM-X is to fully integrate existing solar and upper atmosphere models with climate models, so that the upper atmosphere can be explored with forcing from the top (sun) and bottom (climate system) and the climate system can be fully interactive with the sun.

Right now, WACCM-X2.0 for release in CESM2 is based on WACCM4 (CAM4) physical parameterizations. We will work to move WACCM-X2.0 in CESM2 from WACCM4 (CAM4) to WACCM6 (CAM6) physics. The goal is an integrated model from CAM to WACCM-X based on the same physical and dynamical parameterizations.

D9. WACCM-X development: We request time for 10 ensemble members of 1 year. These runs are needed to validate WACCM6-X at 1° finite volume resolution.

D10. WACCM-X2.0 transient simulations: We request time for 10 ensemble members of 1 year. These runs are needed to validate WACCM6-X with spectral element dycore (WACCM-X-SE) with ne30 resolution, along with the new mapping scheme.

G. PALEOSTRAT basic: 1000-year WACCM6 simulation at 2° horizontal resolution with MAM will be carried out to evaluate the effect of aerosols, including volcanic injections, in the “last millennium” (LM; 850-1850). The simulation uses external forcings appropriate for the Last Millenium adopted and prescribed volcanic aerosol loadings (Gao et al., 2008).

D11. Basic: We request time for 1 ensemble member of 1000 years. This run is required as to evaluate the model's ability to reproduce the climate of the last millennium using prescribed volcanic aerosol loadings.

3. Production Proposal (19.7 M core-hours)

A. ISA-MIP experiments: The Interactive Stratospheric Aerosol Model Intercomparison Project is explicitly for testing models like WACCM with a complete sulfur cycle. WACCM is a key part of ISA-MIP, and we will aim to contribute a full suite of experiments requested. This will better enable us to understand and evaluate WACCM prognostic volcanic aerosols against observations and other models. The experiments requested by ISA-MIP include background, transient, historic emissions, and Mt. Pinatubo sensitivity experiments. All simulations use CESM2-WACCM6 F-compset at 1° resolution.

P1. ISA-MIP background stratospheric aerosol (BG): We request time for 1 ensemble member of 20 years. This run is needed as a 20-year climatology to understand sources and sinks of stratospheric background aerosol and assess the sulfate aerosol load under volcanically quiescent conditions.

P2. ISA-MIP Transient Aerosol Record (TAR): We request time for 4 ensemble members of 15 years each. These runs are needed to evaluate models over the period 1998–2012 with different volcanic emission data sets and understand drivers and mechanisms for observed stratospheric aerosol changes since 1998.

P3. ISA-MIP Historic Eruption SO2 Emission Assessment (HErSEA): We request time for 36 ensemble members of 5 years each. These runs are needed to assess how injected SO_2 propagates through to radiative effects for different historical major tropical eruptions in interactive stratospheric aerosol models, to use stratospheric aerosol measurements to constrain uncertainties in emissions and gain new observationally constrained volcanic forcing and surface area density data sets, and explore the relationship between volcanic emission uncertainties and volcanic forcing uncertainties.

P4. ISA-MIP Pinatubo Emulation in Multiple Models (PoEMS): We request time for 30 ensemble members of 3 years each. These runs are needed to compare Pinatubo perturbation to stratospheric-aerosol properties with full uncertainty analysis, to quantify sensitivity of the predicted Pinatubo perturbation stratospheric aerosol properties and radiative effects to uncertainties in injection settings and model processes, and to quantify and compare sources of uncertainty in simulated Pinatubo radiative forcing for different models.

B. PALEOSTRAT volcanic: 100-year WACCM6 simulation at 2° horizontal resolution with MAM will be carried out to evaluate the effect of aerosols, including volcanic injections, in the "last millennium" (LM; 1750-1850). This volcanic simulation (VOL) uses MAM adapted for the stratosphere to compute the evolution of aerosols explicitly based on a time-dependent volcanic injection database developed by Ryan Neely.

P5. Volcanic: We request time for 1 ensemble member of 1000 years. This run is required as 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.

C. Simulations in Support of QBOi: A high vertical resolution version of WACCM5 (WACCM5-110L) was used to carry out simulations in support of phase 1 of the Quasi-biennial Oscillation Initiative (QBOi). A realistic QBO was produced by this model (Garcia and Richter 2018). Phase 2 of QBOi will take place between Oct 2018 - Sep 2020. This time, we anticipate running the High Vertical Resolution WACCM6 to look at interactions between the QBO and the MJO, which was not possible in CESM1, as the MJO was deficient in that model.

P6. GW tuning: We request time for 10 ensemble members of 20 years. These runs with WACCM-SC at 1° resolution are needed to evaluate the model's QBO with parameters adjusted to a range of settings.

D. Using WACCM-X v2.1 (2°): With the updated eddy diffusion scheme and improved thermospheric and ionospheric plasma density, we will make two transient simulations to study long-term variability of the space climate: Free run (FR) from 1964-2017 with realistic solar and geomagnetic variability; SD run from 1980-2017 with realistic solar and geomagnetic variability.

P7. WACCM-X FR: We request time for 1 ensemble member of 54 years. This run is needed to evaluate free-running WACCM-X over the historical period 1964-2017 with realistic solar forcing and geomagnetic variability.

P8. WACCM-X SD: We request time for 1 ensemble member of 38 years. This run is needed to evaluate specified dynamics WACCM-X over the historical period 1980-2017 with realistic solar forcing and geomagnetic variability.

E. GeoMIP Tier 2 Overshoot and Peak-Shaving Simulations: The SSP5-34 overshoot experiment runs are the baseline simulations for the peak-shaving GeoMIP experiment. This experiment branches from SSP5-85 in 2040 and runs to 2100 (61 years per ensemble member). The peak-shaving GeoMIP experiment runs 2015-2100 (86 years per ensemble member). We request one ensemble member of each as part of our baseline request.

P9. SSP5-34: We request time for 1 ensemble member of 61 years. This run is needed to evaluate climate in the SSP5-34 overshoot scenario, and compare to the peak-shaving GeoMIP experiment.

P10. Peak-shaving GeoMIP: We request time for 1 ensemble member of 86 years. This run is needed to evaluate climate in the peak-shaving GeoMIP experiment.

F. Stratospheric Aerosol Injection Simulations in support of GeoMIP: Most modeling work exploring stratospheric aerosol injection (SAI) as a method of solar geoengineering has focused on injection of SO_2. However, several issues have been found with this approach and injections of H_2SO_4 directly may be more optimal. We will investigate this using CESM2(WACCM) at 1° resolution following a newly developed GeoMIP protocol. Eight 10-year simulations with injections of SO_2 or H_2SO_4 will be carried out. Injections will be both point (30°S/30°N, 20 km altitude) and over a region (19-21 km x 30°S to 30°N and all longitudes). Four injection amounts (2.5, 5, 10, and 25 Tg/yr) will be used.

P11. CESM2-WACCM: We request time for 8 ensemble members of 10 years. These runs are needed to investigate the sensitivity of climate response to latitude, altitude, injection rate, and source of sulfur in a geoengineering context.

References

Garcia, R. R., and J. Richter, 2018: On the momentum budget of the quasi-biennial oscillation in the Whole Atmosphere Community Climate Model. *J. Atmos. Sci.*, submitted.

Kawatani, Y., K. Sato, T. J. Dunkerton, S. Watanabe, S. Miyahara, and M. Takahashi, 2010: The roles of equatorial trapped waves and internal inertia–gravity waves in driving the quasi-biennial oscillation. Part I: Zonal mean wave forcing. *J. Atmos. Sci.* **67**, 963-980, doi: 10.1175/2009JAS3222.1.

Experiment	Configuration	Resolution, vertical levels	Number of runs	Number of years per run	core-hours per simulated year	Total in thousands of Cheyenne core-hours	Total data volume (Tb)	Priority
Development								
Year 1								
D1 CESM Photolysis Development	FWSD	f19_f19_mg16, 88L	1	38	5,130	195	0.5	B
D2 CESM Photolysis Development	FWSD	f09_f09_mg17, 88L	1	38	23,000	874	1.4	A
D4 High Vertical Resolution WACCM6 tuning	FWscHIST	f09_f09_mg17, 110L	5	20	8,540	854	4.6	C
D11 PALEOSTRAT basic	BWmaHIST	f19_g17, 70L	1	1000	3,300	3,300	45.0	A
Year 2								

D3 Evaluation of Halogen Heterogeneous Chemistry	FWSD	f09_f09_mg17, 88L	3	38	23,000	2,622	4.2	A
D4 High vertical resolution	FWscHIST	f09_f09_mg17, 110L	5	20	8,540	854	4.6	B
D5 High vertical resolution	FWHIST	f09_f09_mg17, 110L	5	10	22,000	1,100	2.3	B
D6 Gravity Wave Parameterization Development	FWscHIST	f09_f09_mg17, 70L	8	10	6,100	488	2.4	A
D7 Gravity Wave Parameterization Development	FWscHIST	f09_f09_mg17, 70L	5	10	6,100	305	2.0	A
D8 Gravity Wave Parameterization Development	FWHIST	f09_f09_mg17, 70L	5	10	22,000	1,100	2.3	B
D9 WACCM6-X Development	FX2000climo	f09_f09_mg17, 130L	10	1	150,000	1,500	1.0	A
D10 WACCM6-X SE Development	FX2000climo	ne30, 130L	10	1	300,000	3,000	1.0	B
Production								
Year 1								
P5 PALEOSTRAT volcanic	BWmaHIST	f19_g17, 70L	1	1000	3,300	3,300	45.0	A
P11 Stratospheric Aerosol Injection Simulations in support of GeoMIP	BWSSP245	f09_g17, 70L	8	10	28,000	2,240	5.0	C
Year 2								
P1 Background stratospheric aerosol (BG)	FW2000climo	f09_f09_mg17, 70L	1	20	22,000	440	1.0	B
P2 Transient Aerosol Record (TAR)	FWHIST	f09_f09_mg17, 70L	4	15	22,000	1,320	2.0	A
P3 Historic Eruption SO2 Emission	FWHIST	f09_f09_mg17, 70L	36	5	22,000	3,960	5.3	A

Assessment (HErSEA)								
P4 Pinatubo Emulation in Multiple Models (PoEMS)	FWHIST	f09_f09_mg17, 70L	30	3	22,000	1,980	3.0	B
P6 QBOi	FWscHIST	f09_f09_mg17, 70L	10	20	6,100	1,220	6.0	A
P7 WACCM-X FR	FXHIST	f19_f19_mg17, 130L	1	54	12,000	648	1.0	A
P8 WACCM-X SD	FXSD	f19_f19_mg17, 148L	1	38	14,000	532	1.0	A
P9 GeoMIP SSP5-34	BWSSP534	f09_g17, 70L	1	61	28,000	1,708	3.7	B
P10 GeoMIP peak-shaving	BWSSP534	f09_g17, 70L	1	86	28,000	2,408	5.2	B
Development total						**16,192**	**71.3**	
Production total						**19,756**	**78.2**	
Total						**35,948**	**149.5**	

Cost estimates	Configuration	Resolution, vertical levels	core-hours per simulated year
	BWmaHIST	f19_g17, 70L	3,300
	BWSSP245	f09_g17, 70L	28,000
	BWSSP534	f09_g17, 70L	28,000
	FW2000climo	f09_f09_mg17, 70L	22,000
	FWHIST	f09_f09_mg17, 110L	22,000
	FWscHIST	f09_f09_mg17, 70L	6,100
	FWscHIST	f09_f09_mg17, 110L	8,540
	FWSD	f19_f19_mg16, 88L	5,130
	FWSD	f09_f09_mg17, 88L	23,000
	FX2000climo	f09_f09_mg17, 130L	150,000
	FX2000climo	ne30, 130L	300,000
	FXHIST	f19_f19_mg17, 130L	12,000
	FXSD	f19_f19_mg17, 148L	14,000

Community Projects

C1. Transient Holocene (11.4 M core-hours): The transient Holocene simulation will provide model data to the CESM community to more fully explore multidecadal and longer variability and rapid transitions of, for example: ENSO and other modes of climate variability; monsoons and droughts; the Atlantic meridional overturning circulation; and tropical/extratropical linkages, all in comparison to numerous proxy records. These simulations will include not only the transient orbital, GHG, and ice-sheet reconstructed forcings but also now new reconstructions of solar variability, explosive volcanic events, and land cover during the Holocene. This unprecedented simulation covering the period from 9000 years ago until the beginning of the last millennium simulation (850 AD) – for a total of 8150 years – will be run with the CESM2.1 FV2x1 model version where the atmospheric and ocean models have 2° and nominal 1° horizontal resolutions, respectively. This simulation was included as a community simulation in the last CESM CSL allocation request but needed to be deferred due to the postponed release of CESM2. Our preliminary cost estimate for this model version is 1400 core-hours per simulation year, resulting in 8150 years x 1400 core-hours per year = 11.4 M core-hours. Requested by PaleoWG and LIWG with AMWG and WAWG interests in the behavior of the FV2 model version.

C2. High-resolution ocean (POP) with biogeochemistry (BGC) (15.0 M core-hours): Performing a hindcast eddy-resolving (0.1°) ocean simulation with BGC remains a high-priority. This is a frontier modeling capability and only a few such integrations have been conducted worldwide. Work over the last two years focused on improving ocean forcing data sets, and wind stress calculations at ocean boundaries has the potential to help address known biases in coastal upwelling affecting the BGC simulations. A broad community of researchers has interest in these integrations. The model will use MARBL (Marine Biogeochemistry Library) and will be forced with the newly developed JRA55 inter-annually varying atmospheric data sets based on the Japanese Meteorological Agency Reanalysis Product. The computational cost of this simulation depends strongly on the frequency and quantity of output data. Making judicious choices, we anticipate reducing the cost of the simulation to approximately 300,000 core-hours per simulation year with a storage requirement of about 2.2 TB per simulation year. The hindcast simulation will be performed for the 50-year period from 1967 – 2016, initialized from existing simulations. Note that this experiment was proposed as a community project in the previous allocation cycle, but the community resources were re-directed to CESM2 base model development by the CESM management. The estimated cost is 50 years x 300,000 core-hours per year = 15 M core-hours. Requested by OMWG, PCWG, and BGCWG; directly feeds in to the world-wide ocean modeling community and the activities / efforts of the International CLIVAR Ocean Model Development Panel (OMDP).

C3. Subseasonal-to-seasonal (S2S) hindcasts (2.8 M core-hours): S2S hindcasts for years 1999 - 2018 will be carried out following the Subseasonal Experiment (SubX) protocol. 10-member ensemble hindcasts will be initiated every Wednesday from March to mid-October and run for 45 days each. These experiments compliment the Northern

Hemisphere cold-season simulations proposed in the AMWG request as set P3. Atmosphere will be initialized using ERA-Interim reanalysis and random field perturbation method. The ocean and sea ice initial conditions will come from a forced ocean – sea-ice simulation forced with the new JRA55 atmospheric data sets. Land will be initialized using states from simulations forced with 6-hourly precipitation, temperature, specific humidity, wind speed, lowest atmospheric level pressure, and incoming longwave and shortwave radiation from the Climate Research Unit- National Centers for Environmental Prediction joint dataset (CRU-NCEP). The same hindcast set has already been carried out with CESM1. Comparison of hindcasts with CESM2 to CESM1 will allow for the characterization in changes in model skill coming strictly from the new model physics in CESM2. The analysis will focus on simulation skill of weeks 3 to 6 surface temperature and precipitation as well as the skill of the Madden-Julian Oscillation, which is improved in climate simulations with CESM2 as compared to CESM1. Additionally, flow-dependent subseasonal predictability will be assessed by comparing the forecast skill of forecasts projecting at initial time on low-frequency regimes such as the North-Atlantic Oscillation (NAO) and Pacific North American Pattern (PNA) to those which do not. The simulations will use the CESM2 nominal 1° model version. The estimated cost is 32 weekly starts x (45 days / 365 days) x 10 members x 20 years x 3500 core-hours per year = 2.8 M core-hours. Requested by AMWG with interests from OMWG and PCWG; directly complimenting the national SubX efforts.

C4. <u>CESM2 with RCP8.5 projections (6.3 M core-hours):</u> CESM2 has considerable changes relative to the CESM1 model. In order to understand these changes and their impact on climate variability and change, simulations are needed with identical forcing for the 20th and 21st centuries. Given this, we propose an ensemble set of historical and future projections that apply the same forcing as in the CESM-LE configuration. A frustration between rounds of CMIP has been that the forcing scenarios change each time, making it hard to impossible to assess the projection differences between CMIPs that are due to model changes versus forcing changes. To overcome this challenge, we propose experiments with a 10-member ensemble of CESM2 simulations for the 1920-2100 period, forced by the same historical forcing as the CESM-LE and the RCP8.5 projection scenario. This will allow us to compare the historical and projected climate change under RCP8.5 with the projected climate change in the standard CMIP6 runs with the CESM2 using SSP5-8.5 and SSP3-7.0. Given the huge success and wide use of the CESM LE project, having the opportunity to establish how the CESM2 projections differ from the CESM LE projections will be very beneficial to a large community of scientists. We anticipate that these simulations will be widely used to benchmark the projections of many climate variables under the changed forcing scenarios. This proposed set of simulations will benefit many CESM working groups, as they move into analyzing and interpreting the new CESM2 simulations. These simulations will use the CESM2 nominal 1° model version. The estimated cost is 10 ensemble members x 181 years x 3500 core-hours per year = 6.3 M core-hours. Requested by PCWG with significant interests from CVCWG and AMWG.

C5. Development of a CESM Arctic Prediction System (CAPS) (7.8 M core-hours): CESM is uniquely placed to advance understanding processes and predictability of polar regions. Arctic climate change is accelerating access to the region, requiring better prediction for safe use. Improving process-level understanding spans a range of components and disciplines, including not just meteorology and climate broadly, but land surface, biogeochemistry, the cryosphere (including snow, ice sheets and sea ice) and the ocean. Predictability on scales from sub-seasonal to seasonal (S2S) out to decadal and centennial requires a high resolution coupled system. CESM2 with a refined mesh atmosphere at high resolution (7-15 km) can be coupled to high resolution (0.1° ocean and sea ice, ~10 km land, land ice, and rivers) to represent the detailed structure of topography, vegetation, sea and land ice, and oceans in a global framework to enable predictability and a better understanding of the coupled processes in the Arctic. Because of allocation restrictions, however, we are proposing to do these initial tests and development efforts with a 1° ocean including BGC. Here, we propose a development process to start simulations over year 1 to develop and test a system using other allocations, and in year 2 to do historical (and possibly future) simulations from 1980-present, as well as some nudged simulations (with controlled atmosphere dynamics) from 1980 or 1990-present. We will have an option to do either two historical ensemble members or a future *prediction* (not initialized, free running) to 2050. This request is essentially for the start of a larger development of a coupled prediction system for the Arctic (tentatively called CAPS) that would involve high resolution prediction with initialized forecasts when a more unified system is ready. It is consistent with NSF's 10 big ideas (Navigating the New Arctic) as well as an initial step developing a configuration (with full initialization/assimilation) that is a frontier science focus of the unified atmosphere model system ('Singletrack'). Requested by AMWG, LIWG, LMWG, and PCWG.

Cost estimate:

CAM6 atmosphere, SE refined mesh 14 km, Continental U.S. (CONUS) = 39 K core-hours per year. Our estimate is that Arctic version would be 1.5x Continental U.S. area, requiring about 60K core-hours per year. Fully coupled version would cost about 62 K core-hours per year. Nudged runs would be similar cost.

Simulations:

Development and testing (20 years coupled, 5 years nudged): 25 yrs

Two coupled (uninitialized) simulations – either 2 ensemble members of 1980-2015 simulation or one 1980-2015 and one 2016-2050 simulation: about 70 years

Historical nudged simulation (1985-2015): Coupled, atmosphere nudged from 600-100 hPa to MERRA2….. 30 years

Total = 125 years x 62 000 core-hours per years = 7.8 M core-hours.