

CESM

Community Earth System Model



CESM CSL Accomplishments

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Period of Performance: 01 November 2019 – 31 October 2020

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Cover image: Snapshot of the lowest model level streamlines, draped over the Greenland ice-sheet and colored by wind speed. Simulation was performed with a $1/8^\circ$ refined grid over the island of Greenland using the variable-resolution configuration of the spectral-element atmospheric dynamical core in CESM2. Katabatic winds can be seen accelerating down the eastern slopes of the ice sheet. Visualization was developed by Matt Rehme (CISL) and Adam Herrington (CGD) of the National Center for Atmospheric Research, and was inspired by a visualization of winds over Antarctica by the Polar Meteorology Group at the Byrd Polar & Climate Research Center.

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This Accomplishments Report covers the 01 November 2019 – 31 October 2020 period, corresponding to the second year of our current allocation cycle. Because the majority of our first year allocation was devoted to CESM2 simulations in support of our participation in the Coupled Model Intercomparison Project phase 6 (CMIP6) effort, the second year allocation was devoted to development and production simulations to advance CESM Working Groups (WGs) activities as well as several Community Projects dedicated to broader cross-WG efforts. Although only very few additional CMIP6 Tier 1 simulations have been performed using our remaining allocation for this purpose, WGs performed an extensive set of Tier 2 and higher simulations under their WG's allocations. While the summaries of these latter simulations are provided under WG accomplishments, only a brief summary of CESM CMIP6 accomplishments are included here, noting that a more extensive summary was also provided in our Interim Report that was submitted on 21 September 2019. Therefore, the majority of this Accomplishments Report is dedicated to the WG and Community Project efforts.

CESM2 CMIP6 Simulations

Numerous simulations were performed with both the low-top with limited chemistry, CESM2(CAM6), and the high-top with comprehensive chemistry, CESM2(WACCM6), versions to support CESM's contributions to CMIP6 (Eyring et al. 2016). In addition to the required Diagnostic, Evaluation, and Characterization of Klima (DECK) experiments, CESM2 participated in about 20 CMIP6-endorsed Model Intercomparison Project (MIP) efforts. The majority of these simulations were performed using the nominal 1° horizontal resolution configuration in all component models. To provide a computationally more economical model for long time scale, e.g., paleoclimate, applications, several DECK and MIP simulations were also conducted with a version that uses a 2° horizontal resolution in its atmospheric component only.

CESM2 was already released to the community in June 2018. To expedite the use of CESM2 by the community primarily for CMIP6-related science and simulations, three *incremental* releases of CESM2 with the same base code were made available in December 2018 (CESM2.1.0), June 2019 (CESM2.1.1), and February 2020 (CESM2.1.2) in which many of these simulations can be run as out-of-the-box configurations. All model versions are available at www.cesm.ucar.edu/models/cesm2/.

The data sets from CESM2 CMIP6 simulations are available on the Earth System Grid Federation (ESGF; <https://esgf-node.llnl.gov/search/cmip6>). To date, about 1000 CMIP6 experiments – including some Tier 2 and higher simulations for several MIPs – have been run. About 1.7 PB of lossless-compressed time series files have been generated. 600 TB of these time series files, corresponding to over 830,000 files, have been published on the ESGF. This volume of data is roughly 7 times larger than CESM1's contributions to CMIP phase 5.

Manuscripts describing and analyzing these CESM2 CMIP6 experiments in detail are collected in *the AGU CESM2 Virtual Special Issue*. As CESM2 simulations are used in

many studies, including national and international climate assessments, it is important that its main characteristics are thoroughly analyzed and documented. The Special Issue is spread across several AGU journals that include *Journal of Advances in Modeling Earth Systems*, *Global Biogeochemical Cycles*, *Journal of Geophysical Research – Atmospheres*, *Journal of Geophysical Research – Earth Surface*, *Journal of Geophysical Research – Oceans*, and *Geophysical Research Letters*. To date, over 40 published or submitted manuscripts have been contributed by members of the broad Earth system modeling community. For timely dissemination of the results, we have made all the to-date published and submitted manuscripts available at <http://www.cesm.ucar.edu/publications/>.

An introduction to CESM2 is provided in Danabasoglu et al. (2020), summarizing many new scientific and technical advances in CESM2 compared to its previous version, CESM1. Among many others, such advances include improved representations of clouds (Golaz et al. 2002), crops (Lawrence et al. 2019), and Greenland's evolving ice-sheet (Lipscomb et al. 2019). In comparison to both available observations and CESM1, CESM2 historical simulations show reduced precipitation and shortwave cloud forcing biases. Many aspects of the El Nino – Southern Oscillation (ENSO), including its dominant time scale and associated teleconnections (Capotondi et al. 2020), as well as those of the Madden-Julian Oscillation are simulated well (Danabasoglu et al. 2020). In addition, the representations of storm tracks and the Northern Hemisphere stationary waves and winter blocking are significantly improved (Simpson et al. 2020).

Equilibrium Climate Sensitivity (ECS; equilibrium change in global-mean surface temperature after CO₂ doubling) and Transient Climate Response (TCR; change in global-mean surface temperature around the time of CO₂ doubling when CO₂ increases by 1% per year) are two of the emergent properties of the coupled simulations. The CESM2 ECS values of 5.1°C – 5.3°C are considerably higher than those of its previous versions which had ECSs of around 4.0°C. The increased ECS in CESM2 is largely due to a combination of relatively small changes to cloud microphysics and boundary layer parameters, resulting in changes in clouds and in their feedbacks particularly over the Southern Ocean, but also over the tropical oceans (Bacmeister et al. 2020; Zelinka et al. 2020; Gettelman et al. 2019). In contrast, the CESM2 TCR values remain around 1.9°C – 2.0°C, similar to those of its previous versions. Such similarity in this integrated value, however, masks significant regional differences in warming magnitude and patterns (Bacmeister et al. 2020).

Interestingly, CESM2 does not appear to be alone in exhibiting an increased ECS. Indeed, as shown in Fig. 1, one third of the CMIP6-generation models (13 out of 39) studied in Meehl et al. (2020a) have ECS values of higher than the so-called canonical value of 4.5°C, with 6 of the models showing even higher ECS values of more than 5°C. Meehl et al. (2020a) also report a range of 1.8°C – 5.6°C for ECS in these new generation models. Both this range and the high ECS values in CMIP6 are significantly larger than seen in previous generation models. As in CESM2, cloud feedbacks and cloud – aerosol interactions are identified as the likely contributors to increased ECS with details of sensitivities possibly differing among models (Meehl et al. 2020a).

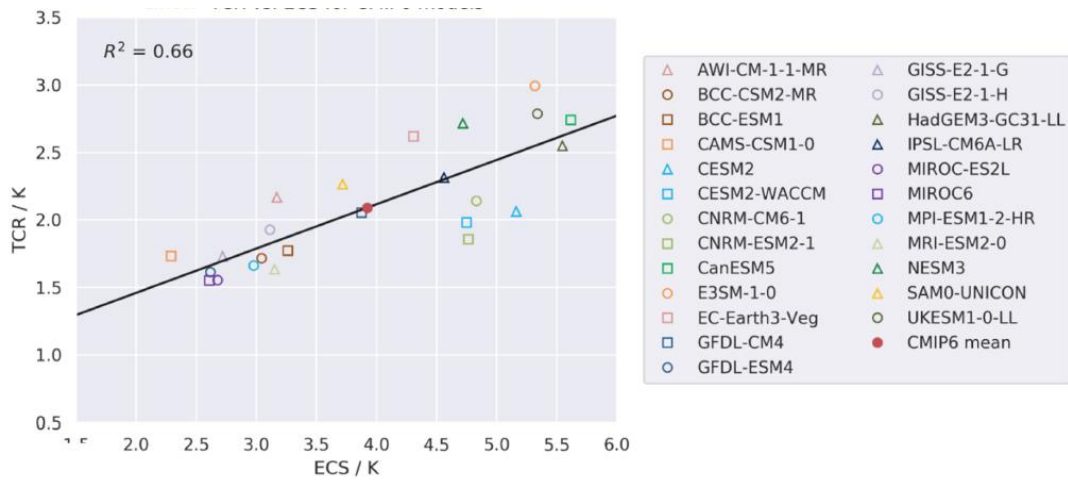


Figure 1. Equilibrium Climate Sensitivity (ECS) vs. Transient Climate Response (TCR) from models participating in CMIP6 (from Meehl et al. 2020a).

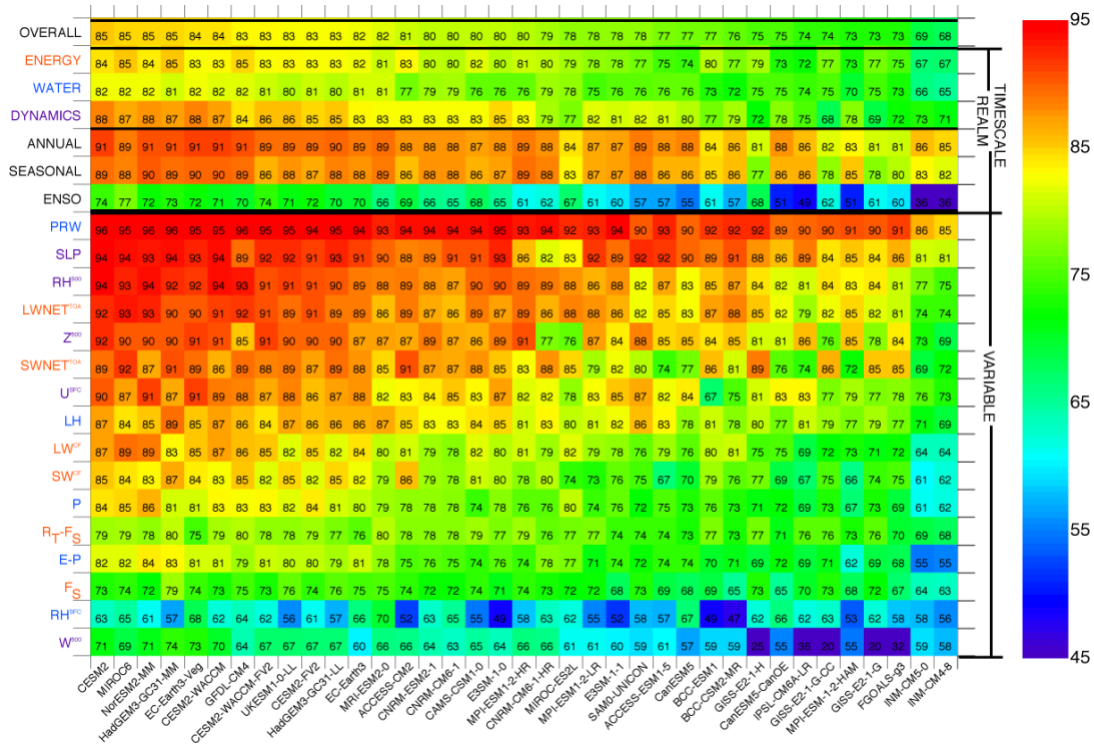


Figure 2. A model performance summary obtained using the Climate Model Analysis Toolkit (CMAT; from Fasullo 2020). Simulated fields related to energy budget, water cycle, and dynamics are evaluated in comparison to available observations, considering their annual-means, seasonal contrasts, and inter-annual variability. Only one member is used from 37 historical (transient) simulations submitted to the CMIP6 archive.

The *AGU CESM2 Virtual Special Issue* manuscripts highlight many improvements in model solutions and advances in our scientific understanding with CESM2. Figure 2 shows an evaluation of some simulated fields related to energy budget, water cycle, and dynamics considering their annual-means, seasonal contrasts, and inter-annual variabilities in comparison to available observations from 37 historical (transient) simulations submitted to the CMIP6 archive (Fasullo 2020). This analysis indicates that CESM2 simulations rank among the most realistic coupled models in the CMIP6 archive with all CESM2 simulations being in the top ten.

Despite these improvements, many shortcomings remain. These include local precipitation biases, larger-than-observed ENSO amplitude, some degradations in Southern Hemisphere circulation properties, thin Arctic sea-ice in some simulations, and some other persistent biases such as incorrect path of the North Atlantic Current. As we move towards our next generation model, i.e., CESM3, with many planned advances to be incorporated in strong collaborations with the community, including a new ocean model component and higher atmospheric vertical resolution with a new dynamical core, it is anticipated that some of these biases will be addressed.

Atmosphere Model Working Group (AMWG)

The AMWG CSL allocation was used for Community Atmosphere Model (CAM) development and testing for use in the larger coupled system, as well as for participation in community projects. As the “sphere” that mediates the Earth’s radiation budget and the only component which communicates with all other components, the atmospheric model is the linchpin of the fully-coupled system. Use of CSL resources has allowed us to produce an atmosphere model that is compatible with other CESM components and gives a credible coupled climate simulation in both preindustrial and 20th century configurations.

Over the last year, AMWG has continued simulations to diagnose the CESM2 coupled system (Danabasoglu et al. 2020) as well as to explore new configurations for community use and for future coupled modeling systems. AMWG researchers completed a study examining the origins of the dramatically increased ECS in CESM2 4xCO₂ experiments (5.3°C) versus CESM1 4xCO₂ (4.2°C) (Bacmeister et al. 2020), and examined other aspects of the evolution from CESM1 to CESM2 (Neale et al. 2020).

During the last year, AMWG also began to take concrete steps towards developing the next version of CAM, including a systematic study of vertical resolution aimed at delivering a single unified atmospheric model for CESM3, replacing the current high-top/low-top dichotomy. AMWG also undertook sensitivity studies of CAM6 physics behavior in high-resolution (25 km) configurations.

AMWG has been leading the effort to implement and evaluate different dynamical cores (dycores) in CESM(CAM). Currently, three new dycores are under consideration: spectral element (SE), NOAA’s finite volume cubed-sphere (FV3), and NCAR’s Model for Prediction Across Scales (MPAS). Each of these dycores has been implemented using CSL resources. Testing and evaluation in fully coupled configurations have begun for SE and

FV3. Simple model evaluations were conducted with MPAS with the expectation of more complete evaluation in the next two years.

Finally, a small portion of AMWG's 2018-2020 allocation was used to conduct explicit high-resolution simulations of gravity wave breaking to inform development of gravity wave drag parameterizations for CAM. These were done with the Weather Research and Forecasting (WRF) model. In the future AMWG intends to expand its use of high-resolution models for physics development, as will be detailed in our 2020-2022 Allocation request.

Development

Diagnostic Studies of CESM2

In the last year, AMWG focused on analysis of CESM2(CAM6) behavior and its relationship to model changes that took place between CESM1(CAM5) and CESM2(CAM6). A focus of investigation continued to be the surprising increase in CESM's ECS which went up from values near 4°C in CESM1 to values over 5.3°C in CESM2. CESM2 was one of several major international coupled modeling systems that reported dramatic increases in ECS between their CMIP5 and CMIP6 versions (Zelinka et al. 2020). ECS determined from CESM 4xCO₂ experiments was investigated by Bacmeister et al. (2020). They found that the increase is due to a combination of increased shortwave cloud feedbacks in CESM2, notably over the Southern Ocean, along with a complex pattern of tropical cloud changes between CESM1 and CESM2.

A thorough investigation of other aspects of CESM climate simulations has also been undertaken by AMWG researchers and collaborators. Simpson et al. (2020) examined high-frequency variability and found general improvements in CESM2. Notably, they found an increase in high-frequency variability in the lee of the Rockies and Andes which are traceable to changes in the parameterized drag from subgrid topography. Neale et al. (2020) will report on an exhaustive set of analyses using a suite of prescribed sea surface temperature (SST) experiments with intermediate physics. Among other things, they have found large sensitivity in the simulation of upper winds to the turbulence scheme used in the model, i.e., CLUBB in CAM6 vs. the UW scheme used in CAM5. With prescribed SSTs the UW scheme yields better wind simulations, however, with SSTs derived from fully-coupled CESM2, simulated winds are improved over those in CESM1. These sensitivities will be further explored with the 2020-2022 allocation.

Diagnostics with Simpler Models

Significant advances in Simpler Model configurations for CESM2 took place. Aquaplanet compsets for CESM2 were finalized. Included in the CESM2 release were compsets that provide a sensible default aquaplanet with either fixed SST or a slab-ocean. More recently work has been done to incorporate new simplified physics options such as Gray radiation and Kessler moist physics.

An important demonstration of the diagnostic utility of Simpler Models was also completed: A series of idealized experiments was conducted to investigate aerosol-cloud

interactions in CAM6. The experiments used the CESM2(CAM6) aquaplanet configuration modified to have the same aerosol effects as standard CAM6 simulations. Preindustrial aerosol emissions were distributed in different spatial patterns. The results show that where aerosols are emitted is important for their climatic effect, measured through the effective radiative forcing. In CAM6, aerosols emitted in the tropics and subtropics have an outsized climatic impact because the clouds in those regions show a stronger response to aerosol perturbations (Medeiros 2020).

Dynamical Core Development

AMWG's 2018-2020 CSL allocation was used to finalize the implementation and begin the evaluation of two new dycores for CAM: 1) SE dycore with a dry mass vertical coordinate and flexible physics-dynamics coupling and tracer transport on an approximately uniform sub-element physics grid (SE-CSLAM/Physgrid; Lauritzen et al. 2017; 2018); and 2) NOAA's FV3 dycore.

Further development of the SE and SE-CSLAM included several algorithmic improvements that were evaluated before being adopted. These features are to be released with CESM2.2. Computing time was also used to develop SE and SE-CSLAM with full chemistry (CAM-Chem) and high-top (WACCM). The FV3 core has been fully integrated into CESM. AMWG computing time has been used extensively to tune and validate these dycores in standard climate applications. The key accomplishment of this integration effort has been a set of successful fully-coupled climate simulations with both new dycores. These runs reached equilibrium and the resulting mean climate is competitive with our current CMIP6 workhorse dycore (FV-latlon). Figure 3 shows the JJA total precipitation rate bias with respect to the Global Precipitation Climatology Project (GPCP) data set (Huffman et al. 2009) for these new dynamical cores compared with that from the FV-latlon dycore. These are fully coupled CESM2 simulations.

In addition to the work with FV3 and SE-CSLAM, AMWG made substantial progress in integrating MPAS into CESM. This has necessitated updating CAM's physics-dynamics coupling infrastructure to allow for vertical coordinates because MPAS is formulated in terrain-following height coordinates. In addition, this integration revealed issues with model initialization in the CESM infrastructure that arise at ultra-high resolutions. Currently, MPAS has been run in simple-physics configurations at climate resolutions. Complete integration is expected as part of the next AMWG CSL allocation.

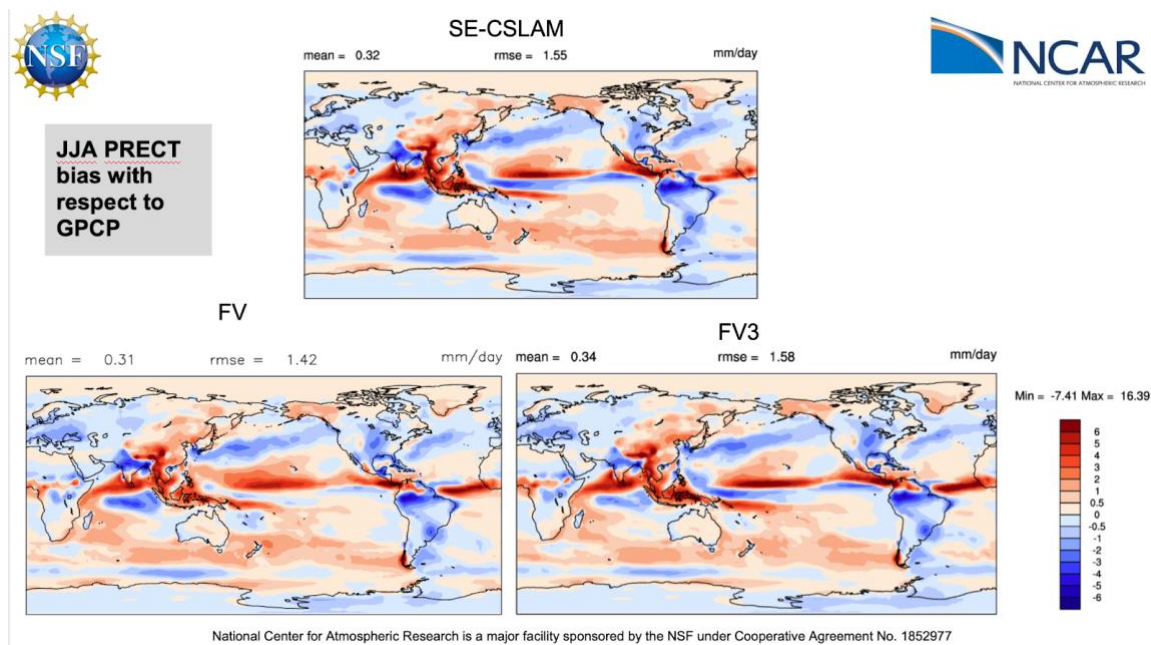


Figure 3. Spatial distributions of June-July-August mean precipitation biases from fully-coupled runs using three different dycores in CESM2. Biases are with the GPCP observational estimates.

Vertical Resolution/Model Top

AMWG resources were used extensively in a preliminary investigation of a variety of vertical grid configurations for the CESM atmosphere component. The aim is to develop a single unified atmospheric model in CESM, with a well-resolved stratosphere and, optionally, a complete chemistry simulation. This is intended to simplify the delivery of full Earth system results to the community, an effort which currently requires ancillary simulations with a 150-km top model (WACCM) to generate chemical forcings for climate runs. In addition, a new model with a top around 80 km, above CAM's current 40 km but below WACCM's 150 km, will enable focusing vertical resolution in the free troposphere and stratosphere at an acceptable computational cost. This effort is long-overdue, CAM's vertical resolution is well below most other major global models', and has been specifically requested by the CESM Scientific Steering Committee (SSC).

Figure 4 shows candidate vertical grids (top 3 panels) as well as ERA5 equatorial zonal winds and simulated equatorial zonal winds in CESM. The figure highlights the equatorial quasi-biennial oscillation (QBO) in zonal winds – a key feature in the variability of Earth's stratosphere. The right panel in the second row illustrates that while present to some extent QBO in the current 70 level WACCM is deficient in many respects, including nearly absent signal below 50 hPa that may have negative consequences for attempts to investigate tropical-midlatitude teleconnections. Grids with vertical resolutions of $\Delta z=500$ m (bottom row) exhibit clear improvements, independent of whether the model top is at

150 km (left) or 80 km (right). Isla Simpson (AMWG member) is chairing a committee of AMWG and WACCM scientists involved in the development of the new vertical grid configuration, and reported to the SSC in Summer 2020.

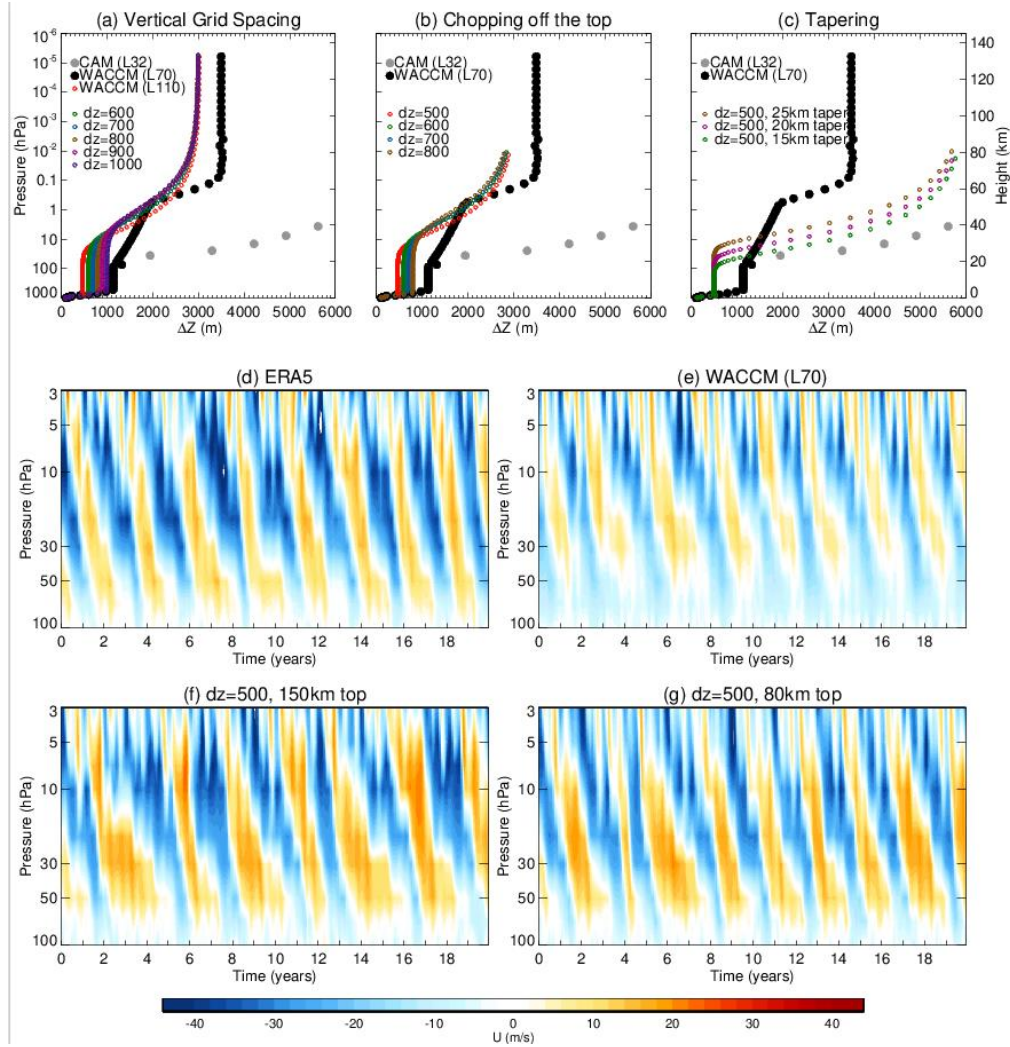


Figure 4. (top 3 panels) A variety of vertical grid configurations tested in CAM. The quantity plotted is the vertical grid spacing (Δz) as a function of pressure. Current operational grids in CESM – CAM L32 (grey) and WACCM L70 (black) have Δz of 1200 m or more above the boundary layer. (rows 2 and 3) Mean equatorial zonal wind (5°S – 5°N) as a function of pressure and time in ERA5 re-analysis, default WACCM L70 and two new configurations with $\Delta z=500\text{m}$ throughout the free-troposphere and stratosphere.

High-Resolution Process Studies

The AMWG CSL allocation was also used to conduct a small amount of high-resolution process-study simulations using WRF. These experiments were conducted to inform the development of gravity wave parameterization development as well as to assist in the

development of a high-top WRF configuration to be used in collaborative studies of mountain wave generation (e.g., Kruse et al. 2020). Figure 5 shows results from these simulations using a horizontal grid spacing of 500 m. In this set of simulations, it was determined that 3D turbulence closures were actually detrimental in producing resolution insensitive results across spacings of 5 km to 500 m.

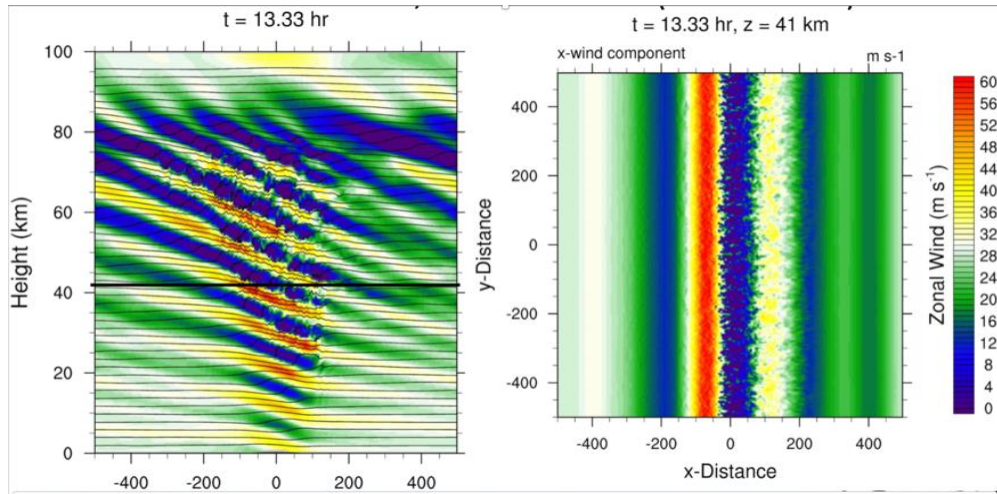


Figure 5. Cross-section (left) and horizontal slice at $z=41$ km (right) through a high-resolution simulation of flow over topography.

Production

Cloud-Feedback Model Intercomparison Project (CFMIP)

The CFMIP Tier 2 simulations were completed, processed, and published to the ESGF. This suite of 18 experiments is focused on better understanding climate feedbacks and sensitivity under a variety of forcing, complementing the six Tier 1 experiments and the broader CMIP6 effort. The experiments, totaling over 1100 simulated years, include coupled simulations with 2x and 0.5x preindustrial CO₂ as well as plus and minus 4% insolation changes. Among the topics that can be explored with these experiments are the *pattern effect*, which can be analyzed by comparing experiments using prescribed SST with uniform versus spatially varying anomalies, and cloud-circulation coupling with experiments that remove the longwave cloud radiative effect.

Biogeochemistry Working Group (BGCWG)

The BGCWG CSL allocation is used primarily to develop biogeochemical parameterizations (ocean, land, and coupled) in and for CESM, perform benchmark experiments of the developed model to assess the model's skill at reproducing observed phenomenon and its emergent properties, and use the model as a tool to study scientific questions. Our usage of CSL resources over November 2019 through October 2020 has

been primarily focused on: i) continuing CMIP6 experiments; ii) development of new ocean and land biogeochemistry parameterizations; and iii) using the model as a tool to study scientific questions.

Some CMIP6 experiments (CAM-based future scenario experiments) were redone because a bug was discovered in the configuration of certain emissions. BGCWG computational resources were also used, via donation to another WG, to support future scenario extension experiments being run out to 2300.

The BGCWG allocation provided the computing resources necessary to tune Marine Biogeochemistry Library (MARBL) for ocean-ice configurations in the CESM2.2 release. MARBL parameters were tuned so that simulated values best matched observations of, e.g., ocean nutrient distributions.

Work continued on the development of the size-structured ecosystem configuration of MARBL, called the Size-Based Plankton Ecological Traits (SPECTRA) model, which contains 9 phytoplankton and 6 zooplankton. Recent simulations have been able to reproduce observed large-scale phytoplankton community structure as well as micro- and meso-zooplankton productivity patterns.

Using a recently developed ocean BGC parameterization of explicit calcifying organisms, experiments were done to characterize the effect of marine calcifying organisms in the Southern Ocean on the global distribution of alkalinity in the ocean. The distribution of alkalinity is important because it influences how much carbon dioxide the ocean can absorb from the atmosphere. We ran five forced ocean – sea-ice CESM simulations (310 years each) with varying levels of calcification in the Southern Ocean. This study, currently in review for publication in the journal *Global Biogeochemical Cycles*, highlights the importance of biological processes in the Southern Ocean on global biogeochemistry.

The allocation was used to run fully-coupled simulations to determine how agricultural management changes seasonal patterns of the seasonal cycle of simulated atmospheric CO₂. A manuscript is currently in preparation.

The Mechanism of Intermediate complexity for Modelling Iron (MIMI; Hamilton et al. 2019) was ported to CESM2(CAM6). Using MIMI, recent trends and preindustrial to present day to future changes in soluble iron deposition to the ocean from dust, fires, and anthropogenic sources were quantified (Hamilton et al. 2020 and Hamilton et al. *in review at GRL*); both papers highlight that wildfires are an important source of soluble iron in regions relevant for ocean biogeochemistry and thus marine carbon-nitrogen cycles. Dust aerosol representation has been further improved to include the aspherical shape effect of particles on estimates on their optical depth and lifetime, resulting in improved dust emission estimates and transport representation (Hamilton et al. *in review at GRL* and Li et al. *in review at ACP*). In addition, work in progress (Li et al. 2020) highlights the importance of the mixing state of iron oxides with non-iron-oxide aerosols, which is also realized in the advanced CESM2(CAM6) framework for the dust radiative impact estimates at the shortwave band. Before the end of the allocation cycle, two CESM2 simulations, including MIMI, will be undertaken from 1850-2100 to further understand the coupling of land-atmosphere-ocean processes and feedbacks on climate via the iron cycle.

Chemistry-Climate Working Group (ChCWG)

The ChCWG used their CSL allocation since the 2019 Accomplishments Report for a number of developments for updates to CESM2 as well as for scientific analyses.

Chemistry, Photolysis, Aerosol Development; Nitrate and Brown Carbon climate evaluation

Several development activities related to tropospheric and stratospheric aerosols have been performed over the past year. Through collaboration among University of Wyoming, PNNL, and NCAR, the MOSAIC gas-aerosol exchange parameterization has been implemented in CAM6-chem and the impact of having an improved representation of nitrate aerosols in the model has been studied (Zaveri et al. 2020; Lu et al. 2020). To properly account for a coarse mode for stratospheric sulfate aerosols, particularly from fresh volcanic emissions, in addition to the coarse mode for dust and sea salt, a 5th mode has been added to the Modal Aerosol Model (MAM5). Preliminary tests of this development have been performed, and will be fully evaluated in CESM2.2.

Work was done improving the representation of dust in the recently-released version of CESM2(CAM6), focusing on the implementation of a new physically-based dust emission scheme (Kok et al. 2014). We evaluated the performance of the default and new dust emission schemes against observations and have been working to understand the influence of the different dust size representations in CAM6 on the dust cycle simulation and estimates of the dust climatic impact, and to understand climatic implications of the more physically-based dust emission scheme (Li et al. 2020).

CAM-SE-RR-chem Development

Testing of the configuration of CAM-chem with the SE dycore with regular grids as well as regional refinement (approximately $1/8^\circ$) over the continental U.S. continued over the past year. Also, simulations with different forms of nudging were tested. CAM-SE-RR_chem forecast has been run and tested, and soon will be running operationally.

Field campaign analysis

CAM-chem simulations, at 1° and 0.5° , with several different complexities of chemical mechanisms, have been run to support analysis of a variety of atmospheric chemistry field experiments. This research is ongoing, including collaborations with the experimentalists in the NCAR Atmospheric Chemistry Observations and Modeling (ACOM) Laboratory and the university community. In particular, simulations for participation in a model intercomparison connected with the NASA-led KORUS-AQ experiment have been performed, and a publication is in preparation (Park et al. 2020).

Air Quality reanalysis

A long specified dynamics simulation of CAM-chem (2001-present) has been completed and made available to the community for use as boundary conditions for regional models (6-hr output of all long-lived compounds): <https://www2.acom.ucar.edu/gcm/cam-chem->

[output](#) (Buchholz et al. 2019). This reanalysis is updated every few months to continue the record to the present.

10-day forecasts with WACCM

Forecasts of global atmospheric composition (“chemical forecasts”) are run continuously using two different fire inventories, and the results shared with the community and public through websites: <https://www2.acom.ucar.edu/acresp/forecasts-and-near-real-time-nrt-products>, both as images and data files.

VSL Halogen simulations

The development of the next generation of Very Short Lived Halogen chemistry within CAM-chem was nearly completed. This required moving all the chemistry modules into the CESM2 framework. The goal is to have this completed by Fall 2020 and released to the atmospheric science community. The initial results of this effort were presented at the EGU 2019 Meeting (Kinnison et al. 2019).

Climate Variability and Change Working Group (CVCWG)

In the past year, all remaining simulations of broad community interest that were proposed in the 2018-2020 cycle have been completed or are near to completion. To complement the existing suite of CESM1 prescribed historical SST simulations that have been made available through the WG, two additional 10-member ensembles of prescribed historical SST simulations have been performed with CESM2. One ensemble (the GOGA ensemble) uses prescribed historical SSTs globally and the other (the TOGA ensemble) uses prescribed observed historical SSTs in the tropics and observed climatological SSTs elsewhere. In addition, we have performed a 10-member ensemble of pacemaker experiments with CESM2 for the tropical Pacific Ocean, and we expanded our pacemaker ensembles with CESM1 by adding ensembles of Indian Ocean and Southern Ocean pacemaker experiments (Yang et al. 2020). These are historical simulations in which the SST anomalies in the respective ocean region are relaxed towards observations. These ensembles will be of great value for studies exploring ocean forced climate variability. We also conducted ensembles of idealized pacemaker simulations in which the Pacific Ocean is forced not by observations but by varying magnitudes of the Interdecadal Pacific Oscillation (IPO) pattern. Used in conjunction with idealized Atlantic Multidecadal Variability (AMV) simulations conducted by OMWG, we investigated the roles of each of these basins on the other (Meehl et al. 2020b).

In addition, we have extended the CESM2 preindustrial control run that was performed for CMIP6 from 1200 years out to 2000 years and we have performed a 1000-year preindustrial control run in which SSTs were prescribed to the climatology from the coupled preindustrial control. These experiments will be valuable for examination of coupled and atmosphere – land-only variability in CESM2 and represent important baselines for comparison to the forthcoming CESM2 large ensemble.

In contribution to the CMIP6 effort, we completed all of the simulations for Scenario Model Intercomparison Project (ScenarioMIP), Detection-Attribution (DA) MIP, Cloud Forcing (CF) MIP, and Polar Amplification (PA) MIP that were proposed. These data were published on the ESGF.

Toward efforts of high-resolution with CESM, CVCWG used a portion of its allocation to begin a preindustrial control simulation at the 0.1° ocean and ice coupled to the 0.25° atmosphere and land resolution with the CESM1.3-SE configuration. This control simulation enabled follow-on historical and future scenario simulations. Using the same CESM1.3-SE model version, we also conducted a complementary full suite of experiments at the nominal $1^\circ \times 1^\circ$ resolution. This is the first suite of experiments using the SE grid for low-resolution simulations and along with the $0.25^\circ \times 0.1^\circ$ simulations as well as a full suite of simulations using the $0.25^\circ \times 1^\circ$ (conducted previously) allow for direct comparison of the impacts of resolution (Meehl et al. 2019).

The CVCWG proposal also included simulations for exploration of climate extremes. Under this category, we conducted simulations using the CAPT framework to investigate drought as well as idealized simulations for the purpose of investigating tropical cyclones.

A series of retrospective forecasts with CESM1.3 was conducted with the standard 1° configuration. Forecasts were initialized starting in late 2009 through 2016. To run the forecasts from a properly spun up land-surface, a separate spin-up procedure was conducted with CLM in a “stand alone” configuration. Forecasts were initialized every 5 days, and were run for 20 days to reach into the subseasonal scale. Analysis of the forecasts so far has focused on extreme temperatures, including heatwaves. In collaboration with an undergraduate SOARS protege, the extreme temperature events identified in the forecasts are being compared with those found in climate simulations and with observed heatwaves. Initial assessment of daily high and low temperatures shows that CESM1.3 has reasonable skill to lead times of more than a week. In the next stage of analysis, we plan to compare with similar forecasts run at 0.25° grid spacing to assess whether higher resolution improves the representation of temperature extremes.

We also conducted investigations of tropical cyclones (TCs) which can alter surface and subsurface ocean temperature patterns and variability, affect ocean energetics, and influence ocean meridional heat transport and ocean heat content. To understand the role of TCs within the fully coupled climate system, we conducted a suite of low-resolution fully coupled CESM simulations, in which we added TC surface wind forcing extracted from a high-resolution TC-permitting coupled CESM run. We performed a small ensemble with different climate initial states (i.e., El Nino year vs. La Nina year) to test the sensitivity of the results.

A portion of the CVCWG allocation was used for a sensitivity study of Atlantic Meridional Overturning Circulation (AMOC) to the Tibetan Plateau because previous studies suggest that the rising of the Tibetan Plateau may have played a role in AMOC. We conducted a set of simulations to test whether a critical height for the Plateau exists in order to block the moisture escaping from the Pacific Basin into the Atlantic Basin. We conducted a set of four experiments: completely removing the Tibetan Plateau as a

topographic feature, followed by subsequent experiments reducing the height by 25%, 50%, and 75%. Each simulation used the CESM2 model version at the nominal 1° resolution and was integrated for 200 years under preindustrial conditions.

Finally, all of the community simulations conducted by CVCWG are made available via the ESGF, and a list of available data can be viewed under “Our Simulations” on the CVCWG webpages at: http://www.cesm.ucar.edu/working_groups/CVC.

Land Ice Working Group (LIWG)

Development

The development allocation has supported work to improve Community Ice Sheet Model’s (CISM) computational efficiency through algorithmic changes and load balancing. Model costs for whole-ice-sheet runs were reduced by a factor of 3 for a given spatial resolution and time step. We also ran a large suite of standalone CISM simulations of the Antarctic Ice Sheet (AIS), testing the ice sheet sensitivity to grid resolution, sliding laws, grounding-line parameterizations, and schemes for translating far-field ocean temperature to sub-ice-shelf melting. We completed long spin-ups and climate change simulations for the entire AIS at resolutions as high as 2 km (Lipscomb et al. 2020). Other development runs have focused on High Mountain Asia, a new focus area for LIWG, with simulations on a variable-resolution grid with refinement to 7 km in high-mountain regions, allowing improved simulation of orographic precipitation and other regional climate features.

Production

Part of the production allocation was used to complete a set of Tier 1 and Tier 2 coupled CESM2(CISM) simulations for Ice Sheet Model Intercomparison Project (ISMIP6), with an interactive Greenland Ice Sheet (GrIS) responding to climate warming. These included a preindustrial control run, a historical run (1850–2014) followed by a SSP5.8-5 run (2015–2100), and a 350-year run with CO₂ increasing by 1%/year to quadrupling. LIWG was the first modeling group to complete these experiments and publish results (Muntjewerf et al. 2020a; 2020b). The 4xCO₂ run is now being extended to study Greenland deglaciation. In this simulation, CESM2 is first run synchronously with CISM for another 150 years, and then asynchronously (5 CISM years per CESM2 year) until the ice sheet melts completely, with vegetation updated periodically based on the BIOME4 model. This run allows us to study long-term patterns of climate change in the North Atlantic in response to ice sheet lowering and retreat. Meanwhile, the SSP5.8-5 run is being extended to 2300.

We have also run several paleoclimate simulations with interactive ice sheets. Jointly with PaleoWG, we have run two long transient simulations of GrIS retreat and recovery during the Last Interglacial (LIG), from 127 ka to 119 ka (Sommers et al. 2020). The vegetation map is updated using BIOME4 in one run, and held fixed in the other. We have shown that vegetation changes result in a lower albedo and more rapid ice-sheet retreat. Next, using an extended 4-km CISM grid for the Northern Hemisphere, we have simulated glacial

inception at the end of the LIG, beginning at 116 ka. Inception is observed everywhere it is expected, including Canada, Scandinavia, and Siberia, with an ice volume increase consistent with sea-level estimates from proxy data. Finally, we have configured and run preliminary simulations of Northern Hemisphere climate and ice-sheet evolution at the time of the Last Glacial Maximum.

Land Model Working Group (LMWG)

Development

The LMWG development allocation has been used to continue development of a representative hillslope scheme within the Community Terrestrial Systems Model (CTSM) to capture within-grid cell water redistribution across topographic and water table gradients as well as the influence of slope aspect. In particular, over the past year there has been an emphasis on developing and testing global and regional input datasets for the representative hillslope model. Initial efforts to couple the hillslope model to CTSM with Functionally Assembled Terrestrial Ecosystem Simulator (FATES) have also been completed, though this is anticipated to be a long-term project. Other model development projects include ongoing expansion of crop management, including implementations of tillage practices, manure, multiple irrigation methods (sprinkler, drip, flood), and forest management, including harvesting and silvicultural treatments. Allocations have also been used to continue the development of a multi-layer canopy scheme, a new river model (mizuRoute), and adding the capability for lake area to change over the course of a simulation. Finally, work is ongoing to develop a Light-weight Infrastructure for Land-Atmosphere Coupling (LILAC) which allows CTSM to be coupled, in principal, to any atmospheric model. An initial coupling to WRF has been implemented and released to the research community.

Production

The LMWG production allocation has been used to rerun CMIP6 Tier 1 LUMIP projection period simulations and to finish LS3MIP coupled prescribed soil moisture simulations that enable assessment of soil moisture feedbacks onto climate and extremes. CLM is participating in several other MIPs, including TRENDY (historic simulations to track global carbon flows for Global Carbon Project annual report), ONEFLUX, and PLUMBER2. Coupled CAM-CLM simulations have been conducted to support investigations into land-atmosphere interactions in South America. CESM2 simulations have been done to isolate the impact of agriculture on the growth of the annual amplitude of CO₂. Additional CAM-CLM simulations have been completed to investigate various impacts of land on the atmosphere, including a study of the impact of trends in lake areas due to the development of reservoirs and the impact of land-use and land-cover change on the South Asian monsoon.

Ocean Model Working Group (OMWG)

Development

As described in the proposal, the development efforts within OMWG are focused on transitioning the ocean dynamical core from the legacy Parallel Ocean Program version 2 (POP2) model to Modular Ocean Model version 6 (MOM6). A significant milestone achieved during the reporting period was the first public release of a version of CESM(MOM6) in CESM2.2. During the first half of the allocation period (the previous reporting period), the primary focus of CESM(MOM6) development was on technical aspects of interfacing to CESM infrastructure and other component models. During the current reporting period the focus shifted to the iterative process of evaluating and mitigating simulation biases through tuning and comparing different model configuration options, primarily in the $2/3^\circ$ *workhorse* configuration. Among the issues addressed were the circulation of the equatorial Pacific with an exploration of different combinations of lateral viscous dissipation; exploiting the subgrid-scale topography options in MOM6 to more accurately represent straits and passages such as the Mediterranean exchange with the Atlantic; exploring new vertical coordinate options within the MOM6 Arbitrary-Lagrangian-Eulerian (ALE) framework; implementation of a near surface lateral mixing scheme; and tuning an eddy energy backscatter parameterization. In addition to the $2/3^\circ$ version of CESM(MOM6), an eddy-resolving version based on the same 0.1° grid as the high-resolution CESM(POP2) model was implemented and initial integrations are underway.

Beyond a configuration of MOM6 for standard CMIP-class versions of CESM, two idealized geometry configurations of MOM6 were implemented for fully-coupled “aquaplanet” like models in the CESM simplified modeling suite. A parsimonious choice of parameterizations was chosen with computational economy and simplicity in mind. Long (~500 year) control integrations were completed in each of the two geometries and an initial manuscript (Wu et al. 2020) was submitted documenting this new CESM capability.

There have been several efforts over the last 5-10 years to develop nested regional ocean modeling capability in the CESM framework using ocean components other than POP2. This includes work supported by this allocation in the current reporting period in the Regional CESM (R-CESM) project coupling the Regional Ocean Modeling System (ROMS) to WRF within the framework of Common Infrastructure for Modeling the Earth (CIME) and CESM2. As such, R-CESM can be used as a regional dynamical downscaling tool for the global CESM solutions and as a standalone high-resolution regional coupled model. The CSL allocation has been used to test the implementation of CESM air-sea flux scheme in WRF, and to further development of an online ensemble coupled data assimilation (ECDA) procedure. The R-CESM is introduced and an overview of its solutions is presented in Fu et al. (2020).

However, these regional modeling efforts have always proven difficult to sustain and support because they involve the use of component models foreign to CESM. A major step toward a more sustainable path forward was made in the current reporting period with a

successful prototype of a regional ocean model based on the CESM(MOM6) code base and the same interface to the coupler as used in the global ocean component. The initial application of this prototype to prediction of coral larval transport in the eastern equatorial Pacific is underway.

Production

Experimentation with the POP2 based CESM2 was conducted in both the standard eddy-parameterized (nominal 1°) and higher eddy-resolved / -permitted (nominal 0.1°) resolutions. Toward the effort of high-resolution with CESM, and as part of the CESM's contribution to the High-Resolution Model Intercomparison Project (HighResMIP), we used a portion of this allocation to develop 1950-control and 1950-2050 transient simulations at the 0.1° ocean and sea-ice coupled to the 0.25° atmosphere and land resolution (ne120_t12) with the CESM1.3-SE configuration. Using the same CESM1.3-SE model version, we also conducted a complementary suite of coupled and forced ocean experiments at the nominal 1°x1° resolution (ne30_g16). In addition, we conducted complementary atmosphere-only simulations at high- (ne120_ne120_mt12) and low-resolutions (ne30_ne30_mt12) to develop a full suite of CESM1.3-SE simulations.

Paleoclimate Working Group (PaleoWG)

Using Year 2 resources, PaleoWG set up and conducted several CESM2 simulations for Tier 1 contributions to CMIP6 and the Paleoclimate Model Intercomparison Project phase 4 (PMIP4). These simulations include:

- Two of these CMIP6/PMIP4 simulations with CESM2(CAM6) FV1x1: *lig127k* (last interglacial at 127,000 years before present, BP) and *midHolocene* (6000 years BP) investigate variations in Earth's orbital configuration as primary drivers of climate change. Each was run for years beyond a spin-up phase of several hundred years.
- A third CMIP6/PMIP4 Tier 1 simulation with CESM2(CAM6) FV1x1, *midPliocene-eoi400*, was conducted for the mid-Piacenzian warm climate period of the Pliocene (~3.2 Million years BP), when sea levels were high, but the atmospheric CO₂ level was similar to today. This simulation has been run for 1500 years due to the long spin-up time of CESM2.
- The CMIP6/PMIP4 Tier 1 *lgm* simulation of the last glacial maximum period with CESM2(CAM6) FV1x1 is underway and being compared to earlier simulations conducted with CESM1(CAM5).
- The CMIP6/PMIP4 Tier1 *past 1000* is currently being run with CESM2(WACCM6ma) FV2x1 in collaboration with WAWG. This configuration of CESM2 is a contribution to CMIP6, having completed the required DECK and historical simulations.

Analyses from these CMIP6 simulations are the focus of a few CESM2 special issue papers (Feng et al. 2020a; Otto-Bliesner et al., 2020a). The completed CMIP6/PMIP4 simulations have been archived on the ESGF, and have contributed to several CMIP6 and

PMIP4 model intercomparison papers (Brierley et al. 2020; Brown et al. 2020; Haywood et al. 2020; Kageyama et al. 2020; McClymont et al. 2020; Otto-Bliesner et al. 2020b). A simulation for the *lig127k* experiment was also set up, tested and conducted with the lower FV2x1 resolution configuration of CESM2. Additional testing for CMIP6 Tier 2 simulations are in progress, including a transient Heinrich 11 meltwater event and mid-Pliocene simulations to allow factoring out the contributions of various forcings to the warm equilibrium climate state.

CESM2 simulations were also conducted in slab ocean configurations at various CO₂ levels (e.g., 1x, 2x, 4x, and 8x the preindustrial value) to explore the state dependence of ECS. It was found that ECS in CESM2 increases with the background global warming associated with higher CO₂ levels, i.e., ECS was 5.5°C when CO₂ was doubled from 1x to 2x the preindustrial level and was 6.9°C when CO₂ was further doubled from 2x to 4x. The ECS increases with background warming in CESM2 were qualitatively similar to that found in CESM1 and CCSM4. Increases of the cloud feedback with global temperature over both low and high latitudes were identified as the primary cause for the ECS increases (Zhu and Poulsen 2020). CESM2 simulations were also performed for the Early Eocene using the latest paleoclimate reconstructions of boundary conditions from the Deep-time Model Intercomparison Project. It was found that CESM2 produced a global mean temperature that is ~5.5°C warmer than the upper end of proxy estimates of the Early Eocene. This result suggests the CESM2 is too sensitive to external forcings (Zhu et al. 2020).

Simulations of the mid-Piacenzian climate were completed with earlier versions of the CESM: CCSM4 and CESM1.2. CSL computing resources were dedicated to spin up the land biogeochemical cycle, test spin-up procedures for the ocean physical state, and finally, production runs of >1000 model years. Together, these mid-Piacenzian simulations suggest increased Earth system sensitivity beyond the ECS between CCSM4 and CESM2. A comparison to mid-Piacenzian SST records suggests CESM2 may be overly sensitive to mid-Piacenzian climate forcings (Feng et al. 2020a). Ongoing work reveals that much of the simulated land water input (precipitation minus evaporation, P-E) is driven by forcings from prescribed mid-Piacenzian changes of vegetation and ice sheet, reconciling the discrepancies from simulated, CO₂ driven, future P-E changes (Feng et al. 2020b).

The resources were also used to conduct transient ice-sheet – climate simulations for the last interglacial period, from 127-119 ka with CESM2 fully coupled to CISM2. The ice sheet model and orbital parameters were accelerated by 5 times relative to the other model components for computational feasibility, and the vegetation distribution was updated every 500 years based on biomes simulated offline with BIOME4.2. Results show a substantial retreat of GrIS, reaching a minimum extent at 121 ka, equivalent to 4.2 m sea level rise, followed by gradual regrowth (Fig. 6). An additional experiment examined the reduced sensitivity when keeping vegetation at its preindustrial potential distribution. Importantly, CESM2(CISM2) is able to simulate a realistic retreat and regrowth of GrIS, the first CMIP6 model that has done so with success, providing confidence for future projections. The model output contains a wealth of climate data and will be made publicly

available for interested researchers to explore or analyze different aspects of the LIG climate.

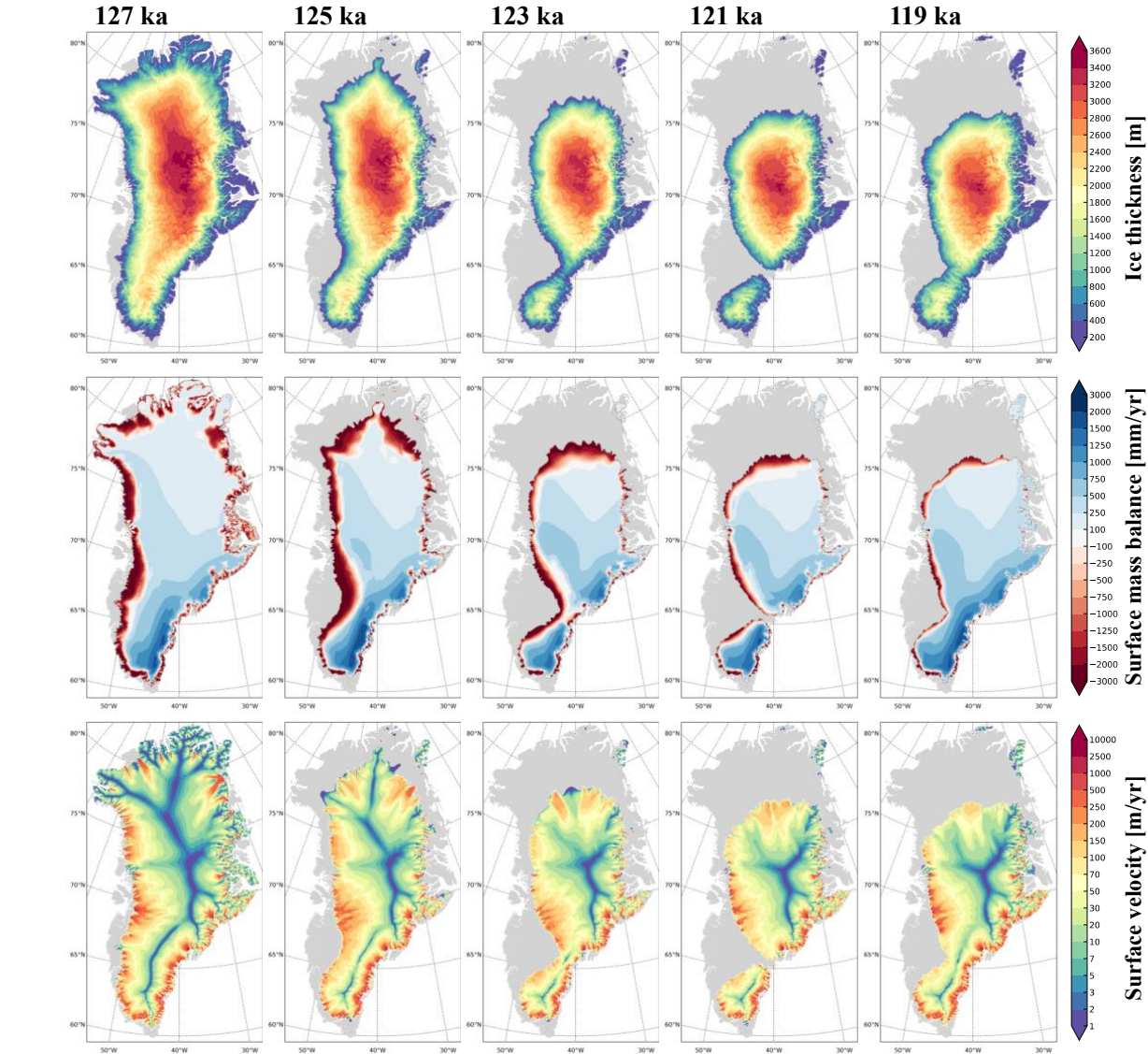


Figure 6. (top row) Thickness, (middle row) surface mass balance, and (bottom row) surface velocity of the Greenland ice sheet, shown every 2000 years from 127-119 ka, as simulated in a coupled, transient CESM2(CISM2) simulation.

Polar Climate Working Group (PCWG)

PCWG development resources have been used to update and test the CICE6 sea-ice model with functionality available in the CESM code version. Optimal tuning for the sea-ice model within the context of coupled simulations has also been explored. In terms of CICE6

developments, we have updated the CICE Consortium model to include recent CESM2(CICE5) related changes. This includes the incorporation of water isotopes within the ice model, atmospheric boundary layer flux iteration code, sending shortwave by component (visible direct, visible diffuse, infrared direct, infrared diffuse) and a few software changes and bug fixes. Also, relevant to this, we have created a NUOPC (National Unified Operation Prediction Capability) cap to run CICE6 with CESM. Some of this is in preparation for coupling with MOM6. We ran several simulations with the CICE Consortium code on Cheyenne as well as a CESM development tag with the NUOPC cap and CICE6.

PCWG production resources have been used to assess a number of aspects of polar climate variability and change. This includes experiments to identify the influence of sea ice processes, including snow on sea-ice (Holland et al. 2020) and lateral sea-ice melting (Smith et al. 2020), on climate feedbacks. Experiments were also run to test a novel satellite sea-ice thickness emulator within CESM for comparison with new satellite observations (Roberts et al. 2020; DuVivier et al. 2020). The influence of polar clouds has also been a PCWG science focus and simulations have been performed to assess polar clouds and precipitation in CESM2 (McIlhatten et al. 2020; Lenaerts et al. 2020), to explore the influence of cloud parameterizations on the simulated climate (Huang et al. 2020), and to quantify polar cloud feedbacks. Factors responsible for historical Arctic sea-ice trends have been investigated including the role of changing Arctic winds (Blanchard-Wriggelsworth et al. 2020a) and the importance of the mean sea ice state for the simulated transient sea ice response (Kay et al. 2020). The role of changing winds on Antarctic sea-ice trends and variability has also been considered (Blanchard-Wrigglesworth et al. 2020b). The role of changing external forcing on Arctic 20th-21st century transient climate change has also been explored. This includes simulations to assess the consequences of technically-feasible reductions in the 21st century emissions of black carbon, organic carbon, sulfur dioxide, ozone precursors, and methane. Simulations to quantify the role of biomass burning on 20th-21st century Arctic climate change have also been performed and are being analyzed.

Software Engineering Working Group (SEWG)

The SEWG CSL allocation primarily supported software testing of individual CESM2 components and CESM as a whole, both for incremental releases of CESM2.1 and for development versions on the path towards CESM2.2. This testing, which is run frequently as features are added and issues are addressed, caught many bugs before they affected users. Another major use of this allocation was for the development and testing of the Community Mediator for Earth System Prediction Systems (CMEPS) as part of the NCAR-NOAA Memorandum of Agreement (MOA). CMEPS is planned to become CESM's default driver/mediator starting with CESM2.3. Finally, about 15% of the SEWG allocation was used for regression tests of the Earth System Modeling Framework (ESMF). CMEPS and a new set of data models (the Community Data Models for Earth Prediction

Systems, CDEPS) are built on top of ESMF; thus, ESMF is becoming a critical infrastructure supporting CESM moving forwards.

Whole Atmosphere Working Group (WAWG)

Development

CESM Photolysis Development

A new WACCM photolysis approach was developed which included a fast in-line radiative transfer (RT) approach based on the Tropospheric Ultraviolet and Visible Radiation Model. With inline RT, one can better represent clouds and aerosol impacts. Work is ongoing to incorporate this into the CESM2(WACCM6) community version.

Evaluation of Halogen Heterogeneous Chemistry

WACCM run in specified dynamics mode was used to examine the influence of the Matsuno-Gill tropical circulation pattern on stratospheric heterogeneous chemistry. This study demonstrates that anticyclonic Rossby wave gyres that form near the tropopause due to equatorially-symmetric heating in the troposphere provide a dynamical mechanism that influences tropical and subtropical atmospheric chemistry during near-equinox months. The anticyclonic flow entrains extratropical air from higher latitudes into the deep tropics and associated upwelling induces adiabatic cooling in the already cold upper-troposphere /lower-stratosphere. These aspects of the circulation enhance heterogeneous chlorine activation on sulfuric acid aerosols, primarily via the $\text{HCl} + \text{ClONO}_2$ reaction. A publication on this work is in review (Wilka et al. 2020).

A second study was completed that examined the heterogeneous chemistry of the subpolar lower stratosphere. In this work, both the means and distributions of NO_2 measurements from the Stratospheric Aerosol and Gas Experiment III (SAGE3m) were compared to simulations from a coupled climate-chemistry model to better characterize and quantify subpolar heterogeneous halogen chemistry. We have shown that: (1) there is strong evidence for considerable heterogeneous halogen activation occurring locally in the subpolar lower stratosphere in September-October, as illustrated by the occurrence of extremely low NO_2 concentrations; (2) concentrations of NO_2 from observations and model simulations with heterogeneous chemistry turned on are drawn from the same distribution, and the inclusion of heterogeneous chemistry at both subpolar and polar latitudes appears to be essential for model–observation agreement. A publication is in review (Zambri et al. 2020).

High Vertical Resolution WACCM6 tuning

CESM2(WACCM6) has now been run in a 110 level (110L) configuration to produce a realistic QBO by adjusting the efficiency of the tropical gravity wave parameterization. The results are consistent with those reported by Garcia and Richter (2019) using CESM1(WACCM5.4). These QBO-producing WACCM6-110L simulations were carried out with vertical resolution $\text{dz} = 500$ m from the top of the boundary layer to

approximately 25 km. The experience gained from this work has proved useful in guiding the ongoing development of the future CESM workhorse model.

Gravity Wave (GW) Parameterization Development

The new surface drag scheme, developed by J. Bacmeister, has been implemented and tuned in CESM2(WACCM6) in both 70L and 110L versions. The source of problems with the diffusivity approach in the GW parameterization was identified and an update proposed to eliminate it. However, lack of time and resources has precluded implementation in WACCM6 to date. We have re-tuned the Beres tropical wave parameterization for use with WACCM6, and identified the optimal value of the Beres efficiency that produces a realistic QBO compared to observations.

WACCM-X development

We have merged WACCM-X with CAM6 physics, and have completed WACCM-6X simulations under perpetual solar maximum, moderate and minimum conditions with both 2° and ~1° horizontal resolutions.

PALEOSTRAT basic

We opted to forgo this simulation because the prescribed volcanic aerosol loadings could not be adapted easily for use in CESM. We instead used the resources to examine the reasons behind climate drift that occurred in the Last Millennium (LM) simulations started from the LM Control. The original LM Control imposed background, continuous volcanic forcing averaged from the ensemble of volcanoes for the period 850-1850. When the averaged forcing is removed, the climate drifts warmer. We are now re-doing the LM Control without background volcanic forcing to produce a steady LM-Control climate that will not drift once the LM simulation is started.

Production

ISA-MIP experiments

The Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP) is explicitly for testing models like WACCM with a complete sulfur cycle. WACCM is a key part of ISA-MIP, and we aim to contribute a full suite of experiments requested. This will better enable us to understand and evaluate WACCM prognostic volcanic aerosols against observations and other models. The experiments requested by ISA-MIP include background, transient, historic emissions, and Mt. Pinatubo sensitivity experiments. All simulations use CESM2(WACCM6) atmosphere-only at 1° resolution. To date, we have completed only one of the simulations. Other ISA-MIP experiments have been delayed due to questions about how to generate requested outputs for cross-tropopause fluxes. These issues are currently being worked out.

PALEOSTRAT volcanic

We carried out our proposed 1000-year WACCM6 simulation at 2° horizontal resolution with MAM and found that the climate had a slow, underlying warming trend, for reasons

having to do with how the original LM Control was constructed (see above). We will need to redo this simulation and will be requesting resources to do so in the WAWG 2020-2022 CSL Proposal.

Simulations in Support of QBOi

WACCM-110L configuration has been used to perform simulations in support of various papers contributed to the SPARC-QBO initiative, including Bushell et al. (2020) on the evaluation of QBO models; Richter et al. (2020) on the response of the QBO to climate change; and Holt et al. (2020) on the evaluation of waves that force the QBO. We plan to use WACCM6-110L for additional contributions to QBOi; results obtained as part of an ongoing NCAR Strategic Capability project will be used to study the Madden-Julian Oscillation-QBO relationship.

Using WACCM-X v2.1 (2°)

We completed WACCM-X (v. 2) solar minimum and solar maximum simulations for two scenarios of lower boundary conditions, ~30 years apart (1972-1976 and 2001-2005), to calculate the effect of anthropogenic emissions on upper atmosphere and thermosphere/ionosphere temperature and density (Solomon et al. 2019). We have also completed runs using SD-WACCM-X (with CAM4) physics (with MERRA2) for the period of 1980-2017. The results have now been put on the climate data gateway for community use. A paper has been published using the model output (Gasperini et al. 2020).

We have made several month-long WACCM-6X runs with ~0.5° horizontal resolution. The results have been used to drive SAMI3 plasmasphere/ionosphere model to study bubble formation (Huba and Liu 2020). With our remaining allocation, we are completing the WACCM-6X, 1° free running simulation for one solar cycle (2000-2010) and the SD-WACCM-6X (2000-2019), 2° simulation.

GeoMIP Tier 2 Overshoot and Peak-Shaving Simulations

GeoMIP Tier 2 experiments have been performed using these allocations, supplemented with resources from a different NSF account. A paper on the results has been published (Tilmes et al. 2020).

Stratospheric Aerosol Injection Simulations in support of GeoMIP

Stratospheric Aerosol (H₂SO₄) Injection Simulations for Geoengineering MIP (GeoMIP) have been performed. The results have been made available to the community and a couple of papers are in preparation.

Community Projects

C1. Transient Holocene

The transient Holocene simulation from 8000 years before present to the beginning of the last millennium simulation (850 CE), a total of 8150 years, is underway. New forcing datasets for

the solar variability, greenhouse gases, volcanic eruptions, and land use – land cover have been created in collaboration with WAWG and LMWG. The original intention was to use the CESM2(CAM6) FV2x1 model version. This turned out not to be achievable. We were able to get access to a pre-release Holocene volcanic dataset from colleagues in Canada. The sheer number of volcanic eruptions (1400) made it not feasible to derive a dataset using scaled eruptions from our WACCM6ma *past1000* simulation to force CAM6. The alternative, which has now started, is to use this dataset of volcanic stratospheric sulfur injections and CESM2 (CAM6-chem) at FV2x1 resolution. This unprecedented simulation will be a new resource to the CESM community to more fully explore multidecadal and longer variability and rapid transitions of, for example: ENSO and other modes of climate variability; monsoons and droughts; AMOC; and tropical – extratropical linkages.

C2. High-resolution ocean (POP) with biogeochemistry

A high-resolution CESM2 ocean – sea-ice integration with active biogeochemistry was begun. The run was forced with the new JRA55-do Japanese reanalysis data set (Tsujino et al. 2018) and configured with the latest tunings available for MARBL, the marine biogeochemistry component of CESM. The intention was to run for one full forcing cycle, 1958 to near-present. However, delays in finalizing the model and slow throughput on Cheyenne due to queue delays precluded completion of the full cycle so far. Nevertheless, the run is progressing now, and there are great expectations for its ultimate utility (Fig. 7). In particular, collaborations facilitated within NCAR and at universities will make this integration a valuable community resource. There are plans to investigate oxygen minimum zone ventilation process, interannual variation in carbon uptake, eddy-mediated dynamics in primary production and export, mechanisms sustaining populations of Antarctic marine predators, as well as the distribution of *Sargassum* weed in the North Atlantic. Our objectives include cultivating collaborative frameworks for analysis of this run, enabling a broad group of researchers to leverage each other's code and understanding.

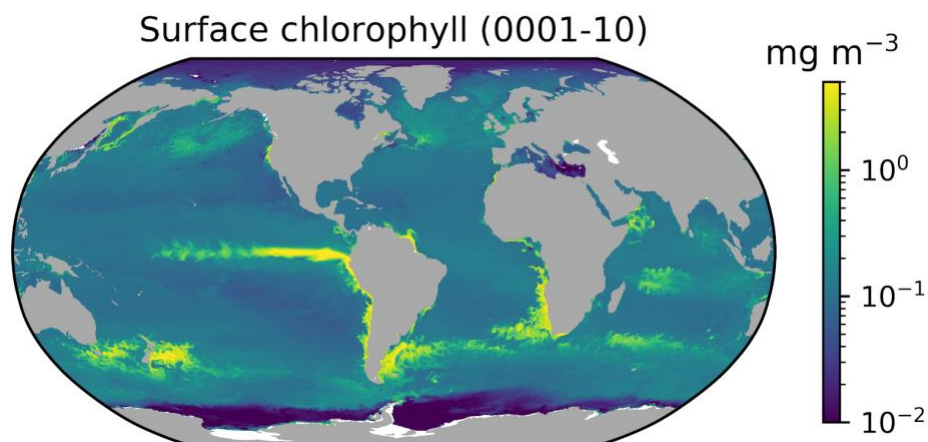


Figure 7. Monthly-mean surface chlorophyll distribution in the 0.1° JRA-forced ocean – sea-ice integration.

C3. Subseasonal-to-seasonal (S2S) hindcasts

S2S hindcasts for years 1999-2018 were carried out with CESM1. These hindcasts followed the SubX protocol (Pegion et al. 2019) with initializations every Monday, 11 ensemble members for each start date, and a 45-day running period. At each initialization time, the atmosphere was initialized using CFSv2 reanalysis. CLM5 was used to produce land initial conditions that reflected the observed surface state and fluxes using a stand-alone simulation forced with CFSv2. Ocean and sea-ice initial conditions came from a CESM hindcast ocean – sea-ice simulation that was forced with the state fields and fluxes from the JRA55-do reanalysis data set (Tsujino et al. 2018). Analysis of this new S2S data set is underway and data will be shared with the new Earth System Prediction WG and broader community.

C4. CESM2 with RCP8.5 projections

As detailed in many papers in the *AGU CESM2 Virtual Special Issue*, there are significant differences in simulated climate properties between CESM2 relative to the earlier CESM1 model. These differences occur across the atmosphere, ocean, sea-ice, and land conditions and encompass modes of climate variability. This results from model parameterization improvements in CESM2 and also from modified external forcings prescribed in the simulations. The external forcing differences are particularly important for the transient climate response in the 20th and 21st centuries. Based on the CMIP6 CESM2 simulations alone, it is not possible to disentangle the relative importance of the different model physics versus the different model forcing.

In order to elucidate the role of modified external forcing in the simulated CESM2 climate, we have performed a set of simulations of CESM2 in which CMIP5 forcings are applied. In particular, we use the forcings from the CESM1 Large Ensemble simulations. The simulations performed include a 500-year preindustrial control simulation and six ensemble members of the historical and RCP8.5 future scenario. Analysis of these simulations is underway, and they will be instrumental in furthering our understanding of the influence of external forcing on the climate system response. They will also allow for a better understanding of the CESM2 transient climate change behavior and how it relates to simulations with CESM1.

As one example, these simulations are providing information on the 20th and 21st century Arctic sea ice loss (Fig. 8). With the standard CMIP6 forcing, the Arctic sea ice undergoes rapid loss in late summer/early fall (most apparent in the August, September, October timeseries) starting around 1995. The simulations with CMIP5 forcing, shown in purple, have a considerably more gradual sea ice loss. The reasons for these discrepancies are being investigated further and will be included in a forthcoming publication (DeRepentigny et al. 2020). Notably these runs are available to all interested parties to assess multiple aspects of the changing climate in CESM2.

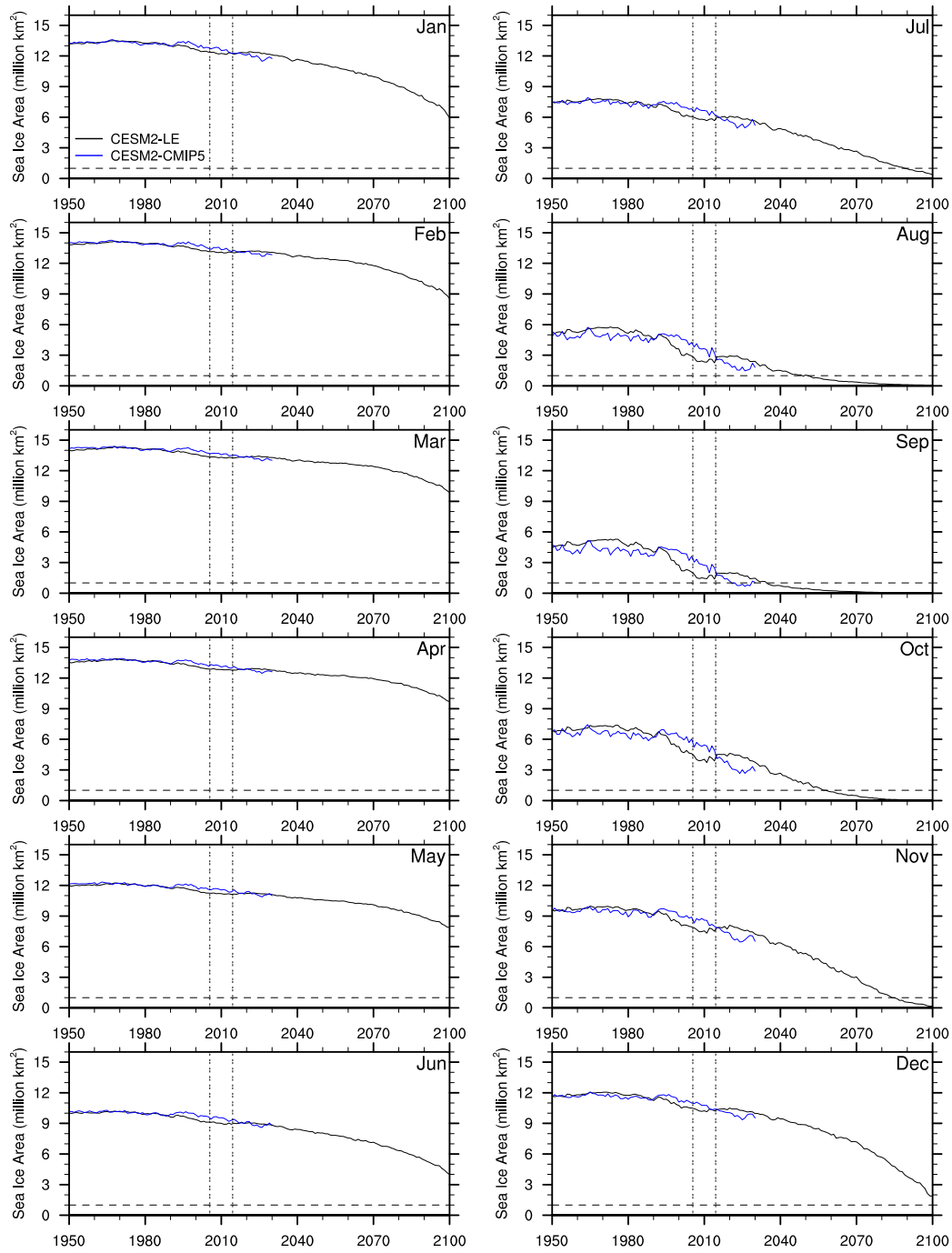


Figure 8. The timeseries of Arctic sea-ice area for individual months for the CESM2-LENS (in grey) which is run with CMIP6 forcing and the CESM2-CMIP5 integrations (in purple). (Figure courtesy of Patricia DeRepentigny)

C5. Development of a CESM Arctic Prediction System (CAPS)

In a collaboration between AMWG, LWMG, LIWG, and PCWG, simulations were completed using regionally refined grids over the Arctic. Two grids were developed (Fig. 9), referred to as the ARCTIC and ARCTICGRIS grids. The ARCTIC grid has uniform base resolution of 1° with $\frac{1}{4}^\circ$ refinement over the broader Arctic. The ARCTICGRIS grid is identical to the ARCTIC grid but contains an additional $\frac{1}{8}^\circ$ refined patch over Greenland.

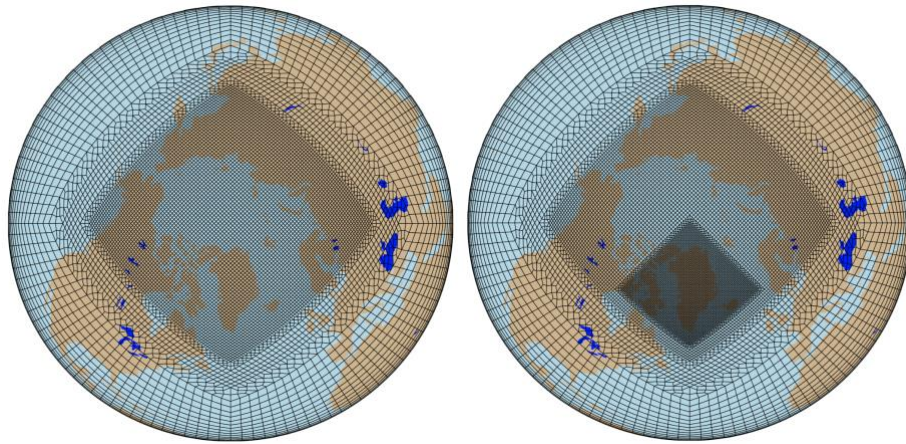


Figure 9. ARCTIC (left) and ARCTICGRIS (right) element grids.

Greenland Surface Mass Balance

The simulations have demonstrated substantial improvements to the simulated meteorology and climate of GrIS compared with standard 1° and coarser grids in CESM. Higher horizontal resolution relieves long standing biases through resolving the steep margins of GrIS, permitting realistic orographic precipitation and accurately representing narrow ablation zones. These improvements translate into a more realistic surface mass balance (Fig. 10), positioning variable resolution CESM (VR-CESM) as a valuable tool for providing accurate projections of cryospheric contributions to sea level rise over the next centuries.

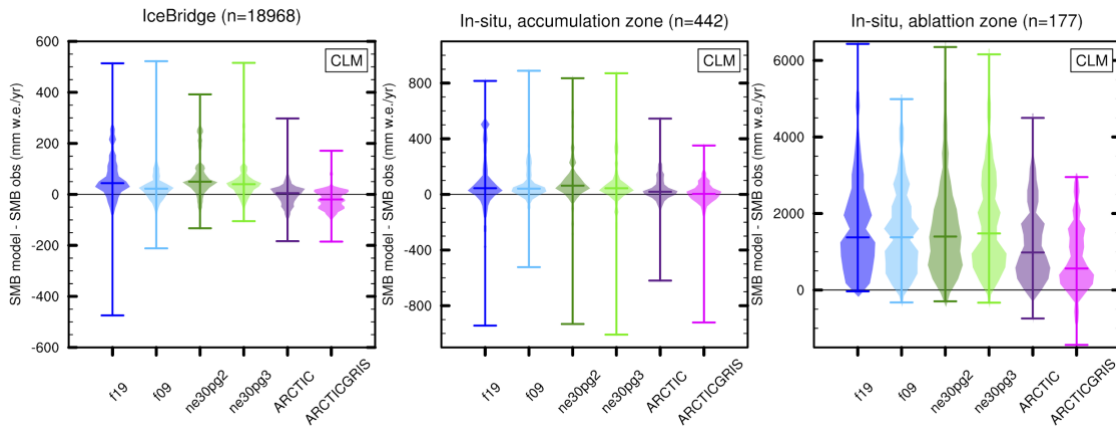


Figure 10. PDFs (flipped vertically) of the pointwise differences of the surface mass balance in simulations of observations. Left panel refers to the radar dataset IceBridge, while the other two panels refer to in-situ observations (pits, cores, and stakes) in the accumulation zone (middle panel) and ablation zone (right panel). The six different colors correspond to different grids and dycores.

Coupling to POP and CISM

The $\frac{1}{4}^\circ$ refined Arctic grid is currently being coupled to the 1° POP2 and the 4-km CISM ice-sheet model. This configuration is unique for its ability to resolve complex interactions at high-resolution between sea-ice, ocean, ice sheets and the atmosphere, and is being spun-up to provide a dynamic representation of GrIS during the preindustrial period. A branch supporting this configuration has been developed and preparations for a JG/BG spin-up have begun. This work is ongoing and planned for completion by 31 October 2020.

Katabatic Winds

Katabatic winds are important for regional temperatures and can impact the ice-sheet mass balance. They can only be explicitly resolved at high resolution. The regionally refined $\frac{1}{8}^\circ$ polar grid resolves these winds, as shown in Fig. 11. Winds can be seen accelerating down the eastern slopes of the ice sheet. We are working with CISL to develop high quality visualizations of mesoscale features in the ARCTICGRIS simulation.

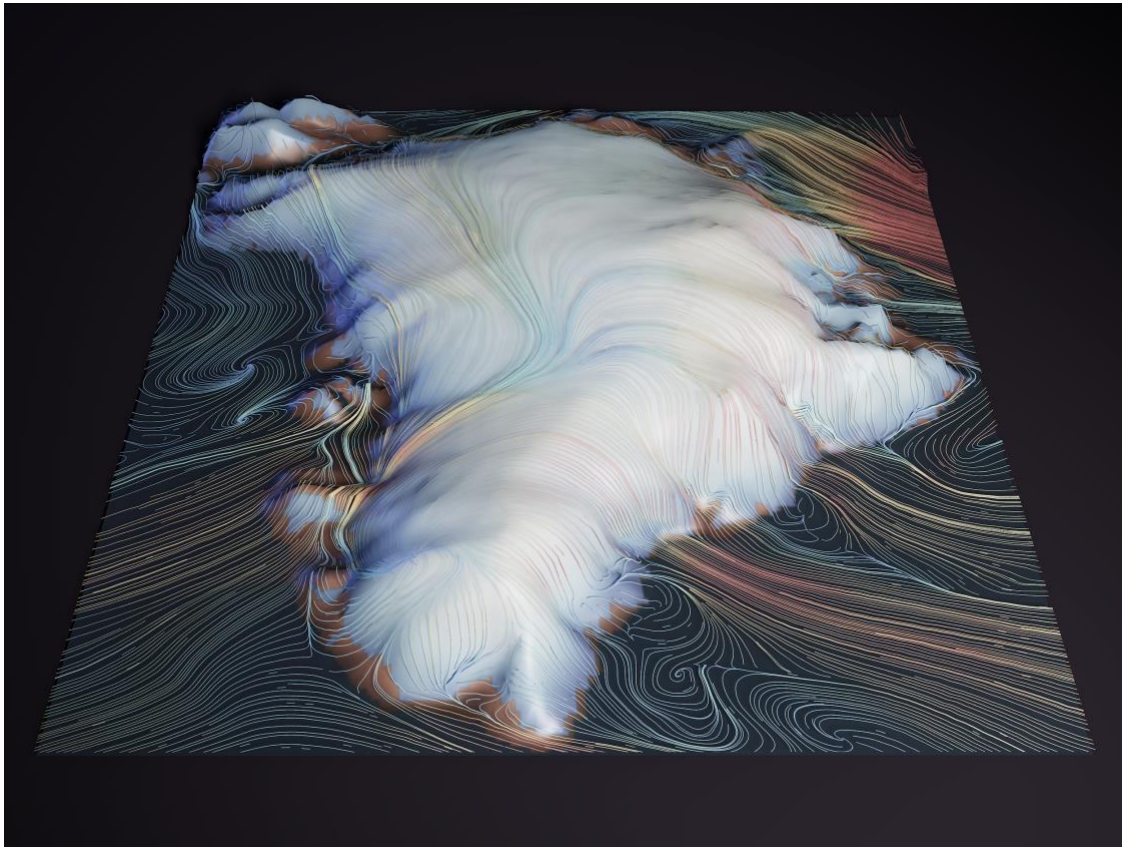


Figure 11. Snapshot of the lowest model level streamlines, draped over the Greenland ice sheet and colored by wind speed. Simulation was performed with a $1/8^\circ$ refined grid over Greenland using the variable-resolution configuration of the SE atmospheric dycore in CESM2. Katabatic winds can be seen accelerating down the eastern slopes of the ice sheet. Visualization was developed by Matt Rehme (CISL) and Adam Herrington (CGD), and was inspired by a visualization of winds over Antarctica by the Polar Meteorology Group at the Byrd Polar & Climate Research Center.

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