Supplementary Material

This supplement presents the complete list of experiments and their associated cost. We provide here the description from each Working Group and for the selected Community Projects. Except where noted, all core-hours numbers are provided as Cheyenne core-hours.

Atmosphere Model Working Group (AMWG)

1. ***Broad Overview of Working Group and Research Plan***

The Atmosphere Model Working Group 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 is also covers sensitivity experiments aimed at understanding the many interactions among the represented physical and dynamical processes across climate regimes and multiple timescales.

CAM6 will be released as part of CESM2. Recent CSL resources were used to comprehensively test the parameterizations and dynamical developments in this model to make ready for coupling with surface components and use by the community, primarily in CMIP6 experiments. Resources requested here will be used to address somewhat broader science goals than pure model development. Firstly, shortcomings remain in CAM6, some of which have already been identified and CSL resources will be used in order to determine the role of particular physical and dynamical processes and enable potential remedies. Examples of potential model shortcomings include biases in shallow and stable boundary layers, poorly located surface flow and precipitation in, and flow around, orography. Parameterized processed play a role in many of these biases and given the comprehensive representation of most of the moist processes in CAM, the recently included Cloud Layers Unified By Binormals (CLUBB, Bogenschutz et al., 2013) scheme will be central to addressing many of these biases.

The AMWG will be making a more concerted effort to advance high resolution (both horizontal and vertical) and regional modeling capabilities through this CSL cycle. It will take the form of both improved global uniform high-resolution simulations, and regional refinement capabilities with a global configuration available through both the Spectral Element (SE) and Model Prediction Across Scales (MPAS) dynamical cores. This will inevitably require research with the existing CAM6 and future physical parameterizations in order to make them scale aware. Properties of scale-awareness enable schemes to work consistently between global high- and low-resolution grids and within regionally refined simulations where grid scales can vary by up to an order of magnitude.

There will be an enhanced investment of resources in model assessment and validation through more non-standard techniques. This includes the Cloud Associated Parameterization Testbed (CAPT) hindcast framework, idealized model testing and nudging capabilities. AMWG will also continue to need more production-type dedicated resources to evaluate model developments in more standardized (often CMIP-type) configurations, both for formal comparisons with previous model versions and for readiness of new configuration with the whole coupled system.

2. ***Development Proposal*** (29.3M core-hours)

a. Goals

The main goals for development resources are three-fold. First, to further understand the role of the parameterized physics in CAM6 shortcomings, and to advance existing or develop new parameterizations for newer model versions. Second, to advance model configurations for higher horizontal (<=25 km) and vertical (>32 levels) resolution and for, raising the model top (currently at 3 mb). With these increases in resolution and domain extent a parallel effort is needed to understand the sensitivities with the existing CAM6 dynamics and physics, but also to develop new scale-aware capabilities for processes across the wide range of supported atmosphere models in CESM. Thirdly, a number of disparate and unorganized model evaluation techniques already exits within mostly CAM infrastructure. The target with these tools is to organize them much more cleanly within the CESM workflow. This will allow CAPT and dy-core tests to then be used in a more impactful and timely ways to assess model changes and developments.

b. Specific simulations and computational requirements

(D1) CAM6 climate investigation (1.7M Year, 1.2M Year2)

These simulations are intended to deepen our understanding of the nascent CAM6 climate from the CESM CMIP6 experiments at predominantly low resolution (100 km grid scale). The findings from these experiments will help us to address existing model biases and uncover and address new biases. Outstanding biases in CAM6 include many features important to both the atmosphere and the coupled system as a whole. Recognized errors exist in cloud representation such as multi-environment stratiform-topped stable boundary layers and stratiform-cumulus transition regions and orographic precipitation features. These biases will be a primary focus since a central role is now being played by CLUBB, the most recent and extensive moist physics to be incorporated in CAM6. *Resource use is expected to be greatest in year 1 due to timely efforts for CMIP6 then ramp down in year 2. Year 2 a more limited set of experiments will be run.*

(D2) CAM physics development (2.9M year1, 4.8M Year2)

CAM6 was a major advancement in the representation of physical processes in the atmosphere model. Although this was a comprehensive updating of the physics, impactful parameterization is still expected to occur within this CSL cycle. The primary research activity is expected to be on the representation of deep convective processes. The existing Zhang-McFarlane 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 continuing to advance the UNICON (Unified Convection, Park 2014) scheme will be performed. The final approach will be to remove the separate scheme entirely and allow CLUBB to represent all moist turbulence. As part of both the extension of CLUBB and to facilitate its capability across model resolution a sub-column capability will be investigated and fully implemented. Simulations will also be performed for incremental improvements to the Morrison Gettelman (MG) microphysics, encompassing modifications from high-resolution, forecast-based versions of the scheme, and to continued improvements of the Beljaars surface drag modifications included in CAM6. Finally, the CFMIP Cloud Simulator Package (COSP, Bodas-Salcedo et al., 2011) will be updated to the most recent version, with bug fixes and instrument forward model improvements. This package will be used in a limited set of development simulations.

While there will be some limited development simulations with the Finite Volume (FV) dy-core for comparison with existing CMIP6 configurations, we intend to transition to Spectral Element (SE) dy-core simulations as FV is no longer actively supported, and SE computational cost and throughput are now within acceptable limits. The added resources that Cheyenne provides will allow us to extend the simulation lengths that have been used in the past to enable more robust signals of climate changes with each proposed model development. *Year 1 initial development of individual schemes, particularly those readily available (CLUBB/Beljaars). Year 2 move forward with year-1 developments to improve simulated climate.*

(D3) Dynamical core testing and adoption (1.9M Year 1, 1.9M Year 2)
Recent efforts in transitioning CAM to a more advanced dynamical core option have focused on the spectral element (SE), cubed sphere core. There is however expected to be opportunities to consider additional cores for future inclusion in CESM (model for prediction across scales: MPAS, and finite volume cubed sphere: FV3). The scientific priority for the AMWG is to provide a work horse model, at low resolution (currently 1 deg and 32 vertical levels) for use by the wider community. Therefore to adopt new dynamical cores a multi-metric assessment has to be performed with the new cores coupled to the CAM physics package. Primarily these will include like-for-like comparisons in different climate configurations such as AMIP, multi-century fully coupled pre-industrial climate experiments, and slab-ocean experiments. Such an analysis has previously revealed an unexpected sensitivity to dynamical core differences (using SE instead of FV) in fully coupled experiments that proved difficult to resolve. Therefore, these tests are crucial if an alternative dynamical core is to be adopted. The assessment will also include tests of the scaling, computational cost and throughput with each dynamical core.

Ongoing efforts to implement a separable physics and dynamics grid will be continued with simulations to demonstrate capability (potentially with the newer alternative dynamical cores) and to provide recommendations for future use. In concert with this capability the Conservative Semi-Lagrangian Multi-Tracer scheme (CSLAM) will be further tested and investigated to improve computation and solution performance. This is crucial as the number of advected tracers continues to increase, particular for advanced chemistry applications.

The MPAS and FV3 cores currently have a non-hydrostatic solution capability, in contrast to the existing FV and SE dynamical cores (SE non-hydrostatic is in development). This will allow a more accurate representation of vertical motions as we approach the hydrostatic limit beyond approximately 10-km horizontal resolution. Exploratory simulations will be performed within this resolution range in order to examine the suitable of the existing physical parameterizations. *Year 1, full implementation and testing of MPAS/SE with shorter test simulations. Year-2 implementation of FV3 and climate testing with all cores.*

(D4) Advancing CAM high-resolution climate (5.0M year 1, 4.0M year 2)
Global horizontal resolution (25-km grid spacing or finer) simulations pose significant challenges due to high computational cost and the poor performance of the physical parameterization when translated from low-resolution configurations (Bacmeister et al., 2104). However, there is a need to provide a tuned version of the global high-resolution model for certain applications (e.g., the CMIP6 HighResMIP contribution), and as a tool for testing the representativeness or scale-awareness of individual parameterizations across global uniform resolutions. A limited set of simulations will be needed to test parameterization response globally and to validate response seen in the regional refined model.

Vertical resolution increases (and an elevated model top) were not included in default version of the CAM6 model due to computational concerns. However, CAM is becoming increasingly limited and dated by the presence of just 32 vertical levels. Therefore, simulations will examine an increase in vertical resolution with the aim of finding a compromise between cost, level/lid placement and level numbers. This development will build on 60- and 46-level versions originally proposed for inclusion in CAM (Richter et al., 2014). It will require a significant effort to understand the response of the parameterized physics to these changes as, in some cases large sensitivities are expected to emerge. *Year 1, progress can be made on investigating the optimal vertical level distribution and lid position, with high-resolution sensitivity testing. Year 2 will investigate final vertical resolution configurations and perform benchmark high horizontal resolution simulations.*

(D5) Regionally refined capability (2.1M year 1, 4.1M year 2)
The regional refinement capability in CAM-SE (although it will also be available as part of CAM-MPAS) has been advanced as a more economical framework to investigate high–resolution regional climate problems within a global domain (e.g., Zarzycki et al., 2015). Phenomena of interest continue to be the simulation of tropical cyclone statistics, particularly in the North Atlantic, central US meso-scale convective organization and tropics. *In year 1 the standard grid locations and configurations will be testing for option within the CESM scripts. Year 2 will see more research problems with regional refinement being used with traditional hydrostatic dynamical core and parameterization representations, in addition to investigating non-hydrostatic scale problems available in MPAS and possibly FV3.*

(D6) Alternative model development testbeds (1.0M year 1, 2M year 2.1)
Alternative techniques for model validation, testing and analysis continue to be advanced within CAM and CESM. Chief among these are the Cloud Associated Parameterization Testbed (CAPT) multi-hindcast framework and the suite of simpler model configurations (including dy-core tests, radiative convective equilibrium frameworks and aqua-planets). CAPT is an increasingly important tool for model development and validation as increasing resolution and increasing physics computational costs combine to make standard long climate simulations, the core of low-resolution model testing, prohibitively expensive. Our simulations activity with CAPT configurations will have two main tasks. The existing research activity aimed at understanding the role of parameterizations in model biases, without the challenge of understanding equilibrium solutions in traditional climate simulations, will be continued and expanded. Resources will also be used to examine additional configuration sensitivities associated with initialization (choice of analysis product, including DART), dynamical core and the role of nudging for hindcast initialization. Output data variables are non-standard, but volumes are expected to be approximately the same as for an equivalent length AMIP simulation. *For year 1 dy-core configurations will continue to be tested and CAM6 configuration examined through CAPT 5-day forecasts. In year 2, CAPT will be applied to assess individual model developments in a more real-time manner.*

3. ***Production Proposal*** (16M core-hours)

a. Goals
Further, production-type experiments will be run to examine specific mean climate features and the major modes of atmospheric variability in order to understand the sensitivities as it relates to the representations of individual processes and the role the physical and dynamical process interactions play. This analysis will be enhanced by contrasting the findings with previous model versions (CAM5, CAM5.5) and perturbation model configurations (e.g., different dynamical cores). *Year 1, it is expected benchmarking simulations will mostly be AMIP. In Year 2, further AMIP with control and historical coupled simulations will be performed.*

b. Specific simulations and computational requirements

(P1) Validation of milestone configurations (2.0M year 1, 4.0M year 2)
Core CAM development will be of a lower level than the lead up to the CESM2 release, but there will be a need to perform a number of milestone CMIP-type experiments to provide a new incremental baseline for contrasting of performance against CAM6. Most likely, baselines will be required when major modifications are made to CLUBB, including the representation of stable boundary layers, and its adoption for the calculation of deep convection. Baselines will also be needed to investigate vertical resolution increases that will be of order two times more expensive than the default model version. Most simulations will be of either AMIP or pre-industrial control simulations. *Year-1 simulations will be limited as resolution*

and physics developments begin. In year 2 configurations will mature that require production runs for validation.

(P2) Comparison of Climate Simulations with Alternative Dynamical Cores (1.0M year 1, 2.7M year 2)
The development efforts to make existing and proposed dynamical core consistent within the CESM framework will require standardized experiments for comparisons using CAM6 and the contemporary versions of the surface components. This will include AMIP-type, CAPT initialized and fully coupled pre-industrial control configurations. Comparisons will enable verification with observational and previous dynamical core (FV) CAM6 benchmarks. The results form the main basis for how to move forward with dynamical cores in CAM for the broad range of applications in the coming years. *Year 1 will have a limited number of longer simulations for dy-core climate validation. Year 2 will increase validation through increased pre-industrial coupled simulations.*

(P3) Seasonal Forecasting (1.0M year 1, 1.0M year 2)
Recent changes to CAM's orographic drag parameterizations have resulted in improved simulations of climatological sea-level pressure and surface wind stress. Stratospheric climate simulations in WACCM have also improved with the new orographic drag schemes. We have also seen improvements in 5-day forecasts conducted with CAM using the CAPT framework. We would like to explore the impact of both orographic drag parameterizations and better representation of the stratospheric circulation on intra-seasonal to seasonal forecasts. We will conduct these studies using the standard 32-level CAM as well as a 46-level configuration with a higher model top and reasonable stratospheric climatology. The runs to be performed will include 1-deg atmosphere-only, 60-day forecasts initialized from re-analyses and may be extended to incorporate initialized coupled forecasts. *Year 1 will focus on scoping experiments using possible model configurations, and testing and decision-making regarding experiment designs. Year 2, simulations with a more production focus will be run.*

(P4) Decade-length Hindcast Experiments (1.1M Year 1, 3M Year 2)
As CAPT hindcast simulations are increasingly crucial for the development, testing and validation of physical parameterizations, there is also an increasing desire to demonstrate the actual intra-seasonal prediction capabilities of CAM within this lower cost simplified framework. This will be used to demonstrate the sources of intraseasona skill as a function of modes of variability that occur on these timescales, such as the Madden Julian Oscilliation (MJO), mid-latitude atmospheric blocking and the North Atlantic Oscillation (NAO). Hindcasts will consist of 10-day simulations initialized everyday for approximately one year with CAM6 SE. This simulation set has been performed by GFDL and so would represent an invaluable experiment set for a side-by-side comparison. *In year 1 we will begin the decade-long simulations at low resolution. These will continue into year 2, with a shorter equivalent experiment set at higher (25 km/ne120) resolution.*

References

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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	F2000	fv0.9	50	5	2920	730	3.03	A
D1	F2000	se30	50	5	3800	950	3.03	B
D2	F2000	se30	150	5	3800	2850	9.1	B
D3	F2000(MPAS)	1 deg equiv	20	5	4940	494	1.21	B
D3	F2000(FV3)	1 deg equiv	20	5	4500	450	1.21	B
D3	F2000	ne30	50	5	3800	950	3.03	A
D4	F2000	ne120	10	5	80000	4000	9.7	A
D4	F2000	ne30_L60	25	5	7600	950	3.03	B
D5	F2000	ne30r_ne120	50	3	13680	2105	3.28	C
D6	FAMIP	ne30	12	5	3800	228	0.73	C
D6	FAMIP	ne120	2	5	80000	800	1.94	C
Total Y1						14507	39.29	
Year 2								
D1	F2000	fv0.9	20	5	2920	292	1.21	B
D1	F2000	se30	50	5	3800	950	3.03	A
D2	F2000	se30	250	5	3800	1520	15.16	A
D3	F2000(MPAS)	1 deg equiv	20	5	4940	494	1.21	A
D3	F2000(FV3)	1 deg equiv	20	5	4940	494	1.21	A
D3	F2000	ne30	50	5	3800	950	3.03	B
D4	F2000	ne120	8	5	80000	3200	7.76	C
D4	F2000	n30_L60	20	5	7600	760	2.43	C
D5	F2000	ne30_ne120	60	5	13680	4104	58.23	B
D6	FAMIP	ne30	25	5	3800	475	1.52	B
D6	FAMIP	ne120	4	5	80000	1600	3.88	B
Total y2						14839	98.67	
Total Dev.						29346		
Production								
Year 1								
P1	FAMIP	ne30	6	27	3800	616	1.96	A
P1	B1850	ne30_gx1v6	3	100	4500	1350	15.14	B
P2	FAMIP	ne30	3	27	3800	308	0.98	A
P2	B1850	ne30_gx1v6	3	50	4500	675	7.57	A
P3	FAMIP	ne30	50	5	3800	950	3.03	C
P4	FAMIP	ne30	3	100	3800	1140	3.64	C
Total Y1						5039	32.32	
Year2								
P1	FAMIP	ne30	5	27	3800	513	1.64	B
P1	B1850	ne30_gx1v6	3	100	4500	1350	15.14	A
P1	BHIST	ne30_gx1v6	3	160	4500	2160	24.22	A
P2	B1850	ne30_gx1v6	6	100	4500	2700	32.67	B
P3	FAMIP	ne30	50	5	3800	950	3.03	C
P4	FAMIP	ne30	4	100	3800	1520	4.85	B
P4	FAMIP	ne120	1	20	80000	1600	3.88	
Total Y2						10793	85.43	
Total Prod.						15832		
Total						**45178**	255.71	

Biogeochemistry Working Group (BGCWG)

1. Broad Overview and Research Plan

The goal of the biogeochemistry working group 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 magnitude 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 affect 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 (18.1 M core-hours)

    a. Goals

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

- continued development of the Newton-Krylov fast spin-up technique
- continued development of biogeochemical parameterizations
- porting of MARBL software engineering framework to other GCMs
- regional simulations with MARBL in MPAS-O
- coupling across components and understanding interactions

b. Specific simulations and computational requirements

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 solvers, are currently being applied successfully to ocean tracers with simple dynamics, 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.

Ocean biogeochemistry development is ongoing and we will dedicate some of our computational resources to support this. Examples of processes that we will focus our efforts on are: feedbacks of ocean acidification onto biogeochemical processes (formation and dissolution of $CaCO_3$) and incorporation of processes related to the methane and sulfur cycles. This development work naturally separates into shorter runs focused on near-surface ecosystem dynamics and longer runs focused on deeper processes that have longer time-scales. In the past, ocean ecosystem parameters have been determined by evaluating parameter perturbation experiments, where the parameter values have been selected by expert judgment. We will explore applying automated parameter optimization strategies to this process.

The developments described above will be carried out within the MARBL framework that has been developed with previous CSL allocations. As part of the development of MARBL, we will couple it to the MPAS-O ocean model, performing numerous validation experiments. We will perform a standard ocean-ice hindcast experiment, in order to evaluate how our ocean biogeochemistry model performs in a standardized experiment with a different ocean GCM. A key feature of MPAS-O is its ability to run with a regionally refined grid. We aim to perform experiments with MARBL in MPAS-O in a configuration with grid refinement in the vicinity of the California current, evaluating how our ocean biogeochemistry model performs in this well-observed region.

A goal of CESM is to include enhanced coupled between the biogeochemistry parameterizations in the land and ocean to the chemistry parameterizations in the atmosphere. We will conduct experiments where we consider: enhanced coupling of the nitrogen cycle, a full methane cycle, prognostic DMS emissions from the ocean. While most of these experiments will be production runs, development work is necessary to evaluate model configurations.

3. Production Proposal (14.98 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:

- Additional fully coupled carbon cycle sensitivity experiments with CESM1.2(BGC)
- New spin-ups of ocean biogeochemistry for CMIP6 experiments
- CMIP6 Tier2 experiments
- Additional fully coupled carbon cycle sensitivity experiments

    b. Specific simulations and computational requirements

In our previous CSL computing allocation, we performed coupled carbon-climate experiments with CESM1.2(BGC), evaluating how model developments that occurred after CESM1 impact the land and ocean carbon cycles, their mean state, seasonal cycle, variability and response to transient forcing. We propose to perform additional experiments with this version of the model to evaluate how these developments impact the carbon-climate feedbacks of this version of the model.

Ocean BGC will need to be spun up to generate initial conditions for coupled and ocean-ice CMIP6 experiments. Both spin-ups will be done in a less costly ocean-ice configuration. We will be able to begin these experiments once the CMIP6 version of CESM is finalized. These runs are done with reduced frequency output.

In order to participate fully in CMIP6, we will be performing Tier 2 experiments for C4MIP and OMIP. The C4MIP Tier experiments consist of additional CO2 1% ramping experiments to evaluate carbon-climate feedbacks, and a CO_2 concentration driven experiment out to 2300. As we have previously done, we will augment the 1% experiments with an additional experiment where land CO2 is fixed, enabling us to more cleanly evaluate ocean uptake in a constant climate scenario.

As described above, we will conduct experiments with enhanced coupling between biogeochemistry and atmospheric chemistry. Once the coupling has been performed and tested, we will conduct a multi-century 1850 control run and a 1850-2100 transient simulation, to explore how these couplings co-evolve with a changing climate.

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

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								
Newton-Krylov	GECO	T62_g16	100	10	500	500	0	A
BEC Dev	GECO	T62_g16	50	25	500	625	50	A
BEC Dev	GECO	T62_g16	10	250	500	1250	100	B
Param Optim	GECO	T62_g16	100	10	500	500	0	B
MARBL MPAS dev	G MPAS	MPAS lo-res	25	25	3000	1875	37.5	.5A, .5B
MARBL MPAS hindcast	G MPAS	MPAS lo-res	1	310	3000	930	18.6	B
MPAS in other GCMs			10	25	500	125	15	
BGC-Chem Dev	B+Chem	f09_g16	10	20	8500	1700	12	.5B, .5C
Misc. Sensitivity	B	f09_g16	3	150	3000	1350	22.5	.5B, .5C
Development Year 1 Total						8855	255.6	
Development, Year 2								
Newton-Krylov	GECO	T62_g16	100	10	500	500	0	A
BEC Dev	GECO	T62_g16	50	25	500	625	50	A
BEC Dev	GECO	T62_g16	10	250	500	1250	100	B
Param Optim	GECO	T62_g16	100	10	500	500	0	B
MARBL MPAS hindcast	G MPAS	MPAS lo-res	2	310	3000	1860	37.2	B
MARBL MPAS hi-res	G MPAS	MPAS calif current	2	15	100000	3000	15	B
MPAS in other GCMs			15	25	500	187.5	15	
Misc. Sensitivity	B	f09_g16	3	150	3000	1350	22.5	.5B, .5C
Development Year 2 Total						9272.5	239.7	
Production, Year 1								
Sensitivity Experiments	B, CESM1.2(BGC)	f09_g16	2	250	2000	1000	20	.5 A, .5 C
C4MIP Tier 2 1% runs	B	f09_g16	3	140	3000	1260	21	A
C4MIP Tier2 1850-2300	B	f09_g16	1	450	3000	1350	22.5	A
CESM2 Ocean spin-up	GECO	f09_g16	1	3000	500	1500	0	A
OMIP Tier 2 spin-up	GECO	f09_g16	1	3000	500	1500	0	A
OMIP Tier 2	GECO	f09_g16	1	310	500	155	12.4	A
Production Year 1 Total						6765	75.9	
Production, Year 2								
Additional 1% runs	B	f09_g16	2	140	3000	840	14	A
BGC-Chem Control	B+Chem	f09_g16	1	300	8500	2550	18	.5B, .5C
BGC-Chem Transient	B+Chem	f09_g16	1	250	8500	2125	15	.5B, .5C
Misc. Sensitivity	B	f09_g16	6	150	3000	2700	45	.5B, .5C
Production Year 2 Total						8215	92	

Chemistry-Climate Working Group (CHWG)

1. Broad Overview of Working Group and Research Plan

The goal of the Chemistry-Climate Working Group (CHWG) is to continue development of the representation of chemistry and aerosols in the 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, to understand the role of climate change on tropospheric composition and changes in ozone in the lower stratosphere.

The representation of tropospheric chemistry and aerosols continues to be developed and improved in CESM by the CHWG. Inorganic nitrate aerosols are being 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. The formation and removal of secondary organic aerosols (SOA) will continue to be developed and evaluated as CESM evolves and more observational data sets from recent field campaigns become available. CAM-chem is a valuable tool for the interpretation of observations, and simulations with the improved nitrate and SOA schemes will be used to analyze recent campaigns. The previously developed very short-lived (VSL) organic halogen chemical mechanism will be used in model evaluations with field campaigns over remote oceans. The coupling of biogenic and fire emissions of chemical compounds and aerosols generated in the land model to the chemistry in the atmosphere will be evaluated and further developed in CESM2. The spectral element and MPAS dynamical models will provide valuable opportunities to study atmospheric chemistry, air quality and climate interactions on regional and local scales, and provide interpretation of field campaigns. As soon as large numbers of tracers can be transported efficiently in these models, the detailed tropospheric chemistry schemes will be tested in them.

The CHWG will work with the Whole Atmosphere Working Group to perform the community simulations for DECK and CMIP6 and plan to provide simulations from a single model combining the full altitude range of WACCM with the full tropospheric and stratospheric chemistry scheme of CAM-chem. CAM-chem simulations will continue to be provided for other international model intercomparison and assessment activities, such as the WMO 2018 ozone assessment.

2. Development Proposal (5.9M core hours)
    a. Goals

The CHWG Development allocation will be used to refine and evaluate expanded tropospheric chemistry and aerosol representations, including more detailed isoprene and terpene oxidation schemes, secondary organic aerosol formation, and inorganic nitrate aerosols. The algorithms for vertically distributing gases and aerosols from fire emissions will be computationally optimized while providing realistic results, as evaluated with satellite and in situ observations. The MEGAN (Model of Emissions of Gases and Aerosols from Nature) emissions model, already included in CLM, continues to be developed to account for drought and other stresses on biogenic emissions and these will be incorporated and evaluated in CESM. CESM will be run in free-running and specified dynamics modes to evaluate the modeled chemical composition at higher resolutions, with new dynamics parameterizations and new dynamical cores.

b. Specific simulations and computational requirements

(D1) <u>Nitrate aerosol evaluation with specified dynamics</u>
To evaluate simulations of nitrate aerosols with aircraft and ground-based observations, CAM5-chem will be run at 1-degree resolution in specified dynamics (SD) mode with full tropospheric chemistry and MAM4. Comparisons of runs with and without nitrate aerosols will be made covering time periods of field campaigns (e.g., 2004-2008, 2012-2016). (0.7M core-hrs; Year 1)

(D2) <u>Nitrate aerosol climate evaluation</u>
The climate impacts of the nitrate aerosols will be evaluated through simulations of F2000 configurations. Comparisons of simulations with and without nitrates of 10 years each, will be needed. (0.5M core-hrs; Year 1)

(D3) <u>SOA-VBS testing and evaluation</u>
The VBS representation for SOA in high and low NOx conditions, further extensions to isoprene oxidation chemistry and linking to SOA will continue to be tested and evaluated in CAM5-chem. The tuning of parameters in the SOA-VBS framework will be performed with CAM5-chem at 2-degree resolution. Free-running climate simulations of 30-years each will be needed to account for interannual variability. (0.5M core-hrs; Year 1)

(D4) <u>CLM fire emissions and vertical distribution testing</u>
The vertical distribution of fire emissions, produced by CLM, will be tested and evaluated in CAM-chem. Five runs of 10 years each, CAM5-chem-SD to test various vertical distribution parameterizations of fire emissions produced in CLM, and to evaluate with satellite and aircraft observations. (0.8M core-hrs; Year 1)

(D5) <u>CAM-chem SD high resolution tuning</u>
CAM-chem with specified dynamics will be tested at 0.5-degree and 0.25-degree resolutions, driven by MERRA2 meteorology, and the tunings for lightning NO and dust emissions determined. An equivalent of five 1-year 0.5-degree simulations will be run. (0.4M core-hrs; Year 1)

(D6) <u>CESM2 with interactive fires</u>

CESM2, with CLM fire emissions coupled to the atmosphere, SOA-VBS formation and nitrate aerosols, will be run for 40 years at 1850 conditions for tuning. (0.5M core-hrs; Year 2)

(D7) Evaluate chemistry in CESM2 with new dynamics
The new dynamics parameterizations in CAM6, such as CLUBB-Deep, will be evaluated in CAM6-chem, with 1-degree simulations, 10 years each. (1.0M core-hrs; Year 2)

(D8) CLM-MEGAN-v3 biogenic emissions testing
The MEGAN biogenic emissions (in CLM) will be improved and adapted to the Ecosystem Demography representation in CLM (in collaboration with Alex Guenther, UCI). CAM-chem at 1-degree resolution, in specified dynamics and free-running climate configurations, will be tested with new versions of MEGAN. (1.3M core-hrs; Year 2)

(D9) Test chemistry in spectral element model with CSLAM and CESM-MPAS
The next generation dynamical cores, Spectral Element/CSLAM and CESM-MPAS, will tested with full tropospheric-stratospheric chemistry and evaluated against finite volume simulations and observations. 10-year simulations will be used to verify performance. (0.2M core-hrs; Year 2)

3. Production Proposal (8.1M core-hours)
    a. Goals

The CHWG Production allocation will be used to contribute to the WMO ozone assessment, as well as a variety of studies on air quality and interpretation of field campaigns. The impact of model resolution and chemical complexity, as well as climate impacts, on air quality, will be examined. The impact of model resolution will also be studied in the context of the role of short-lived organic halogen compounds in tropospheric and lower stratospheric chemistry in comparison to aircraft field campaigns. The data assimilation experiments proposed here will be focused on interpretation of the recent KORUS-AQ aircraft campaign observations in S.Korea, and develop improved emissions inventories for East Asia. The impact of the new chemistry and aerosols, as well as the interactive fire emissions, will be studied in fully coupled simulations with CESM2.

    b. Specific simulations and computational requirements

(P1) CAM4-chem-CCMI for WMO2018
CAM-chem simulations will be performed for the WMO 2018 Ozone Assessment. Tropospheric sensitivity forcing experiments will be performed with CAM4-chem, using the CCMI REFC1 configuration: 3 ensemble members of 5 scenarios, for 60 years (900 sim-years). Emissions will be held fixed at 1980, as has already been run for CCMI REFC1SD cases. Each simulation will use the 1.9x2.5x66L CESM1(CAM4-chem)-CCMI with prescribed ocean and sea-ice. Three ensemble members of 5

scenarios, for 60 years each, will be run. The cost for this model was 750 core-hrs/sim-year on Yellowstone. (0.5M core-hrs; Year1)

(P2) Air quality simulations

The impact of resolution and chemical complexity on air quality over the U.S will be evaluated by the MIT (Selin & Brown-Steiner) group. This work examines the uncertainties associated with the choice of chemical mechanism, forced meteorology, and resolution on the ability of CESM to adequately simulate the surface chemistry of ozone and PM2.5 in the US. Simulations will use the MOZART-4, Reduced Hydrocarbon, Superfast, and BAM-Only chemical mechanisms in CAM4-chem. Simulations will be 10 - 20 years in length at 1.9x2.5 degree resolution using a specified meteorological product. (0.1M core-hours; Year 1)

(P3) VSL halogen simulations

The role of horizontal resolution on tropospheric transport and chemistry will be examined using the SD CESM1 (CAM4-Chem) model with very short-lived (VSL) halogen chemistry. Each scenario will be run from 1995-2016. There will be three different resolutions tested (i.e., ~0.5, ~1.0, and ~2.0). CAM4-chem with VSL halogen chemistry for 1995-2016, comparing horizontal resolutions in evaluations with aircraft campaigns. (1.1M core-hours; Year 1)

(P4) Field campaign analysis

Simulations for analysis of recent tropospheric composition campaigns (DC3, NOMADSS/SOAS, SEAC4RS, KORUS-AQ, ATom – 2012-2016). CAM5-chem with expanded tropospheric chemistry, SOA-VBS and nitrates, at 0.5 deg resolution. Short time periods (~2 months) will be run for various campaigns. (0.4M core-hrs; Year 1)

(P5) DART/CAM-chem for KORUS-AQ

The DART/CAM-Chem system was used for forecasting during the KORUS-AQ field campaign. The assimilation system will be rerun to estimate emissions for the period of the campaign (May-June 2016). The objective is to evaluate the impacts of increasing the spatial resolution from 1 degree to 0.5 degree while assimilating retrievals of carbon monoxide (CO) (MOPITT V7 profiles and IASI total columns) to characterize emissions from Korea versus inflow, as well as to quantify secondary pollutant (e.g., ozone) formation. The transport of pollutants at mid-latitudes, for example the impact of Asian emissions to the US background ozone, will also be studied. The higher spatial resolution will allow estimating NO_x emissions from NO_2 retrievals from the OMI instrument. The impact of reducing the localization length (extension of the spatial increments from one assimilation step) for the higher resolution simulation will be tested. DART/CAM4-chem-SD with assimilation of MOPITT and IASI CO; 30 ensemble members; 2-month simulations. 1 ensemble at 0.9x1.25x56L, 2 ensembles at 0.5x0.6x56L to test localization, 1 ensemble at 0.5x0.6x56L to include assimilation of OMI NO_2. (1.2M core-hrs; Year 1)

(P6) Climate impact on ozone

To assess the impact of background climate conditions on aerosol and ozone formation, CESM(CAM5)-chem, with fully coupled ocean, will be run with fixed emissions. Three cases will be run at 2-degree for 95 years (2006 to 2100). (0.7M core-hrs; Year 2)

(P7) CESM2 with nitrates, SOA, fires
Fully coupled CESM2 will be run for a transient simulation (1850-2010) with updated SOA, nitrate aerosol and interactive fires to evaluate climate impacts. (2.0M core-hours; Year 2)

(P8) VSL halogen PI vs PD
What is the role that VSL chlorine, bromine, and iodine species have on the ozone budget and climate from pre-industrial to present-day? The following scenarios will be for perpetual 1850 and 2000 conditions. Simulations based on these scenarios will be run in the SD mode. The meteorological fields will be taken from the reference perpetual 2000 simulation. Present-day vs pre-industrial simulations with VSL halogen chemistry. The model will be CESM1 (CAM4-Chem-VSL) run at 1-degree. There will be 7 scenarios for each period (1850 and 2000). Each scenario will be run for 10 years. (2.2M core-hours; Year 2)

Experiment	Configuration	Resolution	Number of runs	Number of years per run	Core-hours per simulated year (CH)	Total in thousands of core-hours	Total data volume (Tb)	Priority (A/B/C)
Development								
Year 1								
D1. Nitrate aerosol SD evaluation	FSD, CAM5-chem-TS1	0.9x1.25, 56 levels	6	5	23000	690	10	A
D2. Nitrate aerosol climate evaluation	F2000, CAM5-chem-TS1	0.9x1.25, 32 levels	4	10	12600	504	10	A
D3. SOA-VBS testing and evaluation	F, CAM5-chem-TS1	1.9x2.5, 32 levels	6	30	2500	450	10	A
D4. CLM fire emissions and vertical distribution testing	FSD, CAM5-chem-TS1	0.9x1.25, 56 levels	5	10	16400	820	15	A
D5. CAM-chem SD high resolution tuning	FSD, CAM-chem-TS1	0.5x0.6, 56 levels	5	1	82000	410	10	
Total Development Year 1						**2874**	**55**	
Year 2								
D6. CESM2 with interactive fires (1850)	B, CAM-chem	0.9x1.25, 32 levels	1	40	12500	500	10	A
D7. Evaluate chemistry in CESM2 with new dynamics	FSD, CAM6-chem-TS1	0.9x1.25, 56 levels	6	10	16400	984	20	A
D8. CLM-MEGAN-v3 biogenic emissions testing	FSD, CAM-chem-TS1	0.9x1.25, 56 levels	8	10	16400	1312	25	A
D9. Test chemistry in spectral element model with CSLAM and CESM-MPAS	F, CAM-chem-TS1	ne30np4	4	10	5560	222	5	A
Total Development Year 2						**3018**	**60**	
Total Development (2 years)						**5892**	**115**	
Production								
Year 1								
P1. CAM4-chem-CCMI for WMO2018	F, CAM4-chem-CCMI	1.9x2.5, 66 levels	15	60	615	554	10	A
P2. Air quality simulations	FSD, CAM4-chem	1.9x2.5, 56 levels	6	20	615	74	5	A
P3a. VSL halogen simulations	FSD, CAM4-chem-VSL	1.9x2.5, 56 levels	1	22	820	18		A
P3b. VSL halogen simulations	FSD, CAM4-chem-VSL	0.9x1.25, 56 levels	1	22	5000	110		A
P3c. VSL halogen simulations	FSD, CAM4-chem-VSL	0.5x0.6, 56 levels	1	5	25000	125		A
P3d. VSL halogen simulations	FSD, CAM4-chem-VSL	0.25x0.3, 56 levels	1	2	100000	200	15	B
P4. Field campaign analysis, ATom, KORUS	FSD, CAM5-chem-TS1	0.5x0.6, 56 levels	12	0.4	82000	394	10	A
P5. DART/CAM-chem for KORUS-AQ	FSD, CAM5-chem-TS1	0.5x0.6, 56 levels	4	0.15	2400000	1440	25	A
P6. Climate impact on ozone	B, CAM5-chem	1.9x2.5, 32 levels	3	95	2500	713	15	B
Total Production Year 1						**3626**	**80**	
Year 2								
P7. CESM2 with interactive fires	B, CAM5-chem	0.9x1.25, 32 levels	1	160	10250	1640	25	A
P8: VSL halogen PI vs PD	FSD, CAM4-chem-VSL	0.9x1.25, 56 levels	14	10	20500	2870	50	A
Total Production Year 2						**4510**	**75**	
Total Production (2 years)						**8136**	**155**	

Climate Variability and Change Working Group (CVCWG)

1. Broad Overview of Working Group and Research Plan

The goals of the Climate Variability and Change Working Group (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, and AMIP and "Pacemaker" style historical runs.

The main foci for research and computing using the CSL resources over the next 2 years are simulations with the CESM2 model hierarchy and contributions to CMIP6. The CVCWG will contribute to the Detection and Attribution Model Intercomparison (DAMIP), Scenario MIP (ScenarioMIP), Flux Anomaly Forcing MIP (FAFMIP), and Cloud Forcing MIP (CFMIP). Analyses will target forced climate changes and associated uncertainties due to natural variability (assessed by running large ensembles), changes in variability and extremes and associated uncertainties, and changes across collections of ensemble members with different scenarios to assess forcing-related uncertainties.

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. 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 (WGs). In particular, for contribution to CMIP6, the CVCWG will work closely with the Societal Dimensions WG on ScenarioMIP, with the Atmospheric Model WG on CFMIP, and outside collaborators on DAMIP.

2. Production Proposal (43.6 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 community allocation of the CSL will be used for all Tier 1 required simulations for which the CESM will contribute (for the nominal 1° version). A single simulation is required for participation in ScenarioMIP Tier 1 and 2 experiments. To reduce uncertainty we, along with the SDWG, will add additional ensemble members in order to obtain a total of three members for all scenarios, including the extensions to year 2300, and five for each bracketing scenario. The CVCWG plans to conduct all Tier 2 and the majority of the Tier 3 simulations to DAMIP providing three ensemble members for each scenario. These include many single forcing historical simulations (CO2-only, stratospheric ozone-only, volcano-only, and solar-only) as well as extensions of the single forcing historical simulations to the year 2100 using the SSP2-4.5 forcing (GHG-only, stratospheric ozone-only, aerosol-only, and natural-only). Finally, for contribution to FAFMIP, the CVCWG plans to conduct all Tier 2 simulations contributing three ensemble members (when one is the requirement). These include an experiment to investigate simultaneous surface flux perturbations of momentum, heat, and freshwater (faf-all) and an experiment in which a surface flux, equal to the surface heat flux perturbation of the Tier 1 faf-heat experiment, is applied as a passive "added heat" tracer (initialized to zero, faf-passiveheat).

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. A hierarchy of model configurations will be used, including the atmospheric model coupled to the land model (A-L model configuration) forced by a repeating seasonal cycle of SSTs and sea ice (taken from the CESM control), the A-L model coupled to an upper-ocean mixed layer model (CoupML configuration), 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, ocean mixed layer physics, 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 CoupML and CESM2 models 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.

We will also continue ongoing individual group member science investigations. Toward this effort, we have planned experiments to investigate the recent global warming hiatus. Previous studies indicate that the interaction of anthropogenic forcing and internal climate variability in contribution to the hiatus is complicated. Specifically, we would like to investigate how these two interact in regard to the Interdecadal Pacific Oscillation (IPO) using a set of idealized climate simulations.

b. Specific simulations and computational requirements

(PP1) A 2200-year control run of the CAM6/CLM model under 1850 radiative forcing conditions. This will provide crucial baseline statistics of the model's internally-generated atmospheric variability. (4329K core hours; Year 1)

(PP2) A 10-member AMIP ensemble with CAM6/CLM6 using historical radiative forcing and specified observed SSTs in the tropics and a repeating seasonal cycle outside of the tropics for the period 1880-present. This ensemble will provide crucial information for detection and attribution studies. (2657K core hours; Year 1)

(PP3) A 10-member "Pacemaker" ensemble with CESM2 using historical radiative forcing and 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 tropical Pacific SST variability for detection and attribution studies in a more realistic (e.g., coupled) setting than PP2. In conjunction with PP2, researchers will be able to assess the role of air-sea interaction in the remote atmospheric response to tropical Pacific SST variability. (3985K core hours; Year 1)

(PP4) A 10-member "Pacemaker" ensemble with the CAM6/CLM coupled to the upper-ocean mixed layer model (aka the "pencil model") using historical radiative forcing and SST anomalies nudged to observations in the eastern tropical Pacific for the period 1880-present. In conjunction with PP2 and PP3, researchers will be able to assess the roles of thermodynamic and dynamical air-sea interaction in the remote atmospheric response to tropical Pacific SST variability. (3985K core hours; Year 2)

(PP5) A 1420-year extension of the DECK control run of the fully-coupled CESM2 under 1850 radiative forcing conditions. This will provide crucial baseline statistics of the model's coupled variability, including ENSO and decadal-centennial fluctuations in the Atlantic, Pacific and Indian Oceans. (4192K core hours; Year 2)

(PP6) A 1500-year control run of the CAM6/CLM coupled to the upper-ocean mixed layer model (aka the "pencil model") under 1850 radiative forcing conditions. This will provide crucial baseline statistics of the model's thermodynamically-coupled variability. In conjunction with PP1 and PP5, researchers will be able to assess the contributions of internal atmospheric variability, ocean mixed layer physics, and full ocean physics to the various patterns and timescales of climate variability. (4059K core hours; Year 2)

(P1) All historical simulations for Tier 2 and Tier 3 for DAMIP will be conducted. There will be 3 members of histSOZ (stratospheric ozone only), histSOL (solar only), histVLC (volcanoes only), and histCO2 (carbon dioxide only). These simulations span 1850-2020 using SSP2-4.5 to extend the runs to 2020. (6057K core hours; Year 1)

We plan to extend the historical simulations in DAMIP (P1) to 2100 using SSP2-4.5 to satisfy Tier 2 and Tier 3 requirements. These include greenhouse gas only (ssp245GHG), stratospheric ozone only (ssp245SOZ), and aerosol only (ssp245AER). (2125K core hours; Year 2)

(P2) The CVCWG plans to conduct Tier 2 simulations for FAFMIP, namely faf-all and faf-passiveheat. Each run will be 70 years in length and be branched from the PI Control at same point as the 1%CO2 run. For the faf-all simulation, surface flux perturbations of momentum, heat and freshwater are simultaneously applied. For the faf-passiveheat simulation, surface flux equal to the surface heat flux perturbation of the faf-heat experiment (completed as part of TIer 1) is applied instead to a passive "added heat" tracer initialized to zero. (1653K core hours; Year 1)

(P3) (1) To address the interaction of the IPO variability with anthropogenic forcing, we have planned simulations forced with an idealized IPO pattern. We will run the CESM1 with positive or negative IPO (IPO+/-) phase in combination with increasing CO2 1% or 2% per year for 30 years (year 1, 3 members run on Yellowstone in Nov-Dec, 2016). We will also test the IPO neutral transition phase from IPO positive to negative and IPO negative to positive (year 1). We would like to do 5 ensemble members for each for a total of 1200 years. (2) Same as in (1), but using a background IPO pattern, such as two standard deviations of IPO+ or IPO-, and also the climatological IPO neutral phase. We have planned 4 ensemble members, and will conduct 5 if resources allow (year 2). (1766K core hours in year 1 with 700K on Yellowstone in 2016, 1413K core hours in year 2)

(P4) The CVCWG plans to contribute additional ensemble members for bracketing purposes to Tier 1 and Tier 2 simulations for ScenarioMIP as well as conduct the Tier 2 extensions to 2300. We plan to add 2 ensemble members to SSP1-2.6 and SSP5-8.5 in Tier 1 spanning 1850-2015 and to SSP4-6.0 and SSPx-y (a scenario to keep global temperature below 1.5˚C) in Tier 2 spanning 2016-2100. In combination with the SDWG proposal, this will provide 5 ensemble members for each of these scenarios. We also plan to conduct the Tier 2 simulations extending from 2101 to 2300, namely SSP5-8.5ext, SSP1-2.6ext, and SSP5-3.4-OSext. (7321K core hours; Year 2)

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)
PP1. F-case Control	CESM2 FC6CLUBB	f09_f09	1	2200	1968	4329.6	27.5	A
PP2. FAMIP-TOGA	CESM2 FC6CLUBB	f09_f09	10	135	1968	2656.8	16.875	A
PP3. Pacemaker Tropical Pacific	CESM2-BGC B1850	f09_g16	10	135	2952	3985.2	74.925	A
P1. DAMIP historical Tier 2 and 3 -histSOZ	CESM2-BGC B20C/BRCP	f09_g16	3	171	2952	1514.376	28.4715	A
P1. DAMIP historical Tier 2 and 3 -histSOL	CESM2-BGC B20C/BRCP	f09_g16	3	171	2952	1514.376	28.4715	A
P1. DAMIP historical Tier 2 and 3 -histVLC	CESM2-BGC B20C/BRCP	f09_g16	3	171	2952	1514.376	28.4715	A
P1. DAMIP historical Tier 2 and 3 -histXO2	CESM2-BGC B20C/BRCP	f09_g16	3	171	2952	1514.376	28.4715	A
P2. FAFMIP Tier 2 -faf-all	CESM2-BGC B1850	f09_g16	5	70	2952	1033.2	19.425	A
P2. FAFMIP Tier 2 -faf-passiveheat	CESM2-BGC B1850	f09_g16	3	70	2952	619.92	11.655	A
P3. IPO variability -IPO+ 1%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPO- 1%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPOneut from IPO+ 1%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPOneut from IPO- 1%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPO+ 2%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPO- 2%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPOneut from IPO +2%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
P3. IPO variability -IPOneut from IPO -2%	CESM1 B1850	f09_g16	5	30	1472	220.8	8.325	A (members 4-5 are B)
Year 1 Totals			**81**	**3534**		**20448.624**	**330.866**	
PP4. Pacemaker Tropical Pacific w/"pencil" model	CESM2-BGC B1850	f09_g16	10	135	2952	3985.2	74.925	B
PP5. Coupled Control (extension of DECK)	CESM2-BGC B1850	f09_g16	1	1420	2952	4191.84	41.625	A
PP6. Slab Ocean (or "pencil" model) Control	CESM2 EC6CLUBB	f09_f09	1	1500	2706	4059	18.75	A
P1. DAMIP historical extensions -ssp245GHG	CESM2-BGC BRCP	f09_g16	3	80	2952	708.48	13.32	A (members 2-3 are B)
P1. DAMIP historical extensions -ssp245SOZ	CESM2-BGC BRCP	f09_g16	3	80	2952	708.48	13.32	A (members 2-3 are B)
P1. DAMIP historical extensions -ssp245AER	CESM2-BGC BRCP	f09_g16	3	80	2952	708.48	13.32	A (members 2-3 are B)
P4. ScenarioMIP Tier 1&2 -SSP1-2.6 (tier 1)	CESM2-BGC BRCP	f09_g16	2	85	2952	501.84	9.435	C
P4. ScenarioMIP Tier 1&2 -SSP5-8.5 (tier 1)	CESM2-BGC BRCP	f09_g16	2	85	2952	501.84	9.435	C
P4. ScenarioMIP Tier 1&2 -SSP4-6.0 (tier 2)	CESM2-BGC BRCP	f09_g16	2	85	2952	501.84	9.435	C
P4. ScenarioMIP Tier 1&2 -SSPx-y (tier 2)	CESM2-BGC BRCP	f09_g16	2	85	2952	501.84	9.435	C
P4. ScenarioMIP Tier 1&2 -SSP5-8.5ext (tier 2)	CESM2-BGC BRCP	f09_g16	3	200	2952	1771.2	33.3	A (members 2-3 are B)
P4. ScenarioMIP Tier 1&2 -SSP1-2.6ext (tier 2)	CESM2-BGC BRCP	f09_g16	3	200	2952	1771.2	33.3	A (members 2-3 are B)
P4. ScenarioMIP Tier 1&2 -SSP5-3.4-OSext (tier 2)	CESM2-BGC BRCP	f09_g16	3	200	2952	1771.2	33.3	A (members 2-3 are B)
P3. IPO variability -2xIPO+ 1%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPO- 1%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPOneut from IPO +1%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPOneut from IPO -1%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPO+ 2%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPO- 2%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPOneut from IPO +2%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
P3. IPO variability -2xIPOneut from IPO -2%	CESM1 B1850	f09_g16	4	30	1472	176.64	6.66	A (member 4 is B)
Year 2 Totals			**70**	**4475**		**23095.56**	**366.18**	

Land Ice Working Group (LIWG)

1. Broad Overview of Working Group and Research Plan

The first application of the requested resources will be to continue development of a self-consistent pre-industrial coupled ice-sheet/climate state, which will form the basis for future transient simulations. This spin-up will be computationally expensive and also employ novel component set combinations, in light of the 10^4-year Greenland Ice Sheet (GrIS) equilibration time scale due to characteristic mass balance and ice velocity rates. In addition, additional resources will be required to perform mid-spin-up re-calibrations, based on validations to available observations.

Once spin-up and validation/calibration exercises have been successfully concluded, a series of transient past and future coupled ice-sheet/climate simulations will be performed in support of a number of funded efforts with LIWG members as PI's. In particular, paleoclimate simulations of the past recent deglaciations during the Pliocene, the Last Interglacial (LIG) and the Holocene will assess the past sea level rise from Greenland due to natural climate forcings, as part of the Department of Energy (DOE) SciDAC Project "Modeling Long-Term Changes in Climate, Ice Sheets and Sea Level" (B. Otto-Bliesner, PI; Pliocene and LIG themes) and of the European Research Council Starting Grant (ERC-StG) "CoupledIceClim" (M. Vizcaino, PI; LIG and Holocene themes). In contrast, future simulations will address the fully coupled response of the Greenland ice sheet to anthropogenic forcing on CMIP6 and longer time-scales in support of the previous-stated projects as well as other efforts funded by DOE (J. Fyke, PI), and two projects funded by Dutch National Science Foundation (NWO; M.Vizcaino, PI; Jan Lenaerts, PI).

In addition to the fully coupled simulations described above, the LIWG has scientific interests that would motivate a set of other, less-coupled simulations. For example, LIWG members actively researching the impact of climate variability and climate change on Antarctic snow accumulation with CAM simulations, Antarctic Ice Sheet (AIS) CISM2 standalone simulations, and CAM and CLM development simulations leading to improved representations of both Greenland and Antarctic surface conditions. Last but not least, given the still-new nature of ice sheet representation in the coupled CESM system, we will continue to work on fundamental development, validation and debugging efforts.

2. Development Proposal (7.3 M (Cheyenne) core hours)*

(note that the individual development (D1, D2,..) and production (P1, P2,…) core hour requests are given in Yellowstone equivalent, and the total in Cheyenne equivalent.)*

a. Goals

After a substantial development effort during the last few years, the LIWG has completed the development of the coupled CESM-CISM model, allowing for a dynamic

GrIS that is fully interactive with the climate system. In the coming years, the LIWG strives to further improve this coupling infrastructure, and extend it to other ice sheets, including Antarctica.

b. Specific simulations and computational requirements

(D1) Refining coupling between CISM and CESM for Greenland (0.4 M, Year 1, Priority A)
Two-way coupling between CISM and CESM, while complete in all senses except for ocean-ice coupling, will require continual improvements to better the representation of feedbacks between ice sheets and the broader climate system. For example, currently, icebergs are represented as an annually-constant flux of water and (negative) heat to POP. An improvement would be to route the flux to an iceberg model within CICE. As another example, ice-sheet/climate coupling happens once per year: moving to more frequent coupling could improve simulation fidelity. Finally, we would like to improve the evolution of the land surface state when glaciers retreat by modifying CLM's handling of the conservation of water, energy, carbon and nitrogen. All of these developments will require extensive test simulations.

(D2) Provide offline ice sheet spinup for various CESM forcing (0.3 M, Year 2, Priority A)
Given the long equilibration time of ice sheets relative to all other climate system components, it will likely be necessary to perform ensembles of periodic, long standalone CISM2 simulations to redo the transient spin-up method of Fyke et al. (2014c) and perform observationally-constrained ice sheet optimization exercises as in Lipscomb et al. (2013) to improve model resolution of GrIS characteristics.

(D3) Firn model development (1.3 M, Year 1&2, Priority B)
We will further improve the firn model by including a representation of meltwater standing on ice (which decreases albedo, and further enhances melt), as well as including drifting snow sublimation in CLM. This will require many short test simulations with CLM as well as some longer coupled simulations.

(D4) Add support for additional ice sheets on Northern Hemisphere (0.8 M, Year 1&2, Priority C)
The LIWG and PaleoWG will investigate large-scale ice-climate interaction during the last glacial cycle, starting by deglaciation following the Last Glacial Maximum (21k), and glacial inception at 116k. Only the Greenland ice sheet is currently simulated with CISM. For the LIWG and PaleoWG scientific goals, adaption of CISM for other Northern Hemisphere ice sheets and coupling to CESM is necessary. Development simulations will be used to adapt CISM and couple it to CESM over Eurasia and North America. The novelty of our research plans with respect to state-of-the-art is the use of energy-balance-based SMB calculations.

(D5) Include Antarctic Ice Sheet (1.6 M, Year 1&2, Priority B/A)
Over the next 3 years, a major development target will be progressing towards an ability to simulate Antarctica as well as Greenland. This will require developments in CISM, the new (to-be-determined) CESM ocean model, and the coupler. This work will start in Year 1, ramping up significantly in Year 2. This will require many runs of CISM, as well as the new ocean model.

(D6) Develop physical parameterizations - university support (2 M, Year 1&2, Priority B)
Over the next two years, the LIWG plans to significantly expand collaborations with university groups for the development of improved physical parameterizations. Details are uncertain at this time, because the needed outreach has not yet been done, but likely examples are improvements to basal hydrology and calving. The LIWG would like to provide computing resources to encourage and support these new collaborations.

(D7) Software and infrastructure testing (1.5 M, 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 usage consists of running the CLM automated test suite.

3. Production Proposal (10.6 M (Cheyenne) core-hours)

a. Goals
CESM with one-way coupling to the GrIS and AIS has enabled scientific advances in understanding changes to the ice sheet's SMB. With inclusion of a two-way coupled ice sheet in CESM2, and SMB downscaling automatically active over ice sheets in all CESM2 simulations, we will move from SMB-focused studies to an analysis of the full ice-sheet/climate response to past and future climate forcings, with the main (though not only) production goal under this proposal being to use the new two-way coupling between CISM and CESM to explore the future evolution of the GrIS under anthropogenic forcing. Much of the proposed work is embedded into the Ice Sheet Model Intercomparison Project 6 (ISMIP6, http://www.climate-cryosphere.org/activities/targeted/ismip6/experiments), integral part of CMIP6, but also extends beyond CMIP6/ISMIP6 to longer runs assessing ice sheet stability. While the first 650 years of the spin-up simulation with interactive ice sheet are part of the CESM2 Tier-1 simulations, this proposal contains additional spin-up time, two long-term future climate change scenarios, and past climate simulations with CESM-CISM. The LIWG will carry out two additional spin-up simulations with the recently developed asynchronously coupled (JG/BG) technique, which in principle significantly (~50%) reduces runtime. We expect to augment this CSL time with core hours elsewhere (e.g., on DOE computers) to increase simulation lengths and ensemble sizes.
Meanwhile, the LIWG will strengthen its focus on Antarctica. While a fully coupled model infrastructure for Antarctica as well as Greenland while be in development, we will focus, among others, on the impact of sea ice and Southern Ocean dynamics on Antarctic SMB.

b. Specific simulations and computational requirements

(P1) Providing a Greenland ice sheet in equilibrium with the present-day climate (4 M, Year 1&2, Priority B)
A large segment of our production resources will be necessarily devoted to generation of a robust and validated pre-industrial steady state climate to be used as the basis for all historical and future transient simulations. We are only tangentially able to piggy-back on non-ice-sheet-enabled CESM spin-up efforts, given the lack of coupled ice sheets in these simulations. Spin-up of ice-sheet-enabled climate models is made

particularly complex by the long timescales of ice sheets, and their current thermodynamic/dynamic memory of past glacial cycles. As a result, this request will be devoted to the first spin-ups to use a novel 'iterated' spin-up technique that, by selective removal of CAM expense, cheapens the overall cost of simulations. We budget 4x spin-ups, given a targeted expense of 1 M hours per spin-up using the new method.

(P2) Determine long-term Greenland ice sheet evolution: feedbacks, reversibility and deglaciation thresholds (3.8 M, Year 1&2, Priority A)
We will perform CESM-CISM coupled simulations for pre-industrial control, 4xCO_2 and SSP5-8.5, as indicated by ISMIP6. We will extend these simulations beyond the length requested by ISMIP6 to investigate processes of ice-climate interaction that delay or speed-up deglaciation, and determine the timing, irreversibility and thresholds of future Greenland ice sheet loss. We will run 350 years for the control in addition to 650 years included in the CMIP6 proposal, plus 350 years per climate change scenario.

(P3) Past as a key for the future: Greenland in previous warm periods and Northern Hemisphere deglaciation after the LGM (5.6 M, Year 1&2, Priority B/C)
The LIWG is interested in comparing the sensitivity of the GrIS to the greenhouse-gas and insolation driven warm climates of the Pliocene, the Last Interglacial (LIG), and the Holocene. These experiments are a collaboration between the LIWG and PaleoWG. Both experiments will start from an accelerated ice-sheet component spinup. The Pliocene experiment is designed to investigate conditions for glacial inception in Greenland and will require a total of 300 CESM-CISM years. For the LIG experiment we will run a 350-year long simulation in Year 1 to investigate the sensitivity of the ice sheet to high boreal insolation. An additional 350-year sensitivity experiment for the LIG will be conducted in Year 2, to analyze the importance of basal sliding and isostatic adjustment. For the post-LGM deglaciation, we will perform a coupled CESM-CISM simulation to analyze 9k to 0k Greenland evolution (computing time secured elsewhere), and a one-way-coupled CESM-CISM simulation to investigate Northern Hemisphere deglaciation after the LGM, which both require spin-up conditions.

(P4) Analyzing Antarctic SMB sensitivity to Southern Ocean sea-ice and ocean variability and change (0.5 M, Year 1, Priority B)
Here we study the impact of sea ice variability and change, both internally or human-induced, on Antarctic ice sheet SMB. A pilot project with isotope-enabled CAM and forced sea-ice fields shows a discernible impact of sea ice on Antarctic SMB. We will extend this preliminary analysis and carry out about 10 simulations with atmosphere-only, each about 10 years long.

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)
Year 1 Development								
D1. Refine coupling	TGIS2	f09_g16_gl4	600	2000	0.34	408	10	A
D3. Firn model	IG	f09_g16_gl5	200	20	234	936	15.32	B
D4. NH ice sheets	JG/BG	f09_g16	20	100	400	800	2.4	C
D5. Antarctica	various	various	many	various	various	400	1	B
D6. University support	various	various	many	various	various	1000	10	B
D7. Software and infrastructure testing	various	various	many	various	various	750	10	A
total Year 1					**Cheyenne equivalent**	**3521.08**	**48.72**	
Year 2								
D2. Offline Greenland spinup	TGIS2	f09_g16_gl4	100	10000	0.34	340	10	A
D3. Firn model	IG	f09_g16_gl5	100	20	234	468	7.66	B
D4. NH ice sheets	JG/BG	f09_g16	20	100	400	800	2.4	B
D5. Antarctica	various	various	many	various	various	1200	1	B
D6. University support	various	various	many	various	various	1000	10	B
D7. Software and infrastructure testing	various	various	many	various	various	750	10	A
total Year 2					**Cheyenne equivalent**	**3737.56**	**41.06**	
Total Year 1 + 2						**7258.64**	**89.78**	
Year 1 Production								
P1. Coupled ice sheet spinup	JG/BG	f09_g16	1	2500	400	1000	3	A
P2. Future Greenland (control)	BG	f09_g16	1	350	3624	1268.4	17.6575	A
P3. Paleo-Greenland (spinup)	JG/BG	f09_g16	2	1250	400	1000	3	A
P3. Paleo-Greenland (LIG)	BG	f09_g16	1	350	3624	1268.4	17.6575	A/B
P4. Antarctic SMB vs. sea ice	F_CAM5 (isotope enabled)	f09_g16	10	10	5000	500	1	B
total Year 1					**Cheyenne equivalent**	**4130.176**	**42.315**	
Year 2								
P1. Coupled ice sheet spinup	JG/BG	f09_g16	2	2500	400	2000	6	A
P2. Future Greenland (scenarios)	BG	f09_g16	2	350	3624	2536.8	35.315	A
P3. Paleo-Greenland (spinup)	JG/BG	f09_g16	2	1250	400	1000	3	A
P3. Paleo-Greenland (LIG)	BG	f09_g16	1	350	3624	1268.4	17.6575	B
P3. Paleo-Greenland (Pliocene)	BG	f09_g16	1	300	3624	1087.2	15.135	C
total Year 2					**Cheyenne equivalent**	**6471.768**	**77.1075**	
Total Year 1 + 2						**10601.944**	**94.765**	

Land Model Working Group (LMWG)

1. ***Broad Overview of Working Group and Research Plan***

The goals of the Land Model Working Group are to continue 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 Land Model Working Group request. A portion of the proposed terrestrial carbon cycle production work has been included in the Biogeochemistry Working Group request.

The Land Model Working Group has pursued an ambitious program of model development, which will culminate with the release of CLM5 during this CSL allocation period. Several additional large development projects have been progressing in parallel to CLM5 development including a multi-layer canopy scheme, a hill-slope hydrology model, and the Ecosystem Demography version of CLM. These projects will continue into the next CSL along with other development projects. Parameter estimation/calibration is an increasingly important feature of CLM development.

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 (Figure 1). CESM will participate in each of these MIPs, utilizing CLM5 in both coupled and land-only experiments.

2. ***Development Proposal*** (12.6 M core hours)

a. Goals

We lump the requested resources for model development into several classes of integrations that would be completed during a typical model development cycle. 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 (this is required because the carbon state of the model is significantly different in a transient relative to an equilibrium simulation). The spinup of the carbon and nitrogen states has been accelerated by a factor of four in CLM5. Equilibrium can now typically be reached within ~500 years. Time is requested for several CLM spinup simulations.

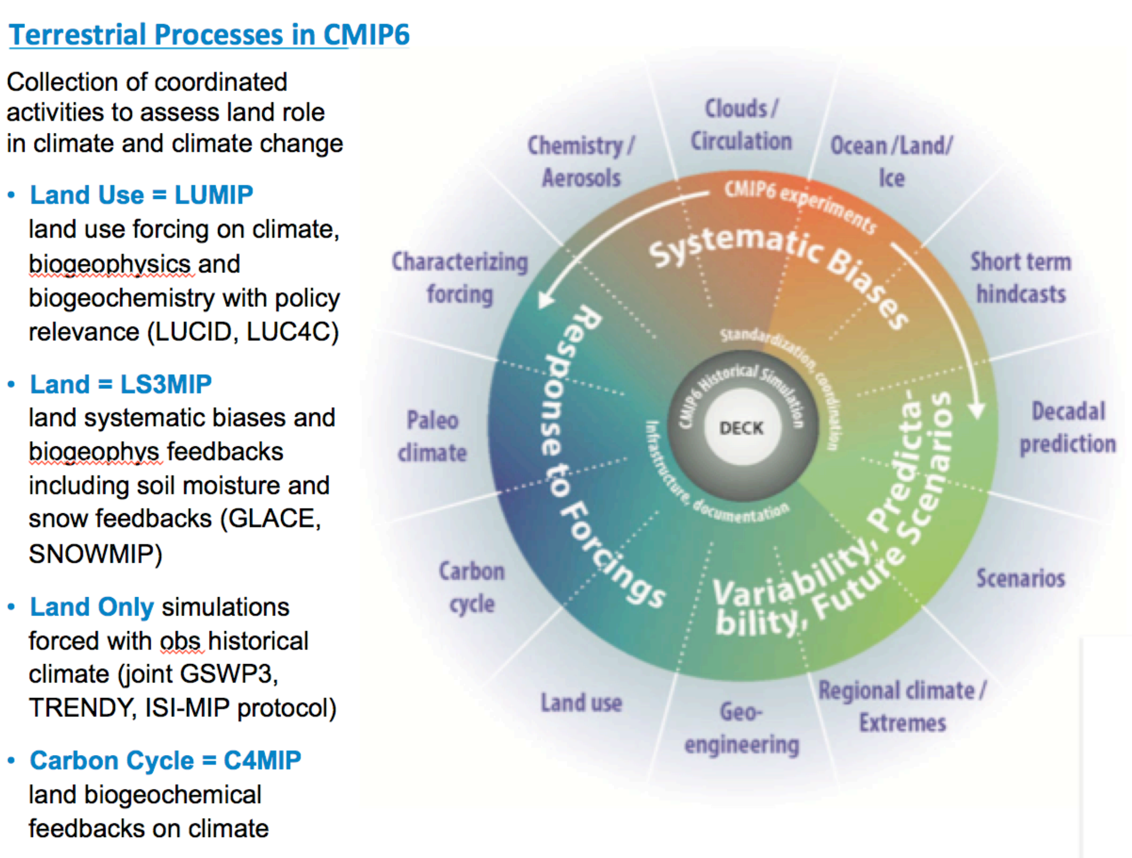

Figure 1. Terrestrial processes in CMIP6. Tier 2 experiments from these MIPs are included in the LMWG request.

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) and longer timescale processes (order 100 years, e.g., those related to soil carbon and nitrogen processes).

Also includes is a request for time for decadal-scale CAM-CLM simulations to test and evaluate the impact of new parameterizations on climate and land-atmosphere interactions. Additionally, implicitly embedded within our request for allocations devoted to model development are resources that the LWMG will grant to external model development collaborators. Past experience suggests that collaborators come to us with useful model development projects that were not included in the original CSL proposal but that are best tested and integrated on NCAR computer systems. We plan to accommodate reasonable requests for computation time under the LMWG allocation. Selected model development activities that we anticipate over the length CSL allocation period are outlined below. Several smaller projects are not explicitly listed.

b. Specific model development projects

- *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.
- *Ecosystem Demography (FATES):* The CLM Functionally-Assembled Terrestrial Ecosystem Simulator (FATES, formally named ED) 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/ACME-Land(FATES) as the basis for it's $100M model-experiment interaction project. Further, proposals have been funded to work on fire (NSF: North Carolina State Univ), hydraulics and nitrogen cycling (DOE: Los Alamos National Lab) within the CLM(FATES).
- *Crop and Forest Management:* As part of a funded NSF EaSM-3 proposal, crop management (no-till, nitrogen use, irrigation, crop selection, cover crops) and forest management (harvesting, site preparation, silvicultural treatments) are being developed for CLM.
- *Hillslope hydrology:* CLM is collaborating with CUAHSI on a funded NSF project to advance the representation of hydrological processes in ESMs (Clark et al. 2015). Initial work is focusing on the introduction of within-grid cell hillslope hydrology that will enable the model to capture the stark differences in ecosystem/water cycle behavior in upland versus lowland environments.
- *Urban Model:* In support of NSF EaSM2 project (Linking Human and Earth System Models to Assess Regional Impacts and Adaption in Urban Systems and their Hinterlands), develop methods of incorporating future urban scenarios into the climate model.
- *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 EnKF framework.

3. ***Production Proposal*** (15M core-hours)

a. Goals

For the CESM2 release, the LMWG will provide control integrations with several different atmospheric forcing datasets. 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, CLM routinely participates in several additional MIPs focused on the carbon cycle (TRENDY), the water cycle (GSWP3), and fire (FIREMIP). Within the working group, there is an expanded emphasis on human management of the terrestrial system and allocations are requested to support several funded 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, also in support of funded projects, are also included in the request. The new fire emissions capability will be utilized and assessed in fire experiments.

b. Specific simulations and computational requirements

LUMIP: A set of 20 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.

LS3MIP: Land-only simulations with alternative historical forcing datasets; land-only simulations anomaly-forced with future climate projections. Coupled simulations with prescribed soil moisture and prescribed snow to assess soil moisture/snow feedbacks.

TRENDY, GSWP3, FireMIP: Historical period land-only carbon, water, and fire MIPs.

Human management of land: Land-only simulations that assess how new model features such as a multi-layer canopy, ecosystem demography, and hillslope-hydrology affect the representation of land-use impact on climate. Crop and forest management simulations. New urban model features will be tested for their impact on surface fluxes, the urban heat island, energy use, and heat stress on humans in present-day and future urban time slice experiments in support of NSF EaSM2 project (Linking Human and Earth System Models to Assess Regional Impacts and Adaption in Urban Systems and their Hinterlands). Datasets have been developed that described several potential future scenarios of urban development.

Fire: 21st century fire projection (land-only for 4 RCPs) and sensitivity experiments; fire full coupling experiments (CAM-CLM-CHEM-MAM4).

Ecosystem dynamics: Simulations assessing trait filtering and sensitivity of terrestrial ecosystems to representation of plant diversity.

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						**5976.25**	**5.86875**	
CLM Development	CLM5	1°	50	165	205	1691.25	3.0525	A
CLM Spinup	CLM5	1°	10	500	205	1025	0	A
Parameter estimation	CLM5	4°	1000	50	20	1000	1.15625	
CAM-CLM testing	CAM6-CLM5	1° (FV)	20	30	2400	1440	0.66	A
CLM(FATES) Development	CLM5(FATES)	2°	50	200	82	820	1	A
Year 2						**6642.5**	**6.59125**	
CLM Development	CLM5	1°	50	150	205	1537.5	2.775	A
CLM Spinup	CLM5	1°	10	500	205	1025	0	A
Parameter estimation	CLM5	4°	1000	50	20	1000	1.15625	
CAM-CLM testing	CAM6-CLM5	1° (FV)	20	30	2400	1440	0.66	A
CLM(FATES) Development	CLM(ED)	2°	50	200	82	820	1	A
CLM-DART	CLM	2°	100	100	82	820	1	
Production								
Year 1						**7153.1**	**79.323**	
MIPs (TRENDY, GSWP3)	CLM5	0.5°	7	165	820	947.1	8.778	A
MIPs Spinup		0.5°	2	500	820	820	0	
LUMIP hist-noLu, ssp ensembles	CESM2	1°	4	250	2950	2950	54	A
LUMIP Tier 2 LU manage factorial	CLM5	1°	20	165	205	676.5	12.54	A
LS3MIP Tier 2 Coupled	CESM2	1°	3	150	2950	1327.5	2.025	B
Perm. bathplug/iceb ox	CAM6-CLM5	1°	4	45	2400	432	1.98	B
Year 2						**7837.7**	**43.355**	
MIPs (TRENDY, GSWP3, FireMIP)	CLM5	0.5°	14	165	820	1894.2	25.08	A
MIPs Spinup		0.5°	3	500	820	1230	0	
LS3MIP Tier 2 Coupled	CESM2	1°	6	150	2950	2655	2.025	B
Human management	CLM5	1°	10	250	205	512.5	4.75	A/B
Fire	CLM5	2°	12	250	82	246	2.7	B
Fire	CAM6-CLM5	2°	2	150	1000	300	1.2	B
Future vegetation dynamics	CLM5(FATES)	1°	20	200	250	1000	7.6	A/B

Ocean Model Working Group (OMWG)

Broad Science Objectives

The primary goals of the Ocean Model Working Group are to advance the state-of-the-science in the capability and fidelity of the CESM ocean component in support of specific science objectives of the broad CESM effort and community and to conduct curiosity driven research with CESM to advance our understanding of the role of the oceans in the Earth's climate system. Our overall objectives continue to be the leaders in new model developments, particularly in parameterizations, and to deliver a state-of-the-science ocean model to the CESM community for the next generation of the CESM simulations.

Development Proposal

Goals for Development

The primary development activity of the OMWG for the next 2-3 years will be the incorporation of a new ocean model (dynamical core) within the CESM framework. As we look beyond CESM2, it is necessary to formulate a plan for the next generation ocean model component. The Parallel Ocean Program (POP) model has been used as the ocean component of CESM for more than a decade. Despite many desirable attributes and advances in its physics over the years, aspects of the current dynamical formulation of POP are an impediment to improving the model skill and addressing cutting-edge climate research questions. POP will not be developed further by the Los Alamos National Laboratory, and progress on development of the dynamical core aspects of POP within the CESM community has stagnated. In response to the Climate and Global Dynamics (CGD) Laboratory Advisory Panel (CAP) call for a reevaluation of the development path for the CESM ocean model – a path also supported in the latest letter from the CESM Advisory Board (CAB), the OMWG, in consultation with the CESM Scientific Steering Committee (SSC), initiated a process to adapt a new ocean model dynamical core for use in CESM3 and beyond. The challenges in moving to a new base model are accompanied by an opportunity to re-examine the scientific requirements for ocean modeling within the CESM community. Such input from the CESM community was solicited through an e-mail survey early in 2016, and through extended discussions at the 2016 CESM OMWG winter meeting and at the 2016 AGU/TOS/ASLO Ocean Sciences Meeting in New Orleans, both in February.

The high-priority technical requirements for CESM3 identified through this process will ideally include: advanced dynamical core technical capabilities, options for flexible vertical coordinates and resolution, advanced tracer advection schemes, natural boundary conditions on freshwater and tracers, and support for non-Boussinesq configurations; model infrastructure and a development environment that provides strong support for collaborative model development with the university-based CESM community; support for both regional and climate modeling applications; support for a wide range of resolutions and grids, and accompanying scale aware parameterizations; ability to configure and run simpler idealized configurations for process modeling and educational applications; compatibility with the CESM sea-ice model; ability to interface with CESM coupled data assimilation system; and familiar post-processing and analysis capabilities, similar to CESM workflow tools.

Furthermore, the CAP report indicated that collaboration on ocean model development is essential, and having CESM rely on a 'handed-off' model for its ocean component is not a viable option. Instead, a strong collaborative relationship with a partner institution or consortium is favored. An ideal partner will possess strong expertise in ocean dynamical core development. It will also have both the capability and desire to actively collaborate with the CESM enterprise and its community to advance a community ocean model.

As part of the selection process, a small, independent Advisory Panel, AP, was formed in April 2016. At the request of the CESM SSC, the OMWG co-chairs sent a Request For Information (RFI) to six ocean modeling groups, representing HYCOM, MITgcm, MOM6, MPAS-O, NEMO, and ROMS modeling groups, to request specific information and broader input from these ocean model development groups to guide the choice of the next ocean component of the CESM. All groups provided the requested information very enthusiastically. They also participated in a cross-working group meeting dedicated to the CESM3 ocean model at the 21st Annual CESM Workshop in Breckenridge on 21 June 2016. This cross-working group meeting was very useful for getting further input from the modeling groups as well as from the broader CESM community, particularly from the sea-ice, biogeochemistry, land-ice, and paleo-climate communities. Following the Breckenridge meeting, the AP and the OMWG co-chairs have continued their deliberations via email. They will submit their recommendations to the CESM SSC in early September 2016. The SSC and the current OMWG co-chairs will jointly make a decision for the provisional replacement for POP by early October 2016.

In parallel with our primary development objective detailed above, i.e., moving to a new base model, our second development goal is to complete ongoing parameterization development efforts that were started more than a couple of years ago. These include works on anisotropic mesoscale eddy mixing parameterization; prescription of mesoscale eddy diffusity coefficients via steering level approach; tidal mixing parameterization; Langmuir mixing parameterization and WaveWatch-III; estuary and river plume dynamics parameterization; and Community ocean Vertical Mixing (CVMix) framework. These developments follow a modularized approach, and it is our intent to port them to our new ocean model.

Additional resources are also requested for i) several data assimilation developments; ii) final evaluations of a new atmospheric data set used for forcing ocean – and sea-ice coupled simulations; iii) testing of this new data set for use in high-resolution version of the POP ocean model; and iv) developing and testing a regional ocean model with a biogeochemical model for the coral triangle region.

Both the development and production endeavors detailed in this request strongly leverage the efforts of the university community and involve several projects funded by the National Science Foundation (NSF) under the Earth System Model (EaSM) and Climate Process Team (CPT) efforts – the latter is officially over but the work is still continuing, the National Oceanic and Atmospheric Administration (NOAA), and the Department of Energy (DOE) under Scientific Discovery through Advanced Computing (SciDAC) program. We will continue to collaborate with the Biogeochemistry Working Group (BGCWG) members in evaluation of our new ocean model as well as in assessments of new parameterizations.

Use of high-resolution (eddy-permitting / -resolving) ocean models in climate applications – requiring many long simulations – remains prohibitively expensive as now also recognized by many other climate centers worldwide. Thus, unless otherwise stated, all of our proposed simulations (both development and production) use the nominal 1° horizontal resolution versions of all component models. We note that the OMWG has a 0.1° horizontal resolution version of the POP model used for research purposes. This version of the model will be used for the high-resolution ocean – sea-ice hindcast simulation proposed under the CESM CSL community allocation. In the following descriptions, we use the CESM component set terminology. Consequently, the ocean – sea-ice coupled simulations are referred to as G-compset and the fully-coupled integrations are called B-compset. With the exception of one set of experiments in D5, all of the G cases will be forced with versions of the Coordinated Ocean-ice Reference Experiments (CORE) inter-annually varying atmospheric data sets, referred to as CORE-II. The existing, original CORE-II data sets cover the 1948-2009 historical period. Hence, a 310-year simulation, for example, cycles this forcing data five times. In most of our coupled simulations, we use the CESM1.1 model version – the same model version used in the CESM Large Ensemble (LE) simulations, because we intend to make use of our existing simulations as control cases to the extent possible. Finally, unless otherwise stated, all simulations include ocean biogeochemistry.

Specific simulations and computational requirements

<u>D1. New ocean model:</u> As summarized above, the primary development goal and task of the OMWG for the next 2-3 years will be the incorporation of a provisional ocean model within the CESM framework for use in the next generation versions of the CESM, starting with CESM3. As this represents our third such model adaption effort since the beginning of the Climate System Model (CSM) at NCAR, we are very familiar with the daunting task laid out for the OMWG, and we anticipate at least 2-3 years' of dedicated work to accomplish our goal. We note that there will be additional resources within the Ocean Section devoted to this effort. Even though the choice of the ocean model and its computational cost are not known at present, it is reasonable to assume that its cost will be similar to those of our present ocean and coupled models. Based on our previous experience, we anticipate performing many forced ocean – sea-ice coupled and fully-coupled simulations, ranging from months to centuries in duration. Our conservative estimate is that we will need order 4000 years of G-compset and order 2000 years of B-compset simulations. While the latter simulations will include the ocean biogeochemistry, we anticipate

running without biogeochemistry in about half of the G-compset simulations to test physics first.

D2. Completion of ongoing parameterization developments in POP: We intend to complete several ongoing parameterization development efforts. Specifically, we plan to work on anisotropic mesoscale eddy mixing parameterization; prescription of mesoscale eddy diffusity coefficients via steering level approach; tidal mixing parameterization; Langmuir mixing parameterization and WaveWatch-III; estuary and river plume dynamics parameterization; and CVMix framework. All of these are already implemented in POP and CESM, but parameter sensitivity and solution evaluations are not complete yet, requiring additional simulations. Furthermore, within the CVMix framework, we are revisiting some of the choices made more than two decades ago in the KPP vertical mixing parameterization. This latter effort involves using solutions from Large Eddy Simulations (LES) as the truth to possibly modify some KPP physics and algorithms. Based on our previous experience, we anticipate first performing many ocean – sea-ice forced hindcast simulations, ranging from one to five CORE-II forcing cycles – totaling about six 310-year simulations. Following these experiments, we plan to perform order five 100-year B-compset simulations with the most recent version of the coupled model. Because these efforts are already ongoing, we plan to continue to use our Yellowstone development and production allocations for November-December 2016 for the initial phase of these efforts. Use of Yellowstone production allocation for this purpose is justified because some of the simulations will be used in documentation and publications of the parameterizations' impacts.

D3. Ongoing development of CESM data assimilation capabilities: 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 development and testing of three data assimilation initiatives. These efforts are with either the POP-DART, i.e., ocean reanalysis only, or the fully-coupled CESM-DART frameworks and they are for: i) configuration and initial testing of the 0.1° horizontal resolution version of POP-DART; ii) debugging and initial testing of the cross-component data assimilation system with the nominal 1° horizontal resolution version of the CESM-DART; and iii) debugging and testing of the "pause-resume" capabilities using the nominal 1° horizontal resolution version of POP-DART. We plan to perform many simulations totaling about 1 month, 6 months, and 1 year for the respective development efforts. The cost and storage estimates are based on our test simulations on Yellowstone, but scaled for Cheyenne.

D4. "Reduced-cost" CESM-DART: Increasing computational cost of the CESM with its new physics, particularly in the atmospheric component, combined with the need for many ensemble members for DART, makes the use of CESM-DART framework expensive for many applications. Here, we propose to evaluate the performance of a "reduced-cost" CESM-DART for more affordably obtaining coupled climate states for use in initialization of seasonal to decadal climate prediction studies. Specifically, resources are requested for the development and testing of a CESM-DART coupled data assimilation integration using either an older version of the atmospheric model, e.g., CAM4, or a more affordable version of CAM5 at coarser horizontal resolutions, e.g., 2°, with 1-day assimilation frequency. Noting that the present CESM-DART integrations require about 1 M core hours per simulation year at 1° resolution, we target cost reductions of about a factor of four, down to about 200-250 K hours per simulation year. We anticipate performing several simulations ranging from a few days to a year and expect to use about 1 M hours. This a very conservative estimate based on our previous experience with the present CESM-DART configuration.

D5. Development of new forcing data sets for G-compset simulations (JRA-55): Development and maintenance of the atmospheric forcing data sets as well as updates of the forcing protocol used for driving the ocean – sea-ice coupled simulations – collectively known as the CORE with its inter-annually varying version referred to as CORE-II – remain an important activity of our working group. The data sets were originally developed at NCAR. They are now being routinely used worldwide in evaluations of the ocean and sea-ice components of many coupled models participating in the Coupled Model Intercomparison Project (CMIP). Indeed, the current CORE forcing data sets and the protocol form the foundations of the newly-established Ocean Model Intercomparison Project (OMIP) within the CMIP6. As such, maintenance, updates, revisions, and extensions of these data sets comprise an important OMWG community service. Additionally, within the OMWG community, there are many funded projects that rely on these data sets to advance ocean – sea-ice historical state estimation and variability research. While the success and visibility of the CORE effort have been steadily increasing, no significant new developments or maintenance of the data sets or the protocol have occurred during the last 6-7 years. In the meantime, various shortcomings with the current CORE-II data sets and the protocol have been identified during the course of the recent CORE-II studies. Important shortcomings include the coarse temporal and spatial resolution and the unavailability of the data sets beyond 2009. To overcome such deficiencies of the data sets, we – in collaboration with the CLIVAR Ocean Model Development Panel (OMDP) – decided to switch to the JRA-55 reanalysis product from the Japanese Meteorological Agency. This effort involves extensive collaborations with our Japanese colleagues. Over the past year, we tested various correction approaches for the new data sets, and we are now in a position to perform long simulations, i.e., a minimum of five repeat-cycles of the 58-year forcing data sets, covering the 1958-2015 period. In addition to evaluation of the CESM ocean –sea-ice coupled simulations, our goals include revisiting the need and choices for surface salinity restoring; options for initialization of the simulations and forcing cycling issues; and creation of a representative single-year forcing data set, i.e., a repeat annual cycle forcing (RAF). We anticipate performing order twenty 270-year simulations with half of the simulations including ocean biogeochemistry. 270 years correspond to five repeat cycles of the new forcing. We note that while some integrations may be longer, some will be only for one forcing cycle. Furthermore, we account for the cost of a few RAF experiments in the estimated number of simulations.

D6. Forcing high-resolution ocean model with JRA-55: Performing a forced hindcast simulation with the high-resolution version (0.1°) of the ocean model is of interest to many members of the OMWG (see section P1). However, before performing such a simulation, we would like to investigate impacts of several wind stress calculation methods at the ocean – land boundaries, particularly focusing on the changes in the sea surface temperature (SST) biases off the west coasts of continents. In contrast with the solutions from the 1° horizontal resolution version, improvements to western boundary SSTs are obtained in the 0.1° version, but for coastal upwelling regions, the original CORE-II data sets with their approximately 2° resolution do not allow a *good* wind forcing. Now, preliminary (and promising) results have been obtained using the 1° ocean model version forced with the new JRA-55 data sets with the reductions in the west coast SST biases attributed to the more realistic forcing, resulting from higher special resolution (~55 km) of the JRA-55 data. However, SST and deeper temperature biases remain, due in part to lack of resolution of ocean coastal currents. We now propose to force the 0.1° POP with the JRA-55 data sets to give both good forcing and resolved coastal upwelling. Because JRA-55 is still coarse relative to 0.1° POP, we will investigate several wind stress calculation methods to pre-apply to JRA-55, including an iterative smoothing method at the coasts to remove any excessive influence of land on winds over coastal ocean grid cells. We anticipate performing many short integrations of order 1 month or less, totaling about 2 years of simulation, with only few output fields and without biogeochemistry. We note that this development effort is in support of a high-resolution (0.1°) ocean – sea-ice hindcast simulation proposed under the *Community Projects* allocation of this proposal.

D7. Marine ecosystem experiments using ROMS: This developmental research focuses on using the Regional Ocean Modeling System (ROMS) to examine and predict the vulnerability of coral reef ecosystems in the Coral Triangle (region of maximum marine biodiversity, spanning the Philippines through Indonesia and Papua New Guinea). The region is thought to have considerable variability in ocean carbonate chemistry, but biogeochemical data – both observations and modeling – are limited. We would like to couple our ROMS implementation of the Coral Triangle region (CT-ROMS) with a biogeochemical model, to determine the natural spatial variability in ocean pH, alkalinity, and nutrients. CT-ROMS covers 25°S–30°N and 95°–170°E and has a ~5 km grid that resolves the complex bathymetry of the area, including the narrow passages of the Indonesian Throughflow. This ROMS version uses the lateral boundary conditions provided from a CESM coupled or forced ocean simulation. We are requesting resources to develop and test the coupling of ROMS with the Carbon, Ocean, Biogeochemistry, and Lower Trophics model (COBALT). We estimate that one year of simulation will require about 150,000 core hours, and that we need a minimum 3-year run to produce output suitable for comparison with existing observations.

Production Proposal

Goals for Production

The OMWG production request targets several science goals. We recently developed a one-dimensional (1D) version of the ocean model that does not explicitly allow any horizontal physics. This configuration is of substantial interest to the broader CESM community for various science applications, most importantly for deciphering the role of ocean dynamics in climate and its variability. For this purpose, we request resources to perform experiments in which the 1D ocean model is coupled to the other active CESM components. We also propose experiments in support of several projects funded by NSF EaSM-II, NSF EaSM-III, and NOAA. They include evaluations of CESM-DART reanalysis in comparison with initialized, coupled hindcast simulations; and investigations of the Labrador Sea hydrographic properties, the North Atlantic Oscillation (NAO)-related surface heat fluxes, and surface freshwater flux anomalies on the mean and variability in the North Atlantic, with a particular focus on the Atlantic meridional overturning circulation (AMOC). We note that the *small* ensemble sizes proposed in the following simulations reflect availability of limited resources.

Specific simulations and computational requirements

P1. 1D ocean and role of ocean dynamics in climate: The OMWG developed a 1D, vertical-physics-only version of the ocean model, also referred to as the pencil model. We plan to complete its testing and verification of the resulting simulations by early 2017 – requiring only a small amount of computational resources. The pencil model represents an attractive alternative to the traditional slab ocean models used in various applications, including climate sensitivity experiments. Its primary use is anticipated to be for deciphering the role of ocean dynamics in many applications, such as in the Atlantic Multidecadal Variabilty (AMV). Here, we request time to perform i) a 600-year fully coupled 1850 control simulation and ii) 5 ensemble member historical simulation (1850-2015) with appropriately constructed 1D ocean model. Because we would like to use the existing simulations as our control experiments, we will use the CESM1.1 model version. In our previous analysis of climate variability on decadal to multi-decadal time scales, we found that order 600-year simulations are necessary for robustness of statistical properties. Thus, both here and in the subsequent experiments, we propose to perform 600-year integrations, also matching the duration of our existing simulations. The computational cost of the 1D ocean model is much less than that of the full ocean model, but the coupled model cost is dominated by the atmospheric component. Therefore, we use 1500 core-hours per simulation year in our estimates.

P2. Evaluation of CESM-DART Reanalysis: To provide a more comprehensive comparative evaluation of our existing CESM-DART coupled reanalysis product, we plan to perform a 30-member ensemble with the B-compset, using again the CESM1.1 version since our existing reanalysis product is based on this model version. We believe that only 10-year long simulations will be sufficient for our purposes. Thus, we propose to consider the 1970-1979 period – to match our reanalysis segment – with the new simulations initialized identically as our reanalysis integrations.

P3. Labrador Sea and AMOC: We request resources to investigate the role of the Labrador Sea, LS, hydrographic properties in setting the mean and variability of the AMOC as well as of the heat content of the North Atlantic subpolar gyre during the recent historical period. For this purpose, we plan to perform only two sets of 56-year simulations for the 1960-2015 period. While potential temperature and salinity distributions in the LS will be relaxed to the historical conditions obtained from the CORE-II forced ocean hindcast in one set of simulations, the second set will use a reanalysis product, such as ORAS4, for relaxation data. Because we intent use the existing LE 20th century simulations as our control, we will use the CESM1.1 version. Also, we plan to obtain 5 ensemble members for each set of simulations.

P4. NAO and AMOC: Resources are requested to investigate the variability mechanisms associated with the NAO-related historical forcing anomalies in fully-coupled simulations. Specifically, we plan to impose observed NAO-related surface heat flux anomalies only over the LS region. This experimental setup makes the ocean model experience additional heating or cooling only in the LS while the atmosphere freely responds to changes in the ocean model, resulting from the imposed flux anomalies. Thus, the protocol enables us to investigate to what extent such NAO-related buoyancy forcing is responsible for the observed AMV and associated climate variability through the modulation of the AMOC variability in a fully-coupled context. We plan to perform five ensemble member simulations for 156 years each, covering the 1850-2005 historical period. Again, because our current work uses the CESM 1.1 version, we intend to perform this study using the same model version.

P5. Impacts of surface freshwater fluxes and freshwater transport on AMOC variability: Understanding the roles of surface freshwater fluxes and meridional freshwater transports in the Atlantic basin in impacting decadal to multi-decadal variability in the Atlantic Ocean, particularly variability of AMOC, remains an urgent science question to improve our understanding of decadal climate variability. Here, we propose to perform sensitivity experiments in which the coupled CESM will be modified with controlled perturbations to the air-sea and/or air-ice freshwater fluxes. These experiments will be designed to test and elucidate a limited set of potential mechanisms and will be similar in their constructions to the NAO heat flux perturbation experiments discussed in section P4 above. Ensembles of coupled CESM at constant radiative forcings, e.g., present-day, will be integrated forward with anomalous freshwater forcing added on top of the model's internally-generated freshwater fluxes. Care will be taken to ensure that the extra forcing does not alter global budgets. The difference between the sensitivity ensemble and a control ensemble can then be interpreted as the impact of the anomalous freshwater forcing. The anomalous forcings will be constructed to test the impacts of various spatio-temporal patterns of freshwater forcing. As before, because we would like to use the existing simulations as our control experiments, we will use the CESM1.1 model version. Given the need for long integrations with multiple ensemble members, we fully recognize that we need to be very careful in choosing our flux anomalies because we can realistically afford to run only a few such sets of simulations. Thus, our plan is to perform three 500-year simulations in pre-industrial conditions with three ensemble members each to start with.

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)
Yellowstone (Development and Production)								
D2. Ongoing parameterization developments	GECO		3	310	621	577.5	35.5	A
	B		2	100	3624	724.8	10.1	A
TOTAL						1302.3	45.6	
Development (year 1)								
D1. New ocean model	G		N/A	1000	173	173	14.7	A
	GECO		N/A	1000	509	509	38.2	A
	B		N/A	250	2972	743	12.6	A
D2. Ongoing parameterization developments	GECO		3	310	509	473.4	35.5	A
	B		3	100	2972	891.6	15.1	A
D3. Data assimilation capabilities	POP-DART	0.1°	N/A	0.083	12M	1000	20	A
	CESM-DART		N/A	0.5	1M	500	1.4	A
	POP-DART		N/A	1	0.2M	200	2.5	A
D5. New CORE-II data sets (JRA-55)	G		10	270	173	467.1	39.7	A
	GECO		5	270	509	687.2	51.5	A
D6. High-res ocean with JRA-55	G	0.1°	N/A	2	75000	150	~0	A
TOTAL						5794.3	231.2	
Development (year 2)								
D1. New ocean model	G		N/A	1000	173	173	14.7	A
	GECO		N/A	1000	509	509	38.2	A
	B		N/A	1750	2972	5201	88.3	A
D4. Reduced-cost data assimilation	CESM-DART		N/A	4	250	1000	2.5	B
D5. New CORE-II data sets (JRA-55)	GECO		5	270	509	687.2	51.5	A
D7. Marine ecosystem in ROMS	ROMS		1	3	150000	450	1	B
TOTAL						8020.2	113.8	
Production (year 1)								
P1. 1D ocean	B (CESM1.1)		1	600	1500	900	6	A
P2. Evaluation of CESM-DART	B (CESM1.1)		30	10	1640	492	15	B
P3. Labrador Sea and AMOC	B (CESM1.1)		10	56	1640	918.4	28	A
P4. NAO and AMOC	B (CESM1.1)		5	156	1640	1279.2	39	A
P5. Freshwater fluxes and AMOC	B (CESM1.1)		3	500	1640	2460	78.5	A
TOTAL						6049.6	166.5	
Production (year 2)								
P1. 1D ocean	B (CESM1.1)		5	166	1500	1245	8.3	A
P5. Freshwater fluxes and AMOC	B (CESM1.1)		6	500	1640	4920	130	A/B
TOTAL						6165	138.3	

Paleoclimate Working Group (PaleoWG)

1. Broad Overview of Working Group and Research Plan

The Paleoclimate Working Group 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 these capabilities that are being used in projections of the future. That is, for forcing and boundary condition changes much larger than during the historical period. Examples include testing new configurations of CESM, such as the capability to simulate the inception and retreat of Greenland, North American, and Eurasian ice sheets when coupled to CESM and to test emission scenarios for a large asteroid impact with CARMA coupled to WACCM. Efforts are also being focused on development of a version of CESM2 for deep-time paleoclimate research.

The Paleoclimate Working Group production goal is to provide benchmark simulations of past climates to the community. These simulations offer the opportunity to test the CESM 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 – CMIP6, PMIP4, VOLMIP, and ISMIP6. Our proposed Production simulations are the Tier 2 and 3 simulations of PMIP4 and VOLMIP, 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 on Yellowstone.

2. Development Proposal (17.3M core hours)

a. Goals

The development objectives focus on testing and exploring the capabilities of CESM when coupled to expanded components, i.e. ice sheets, aerosols, in explaining events recorded in Earth history, as well as development of a paleo-CESM2 suitable for deep-time paleoclimate research. They also contain a component that includes development of the forcings and boundary conditions and emphasizes explorations of the uncertainties associated with these inputs.

We are requesting computing resources to address the following development goals:

- Create the CESM2 volcanic forcing dataset for the *past1000* CMIP6 Tier1 simulation;
- Develop and test a CESM2 version for deep-time paleoclimate research;
- Explore explanations for the mass extinction (including the dinosaurs) event at

the Cretaceous – Paleogene boundary using WACCM coupled to CARMA;
- Evaluate the sensitivity of the climate responses during the last millennium and the Last Glacial Maximum to forcing and boundary conditions uncertainties and how these are implemented in CESM2;
- Test and evaluate the ability of CESM2 coupled to CISM2.1 to simulate glacial inception.

b. Specific simulations and computational requirements

(D1) Volcanic forcing dataset for *past1000* CMIP6 Tier1 simulation – The CESM2 *past1000* CMIP6 Tier1 simulation will use a volcanic forcing dataset resulting from a WACCM6-MA, 2° simulation forced with the Toohey and Sigl emission dataset. The latter is chosen to be consistent with the CMIP6 protocols for this experiment (5.0M core hours; Year 1)

(D2) Sensitivity of *past1000* simulation to emission dataset – The CESM2 *historical* CMIP6 Tier1 simulations will use a volcanic forcing dataset resulting from a WACCM6, 1° simulation forced with the Nealy and Schmidt emission dataset. To establish the sensitivity of CESM2 to the two different forcing datasets, a comparison simulation for the volcanically active 19th century (1790-1899) will be completed (1.0M core hours; Year 1)

(D3) Deep-time development and testing – Development of CESM2 for deep-time research (0.6M core hours; Year 1)

(D4) K-Pg extinction event – CESM is now able to simulate the chemical, physical, and dynamical responses to the Chicxulub impact event that led to mass extinction ~66 Ma. Starting from a previously equilibrated Cretaceous simulation, a series of simulations will explore a range of emission (soot, dust, water, halogens) scenarios to better understand the Earth system responses to the impact. These simulations will help explain the patterns of extinction across the K-Pg (1.3M core hours; Year 1)

(D5) LGM sensitivity – PMIP4 Tier 2 simulations. Various experiments will explore uncertainties in Last Glacial Maximum PMIP4-CMIP6 forcings and boundary conditions, i.e. ice sheet topography and albedo, vegetation, dust (1.8M core hours; Year 2)

(D6) Glacial inception – PMIP4 Tier 2 simulations. CISM2.1 will be extended to enable simulation of the North American and Eurasian ice sheets, in addition to the Greenland ice sheet. Experiments using CESM2 coupled to CISM2.1 (possibly accelerated) will explore the capability of CESM2-CISM2 to simulate glacial inception at 116ka and sensitivity to Preindustrial and 240 ppm CO_2 concentrations (7.6M core hours; Year 2)

3. Production Proposal (22.8M core-hours)

a. Goals

The production objectives focus on the application of the CESM to fundamental questions in basic paleoclimate science in support of community activities. Several Model Intercomparison Projects (MIPs) and benchmark simulations involve applying CMIP models used for present and future climates for simulating past climates. These simulations allow for exploration of the structural differences among models as well as evaluating these state-of-the-art models for reproducing 'out-of-sample' climate states. The assessment against data is an important component of the paleo-MIPs. These MIPs also contain a component that emphasizes explorations of the uncertainties associated with forcings and boundary conditions and the need to assess internal variability.

The PMIP4-CMIP6 Tier 1 simulations: *past1000, midHolocene, lig127k, lgm,* and *plioceneEoi400* will be done on the YS2017 Community allocation. The Paleoclimate Working Group is requesting computing resources to complete additional Tier 2 and 3 simulations to support the community's analyses of the PMIP4 and VOLMIP Tier 1 simulations. Our request addresses the following production goals:

- Contribute to the next phase of the international intercomparison project (PlioMIP2) to understand the mid-Pliocene warm period;
- More fully understand the Holocene time period, its similarities and differences with the Last Interglacial;
- Evaluate the sensitivity of the Last Interglacial climate to the transition out of the previous glaciation;
- Further explore the contribution of volcanic forcing to the spatial and temporal patterns of climate of the early 19th century, the coldest period of the past 500 years.
- Address questions related to greenhouse gases aerosol-cloud interactions, and atmospheric chemistry during deeper time periods.

b. Specific simulations and computational requirements

(P1) PlioMIP2, PMIP4 Tier 2 simulations – A set of four Mid-Pliocene warm period sensitivity experiments to facilitate investigation of climate (Charney) sensitivity as compared to Earth system sensitivity and to assess the relative importance of various boundary condition changes contributing to the Pliocene warmth (7.4M core hours; Year 1)

(P2) Early Holocene, PMIP4 Tier 2 simulation – Time-slice simulation for 9000 yrs ago to compare to CMIP6 *midHolocene* and *lig127k* simulations. The early Holocene had insolation anomalies greater than the Mid-Holocene but less than the Last Interglacial. A remnant ice sheet over North America remained. This simulation will be a starting point for a transient Holocene simulation being proposed for the CESM CSL Community allocation (1.7M core hours; Year 1)

(P3) *past1000_volc_cluster,* PMIP4 and VOLMIP Tier 3 simulations – Ensemble of 3 simulations with forcing protocols from VOLMIP starting at 1790 CE to explore the contribution of volcanic forcing to the climate of the early 19th century, the coldest period of the past 500 years. Provides additional ensembles to *past1000* for this interesting 100-year period (1.3M core hours; Year 1)

(P4) Last Interglacial, PMIP4 Tier 2 simulations – A set of experiments to understand the influence of the bipolar response to Heinrich Event 11 and the disintegration of the West Antarctic ice sheet (WAIS) on the early Last Interglacial climate. Results are expected to be useful for exploring atmospheric and oceanic forcing on the WAIS, likely a major contributor to the LIG global mean sea level rise (5.9M core hours; Year 2)

(P5) Deep-time simulations – A set of experiments for deeper times in the past (when continental positions were different than today) will expand on previous studies to understand questions regarding sensitivities related to greenhouse gases, aerosol-cloud interactions, and atmospheric chemistry (6.5M core hours; Year 2)

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)
Year 1								
D1. Volcanic forcing for *past1000 CMIP6 Tier 1*	B,WACCM6-MA	2°	1	1165	4300	5010	32	A
D2. *past1000 CMIP6 Tier 1 segment with NS*	B,CESM2	1°	1	225	4240	954	11.4	B
D3. Deep-time development and testing	B,CESM2	1 and 2°	various	various	1013 (2°) and 2972 (1°)	590	17.2	A
D4. K-Pg Impact	B,WACCM4 with MOZART & CARMA	2°	10	various	4650	953	3.6	A
	B,CESM1(CAM 4), 2°	2°	1	1	310	310	15	B
Year 1 Total - development						**7817**	**79.2**	
P1. Pliocene, PMIP4 Tier 2	B,CESM2	1°	4	435	4240	7378	87.8	A
P2. Early Holocene, PMIP4 Tier2	B,CESM2	1°	1	400	4240	1696	20.2	A
P3. *past1000_volc_cluster,* VOLMIP Tier2	B,CESM2	1°	3	100	4240	1272	15.1	B
Year 1 Total - production						**10346**	**123.1**	
Year 2								
D5. *lgm* ice sheet sensitivity – PMIP4 Tier2	B,CESM2	1°	various	various	4240	1803	21.5	B
D6. Glacial inception – PMIP4 Tier2	BG,CESM2	1°	2	900	4240	7632	90.8	A
Year 2 Total - development						**9435**	**112.3**	
P4. Last Interglacial, PMIP4 Tier2	B,CESM2	1°	2	1000/400	4240	5936	70.7	A
P5. Deep-time	B,CESM2	1 and 2°	various	various	1013 (2°) and 2972 (1°)	6516	190	A-B
Year 2 Total - production						**12452**	**260.7**	
YS2016 – Dataset creation, setup, and testing of PMIP4-CMIP6 simulations	B,CESM2	1°	various	various	4240	**1912**	**22.8**	A

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

2. ***Development Proposal*** (8.1 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 Polar Climate Working Group 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, and to test a new ice-only high-resolution model configuration.

b. Specific simulations and computational requirements

D1) Improve the representation of sea ice processes within CESM by developing a next-generation sea ice model ("CICE6") (joint with OMWG). Over the period of this CSL proposal, a new ocean model will be implemented within CESM. As the ocean and sea ice run on the same grid, we anticipate a large amount of development work to adapt the sea ice model columnized physics in CICE for the new ocean model grid. Resources are requested to develop and test this next-generation sea ice model for CESM. The runs we plan include fully coupled runs, ice-only runs, and slab ocean model runs. We anticipate multiple experiments as we integrate with the new ocean component and test both the scientific solutions and the software engineering. These CICE6 development runs are our top development priority over this CSL period.

D2) Observational – Modeling Workshop and Follow-on Research For Improving Polar Processes in CESM. As a part of a funded NSF proposal (OPP 078339587, Holland PI), the PCWG has funding to host one workshop per year to engage scientists working primarily with observations in CESM polar-related model development and bias reduction. We will hold our second and third workshops during this CSL allocation. As such, we request resources to do sensitivity simulations for the workshop and also for workshop participants to implement parameterization improvements inspired by the workshop.

D3) Implementing simulators to assess moist atmospheric processes (joint with AMWG). Historically, the suitability of proposed atmospheric moist physics for polar regions has received less attention than lower latitudes. Yet, the polar regions often have unique processes and global importance. As a result, the PCWG requests resources to evaluate and improve atmospheric model moist physics parameterizations with a specific emphasis on polar boundary layer, turbulence, clouds, and precipitation processes. Evaluation of CESM with satellite observations will use the instrument simulator package COSP (Bodas-Salcedo et al. 2011, Kay et al. 2012, Kay et al. 2016). As such, computing resources are requested to finalize implementing CESM-specific diagnostics for precipitation occurrence and cloud opacity within CESM2 and COSP version 1.4 (year 1), for implementing COSP version 2.0 into CESM (year 2), and for evaluating CESM3 candidate moist physics using COSP version 2.0 (year 2).

D4) High resolution ice-only (joint with the OMWG). The PCWG remains committed to exploring and using high-resolution versions of the CESM with active sea ice. The OMWG is proposing a 60-year hindcast high-resolution ice-ocean run at the 0.1-degree resolution. Yet, there are uncertainties about how to initialize the ice at this resolution. Thus, we propose to run an active ice-only run at the 0.1-degree resolution for 60 years. Scientifically, it will also be interesting to contrast the ice state in this proposed ice-only run with other high-resolution simulations.

3. ***Production Proposal*** (8.0 M core-hours)

a. Goals: The over-arching PCWG production goal is to enable important and topical polar science research using CESM. Our proposed experiments leverage and enhance community production experiments and expertise. Our production experiments will be run by 8 different investigators (6 university, 3 NCAR), mostly in support of proposals funded by NSF.

b. Specific simulations and computational requirements

P1) Fresh water tracer experiments. Resources are requested for Arctic freshwater tracer production simulations to support a funded NSF-OPP proposal (Jahn PI) to better understand the impact of 20th -21st century changes in the Arctic Ocean on ocean circulation and deep convection. The tracers tag freshwater from different sources, for example Pacific freshwater, sea ice meltwater, and river runoff (see Jahn et al. 2010). Two additional 1920-2100 CESM-LE members with fresh water tracers are proposed. These additional members will enhance analysis of the freshwater dynamics in the CESM-LE, revealing dynamics in the context of internal variability. In addition, additional daily output from the sea ice model will be saved, to help with the assessment of the simulated melt season length compared to observations, in preparation for CMIP6 sea ice analysis.

P2) The importance of observational system limitations for seasonal sea ice prediction. Observational systems have numerous limitations that can affect initialized forecasts of sea ice conditions. Here we propose idealized experiments to investigate the influence of various initial condition errors on sea ice prediction skill. These will include experiments designed to address the importance of (1) measurement error, (2) sparse observations and (3) incomplete observations. These experiments will target variables that previous studies suggest may provide some predictive potential, such as ice thickness and upper ocean heat content. We propose experiments that make use of the CESM-LE configuration and can be compared to a set of completed "perfect" initial condition ensemble simulations that have already been performed. This will allow us to determine the degradation of predictive potential, what sources of initial condition errors are most critical for a loss of predictive capability, and whether the degradation in predictive potential varies for different variables, regions, and times of year. To assess predictability characteristics requires multiple ensemble members and different start dates. We propose to perform 20 members for each of 3 observational model experiments for several (3) start dates to be run for 2 years.

P3) Detectability of polar cloud and precipitation change. Satellite simulators enable assessment of the capabilities of current-generation satellites to measure future changes in clouds and precipitation as projected by climate models. Leveraging new CESM-specific cloud and precipitation diagnostics being developed through a funded NASA proposal (15-CCST15-0025, Kay/L'Ecuyer PIs), we propose to run current and future simulations to assess detectability of polar cloud and precipitation changes. As they are global, these simulations will be of interest to a broad community studying moist atmospheric processes and how will change over the 21st century. We will run two ensemble members over two time periods: 1985-2024 and 2080-2100 under RCP8.5. In year 1, we will use CESM-LE. In year 2, we will use CESM2.

P4) Global climate impacts of Southern Ocean. The Southern Ocean plays a pivotal role in the global response to climate change through heat and carbon uptake and the integration of the major water masses of the global ocean. Recent trends (1979-present) in Southern Ocean surface climate are unique in the global context, characterized by surface cooling, sea ice expansion, and the intensification of the westerly winds. Resources requested to support a recently funded NSF CAREER proposal (AGS-1554659 Kay PI) and pending NSF OPP grant to study atmosphere-ocean interactions in the Southern Ocean. We propose a 10-member ensemble of Southern Ocean "pacemaker" experiments over the period 1979-2016 using the CESM-LE framework. The "pacemaker" experiments have model monthly sea surface temperature anomalies nudged to observations and will enable the investigation of the global impacts of Southern Ocean surface ocean conditions. We also propose runs to enable climate assessment of the impact of modifications to the CESM-LE that dramatically reduce large absorbed shortwave radiation biases over the Southern Ocean (Kay et al. 2016). We propose a 100-year extension of an existing 1850 control run, a 100-year extension of an existing 2xCO2 1850 control run, one historical (1850-2005), and six RCP8.5 (2006-2100) CESM-LE members, all with the dramatically improved radiation balance when compared to observations.

P5) Winter atmospheric response to Arctic sea ice loss. The atmospheric dynamics behind the development of the high latitude winter pressure response (high pressure over Eurasia, low pressure over the Arctic and North America) to Arctic sea ice loss is an outstanding and unsolved research question. We propose idealized CAM5 1-degree with sea ice loss to investigate this research question. The runs will include four 100-member ensembles of 6-month runs (200 years total).

P6) Assimilation of new ice-thickness measurements. Ice-thickness initialization using observations is essential for short-term sea ice forecasting. We propose runs to support a pending NASA proposal to the Ice Bridge science team to fund these first-of-its kind weekly-to-seasonal sea ice forecast experiments. The runs include both perfect model and real-world sea ice forecasts that assimilate Ice Bridge domain observations. We anticipate 8 forecast ensembles of 20 members each run for 8 months.

P7) Local vs. imported Arctic climate variability. An important open research question is the influence of lower latitudes on Arctic climate variability. We propose simulations to support a pending NSF proposal that aims to partition Arctic climate variability into locally generated variability and imported variability. We propose to run a version of CESM where the atmosphere and ocean south of the Arctic circle is nudged to an observed climatology. We will run a dated but relatively inexpensive version of CESM (2-degree CAM4 fully coupled) for 3000 years.

P8) Short-lived climate pollutants. Recent assessments from the Arctic Monitoring and Assessment Programme (AMAP) and other organizations have quantified impacts of short-lived climate pollutants (e.g., aerosols and ozone-precursors) on Arctic surface temperatures, offering some insight on climate mitigation strategies by Arctic Council and other nations. To advance this research, we propose follow-on modeling experiments that explore impacts on other important properties of the Arctic climate system, including Greenland surface melt and Arctic sea-ice extent. CESM2 will be an excellent tool for assessing these impacts. We therefore propose to conduct ten 15-year simulations, where each of the ten simulations includes perturbed aerosol/gas pollutant emissions from different sectors and regions. This work supports NSF CAREER award (ARC-1253154 –Flanner PI).

P9) Enabling data assimilation within CICE using Data Assimilation Research Testbed (DART, Anderson et al. 2009). Data assimilation in the CESM sea ice model offers diverse opportunities, such as a means of creating a sea ice state estimate or producing subseasonal-to-annual sea ice predictions. In addition, it is beneficial to the entire coupled system to have data assimilation capabilities available in all CESM model components. To meet these needs, we are linking CICE5 within CESM1.5 to DART with funding from NOAA. We propose to do experiments to test the benefit of using a variety of different variables and configurations. We propose experiments with a thermodynamic slab ocean, prescribed atmosphere, and data assimilation only in the sea ice model. We also propose experiments with a full-depth ocean, a prescribed atmosphere and data assimilation in the sea ice and ocean models. These experiments are the most expensive in terms of core-hours per simulated year of the entire PCWG proposal, but they are cutting edge and benefit the entire project by bringing a more complete data assimilation capability to the CESM as a whole.

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Experiment	Configuration	Resolution	Number of runs	Number of years per run	Yellowstone Core-hours per simulated year	Cheyenne Core-hours per simulated year	Total in thousands of Cheyenne core-hours	Total data volume (Tb)	Priority (A/B/C)
Year 1 Development									
D1 - CICE6	B1850	f09_g16	9.0	50.0	5158.0	4298.3	1934.3	11.9	A
D1 - CICE6	G	T62_g16	30.0	50.0	75.0	62.5	93.8	22.5	A/B
D1 - CICE6	E1850	f09_g16	4.0	40.0	2070.0	1725.0	276.0	2.3	A/B
D2 - PCWG workshop	B1850LENS	f09_g16	6.0	50.0	2300.0	1916.7	575.0	7.9	B
D3 - COSP1.4 in CESM2	FAMIPCFCN with COSP	f09_f09	5.0	10.0	6000.0	5000.0	250.0	4.0	B
D4 - High-resolution ice-only	G	tx0.1v2	1.0	60.0	10000.0	8333.3	500.0	0.9	C
Year 2 Development									
D1 - CICE6	B1850	f09_g16	12.0	50.0	5158.0	4298.3	2579.0	15.8	A
D1 - CICE6	G	T62_g16	30.0	50.0	75.0	62.5	93.8	22.5	A/B
D1 - CICE6	E1850	f09_g16	8.0	50.0	2070.0	1725.0	690.0	5.8	A/B
D2 - PCWG workshop	B1850LENS	f09_g16	6.0	50.0	2300.0	1916.7	575.0	7.9	B
D3 - COSP2.0 in CESM3	FAMIPCFCN with COSP	f09_f09	10.0	10.0	6000.0	5000.0	500.0	7.9	C
Year 1 Production									
P1 - Freshwater tracers	B20TRLENS/BRCP85LENS	f09_g16	2.0	180.0	2300.0	1916.7	575.0	9.5	A
P2 - Sea ice prediction	B20TRLENS	f09_g16	20.0	3.0	2300.0	1916.7	115.0	1.6	A
P3 - Detectability of polar change	B20TRLENS/BRCP85LENS with COSP	f09_g16	2.0	40.0	4500.0	3750.0	300.0	6.3	A
P4 - Southern Ocean "pacemaker"	B20TRLENS	f09_g16	5.0	37.0	2300.0	1916.7	354.6	4.9	B
P4 - Southern Ocean reduced bias transient	B20TRLENS	f09_g16	1.0	155.0	4500.0	3750.0	581.3	4.1	A/B
P5 - SLP response to ice loss	FAMIPC5	f09_f09	200.0	0.5	1078.0	898.3	89.8	1.2	B
P6 - Assimilate ice thickness	B1850LENS with ice thickness assimilation	f09_g16	80.0	0.7	4600.0	3833.3	204.4	2.7	B
P7 - Arctic climate variability	B1850CN	f19_g16	2.0	500.0	334.0	278.3	278.3	10.0	C
P8 - Short-lived pollutants	B2000	f19_g16	5.0	15.0	1500.0	1250.0	93.8	0.8	A
P9 - CICE/DART	slab ocean, prescribed ATM, DA in CICE	f09_g16	5.0	10.0	4735.0	3945.8	197.3	0.7	A/B
P9 - CICE/DART	full-depth ocean, prescribed ATM, DA in CICE/POP	f09_g16	2.0	10.0	40800.0	34000.0	680.0	0.5	A/B
Year 2 Production									
P2 - Sea ice prediction	B20TRLENS	f09_g16	40.0	3.0	2300.0	1916.7	230.0	3.2	A
P3 - Detectability of polar change	B20TR/BRCP85 with COSP	f09_g16	2.0	40.0	10316.0	8596.7	687.7	6.3	A
P4 - Southern Ocean "pacemaker"	B20TRLENS	f09_g16	5.0	37.0	2300.0	1916.7	354.6	4.9	B
P4 - Southern Ocean reduced bias 1850	B1850LENS	f09_g16	2.0	100.0	2300.0	1916.7	383.3	5.3	A/B
P4 - Southern Ocean reduced bias transient	BRCP85LENS	f09_g16	6.0	94.0	2300.0	1916.7	1081.0	14.9	A/B
P5 - SLP response to ice loss	FAMIPC5	f09_f09	200.0	0.5	1078.0	898.3	89.8	1.2	B
P6 - Assimilate ice thickness	B1850LENS with ice thickness assimilation	f09_g16	80.0	0.7	4600.0	3833.3	204.4	2.7	A
P7 - Arctic climate variability	B1850CN	f19_g16	4.0	500.0	334.0	278.3	556.7	20.0	C
P8 - Short-lived pollutants	B2000	f19_g16	5.0	15.0	1500.0	1250.0	93.8	0.8	A
P9 - CICE/DART	slab ocean, prescribed ATM, DA in CICE	f09_g16	5.0	10.0	4735.0	3945.8	197.3	2.5	A/B
P9 - CICE/DART	full-depth ocean, prescribed ATM, DA in CICE/POP	f09_g16	2.0	10.0	40800.0	34000.0	680.0	1.0	A/B

	Total Cheyenne Thousand CH	Total volume Terabytes
D - year 1	**3,629**	**49**
D - year 2	**4,438**	**60**
P - year 1	**3,469**	**42**
P - year 2	**4,559**	**63**
Total Year 1	**7,098**	**92**
Total Year 2	**8,996**	**123**

Societal Dimensions Working Group (SDWG)

1. ***Broad Overview of Working Group and Research Plan***

The SDWG seeks to improve understanding of the interactions between human and earth systems by enhancing CESM and its application through studies of climate change impacts, adaptation, and mitigation that use CESM output in their analyses. To pursue this mission, the working group fosters dialogue between the CESM community and other researchers and practitioners involved in the interaction of society and climate change. The working group also carries out CESM simulations of particular relevance to scientific and applications communities, and reviews and approves new CESM code that provides linkages to human system models. A wide range of topics is of interest to the working group, including interactions between the climate system and the use of energy, land, and water; emissions of air pollutants and their consequences; socio-ecological impacts of climate change; geoengineering; and ocean acidification. The working group is also interested in diagnosis of CESM performance from an applications perspective, with an emphasis on model improvement.

The request for this working group supports core projects in linkages between CESM and integrated assessment models (IAMs) while also reaching out to engage additional impacts, adaptation and vulnerability user communities consistent with the broadened focus of the working group. It also supports CESM/SDWG contributions to important community processes such as the design of CMIP6 experiments, particularly those related to future scenarios and land use (ScenarioMIP, LUMIP). The request was developed with input from an open call to the SDWG members for proposed experiments.

2. ***Development Proposal*** (6.7M core-hours)

a. Goals

This request supports two major objectives of development within the SDWG mission: integration between CESM and Integrated Assessment Models, and improving the implementation of land use, a key process through which human and earth systems interact.

These objectives will be pursued through three sets of experiments. The first set will further develop a set of tools for facilitating model linkages in the urban, agricultural, and forestry sectors as part of the Toolbox for Human-Earth System Interaction & Scaling (THESIS). Initial development supported through the previous CSL proposal led to a first set of THESIS tools that is now available to the wider CESM community (https://www2.cgd.ucar.edu/sections/tss/iam/THESIS_tools). The second set of experiments will investigate the sensitivity of integrated IAM-CESM scenarios to assumptions about the initial land cover state using the iESM, a model that integrates the GCAM integrated assessment model with CESM. This project will inform improvements to the representation of land use and land cover information in CLM. A third set will investigate whether representing land use in terms of gross (as opposed to net) land use transitions is important in reproducing historical or projecting future carbon cycle and climate response to land use.

b. Specific simulations and computational requirements

<u>(P1) THESIS Development (2.2M core-hours; Years 1 and 2).</u> This computing project will build on THESIS work that was supported during the previous SDWG computing cycle by further developing THESIS tools (and their application) for crop yields, urban areas, and forestry. The THESIS Crop Yield Tool, which aggregates CLM results for use as input to IAMs, will be updated to take advantage of the ability in CLM5 to run transient cropland and management scenarios, allowing for a much more accurate representation of the effects of climate on yield under different management conditions. Simulations will also support participation in Phase 2 of the Agricultural Model Intercomparison and Improvement Project (AgMIP) to evaluate yield responses to future scenarios of climate change and management. For urban areas, the new THESIS building properties tool will be used to carry out CLM simulations of building energy use and urban climate for investigating sensitivity to specific building properties (insulation value, albedo, window types, etc.), to test an updated base year urban area dataset, and to test the effect of new projections of future changes in urban area. For forestry, a new THESIS tool will be developed for linking CLM land use emissions for use in the iPETS integrated assessment model, but will draw on existing and other planned simulations rather than requiring new runs.

<u>(P2) iESM initial land cover (1.4M core-hours; Year 1; Yellowstone).</u> This computing project will build on iESM work that was supported during the previous SDWG computing cycle, by extending the simulations into the 21st century. The iESM is a synchronous, two-way coupling of the Global Change Assessment Model (GCAM) with the Community Earth System Model (CESM). Initial iESM simulations, like all ESM simulations, used a single estimate of historical land cover. The simulations in this project will investigate the sensitivity of carbon dynamics, climate, and feedbacks onto the human system of uncertainty in historical land cover. In particular, these simulations will use bounding cases with minimum and maximum initial forest, with and without feedbacks to the human system. The results of this experiment have implications for LUMIP and CMIP, as these experiments are perturbations of the existing CMIP protocols and datasets. This project will use Yellowstone resources. *For ease of integration with the other requests, the requested amount is listed (after conversion) as Cheyenne core-hours.*

<u>(P3) Gross vs net land use transition (3076k core-hours; Years 1 and 2).</u> This project will investigate the global and regional effects of gross versus net land use and land cover change (LULCC) transitions on climate and the carbon cycle in CLM5 and CESM2. The simulations involved will be particularly important as an extension to

Land Use (LUMIP) and Scenario (ScenarioMIP) projects in CMIP6. Representation of land use as gross vs net transitions has been identified as a key issue regarding the consequences of land use in Earth System Models (Wilkenskjeld et al., 2014). Gross transitions are represented as differences in annual vegetation state, while net transitions are explicitly represented by all of the individual transitions that would occur between all vegetation types in a single year, with potentially substantial differences in impacts on the carbon cycle between the two approaches. A LUMIP Tier 2 experiment (Lawrence et al. 2016 in review) will be carried out, involving offline historical simulations comparing these approaches, and fully coupled CESM2 simulations assuming gross transitions will be run under historical and future scenarios (from ScenarioMIP). These new gross LULCC simulations will be compared to the equivalent LUMIP Tier 1 simulations that assume net transitions. This comparison will allow a more complete testing of the effect of gross vs net transitions by accounting for their effects on the climate system (and possible climate feedback on the carbon cycle).

3. ***Production Proposal*** (10.7M core-hours)

a. Goals

This request supports two major production objectives within the SDWG mission: applying CESM to analyses of issues of societal relevance (particularly mitigation, impacts, or adaptation analyses), and supporting CESM contributions to important community projects such as CMIP6.

These objectives will be pursued through a set of four experiments. The first set will explore the implications of global land use decisions on climate. These experiments are complementary to those proposed under the LUMIP portion of CMIP6. The second set of experiments will investigate the implications of geoengineering when targeting low radiative forcing levels, focusing on the role of geoengineering in 1.5 degrees C worlds. The third set of experiments examines the effects of regional climate models as a driver of crop models. The final set of experiments are part of the ScenarioMIP simulations, including Tier 2 experiments as well as additional ensemble members for Tier 1 experiments. These experiments are tied to CMIP6 and thus have broad community relevance.

b. Specific simulations and computational requirements

<u>(P4) Global land use decisions (3.0M core-hours; Years 1 and 2)</u>. This project will test the effect of alternative global land futures—increasing forest cover, decreasing forest cover and increasing biofuels—on climate, ecosystems, and the services they provide, at both the global scale and at a focal region in East Africa. Ultimately, it aims to understand the extent to which land-based mitigation through expanding forest cover can offset fossil-fuel driven climate change through biogeophysical and biogeochemical processes. Simulations will contrast forest-rich futures with forest-

poor futures while holding energy emissions constant, an approach that has been incorporated into CMIP6, but this project will significantly deepen the planned investigation. LUMIP is testing the effect of alternative land use pathways by comparing the SSP3-7.0 scenario from ScenarioMIP with runs in which the deforestation trajectory in this scenario is substituted with the afforestation trajectory of the SSP1-2.6 scenario (and vice versa). We will add trajectories that are also based on SSP3-7.0 but bracket plausible land use scenarios featuring 1) biofuel extensification, 2) maximum deforestation, and 3) maximum afforestation. A second set of experiments will add another dimension by driving runs with emissions rather than concentrations. Comparing concentration- versus emission-driven runs will allow us to explore the amplification effect of carbon cycle feedbacks on climate, ecosystems and well-being that may be considerable given the substantial differences between land use trajectories. While C4MIP plans an experiment to explore carbon cycle feedbacks in a higher forcing scenario (SSP5-8.5), we will explore these feedbacks in SSP3-7 for alternative land use assumptions.

<u>(P5) Geoengineering (0.9M core-hours; Years 1 and 2).</u> This project will evaluate a range of physical climate outcomes as well as crop yields when a forcing pathway aimed at limiting global mean temperature change to 1.5 C by 2100 is achieved through a combined emissions reduction/geoengineering strategy, and compare them to those occurring under the same forcing pathway achieved through emissions reduction only. This question is of scientific and policy relevance because climate outcomes could differ substantially, especially on a regional level and for precipitation, if a given forcing target is achieved through geoengineering versus emissions reduction. Investigating the consequences for this particular scenario is of special interest given that in the recent Paris Agreement most countries agreed to a long-term goal of limiting warming to well below 2 C and possibly to 1.5 C. Climate scenarios leading to 1.5 C and associated impact assessments are scarce, and the IPCC will produce a special report over the period 2016-2018 assessing the relevant literature. We plan to use and extend scenarios from ScenarioMIP and to produce results that can help inform the IPCC special report as well as the IPCC AR6. Our approach will be similar to that taken in Tilmes et al. (2016), supported by the previous CSL proposal, which investigated mixed mitigation/geoengineering scenarios to achieve 2.5 and 2.0 C maximum warming. The geoengineering approach will be stratospheric sulfur injection, a form of solar radiation management.

<u>(P6) Regional climate downscaling (2.2M core-hours: Years 1 and 2)</u>. This project will assess the effect of climate change on crop yield in the Americas, using multiple regional climate model simulations to force CLM5 crop model. In particular, the project will contrast the effect of using boundary conditions from 6 individual GCM simulations in the regional climate model with using an ensemble mean climate as a boundary condition. The simulations will test whether a single regional climate simulation, forced with the ensemble mean, can capture mean climate and provide a realistic magnitude of interannual variability. If successful, the proposed method would reduce the number of simulations required in future impacts studies. This project has relevance to the climate impacts research community, as it tests the

appropriateness of a new method with the potential to capture uncertainty in climate with less computational expense. Additionally, this project has relevance to CORDEX, providing information on potential modifications to its experiment protocol.

(P7) ScenarioMIP simulations (4.5M core-hours; Years 1 and 2). This project, in combination with a similar project in the CVCWG, will complete the ScenarioMIP Tier 2 simulations (O'Neill et al., 2016). The ScenarioMIP Tier 2 simulations explore the effect of different emissions, land cover scenarios on future climate. In particular, Tier 2 adds simulations with radiative forcings of 6.0 W/m^2, 3.4 W/m^2, 1.9 W/m^2, as well as an overshoot scenario that branches from the 8.5 W/m^2 scenario and reaches 3.4 W/m^2 in 2100. Such radiative forcing pathways are important as they fill gaps between existing scenarios and the new ScenarioMIP Tier 1 simulations. The full suite of simulations will contribute to assessments of differential changes in climate, and climate impacts. These simulations have broad community appeal and will be used in CMIP6 analyses, as well as the IPCC special report on 1.5 degrees and the IPCC AR6.

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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)	Note
Year 1									
P1. THESIS									Development
- crop hist	I, CLM5Crop	1 degree	4	266	380	404	3.5	A	
- crop RCP4.5	I, CLM5Crop	1 degree	4	86	380	131	2	A	
- crop RCP8.5	I, CLM5Crop	1 degree	4	86	380	131	2	A	
P2. iESM									Development needs to be run on Yellowstone
- max forest, feedback	B, iESM1.0, CESM1.1.2-CL	1 degree	1	90	3888	350	6	A	
- max forest, no feedback	B, iESM1.0, CESM1.1.2-CL	1 degree	1	90	3888	350	6	A	
- min forest, feedback	B, iESM1.0, CESM1.1.2-CL	1 degree	1	90	3888	350	6	A	Development
- min forest, no feedback	B, iESM1.0, CESM1.1.2-CL	1 degree	1	90	3888	350	6	A	
P3. Gross vs net land use									Development
- Hist I	I, CESM2	1 degree	1	166	500	83	1	A	
- Hist B	B, CESM2	1 degree	1	166	2952	490	6.5	A	
P4. Global land use decisions									Production
- max afforest	B, CESM2-CLM5, BDRD	1 degree	3	86	2952	762	22.3	A	
- max deforest	B, CESM2-CLM5, BDRD	1 degree	3	86	2952	762	22.3	A	
P5. Geoengineering									Production
- SSPX-2.0-SSI	B, CESM2	1 degree	3	86	2952	762	24	A	
- Test	B, CESM2	1 degree	1	30	2952	89	4	A	
- SSPX-2.0-SSI I	I, CLM5	1 degree	3	86	200	52	4	A	
P6. Regional downscaling									Production
CLM5	I, CLM5	0.25 degree	4	40	714	114	2	B	
- RCM-CLM	RCM-CLM	50km	4	40	7140	1142	18	B	
P7. ScenarioMIP									Production
- SSP1-2.6 (tier 1)	B,CESM2-BGC	1 degree	2	85	3600	502		A	
- SSP2-4.5 (tier 1)	B,CESM2-BGC	1 degree	2	85	3600	502		A	
- SSP5-8.5 (tier 1)	B,CESM2-BGC	1 degree	2	85	3600	502		A	
- SSPa-b (tier 2)	B,CESM2-BGC	1 degree	3	85	3600	753		A	
Total Year 1						**8581**	**136**		
Year 2									
P1. THESIS									Development
- AgMIP spinup	I, CLM5Crop	1 degree	1	400	380	152	2	A	
- AgMIP TWP	I, CLM5Crop	1 degree	92	31	380	1084	11	A	
- Urban	I, CLM5Crop	1 degree	9	86	380	294	4	A	
P3. Gross vs net land use									Development
- Hist B	B, CESM2	1 degree	2	166	2952	980	6.5	A	
- SSP1 gross	B, CESM2	1 degree	3	86	2952	762	5.5	B	
- SSP3 gross	B, CESM2	1 degree	3	86	2952	762	5.5	A	
P4. Global land use decisions									Production
- deforest/biofuels	B, CESM2-CLM5, BDRD	1 degree	3	86	2952	762	22.3	A	
- default LU	B, CESM2-CLM5, BPRP	1 degree	1	86	2952	254	7.5	B	
- SSP1 afforest	B, CESM2-CLM5, BPRP	1 degree	1	86	2952	254	7.5	B	
- no LULCC	B, CESM2-CLM5, BPRP	1 degree	1	86	2952	254	7.5	C	
P6. Regional downscaling									Production
CLM5	I, CLM5	0.25 degree	3	40	714	86	2	B	
- RCM-CLM	RCM-CLM	50 km	3	40	7140	857	18	B	
P7. ScenarioMIP									Production
- SSP4-6.0 (tier 2)	B,CESM2-BGC	1 degree	3	85	3600	753		A	
- SSP4-3.4 (tier 2)	B,CESM2-BGC	1 degree	3	85	3600	753		A	
- SSP5-3.4-OS (tier 2)	B,CESM2-BGC	1 degree	3	85	3600	753		A	
Total Year 2						**8760**	**99**		
Total Both Years						**17341**	**235**		

Software Engineering Working Group (SEWG)

1. Broad Overview of Working Group and Research Plan

The role of the Software Engineering Working Group (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 (8 million core hours per year)

The above request is needed ensure a successful CESM2.0 release, in addition to periodic updates. It is also needed to support the upcoming CMIP integrations as well as new workflow capabilities that will be associated with those integrations.

Whole Atmosphere Working Group (WAWG)

1. Broad Overview of Working Group and Research Plan

The WACCM working group research plan involves development designed to continue the move towards a unified sun-to-earth modeling framework with high fidelity. The sun to earth modeling will integrate CESM with the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) developed in HAO. We also will advance the science of WACCM with advances in chemistry. All of this development work involves continuing work on a number of development projects across NCAR laboratories and with outside collaborators. . We intend to use the model for several experiments in the next few years as detailed below: looking at volcanic effects on climate now and in the past, ozone trends, and contributing to CMIP6 experiments. It also involves significant simulations that will be available to the community.

On the development side our goal beyond WACCM6 is a unified sun-to-earth modeling framework. We propose to advance the photolysis treatment, explore higher vertical resolution, improve gravity waves, and bring WACCM-X, the solar weather model, up to the same climate model version as the rest of CESM. This will provide a better basis for future science and benefit larger communities of the ChemWG and bring in space weather to CESM.

On the production side, we propose to continue work on WACCM-CARMA with some small projects to look at aerosols in the UT/LS region, and explore possible geo-engineering solutions. We also intend to use our production allocation for several 'MIPs'. This will include contributions to the WMO2018 ozone assessment. Production will also include WACCM contributions to CMIP DECK experiments for a specified chemistry version (WACCM6-SC) and ISA-MIP for intercomparison of stratospheric aerosols. We hope that further contributions of WACCM with chemistry will be made to GeoMIP, PMIP and ScenarioMIP under community projects.

2. Development Proposal (17.8M core-hours)

WACCM development will include aerosol and volcanic aerosol explorations, as well as tuning and adjustment of WACCM in different configurations for both low horizontal and high vertical resolution. We will also work on advanced photolysis treatments for better model evaluation. Continued work on gravity waves, and WACCM-X is also proposed.

A. CU Based WACCM CARMA Simulations: With collaborators at the University of Colorado, we will perform aerosol simulations and geoengineering using WACCM CARMA. This model has a detailed sectional microphysics scheme to better represent the evolution of aerosols in the atmosphere. We will continue to extend and integrate the model for cirrus with sectional models for sulfate and dust. In particular, the geoengineering simulations will use a detailed sulfate representation. This model will help us benchmark and evaluate the standard version of WACCM.

(D1) WACCM-CARMA Simulations (Zhu) 15 years, 123K core-hours
(D2) Aerosol Effects on UTLS (Yu) 100 years, 769K core-hours
Total = 0.8M core-hours

B. 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 radative 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.

(D3) CESM1 (SD-WACCM/MERRA), 2° 37 years, 190K core-hours
(D4) CESM2 (SD-WACCM/MERRA), 1° 37 years 760K core-hours

C. Low resolution tuning: The standard version of WACCM6 will be 1˚ horizontal resolution and 70 levels. This is an expensive model (~25K cpu hrs/yr). So for long simulations (such as for paleoclimate work) we will develop a more efficient version. This is a 2˚ horizontal WACCM6 model with a middle atmospheric chemistry package instead of full chemistry. These simulations will require some tuning to get correct, as the climate of the base CAM6 is different at 2˚ from 1˚, and the gravity wave forcing is slightly different. The configuration will be released to the community as a functional comp set for CESM2.1.

(D5) 5*40 = 200 years, 0.5M core-hours.

D. High Vertical Resolution WACCM6 tuning: In addition to a low resolution model, we also want to make a high vertical resolution model. This will be done in conjunction with 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 below 500m spacing in the upper troposphere and lower stratosphere. This puts the correct gravity wave momentum focring in the right place. A 110 level WACCM version (up from 70 levels) has been shown to provide a robust representation of the QBO, and this will be our target high vertical resolution. For testing, assume this will be 200 years with an estimated WACCM6 * 1.4 cost. The configuration will be released to the community as a functional comp set for CESM2.1.

(D6) High Vertical Resolution WACCM (WACCM6 L110 1˚) 200 years, 3.8M core-hours

D. Gravity Wave Scheme Development: Forcing of the middle atmosphere (stratosphere) and above critically depends on the deposition of momentum from parameterized gravity waves. CESM2 (CAM6) will add some new 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 particular, we will focus on development of the frontal gravity wave drag scheme.

(D7) GW Tuning (CESM2 (WACCM-SC), 1°) 80 years, 1.1M core-hours

E. WACCM-X development: WACCM-X is the extension of WACCM up to the thermosphere (500km now, 700km soon) 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 off of WACCM4 (CAM4) physical parameterizations. We will work to move WACCM-X2.0 in CESM2 from WACCM4 (CAM4) to WACCM6 (CAM6) physics, and finish development of thermospheric modules and the TIE-GCM physics implementation or auroral modules, neutral density species as well as adjustments for the deep atmosphere approximations for the dynamical core in CAM and WACCM. The goal is an integrated model from CAM to WACCM-X based on the same physical and dynamical parameterizations.

(D8) WACCM-X Development (CESM2 (WACCM-X), 1°) 100 years, 3.1M core-hours

Also requested are test WACCM-X climate simulations: Two transient simulations to assess the role of greenhouse gas trends on thermosphere/ionosphere climate: 1960-2016 with constant solar and geomagnetic forcing, and 1964-2016 with realistic solar and geomagnetic variability. This is a development prelude to future production simulations.

(D9) WACCM-X2.0 Transient Simulations (CESM2-WACCM-X2.0) 114 years, 1.5M core-hours

F. WACCM Volcanic Events: WACCM6 recently introduced the ability to prognose the evolution of volcanic sulfate emissions in the atmosphere. This capability is integrated into CESM2 for WACCM. We have extensively evaluated the model against the 1991 Mt. Pinatubo eruption. But more work is needed on other historical eruptions. Some paleo-work will be done at low (2˚) resolution for volcanoes, but we propose sensitivity tests of the recent past (last 150 years) to examine the impact of historical volcanic events of similar or greater magnitude such as

Krakatoa (1883), Tambora (1815) and Laki (1783-4). Historical present day runs to examine the impact of prognostic volcanoes. This will be done with the 1° CMIP6 model (WACCM6) with full chemistry and a stratosphere.

(D10) WACCM6 volcanic events (CESM2-WACCM6 1°) 200 years, 4.1M core-hours

G. WACCM6 Geoengineering Feedback: We are committed to performing WACCM6 experiments for GeoMIP: the Geoengineering Model Intercomparison Project. Several GeoMIP simulations are in the CMIP6 request. However, we also want to perform a prepatory simulation that adjusts the stratospheric forcing every year to maintain constant temperature. This is an extra simulation. It will involve preparatory development work with WACCM6 for future production and off CSL use by the WAWG for other experiments and community simulations.

(D11) WACCM6 Geoengineering Feedback (CESM2-WACCM6 1°) 90 years, 1.8M core-hours

3. Production Proposal (21.4M core-hours)

The WACCM production allocation includes several different categories of simulations. With collaborators we propose significant work on geoengineering with more detailed aerosol models in WACCM. WACCM will make a significant contribution towards the 2018 WMO Assessment of Stratospheric Ozone by running simulations. We will investigate the causes of recent ozone trends with collaborators in the community. Several experiments will explore stratospheric aerosols and volcanic impacts on climate. Finally, we will contribute a specified chemistry version of WACCM (WACCM6-SC) to the CMIP6 archive so that differences between full chemistry and fixed chemistry with the same model can be assessed.

A. WACCM CARMA Geoengineering Simulations: With collaborators at the University of Colorado we propose significant work on geoengineering with more detailed aerosol models in WACCM. This is a companion to our geoengineering work with standard WACCM. It will use the CARMA aerosol model we are working with on the development side. Simulations will be perfomed at lower resolution to assess different levels of geoengineering. Specifically we will focus on issues of how aerosols coagulate (which is best done with the explicit interactions of a sectional aerosol model).

(P1) Geoengineering (English) 3x30 years at 618K core-hours per year
Total= 0.7M core-hours

B. Simulations in Support of WMO2018: WACCM6 will perform a suite of experiments requested as part of the WMO 2018 Assesment of Stratospheric Ozone. This will be a significant contribution of WACCM to the community. We will perform historical simulations with WACCM4 (CESM1-WACCM-CCMI) for the historical and future scenarios. These simulations will be used by the authors of the assessment with select other models for an updated snapshot of ozone depletion.

(P2) WMO 2018 Simulations: (CESM1(WACCM)-CCMI, 2°) 840 years, 2.0M core-hours

C. Mid to High Latitude Ozone trends: Working with Susan Solomon (MIT) and other WACCM colleagues, we will examine the UTLS mid-to-high latitude ozone trends (1950-2015). This work will examine the role of heterogeneous chemistry process on cirrus clouds. The tropospheric climate impact of this process will be evaluated. We will need ~6 realizations using the CESM1(WACCM)-CCMI model at 1.9x2.5x66L. These will be sensitivity tests with different versions of the chemistry scheme to look at the impacts of different specific reactions.

(P3) Mid-to-high latitude ozone trends (CESM1(WACCM)-CCMI, 2°), 390 yrs, 0.9M core-hours

D. WACCM-SC DECK experiments: We will perform a set of DECK runs with The Specified Chemistry version of WACCM 6 (WACCM6-SC). These simulations will be a companion of those done with WACCM DECK simulations full WACCM6. This will enable a detailed comparison of the effect of chemistry and the stratosphere on the coupled earth system, with otherwise the same model configuration. There is unique science to be done that collaborators (Columbia University, L. Polvani) are interested in. The WACCM6-SC control will be done with the CESM2 spinup. So we are just proposing a minimal DECK simulation set: 150 year historical simulation, abrupt 4xCO_2 (150 years), 1% CO_2 150 years. Total =450 years WACCM-SC

(P4) WACCM6-SC DECK (CESM2 (WACCM-SC), 1°) 450 years, 6.2M core hours

E. Volcanic Aerosol Testing: We will compare the current interactive prognostic stratospheric aerosol approach in WACCM6 with a simplified framework proposed by the community, the Easy Volcanic Aerosol (EVA) approach. We will run both approaches in WACCM6. This is done because EVA will be used in many other climate models. It will build off of the prescribed tests of aerosols to be performed with CESM2 low top models (CAM6) as part of CESM2. This will require several 20th century simulations, but this will be done with a low resolution WACCM6 developed as part of this proposal.

(P5): Volcanic Aerosol Testing (CESM2(WACCM), 2°, MA), 344 years, 0.9M core-hours

F. 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. A total of ~500 years of simulation is requested. Note that 245 of these are for the Pinatubo sensitivity experiments. We may shorten these as necessary depending on the results of the first set of these ensemble members.

(P6) ISA-MIP Background (CESM2-WACCM6 1˚) 40 years, 0.8M core-hours
(P7) ISA-MIP Transient (CESM2-WACCM6 1˚) 60 years, 1.2M core-hours
(P8) ISA-MIP Transient (CESM2-WACCM6 1˚) 180 years, 3.7M core-hours
(P9) ISA-MIP Pinatubo (CESM2-WACCM6 1˚) 245 years, 5M core-hours

Experiment	Category	Configuration and resolution	Number of runs	Number of years per run	kPE-hours / simulated year (Ys)	kPE-hours / simulated year (Ch)	Total in kPE-hours (Ch)	Total data volume (Tb)	Priority (A/B/C)
Development Year 1									
WACCM-CARMA	Development	SD-WACCM/CARMA, 2°	30	0.5	10.00	8.20	123.00	3	C
WACCM-CARMA	Development	WACCM CARMA 2˚	4	25	9.38	7.69	768.75	3	C
WACCM6 2° MA tuning	Development	CESM2(WACCM), 2°, MA	5	40	3.29	2.70	539.47	5	A
High vertical resolution	Development	CESM2 (WACCM-SC), L110 1˚	5	40	23.33	19.13	3,826.67	30	A
GW parameterization	Development	CESM2 (WACCM-SC), 1°	2	40	16.67	13.67	1,093.33	96	A
Development Year 2									
Photolysis	Development	CESM2-SD-WACCM 2°	1	37	6.25	5.13	189.63	1	A
Photolysis	Development	CESM2-SD-WACCM 1°	1	37	25.00	20.50	758.50	5	A
WACCM-X2.0 Transient	Development	WACCM-X2.0	2	77	12.00	9.84	1,515.36	20	A
WACCM6-X Development	Development	CESM2 (WACCM6), 1°	10	10	37.50	30.75	3,075.00	13	A
WACCM6-Volcanic Events	Development	CESM2 (WACCM6), 1°	2	100	25.00	20.50	4,100.00	104	B
Geoengineering-Feedback	Development	CESM2 (WACCM6), 1°	1	90	25.00	20.50	1,845.00	47	
Production Year 1									
CARMA Geoenginering	Production	WACCM6 CARMA 2˚	3	30	9.38	7.69	691.88	4	C
WMO2018	Production	CESM1(WACCM)-CCMI, 2°	6	140	2.90	2.38	1,997.52	109	A
Mid-to-high latitude ozone trends	Production	CESM1(WACCM)-CCMI, 2°	6	65	2.90	2.38	927.42	51	B
20thC strat	Production	CESM2(WACCM), 2°, MA	2	167	3.29	2.70	900.92	33	B
ISA-MIP Background	Production	CESM2 (WACCM6), 1°	2	20	25.00	20.50	820.00	21	A
ISA-MIP Transient	Production	CESM2 (WACCM6), 1°	4	15	25.00	20.50	1,230.00	31	A
DECK runs with SC-WACCM6	Production	CESM2 (WACCM-SC), 1°	3	50	16.67	13.67	2,050.00	45	A
Production Year 2									
DECK runs with SC-WACCM6	Production	CESM2 (WACCM-SC), 1°	3	100	16.67	13.67	4,100.00	90	A
ISA-MIP Historic	Production	CESM2 (WACCM6), 1°	45	4	25.00	20.50	3,690.00	94	A
ISA-Pinatubo	Production	CESM2 (WACCM6), 1°	49	5	25.00	20.50	5,022.50	127	B/C for all
Development total							17,834.71	327	
Production total							21,430.24	605	
Total							39,265	932	

WACCM6 Timings used	B Case	F Case	Output
WACCM6 1˚ kcpu/yr (YS)	25.00	22.00	0.52
WACCM6-SC 1˚ kcpu/yr	16.67	14.67	0.3
WACCM6 2° kcpu/yr (YS)	6.25	5.50	0.15
WACCM6 2° MA kcpu/yr	3.29	2.89	0.1
CESM1(WACCM)-CCMI,			0.13

Community Projects

1. WACCM Scenario MIP Runs (3.5M core-hours): these simulations are aimed at adding 2 ensemble members to the current single simulation being performed under the CMIP6 allocation (SSP3-7). Since WACCM will be providing the chemical fields for the other CESM simulations, these additional ensemble members will provide some information on the importance of internal variability on those fields.

2 x 85 years @ 20.5K core-hours/yr = 3.5M core-hours

2. PALEOSTRAT (5.4M core-hours): Two 100-year WACCM simulations will be carried out to evaluate the effect of aerosols, including volcanic injections, in the "last millennium" (LM; 1750-1850). This is part of a project in collaboration with D. Barriopedro, N. Calvo and R. Garcia (U. of Madrid, Spain), G. Chiodo (Columbia U.), and R. Neely (U. of Leeds, UK).

All simulations will use WACCM5.4 with MAM adapted for the stratosphere:

Basic simulation (BAS): Uses external forcings appropriate for the LM adopted and prescribed volcanic aerosol loadings (Gao et al., 2008).

Volcanic simulation (VOL): As in Basic, but using MAM adapted for the stratosphere to compute the evolution of aerosols explicitly based on a time-dependent volcanic injection database developed by Ryan Neely.

BAS: 1000 years @ 2400 core-hours/yr = 2.4M core-hours
VOL: 1000 years @ 2400 core-hours/yr = 2.4M core-hours
Testing and tuning of model 250 yr @ 2400 p.e. hr/yr = 0.6M core-hours

3. HOLOCENE (14.2M core-hours): The *transient Holocene* simulation will provide model data to more fully explore multidecadal and longer variability of, for example: ENSO and other modes of climate variability; monsoons and droughts; the AMOC; and tropical/extratropical linkages. These simulations can also be used to explore the early anthropogenic hypothesis of Ruddiman. In addition, both experiments will provide additional ensemble members for comparison to the *past1000* CMIP6 simulation, albeit with different initial conditions at 850 CE, and for the *transientHolocene* simulation at the CESM2 2° resolution. This is an unprecedented transient simulation covering the period from 9000 years ago until present.

9165 years @ 1550 core-hours/yr = 14.2M core-hours

4. OCEAN HINDCAST (17.4M core-hours): this request is for performing a 58-year forced ocean – sea-ice hindcast simulation for the 1958-2015 historical period with the 0.1° horizontal resolution version of the ocean model, using the new JRA-55 forcing data sets. This simulation will provide unmatched statistics on ocean circulation.

58 years @ 300K core-hours/yr = 17.4M core-hours

5. HIGH-RESOLUTION CMIP6 SIMULATIONS (42.5M core-hours): this request covers all the CMIP6 simulations that are proposed to be performed under this computer allocation using the 1/4^{o} version of CESM2. It is limited to the pre-industrial control, in addition to two additional AMIP (specified sea-surface temperatures) for specific MIPs (GMMIP and HighResMIP) simulations. It will provide information on the performance (e.g., climate sensitivity, modes of variability, biases, …) of this model version that are currently unavailable.

Pre-industrial control: 175 years @ 125K core-hours/yr = 21.5M core-hours
GMMIP simulation: 145 years @ 100K core-hours/yr = 14.5M core-hours
HighResMIP: 65 years @ 100K core-hours/yr = 6.5M core-hours