Summary for Year 2 (November 2015-October 2016)

The overarching goal of the 2014-2016 CSL proposal was the development and testing of CESM2. In particular, the majority of the Community Projects allocation (which we define as projects that cut across several CESM Working groups) was centered on the testing of CESM2 in a ***coupled*** configuration. As of August 22 2016, approximately 85% (out of an expected 81%, 9.75 months out of 12) of the requested allocation for development has been used. The production (including the Community Projects) has approximately used 86% of its allocation, while development has used approximately 80% of the allocation. A summary Table, with the split between all working groups (WGs) is provided below. For the most part, CESM is on track for its full usage of its allocation. However, it is worth noting the following

1) Production usage was significantly higher than expected during summer because of the numerous simulations needed to resolve a sea-ice issue (too extensive freezing of the Labrador Sea) that was first highlighted in the simulations performed in support of the June 2016 Breckenridge meeting. Solving this issue has required numerous multi-decadal simulations with the fully coupled model (at 1^{o}); in addition, because of the time constraint associated with the upcoming CESM release and CMIP6 simulations has required the use of a more expensive-higher throughput configuration of the model. This was however the justification for the Community Project portion of the CSL proposal and such allocation has allowed us to build CESM2 in a very systematic fashion. This is allowing for a documented progression in the implementation of the various components. To be more specific, in the case of the sea-ice issue, this approach has limited the analysis to a manageable number of changes that were made between acceptable and non-acceptable results; however, the very complicated coupled-model nature of the problem has made progress slow. But without such documented and incremental progression, it would have been almost intractable.
2) There has been some limited re-allocation between working groups; this flexibility allows for a better consistent usage of our Yellowstone allocation. Some working groups are currently exhibiting a negative balance and we are in the process of rebalancing to ensure the complete use of our CSL allocation.

A significant departure from previous CSL proposals has been the introduction of a large glade allocation (mostly for development) to limit HPSS long-term storage. This has been very successfully implemented all allocations are close to their allocated limit. Our distribution of results from the Large Ensemble (/glade/p/cesmLE) and Last Millenium Ensemble (/glade/p/cesmLME) are near capacity, since those efforts are completed.

Summary Table for the usage of CSL computer allocation and usage (Nov. 2015-Aug. 2016)

Production	Allocated	Used	Remaining
Total	74,500,000	64,307,627	10,192,373
SDWG	2,300,000	1,089,107	1,210,893
Community	26,510,000	26,585,565	-75,565
WAWG	5,680,000	5,595,226	84,774
OMWG	3,500,000	3,638,518	-138,518
CVCWG	5,620,000	3,342,711	2,277,289
LMWG	4,100,000	4,149,520	-49,520
AMWG	3,850,000	3,872,178	-22,178
CHWG	2,250,000	897,574	1,352,426
PCWG	2,370,000	2,315,609	54,391
BGCWG	3,960,000	1,114,018	2,845,982
LIWG	2,370,000	2,303,393	66,607
CVCWG	6,020,000	4,080,568	1,939,432
PaleoWG	6,510,000	5,316,636	1,193,364

Development	Allocated	Used	Remaining
Total	46,000,000	36,618,762	9,381,238
SDWG	2,020,000	926,456	1,093,544
LIWG	2,100,000	1,394,940	705,060
SEWG	5,861,700	3,088,231	2,773,469
WAWG	4,180,000	4,290,364	-110,364
OMWG	4,290,000	4,385,100	-95,100
PaleoWG	4,960,000	4,324,331	635,669
LMWG	3,430,000	2,000,393	1,429,607
AMWG	9,520,000	8,266,400	1,253,600
CHWG	2,000,000	1,753,232	246,768
PCWG	2,270,000	2,159,845	110,155
BGCWG	4,860,000	4,022,386	837,614

The next major steps in CESM development are 1) the completion of CESM2 and 2) preparation for the CESM2 release (early 2017) and 3) initial CMIP simulations (pre-industrial control and one 20th century simulation).

Summary Table for the usage of glade space (As of Aug. 29, 2016)

As discussed in the original proposal, the working groups have made considerable use of the allocated space for development work (average usage rate of 93%). In addition, the cesm0005 space has been critical in providing the support for the rapid analysis of CESM2 development long simulations; it is currently at 75% in preparation for long (decades or longer CESM2 simulations). The allocations for the Large Ensemble (LE) and Last Millenium Ensemble (LME) have considerable helped the community access and analyzed those simulations.

Space	Used	Quota	% Full
/glade/p/cesm	208	228	91
/glade/p/cesm/amwg_dev	42	42	99
/glade/p/cesm/bgcwg_dev	65	66	99
/glade/p/cesm/chwg_dev	76	84	91
/glade/p/cesm/liwg_dev	3	5	69
/glade/p/cesm/lmwg_dev	16	17	95
/glade/p/cesm/omwg_dev	90	91	98
/glade/p/cesm/palwg_dev	114	120	95
/glade/p/cesm/pcwg_dev	40	40	99
/glade/p/cesm/sdwg_dev	50	57	88
/glade/p/cesm/wawg_dev	91	91	100
/glade/u/cesm-scripts	290	1024	28
/glade/p/cesmLE	124	125	99
/glade/p/cesmLME	79	125	64
/glade/p/cesm0005	179	253	71

Atmosphere Model Working Group (AMWG)

The AMWG CSL allocation is used ostensibly for Community Atmosphere Model (CAM) development and testing for use in the larger coupled system. Use of CSL resources has allowed us to produce an atmosphere model that is ready for use in CMIP6 experiments and that is compatible with the surface components, giving a credible coupled model. Over the year the individual model components have been tested and combined to produce AMIP-type and fully coupled simulations that out perform previous model versions.

Development

Resources have been used to advance our understanding and improvements of a number of atmosphere physical parameterizations. The Cloud Layers Unified By Binormals (CLUBB) was chosen to be included in CAM6 and further development has continued to deepen our understanding of its simulation characteristics. This included modifying aspects of CLUBB, and its tunable parameters, to produce scientifically credible coupled simulations. Particular improvements include the representation of low frequency coupled variability such as El Nino (phase and amplitude) and the strength and vertical structure of the Atlantic Meridional Overturning Circulation (AMOC). Resources were also utilized to improve the overall climate metrics produced by CAM-CLUBB, including improvements to the mean state climate, as well as high frequency tropical variability (Bogenschutz et al, 2016). Furthermore, the continued development and testing using CLUBB as a replacement for the deep convective parameterization, brought this configuration closer to being a credible model configuration for future use. Currently, these tests are exploratory and preliminary, but suggest potential for CLUBB to be used as a unified parameterization of all clouds and convection.

We implemented a new parameterization of mesoscale orographic gravity wave drag (OGWD) as well as a new parameterization of boundary layer form drag induced by subgrid orography (PBL-OFD). The PBL-OFD is the scheme described by Beljaars et al. (2003, QJRMS) and replaces the turbulent mountain stress (TMS) used in CAM5. The Beljaars scheme uses a rigorous spectral derivation of form drag exerted by hills with horizontal scales below 3 km. The end result is a drag that varies roughly as the subgrid topographic variance $\langle h'^2 \rangle$ versus the log$\langle h \rangle$ dependence in the TMS scheme. The Beljaars scheme appears to give better simulations of low-level winds over land along with improved simulations of surface temperatures in some regions, e.g. Greenland.

The new OGWD scheme represents topographic anisotropy (ridges) as well as parameterizing strongly nonlinear flows around high mountains that lead to enhanced low-level drag following Scinocca and McFarlane (2000, QJRMS). The scheme uses new boundary forcing data produced with accurate regridding software developed at NCAR (Lauritzen et al. 2015, GMD). We have found that this scheme contributes to improved simulations of climatological sea-level pressure, surface wind stress and high-latitude upper-air fields. The scheme also leads to improved simulations of stratospheric winds and temperatures in both SH and NH, without the need for arbitrary hemisphere dependent tuning. In addition the gravity wave emissions have been added to the shallow convection scheme in CAM5, demonstrating significant improvements in the Quasi Biennial Oscillation (QBO).

Improvement in a number of CAM6 biases was identified as being critical for the CESM2 release. Biases included the poor simulation of the Winter-time Amazon basin rainfall and the persistent weak tropics-wide simulation of intraseasonal wave variability. Deep convection was the key process in these biases and a suite of CAM simulations, focusing on aspects of the Zhang-McFarlane convection parameterization, led to demonstrable improvements in the existing tropical biases (see Fig. 1). The investigated processes were related to parcel plume approximations, convective organization and dynamical constrains. A subset of the deep convection parameter changes are now included in the CAM6 formulation.

High horizontal resolution development and testing has predominantly been carried out on other allocations. However, resources were used for global 25-km simulations using nudging methodologies to quantify physical parameterization errors in short simulations. Also the regional grid refinement capability in CAM-SE was used to focus on a number of key regions around the globe including over the US and the North Atlantic storm tracks. The simulations demonstrate the ability to obtain the benefits of high resolution locally without the cost of global high resolution (e.g. see Fig. 2 below shown in Zarzycki and Jablonowski (2015)).

A number of new dynamical core capabilities were also developed in CAM-SE (spectral element dynamical core). Firstly, a version of CAM-SE using CSLAM (Conservative Semi-Lagrangian Multi-tracer) for the transport of tracers was investigated. The main challenge has been the consistent coupling between the SE air mass field and the CSLAM mass fields. After a challenging algorithm development and optimization process a robust algorithm has been derived and implemented (Lauritzen et al., 2016). Computing time has been used for idealized testing as well as preliminary aqua-planet testing. Secondly, a dry mass vertical coordinate version of CAM-SE has been developed and implemented. It has been tested in aqua-planet and AMIP configurations. Thirdly, the separation of physics and dynamics grids in CAM-SE has been developed and implemented. The version is currently being tested in aqua-planet configuration. Diagnostics to access energy sources and sinks in the dynamical core and in physics dynamics coupling has been implemented in CAM-SE.

Recent alternative configurations of CAM (5.3, 5.4, 5.5) were used to investigate model sensitivities, fundamental climate dynamics, and continued development of alternative model configurations. A number of aqua-planet simulations were run to produce a candidate for the default aqua-planet configuration with CAM5. We ran alternative configurations with CAM 5.3, and compared with versions of the model with updated physics and a different dynamical core. Results are presented in

Medeiros et al. (2016). Additional experiments were run to assess sensitivities to microphysical assumptions (described in Gettelman et al. 2016). We have also been experimenting with aqua-planet configurations coupled to a slab-ocean model, with the goal of producing a new standard model configuration for use by the community (Zarzycki et al., 2016). Based on these aqua-planet configurations, we have also run a number of experiments that remove fundamental physics and physics interactions to explore the coupling between clouds, radiation and the atmospheric circulation.

We have continued to refine the CAPT methodology ("forecast mode"). Recent work has included updating the regridding software to allow the use of model restart files when using the spectral element dynamical core. Related ongoing work includes developing a robust nearest-neighbor regridding routine that will be useful when running CAM at high resolution. Simulations have been conducted to explore the impacts of resolution and parameterizations on the representation of shallow cumulus clouds. Those simulations included several months of daily hindcasts using the standard 1-degree CAM5.3 with finite volume dynamics, spectral element dynamics, increased vertical resolution, and with regional refinement to 0.25-degree over the tropical Atlantic Ocean. A parallel set of hindcasts was produced using CAM5.5 to examine the impact of changes in parameterized physics.

Improvements, updates and additions have been made to the available simpler models capability in CAM. In particular, idealized baroclinic wave and Held Suarez tests have been tested and included as supported functionality in CESM.

The inclusion of advanced physical parameterizations in CAM6 has increased simulation costs substantially. As a consequence resources were applied to efficiency improvements in parameterization bottlenecks in the model. This included the Morrison Gettelman (MG2) microphysics and the methodology for sub-cycling CLUBB and MG2 calls within the physics timestep. These efforts have led to significant speed-up in run times, which will benefit all CESM CMIP6 experiments.

Production

Production resources were used to perform benchmarking simulations for the fully coupled model configurations. This includes Atmosphere Modeling Intercomparison Project (AMIP)-type simulations, climate sensitivity testing and analysis of aerosol direct and indirect impacts over the 20th century.

More generally, production research has covered a wide range of areas targeting atmospheric processes involved in major atmosphere model features and modes of variability. This has advanced our understanding of these features, including atmospheric blocking, the Inter-tropical Convergence Zone (ITCZs) and polar climate cloud feedbacks. In addition, Whole Atmosphere Model Intercomparison (WACC) long simulations were performed as part of the recent Quasi Biennial Oscillation Intercomparison project (QBOi). They reveal the sensitivity of the QBO to variations in model configuration and forcing scenarios.

Resources have also been used to combine model cloud and climate feedback analyses and relate these to particular applications. One such example is the role of aircraft contrails in the radiative forcing of climate. The present day impacts are small, but with the large increase in aircraft traffic by 2050 the radiative impacts of contrail formation become a significant component of the radiation budget (Chen and Gettelman, 2016).

Figures

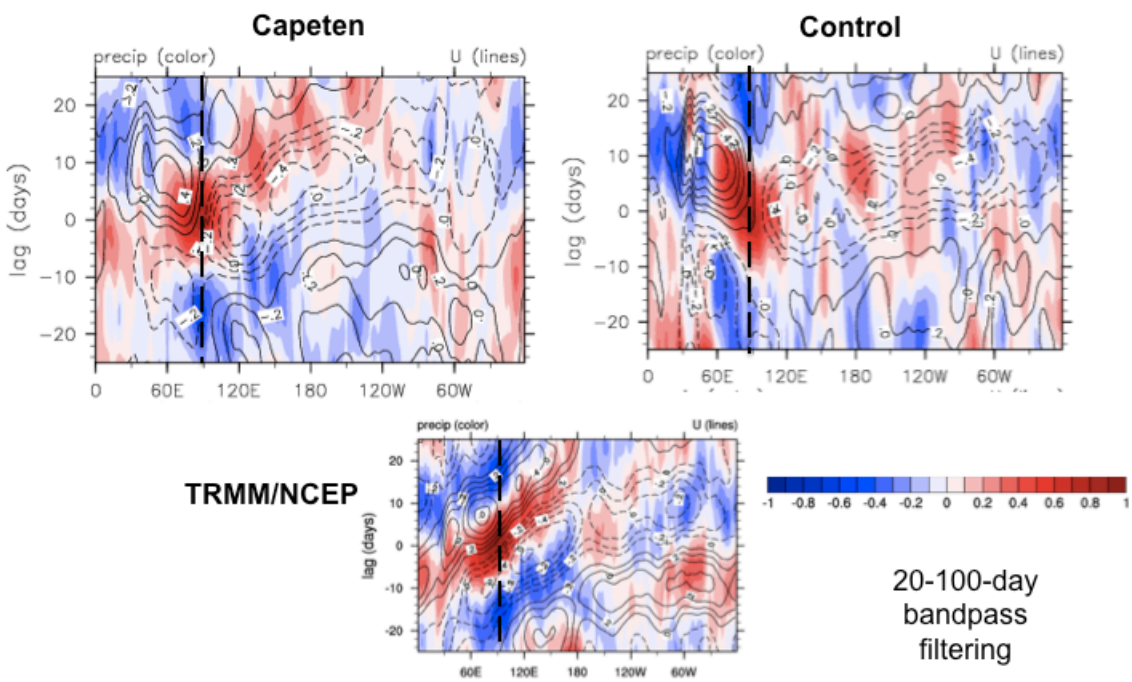


Figure 1. Lag correlations of precipitation (colors) and 850-mb wind (contours) with precipitation at 90E. Daily data are 20-100-day band pass filtered and averaged 10N to 10S. Control is the CAM5.5 climate and capeten is a modification of the deep convection approximation. This illustrates one result from the intense examination of deep convective properties to address tropical biases in CAM5.5.

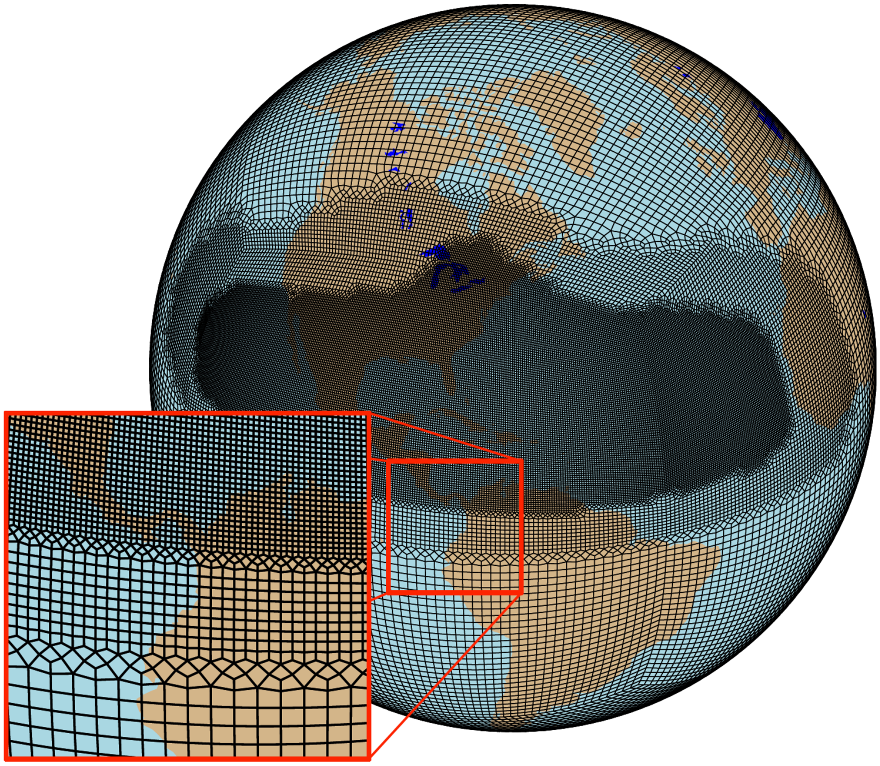


Figure 2. Example of a CAM-SE grid with regional refinements over the Northern Atlantic and Eastern Pacific tropical cyclone regions (shown in Zarzycki and Jablonowski (2015)). The zoomed figure highlights the grid transition region where the grid spacing varies from about 0.5° to 0.125° (55-14 km).

References

Chen, C.-C. and Gettelman, A., 2016. Simulated 2050 aviation radiative forcing from contrails and aerosols, *Atmos. Chem. Phys.*, **16**, 7317-7333, doi:10.5194/acp-16-7317-2016

Bogenschutz, P. A., A. Gettelman, C. Hannay, R. Neale, V. E. Larson, C. Craig, C.-C. Chen, 2016. Coupled Simulations using CLUBB in the Community Atmosphere Model. In preparation for *J. Climate.*

Gettelman, A., L. Lin, B. Medeiros, and J. Olson, 2016: Climate Feedback Variance and the Interaction of Aerosol Forcing and Feedbacks, *J. Climate,* in press. DOI: 10.1175/JCLI-D-16-0151.1

Lauritzen et al., 2016: CAM-SE-CSLAM: Consistent coupling of a conservative semi-Lagrangian finite-volume method with spectral-element dynamics. Submitted to Mon. Wea. Rev.

Medeiros, B., David L. Williamson, and Jerry G. Olson, 2016: Reference aquaplanet climate in the Community Atmosphere Model, Version 5. *J. Adv. Model. Earth Syst*.**,** **8** (1), 406–424. DOI: 10.1002/2015MS000593

Zarzycki, C. M., K. A. Reed, J. T. Bacmeister, A. P. Craig, S. C. Bates, and N. A. Rosenbloom, 2016. Impact of surface coupling grids on tropical cyclone extremes in high-resolution atmospheric simulations, *Geosci. Model Dev.*, **9**, 779-788, doi:10.5194/gmd-9-779-2016

Zarzycki, C. M. and C. Jablonowski, 2015: Experimental Tropical Cyclone Forecasts using a Variable-Resolution Global Model, Mon, Wea. Rev., **143**, 4012-4037

Biogeochemistry Working Group (BGCWG)

The Biogeochemistry Working Group (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 implementing, testing, and evaluating developments targeted for inclusion in the upcoming release of CESM2.

Development

Accomplishments of the Biogeochemistry working group that were done with the CESM CSL Development Allocation fall into the following broad categories: continued ocean biogeochemistry model development, the use of ocean biogeochemistry to evaluate new and updated ocean parameterizations, and continued development of a fast ocean tracer spin-up technique.

Development of the ocean biogeochemistry consisted of modifications to reduce model biases and the inclusion of new functionality. Model developments include: prognostic control of $CaCO_3$ burial to ocean sediments, performing non-linear light-dependent terms of BGC separately under different sea ice thickness categories, improved treatment of DOM pools, atmospheric deposition of PO_4 and SiO_3, prognostic scaling of POM burial to sediments (to balance nutrient net sources and sinks in the global ocean), coupling atmospheric dust and iron deposition to the flux coupler, and prognostic NH_x emissions from the ocean. All of the model improvements summarized above will be included in the CESM 2.0, and initial evaluations suggest substantial improvements in the ability of CESM to match the observed distributions for nutrients and other biogeochemical tracers. We have also transitioned ocean BGC development into the MARBL framework. A notable benefit of this transition is that it will facilitate the transition of ocean BGC to a new ocean model for CESM 3.

We have used simulations that include ocean biogeochemistry to evaluate new and updated ocean parameterizations. This evaluation, which was not performed in the development of previous versions of CESM, had provided insight into the parameterizations that is not evident in simulation that only include temperature, salinity, and ideal age. The fast ocean tracer spinup technique that has been developed over previous allocations was used in these evaluations, by examining the impact of these parameterizations on spun-up abiotic radiocarbon.

Work has progressed on a fast ocean tracer spin-up technique. This technique, based on a Newton-Krylov solver, has been extended to work on low complexity BGC parameterizations.

Production

We continued the suite of experiments to evaluate how model developments introduced in CESM1.2 impact coupled carbon cycle biases that were identified in CESM1. In the previous allocation period, 1850 control runs and 20th century transient simulations were started. Runs in both categories were done with both prescribed CO_2 concentrations and prognostically predicted CO_2 concentrations. The control runs were extended to 300 years, the 20th century simulations were completed, and future scenario runs (with RCP8.5 forcing) were performed. Results from these simulations were presented at the CESM winter working group meeting.

Chemistry-Climate Working Group (CHWG)

The Chemistry-Climate WG used their CSL allocation for Oct 2015-Sep 2016 extensively for the development of a new secondary organic aerosol (SOA) scheme that is based on the volatility basis set (VBS) parameterization. In addition, simulations were completed for international model intercomparison acitivities, as well as chemical data assimilation. Many fewer core-hours were used by CHWG than requested primarily because the CSL account was at its 30-day limit when we were ready to run, so other allocations (ACOM divisional) were used instead. In some cases, our model development plans were based on external sources (e.g., FAST-J, CSLAM) that were not provided when expected.

Development

The development allocation was used to test a number of improvements to the representation of tropospheric chemistry and its coupling with the land model and climate:

- An expanded chemistry mechanism that allows for a more realistic representation of VOC (volatile organic compound) oxidation and ozone production rates in urban and natural environments was tested. The expanded chemistry also provides more detailed prediction of the precursors of SOA.
- The SOA-VBS framework was implemented and tested in CESM-chem. It approximates, with just five compounds, the numerous gas-phase intermediates that exist in nature with a range of reactivity. The model was tested for different resolutions. The setup will be further optimized.
- The capability of prognostic fire emissions in the land model and coupled to the atmospheric chemistry, along with a parameterization for plume rise, was tested. This will be an important feature that will be used in CESM2.
- The coupling between tropospheric ozone and vegetation damage algorithms was tested, and results are being prepared for publication.
- The model was further tested to be able to run a double radiation code to provide diagnostics and output to collaborators (Alan Robock and Lili Xia) working on CESM-chem geoengineering studies. The study "Impacts of Solar Radiation Management on Surface Ozone" is in preparation.
- The development and implementation of nitrate aerosols in the Modal Aerosol Model scheme has been started.

Production

The production allocation was used to complete simulations for model intercomparison activities, including the Chemistry-Climate Model Initiative (CCMI) the Hemispheric Transport of Air Pollutants (HTAP, phase 2). The CAM-chem simulations for CCMI were completed, and the model documented in a peer-reviewed publication (Tilmes et al., 2016). The HTAP simulations used the same model configuration of CAM-chem as for CCMI, but with the HTAP2 emission inventory. An analysis of the aerosol distributions has been submitted for publication (e.g., Stjern et al., 2016).

Some computing time also assisted with the completion of CAM-chem/DART data assimilation of satellite retrievals of carbon monoxide (CO) (Barré et al., 2015; Gaubert et al., 2016). The ensemble methods allow inference of unobserved species by computing the sensitivities between species provided by the ensemble statistics. Figure 1 shows how O_3 can be modified by MOPITT and Infrared Atmospheric Sounding Interferometer (IASI) CO assimilation as applied in several experiments: CO only inferred, CO and O_3 inferred and CO, O_3, VOCs, NO_x inferred. This result is very preliminary but shows the importance of data assimilation effects on O_3 following different localization configurations. In those experiments ozone can be changed by up to 20%.

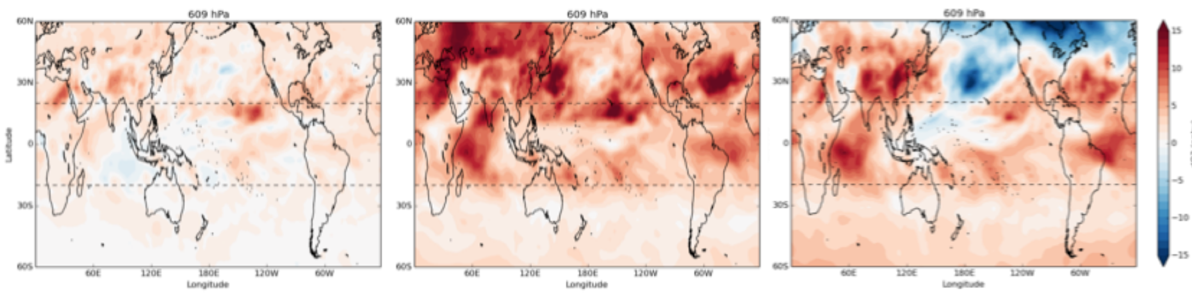


Figure 1. Global maps of O_3 response (Assimilation Run – Control Run) from different satellite CO data assimilation configurations (July 2008 middle troposphere). Left panel: CO assimilated but not inferring any other species. Middle panel: CO assimilated and also inferring O_3, Right panel: CO assimilated and also inferring O_3, VOCs and NOx.

The Selin research group at MIT has evaluated the ability of CESM to simulate air quality while driven by meteorological fields produced by alternative earth systems models. Using an integrated global system model ensemble simulation of 21st century climate change, we examined the potential and challenges associated with operating CAM-Chem in offline mode with meteorology derived from externally generated climate fields. We conducted an ensemble of CAM-Chem, including 1050 years of simulation varying policies and climate sensitivity, to examine dimensions of variability including interannual and multi-decadal variability. We used this ensemble to examine health impacts of U.S. climate mitigation policies, and the role of natural variability on ozone concentrations over the U.S. We continue to examine results from this ensemble to address trans-Pacific transport of climate change and uncertainty in climate-air quality connections (Garcia-Menendez et al., 2015; Garcia-Menendez et al., in review).

References

Barré, J., et al. (2015), Assessing the impacts of assimilating IASI and MOPITT CO retrievals using CESM-CAM-chem and DART, *J. Geophys. Res. Atmos.*, *120*,10,501–10,529, doi:10.1002/2015JD023467.

Garcia-Menendez, F., R. K. Saari, E. Monier, and N. E. Selin, U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation, *Environmental Science and Technology, 49*, 7580–7588, 2015.

Garcia-Menendez, F., E. Monier, and N.E. Selin, "The role of natural variability in projections of climate change impacts on U.S. ozone pollution" under review.

Gaubert, B., et al. (2016), Toward a chemical reanalysis in a coupled chemistry-climate model: An evaluation of MOPITT CO assimilation and its impact on tropospheric composition, *J. Geophys. Res. Atmos., 121*, 7310–7343, doi:10.1002/2016JD024863.

Stjern, C.W., et al., Global and regional radiative forcing from 20% reductions in BC, OC and SO4 – an HTAP2 multi-model study, *Atmos. Chem. Phys. Discuss.*, doi:10.5194/acp-2016-443, 2016 (in review for *Atmos. Chem. Phys.*).

Tilmes, S., Lamarque, J.-F., Emmons, L. K., Kinnison, D. E., Marsh, D., Garcia, R. R., Smith, A. K., Neely, R. R., Conley, A., Vitt, F., Val Martin, M., Tanimoto, H., Simpson, I., Blake, D. R., and Blake, N., Representation of the Community Earth System Model (CESM1) CAM4-chem within the Chemistry-Climate Model Initiative (CCMI), *Geosci. Model Dev., 9*, 1853-1890, doi:10.5194/gmd-9-1853-2016, 2016.

Climate Variability and Change Working Group (CVCWG)

Under the previous CSL allocation, the CVCWG conducted the majority of the proposed simulations for the purpose of assessing climate variability and change resulting from a variety of forcing factors as well as sensitivity to model resolution. . Focus areas over these last two years include impacts of volcanic forcing on the early 21st Century hiatus, volcanic and solar forcing impacts on ENSO, investigation of the role of SST variability in different ocean basins on the global coupled climate system, and sensitivity of the hydrological cycle and tropical cyclones (TCs) to model resolution and future climate change.

Production

Unless noted otherwise, all simulations were conducted with the 1 degree version of CESM1.

Under the category of single forcing simulations, the group extended the previously conducted 20th Century transient volcano-only (VOLCOLD, 5 members) simulations to 2013 similar to those used in the IPCC AR5. We also conducted a companion 5-member ensemble using a new volcano dataset (VOLCNEW) with more recent volcanic forcing estimates over the period 1990 to 2013. To have a 5-member control set, we also ran two additional 20th Century simulations. Unlike VOLCOLD, VOLCNEW includes an estimate of volcanic aerosol changes caused by a succession of "moderate" early 21st century eruptions. For each of the four major eruptions in the comparison period (Agung, Fuego, El Chichón, and Pinatubo), VOLCOLD and VOLCNEW show noticeable differences in peak stratospheric aerosol optical depth and its subsequent decay. Over the 1998 to 2011 "warming hiatus" period, more realistic treatment of volcanic forcing yields simulated climate changes that are in closer accord with observations (Santer et al., 2015).

Three ensembles of "pacemaker" (or regionally-forced) coupled simulations in which SST anomalies in a particular region are nudged to observations have been completed. Two ensembles were conducted to investigate oceanic forcing of the climate system by the Atlantic versus Pacific Basins. Both relax SST to observations in their respective basins, specifically the North Atlantic and equatorial Pacific, following the identical protocol of Kosaka and Xie (2013) except for the use of ERSSTv3b in place of HadISST for SST observations. Each ensemble contains 10 members and covers the period from 1920 to 2013. To date, this ensemble has been used to investigate the importance of ENSO phase for detection and attribution of the response of global-mean temperature (Lehner et al., 2016) and the Southern Annular Mode (McGraw et al., 2016) to volcanic eruptions. A follow-on to the "Pacific pacemaker" ensemble was conducted branching from each member at 1990 and extending to 2013 but using an updated volcanic forcing (the same as that used for VOLCNEW above).

The CVCWG has also conducted a similar set of "idealized pattern" simulations in which SST is relaxed to an idealized Interdecadal Pacific Oscillation (IPO) pattern in the Pacific. Three ensemble sets were conducted: the "control" which relaxes to model climatology and two experiment ensembles that relax to IPO+ and IPO- patterns. Each set contains 10 members generated by using 10 different initial conditions, again based on the state of the IPO.

In addition to the Pacemaker runs, the CVCWG completed a 10-member "AMIP" ensemble of 1-degree CAM5 simulations forced by the observed (ERSSTv4) evolution of SSTs in the tropics (equatorward of approximately 28 degrees latitude) during the period 1880-2014, and a climatological seasonal cycle elsewhere. Additional members of a larger set of coupled CCSM4 simulations using a half degree version of CAM4 (but retaining the 1 degree ocean model component), were conducted. The additional members include two ensemble members for the 20th and 21st Centuries under historical and RCP8.5 forcing, respectively. In addition, a 300-year 1-degree climate sensitivity simulation was also conducted. The higher resolution model runs showed improvements in many aspects of the hydrological cycle, including representation of extreme precipitation, atmospheric rivers, and the South Asian and North American monsoons, compared to the coarser resolution model simulations (Shields and Kiehl, submitted; Shields et al., 2016).

The group also conducted ensembles of idealized simulations to investigate the effects of volcanoes and solar forcing on the state of ENSO. The simulations are initialized from the control simulation at time points corresponding to El Niño, 6 months before El Niño, La Niña, or 6 months before La Niña. In the volcano ensemble, a Pinatubo-like eruption occurs in the first time step while in the solar ensemble, an upward trend in solar forcing begins immediately. Preliminary results from both ensembles indicate that starting with an initial condition corresponding to a La Niña or 6 months before a La Niña state results in systematically warmer conditions in the central and eastern tropical Pacific 3-5 years later compared to the control simulation. Results from the simulations that begin in an El Niño state or moving toward an El Niño are less clear.

The CVCWG also performed tuning and conducted two ensemble members as part of a much larger set of present day (1979-2012) and future (2070-2099) "time slice" AMIP experiments at high resolution (0.25deg). The full set of simulations has resulted in many publications thus far. Examining model configuration, Reed et al. (2015) determined that tropical cyclones (TCs) are affected by the dynamical core of the model (finite volume vs. spectral element), and Zarzycki et al. (2015) conclude that the grid on which coupler fluxes are calculated also affects the representation of TCs. Bacmeister, et al. (2016) concluded that there are fewer TCs in future scenarios, but the ones that do form will likely be stronger. Building on this, Gettelman, et al. (2016) assessed TC damage estimates.

Finally, all of the community simulations conducted by the CVCWG are made available via the CVCWG webpages at: http://www2.cesm.ucar.edu/working-groups/cvcwg

References

Bacmeister, J. T., C. Hannay, S. Bates, P. Lawrence, J. Truesdale, N. Rosenbloom, K. A. Reed, and M. F. Wehner, 2015: Tropical cyclone activity under RCP4.5 and RCP8.5 compared to the present. Submitted to Special Issue on Benefits of Reduced Anthropogenic Climate changE (BRACE), Guest Editors: Brian O'Neill, Andrew Gettelman, NCAR, *Climatic Change.*

Gettelman, A., C. C. Chen, D. Bresch, J. Truesdale, and J. Bacmeister, 2016: Simulated Tropical Cyclone Damage Estimates. In preparation.

Lehner, F., A. P. Schurer, G. C. Hegerl, C. Deser and T. L. Frölicher, 2016: The importance of ENSO phase during volcanic eruptions for detection and attribution. Geophys. Res. Lett., 43, doi: 10.1002/2016GL067935.

McGraw, M. C., E. A. Barnes and C. Deser, 2016: Reconciling the Observed and Modeled Southern Hemisphere Circulation Response to Volcanic Eruptions. Geophys. Res. Lett., in press.

Reed, K. A., J. T. Bacmeister, N. A. Rosenbloom, M. F. Wehner, S. C. Bates, P. H. Lauritzen, J. E. Truesdale, and C. Hannay, 2015: Impact of the dynamical core on the direct simulation of tropical cyclones in a high-resolution global model. *Geophys. Res. Lett.*, ***42***, 3603–3608. http://dx.doi.org/10.1002/2015GL063974

Santer, B., R.R. Neely III, G.A. Meehl, J.-F. Lamarque, S. Solomon, D.A. Ridley, C. Bonfils, J. Painter, and M. Zelinka, 2015: Climate impact of volcanic forcing uncertainty. *Nature Geoscience*, submitted.

Shields, C.A. and J.T. Kiehl: Simulating the Pineapple Express in the Community Climate System Model, CCSM4, *Geophysical Research Letters* (in review).

Shields, C.A., J. T. Kiehl, G. A. Meehl, 2016: Future Changes in Regional Precipitation as Simulated by a Half-degree Coupled Climate Climate Model, *J.Adv. Model. Earth Syst.*, 8, doi:10.1002/2015MS000584.

Santer, B., R.R. Neely III, G.A. Meehl, J.-F. Lamarque, S. Solomon, D.A. Ridley, C. Bonfils, J. Painter, and M. Zelinka, 2015: Climate impact of volcanic forcing uncertainty. *Nature Geoscience*, submitted.

Zarzycki, C. M., Reed, K. A., Bacmeister, J., Craig, A. P., Bates, S. C., and Rosenbloom, N. A., 2015: Impact of ocean coupling strategy on extremes in high-resolution atmospheric simulations. *Geosci. Model Dev. Discuss.*, **8**, 7983-8007, doi:10.5194/gmdd-8-7983-2015, 2015.

Land Ice Working Group (LIWG)

The Land Ice Working Group (LIWG) has analyzed the present-day **Greenland and Antarctic surface climate and SMB** of CESM1-CAM5 in detail, which resulted in three publications (Fyke et al., 2014a,b; Lenaerts et al., 2016). Moreover, we have forced CESM1-CAM5 with realistic ice sheet melt scenarios to investigate the effect on oceanic circulation (Lenaerts et al., 2015).
As a result of extensive and pioneering developments to couple ice sheets into climate models, CESM now contains **a two-way coupled Greenland Ice Sheet (CESM-CISM)**. Achievement of this state required extensive development simulations to test various aspects of coupling. For example:

- we performed multiple simulations to stress-test and debug the new, higher order CISM2 ice sheet model within the coupled framework (presented at LIWG session at 2016 CESM Winter Meeting)
- we performed a range of simulations to assess new runoff coupling between CISM and POP
- we extensively updated and tested the dynamic CAM topography updating scheme
- there has been substantial progress towards dynamic landunit capabilities in CLM, which allows glacier advance or retreat to be reflected in the land surface conditions. The infrastructure to allow this is now in place, and has been exercised via a number of simulations. A major recent addition to this infrastructure was the conservation of below-ground carbon and nitrogen in these landunit transitions.
- we moved the CLM-CISM coupling to the coupler. This was important so that the coupling could be done conservatively, so that it could handle irregular land grids, and to facilitate bringing in alternative land ice models.
- we investigated and reworked the downscaling of atmospheric fields sent to the glacier elevation classes

We are presently carrying out a first full production spin-up of CESM-CISM in preparation for a range of scientific studies. This involves a novel 'iterated' technique to lessen total computational expense by more than 50%: establishment of this technique has involved extensive software engineering and associated coupled model test simulations. A manuscript describing the coupling is currently in preparation for Geoscientific Model Development.

We have carried out a number of experiments investigating the **robustness of CESM-CISM** under extreme forcing scenarios in the past. More specifically, we have investigated the model's ability to realistically simulate the spatio-temporal evolution of the Greenland ice sheet in the last interglacial warm period (results presented at the CESM Summer Meeting 2016) as well as the glacial inception and initial build up of the Greenland ice sheet in the late Pliocene (results presented at the CESM Winter Meeting 2016).

An improved **polar snow model** (firn model) has been developed and has become a standard part of CESM. The firn model includes a deeper snow pack with more layers, improved density calculations and more user-friendly history output. The model has been tested using offline reanalysis data (ERA-Interim and GWSP3) in various configurations. The most model years have been run in a two-degree resolution setup, but also single-column runs and one-degree simulations were performed. In total, about 280,000 core hours were spent on performing these simulations. The new firn model has been shown to enhance refreezing and thus reducing liquid runoff from ice sheets. On Antarctica, this change was much needed as liquid runoff was too high. A manuscript describing these new firn model is currently in preparation.

A number of sensitivity experiment have also been conducted to investigate the performance of new parameterizations in CAM, CLM and CISM as part of the coupled model. The results show that the last year's model development has greatly **improved the simulated Greenland climate**; however, several important model biases still remain that hopefully can be solved before the model release later this year. In collaboration with the AMWG (Andrew Gettelman and others) we have tested and analyzed the impact of various atmospheric cloud microphysical schemes in CAM5 on the ice sheet surface climate. This was done using various short simulations with slab ocean and interactive land-atmosphere settings. This work will result in a collaborative publication to be finished before the end of 2016.

Finally, the LIWG has been working on detecting and repairing CESM surface biases over the **Antarctic ice sheet**, which were signaled as one of the outstanding biases of CESM during the CESM joint meeting in February 2016. To that end, we have done CLM-only and coupled simulations varying atmospheric models and snow parameters. These simulations allowed us to conclude that the CESM1.5 is very sensitive to the melt-albedo feedback, allowing snow albedo to drop too rapidly in summer. We also defined modest parameter tunings we can use apply to alleviate this issue.

Development
The development allocation was used to develop and test the coupled CESM-CISM, to improve the firn model, and test the impact of various new parameterizations in the new CESM model (towards CESM2) on the ice sheet climate.

Production
The production allocation was used to perform present-day simulations with CESM-CAM5, and multiple paleo-simulations with CESM-CAM5 and CESM-CISM.

References

Fyke, J. G., Vizcaíno, M., Lipscomb, W. & Price, S. Future climate warming increases Greenland ice sheet surface mass balance variability. *Geophys. Res. Lett.* **41,** 470–475 (2014a).
Fyke, J. G., Vizcaíno, M. & Lipscomb, W. H. The pattern of anthropogenic signal emergence in Greenland Ice Sheet surface mass balance. *Geophys. Res. Lett.* **41,** 6002–6008 (2014b).
Lenaerts, J. T. M. *et al.* Representing Greenland ice sheet freshwater fluxes in climate models. *Geophys. Res. Lett.* **42,** 6373–6381 (2015).
Lenaerts, J. T. M., Vizcaino, M., Fyke, J., Kampenhout, L. & Broeke, M. R. Present-day and future Antarctic ice sheet climate and surface mass balance in the Community Earth System Model. *Clim. Dyn.* 1–15 (2016). doi:10.1007/s00382-015-2907-4

Land Model Working Group (LMWG)

Resources have been and continue to primarily be used to support development and understanding of CLM5, the version of CLM that will be used in CESM2. The focus over the past year has been on integration and understanding of the many new parameterizations and features that are being included in CLM5 (Figure 1). In addition, considerable computational resources have been devoted to parameter optimization, which the LMWG is attempting for the first time to calibrate CLM. 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.

Development

CLM5 developments are wide ranging and include 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, the urban model, and water isotopes (see Figure 1).

Figure 1. List of developments for CLM5.

A major addition to development activities over the past year 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 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 CLM6 include:

1. A next generation multi-layer canopy model for CLM.
2. A hillslope hydrology formulation in collaboration with CUAHSI.
3. Ecosystem Demography model (rechristened as FATES, Functionally-Assembled Terrestrial Ecosystem Simulator).

Production

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

1. Analysis of atmosphere – canopy stability interactions at multiple forested sites in collaboration with CU.
2. Examination of surface energy flux changes due to land use change in land-only and variable resolution CAM simulations with a focus on NE United States (Burakowski et al. 2016).
3. Assessment of the impact of including soil microbial functional traits in the MIMICS model for soil biogeochemistry (Wieder et al., 2015).
4. Assessment of impact of a representation of observed nighttime conductance on global hydrology and carbon budgets in CLM4.5 (Lombardozzi et al. 2015).
5. Photosynthetic and leaf respiratory temperature acclimation increases land carbon uptake over the 21st century (Lombardozzi et al. 2015).
6. An assessment of GRACE-Era terrestrial water trends and an assessment of the role of anthropogenic climate change in these trends (Fasullo et al., 2016).
7. Examination of the role of fire on surface air temperature and the global land water budget during the 20^{th} century (Li and Lawrence, 2016; Li et al. 2016)
8. Diagnostic evaluation of the Community Earth System Model in simulating mineral dust emission with a focus on large-scale dust storm mobilization in the Middle East and North Africa (MENA) (Parajuli et al. 2016).

References

Burakowski, EA, AB Tawfik, A Ouimette, L Lepine, C Zarzycki, KA Novice, SV Ollinger, and G Bonan. Simulating surface energy fluxes using uncoupled and coupled Earth System Models and eddy covariance tower clusters. Agricultural and Forest Meteorology, in review. AGRFORMET-D-16-00572.

Cleveland CC, P Taylor, D Chadwick, K Dahlin, CE Doughty, Y Malhi, WK Smith, B Sullivan, WR Wieder, AR Townsend (2015). A comparison of plot-based, satellite and Earth system model estimates of tropical forest net primary production. Global Biogeochemical Cycles 29, 626-644 doi:10.1002/2014gb005022.

Fasullo, J.T., D.M. Lawrence, S. Swenson, 2016: Are GRACE-Era Terrestrial Water Trends Driven By Anthropogenic Climate Change? Adv in Meteor., 2016, doi:10.1155/2016/4830603.

Li, F. and D.M. Lawrence, 2016: Role of fire in the global land water budget during the 20th century through changing ecosystems. Submitted to J. Climate.

Lombardozzi, D, M Zeppel, R Fisher, A Tawfik. 2015. Incorporating observed nighttime conductance alters global hydrology and carbon budgets in CLM4.5. Geoscientific Model Development Discussions 8: 10339-10363

Lombardozzi, D, G Bonan, N Smith, J Dukes. 2015. Photosynthetic and leaf respiratory temperature acclimation increases land carbon uptake over the 21st century. Geophysical Research Letters 42 doi:10.1002/2015GL065934

Parajuli, S.P., Z.-L. Yang, and D.M. Lawrence, 2016: Diagnostic evaluation of the Community Earth System Model in simulating mineral dust emission with insight into large-scale dust storm mobilization in the Middle East and North Africa (MENA). Aeolian Research21, 21-35.

Wieder WR, AS Grandy, CM Kallenbach, PG Taylor, GB Bonan (2015). Representing life in the Earth system with soil microbial functional traits in the MIMICS model. Geoscientific Model Development, 8(6), 1789-1808, doi:10.5194/gmd-8-1789-2015.

Ocean Model Working Group (OMWG)

Development

During the last year of our two-year CSL allocation, the primary goal of the OMWG has been to deliver an updated ocean model for use in CESM2. We completed implementations and preliminary testing of all the model development and update efforts that the OMWG decided to continue to pursue last year. These developments are: i) a Langmuir mixing parameterization and prognostic and diagnostic wave models (NOAA WaveWatch-III) within the CESM framework (Li et al. 2016); ii) an anisotropic mesoscale mixing parameterization that represents an alternative to the existing isotropic form; iii) a new prescription for specification of isopycnal and thickness diffusivity coefficients based on steering level approaches; iv) a simple parameterization of the diurnal warm layer for the flux coupler; v) a conservative Robert time filter to replace the time-averaging time step, allowing sub-daily coupling of the ocean model; vi) several new and modified tidal mixing parameterizations and tidal dissipation energy data sets; vii) parameterizations to represent exchanges of freshwater between the terrestrial and oceanic systems that include an estuary box model parameterization for a comprehensive set of large river systems; viii) salinity dependent freezing point temperature (both in the ocean and sea-ice components); ix) update of the existing, buoyancy frequency-dependent mesoscale eddy diffusivity specification to have enhanced isopycnal diffusivities at depth to increase tracer uptake; x) prognostic chlorophyll; xi) frazil ice formation every ocean time step; and xii) a new barotropic solver algorithm that scales much better than the existing solver. After completing preliminary testing of these new developments, we have been performing numerous parameter evaluation and ocean and climate sensitivity experiments in ocean – sea-ice coupled (G-compset) and / or fully-coupled (B-comspet) configurations – both usually with biogeochemisty, considering each development individually first. Detailed assessments of the solutions from these experiments have shown that some of these developments need further investigations, requiring additional sensitivity experiments that would not be completed in time for CESM2. Thus, the OMWG has decided to include only the following developments in the CESM2 ocean component: the Langmuir mixing parameterization with a prognostic WaveWatch-III model; two-hourly coupling of the ocean model; salinity dependent freezing point temperature; enhancement of isopycnal diffusivities at depth; use of prognostic chlorophyll; frazil ice formation every ocean time step; and the new barotropic solver algorithm. We note that the present two-hourly ocean coupling does not use the Robert time filter yet, due to a minor budget conservation issue (just resolved); and that the estuary box model will likely be included for CESM2 given the delay in the science freeze deadline for the coupled model.

In addition to our primary activity detailed above, we have completed proposed work on the following efforts: i) preliminary testing and necessary adjustments for the new JRA-55 atmospheric data sets for forcing ocean – sea-ice coupled simulations; ii) fast spin-up of active tracers – detailed in the BGCWG accomplishments; iii) development and refinement of the semi-prognostic approach to correct the Gulf Stream and North Atlantic Current paths adiabatically for studies investigating the impacts of these biases on variability and mechanisms in the North Atlantic; and iv) development and testing of satellite altimetry assimilation capabilities for the POP2 – DART ensemble ocean data assimilation system.

An OMWG activity that was not proposed in the 2014 request involves the development of a 1D, vertical-physics-only version of the ocean model, also referred to as the *pencil model*. This new configuration needs a bit more testing before it's made available for community use. It represents an attractive alternative to the traditional slab ocean models used in various applications, including climate sensitivity experiments. We also anticiape that it will be extensively used in studies concerning the role of ocean dynamics in climate and variability.

The computational costs of both G- and B-compset simulations were severely underestimated in the 2014 CSL proposal. For example, the B-compset simulations cost more than 5100 CPU hours per simulation year now, in contrast with the estimate of about 1450 CPU hours per simulation year in the 2014 request. Additionally, there has been an unanticipated problem with the recent coupled simulations that bring all the component model developments together towards CESM2 that show excessive sea-ice formation in the Labrador Sea region, leading to cease of deep convection and weakening of the Atlantic meridional overturning circulation (AMOC). This particular problem appears to have time scales ranging from years to order a century, necessitating century-scale simulations. The OMWG has been performing simulations in support of understanding and solving this problem. As a consequence of higher computational cost and need for additional simulations, we have used all of our development and production allocations as of July 2016 and received some supplemental hours from other working groups. From the development side, we eliminated proposed work on air-sea coupling numerics and physics.

Production

Following our original request, we devoted the majority of our production allocation to the preliminary assessments of our model development efforts summarized above. As discussed, we used much more computer time than originally anticipated. However, we believe that such use is well justified both to define the CESM2 ocean component and help diagnose and solve the excessive sea-ice problem in the Labrador Sea region present in the ongoing CESM2 simulations. Thus, due to resource limitations, we decided not to pursue proposed efforts on ocean – atmosphere interactions at the mesoscale; North Atlantic Oscillation (NOA)-related variability in the AMOC; and additional decadal prediction simulations.

We are happy to report that we completed the study investigating the climate impacts of the observed sea surface temperature (SST) anomalies associated with the Atlantic Multi-decadal Variability (AMV). In this collaborative work with GFDL, the North Atlantic SSTs are restored to fixed anomalies corresponding to the internally-driven component of the observed AMV in fully-coupled CESM simulations. In addition to the full AMV SST pattern, its subpolar and tropical patterns are considered in isolation in separate sensitivity experiments. Each set of experiments was run for 10 years with 30 ensemble members. Our results, documented in Ruprich-Robert et al. (2016), show a robust SST response in the Pacific Basin that is very similar to a negative phase of the Pacific Decadal Oscillation in its pattern (Fig. 1, top left). A major finding is that most of the simulated global-scale impacts are driven solely by the tropical part of the AMV, except for the NAO-like response over the North Atlantic/European region, which is shown to be driven both by the subpolar and the tropical parts of the AMV (Fig. 1).

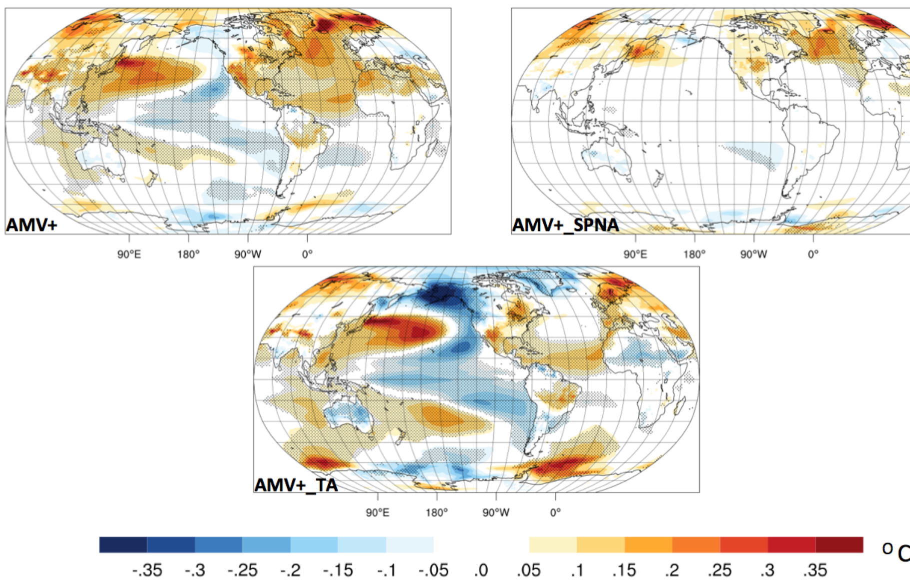


Figure 1. 2-m air temperature distributions from the CESM AMV experiments with the full AMV pattern (AMV+; top left), with the AMV pattern imposed in the subpolar North Atlantic only (AMV+_SPNA; top right), and with the AMV pattern imposed in the tropical (North) Atlantic only (AMV+_TA; bottom). In each panel the difference distributions between the sensitivity experiment that uses the respective AMV positive anomaly patterns and the control are shown.

References

Li, Q., A. Webb, B. Fox-Kemper, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein, 2016: Langmuir mixing effects on global climate: WAVEWATCH III in CESM. *Ocean Modelling*, **103**, 145-160, doi: 10.1016/j.ocemod.2015.07.020.

Ruprich-Robert, Y., F. Castruccio, R. Msadek, S. G. Yeager, T. Delworth, and G. Danabasoglu, 2016: Assessing the climate impacts of the observed Atlantic multidecadal variability using the GFDL CM2.1 and NCAR CESM1 global coupled models. *J. Climate* (submitted).

Paleoclimate Working Group (PaleoWG)

Implementations of water and carbon isotopes in CESM are now nearly complete and are on track to be released in late 2016. Results are very promising (see figure). Development foci also include testing of new components and modules for CISM and prognostic fire to allow inclusion of these in paleoclimate simulations, tracking down a bug for high CO2 simulations, and first testing of CESM1.5 for the LGM simulation that will be completed with CESM2 for CMIP6. We have further extended our LME simulations to include more full-forcing and ozone-aerosol only members and have completed additional scenarios for solar and volcanic forcings. Production accomplishments also include new 'fingerprint' simulations, PlioMIP2 sensitivity simulations, and coupled CESM-CISM simulations for the Last Interglacial and Pliocene.

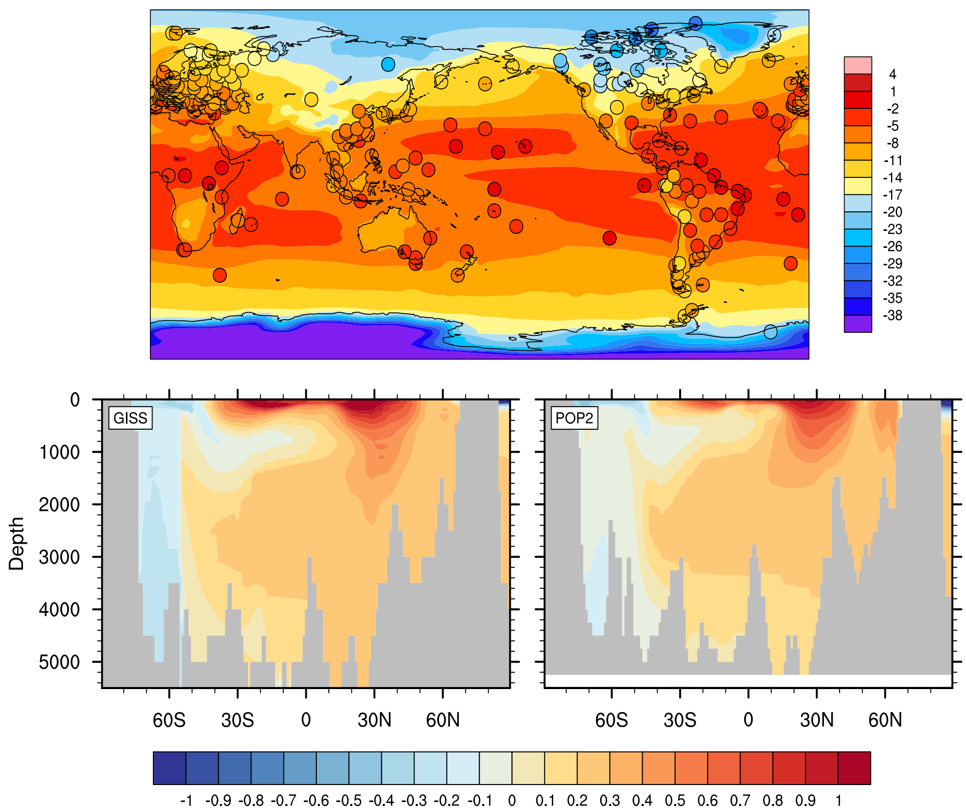


Figure 1. Comparisons of preindustrial water-isotope-enabled CESM simulation with present-day site measurements as compiled by GISS: (top) AMIP CAM5 $\delta^{18}O$ of precipitation and (bottom) coupled POP2 $\delta^{18}O$ of seawater in Atlantic transect at 30.5°W. Units are per mil.

Development

The development allocation was used for:

- Simulations of modern with the water-isotope-enabled version of CESM

The water-isotope enabled versions of CAM5 and CLM4 were used to simulate the modern isotopic climatology for various different resolutions and parameter values, in order to describe the capability of the model to match modern day observations, and to quantify any potential biases or errors that might be important for model users and future model development. Spin-up experiments were completed, to assess the sensitivity of the soil moisture isotope simulation to initial conditions, as well as numerous experiments investigating the impact of the land surface isotopic kinetic fractionation factors on the quality of the coupled land/atmosphere isotopic simulation. Data assimilation methods (Kalman filter and Bayesian model calibration) were implemented in isotope-enabled CLM4, and revealed that the hydrological connectivity of the native CLM4 soil moisture scheme is too weak, and that the native CLM4 soil hydrological scheme is likely responsible for a large portion of the structural errors seen in the modeled isotope ratios relative to observational data. The newly-developed water tagging capabilities of CAM5 were also tested in the context of examining atmospheric rivers in modern and future climate states, as using the model to evaluate moisture source changes will be critical in determining the cause of isotopic changes in paleoclimate proxy records.

- Improvements in CESM and CISM for coupled paleoclimate-ice sheet simulations

A substantial effort has been put in to test new model parameterizations and validate the accuracy of the simulated climate in the coupled CESM-CISM system. The primary focus has been on the atmospheric component (CAM) and the Greenland ice sheet component (CISM) and has been conducted in close collaboration with the model developers. Targeted in CAM were: improvement of the surface drag parameterization to yield more realistic low level winds and turbulent fluxes in the planetary boundary layer, implementation of a robust, versatile and fast topography updating procedure in areas where the ice sheet topography changes in coupled CESM-CISM simulations, and investigation of the strengths and weaknesses of FV1 and FV2 CESM. Targeted in CISM were to: identify issues with the implementation of isostatic adjustment and sliding, test out a new sliding parameterization, and investigate the transient ice sheet response to the atmospheric resolution.

- Testing of prognostic fire implementation for paleo

We have continued our testing of the implementation of the prognostic fire module and emission as well as the spin-up of biogeochemical cycle under CESM1.5 framework for Pliocene boundary conditions. A 600-yr spin-up run for Pliocene has been completed. After three test runs with prognostic fire, a 50-yr preindustrial run using coupled land-atmosphere model and prognostic fire emissions is being completed.

- Testing of CESM1.5/2 for Last Glacial Maximum (LGM) forcings

In anticipation of CMIP6, we have begun developing the LGM forcing datasets and running these in the version of CESM1.5 discussed at the CESM mini-Breck workshop in February 2016. Ocean radiocarbon is being spunup using the Newton-Krylov method.

- Diagnosis of high-CO_2 stability issues

CESM1.2 has had difficulty with simulations for high-CO_2 scenarios (paleo and future). The problem has been found to be associated warm/wet earth conditions, and ultimately pinpointed to code in the long-wave radiation with help of a stand-alone version of the radiation model (PORT). A fix is being introduced to the respective development lines as well as prior model versions where paleo researchers will benefit from this work.

Production

The production allocation was used for:

- Additional Last Millennium Ensemble (LME) simulations

To further enhance the usefulness of the LME for the community, additional simulations were completed: three full-forcing simulations, two ozone-aerosol simulations, a second enhanced solar variability simulation, a Samalas (1258CE) ensemble with the eruption occurring in varying calendar months, and a RCP8.5 scenario with Tambora-sized eruptions occurring in 2015, 2050, and 2085.

- Additional “fingerprint” simulations for the Quaternary

Additional single-forcing "fingerprint" simulations were run to explore the climate response to different types of forcing in isolation. To complement simulations already completed, a zero eccentricity simulation was run, two precession simulations (perihelion at NH austral and vernal equinox) were completed, and high obliquity and half CO_2 simulations were extended.

- PlioMIP2 simulations

In preparation for the CMIP6 PlioMIP2 CESM2 simulation, we have explored the response of Pliocene climate and climate sensitivity to the changed paleogeography, orbital parameters, and CO_2 concentrations in CESM1.2. We have further completed simulations to understand the responses to a cleaner atmospheric background condition, using the prognostic aerosol-cloud interaction implemented in CAM5, which has not been used much for paleoclimate studies.

- Coupled CESM-Greenland ice sheet simulations

We investigated the conditions for glacial inception in Greenland in the mid- to late Pliocene. Experiments were conducted using prescribed SST/SIC from PlioMIP2 sensitivity experiments using different configurations of open and closed ocean gateways in the Arctic. We were able to build a substantial Greenland ice sheet when using an orbital configuration with a low boreal summer insolation, low concentrations of atmospheric greenhouse gases and the simulation with colder SST/SIC boundary conditions. We have carried out a multi-centennial simulation of the Last Interglacial warm period with the FV2 version of CESM-CISM. We have identified issues with the current implementation of basal sliding and the ocean circulation in recent tags of CESM. New experiments are currently being carried out with the FV1 model with a new basal sliding parameterization.

References

Fasullo, J.T., B. Otto-Bliesner, E. Brady, S. Stevenson, R. Tomas, & E. Wahl 2016 “A Future Without A

Summer", in preparation for *Nature.*
Feng, R., B. Otto-Bliesner, C. Tabor, & E. Brady 2016 "Contributions to Pliocene Arctic Terrestrial Warmth from Radiative Forcing and Arctic Ocean Gateways", in preparation for *EPSL.*
Nusbaumer, J. 2016. An Examination of Atmospheric River Moisture Transport and Hydrology using Isotope-enabled CAM5 (Doctoral Dissertation). University of Colorado, Boulder.
Otto-Bliesner, B., Brady, E., Fasullo, J., Jahn, A., Landrum, L., Rosenbloom, N., Stevenson, S., Fasullo, J., Mai, A. & Strand, G. 2016 "Climate Variability and Change since 850 C.E.: An Ensemble Approach with the Community Earth System Model (CESM)", *BAMS*, 97, 735-754.
Otto-Bliesner, B.L., A. Jahn, R. Feng, E. Brady, & M. Lofverstrom, 2016 "Arctic Gateways and a Stronger Atlantic Ocean Conveyor During the Pliocene", submitted to *Nature Geosciences.*
Stevenson, S., Otto-Bliesner, B., Fasullo, J. & Brady, E. 2016 "El Nino-Like Hydroclimate Responses to Last Millennium Volcanic Eruptions", *Journal of Climate*, 29, 2907-2921.
Stevenson, S., Otto-Bliesner, B., Fasullo, J., Brady, E., Tomas, R., & Gao, C. 2016 "Considering Eruption Season to Reconcile Model and Proxy Responses to Tropical Volcanism", submitted to *PNAS.*
Wong, T.E. (advisors: D.C. Noone and W. Kleiber) 2016. The Impact of Stable Water Isotopic Information on Parameter Calibration in a Land Surface Model. PhD Thesis, University of Colorado, Boulder, Colorado, USA.

Polar Climate Working Group (PCWG)

The Polar Climate Working Group (PCWG) simulations utilizing CSL resources from November 1, 2014 to October 31, 2016 have included both development and production experiments. For development, the CSL resources were used to improve polar climate processes and diagnostics for CESM2. For production, the CSL resources were used to analyze high-latitude climate processes in CESM and their connections with the global climate system. The PCWG CSL has engaged a wide variety of university and national lab collaborators. All runs are available for use by the CESM community. Many activities are ongoing.

Development

To enable progress towards improved representation of polar processes within CESM, simulations were done in support of: 1) sea ice model development, 2) sea ice model sensitivity tests, 3) development of satellite simulators for assessing moist atmospheric physics in polar regions, and 4) development of data assimilation for the sea ice model component.

<u>1) Sea ice model development:</u> CSL resources were used to complete simulations to enable migrating from version 4 code to version 5 of Los Alamos Sea Ice Model (CICE). With the version 5 code base came several new physics options, all of which we had to assess in fully-coupled/partially coupled configurations so we could decide which physics to use in the CESM2 default configurations. The new physics we tested included the mushy-layer physics option (Turner and Hunke 2015), the level melt ponds (Hunke et al. 2013), increased vertical levels in the sea ice and snow, the anisotropic sea ice dynamics, and the air-ice form drag parameterization. Through a systematic series of experiments in which we tested each individually, plus combinations of the above, it was determined that the default configuration moving forward would include the first three of these physics options.

<u>2) Sea ice model sensitivity tests:</u> Sea ice model sensitivity experiments completed during this CSL allocation were designed in conjunction with the first of a 3-part series of observational–modeling workshops for improving polar processes in CESM funded by NSF proposal (OPP 078339587). Both the sensitivity experiments and this first observation-modeling workshop focused on the representation of snow processes on sea ice.

<u>3) Implementing satellite simulators for assessing moist atmospheric physics:</u> The PCWG used development CSL resources to implement satellite simulators that enable robust evaluation of CAM clouds and precipitation in polar regions using satellite observations. Specifically, CSL resources were used to implement and validate the latest version of the satellite simulators (COSP1.4) within CESM2 (Kay et al. 2016a). The new diagnostics have been used to evaluate and improve the representation of cloud phase within CAM5, and also to evaluate candidate versions

of CAM6 for CESM2. With collaborators at University of Wisconsin and University Marie Curie in Paris, France, we also began implementation of CESM-specific diagnostics that improve evaluation of polar precipitation. Cloud phase and precipitation biases have important impacts on surface energy budgets and sea ice growth/melt. Thus, having tools in place to evaluate these two biases within CESM2 is an important advance enabled by CSL resources.

4) Enabling data assimilation within the CESM sea ice component: Research on sea ice predictability has shown that forecast skill arises primarily from persistence of sea ice thickness and sea surface temperature and salinity anomalies, including the transport of these anomalies; accurate knowledge of sea ice conditions at melt onset; and coupled interactions of sea ice with the atmosphere and ocean. For these reasons, forecast systems need accurate initialization with detailed spatial information in the sea ice and other components. To meet these needs, researchers at the University of Washington used Development CSL resources to add the CESM sea ice component to the Data Assimilation Research Testbed (DART). Computing time was used for testing and evaluating the initial conditions produced with data assimilation in CICE.

Production

Production resources were used to enable progress towards understanding polar processes and their role in the global climate system. CESM experiments were done to assess: 1) shallow convective cloud phase influence on polar and global climate, 2) fresh water tracers, 3) attribution of 20th-Century trends and decadal variability in the atmospheric circulation of the polar regions, and 4) idealized climate change simulation in support of a community project. Production CSL resources were also used to support analysis of the CESM Large Ensemble by early career scientists at multiple universities including the University of Washington, the University of Wisconsin-Madison, and the University of Colorado-Boulder.

1) Shallow convective cloud phase influence on polar and global climate: CSL resources were used to design experiments that assess the influence of shallow convective cloud phase on mean climate and climate change. For the mean climate, improving the representation of shallow convective cloud phase dramatically reduced a long-standing absorbed shortwave radiation bias over the Southern Ocean. The experiments with and without a fully coupled ocean revealed the importance of dynamical ocean coupling to climate system response. Results of the mean state experiments are in Kay et al. (2016b). For climate change, improving the representation of shallow convective cloud phase increased climate sensitivity (global warming in response to carbon dioxide doubling) by 1.5 degrees Celsius. The increased climate sensitivity results from cloud phase and cloud amount feedbacks over the Southern Ocean. The impact of the ocean circulation on these cloud feedbacks has also been assessed. Analysis of the climate change experiments is largely complete and the paper will be submitted this Fall (Frey and Kay, in prep).

2) Fresh water tracers: Resources were used for Arctic freshwater tracer production simulations to support a funded NSF OPP proposal to better understand the impact of 20th -21st century changes in the Arctic Ocean on ocean circulation and deep convection. The tracers tag freshwater from different sources, for example Pacific freshwater, sea ice melt water, and river runoff (see Jahn et al. 2010). Two classes of experiments are being run. First, two additional 1920-2100 CESM-LE members with fresh water tracers are ongoing. These additional members will enhance analysis of the freshwater dynamics in the CESM-LE, revealing dynamics in the context of internal variability. The second class of experiments 360 years of CORE forced ocean-sea ice only runs used to compare the simulated variability of Arctic freshwater and its tagged components (e.g. river runoff, Pacific freshwater) directly with observations of different components of Arctic freshwater from the Arctic switchyard region (collaboration w/Columbia University) and Fram Strait.

3) Attribution of 20th-Century trends and decadal variability in the atmospheric circulation of the polar regions. Resources were used to support a funded NSF project (OPP 1341621) on attribution of 20th century trends and variability. Traditional atmosphere-only experiments are ambiguous to interpret, as they do not elucidate the extent to which sea surface temperature-driven circulation trends are associated with anthropogenic warming. This ambiguity is especially problematic in polar regions. The ongoing simulations enable a systematic comparison of the forcing of polar climate change. Four runs span 1904-2013 (110 years each), consistent with the available observational data and providing a long timescale perspective. Additional resources (beyond this CSL) are being used to finish the proposed experiments.

4) Idealized climate change simulation in support of a community project. Resources were used to complete an idealized climate change experiment using the CESM Large Ensemble code base. The experiment is an instantaneous doubling of carbon dioxide in a fully coupled model and has been run out 300 years. The simulation length is long because the timescale of the deep ocean equilibrates to carbon dioxide forcing on multi-century timescales. The simulation complements the existing transient 20th-21st century ensemble members and 2000+ year 1850 fully coupled control run.

References

Frey, W. R. and J. E. Kay (in prep), The influence of extratropical cloud phase and amount feedbacks on climate sensitivity modified by ocean heat uptake, *Climate Dynamics*, to be submitted Fall 2016

Hunke, E. C., Hebert, D. A. and O. Lecomte (2013). Level-ice melt ponds in the Los Alamos Sea Ice Model, CICE. *Ocean Modelling*, 71, 26–42. doi: 10.1016/j.ocemod.2012.11.008. LA-UR-12-21874

Jahn, A., L. B. Tremblay, R. Newton, M. M. Holland, L. A. Mysak, and I. A. Dmitrenko (2010), A tracer study of the Arctic Ocean's liquid freshwater export variability, *J. Geophys. Res.*, 115, C07015, doi:10.1029/2009JC005873.

Kay, J. E., Bourdages, L., Chepfer, H., Miller, N., Morrison, A., Yettella, V., and B. Eaton (2016a), Evaluating and improving cloud phase in the Community Atmosphere Model version 5 using spaceborne lidar observations, *Journal of Geophysical Research - Atmospheres*, 121:8, 4162–4176, DOI: 10.1002/2015JD024699

Kay, J. E., Wall, C., Yettella, V., Medeiros, B. Hannay, C., P. Caldwell, and C. Bitz (2016b), Global climate impacts of fixing the Southern Ocean shortwave radiation bias in the Community Earth System Model, *J. Climate*, 29:12, 4617–4636, doi:10.1175/JCLI-D-15-0358.1

Turner, A. K. and E. C. Hunke. Impacts of a mushy-layer thermodynamic approach in global sea-ice simulations using the CICE sea-ice model (2015). *J. Geophys. Res. Oceans*, 120: 1253–1275. DOI: 10.1002/2014JC010358. LA-UR-14-25975

Societal Dimensions Working Group (SDWG)

Computing within the SDWG supported core projects in linkages between CESM and integrated assessment models (IAMs) and in water-related impacts, while also investigating a new topic in geoengineering through solar radiation management. It supported CESM/SDWG contributions to important community processes such as an agricultural model comparison project (AgMIP) and the design of CMIP6 experiments relevant to the SDWG, particularly those related to future scenarios and land use (ScenarioMIP, LUMIP). Key outcomes included papers on the linking of CESM to an integrated assessment model to assess future impacts on agriculture, and on the role that solar radiation management combined with mitigation could play in meeting future climate goals (Figure 1). Several additional papers are in progress on the role of land use in carbon cycle and regional climate outcomes, uncertainty in hydrologic extremes, and implications of uncertainty for regional water planning.

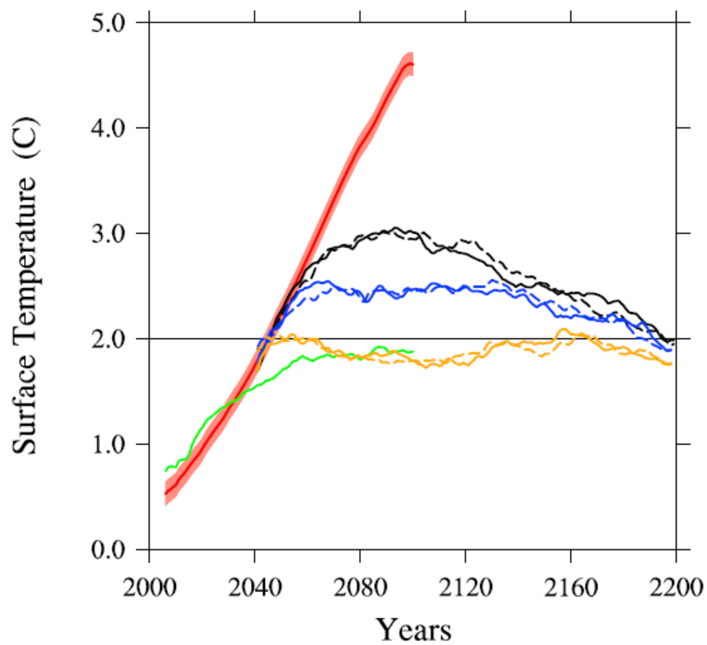


Figure 1. CESM simulations of a delayed mitigation scenario (black) and scenarios that add solar radiation management to limit warming to 2.5 C (blue) and 2.0 C (orange). RCPs 8.5 (red) and 2.6 (green) are shown for comparison. From Tilmes et al., 2016.

Development

The development allocation was used to investigate methodological issues related to links between CESM and integrated assessment models, as well as to downscaling of CESM for hydrological impact assessment. Simulations were carried out to:

- **Further develop links between integrated assessment models and CESM through the development and application of the Toolbox for Human-Earth System Integration and Scaling (THESIS).** Simulations of CLM-Crop were carried out over both historical and future periods. Historical runs supported CLM participation in a Global Gridded Crop Model Intercomparison (GGCMI) project as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP). Results will be included, along with results from other models, in AgMIP GGCMI papers and separately as a paper comparing CLM Crop to the 1961 – 2013 UNFAO Crop Database. The simulations of future scenarios were used as the basis for development of the THESIS Crop Yield Tool, which produces regional aggregate impacts of climate on yield based on inputs from the iPETS integrated assessment model. This tool was used in an analysis of biophysical and economic impacts of climate on agriculture that linked iPETS and CLM, as part of the Benefits of Reduced Anthropogenic Climate Change (BRACE) project (Ren et al., submitted).
- **Evaluate uncertainty related to land use in the integrated Earth System Model (iESM).** The iESM links CESM to the GCAM integrated assessment model. Simulations assessed the sensitivity of land-related outcomes to uncertainty in land cover conversion uncertainty, initial land cover conditions, CO2 fertilization, climate change, and nitrogen deposition on terrestrial carbon. A draft manuscript has been prepared for submission to Geographical Research Letters. Results show that LULCC accuracy and uncertainty are critical for estimating the response of the carbon cycle, and also that LULCC may be an important lever for constraining global carbon estimates. Furthermore, differences in land conversion assumptions generate regional differences of up to 0.8 °C, highlighting the need for more accurate LULCC scenarios with quantified uncertainty in earth system simulations in order to provide robust historical and future projections of carbon and climate.
- **Evaluate the uncertainty in hydrologic responses to climate change at continental scale.** CLM simulations were used to test the sensitivity of runoff to four different statistical downscaling methods applied over the US. Results provided information to guide scoping decisions about downscaling methods and hydrologic models to evaluate climate change impact on hydrology for different types of water planning assessments (e.g., flood risk assessments at local scales versus long term water supply assessments). A paper discussing the implications for future water resources planning is in progress.

Production

The production allocation was used to carry out simulations related to better understanding hydrologic extremes and the potential roles of land use and geoengineering in future emissions scenario. Simulations were carried out to:

- **Develop a low-resolution CESM version in preparation for a CESM perturbed physics experiment focused on the hydrological cycle.** Simulations were carried out in order to develop a stable, running, low resolution version of CESM. In collaboration with Lawrence Berkeley National Lab, a low resolution (10x15 degree) version of CESM was tested such that coupled simulations could be performed to rapidly sample the parameter space of the model, and a small parameter ensemble was constructed in order to tune the configuration. The next stage of this research involves a joint ensemble, with a dense sampling of the low resolution model version and a sparse sampling of the conventional 1 degree model (to be carried out primarily at NERSC), to investigate the impact of parameter uncertainty on extremes.
- **Investigate the potential role of geoengineering in meeting future climate goals.** CESM simulations were carried out of scenarios combining delayed emissions mitigation with geoengineering via stratospheric sulfate injection (SSI). Results were recently published in GRL (Tilmes et al., 2016) and showed that a gradual increase and then decrease of SSI over this period reaching a maximum of either 0.8 or 1.5 times the aerosol burden resulting from the Mt Pinatubo eruption in 1992 would limit the increase in GMT to either 2.5 or 2.0 degrees (Figure 1). SSI produces mean and extreme temperatures that are comparable to those that would be result from achieving the same scenario through mitigation alone, but aridity is not ameliorated to the same extent.
- **Investigate land cover change in CESM 1.2/CLM4.5 to guide CMIP6.** Ensembles of land cover simulations were run for the historical, RCP 4.5, and RCP 8.5 time periods following the CMIP5 protocol. The new simulations compared CMIP5 land cover change to no land cover change, to alternative RCP land cover change, and to maximum afforestation and agricultural expansion. The results of the carbon impacts (see Figure 3) have been written up for submission as a paper to the Journal of Geophysical Research: Biogeosciences. A paper on the climate impacts is also underway for Climatic Change as part of the BRACE special issue.

References

Ren, X., Weitzel, M., O'Neill, B.C., Lawrence, P., Balistreri, E., Dalton, M. Avoided economic impacts of climate change on agriculture: Integrating a land surface model (CLM) with a global economic model (iPETS). Climatic Change, in review.

Tilmes, S., Sanderson, B. M., O'Neill, B. C., 2016. Climate impacts of geoengineering in a delayed mitigation scenario. Geophysical Research Letters, 43. DOI: 10.1002/2016GL070122.

Software Engineering Working Group (SEWG)

Development

During the past year, the CSL CESM SEWG development allocation was used to incorporate major science and infrastructure changes across the CESM system as part of constructing intermediate development versions leading to CESM2. In particular, 33 development snapshots (i.e. "beta tags") of the model system were created, each containing both new software 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 CISL 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 Common Infrastructure for Modeling the Earth or CIME. CIME is an emerging paradigm for the collective construction and maintenance of the infrastructure required by earth system model development and applications. CIME was developed as a response to the February 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. The key concept in CIME is that it enables separation of the distribution of infrastructure (where there is generally no intellectual property) from the distribution of scientific development code base (where there is intellectual property). Most importantly 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, share experience

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. CIME is publicly available in a stand-alone package that can be compiled and tested without full prognostic components

Over the last year, the ACME software engineering group has become actively engaged in an informal collaboration on CIME, with negotiations underway on a more formal agreement. As a result of this collaborative effort, the CIME scripting infrastructure has been completely rewritten in python using object oriented design and test driven development. CSEG utilized the SEWG CSL allocation to carry out a large part of this refactoring effort.

Integration of python based parallel post processing for CESM workflow management and automation:

In preparation for the CMIP6 experiments, CSEG developers worked 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.

References

Baker, A.H., D.M. Hammerling, M.N. Levy, H. Xu, J.M. Dennis, B.E. Eaton, J. Edwards, C. Hannay, S.A. Mickelson, R.B. Neale, D. Nychka, J. Shollenberger, J. Tribbia, M. Vertenstein, and D. Williamson, "A new ensemble-based consistency test for the community earth system model." *Geoscientific Model Development*, 8, 2829–2840, doi:10.5194/gmd-8-2829-2015, 2015.

Baker, A.H., Y. Hu, D.M. Hammerling, Y. Tseng, X. Hu, X. Huang, F.O. Bryan, and G. Yang, "Evaluating Statistical Consistency in the Ocean Model Component of the Community Earth System Model (pyCECT v2.0)." *Geoscientific Model Development,* 9, 2391-2406, doi:10.5194/gmd-9-2391-2016 2016.

Whole Atmosphere Working Group (WAWG)

The Whole Atmosphere Community Climate Model (WACCM) Working Group (WAWG) has made significant strides using CSL resources in the last year. These include updates to gravity waves, stratospheric sulfur, advancements of WACCM-X and participation in several community projects with production runs. We are also on track to have a common code base for WACCM6 with CAM6 in CESM2 and new functionality for WACCM-X

Development

The development allocation was used to prepare WACCM6 and WACCM-X2.0 for CESM2. This included development of new capabilities for WACCM-X that replicate much of the functionality of the TIME-GCM for the upper atmosphere. A prognostic stratospheric volcanic module was developed to improve the representation of volcanic impacts on climate (Mills et al., 2016). New D region ion chemistry have been added to WACCM (Verronen et al., 2016) to better represent geomagnetic forcing of the middle atmosphere. Stratospheric chemistry was updated to the latest community accepted rate constants. In addition, the WAWG has been working hard to ensure consistency between CAM6 and WACCM6 for CESM2 so a fully unified model of the atmosphere including chemistry can be delivered.

WACCM-X

The WAWG has been expanding the functionality of WACCM-X to better represent the atmosphere from the surface through the thermosphere. Recently improvements include a more self-consistent ionosphere module for WACCM-X that includes computation of electron and ion temperatures, interactive electric wind dynamo, and O+ transport in the ionospheric F-region. The dynamical core of the model has also been recently improved to represent the species dependency of specific heats and mean atmosphere mass in the thermosphere. This is necessary to represent an interactive Ionosphere-Plasmasphere. Functionality for key components of the upper atmosphere has been added and WACCM-X2.0 will be released in CESM2.

Volcanoes

We have completed, validated, and documented the implementation of prognostic stratospheric aerosol for use in WACCM6 and CAM6-chem. This work has involved extending sulfur chemistry and modal aerosol model (MAM) developed with CAM5 to include source gases, aerosol growth, evaporation, and swelling processes important in the stratosphere. In addition, we have developed a 4D emission inventory of SO_2 from explosive volcanic eruptions for the period from 1850 to 2015. We have performed simulations for the period 1990-2015, which we have validated against ground-based and in situ observations. The description of this capability and validation of aerosol properties have been published in Mills et al. (2016). Validation of volcanic impacts on Antarctic ozone chemistry have been published in Solomon et al. (2016).

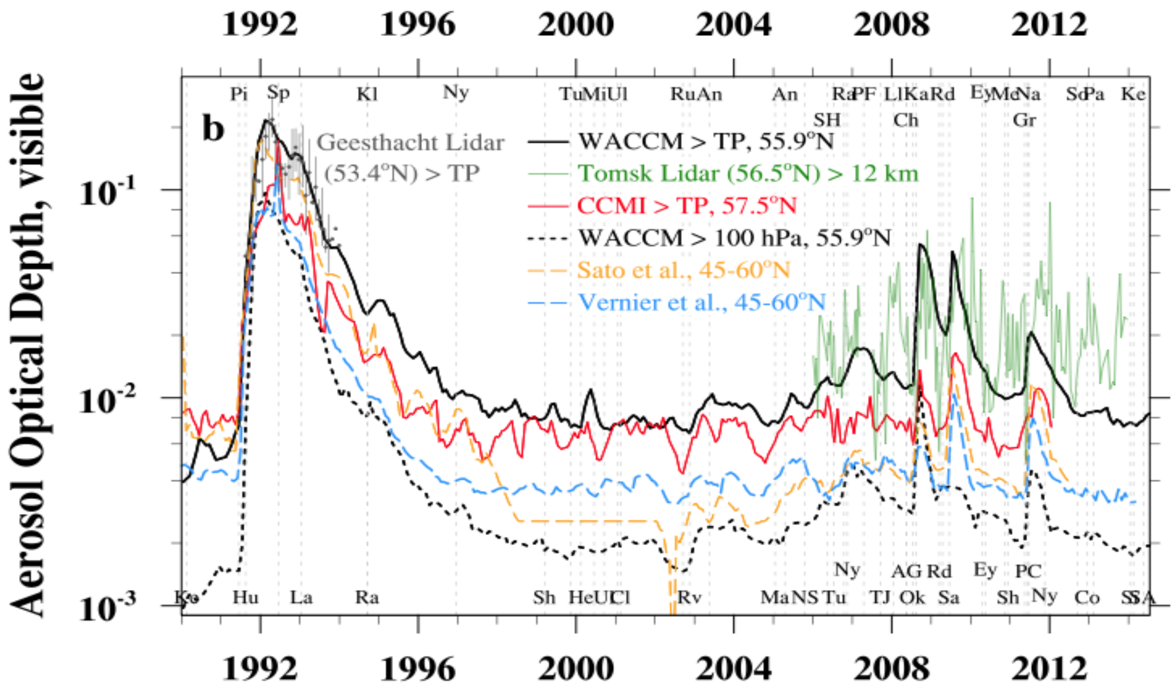


Figure 1. Stratospheric aerosol optical depths calculated in CESM(WACCM) are compared to observations. Model calculated zonal mean AOD above the tropopause compares very well to lidar observations, shown here from the Pinatubo period (1991-93) in Germany and for 2005-13 in Russia. Climate models generally prescribe volcanic aerosols based on analyses of satellite observations (Sato et al. and Vernier et al. shown here), which neglect aerosol below 100 hPa due to cloud interference with satellite retrievals. The model indicates that at mid-latitudes this approach misses about 80% of the stratospheric aerosols, which are between the tropopause and 100 hPa. (Adapted from Mills et al., 2016)

Gravity Waves

We have worked to adjust the middle atmosphere forcing from gravity waves to reproduce existing climatologies of temperature. This involved removing the use of the "land fraction factor" from the parameterization and adjusting the source fluxes of orographic gravity waves in the Southern Hemisphere. The model now produces polar cap temperatures in very close agreement with observations (within 1-3 K throughout much of the year in the ozone hole region). The simulation of ozone loss has improved accordingly; for example, the calculated evolution of the ozone column during the ozone hole period is now virtually indistinguishable from observations during most months except December, when the model still simulates a somewhat late breakdown of the polar vortex in the lowermost stratosphere. In addition, the more accurate representation of the zonal winds has improved the frequency and seasonal timing of Sudden Stratospheric Warmings (SSW), winter-time reversals of the zonal-mean zonal wind in the middle stratosphere.

The parameterization of tropical gravity waves excited by convection was also modified in order to provide adequate forcing to produce an equatorial quasi-biennial oscillation (QBO). As a result, WACCM6 will be the first publicly available version of WACCM to have an internally generated QBO, and will therefore be useful to study the impact of the QBO on transport of chemical species, and its influence on the frequency of SSW in northern hemisphere winter. The figure below shows the equatorial zonal-mean zonal wind over 10 years of a recent WACCM6 simulation (bottom) compared to observational data (top). The amplitude, period and structure of the QBO is realistic above about 20 km. Below this altitude, WACCM6 fails to capture the full development and duration of the westerly phase of the QBO. This is a known problem with models, such as WACCM6, that have limited vertical resolution (coarser than about 500-700 m). In such models, the low frequency equatorial Kelvin waves that drive the westerly phase in the lowermost stratosphere cannot be represented properly and the momentum source due to these waves is therefore missing.

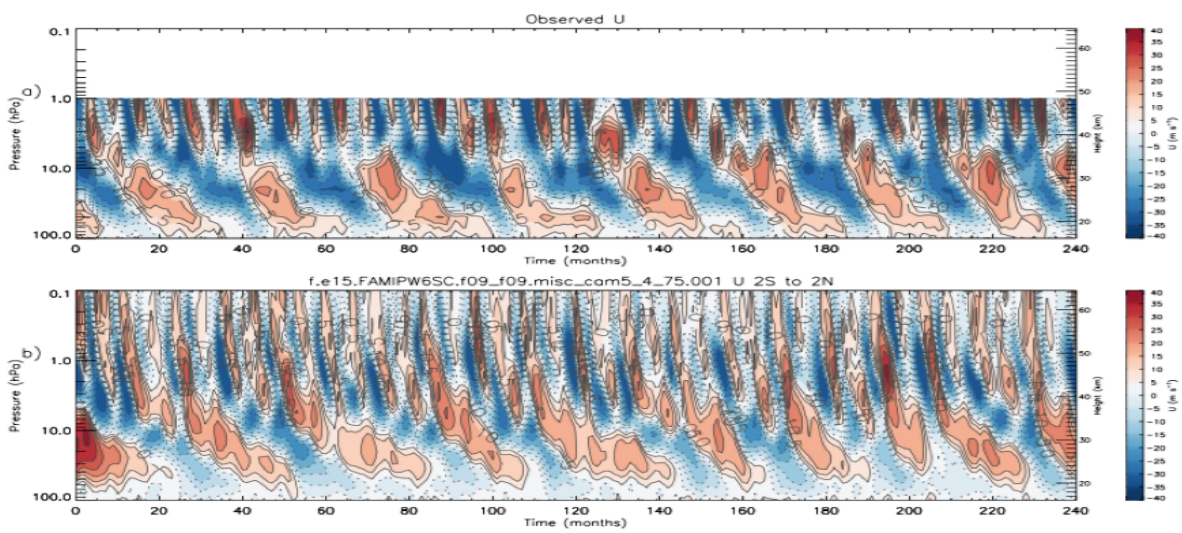


Figure 2. Tropical average (2^{o}S to 2^{o}N) of zonal mean wind. Top: ERA-Interim, Bottom: WACCM6 simulation.

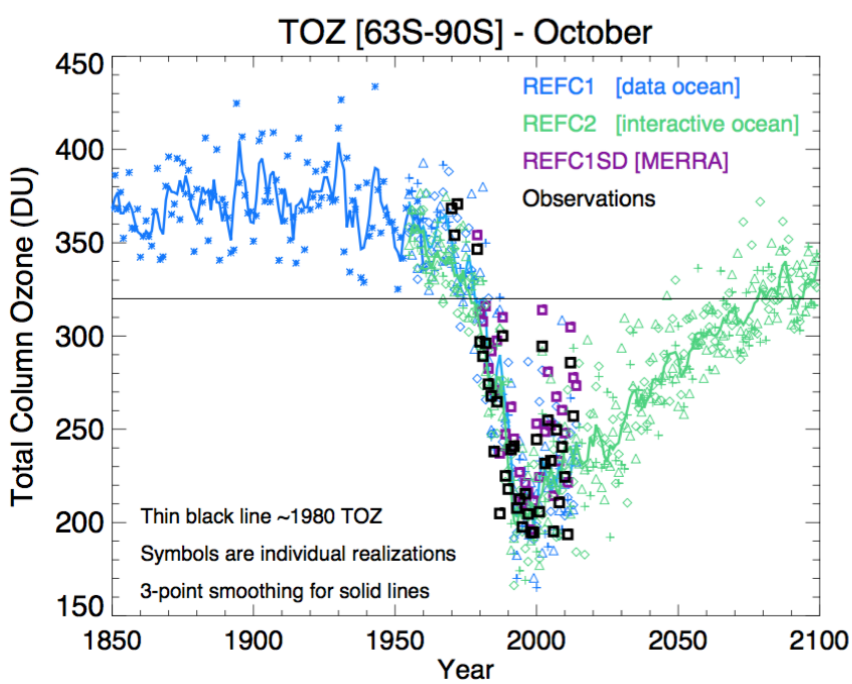
WACCM6 in CESM2

WACCM6 will be released with the same physical representations as CAM6. This required significant development work to test and modify CAM6 physics. Numerous issues were discovered in new physical parameterizations (including water conservation issues) thanks to work with WACCM. WACCM6 will also be working with new CAM6 momentum forcing for surface stress and for orographic waves.

Production

The production allocation was used to evaluate and complete a last millennium run with WACCM4 to better understand the influence of past solar variability on climate. WACCM was run for the Chemistry Climate Model Initiative (CCMI) intercomparison project to assess both chemistry and climate, with historical and future simulations. WACCM also has been run for the GEOMIP Geo-Engineering model intercomparison. We have also performed simulations with asteroid impacts and sectional aerosol and cloud microphysics (WACCM-CARMA).

The WACCM simulations in support of the IGAC / SPARC Chemistry Climate Model Initiative (CCMI) effort was completed using the Whole Atmosphere Working Group (WAWG) CSL production allocation. This included seven different hindcast and projection scenarios that spanned the period between years 1850 and 2100 – a total of over 2600 simulations years. The results have been CMOR'ized and made available on the Earth System Grid. An example of these results is shown below. Here, the southern hemisphere total column ozone (TOZ) polar cap average is shown for October. The WACCM ozone hole chemistry as described in Wegner et al., [2013] and Solomon et al., [2015] accurately represents the observed ozone depletion. The WACCM model suggests that the polar TOZ will recover to 1980 conditions around year 2060.



References

Mills, Michael J., Anja Schmidt, Richard Easter, Susan Solomon, Douglas E. Kinnison, Steven J. Ghan, Ryan R. Neely, et al. "Global Volcanic Aerosol Properties Derived from Emissions, 1990–2014, Using CESM1(WACCM)." *Journal of Geophysical Research: Atmospheres* 121, no. 5 (March 16, 2016): 2015JD024290. doi:10.1002/2015JD024290.

Solomon, S., D. E. Kinnison, J. Bandoro, R.Garcia, Simulations of Polar Ozone Depletion: An Update, *J. Geophys. Res.,* 120, 7958-7974, doi:10.1002/2015JD0233652015.

Solomon, S., Ivy, D. J., Kinnison, D. E., Mills, M. J., Neely, R. R., III, & Schmidt, A. (2016). Emergence of healing in the Antarctic ozone layer. *Science*, *353*(6296), aae0061–274. doi:10.1126/science.aae0061.

Verronen, P. T., M. E. Andersson, D. R. Marsh, T. Kovács, and J. M. C. Plane (2016), WACCM-D—Whole Atmosphere Community Climate Model with D-region ion chemistry, *J. Adv. Model. Earth Syst.*, 8,954–975, doi:10.1002/2015MS000592.

Wegner, T, D. E. Kinnison, R. R. Garcia, S. Madronich, and S. Solomon, Polar Stratospheric Clouds in SD-WACCM4, *J. Geophys. Res.*, VOL. 118, 1-12, doi:10.1002/jgrd.50415, 2013.