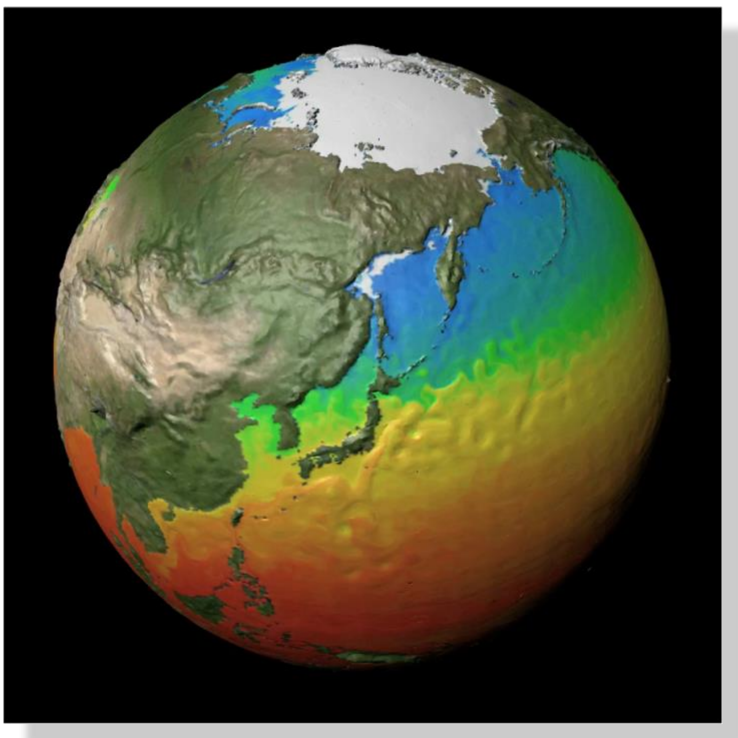
CESM

Community Earth System Model



CESM CSL Accomplishments

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CESM2 Development and CMIP6 Simulations

As discussed in the Summary Report for use of the CESM CSL allocation during the first year of the proposal cycle submitted in September 2017, CESM2 model showed two unacceptable features in its simulations. The first concerned formation of unrealistically extensive sea-ice cover over the Labrador Sea, extending into the Northern North Atlantic, that results in cessation of deep water formation in the Labrador Sea in some of the pre-industrial control simulations. The second was that the global surface temperature time series in historical simulations showed a significant and quite unrealistic cooling during the second half of the 20th century with the end-of-the century temperatures being actually colder than in 1850s. Substantial people and computational resources were dedicated to address these major challenges, together with several other problems that emerged along the way. About 120-140, mostly fully-coupled simulations of varying lengths – from several decades to more than 100 years – were performed, first, on Yellowstone until its decommissioning and, then, on Cheyenne. Because our CSL allocation on Cheyenne did not have a specific allocation for these simulations, they were performed under the *community simulations* allocation. The presence of extensive ice cover over the Labrador Sea region proved to be a very difficult problem to address robustly. For example, of the five identical coupled pre-industrial simulations that differed only in their initial atmospheric potential temperatures at round-off level, only one showed extensive sea ice cover while the others did not exhibit such behavior. It was also difficult to come up with a robust mechanism that would hold across different simulations with extensive ice formation. A practical solution was to continue with one of the ensemble members or cases without this unrealistic behavior. The global cooling issue was addressed in two ways. First, some errors were identified in the CMIP6 (Coupled Model Intercomparison Project phase 6) emissions data sets (before September 2017). Second, several adjustments were made to the model representation of aerosol cloud interactions to make specific processes better match available observations. Combination of these two largely addressed global surface temperature cooling problem. Essentially, CESM2 code base was frozen in early May 2018.

Subsequently, a major milestone was the long-waited, community release of the CESM version 2.0, CESM2.0, in early June 2018. This new version contains many substantial science and infrastructure improvements and capabilities for use of the broader CESM and international community. These new advancements include: an atmospheric model component that incorporates significant improvements to its turbulence and convection representations, opening the way for an analysis of how these small-scale processes can impact the climate; improved ability to simulate modes of tropical variability that can span seasons and affect global weather patterns; a land ice sheet model component for Greenland that can simulate the complex way the ice sheet moves – sluggish in the middle and much more quickly near the coast – and does a better job of simulating calving of the ice into the ocean; a global crop model component that can simulate both how cropland affects regional climate, including the impacts of increased irrigation, and how the changing climate will affect crop productivity; a wave model component that simulates how wind creates waves on the ocean, an important mechanism for mixing of the upper ocean; an updated river model component that simulates surface flows across hill sides and into tributaries before entering the main river channel; and a new set of infrastructure utilities that provide many new capabilities for easier portability, case generation and user customization, testing functionality, and greatly increased robustness and flexibility. A full list of updates with more technical descriptions is available at http://www.cesm.ucar.edu/models/cesm2/whatsnew.html.

It is important to note that CESM2.0 forms the code base for our CMIP6 simulations – that is, no code changes (i.e., no physics changes or tunings, parameter changes, etc.) are allowed with the possible exception of bug corrections. The CMIP6 pre-industrial simulations require spun-up land and ocean biogeochemisty (BGC) fields for initialization. These spun-up states were obtained in mid-July 2018, permitting us to start our pre-industrial control simulations. During the process of obtaining spun-up states for ocean BGC, some deficiencies in ocean BGC simulations were identified, resulting largely from deficiencies in ocean circulation. Tuning of ocean BGC was allowed to partially alleviate ocean BGC deficiencies. A new model version that incorporates these spun-up states along with additional non-answer-changing diagnostics and component sets relevant for many other CMIP6 simulations will be released in Fall 2018 as CESM2.1.

The computational time required to address the primary shortcomings of the CESM2 simulations – primarily due to the need for long pre-industrial control simulations (> 100 years) and the subsequent historical simulations to expose these issues, placed a major burden on our Cheyenne allocation. Specifically, the *community simulations* allocation was depleted in early June 2018. The Working Groups were requested to review their anticipated usage until 31 October 2018 (the end of our current allocation cycle) and donate any core-hours that would not be utilized. This process ended up re-allocation of Working Group resources by about 45 M Cheyenne core-hours to the *community simulations* project account. A significant portion of this re-allocated amount was used to address a few additional issues identified, including investigation of a couple of bug corrections; spin-up of land and ocean BGC, etc. The CESM2 CMIP6 simulations were finally started in late July 2018. As of writing of this report, two pre-industrial control simulations with WACCM and CAM6 atmospheric models, respectively, and three ensemble members of the historical simulation with WACCM are progressing. With our remaining allocation until 31 October 2018, we anticipate nearly completing these simulations. We also anticipate completing several ensemble members of the historical simulation with CAM6 during this period.

Atmosphere Model Working Group (AMWG)

The AMWG CSL allocation is used for Community Atmosphere Model (CAM) development and testing for use in the coupled system. As the "sphere" that mediates the Earth's radiation budget and the only component which communicates with all other components in an Earth System Model, the atmospheric model is the linchpin of the fully-coupled system. Use of CSL resources has allowed us to produce an atmosphere model that is compatible with other CESM components and gives a credible coupled climate simulation in both pre-industrial and 20th century configurations. Over the last two years the AMWG has addressed multiple problems and biases that arose in the coupled system, e.g., in Greenland and Amazon precipitation, and Labrador Sea ice dynamics. This involved examination of, among other things; interactions between surface drag and upslope precipitation around ice-sheet edges, sensitivities of parameterized deep convection to stable layers in the free-atmosphere, and the effects of momentum transport in the boundary layer. Most importantly, during the last year using CSL resources, the AMWG played a key role in understanding and correcting the cooling 20th century that arose in CESM2 when the CMIP6 aerosol emissions data were introduced in the system. This effort entailed an exhaustive investigation of aerosol-cloud interactions and sea surface temperature (SST)-cloud interactions in CESM.

In addition, CSL resources were used for the advancement of simpler model configurations as well as for further development of the spectral element dynamical core and variable mesh capabilities for CAM. More details on AMWG accomplishments are included below.

Model development for CMIP6

AMWG CSL resources were used to address a serious defect, i.e., cooling of the global mean surface temperatures over the mid- to late 20th century, that appeared in CESM2 with the introduction of CMIP6 emissions data. A number of explanations were considered for this behavior. Studies of cloud properties influenced by volcanic sulfate emissions (Malavelle et al. 2017) suggested that CAM6 microphysics may be overestimating the 2nd indirect aerosol effect (the 'lifetime' effect). The lifetime effect is essentially a consequence of a droplet number effect on auto conversion rates that goes as ~ $N^{-\alpha}$ where N is the cloud droplet number concentration, which is directly related to aerosol concentrations. As the exponent α becomes larger, auto conversion rates become slower so that "dirtier" air leads to longer lived cloud. Removing the N dependence altogether, i.e., α=0, appeared to resolve the cooling. However, this is not considered a physically plausible option. Extensive experimentation with alternate formulations of the auto conversion dependence on N was conducted. A compromise formulation with α=1.1 similar to that used in DOE's E3SM was adopted.

AMWG also explored adjustments of the prescribed vertical structure of CMIP6 aerosol emissions as well as sensitivity tests exploring geographical distributions of the emissions. A consistent message of these studies was that cloud forcing over eastern oceans (stratus decks) was stronger with CMIP6 emissions than CMIP5. This difference was traced to a systematic westward shift in emissions over continents in the CMIP6 data. To compensate for this, sulfate lifetimes were reduced.

In addition, during the last year errors in large-scale rain re-evaporation modules were found and fixed. These errors had to be compensated by explicitly adjusting convective rain evaporation. Continued development of the land surface was accommodated. The cumulative impact of all of the development discussed led to the substantially improved simulation of global mean surface temperatures.

Simpler Models

We have refined the aqua planet compsets for CESM2. Included in the release are compsets that provide a sensible default aqua planet with either fixed SST (QPC4, QPC5, QPC6) or a slab-ocean (QSC4, QSC5, QSC6). Along with sensible defaults, new functionality has been added. Switching across several analytic SST distributions is now very easy. A new option to provide a user-defined netCDF file with SST has also been added.

A number of sensitivity experiments have been conducted with the aqua planet configuration. We have tested for sensitivity to resolution, surface conditions, and atmospheric physics. Another set of experiments is being used to explore the aerosol assumptions made in the aqua planets, and is likely to lead to a small change in the default aqua planet in CESM2.1 (or a later release). Experiments with increased SST and/or increased atmospheric carbon dioxide were used to probe climate feedbacks and compare with development versions of CESM2.

The aqua planet configuration was also used to do initial tests with a shallow lowest model level. Moving from the default level midpoint of about 65 m down to about 8 m showed substantially degraded results. These experiments directly inform how we will proceed with increasing vertical resolution in the atmospheric boundary layer.

Other simple configurations

Radiative-convective equilibrium experiments have been used to understand how convective aggregation and extreme precipitation change with surface temperature.

Idealized physics are also now updated to be included in CESM2 as standard compsets. This includes simple Held-Suarez physics, the Polvani et al. (2004) baroclinic lifecycle test, a moist baroclinic wave with simple warm-rain physics, and Lauritzen's terminator chemistry test.

A cloud-locking methodology was developed and implemented in CESM1 and CESM2. This approach uses an external cloud dataset in the radiation calculation to decouple the cloud radiative effect from the predicted atmospheric state. This helps in understanding the role of cloud radiative feedbacks, both in the mean state and under climate-change conditions.

CAPT simulations

Hindcasts were conducted to explore the representation of shallow cumulus in CAM5 and (prototype) CAM6. The finding was that both models exhibit some systematic biases in cloud structure. When vertical resolution was increased (simple doubling), both models showed further degradation of the cloud vertical structure. In regionally refined hindcasts, the clouds were examined with grid spacing of about 27 km and 14 km. Neither resolution showed improvements with CAM5 physics, but the development version of CAM6 showed some improvement in cloud cover and vertical structure.

Additional hindcasts were conducted to investigate the predictive skill of tropical variability, especially the Madden-Julian Oscillation, in CAM5. A series of hindcasts were produced with the standard 1° resolution, regionally refined meshes (approximately 25 km grid spacing) over the Indian Ocean, the maritime continent, and the western Pacific Ocean, and finally a global 25 km grid was used (spectral element ne120 configuration). Results from these experiments are still being analyzed, but initial results are mixed. Increasing resolution does not improve large-scale structures, but can show improvement at smaller scales but only away from topography. Near topography, the small scales do not improve, and that is detrimental to the Madden-Julian Oscillation (MJO) propagation across the maritime continent. Increased resolution over the Indian Ocean does improve skill, showing that resolving smaller scales aids in the initiation of MJO events. Repeating the hindcasts at 1° with CAM6 showed rather poor MJO behavior; this is somewhat paradoxical because CAM5's predictive skill for the MJO is relatively good but in free-running simulations the MJO is poor, while CAM6 exhibits a good MJO in free-running simulations but has marginal skill in the hindcasts.

SE-CSLAM Development

CSL allocations were used to develop and evaluate new versions of the spectral-element (SE) dynamical core in CAM/CESM. A dry mass vertical coordinate was introduced to facilitate physics-dynamics coupling and facilitate the more accurate handling of condensates in SE; and thereby ensuring a more comprehensive total energy conservation. Details of the viscosity operators in SE were also changed to allow for reduced viscosity coefficients and the use of rougher orography (simultaneously). This model version is in the CESM2.0 release of SE and has been documented and evaluated (in aqua planet setup) in Lauritzen et al. (2018) using this CSL allocation

Despite recent these improvements in CAM-SE, potential problems with element noise and spurious dependence of climate statistics on location within elements remain. Also, the tracer transport scheme preserves correlations less well than the existing “work-horse” dynamical core, CAM-FV. To address these issues and improve tracer transport efficiency with respect to SE for large tracer counts, the CAM-SE-CSLAM version (Lauritzen et al. 2017) has been developed with the CSL allocation. This model version is currently being tested in *real-world* AMIP configurations. Early results have shown that element noise is significantly reduced and a long-standing bias of too much precipitation over high orography has been significantly reduced.

Regional Refinement

Development of regionally refined configurations of the SE dynamical core was performed under the CSL allocation as well as other allocations. A configuration with refinement over the continental US (CONUS) was tested and documented (Gettelman et al. 2018b). Comparisons of regionally refined configurations were compared with uniform high-resolution configuration. The regionally-refined models were found to faithfully reproduce the climate of the high-resolution simulations within the refined region.

Global High-Resolution

Extended global high-resolution simulations were primarily conducted using other allocations. However, CSL resources were utilized for some extended simulations and during development of high-resolution configurations. Studies examining tropical cyclone climatologies in CAM5 high-resolution simulations were completed and published (Bacmeister et al. 2018, Gettelman et al. 2018a).

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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:

- finalizing the configuration of ocean biogeochemistry for the upcoming release of CESM2.1, including a spinup for initializing the CESM CMIP6 pre-industrial control runs,
- continued work on the Newton-Krylov solver for fast ocean tracer spinup,
- continued development of MARBL (Marine Biogeochemistry Library),
- development of new ocean biogeochemistry parameterizations, for beyond CESM2.

As the spinup for initializing the CESM CMIP6 pre-industrial control runs progressed, it became clear that the biases in the ocean circulation in the coupled model were leading to unacceptable simulations of biogeochemical tracers. In particular, weak ventilation into the deep Pacific was leading to unrealistic anoxia throughout the deep Pacific. This, in turn, led to elevated levels of denitrification, which was depleting the ocean's inventory of nitrate. A considerable amount of the computational resources used by the BGCWG was devoted to modifying the ocean BGC model in an effort to compensate for these circulation deficiencies.

The efforts on Newton-Krylov solver for fast ocean spinup have led to it being applicable to some, but not all, of the geochemical tracers in the CESM's ocean biogeochemistry model. We have used this technique, where applicable, in the spinup for initializing the CESM CMIP6 pre-industrial control runs.

Two examples of new parameterizations that have been developed with the BGCWG computational resources are: developing an explicit calcifying phytoplankton functional group, and developing a variant of the existing ocean biogeochemistry model that introduces multiple size classes for each current phytoplankton functional group.

Chemistry-Climate Working Group (CHWG)

The CHWG used their CSL allocation for a number of developments for CESM2 as well as scientific analyses.

CAM5-chem and preliminary versions of CAM6-chem were run with Specified Dynamics to test new chemistry mechanisms (more detailed isoprene oxidation and formation of organic nitrates) and evaluate them with field campaign observations. 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.

The impact of resolution and chemical complexity on air quality over the U.S. has been evaluated by Brown-Steiner et al. (2018). Comparisons of three chemical mechanisms of different complexity have been made to assess the accuracy of the simpler mechanisms in predicting tropospheric ozone, and the trade-off in computing costs. This work compared the Superfast, a reduced hydrocarbon, and the MOZART-4 chemical mechanisms, with simulations of 25-years run for each mechanism. This work is in review for publication.

An historical simulation from 1850-2015 with a recent version of CESM2(CAM6-chem) has been performed with the extended description of secondary organic aerosols (SOA). This simulation produced SOA burdens and trends for different emission sectors, including biomass burning, anthropogenic and biogenic emissions. The simulation also included the capability to use SO_2 emissions from explosive volcanoes to form aerosols. The results from the simulation were used to produce a stratospheric aerosols distribution for CESM2 test simulations. Other test simulations with different descriptions of secondary organic aerosols were performed to compare to the simpler scheme in CESM2 without chemistry.

Simulations with different versions of preliminary CESM2 versions were performed to test the performance of the model, updated chemistry, and physical descriptions. Test simulations with SE dynamical core were performed as baseline for current developments of SE regional refinement.

CAM-chem simulations, at 1° and 0.5°, with several different complexities of chemical mechanisms, have been run to support analysis of a variety of atmospheric chemistry field experiments. CAM-chem simulations with the CLM interactive fire module has been tested and a new compset is now available to be released with CESM2.1 that includes interactive fire emissions. A new aerosol dry deposition (Wu et al. 2018) scheme and capability of considering brown carbon impact (Brown et al. 2018) have been implemented in CAM. These new developments were with CAM5, and are ready to be merged to CAM6(-chem) for further testing.

There have been five studies on the impact of very short-lived (VSL) halogen compounds completed using CSL resources. The first study (Koenig et al. 2017) featured CESM1 (CAM4-Chem) results of inorganic bromine profiles over the Western Pacific. This work showed the relevance of local inorganic bromine sources to the distribution of BrO in the tropical tropopause layer during the CONvective TRansport of Active Species in the Tropics (CONTRAST) and the Airborne Tropical TRopopause EXperiment (ATTREX) field campaigns (January and February 2014) based out of Guam. The second study, again using CESM1 (CAM4-Chem), quantified the stratospheric injection of brominated very short-lived substances (VSLS) using aircraft observation and model results in the tropical Western Pacific region. The overall contribution of VSLS to stratospheric bromine was determined to be 5.0 ± 2.1 pptv, in agreement with the 5 ± 3 pptv estimate provided in the 2014 World Meteorological Organization (WMO) Ozone Assessment report, but with lower uncertainty (Wales et al. 2018). The third study (Cuevas et al. 2018) examined the rapid increase in atmospheric iodine levels in the North Atlantic since the mid-20th century. The levels of iodine tripled from 1950 to 2010. This work used CESM1 (CAM4-Chem) and ice core data. Our results suggest that this increase is driven by anthropogenic ozone pollution and enhanced sub-ice phytoplankton production associated with the recent thinning of Arctic sea ice. Increasing atmospheric iodine has accelerated ozone loss and has considerably enhanced iodine transport and deposition to the Northern Hemisphere continents. The fourth study (Fernandez et al. 2017) examined both the impact of bromine chemistry on ozone depletion and the role that this additional VSL bromine chemistry will play on the polar ozone recovery to 1980 conditions. The last study (Navarro et al. 2017) used observation of organic VSL halogens and CESM1 (CAM4-Chem) during the

ATTREX campaigns in both 2013 and 2014. The 2013 campaign was in the Eastern Pacific, and the 2014 campaign was in the Western Pacific. Chemistry implications were highlighted that modified the inorganic bromine partitioning between the two regions.

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Climate Variability and Change Working Group (CVCWG)

The CVCWG has conducted numerous sets of simulations of use to the wider community. These include contributions to sets of simulations at high resolution as well as simulations to investigate climate variability and change.

The working group has contributed to two projects with the goal of providing large sets of high-resolution simulations to the community. For the first, we have nearly completed sets of fully-coupled and atmosphere/land-only configurations of the CESM1.3 using the 0.25° resolution (mostly conducted at other computing centers); however, the two sets used different model tags. Two changes came into the code between those tags. To determine the impact of these changes on climate, we have used Cheyenne to run a series of present day (1979-2012) simulations at the 1° resolution using the SE grid. A comparison of these tag tests will give us confidence in comparing the fully-coupled to the uncoupled simulations. Because, by default, 1° simulations use the FV grid, we did not have comparable 1° simulations to study resolution impacts. Using Cheyenne, we have completed approximately 200 years of a pre-industrial simulation.

The CVCWG has previously conducted numerous pacemaker experiments to help determine how variability in each ocean basin influences climate variability worldwide. Simulations that relaxed sea surface temperature in the North Atlantic to an idealized pattern of the Atlantic Multidecadal Variability (AMV) resulted in a Pacific Decadal Variability (PDV) pattern in its negative phase. To determine the role of aerosols in this connection, we re-ran those idealized AMV experiments but kept aerosols fixed at their 1920 values. Results do indicate that aerosols played a role in this Atlantic-Pacific connection.

The coupling of land to the atmosphere through soil moisture can potentially provide atmospheric predictability on subseasonal to interannual time scales. There is evidence that land initialization can substantially improve operational forecast skill, but the impact of soil moisture on atmospheric circulation has not been carefully investigated with CESM. In this project, we carried out a series of CAM5 stand-alone simulations with prescribed soil moisture anomalies. Each time we perturbed the soil moisture, we ran 100 ensemble members with the atmosphere initial conditions taken from the CESM Large Ensemble (LE) control run. We finished over 2000 years of CAM5 simulations.

Another project was intended to explore the reversibility (or possible hysteresis) in the behavior of the climate system when reverting CO2 concentrations to the level used in the pre-industrial control simulations from the higher concentrations (2x and 4x). Metrics considered are related to ocean circulation, surface mass balance of the Greenland ice sheet, soil carbon and vegetation changes, permafrost melting and ocean stratification, as well as surface temperature and precipitation.

At the 2017 CFMIP meeting, the width of the Inter-Tropical Convergence Zone (ITCZ) and its effects on general circulation were identified as a key research topic. In collaboration with Mike Byrne (Imperial College London), we are developing a MIP protocol for examining the effects of changing the width of the ITCZ and its variation across models. In experiments conducted this past year, we tested possible methods of forcing that may impact the ITCZ width. These methods will be incorporated into the ITCZ MIP.

A 10-member Tropical AMIP ensemble using the most recent observational sea surface temperature product from ERSSTv5 was conducted for the period 1880-2017 with CAM5 at 1° resolution.

In addition to the 20-member “eliminated” single forcing ensembles, i.e., anthropogenic aerosols or GHG held fixed at year 1920, which were led by CVCWG and conducted with community resources, the CVCWG used its own resources to run a 10-member ensemble with biomass burning held fixed at year 1920. These simulations use the CESM LE tag, and run from 1920 through 2080.

Finally, we had a major new release of the Climate Variability Diagnostics Package (CVDP) and developed the Climate Model Assessment Tool (CMAT). Both were helpful for CESM2 development.

Land Ice Working Group (LIWG)

LIWG has continued to develop the Community Ice Sheet Model (CISM) and land-ice-relevant code in the Community Land Model (CLM) and the CESM coupler. This work culminated in the release in June 2018 of CESM2.0 and CISM2.1, both of which have significant new land-ice capabilities. Following the CESM release, work has focused on an interactive ice-sheet/climate spin-up as an equilibrated initial state for coupled experiments under the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6).

Development

CSL computing resources during the past year have supported the following new CISM capabilities:

- Improved parameterizations of key physics processes, including basal sliding, iceberg calving, sub-ice-shelf melting, and grounding-line migration.
- Development of a new scheme for spinning up the Antarctic ice sheet by inverting for basal friction parameters (beneath grounded ice) and basal melt rates (beneath floating ice). This scheme was used to spin up the Antarctic ice sheet for 30,000 years at 4-km resolution, followed by forward runs with changes in surface and basal mass balance. Results from selected forward runs were submitted to several community Model Intercomparison Projects (MIPs): initMIP-Antarctica, LARMIP, ABUMIP, and a precursor to ISMIP6 ice sheet experiments.

Improved parameterizations of sliding, calving, and sub-shelf melting with application to the Greenland ice sheet are described by Lipscomb et al. (2018). The Antarctic inversion scheme and grounding-line improvements will be described in forthcoming work.

In addition, CSL resources supported ongoing CLM development. Following completion of a new model of terrestrial snow and firn (van Kampenhout et al. 2017), recent simulations have tested further snow model improvements, in particular a modified initial snow grain size parameterization to achieve better melt rates on the Greenland Ice Sheet. These results will be published in a CLM5 development paper (Lawrence et al. 2018).

These recent changes in CISM and CLM have been tested in ice-sheet parameter sensitivity studies using a variety of CESM configurations, including T, TG, I, IG, JG, B, and BG compsets. (Here, a “G” denotes that the Greenland ice sheet is run interactively.) These studies include:

- Surface mass balance (SMB) and high latitude climate evaluation and studies with different values of CISM parameters, with the goal of having an optimal SMB / Greenland climate simulation in CESM2.
- Investigation of the downscaling method used to map SMB from the CLM grid to the high-resolution (4-km) CISM grid. A publication with results is planned for *JAMES*.
- Tuning of CISM's new sliding parameterization. A publication on simulation of northern Greenland ice streams is planned for 2018.
- Testing of CISM2.1 with ice shelves, including sub-shelf basal melt parameterizations.
- Simulations in support of the BG/JG spin-up, to evaluate effects of coupling, model biases, time to equilibrium, etc.
- Preparation of a transient simulation of the last deglaciation

As CESM2 neared completion, another set of simulations tested the JG/BG infrastructure for spinning up a fully coupled CESM-CISM simulation in close collaboration with the PaleoWG members. The goal is to equilibrate the Greenland ice sheet in a coupled fashion (estimated to take ~10 kyrs), at a fraction of the cost of a fully coupled simulation of this length. This is done by iterating between a fully coupled setup (BG compset) and a coupled setup with a data atmosphere (JG compset), using atmospheric forcing from the previous fully coupled simulation. Simulations were carried out to identify potential shortcomings of the setup before starting the production run. A strong imprint of the coarse CLM grid was found in regions where the CISM topography transitions between (CLM) elevation classes, and several IG (active land/ice-sheet) simulations were run to diagnose the problem and assess solutions.

LIWG members have also conducted a case study with a variable-resolution version of CAM, refined to 28 km over Greenland for more accurate simulations of ice sheet SMB. Results from the study will be submitted to *The Cryosphere* (van Kampenhout et al. 2018). Associated with these simulations are a new software package to remap CLM vector output to gridded data: https://github.com/lvankampenhout/libvector. AMIP simulations (active atmosphere/land with prescribed sea surface temperature and sea ice) are now being used to study changes in Greenland surface climate with varying versions of CAM. AMIP simulations are also supporting CESM participation in the new SMBMIP led by Xavier Fettweis (University of Liège).

Finally, CSL resources have been used to run software test suites for land ice-relevant changes in CLM and CISM.

Production

Following the CESM2 release, LIWG resources have been used for the JG/BG spin-up described above, with the goal of equilibrating the Greenland ice sheet with the pre-industrial climate. The spin-up consists of alternating BG simulations (35 years each, at 3500 cpu-hrs/yr) and JG simulations (150 years each with CISM accelerated, at a cost of 1000 cpu-hrs/yr). We aim to complete the cycle of simulations by 31 October 2018.

Another set of simulations was used to study Last Glacial Maximum steady states with the coupled CESM-CISM. Results of this study will be published in JAMES.

Other planned production experiments were deferred to the next CSL cycle because of the later-than-expected release of CESM2. These experiments are described in the proposal.

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Land Model Working Group (LMWG)

Resources over the past year have been used to finalize CLM5, the land component of CESM2, and to conduct a set of simulations that are being used for documentation and publication of CLM5 (Fig. 1). The focus over the past year has been on simulations designed to support understanding and assessment of the many new parameterizations and features that have been included in CLM5. Resources have also been used to support a range of scientific studies on land use change, groundwater, plant physiology, and soil microbiology and the impact of these processes on carbon and water trajectories under historic and projected climate change.

	CLM4				CLM4.5				CLM5			
Forcing	SP	BGC	+N, $+CO_2$	no LULCC	SP	BGC	+N, $+CO_2$	no LULCC	SP	BGC crop	+N, $+CO_2$	no LULCC
GSWP3 v1	✓°	✓° ✸	✓	✓	✓	✓° ✸	✓	✓	✓°	✓° ✸	✓	✓
CRUNCEP v7		✓				✓			✓	✓✸		✓
WATCH/ WFDEI									✓[WF]	✓[W]		

Figure 1. Simulations performed for assessment of CLM. ✓indicates historical simulation (1850-2014, [W]1850-2001, [WF]1979-2014). ✸ indicates projection period simulation (RCP8.5, 2015-2300), ° indicates daily and hourly output for selected years. Abbreviations: SP – Satellite Phenology, BGC – biogeochemistry, LULCC – land-use and land-cover change.

Development

CLM5 developments were wide ranging and included model updates to the nitrogen and carbon cycles, soil hydrology, the river model, the snow model, crops, land-cover and land-use change, vegetation phenology, and the urban model.

An addition to development activities over the past several years has been a first attempt at parameter optimization for CLM. Parameter optimization for a global land model is challenging due to the complexity of the model, especially with an active carbon cycle, the long 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 plant functional type (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).

Additional long-term development projects that have been active for CTSM/CLM6 include:

- A next generation multi-layer canopy model for CLM (Bonan et al. 2018).
- A representative hillslope hydrology formulation in collaboration with CUAHSI.
- Ecosystem Demography model (FATES, Functionally-Assembled Terrestrial Ecosystem Simulator) including specifically the development of SPITFIRE fire module. SPITFIRE captures sub-grid heterogeneity in fuels and size- and species-specific mortality as a function of fire disturbance.
- Development of a new global urban properties dataset and tool for inclusion in CLM5.

Production

Additional simulations over the past year have been conducted to support several scientific studies, including:

- Projection period (2006-2100) simulations to determine the impact of future forcings on crop and timber yields (Lombardozzi et al. 2018).
- Development and application of International Land Model Benchmarking (ILAMB) package utilizing CLM output (Collier et al. 2018).
- Permafrost climate-carbon feedback land-only simulations out to 2300 using the CLM anomaly forcing capabilities (McGuire et al. 2018).
- Evaluation of different stomatal conductance models (Franks et al. 2017).
- Coupled CAM-CLM simulations to determine the impact of adding cover crops on climate (Lombardozzi et al. 2018).

- Multi-model assessment, including CLM4.5 simulations, of projected permafrost climate-carbon feedback (McGuire et al. 2018).
- An assessment of the impacts of human interference with fire (ignition and suppression) over the 20th century (Li et al., 2018).
- Impact of biomass heat storage on canopy energy balance and atmospheric stability in CLM (Swenson et al. 2018).
- Examination and improvement of diel cycle of surface energy budget, ET, and momentum fluxes at Niwot ridge (Burns et al. 2018).
- Model-data integration study utilizing artificial warming experiment in Alaska to evaluate model versus field response to warming (Schaedel et al. 2018).
- Ensemble of CLM5 simulations to evaluate model uncertainty including start year uncertainty and structural uncertainty.

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Ocean Model Working Group (OMWG)

The OMWG is in the midst of a major transition of the dynamical core of the CESM ocean component model, moving from the Parallel Ocean Program (POP) that has been used in CESM since CCSM version 2 through the present, to the Modular Ocean Model version 6 (MOM6). The choice of MOM6 as the new dynamical core was finalized shortly after the previous CSL proposal was submitted. Since summer 2017, a large fraction of the OMWG development allocation has been used for configuring a prototype version of MOM6 for CESM; developing the necessary infrastructure to couple MOM6 to the CESM framework; creating a new nominal 2/3° ocean grid; implementing the K-Profile vertical mixing parameterization via the CVMix (Community ocean Vertical Mixing) framework; and incorporating missing aspects of frazil ice formation and melting between the ocean and sea-ice models. Numerous ocean-only and ocean – sea-ice coupled simulations have been performed.

Noting that the CVMix framework is independent of any ocean model dynamical core, we implemented and tested new tidal mixing parameterization choices as well as incorporated some modifications to the Langmuir mixing parameterization within CVMix. Numerous short simulations were performed for testing and evaluation purposes.

Using CSL time, we also initiated the development of a high-resolution ocean data assimilation (DA) infrastructure. We have now implemented a far less expensive *ensemble optimal interpolation* (EnOI) approach within the Data Assimilation Research Testbed (DART) to reduce prohibitively high cost of an ensemble adjustment Kalman filter with the 1/10° eddying POP ocean model. A prototype high-resolution ocean reanalysis using the DART-EnOI implementation and the 1/10° POP ocean model is currently underway on Cheyenne. In an effort to further reduce the cost associated with DA experiments, an active External Systems Processing (ESP) model has been developed as part of the DA pause-resume project. The ESP is able to run the DART filter during the pause cycle of a CESM run. Currently under development is an EnOI DA experiment running an instance of the high-resolution POP in pause-resume mode.

CSL resources were also used to complete the development and evaluation of the new interannually varying atmospheric forcing data sets based on the JRA-55 (Japanese Reanalysis from the Japanese Meteorological Agency) product for the 1958 – near-present period. For this purpose, many ocean – sea-ice coupled hindcast simulations have been performed for one-to-ten repeat forcing cycles, using the nominal 1° model version with POP. Furthermore, several additional, long (order 500 years) simulations have been carried out, using a single-year repeat cycle forcing to evaluate the fidelity of the solutions for several candidate single (*normal*) years. Upon completion of the new JRA-55 data set, several, short ocean – sea-ice coupled simulations with the high-resolution (1/10°) version have also been performed. These short simulations serve to evaluate solutions from this high-resolution version in preparation for longer hindcast simulations.

In another project, fully-coupled ensemble experiments with CESM1 have been conducted designed to isolate the role of the North Atlantic Oscillation (NAO)-induced buoyancy forcing for decadal-scale Atlantic meridional overturning circulation and Atlantic multidecadal variability and associated climate impacts.

Paleoclimate Working Group (PaleoWG)

Development

The PaleoWG development efforts focused on testing and preparing for the CESM2 Paleoclimate simulations to be completed in the 2018-2020 CSL allocation. This included: testing and fixing boundary conditions for Pliocene Model Intercomparison Project Phase II (PlioMIP2); testing the JG/BG infrastructure to equilibrate the ice-sheet component in a coupled fashion (estimated to take ~10 kyrs) at a fraction of the cost of a fully coupled simulation of this length by iterating between a fully coupled setup (BG compset) and a fully coupled setup with a data atmosphere (JG compset), using atmospheric forcing from the previous fully coupled simulation; diagnosing a problem in the downscaling of temperature from the CLM grid (nominal 1° resolution) to the CISM grid (nominal 4 km resolution); extending the CISM2 domain to encompass a large portion of the Northern Hemisphere continents to enable simulations of, e.g., the last glacial maximum (LGM) and the last glacial inception; and initial BG simulations at FV2x1 resolution. We note that the work on fast equilibration of ice sheets were done in close collaboration with the LIWG members.

Production

The PaleoWG production efforts focused on using the water isotope-enabled version of CESM1 (iCESM1; iCESM Project Members 2018). Using this model version, the Last Millennium Ensemble (LME) was extended with extra simulations. These simulations included three iLME ensemble members with all natural and anthropogenic forcings (volcanic, solar, orbital, land-use, greenhouse gas, anthropogenic aerosol), as well as two members run with only volcanic forcing, one each with only GHG forcing, solar forcing, and orbital forcing, and a corresponding control simulation. As such, they provided 8 additional members to the LME as well as provided a smaller ensemble of simulations to be compared to isotopic proxy records by the community.

Additionally, iCESM1 was employed for a freshwater hosing simulation with LGM boundary conditions. The goal of this experiment was to compare the global climatological and isotopic responses of freshwater flux in the North Atlantic. This simulation will allow for refined interpretations of the proxy records at the onset of the last deglaciation. This simulation complemented idealized snapshot experiments completed with an NCAR Strategic Capability (NSC) allocation to quantify the spatial and temporal isotopic responses to changes in Earth's orbit, CO_2 concentration, and ice volume (Tabor et al. 2018).

And third, early Eocene simulations using iCESM1 were completed. The simulations will contribute to the Deep-time Modeling Intercomparison Project (DeepMIP), as part of the Paleoclimate Modeling Intercomparison Project. Multiple long (at least 2000 model years) Eocene simulations with various atmospheric CO_2 concentrations have been completed. In addition, simulations evaluated the impact of soil color, vegetation cover, and cloud parameters. These Early Eocene simulations are being compared with Eocene proxy records to help us constrain climate sensitivity and better understand how climate dynamics work in a hothouse climate (Zhu et al. 2018a, 2018b).

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Polar Climate Working Group (PCWG)

PCWG scientists are interested in understanding and modeling Arctic and Antarctic climate and its relationship to global climate. Over 2017-2018, PCWG CSL resources have been used to complete experiments for both CESM development, evaluation and for scientific research.

Development

The PCWG used development resources to implement diagnostics that enable accurate evaluation of atmospheric model moist physics parameterizations with satellite observations. Specifically, we enhanced the implementation of a satellite simulator package for clouds and precipitation called COSP (Bodas-Salcedo et al. 2011) within CESM. During year 1 (2017), development computing resources were used to port COSP version 1.4 to the CESM Large Ensemble code base and to implement new diagnostics for cloud opacity (Guzman et al. 2017) and precipitation occurrence frequency (Kay et al.

2018). During year 2 (2018), development computing resources were used to implement COSP version 2.0 (Swales et al. 2018) into CESM2. Due to computing support from the PCWG development allocation and NASA funding, COSP version 2.0 was released in CESM2.0 for the community to use in June 2018.

We also developed the interface of CICE5 in the CESM2 framework to run with the Data Assimilation Research Testbed (DART) to enable sea ice data assimilation (Zhang and Bitz 2018). We developed a series of post processing steps and tested them and also ran a series of experiments to test the distance that observations should influence the simulation (known as localization) and methods to create spread in the ensemble. Another major part of our work was to test the influence of assimilating various types of observations. Finally, we explored parameter estimation in the sea ice model. Two papers are in preparation on this new capability.

Simulations were also performed for testing the sea ice model and to obtain output to drive a single column version of the sea ice model (IcePack) which is now available to the research community.

Production

Towards our over-arching PCWG production goal of enabling important and timely polar science research using CESM, we have run numerous experiments that leverage and enhance community projects and expertise. This work has been performed by members of the working group at a number of different universities and at NCAR. Much of this work is ongoing.

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. Using PCWG production resources, we ran 100 years of an 1850 control run and two future ensemble members (2006-2100) under the RCP8.5 emissions scenario within the framework of the CESM Large Ensemble (LE) Project with diagnostics from the satellite simulators contained within COSP1.4 turned on. The simulations include the new cloud and precipitation diagnostics described in Guzman et al. (2017) and Kay et al. (2018). These pre-industrial and future simulations are being used to assess reliability and detectability of future forced polar cloud and precipitation changes. We are making these simulations available for anyone to use on the NCAR Wyoming Supercomputing Facilities. These simulations are of interest to many researchers studying moist atmospheric processes and how they will change over the 21st century, and are already being used for science (e.g., Camron et al. 2018; L'Ecuyer et al. 2018), education (e.g., at an NSF-funded Polar Modeling Workshop held during 13-18 August 2018), and future mission planning (e.g., in planning for future spaceborne radar and lidar as a part of the missions recommended by the 2018 NASA Decadal Survey).

Predictability research: Using 2017-2018 CSL resources, a number of aspects of polar predictability have been investigated. This includes enhancements to a large number of “perfect model” prediction ensemble simulations that are initialized with conditions from the CESM LE at every decade from 1980 to 2040. These have been run for 2 years in length to assess initial value predictability on seasonal to interannual timescales. From these integrations, we find that the predictability characteristics of Arctic sea ice change with the changing climate. In particular, conditions in the early 21st century have enhanced ice prediction skill relative to earlier or later decades. A paper documenting these results is in preparation.

Additional “perfect model” experiments have been run to assess the dependence of sea ice predictability on the state of the tropical Pacific. This includes experiments branched from the CESM1 LE with initial conditions selected during periods of SST extremes in the tropical Pacific. The Arctic sea ice thickness exhibits a strong response, with thinning under El Nino-like conditions and thickening under La Nina. By the summer, the sea ice concentration has a significant signal as well. The sign of the response is not as homogeneous, but there tends to be less sea ice in the Pacific sector in the summer following an El Nino. This work is being written for publication and will be used in the Masters Thesis of a University of Washington graduate student in Atmospheric Sciences.

Additional work to assess polar predictability from extra-polar sources has been performed by running a series of perfect model predictability experiments in which the atmosphere over a fixed extra-polar domain (both 30°N-30°S and 55°N-55°S) is nudged to a parent run. By comparing predictability characteristics in the nudged ensembles to the free-running ensembles, we can partition remote versus local sources of predictability. Preliminary results show that the Arctic is more *local* than Antarctica, with only modest improvement in seasonal predictability in the nudged ensembles relative to the free-running ensemble. The work will be presented at AGU, and is being written for publication.

Freshwater tracer experiments: A further focus of PCWG work has been to understand the changing freshwater distribution in the Arctic ocean. Towards this goal, we have performed one CESM LE member, 1850-2100, with additional tracers in the ocean model to track freshwater from different sources. We are analyzing the simulation to better understand the impact of 20th and 21st century changes in the Arctic Ocean on upper ocean circulation and the storage of freshwater, which has the potential to impact the deep-water formation in the North Atlantic if released in large anomalies. By using the additional tracers, we can assess whether any changes in the dynamics and pattern of Arctic freshwater system are projected to occur. This analysis follows a general analysis of the CESM LE Arctic freshwater export and storage, which has shown large changes in the freshwater export through different pathways. In particular, we have found that the freshwater export west of Greenland increases significantly over the 21st century, and the freshwater tracers will be used to better understand what is driving this simulated shift of freshwater export.

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Software Engineering Working Group (SEWG)

Development

During the past year, the SEWG development allocation was used to incorporate major science and infrastructure changes across the CESM system as part of the finalization and successful release of CESM2.0. In particular, close to 30 development snapshots of the model system were created, each containing both new software infrastructure as well as scientific capabilities. The creation of each model snapshot required hundreds of system and unit tests to be carried out in order to ensure model robustness and optimal model performance. These snapshots also provided out of the box support for bug fixes. As part of this development cycle, the Computational and Information System Laboratory (CISL) Application Scalability and Performance Group (ASAP) Primary Component Analysis tool, pyCect, was used on select beta tags to ensure a statistically valid climate after the introduction of new science code and new machine configurations. In addition, the SEWG CSL allocation was utilized to integrate a new parallel I/O library (PIO2) into CESM and to carry numerous performance optimization studies.

The SEWG CSL allocation was also utilized for two important infrastructure efforts listed below:

Common Infrastructure for Modeling the Earth (CIME): Starting in the fall of 2015, CSEG introduced the CIME. CIME is an emerging paradigm for the collective construction and maintenance of the infrastructure required by Earth system model development and applications. It was developed as a response to the February 2015 summit of the US Global Change Research Program (USGCRP) / Interagency Group on Integrative Modeling (IGIM), which called for greater coordination across centers engaged in Earth system modeling. CIME was created in order to facilitate communication and collaboration on the design and implementation of Earth system model infrastructure software, improve design and execution, avoid duplication and redundancy, and share experiences.

Currently, CIME contains the support scripts, data models, essential utility libraries, a driver, and other tools that are needed to build a single-executable coupled Earth System Model. It is publicly available in a stand-alone package that can be compiled and tested without full prognostic components. CIME is currently being actively developed by both DOE/E3SM and NCAR software engineers and it is anticipated that NOAA will also become an active collaborator.

Over the last year, new capabilities have been introduced into the CIME Case Control System that will enable the user community to more easily port CESM to new platforms, verify that the ports were robust, and more easily add new configurations, resolutions and science to carry out their research.

Integration of python based parallel post processing for CESM workflow management and automation: In preparation for the CMIP6 experiments, CSEG developers continued to work closely with the CISL ASAP group to integrate lightweight parallel python tools into the CESM workflow. These tools include the pyReshaper for converting history time slice files to compressed variable time series files, the pyAverager for computing averages and climatology files used with various working group existing diagnostics packages, and the ASAP PyTools for parallel processing.

Whole Atmosphere Working Group (WAWG)

Despite delays to planned production runs due to the delay in CESM2 development, the WAWG has made significant strides using CSL resources. These include updates to gravity waves, stratospheric sulfur, advancements of WACCM-X and participation in several community projects with production runs. We now have a common code base for WACCM6 with CAM6 in CESM2 and new functionality for WACCM-X. We have finalized updates to WACCM, and have begun the CMIP6 WACCM piControl and historical simulations. These WACCM simulations are producing forcings for the CESM2 CMIP6 simulations (with CAM in place of WACCM as the atmosphere component). We included 14 configuration sets in the CESM2.0 release for WACCM and WACCM-X. We are updating these, and adding new sets for the CESM2.1 release.

CESM1 (WACCM) with Chemistry Climate Model Initiative (CCMI) chemistry

The CSL production allocation has supported the WACCM CCMI science objectives. These resources have directly led to the publication of ~30 peer-reviewed publications during the past two years. We will highlight four of the papers below. The first paper examined the evolution of polar ozone evolution during the depletion (1980-2000) and recovery periods (post 2000). This work examined the "mirrored" changes in ozone and temperature using observations and CESM1 (WACCM). Details regarding the indicators for ozone recovery were discussed (Solomon et al. 2017). The second paper also examined the depletion and recovery period with a focus on global temperature change. Troposphere and stratospheric temperature trends were derived from satellite data compared with ensemble simulations from CESM1 (WACCM). The model captures the observed trend structure in most respects, and the ensemble of simulations provides quantitative estimates of the impact of internal variability on trend estimates (Randel et al. 2017). The third paper used CESM1 (WACCM) with multiple ensemble members to show that there was significant weakening of Brewer-Dobson circulation (BDC) trend over the 21st century as a consequence of the Montreal Protocol. It is well established that increasing greenhouse gases, notably CO_2 will cause an acceleration of the stratospheric BDC by the end of this century. In this work, for the first time, we present compelling new evidence that ozone depleting substances are also key drivers of BDC trends (Polvani et al. 2017). The fourth paper showed the role that the Calbuco eruption played in enhancing the observe ozone depletion. The Southern Hemisphere Antarctic stratosphere experienced two noteworthy events in 2015: a significant injection of sulfur from the Calbuco volcanic eruption in Chile in April and a record-large Antarctic ozone hole in October and November. Here, we quantified the Calbuco's influence on stratospheric ozone depletion in austral spring 2015 using observations and an CESM1 (WACCM) with the specified dynamics option. We analyzed ozonesondes, as well as data from the Microwave Limb Sounder. In addition, the Cloud-Aerosol Lidar with Orthogonal Polarization data was used. The results indicated that enhanced volcanic liquid sulfate 532 nm backscatter values as far poleward as 68°S during October and November (in broad agreement with WACCM). Comparison of the location of the enhanced aerosols to ozone data supports the view that aerosols played a major role in increasing the ozone hole size, especially at pressure levels between 150 and 100 hPa (Stone et al. 2017).

WACCM CARMA (Community Aerosol and Radiation Model for Atmospheres) Simulations

We developed a full PSC model coupled with sulfate model. The model has been tested and compared well with the CALIPSO PSC observations in 2010 Antarctic winter. We also simulate the volcanic aerosols and PSCs after the Calbuco eruption in 2015. The modeled volcanic aerosols compare well with CALIPSO and OSIRIS observation. Results have been published in Zhu et al. (2017a, 2017b).

WACCM Volcanic Events

In Schmidt et al. (2018), we derive a time-series of global-mean volcanic effective radiative forcing (ERF) for the period 1979 to 2015, accounting for volcanic aerosol in the lowermost stratosphere and rapid adjustments by using a detailed volcanic sulfur dioxide (SO_2) emission inventory in CESM1 with comprehensive sulfur chemistry and a prognostic stratospheric aerosol scheme (WACCM-MAM). We find that the most powerful eruptions between 1979 and 2015 had a substantial climatic impact. However, we calculate that their effect on climate is about 20% weaker than previous estimates used by the Intergovernmental Panel on Climate Change (IPCC). In our model simulation this is mainly a result of the volcanic aerosol particles affecting ice clouds, making these clouds less transparent. We also find that it is very rare to have a period with relatively few notable explosive eruptions as was the case during 1996-2002. Further eruptions of small-to-moderate size occur frequently and decrease the transparency of the stratosphere by as much as all non-volcanic sources of aerosol particles combined. These small-sized volcanic eruptions therefore cause a small but noticeable surface cooling and so should be included in climate model simulations, which is rarely done.

PALEOSTRAT

Progress on this project has been limited by the decision to switch from the WACCM5.4 code base to WACCM6, and the delayed release of the latter. Nevertheless, we have now run the 2° version of CAM6 (faster and less expensive) and adjusted parameters in the CLUBB parameterization to obtain top of atmosphere balance under pre-industrial conditions. Tuning requires further refinement to achieve an acceptable balance but a balanced model should be available within the next few weeks. At that point we will switch testing to WACCM6, ascertain the balance in that model under pre-industrial conditions, and proceed to simulate the 20th century. We anticipate that much of this tuning work can be accomplished using remaining resources from the 2016-2018 proposal.

WACCM-X Development

A comprehensive ionospheric package has been implemented in WACCM-X 2.0, including interactive ionospheric electric dynamo, O+ transport, and an electron/ion temperature solver. The model has a more physically realistic representation of the ionosphere and thermosphere system. The WACCM-X 2.0 development is reported by Liu et al. (2018). Historic runs, both with and without tropospheric and stratospheric constraint by MERRA reanalysis, have been made using the model. The results have been used to compare with observations (Liu et al. 2018; Qian et al. 2018) and to study geomagnetic storm time responses. The model results have also been provided for community use through the Earth System Grid. WACCM-X 2.0 has also been used to study space climate and whole atmosphere responses to anthropogenic climate change (Solomon et al. 2018).

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