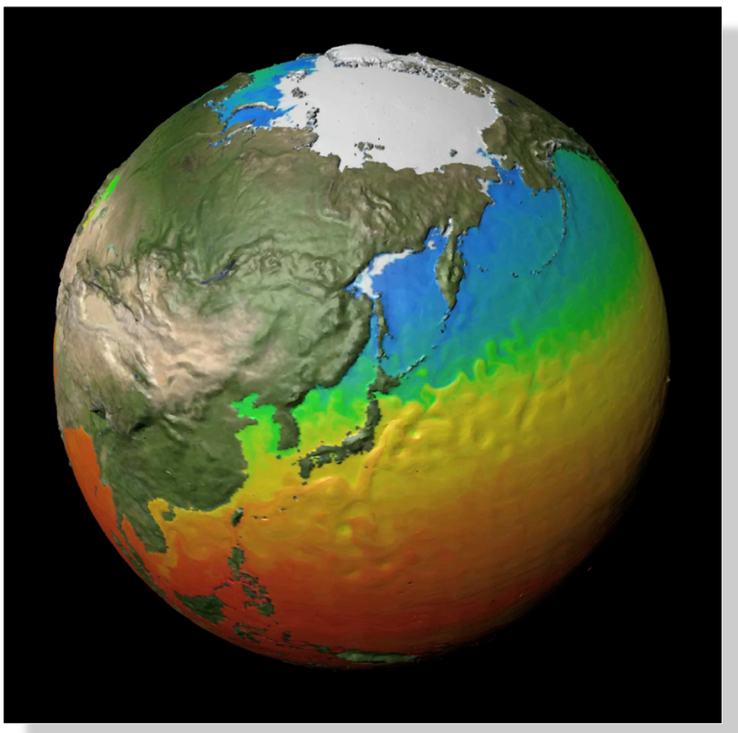
CESM

Community Earth System Model



Interim Progress Report on Use of CSL Resources

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CMIP6 Progress and Accomplishments

A majority of the CESM CSL allocation has been used to perform simulations in support of CESM's participation in the Coupled Model Intercomparison Project phase 6 (CMIP6) as requested in our original CSL proposal. Indeed, as of 20 September 2019, we have used 126.7 M of our requested 147.0 M CPU hours – referred to as CMIP6 allocation. The simulations use the nominal 1° horizontal resolution configuration with both the low-top (with limited chemistry) and high-top with comprehensive chemistry versions of the atmospheric model referred to as CESM2(CAM6) and CESM2(WACCM6) configurations, respectively. The core simulations are the so-called Diagnostic, Evaluation, and Characterization of Klima (DECK) experiments that consist of a long pre-industrial (PI) control simulation; an abrupt quadrupling of CO_2 concentration simulation; a 1% per year CO_2 concentration increase simulation; and an AMIP (Atmospheric Model Intercomparison Project) simulation forced with prescribed observed sea surface temperatures (SSTs) and sea-ice concentrations. These are complemented by multiple simulations of the historical (1850-2014) period. In addition, CESM2 is participating in about 20 Model Intercomparison Projects (MIPs). **We are very pleased to let you know that we have completed all of the DECK simulations and an overwhelming majority of the MIPs Tier 1 simulations as of this writing.** Furthermore, to increase the usefulness of simulations for a broad range of applications, for CESM2(CAM6), we have extended the PI control simulation to 1200 years (from the requested 500 years) and increased the ensemble size to 10 (from the requested 3) for the subsequent historical simulations. Quantitatively, we have finished about 950 experiments / cases and have roughly 50 more to complete with about 20 of them running currently. In addition, several Tier 2 simulations have been completed by the related Working Groups (WGs) using their WGs' allocation as such Tier 2 simulations were not included in the CMIP6 allocation pot (see Progress and Accomplishments by the Working Groups Section below).

We have converted all time slice model output files into time series files. Using lossless compression, the total data volume for these time series files is 1.3 PB. The output fields from these CESM2 simulations are being published on the Earth System Grid Federation (ESGF). So far, we have published about 320 TB of compressed data from about 700 experiments on the ESGF. We have about 110 TB in the process of getting published from the remaining completed cases. In total, we have published about 0.5 million files on the ESGF.

During this entire process, we have paid very close attention to our storage foot print. We decided to eliminate some high frequency data output, but also made reductions in the output fields than originally planned. In our original proposal, we anticipated producing 5.7 PB of data for CMIP6-related simulations and another 1.3 PB of data from various WG simulations during the first year of allocation. As of this writing, we used about 1.7-1.8 PB on Campaign Storage (CS) related to CMIP6 (1.3 PB for time series data plus 320 + 110 TB for ESGF). We also used about 1.3 PB on CS for output from various WG simulations.

The CESM2 was already released to the community in June 2018 (available at www.cesm.ucar.edu:/models/cesm2/). To expedite the use of CESM2 by the community primarily for CMIP6-related science and simulations, two *incremental* releases of CESM2 with the same base code were made available in December 2018 (CESM2.1.0) and in June 2019 (CESM2.1.1) in which many of these simulations can be run as out-of-the-box configurations.

The solutions from these simulations and from several additional simulations designed to further our understanding of some solution characteristics are being analyzed and documented in over 70 manuscripts in the AGU CESM2 Virtual Special Collection with a submisison deadline of 31 December 2019, following the Intergovernmental Panel on Climate Change (IPCC) timelines. A list of anticiapted manuscripts and the ones already published or submitted are available at http://www.cesm.ucar.edu/publications/. Among these, the CESM2 overview manuscript (Danabasoglu et al. 2020) is anticipated to be submitted by mid-October 2019. A draft can be available upon request by the CHAP members.

Adjustments in our Priorities: Since the submission of our CSL request in September 2018, there have been two adjustments / re-programming of our CMIP6 allocation. Specifically, we have decided not to perform the Tier 1 simulations for VolMIP and dcppA-hindcast (component A) simulations for DCPP-MIP. For the former, the reason is that there has been neither continued interest nor somebody to lead this effort. For the latter, after several discussions it was decided that performing a new set of decadal prediction simulations would not be scientifically beneficial without better understanding of our relatively-recent Decadal Prediction Large Ensemble (DPLE) simulations. Indeed, we will be submitting these existing DPLE simulations to the CMIP6 archieve. In the meantime, two new priorities emerged. In response to requests from the community for a coarser – and hence cheaper – version of CESM2 that can be used by researchers with limited computing capabilities, and also for experiments of long timescale such as in paleoclimate applications, we have developed 2° horizonal resolution versions of our atmospheric models, still coupled to the same nominal 1° horizontal resolution ocean and sea-ice models. Thus, we have redirected some of the above savings in resources to perform the PI control and historical simulations with both CESM2(CAM6) and CESM2(WACCM6). The solutions look quite good in comparison to those of the 1° simulations as well as to observations. Consequently, it was decided to include these sets of solutions in our CMIP6 contributions. We are currently performing the remaining DECK simulations. The second new priority is related to preparations for selection of an atmospheric dynamical core for CESM3. Testing and evaluation of several dynamical cores, e.g., SE, FV, and MPAS, will require some dedicated computer time. As this work is about to begin, we would like to use some of our remaining CMIP6 allocation for this purpose.

Some Highlights from Historical Simulations

Surface Temperature

An unacceptable feature of our earlier simulations that substantially delayed our progress until early 2018 was an unrealistic cooling of global-mean surface temperatures in the historical simulations. The cooling started around 1920s, mildly at first and then getting worse roughly during the 1950-1980 period with surface temperature anomalies exceeding

–0.4°C with respect to the 1850s. Even with a subsequent warming trend after 1980s, the end-of-the-century temperatures were colder than in the 1850s. This behavior first appeared when the CMIP6-based emissions were applied in our simulations. Initial investigations uncovered some inconsistencies and errors in the CMIP6 emissions datasets (which were resolved in the final release of the emissions) and their application to CAM6, particularly for anthropogenic sulfur. Simulations with the corrected datasets did show some improvements in terms of warming, but the cooling behavior remained, particularly during the mid-1940s-1980 period, with end-of-the-century temperatures only slightly warmer than in the 1850s. Analysis of CAM6 against recent volcanic sulfur emission events indicated potentially too large a response (Malavelle et al. 2017) regarding the impact of aerosols on the liquid water path. Several modifications were, therefore, made to aerosol – cloud interaction processes, focusing on the warm rain formation process (autoconversion and accretion) to reduce the magnitude of these effects as detailed by Gettelman et al. (2019). With these changes along with several bug corrections, the surface temperature time series became much more realistic as presented in Fig. 1. The figure shows the model global-mean surface temperature anomaly time series in comparison with observations. A reference period of 1850-1870 is chosen to easily identify warming since the pre-industrial conditions. For CESM2(CAM6), both the ensemble-mean and its spread are shown. Only the ensemble-mean time series are included from CESM2(WACCM6) and CESM1(LENS)[1] simulations for clarity. The observations are from the Hadley Centre – Climate Research Unit Temperature Anomalies (HADCRU4.5; Jones et al. 2012); the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP; Lenssen et al. 2019); and the National Oceanic and Atmospheric Administration merged land-ocean global surface temperature analysis (NOAAGlobalTemp; Vose et al. 2012). In general, the CESM2(WACCM6) time series tend to be slightly warmer than those of CESM2(CAM6). Both sets of simulations capture the observed low-frequency variability, and the observations are usually within the ensemble spread of CESM2(CAM6) simulations with a few notable exceptions. One such example is the dip around 1910 evident in observations, but absent in model simulations. This discrepancy may be related to incorrect and / or missing representations of impacts of volcanic eruptions in both models and observations during the 1900-1910 period. Another major discrepancy is seen during the 2000-2014 period with model temperatures being warmer than observed by about 0.2°C and 0.4°C in 2014 in their ensemble means in CESM2(CAM6) and CESM2(WACCM6) simulations, respectively. Although the warming trends between 1975-2000 are comparable between these two model simulations and observations, no ensemble member is able to capture the observed stagnation in the warming trend during roughly 2000-2012. As discussed in Meehl et al. (2014), natural variability plays a dominant role in the creation of this decadal-scale stagnation. Specifically, historical CMIP5 simulations in which the negative phase of the Interdecadal Pacific Oscillation (IPO) coincides, by chance, with the observed negative IPO phase, produce stagnation periods consistent with observations. Because such a match occurs by chance in free-running, uninitialized simulations, it is present only in a very small fraction of the available CMIP5 simulations (10 out of 262) (Meehl et al. 2014). It is

[1] CESM1 Large Ensemble

interesting to note that the observations do show a rapid warming of about 0.2°C immediately following the stagnation phase. In comparison to CESM2 simulations and observations, CESM1(LENS) ensemble-mean time series show generally colder temperatures, usually remaining below or near the lower extent of the CESM2(CAM6) spread. CESM1(LENS) does not capture the observed decadal-scale stagnation, either. However, due to its lower warming trend during the last two decades than in the CESM2 simulations, the warming magnitude in 2014 matches the observations.

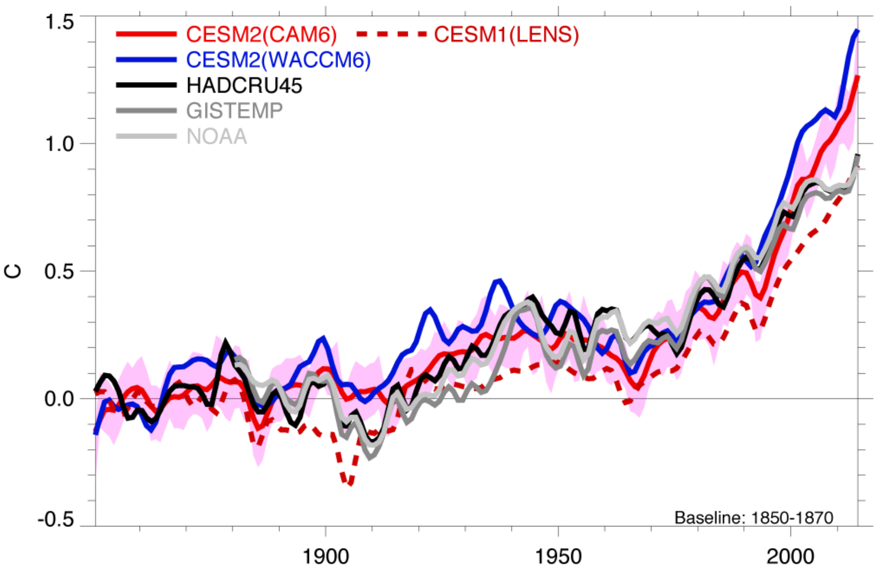

Figure 1. Time series of the global-mean surface temperature anomaly relative to the respective 1850-1870 averages during the historical period from observations, CESM2(CAM6), CESM2(WACCM6), and CESM1(LENS) ensemble simulations. The solid red line and the pink shading show the ensemble-mean and its spread for CESM2(CAM6) simulations. The solid blue and dashed red lines show the 3-member and 40-member ensemble means for CESM2(WACCM6) and CESM1(LENS) simulations, respectively. The CESM1 simulations use the Representative Concentration Pathway 8.5 (RCP8.5) forcing for the 2006-2014 period. The observations are from the HADCRU45, GISTEMP, and NOAAGlobalTemp datasets.

Precipitation

Numerous improvements incorporated into the atmospheric model components have a positive impact on many aspects of the climate of the fully coupled CESM2 system. Figure 2 shows the 1985-2014 average precipitation from CESM2(CAM6), CESM2(WACCM6), and CESM1(LENS) ensemble means in comparison to observational estimates from the Global Precipitation Climatology Project (GPCP; Huffman et al. 2009). As in the SST distributions, CESM2(CAM6) and CESM2(WACCM6) simulations produce nearly identical mean precipitation fields. Both sets of simulations clearly depict a systematic reduction of most biases from CESM1(LENS) to CESM2 with a mean bias of 0.33 mm day^{-1} in CESM1(LENS) down to 0.25 and 0.23 mm day^{-1} in CESM2(CAM6) and

CESM2(WACCM6), respectively. The rms error also improves substantially by about 20%, down from 0.87 mm day^{-1} in CESM1(LENS) to 0.71 mm day^{-1} in CESM2. These improvements arise primarily from the reduction of the major tropical wet biases of the Indian Ocean, the South Pacific Convergence Zone (SPCZ), and the tropical Atlantic Inter-Tropical Convergence Zone (ITCZ). Over land, the dipole of Andean wet and Amazon dry biases is decreased, and Australian and Western US excessive precipitation is reduced. Nevertheless, there are a few degraded regions, including a slightly larger negative bias off Brazil in CESM2 that extends into the South Atlantic Ocean.

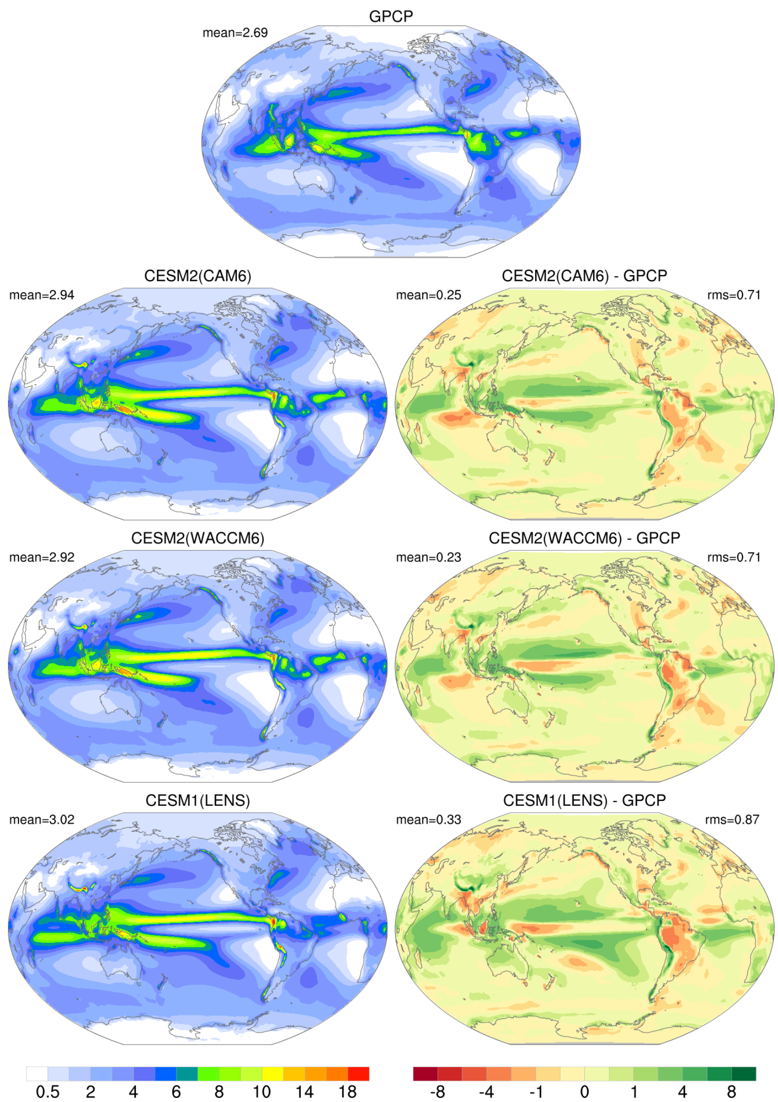

Figure 2. 1985-2014 average total precipitation from (top) GPCP observations and (left) model simulations. The right panels show the respective model minus observations difference distributions. The model distributions represent ensemble means. The global-means for each panel and the root-mean-square error for the difference distributions are also provided. The unit is mm day^{-1}.

Land Carbon Uptake

One of the clearest improvements in CESM2 and CLM5 is the simulated global land carbon accumulation trends. CESM1/CLM4 produced an unrealistically strong nutrient limitation on photosynthesis, which limited the capacity in CESM1 for carbon uptake in response to increases in atmospheric CO_2 concentrations. Consequently, in CESM1 land-use and land-cover change carbon loss fluxes dominate over the CO_2 fertilization response, and CESM1 simulates an accumulated carbon loss over the period 1960 to 2004, whereas the observationally-based estimates indicate a carbon gain of ~40 PgC (Fig. 3). In CESM2(CAM6) and CESM2(WACCM6), the CO_2 fertilization response is more reasonable and, when this is combined with updates to the land-use and land-cover change carbon fluxes, results in a late 20th century accumulated carbon trend that agrees well with observationally-based estimates. Further discussion on the source of improvement for this emergent feature of CESM2, which is also seen in land-only simulations, is provided in Lawrence et al. (2019), Wieder et al. (2019), and Bonan et al. (2019). In addition to the improved accumulated carbon, CESM2 simulations also show evidence of considerable improvements in the amplitude of the annual cycle of net ecosystem exchange, especially at northern high latitudes, which translate to improved annual cycle amplitudes of atmospheric CO_2 concentrations in emissions-driven simulations.

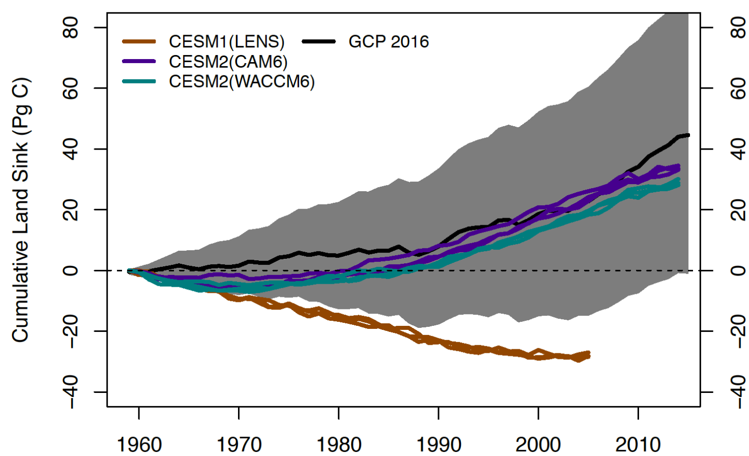

Figure 3. Land carbon accumulation for the period 1960-2014 for 3 historical ensemble members of CESM2(CAM6), CESM2(WACCM6), and CESM1(LENS) along with observational estimates. Observed estimates are from the Global Carbon Project (Le Quéré et al. 2016). Grey shading shows uncertainty range for the observational estimates, using an uncertainty of 0.8 Pg C yr^{-1} and calculated assuming that the errors are additive in time as in Koven et al. (2013).

Equilibrium Climate Sensitivity (ECS)

An important emergent property of the coupled model is its ECS, defined as the equilibrium change in global-mean surface temperature after a doubling of CO_2 concentration. Using a Slab Ocean Model (SOM) configuration of CESM2(CAM6), we obtain about 5.3°C as the CESM2's ECS. This is a significant increase from an ECS of around 4.1°C in CESM1. The evolution of CESM2's climate sensitivity through several development versions of the model is examined in detail in Gettelman et al. (2019) and by Bacmeister (personal communication). These studies both suggest that the increased climate sensitivity in CESM2 has arisen from a combination of relatively small changes to cloud microphysics and boundary layer parameters as well as from changes in land parameters (see AMWG summary below). In particular, the major physics developments in CESM2, e.g., CLUBB and MG2, are not themselves responsible for increased ECS.

Comparison with Other Models

Finally, we present a summary analysis in Fig. 4, comparing CESM2 historical simulations to those from several other modeling groups participating in CMIP6. The figure shows mean pattern correlations across climatological mean, seasonal contrasts (JJA minus DJF), and El Nino Southern Oscillation (ENSO) teleconnections for the first three ensemble members of CESM2(CAM6) and CESM2(WACCM6) and from several other models for 25 atmospheric fields with respect to many observational-based datasets. Indeed, CESM2 simulations are among the best models, comparing very favorably with observations. Further details of this analysis are provided in Fasullo (2020).

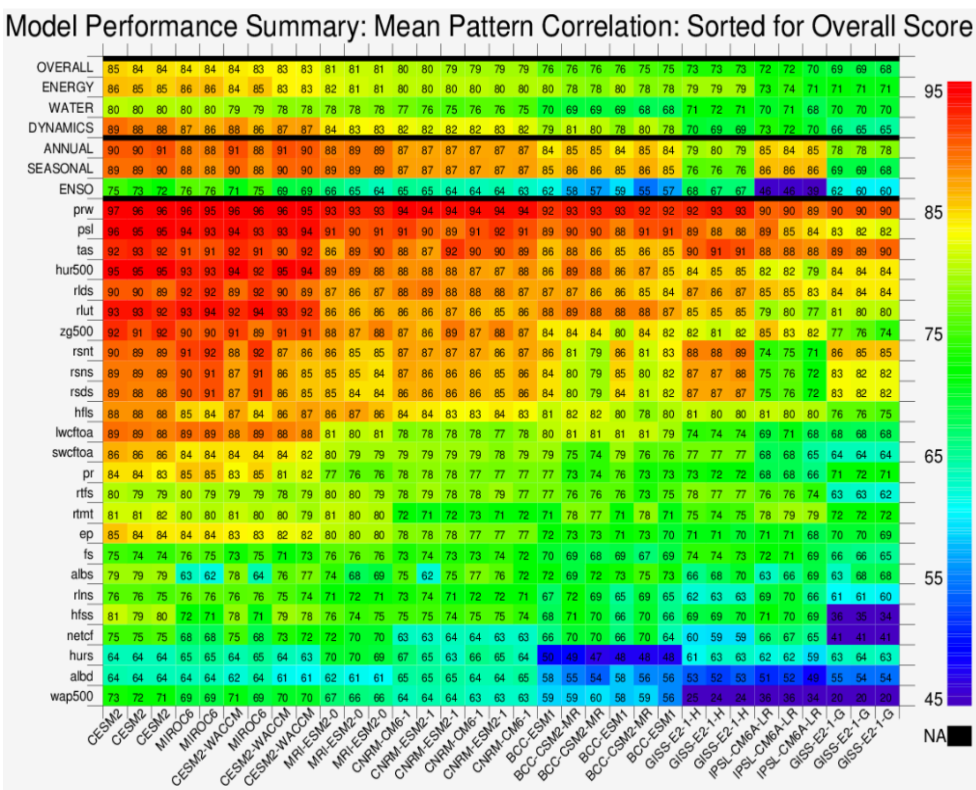

Figure 4. Mean pattern correlations across climatological mean, seasonal contrasts (JJA minus DJF), and ENSO teleconnections for three ensemble members of CESM2(CAM6) and CESM2(WACCM6) historical simulations in comparison with CMIP6 historical simulations from various other modeling groups.

Progress and Accomplishments by the Working Groups

As of 20 September 2019, the CESM WGs have used 27.3 M of their allocated 34.6 M CPU hours on the development side and 31.8 M of their allocated 49.0 M CPU hours on the production side. While several WGs depleted their allocations, the others plan to use their remaining allocations during October 2018 and into the second year of our allocation cycle. The current yet-unused amounts correspond to about 10% of our total CESM CSL allocation of 230 M CPU hours. We provide short summaries of each WG's progress and accomplishments below.

Atmospheric Model Working Group (AMWG)

The bulk of the AMWG computing allocation has been spent on investigating the behavior of CAM6 and its interactions with, and impacts on, the rest of the fully-coupled CESM2. A target of particular interest has been deconvolving the various model physics developments which have led to the dramatically-increased climate sensitivity of CESM2 (~5.3°C) with respect to its predecessor CESM1 (~4.1°C). This effort required a large number of fully-coupled PI control simulations with modified atmospheric and land physics. The suite of PI control simulations was used to establish baseline states for further abrupt CO_2 increase runs using both the fully-coupled model and SOM configurations. This effort has shown that both land and atmospheric physics are contributing to the increased climate sensitivity of CESM2 and that ocean heat transport controls the time evolution and geographical distribution of warming in 4xCO_2 fully-coupled simulations, but may not significantly alter the equilibrium global-mean end states that are used in the strict definition of climate sensitivity. Land parameter changes account for 0.4-0.5°C of the increase in climate sensitivity, while cloud microphysics and cloud "tuning" account for the remaining 0.7-0.8°C. Further investigation of the interactions between low clouds and ocean circulation is required. Parts of this work have already been documented in Gettelman et al. (2019). Additional publications describing the 4xCO_2 experiments will be submitted by December 2019.

In addition to the investigation of climate sensitivity, AMWG undertook a systematic exploration of the bulk physics changes that distinguish CAM6 from its predecessor CAM5 used in CESM1. This exploration was conducted using historical (1979-present) prescribed SST experiments ("F-case" or AMIP-style runs). These runs explore the complete evolution of CAM6 with one-at-a-time replacement of major physics changes, including: 1) CLUBB vs. UW PBL, shallow convection, and cloud-macrophysics; 2) MG2 vs. MG1 microphysics; 3) stricter deep-convective trigger functions; 4) Beljaars vs. TMS PBL form-drag; 5) anisotropic "ridge-generated" mountain waves vs. isotropic orographic gravity waves. Scientific investigation of these runs has only recently begun. Early results suggest a larger-than-expected impact from deep convective triggers.

Significant AMWG computing resources were also devoted to further development of the spectral element (CAM-SE) dynamical core. These efforts included finalizing the regionally-refined continental US (CONUS) configuration and completing the development of the CSLAM-physgrid option for tracer transport and physics-dynamics coupling. The CONUS configuration is now being used by scientists in the Atmospheric Chemistry Observations and Modeling (ACOM) Laboratory of NCAR to develop high-resolution chemical-forecasting capability. The CSLAM-physgrid option has led to promising improvements in simulations of precipitation around orography – a persistent CAM bias – in addition to providing cheaper and more accurate tracer transport than the default CAM-SE.

Biogeochemistry Working Group (BGCWG)

The BGCWG CSL allocation is used primarily to develop biogeochemical parameterizations (ocean, land, and coupled) in and for CESM, perform benchmark experiments of the developed model to assess the model's skill at reproducing observed phenomenon and its emergent properties, and use the model as a tool to study scientific questions. Our usage of CSL resources over the last year has been primarily focused on: 1) development work for configurations of CESM2 using prognostic atmospheric CO_2, 2) Tier 2 CMIP6 experiments (e.g., OMIP2), and 3) development of new ocean and land biogeochemistry parameterizations. Examples of new parameterizations that are under development using BGCWG computational resources include developing a variant of the existing ocean biogeochemistry model that introduces multiple size classes for each current phytoplankton functional group and exploring phosphorus cycling in the terrestrial system.

Initial experiments of CESM2 utilizing prognostic atmospheric CO_2 revealed multiple problems with the implementation of dry tracers in CAM (e.g., initialization, mass conservation, and constant preservation). Computational resources were devoted to developing fixes for these issues and for incremental coupling of prognostic atmospheric CO_2 into CESM2.

Chemistry-Climate Working Group (CHWG)

Several development activities related to tropospheric chemistry and aerosols have been continued over the past year. Through collaboration among University of Wyoming, PNNL, and NCAR, the MOSAIC gas-aerosol exchange parameterization has been implemented in CAM6-chem and the impact of having an improved representation of nitrate aerosols in the model has been studied (Zaveri et al. 2020). Testing of the configuration of CAM-chem with the SE dynamical core with regular grids as well as regional refinement (~1/8°) over the continental US is continuing. Also, simulations with different forms of nudging were tested. A new dust scheme is being developed by Cornell University, and testing of its implementation in CAM6 is being completed this year. The testing of the implementation of Brown Carbon and its radiative impact is still ongoing.

CAM-chem simulations, at both 0.5° and 1°, with several different complexities of chemical mechanisms, have been run to support analysis of a variety of atmospheric chemistry field experiments. This research is ongoing, including collaborations with the experimentalists in ACOM and the university community. In particular, simulations for participation in a model intercomparison connected with the NASA-led KORUS-AQ experiment have been performed, and will result in a publication in the coming year. A long Specified Dynamics simulation of CAM-chem has been completed and made available to the community for use as boundary conditions for regional models (6-hr output of all long-lived compounds): https://www2.acom.ucar.edu/gcm/cam-chem-output (Buchholz et al. 2019).

Forecasts of global atmospheric composition ("chemical forecasts") and spin-up simulations have been run with WACCM for the past year using two different fire inventories, and the results shared with the community and public through websites: https://www2.acom.ucar.edu/acresp/forecasts-and-near-real-time-nrt-products, both as images and data files.

Climate Change and Variability Working Group (CVCWG)

Many goals from the WG's CSL proposal have been achieved using this year's allocation, namely contributions to CMIP6 MIPs, Tropical Ocean Global Atmosphere (TOGA) experiments, regionally forced or "pacemaker-type" experiments, and addition of control-type experiments for resolution comparisons.

Simulations were conducted to aid in protocol development for ITCZ-MIP. The goal of ITCZ-MIP is to improve our understanding of the width of the ITCZ: what drives changes in the width of the ITCZ, and what are the effects of these changes on climate? It is an informal MIP with aqua-planet fixed SST and SOM simulations where changes in the ITCZ width are forced. A poster documenting the MIP protocol and some initial results were presented at the Atmospheric and Oceanic Fluid Dynamics Conference in June 2019, and design and results will again be presented at the CFMIP meeting in October 2019.

CVCWG completed three Tier 2 PAMIP experiments. Furthermore, additional ensemble members were performed for each ScenarioMIP set to obtain three total members for each scenario.

Related to pacemaker experiments, CVCWG has conducted simulations to test the influence of polar warming on mid-latitude circulation and weather under different warming amplitudes using CAM6. An idealized temperature anomaly is added in the polar region or tropics to test the impact of changes in meridional temperature gradient on the mid-latitude circulation. Pacemaker experiments using an idealized SST forcing in the Indian Ocean and Southern Ocean were also conducted. All of the pacemaker experiments have now been used in two submitted manuscripts and have been used in presentations numerous times.

Adding to a line of highly used CESM1 simulations, CVCWG has conducted a ten-member TOGA ensemble at 1° using CESM2. This completes a 4th TOGA ensemble, each forced with different observational estimates of SSTs. This suite of ensembles allows researchers to isolate the role of tropical SST variability in global climate.

Land Ice Working Group (LIWG)

A significant amount of the LIWG's production allocation was used to carry out a fully coupled "JG/BG" spin-up with a dynamic Greenland ice sheet (GrIS). This configuration made it possible to bring the GrIS into equilibrium with the PI climate at an affordable cost, using asynchronous coupling to run for ~10,000 ice sheet years while running only 300 atmosphere years and 1000 ocean years. The spun-up state became the starting point for the coupled CESM-CISM simulations that are part of the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). In addition, CESM-CISM was run in a new configuration with a dynamic Laurentide ice sheet to study the Last Deglaciation. The ISMIP6 Tier 2 simulations were started. These consist of a historical run followed by a SSP5-85 run. CESM2 is one of a small number of Earth system models that will finish the ISMIP6 Tier1 and Tier 2 coupled experiments before the upcoming IPCC publication deadlines.

The development allocation was used for three less computationally intensive efforts: 1) debugging and running CISM in ice-sheet-only configurations, mainly for the stand-alone Greenland and Antarctic experiments that are part of ISMIP6, 2) studying the sensitivity of Greenland surface mass balance to grid resolution using CAM6's new variable-resolution framework, and 3) day-to-day debugging and testing of CESM configurations with ice sheets.

Land Model Working Group (LMWG)

LMWG development allocation has been used to continue development of crop management, including implementations of tillage practices, manure, multiple irrigation methods (sprinkler, drip, and flood) and forest management, including harvesting and silvicultural treatments. CLM is continuing to collaborate with CUAHSI on a funded NSF project to advance the representation of hydrological processes in Earth system models. Over the past year, allocation has been used to develop a representative hillslope scheme within CLM to capture within-grid cell water redistribution across topographic and water table gradients as well as the influence of slope aspect which enables the model to capture the stark differences in ecosystem/water cycle behavior in upland versus lowland environments.

LMWG production allocation has been used to conduct CMIP6 Tier 2 simulations of relevance to terrestrial processes. These simulations include the factorial set of LUMIP Tier 2 land management simulations, which is a set of 16 land-only historical simulations that assess the various impacts of land-management on carbon, water, and energy fluxes. For LS3MIP, land-only simulations with alternative historical forcing datasets have been completed as well as coupled simulations with prescribed soil moisture to assess soil moisture feedbacks onto climate and extremes. Finally, several other land-only simulations have been conducted in support of TRENDY and SOILWAT MIPs. These simulations are mainly historical period land-only simulations focused on understanding of carbon and water cycling.

Ocean Model Working Group (OMWG)

The development efforts within OMWG have focused on transitioning the ocean dynamical core from the legacy POP model to MOM6. Significant progress was made during the reporting period along two fronts. The first is the integration and testing of MOM6 with the CESM infrastructure and running baseline simulations to assess the quality of the climate simulation of MOM6 in both forced and coupled configurations. Several relatively long simulations (~100 years) have been completed with different compsets (C, G, and B), different drivers (NUOPC and MCT), and multiple forcing protocols (CORE-NYF, CORE-IAF, and JRA-55). Particular attention has been focused on assuring correct conservation properties for heat, salt, and seawater mass within MOM6 and across the CESM coupling interface. The interface to sea ice has been significantly modified relative to the GFDL distribution code to adapt it to CESM coupling conventions. The second major development stream has been new science enabled by the more flexible MOM6 dynamical core. Several new features have been added to the parameterization of mesoscale eddies including both deterministic and stochastic energy backscatter. These will form the foundation of a new NOAA/NSF supported Climate Process Team (CPT) on the energetics of the ocean mesoscale. MOM6 has been successfully coupled to the CISM ice sheet model and tested in an idealized geometry configuration. A university led effort to provide an idealized geometry global dynamical ocean component within the CESM simpler models suite was organized and experimentation begun. These configurations are intended to complement the atmospheric aqua-planet configuration, and are suited to theoretical investigations of fundamental questions in climate dynamics.

Experimentation with the POP based CESM2 was conducted in both the standard eddy-parameterized (nominal 1°) and higher eddy-resolved (nominal 0.1°) resolutions. A series of experiments at the standard resolution were proposed to investigate the proclivity exhibited during CESM2 development for the model to transition into a state with an unrealistically cold and sea ice covered northwestern Atlantic, a.k.a., Labrador Sea freezing problem. In a departure from the plan in the proposal, this ensemble of experiments was conducted using the fully coupled model rather than the forced ocean-sea-ice configuration and hence consumed a larger fraction of the resources than planned. Unlike the practice during the CESM2 development, these experiments were conducted using a "clean" initial state based on observed conditions and with the released out-of-the-box model. Interestingly, these experiments exhibit indications of multiple equilibrium climate states with some ensemble members following the cold climate trajectory and some following a climate more similar to modern climate. A process-based analysis of this nonlinear behavior is underway. A significant fraction of the production allocation went to completing an ambitious high-resolution ocean-sea-ice simulation with the new JRA-55do forcing based on the Japanese Reanalysis product. This experiment is already being used by the community in a variety of studies of ocean dynamics, and is being extended by the international Laboratory on High Resolution Earth System Prediction (iHESP) project as the basis for a new high-resolution decadal prediction effort.

Paleoclimate Working Group (PaleoWG)

Resources over the past year have been used to conduct a set of simulations to further explore the sensitivity of CESM1.2 to forcing and boundary conditions during the Quaternary, and for design of paleoclimate simulations with CESM2. The additional simulations with CESM1.2 were conducted to 1) extend several orbital end-member simulations to explore dust variability in the Quaternary, and 2) understand the impact of a Green Sahara on the spatial distribution of d18O and precipitation in a simulation with the water-isotope-enabled version of CESM1.2 for the African Humid Period at 6000 years ago. A series of CESM2 simulations were also performed to 1) adapt and test the setup of new component model features for the CMIP6 Tier 1 Last Glacial Maximum simulation, 2) understand the effects of uncertainties in Eocene atmospheric carbon dioxide concentrations on simulated Eocene temperatures in light of the relatively high climate sensitivity of CESM2, and test the setup for the PMIP4/DeepMIP Early Eocene Climate Optimum simulation, and 3) optimize the effective design of a fully-coupled CESM2-CISM2 transient Last Interglacial (127,000 to 121,000 years ago) simulation, testing the effects of the initial Greenland ice sheet conditions, altered vegetation, orbital acceleration, and treatment of the freshwater flux (runoff and iceberg calving) to the ocean.

Polar Climate Working Group (PCWG)

The PCWG development resources have been primarily used for: 1) a new CESM2(CAM6) 1850 PI control run with re-tuned sea ice; 2) simulations that formed the basis of the 2019 Polar Modeling Workshop; 3) the implementation of COSPv2 (CFMIP Observation Simulator Package) into the CESM2; and 4) some initial simulations for investigating a sea ice thickness satellite simulator package.

Some PCWG production resources have been used also for the retuned CMIP6 1850 PI run as well as the Polar Modeling Workshop simulations as above. In addition, simulations in support of some of the manuscripts for the AGU CESM2 Virtual Special Issue have been performed. The satellite simulators for clouds in precipitation in COSP1.4/CESM1 have been used in detection and attribution and model evaluation research. The PCWG has developed community simulations that have been used in these efforts, and led to the publications by Lenaerts et al. (2020) and Takahashi et al. (2019). Additional simulations have been performed to study tropical and midlatitude impacts on seasonal polar predictability (Blanchard-Wrigglesworth and Ding 2019) as well as to document the role of thicker clouds in accelerated Arctic sea ice decline (Huang et al. 2019).

Software Engineering Working Group (SEWG)

The SEWG CSL allocation primarily supported software testing of CESM2 components and CESM as a whole, both for releases (CESM2.1.0 and CESM2.1.1) and for development versions of CESM2.2. This testing, which is run frequently as features are added and issues are addressed, caught many bugs before they affected users. Another major use of this allocation was for generating "Ensemble Consistency Test" baselines that can be leveraged to easily verify ports of CESM to new machines (http://www.cesm.ucar.edu/models/cesm2/verification/). Additional uses of this allocation included: testing a new workflow mechanism for CESM, including workflows for seasonal forecasts and CMIP6 ensemble experiments, and development runs to validate use of the Community Mediator for Earth System Prediction Systems (CMEPS) as part of the NCAR-NOAA Memorandum of Agreement (MOA).

Whole Atmosphere Working Group (WAWG)

The WAWG CSL allocation has been primarily used for three major activities. First, CESM1(WACCM4) simulations were performed using CMIP6 forcings, which were needed to deliver ozone and nitrogen deposition forcings to Chemisty-Climate Model Initiative (CCMI) and CMIP6. These forcings are being used by models participating in CMIP6 that do not have chemistry needed for such calculations. A second activity is the development of CESM2 and WACCM6 at FV resolution 1.9° latitude x 2.5° longitude resolution. Support for running CESM2 and WACCM6 at this reduced horizontal resolution is a feature of the CESM2.1.1 release. This capability allows CESM2 to be used by researchers with limited computing capabilities, and also for experiments of long timescale climate variability, such as the Last Millennium (850-1850). Third activity is spin-up and development of additional new WACCM compsets supported in the CESM2.1.0 and 2.1.1 releases. This includes support for chemical mechanisms of reduced complexity compared to the standard troposphere/stratosphere/mesosphere/lower thermosphere (TSMLT) chemistry: middle atmosphere (MA), middle atmosphere plus D-region (MAD) for studies of the ionosphere, and specified chemistry.

References

Blanchard-Wrigglesworth, E., and Q. Ding, 2019: Tropical and midlatitude impact on seasonal polar predictability in the Community Earth System Model. *J. Climate*, doi: 10.1175/JCLI-D-19-0088.1.

Bonan, G., D. Lombardozzi, W. Wieder, K. Oleson, D. Lawrence, F. Hoffman, and N. Collier, 2019: Model structure and climate data uncertainty in historical simulations of the terrestrial carbon cycle (1850-2014). *Global Biogeochemical Cycles* (submitted).

Buchholz, R. R., L. K. Emmons, S. Tilmes, and the CESM2 Development Team, 2019: CESM2.1/CAM-chem Instantaneous Output for Boundary Conditions, UCAR/NCAR - Atmospheric Chemistry Observations and Modeling Laboratory, doi: 10.5065/NMP7-EP60.

Danabasoglu, G., and Coauthors, 2020: The Community Earth System Model version 2 (CESM2). *J. Adv. Model. Earth Sys.* (in preparation).

Fasullo, J. T., 2020: A Climate Model Analysis Tool (CMAT; v1.0): Motivation, method, and application to the CMIP archives. *Geophys. Model Dev.* (in preparation).

Gettelman, A., and Coauthors, 2019: High climate sensitivity in the Community Earth System Model version 2 (CESM2). *Geophys. Res. Lett.*, **46**, 8329-8337, doi: 10.1029/2019GL083978.

Huang, Y., and Coauthors, 2019: Thicker clouds and accelerated Arctic sea ice decline: The atmosphere-sea ice interactions in spring. *Geophys. Res. Let.*, **46**, 6980-6989, doi:10.1029/2019GL082791.

Huffman, G. J., R. F. Adler, D. T Bolvin, and G. Gu, 2009: Improving the global precipitation record: GPCP Version 2.1. *Geophys. Res. Lett.*, **36**, L17808, doi: 10.1029/2009GL040000.

Jones, P. D., D. H. Lister, T. J. Osborn, C. Harpham, M. Salmon, and C. P. Morice, 2012: Hemispheric and large-scale land surface air temperature variations: An extensive revision and an update to 2010. *J. Geophys. Res.*, **117**, D05127, doi: 10.1029/2011JD017139.

Koven, C. D., and Coauthors, 2013: The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4. *Biogeosciences*, **10**, 7109-7131, doi: 10.5194/bg-10-7109-2013.

Lawrence, D. M., and Coauthors, 2019: The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *J. Adv. Model. Earth Sys.* (submitted).

Lenaerts, J. T. M., D. Camron, and J. E. Kay, 2020: Combining CloudSat observations and CESM simulations to untangle the past, present, and future of Greenland ice sheet precipitation. (in preparation).

Lenssen, N., G. Schmidt, J. Hansen, M. Menne, A. Persin, R. Ruedy, and D. Zyss, 2019: Improvements in the uncertainty model in the Goddard Institute for Space Studies Surface Temperature (GISTEMP) analysis. *J. Geophys. Res. Atmos.*, doi: 10.1029/2018JD029522.

Le Quéré, C., and Coauthors, 2016: Global Carbon Budget 2016. *Earth Syst. Sci. Data*, **8**, 605-649, doi:10.5194/essd-8-605-2016.

Malavelle, F. F., and Coauthors, 2017: Strong constraints on aerosol – cloud interactions from volcanic eruptions. *Nature*, **546**, 485-491, doi: 10.1038/nature22974.

Meehl, G. A., H. Teng, and J. M. Arblaster, 2014: Climate model simulations of the observed early-2000s hiatus of global warming. *Nature Climate Change*, **4**, 898-902, doi: 10.1038/NCLIMATE2357.

Takahashi, H., M. Lebsock, M. Richardson, R. Marchand, and J. E. Kay, 2019: When will spaceborne cloud radar detect upward shifts in cloud heights? *JGR-Atmospheres*, doi: 10.1029/2018JD030242.

Vose, R. S., and Coauthors, 2012: NOAA's merged land – ocean surface temperature analysis. *Bull. Amer. Meteor. Soc.*, 1677-1685, doi: 10.1175/BAMS-D-11-00241.1.

Wieder, W. R., and Coauthors, 2019: Beyond static benchmarking: Using experimental manipulations to evaluate land model assumptions. *Global Biogeochemical Cycles* (submitted).

Zaveri, R. A., and Coauthors, 2020: Global atmospheric distribution and radiative effects of nitrate aerosol. *J. Adv. Model. Earth Sys.* (in preparation).