CESM

Community Earth System Model

CSL Accomplishments Report
(7/1/12 – 10/31/14)

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Summary

The development and application of CESM and its predecessor (CCSM) involves not only the CSL computing resource, but also other computing resources such as the DOE INCITE (Innovative and Novel Computational Impact on Theory and Experiment) award, other national laboratory computing facilities, and work performed at university computing centers by individual members of CESM working groups. Nevertheless, CSL computer resources have been and remain critical for the CESM project, and without them the many notable achievements since the last CSL award would not have been possible. The following highlights provide only a brief overview of some of the major model developments and achievements under the previous CESM CSL allocations, including the Community Projects. More detailed summaries (by working group) can be found below.

Development

- New atmospheric dynamical core (Spectral Element)
- Fast ocean tracer spin-up technique (Newton-Krylov)
- Representation of short-lived tropospheric halogen chemistry
- Integration of CISM2 in CESM
- Dynamic vegetation representation through Ecosystem Demography
- Exchange of freshwater between the land and ocean
- Water and carbon isotopes for comparison against paleo proxies
- Representation of crops in the land model

Production, including Community Projects

- Quantified the change in climate sensitivity from CCSM4 to CESM1-CAM5 associated with changes in atmospheric physics parameterizations
- Expanded the analysis of the carbon-climate feedbacks to the 22nd and 23rd centuries
- Provided several simulations to the Geo-Engineering Model Intercomparison Project (GeoMIP)
- Performed the 30 ensemble members using CESM1-CAM5-BGC (1920-2100) and distributed the associated model output
- Identified the importance of permafrost thaw and soil decomposition in high-latitude carbon-climate feedbacks
- Studied mechanisms for the variability of the Atlantic meridional overturning circulation (AMOC)
- Performed a larger number of full-forcings and single-forcing 850-2005 to identify the importance of natural forcings on climate change
- Performed additional simulations (RCP4.5) to complement the Large Ensemble and provide data on avoided impacts (from RCP8.5)
- Provided numerous simulations to the SPARC lifetimes assessment of long lived species in the stratosphere, such as chlorofluorocarbons (CFCs)

Community Projects – Large Ensemble

While internal climate variability is known to affect climate projections, its influence is often underappreciated and confused with model error. Why? In general, modeling centers contribute a small number of realizations to international climate model assessments (e.g., Coupled Model Intercomparison Project 5 (CMIP5)). As a result, model error and internal climate variability are difficult, and at times impossible, to disentangle. In response, the Community Earth System Model (CESM) community allocated CSL resources to run a CESM Large Ensemble (CESM-LE) with the explicit goal of enabling assessment of climate change in the presence of internal climate variability. All CESM-LE simulations use a single CMIP5 model (CESM with the Community Atmosphere Model version 5). The core simulations replay the 20-21st century (1920-2100) 30 times under historical and Representative Concentration Pathway 8.5 external forcing with small initial condition differences. Two companion 1000-year long pre-industrial control simulations (coupled, atmospheric) allow assessment of internal climate variability in the absence of climate change. Comprehensive outputs, including many daily fields, are available as single-variable time series on the Earth System Grid for anyone to use. Early results demonstrate the substantial influence of internal climate variability on 20th-21st century climate trajectories. Global warming hiatus decades occur, similar to those recently observed. Internal climate variability alone can produce projection spread comparable to that in CMIP5. Scientists and stakeholders can use CESM-LE outputs to help interpret the observational record, to understand projection spread, and to plan for a range of possible futures influenced by both internal climate variability and forced climate change. More information on the project including variables saved, available diagnostics, and projects planned by the community can be found at the project webpage:
http://www2.cesm.ucar.edu/models/experiments/LENS. A submitted paper also describes the project:

Kay, J. E, C. Deser,A. Phillips, A. Mai, C. Hannay, G. Strand, J. Arblaster, S. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J. -F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein (2014): The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability. *Bull. Amer. Met. Soc.*, submitted April 17, 2014, undergoing minor revisions.

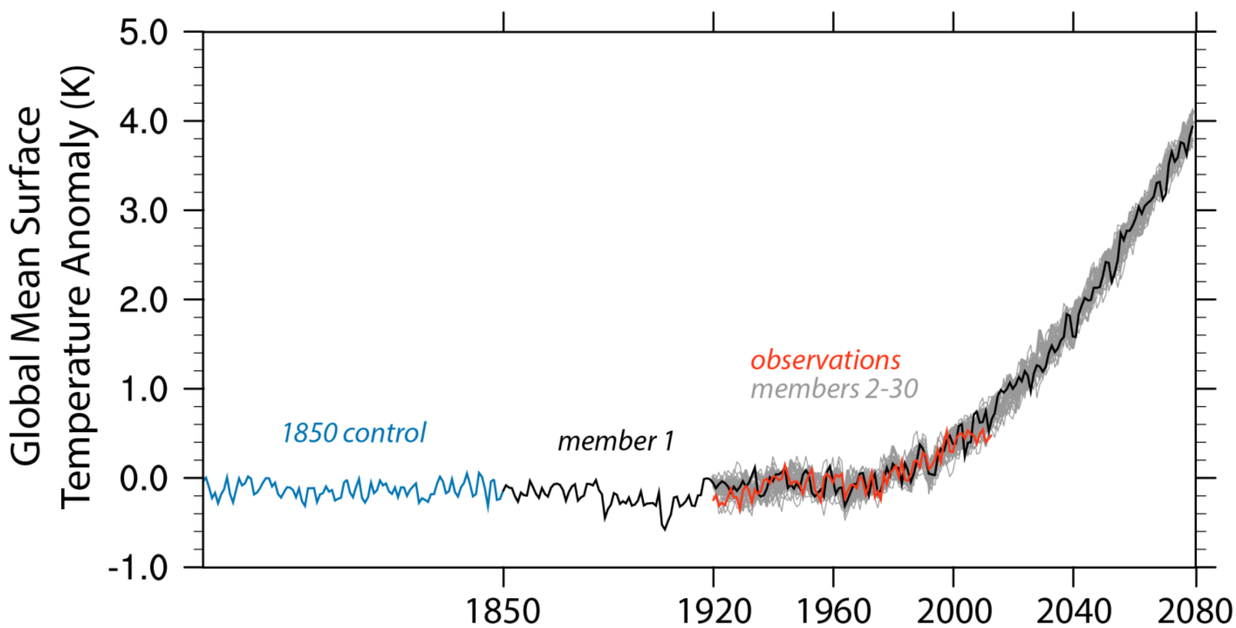

Figure from Kay et al. (2014) – Global surface temperature anomaly (1961-1990 base period) for the 1850 control, individual ensemble members, and observations (HadCRUT4; Morice et al. 2012). *Note: The ensemble has been extended to 2100.*

Community Projects – Last Millennium

The Last Millennium ensemble study has been quite successful with 30 simulations completed for 850-2005AD with CESM1.1 at f19_g16 resolution. This ensemble includes the transient Last Millennium forcings and boundary conditions for solar variability, volcanic eruptions, land use, greenhouse gases, and orbital changes, together and individually. In addition, we added two single forcing simulations for 1850-2005AD to address the contributions of the transient forcings of ozone and aerosols that become important during the 20th century. Output at the temporal frequency required by WRF and other regional models is included for the entire simulation for one full-forcing ensemble member, and the passive ocean tracer 'radiocarbon' is included in the last full-forcing ensemble member. We still hope to complete or nearly complete a solar-only forcing Last Millennium ensemble member with WACCM5 with our current CSL allocation.

The Last Millennium ensemble of simulations will be released at the AGU 2014 Fall Meeting in December and contributed to the CMIP6 archive. We expect that the Last Millennium ensemble will be used to address numerous science questions including:

- The detection and attribution of climate changes over the last millennium, including Medieval versus Little Ice Age changes in climate;
- Interpretation of thermodynamic and dynamic mechanisms that explain regional responses suggested in proxy synthesis;
- Decadal to centennial variability in the ocean and atmosphere and statistics of extremes, and the role of external natural forcings in altering variability and extremes;
- Assessment of "top-down" influences of solar variability.

Expt	# runs	Solar variability	Volcanic eruptions	Land use	Greenhouse gases	Orbital changes	Ozone/ aerosols
Full forcings	10	Transient 850-2005AD	Transient 850-2005AD	Transient 850-2005AD	Transient 850-2005AD	Transient 850-2005AD	Transient 1850-2005AD
Solar only	4	Transient 850-2005AD	None	*	*	*	1850AD
Volcanic only	5	*	Transient 850-2005AD	*	*	*	1850AD
Land use only	3	*	None	Transient 850-2005AD	*	*	1850AD
GHG only	3	*	None	*	Transient 850-2005AD	*	1850AD
Orbital only	3	*	None	*	*	Transient 850-2005AD	1850AD
Ozone Aerosol only	2	*	None	*	*	*	Transient 1850-2005AD

* Fixed at 850AD values

Community Projects – High-resolution

The CESM CSL community resources contributed to high resolution Community Atmosphere Model simulations both in prescribed-SST and fully coupled experiment configuration. The first CESM future climate simulations performed at 25-km resolution were run as time-slice experiments using SSTs from fully coupled large-ensemble experiments. These simulations, coupled with their present-day control equivalent simulations allow, for the first time, the evaluation of extreme weather features such as tropical cyclone statistics and how they may change in a future climate. Further high-resolution experiments also examine the forcing role of inter-annual SST variations in tropical cyclone numbers. This is achieved using perpetual SST experiments whereby several years of simulation are performed under weak and strong tropical cyclone years to identify the strength of any signal associated with the role of the large-scale tropics in tropical cyclone characteristics. Fully coupled high-resolution atmosphere simulations were performed in preparation for the assessment of long control simulations. These exploratory simulations will provide greater insight into the role of atmospheric resolution in long-term coupled modes of variability; a new area of research for CESM.

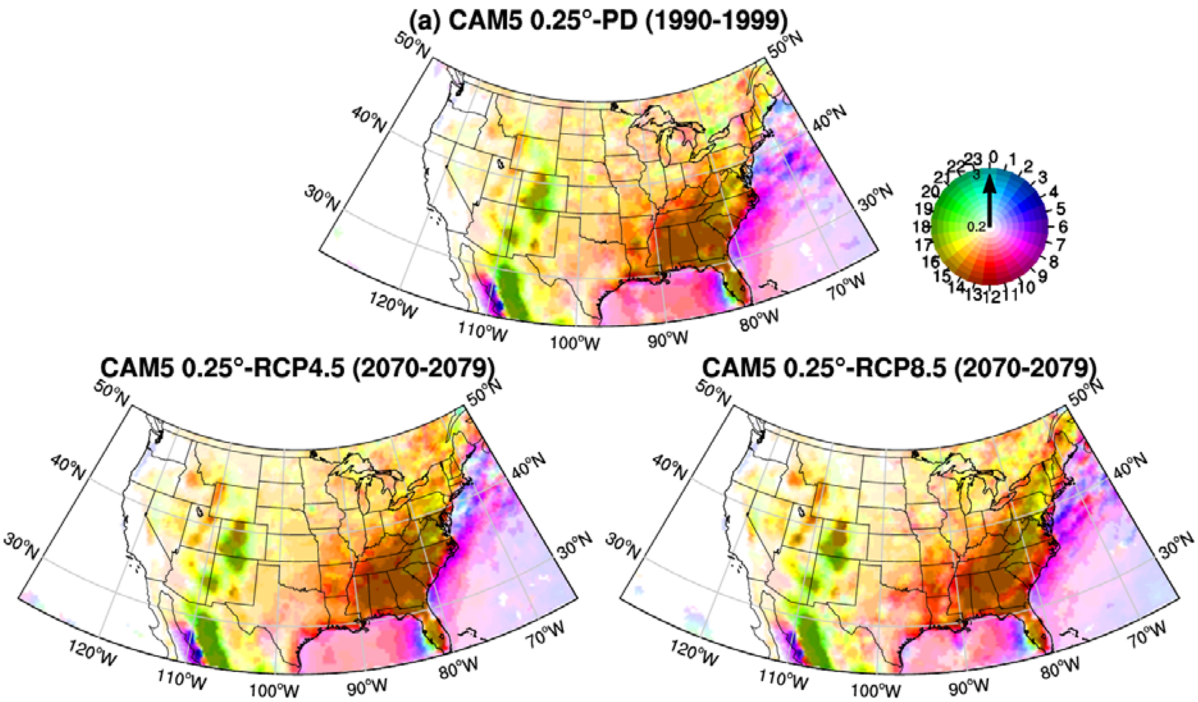

Figure. Change in the diurnal cycle of convection between present-day (top) and late 21st century following two separate RCPs

Atmosphere Model Working Group

The Atmosphere Model Working Group (AMWG) has achieved many of the goals set forth in the previous CSL proposal and made significant progress on the remainder. The use of CSL resources underpins much of the model development and research activities of the group and is a significant factor in addressing the scientific goals in the CESM strategic plan. In addition to the core development activities, resources are used to support the maintenance of an ever-increasing level of functionality within the CAM software framework. This enables the easiest and earliest possible access to model developments for the CESM user community.

Development

Physical parameterization development in CAM continues to account for the largest portion of AMWG CSL time. This has enabled many of the nascent development activities under the previous CSL allocation move closer to a production available status. The UNIfied CONvection Scheme (UNICON) is able to simulate an array of high vertical resolution boundary layer environments, including stable and unstable regimes, significantly better than previous model versions. It continues to exhibit large improvements in modes of variability important to local climate and potential predictability in model simulations. The most important of these are the diurnal cycle of precipitation over land and the tropical Madden Julian Oscillation.

The Cloud Layers Unified By Binormals (CLUBB) scheme has been developed further as a potential replacement for the dry and moist turbulent processes (excluding deep convection). CSL time has been used to couple CAM-CLUBB with the Morrison-Gettelman microphysics, version 2 (MG2). These simulations have revealed the sensitivity of tropical intra-seasonal variability to changes in the coupling characteristics between CLUBB and MG2. Successful fully coupled simulations have also been performed with CAM-CLUBB-MG2

Development and testing of a new version of the stratiform cloud microphysics used in CESM has been completed. MG2, a double-moment microphysics scheme, has been rewritten for speed, clarity and portability. It also now includes prognostic precipitation quantities (rain and snowfall), which have been shown to significantly reduce aerosol indirect effects on clouds, largely by improving the microphysical process rates.

The dynamical core development for CAM continues to use the spectral element capability (CAM-SE). Significant progress has been made in the implementation and development of a new gridding infrastructure in CAM-SE. This is referred to as the "physics grid" option, where the grid on which the dynamics and physics is computed on is separated from the current co-located grid. This allows for computing physics tendencies on an equal-area grid rather than using the native SE (quadrature) grid-point values as is currently done. Simplified validation runs have been performed. The physics-grid option was implemented in preparation for running the Conservative Semi-LAgrangian Multi-tracer transport scheme (CSLAM) in CAM. The computational expense of CAM-SE-CLSAM has been shown to be lower than current configurations for tracer-intensive applications from the Chemistry Climate Working Group (ChemClimWG) and the Whole Atmosphere Working (WAWG). Further development is expected to make CAM-SE-CSLAM cost competitive for standard CAM applications also.

The use of the unstructured cubed-sphere grid for high-resolution allows us to exploit scalability of Yellowstone much more effectively than with the finite volume dynamical core. At 25-km resolutions the CAM parameterized physics have been shown to behave very differently than at the courser 100-km grid scale. In particular, the response of parameterized deep convection at 25 km plays a smaller role in many aspects of the tropical precipitation. The existing resolution simulations produce a global climatology of tropical cyclones that are largely in agreement with observations, for both track densities and category strength. However, the distribution among basins exhibits bias that includes too little tropical Atlantic activity and too strong Western Pacific activity. This activity changes significantly in response to deep convection configurations involving timescale and entrainment.

The effects of increased vertical resolution on climate have initially been analyzed using a 60-Level (L60) configuration of CAM and targeting upper-troposphere and lower-troposphere model biases. With the inclusion of the parameterization of non-orographic gravity waves from the Whole Atmosphere Community Climate Model (WACCM), CAM-L60 is the first version able to simulate the lower stratospheric Quasi-Biennial Oscillation (QBO). In comparison to the default CAM-L30, CAM-L60 also shows improved representation of near-tropopause temperatures, lower stratospheric temperatures, and surface wind stresses. Efforts have also begun at improving the surface mountain stress through testing of a bi-directional sub-grid scale orography specification.

This regional refinement continues to be tested in aqua-planet (ocean covered earth) configurations in order to examine the sensitivity to varying resolution configurations. The grid sensitivities of both the CAM and CAM5 version of the physics have been analyzed. In tropically focused regionally refined simulations, the sensitivities were significant, with CAM4 simulations being more sensitive than CAM5. The differences were most obviously expressed in the vertical distribution of parameterization tendencies, where the combination of heating/moistening terms are, as with many other tropical climate CAM studies, dominated by the response of deep convection. Grid sensitivity was also shown to be a strong function of deep convection timescale.

Cloud-Associated Parameterization Testbed (CAPT) initialized simulations have been used to evaluate moist processes parameterization suites (including CLUBB and UNICON) to identify and evaluate systematic errors in CAM. Analysis of the diurnal cycle of the tropical Pacific has revealed significant biases in the model's representation. CAPT simulations have also been run and submitted to create an archive of forecast results for Transpose AMIP II (in conjunction with the latest CFMIP).

The development of a nudging capability has lead to many improvements in model physics' response to realistic states (see Figure 1). The method involves nudging the CAM atmospheric state toward observations (reanalysis) during climate-type simulations. Further capabilities allow a region-only application of nudging as well as sub-selecting the quantities to nudge to. Nudging has facilitated the systematic identification of model biases and the quantitative assessment of modifications to physics parameterizations. As a test case, this version has been used to study the systematic temperature bias observed in CESM simulations near the surface over Greenland and Antarctica.

Production

AMWG has focused on long AMIP and coupled experiments for climate validation of existing development activities. These simulations have revealed a number of climate biases. For example they have helped identify problems with the coupled climate spin-up seen with the introduction of a CAM-SE atmosphere and the strengthening of ENSO amplitude seen with the introduction of more vertical levels in the atmosphere. In additional, multi-decadal simulations were used to identify the sensitivities of the QBO to increases in vertical resolution and elevation of the model top.

The AMWG has been able to demonstrate a number of applications. We have incorporated current and future, into year 2050, aviation emissions into CAM5 to simulate their climate impact. CAM5 simulations indicated that contrail cirrus could produce a positive radiative forcing over Central Europe and the

Eastern US based on the aviation emissions in 2006 and the radiative forcing could be enhanced to 2 W/m^2 in 2050 over those regions.

The climate sensitivity of CESM and the climate feedbacks in the atmosphere and on the land surface have been investigated in CESM1 using up to date methodologies. Differences between CCSM4 and CESM1, as seen in radiative forcing AMIP experiments, are significant and can be traced to specific parameterization developments.

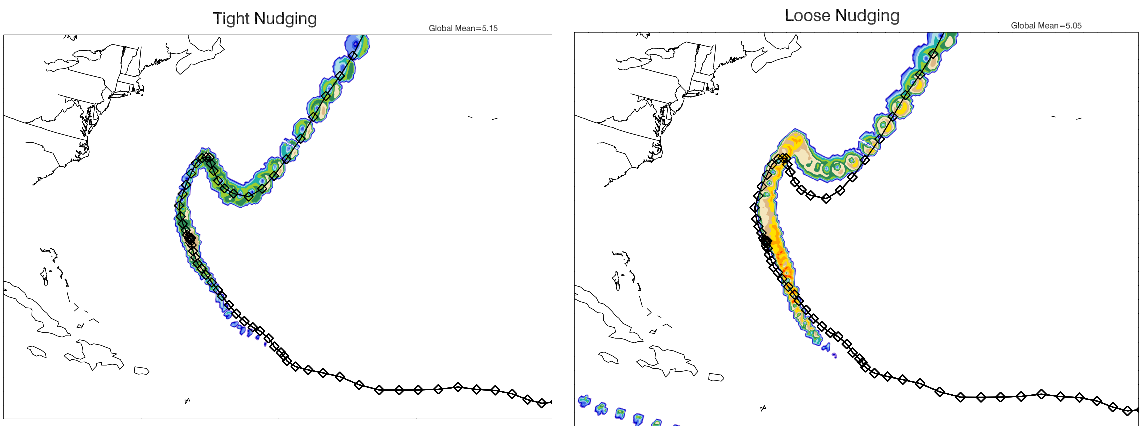

Figure: A comparison of tropical cyclone tracks using tight and loose nudging in 25-km CAM simulations (observed track is black line). Tight nudging constrains CAM to a weak precipitation signal and the observed track, whereas loose nudging allows CAM's track to deviate and generate a larger precipitation signal.

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Biogeochemistry Working Group

Development

Accomplishments of the Biogeochemistry working group that were done with the CESM CSL Development Allocation fall into the following broad categories: preparing for the Large Ensemble experiments, ocean biogeochemistry model development, development of a fast ocean tracer spinup technique, and the conduction of experiments with ocean biogeochemistry with resolved eddies.

The main computational aspect of preparing for the Large Ensemble (LE) experiments was spinning up ocean biogeochemical tracers to be in balance with the ocean circulation from a coupled run using CAM5, the atmospheric model that was used in the LE experiments. This was the first time that the ocean biogeochemistry module had been run with CAM5.

Development of the ocean biogeochemistry consisted of modifications to reduce model biases and the inclusion of new functionality. The following developments were included in version 1.2 of CESM: enhanced treatment of dissolved organic matter, modifications to the remineralization of sinking particles (which reduced biases in the extent of the model's oxygen minimum zones), incorporation of new observational constraints on iron to carbon ratios in plankton, inclusion of riverine inputs of biogeochemical tracers and loss to sediments. Developments that have been done since CESM 1.2, and are targeted for inclusion in CESM 1.3 or 2.0, include: addition of the carbon isotopes 13C and 14C (this was done in collaboration with the Paleoclimate working group), addition of the nitrogen isotope 15N, incorporation of the impact of ocean acidification on CaCO3 dissolution, inclusion of iron and dust into the sea ice model and coupling that to the ocean, and the treatment of light limitation in a heterogeneous sea ice environment.

Work has progressed on a fast ocean tracer spinup technique. This technique, based on a Newton-Krylov solver, is now being applied successfully to ocean tracers with simple dynamics, such as ideal age and abiotic radiocarbon. These tracers provide useful diagnostics on long-term circulation patterns in the ocean.

Multiyear experiments have been conducted using CESM's ocean biogeochemistry module with an ocean model resolution (0.1°) that resolves mesoscale eddies. Initial analysis of the results reveals a spatially heterogeneous relationship between eddies and biogeochemical fields. The regional relationships are consistent with satellite-based observations.

Production

Accomplishments of the Biogeochemistry working group that were done with the CESM CSL Production Allocation fall into the following broad categories: additional ensemble members of 20th and 21st century simulations with CESM1(BGC), and extensions of these experiments, and related carbon-climate feedback experiments, into the 22nd and 23rd centuries.

The additional ensemble members enable us to estimate uncertainty due to internal model variability in future projections. This is particularly useful to determine the statistical significance of differences in sensitivity experiments.

Initial analysis of the carbon-climate feedbacks experiments is revealing that climate effects on ocean biogeochemical cycles increases significantly in the 22nd and 23rd centuries, compared to the effects in the 21st century. This highlights the importance of policy decisions that will be made in coming decades, because the effects of future emissions is amplified on longer timescales than are typically considered in climate change scenarios.

Originally planned experiments that were not conducted were new coupled-carbon climate experiments with CESM 1.2 and experiments with biogeochemistry in different epochs. The new coupled-carbon climate experiments were not performed because initial experiments with CLM4.5 and CAM5 revealed feedbacks that led to a poor biogeochemical simulation in the Amazon Basin. Analysis of these experiments has revealed a bug in the new fire module in CLM4.5. This has now been fixed, and these experiments will commence in the near future. The experiments with biogeochemistry in different epochs were not performed due to lack of dedicated personnel to design, perform, and analyze the experiments.

Chemistry Climate Working Group

Development

The previous CSL development allocation has allowed the Chemistry-Climate Working Group to significantly advance the representation of chemistry and aerosols in CESM.

We have performed numerous simulations to compare the accuracy of the spectral element dynamical core with other transport schemes in representing tracer transport. CAM-SE was shown to perform well in diagnostics such as filament preservation, which is of particular importance for chemistry representation (Lauritzen et al.,2014). Additional papers (on the development of baroclinic waves and comparison with the finite-volume dynamical core) are in preparation.

A chemistry mechanism including very short-lived (VSL) halogen species was developed to assist in the analysis of observations of ozone and halogenated compounds particularly in the marine boundary layer. This unique research has led to 4 papers, in review or submitted (Fernandez, , et al.,2014; Saiz-Lopez et al., 2014; Prados-Roman et al., 2014a; Prados-Roman et al., 2014b).

The Modal Aerosol Model MAM3 was developed and published (Liu, et al.,2012) and has become a standard component of CAM5-chem, providing an improved representation of size-resolved aerosols of various chemical composition.

Production

The production allocation for the CCWG allowed us to provide simulations to several international model intercomparison activities.

Land-use and SOA: We provided CAM-chem simulations for participation in the AEROCOM comparison of secondary organic aerosols, and in the publication of those results (Tsigaridis, et al., 2014).

Impact of Aviation: Simulations with CAM4 and CAM5 were performed to study the impact of NOx emissions from aircraft on ozone and climate in the upper troposphere and lower stratosphere, and a paper has been submitted (Khodayari, et al., 2014).

CCMI (hindcast): – CAM-chem simulations for the IGAC/SPARC Chemistry-Climate Model Initiative were begun in this allocation, after significant testing of several model improvements and bug fixes. The first results of these simulations were presented at the CCMI workshop in Manchester, UK in May 2014. Papers further analyzing these results are in preparation.

GeoMIP:CAM simulations were provided to the Geoengineering Model Intercomparison Project, which have been included in 10 papers, listed below (by authors Curry, Huneeus, Irvine, Jones, Kravitz, Moore, Pitari, Xia). A separate analysis of our simulations resulted in another paper (Tilmes,, et al., 2014)

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Climate Variability and Change Working Group

With the previous CSL allocation, the CVCWG completed numerous simulations for the purpose of investigating climate change attribution, the role of the ocean in internal variability, precipitation extremes, and extremes in a warmer climate. One major change from the CVCWG original plan was that decadal prediction runs were not performed by the CVCWG on Yellowstone. The CVCWG and the OMWG collaborate on these runs and they were conducted on a different machine. Many of the simulations described below are recently completed and currently under analysis. Our intention is to publish the results from all of the research described below.

Simulations contributing to the Meehl et al. (2013) publication addressing the climate response to a possible future Grand Solar Minimum were completed with the previous CSL allocation. The main conclusion from this research is that a grand solar minimum can slow down but not stop global warming. During the solar minimum, a slowing in the rate of global warming occurs, but once the solar minimum ends, the magnitude of global warming returns to nearly the value if the solar minimum had not occurred.

To assess each transient forcing field, many single forcing and modified forcing simulations were conducted. Specifically, anthropogenic-only, greenhouse gas-only, and volcano-only simulations were conducted which completed a full set of single forcing simulations using CESM1-CAM5 for the 20th Century scenario. Additional 20th Century all-forcings ensemble members are currently underway on Yellowstone to complete a 5-member ensemble and include a MOAR simulation for comparison to the single forcing simulations. Additional modified forcings runs were also completed, including simulations in which ozone is eliminated from the all-forcings simulation. This is to complement the traditional single forcing runs to further assess the impact of each forcing on climate. The eliminated ozone simulations will specifically address whether the impacts of the Antarctic ozone hole are larger if the base climate is warmer. A new and improved volcano dataset was also tested from 1960-2011 to determine the impact of improved volcano representation in the model.

As part of an investigation into precipitation extremes and atmospheric rivers, one member of an RCP8.5 scenario using CCSM4 0.5° atm/lnd coupled to a 1° ocn/sea ice was conducted. These are part of a larger effort to obtain a 3-5 member ensemble for the 20th Century, RCP4.5 and RCP8.5, which we have proposed to continue in the 2014-2016 CSL allocation. Another high-resolution simulation intended for investigation of extremes in a future scenario using CESM1-CAM5 with the atmosphere at ¼° is currently underway.

The CVCWG was also able to conduct an ensemble of fully coupled simulations in which the ocean initial condition was perturbed, in contrast to many ensembles in which the atmospheric initial state is perturbed.

A major accomplishment of the CVCWG during this past CSL cycle is the completion of the CESM-CAM5 (1 degree) “Large Ensemble”, a set of 30 simulations for the period 1920-2100 under historical and RCP8.5 forcing. Each of the simulations begins from identical ocean, land and sea ice states, with round-off error perturbations in the initial atmospheric temperatures. This initial-condition ensemble presents the range of possible climate states that is consistent with the model’s internal variability plus its response to external forcing (e.g., GHG increases, etc.). This was a major cross-working group effort, and one that had wide community involvement. Ocean biogeochemistry is active in these simulations, although it does not feedback on the climate system. This project was co-led by C. Deser, co-chair of the CVCWG. The project is detailed in Kay et al. (2014) and on the CESM “Large Ensemble” website (http://www2.cesm.ucar.edu/models/experiments/LENS) put together by CVCWG part-time liaison Adam Phillips. This project is expected to produce numerous scientific papers in the years to come.

Another major accomplishment of the CVCWG during this past CSL cycle is the development of a new CESM diagnostics package for climate variability and change (Phillips et al., 2014). The development of the "Climate Variability Diagnostics Package" (CVDP) (http://www2.cesm.ucar.edu/working-groups/cvcwg/cvdp) was led by NCAR's Climate Analysis Section, in particular CVCWG liaison Adam Phillips and CVCWG co-chair Clara Deser. The CVDP provides quick-look plots of the major modes of climate variability in models and observations. These modes include ENSO, Pacific Decadal Oscillation, Atlantic Multi-decadal Oscillation, Northern and Southern Annular Modes, North Atlantic Oscillation, Pacific North and South American teleconnection patterns, as well as global trend maps and index time series. A unique feature of the CVDP is the ability to specify both CESM and non-CESM models (for example those in the CMIP archives) for comparison, as well as the ability to choose particular observational data sets and time periods for analysis. Other unique features of the CVDP include the ability to run the package on numerous simulations at once, as well as the option to output calculated results to netCDF files for further analysis. The CVDP creates various web pages that allow easy viewing of the diagnostic plots. It has proved to be a very useful tool for evaluating and tracking improvements in the CESM, comparing CESM with other CMIP5 models, and for analyzing the CESM "Large Ensemble". As a demonstration of he considerable community interest, CVDP has already been downloaded 27 since August 17 2014!

In addition to the aforementioned projects, the CVCWG has completed 10-member ensembles of AMIP integrations with CAM4 at 1-degree horizontal resolution. These include TOGA and GOGA simulations (specified observed SSTs within the tropics and the globe, respectively) with and without radiative forcings (e.g., GHG, stratospheric ozone, volcanic aerosols, etc.) over the period 1900-present.

Finally, all of the simulations conducted by the CVCWG are made available via the Earth System Grid (ESG), and a list of available data can be viewed under "Published Data" on the CVCWG webpages at: http://www2.cesm.ucar.edu/working-groups/cvcwg

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Land Ice Working Group

During the last CSL-funded period, LIWG members used CSL development resources (0.22M core hours) for the following activities:

- Developed and demonstrated a transient ice sheet spin-up technique amenable to use in a coupled model (Fyke et al., 2014a)
- Integrated CISM2 (which includes a parallel, higher-order dynamical core) in CESM
- Implemented dynamic landunits in CLM, allowing glacier area to evolve in time, thus remaining consistent with CISM's predicted glacier area
- Implemented two-way coupling between CISM and other CESM components, including dynamic topography in CAM, and solid and liquid runoff sent to POP
- Developed a surface mass balance scheme for non-glaciated regions in CLM, allowing more accurate simulations of glacial inception
- Improved the downscaling of atmosphere fields to glacier elevation classes in CLM
- Added multi-layer snow diagnostic fields to CLM, to aid the development of CLM's snow model.
  In addition, LIWG members used CSL production resources (1.6M core hours) to carry out coupled climate simulations with a Greenland ice sheet, using the new atmosphere model, CAM5. The initial simulations showed that Greenland has an atmospheric cold bias, resulting in too little ablation along the ice-sheet margin. Follow-up simulations to analyze and reduce the bias are ongoing.
  The LIWG used fewer hours than originally planned because work was focused on developing two-way ice-sheet/climate coupling, which required considerable effort but only a modest amount of computer time. Several production experiments were deferred to the next CSL cycle, pending completion of the two-way coupling.

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Land Model Working Group

A significant portion of the Land Model Working Group CSL resources used during the past CSL allocation period were dedicated to analysis of CLM4.5 and preliminary development of CLM5. Model parameterization development and improvement and new capability activities undertaken during this CSL period include:

- Vegetation processes - multilayer canopy and plant hydraulics for CLM5+
- Ecosystem Demography - dynamic vegetation approach that is a statistical approximation of an individual-based forest simulation model that will become the new biogeochemical core of CLM5

- Urban model - Implement and test a new building energy model, multiple urban landunit capability, variables layers for roofs and walls, and new urban properties datasets for CLM4.5 and CLM5
- Crop model - expansion to tropical crop types.
- Hydrology – Dry surface layer soil evaporation and canopy interception
- Stress deciduous phenology – improved stress deciduous scheme
- Fire – revisions and updates to CLM4.5 fire model to resolve tropical biases
- Dynamic landunits – expand model capability by allowing landunit (vegetated, lake, glacier, urban, crop) areas to change throughout a model run either prognostically or prescribed

Resources have also been used to complete several production experiments for projects that are aimed at understanding the terrestrial response to climate change and the resulting feedbacks onto the local and global climate. Projects completed over the past CSL allocation include:

- Urban vs rural climate change - Assessed differences in urban and rural climate using CESM1 under various future climate scenarios. Confirmed the urban heat island and found that urban areas are projected to warm faster than rural areas.
- High resolution urban - CLMU simulations over the U.S. in support of the SIMMER (System for Integrated Modeling of Metropolitan Extreme Heat Risk) project and to support further science development, understanding, and validation for community users of CLMU. For four cities examined in detail, climate change by mid-century increases the number of high heat stress days and nights in both rural and urban areas, the magnitude being highly dependent on the heat stress index, urban density class, and each city's climatic setting. Houston exhibits noteworthy mid-century increases in high heat stress nights, with more than half of summer nights qualifying as high heat stress in not only urban areas but also rural areas, indicating the need to consider vulnerability and adaptive capacity of both rural and urban populations in the context of climate change.
- Crop-climate interactions - EaSM2 simulations where vegetation is idealized to include all managed and unmanaged vegetation in every grid cell globally, so that we may assess changes in plant and crop productivity in the context of climate change. Preliminary results show that different crop types will have different vulnerabilities from region to region. Additional experiments were completed to assess the role of crop cultivation on soil carbon. Cultivation decreases soil carbon by about 1350 gC m^{-2} in the CLM across eight sites from the first cultivation (early 1990s) to 2010. CLM crop simulations without cultivation have soil carbon gain, not loss, over this period, in contrast to the expected declining trends in agricultural soil carbon. A global cultivation simulation for 1973-2004 reduced ecosystem carbon by 0.4 Pg C yr^{-1} over temperate corn, soybean, and cereal crop areas, which occupy approximately 1/3 of global crop area.
- Permafrost-carbon feedback – Series of historical and future experiments designed to assess the potential range of permafrost-carbon feedback. Enhanced vegetation growth due to warmer climate and CO2 fertilization will dominate Arctic terrestrial carbon response for early part of this century. Then, permafrost soil carbon losses will kick in. The future carbon balance of the permafrost region is highly sensitive to the decomposability of deeper carbon with the net balance ranging from 21-164 Pg C losses by 2300. Deep soil nitrogen mineralization reduces nutrient limitations, but the impact of deep nitrogen on the carbon budget is small due to coincident enhanced nitrogen availability from warming surface soils and seasonal asynchrony between deeper nitrogen availability and plant nitrogen demands. The future carbon balance of this region

is projected to hinge more on the rate and extent of permafrost thaw and soil decomposition than on enhanced nitrogen availability for vegetation growth resulting from permafrost thaw.

- Acclimation – Historical and future experiments to understand how temperature acclimation for photosynthesis affects vegetation response to climate change. Photosynthetic and respiration acclimation act to increase the total carbon accumulated on land by 20PgC by the end of the 21st century.
- TRENDY MIP project – model intercomparison study of global and regional carbon cycle response to historic climate change, CO_2 fertilization, and land cover/land use change. Results from these simulations contribute to the annual Global Carbon Project report on the state of the global carbon cycle.
- GLACE-CMIP5 – Simulations were conducted for the GLACE-CMIP5 experiment aimed at assessing the feedbacks of soil moisture trends on climate. Projected soil moisture changes substantially impact climate in several regions in both boreal and austral summer. Strong and consistent effects are found on temperature, especially for extremes (about 1-1.5K for mean temperature and 2-2.5 K for extreme daytime temperature). In the Northern Hemisphere, effects on mean and heavy precipitation are also found in most models, but the results are less consistent than for temperature.

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Ocean Model Working Group

Development

In support of our model development activities in the Parallel Ocean Program version 2 (POP2), the implementations of the three algorithmic improvements have been nearly completed and some limited testing has been done. These developments are i) elimination of virtual salt fluxes in favor of true freshwater surface fluxes; ii) implementation of a new vertical coordinate system, z*; and iii) introduction of a conservative Robert time filter to replace the time-averaging time step.

A series of parameterizations of the exchange of freshwater between the terrestrial and oceanic systems continues to be developed. These parameterizations act as a link between the River Transport Model (RTM) and POP2. The first is a very simple extension of the form that has been in use in CESM since the very beginning: an augmentation of precipitation in the coastal region offshore of a river mouth. The simple extension accounts for vertical mixing of fresh and saline waters in estuaries and on the shelf by prescribing a vertical scale, typically 40-80 m, over which the virtual salt flux is imposed on the ocean. A series of experiments in both forced ocean and coupled configurations were completed and a reduction of coastal region salinity biases of about 5% was achieved. The next more sophisticated parameterization represents estuary mixing processes using a steady state two-layer box model. In contrast to the simplest schemes, saline open ocean water is drawn into the box model and mixes with freshwater to produce brackish surface water that enters the upper ocean. This scheme has been implemented and tested in CORE-forced ocean – sea-ice integrations for the Columbia and Amazon rivers with encouraging results. The necessary input parameters are currently being assembled for approximately 20 of the world’s largest river systems. A second branch of this work has developed a downscaling capability for the complex coastal and estuarine environment of the Northeast Pacific. This model has been run in time-slice mode for the recent past, serving both as a reference solution for the parameterizations described above and to test the ability of standard resolution CESM to provide boundary conditions for downscaling climate change experiments in this region.

On the physics side, the implementation and preliminary testing of an anisotropic version of the Gent and McWilliams mesoscale mixing parameterization have been completed. This anisotropic version generalizes the eddy diffusivity tensor extending the number of parameters from one (isotropic eddy diffusivity) to three: a major diffusivity, a minor diffusivity, and the principal axis of alignment. We have also continued our work on influence of surface wind waves on upper-ocean mixing by including the NOAA Wave Watch III (WWIII) wave model as a separate component of CESM along with a Langmuir mixing parameterization in POP2. Our preliminary results, as anticipated, show that shallow mixed layer depth (MLD) biases and low bias in CFC uptake could be significantly reduced with the inclusion of wave-forcing and Langmuir mixing. These simulations also showed that it is prohibitively expensive to run an active WWIII model. Hence, we would like to develop a data wave model for use in CESM.

We completed all the proposed work associated with incorrect separation of the Gulf Stream (GS) and the subsequent, too-zonal path of the North Atlantic Current (NAC). Specifically, we investigated topographic control of these currents by conducting a systematic exploration of the GS separation and NAC path to some details of the bottom topography, focusing on specifics of how discrete topography is created from available data sets. A major focus was vorticity analysis, showing that balance of vorticity budget terms is surprisingly very similar in coarse and eddy-resolving simulations. Specifically, in contrast with our a priori expectations, we found that GS is rather inviscid in our nominal 1° horizontal resolution model in agreement with eddy-resolving simulations.

We investigated whether nested high-resolution ocean modeling can reduce the biases of sea surface temperature and salinity seen in coastal regions of global CESM simulations. Several 150-year coupled integrations were performed with a 0.1° ROMS imbedded in the North-East Pacific within the global POP2 for the California Current System. The results showed that this model version with the imbedded ROMS better resolves the horizontal flow in the California Current System, producing stronger cold advection from the north, so that the surface temperature bias along the coast was reduced by up to 50% compared to the standard coupled model simulations.

As proposed, the computational resources were also used for i) testing of MIT Darwin ecosystem model within CESM along with a very short proof-of-concept integration; ii) short test integrations for the Coral Triangle region with ROMS (Regional Ocean Modeling System); iii) a few, very preliminary tests with higher vertical number of levels in POP2; iv) infrastructure and mapping tests for unstructured ocean grids; v) update of the eddy-permitting version of POP2 to include the submesoscale mixing, and tidal mixing parameterizations and to increase the number of vertical levels to 62; and vi) several ocean data assimilation developments. For the last two items, longer experiments (beyond short test integrations) were not possible due to severe under-estimation of our general resource requirements in our request. Consequently, simulations involving the eddy-permitting ocean model and decadal prediction experiments were conducted using resources obtained separately.

Production

We finished a vast majority of the proposed work for the two ocean-related Climate Process Teams (CPTs). The first CPT focused on ocean mixing processes associated with high spatial heterogeneity in sea-ice and implications for climate models. For this purpose, we developed and implemented a multi-column ocean grid (MCOG) framework in CESM. This framework enables the sea-ice model to send its subgrid scale ice category spatial extent information to the coupler and allows the ocean model to receive ice-category-dependent surface fluxes. In the ocean model, each horizontal grid is subdivided into columns with each column corresponding to a sea-ice category, including open-ocean. The ocean model then performs vertical mixing for each subcolumn separately. The coupled model simulations showed only small impacts of this MCOG parameterization on the model solutions and climate. In contrast, the parameterization leads to substantial improvements in surface chlorophyll and net primary productivity under sea-ice. Specifically, MCOG parameterization reduces phytoplankton growth, thus leading to more realistic chlorophyll distributions. These improvements result from the nonlinearity of the photosynthesis and irradiance relationship. The second CPT is on representing internal-wave driven mixing in global ocean models. Our focus was on assessing the climate impacts of wind generated near-inertial waves (NIWs) in CESM using a parameterization for NIWs developed at NCAR. Simulations showed that NIWs deepen MLDs by up to 30%, but they contribute little to the ventilation and mixing of the ocean below the thermocline. However, the deepening of the tropical mixed layer by NIWs leads to a change in tropical sea surface temperature and precipitation. Atmospheric teleconnections then change the global sea level pressure fields so that the midlatitude westerlies become weaker.

A systematic assessment of the impacts of several ocean model parameter choices on the Atlantic meridional overturning circulation (AMOC) characteristics in CESM with the primary goal of identifying both robust and non-robust elements of AMOC variability and mechanisms was conducted. The 1500-year pre-industrial Large Ensemble simulation was used as the control. We branched off from this control and performed several 600-year simulations where some poorly-constrained parameter values in mesoscale, sub-mesoscale, vertical mixing, and lateral viscosity parameterizations in the ocean model were changed. We then obtained a three-member ensemble of 600-year perturbation experiments in which the initial atmospheric temperature field was slightly perturbed. A significant finding is that both the amplitude and time scale of AMOC variability differs considerably among all these experiments with dominant time scales of variability ranging from decadal to centennial. There are also substantial differences in the relative contributions of temperature and salinity anomalies to the positive density anomalies created in the model's deep-water formation (DWF) region prior to AMOC intensifications. Nevertheless, we identify some robust elements of AMOC variability mechanisms. These include: i) The Labrador Sea is the key region with upper-ocean density and boundary layer anomalies preceding AMOC anomalies; ii) Enhanced Nordic Sea overflow transports do not lead to an increase in AMOC maximum transports; iii) Persistent positive phase of the North Atlantic Oscillation plays a significant role in setting up the density anomalies that lead to AMOC intensification via surface buoyancy fluxes; and iv) After AMOC intensification, subsequent weakening is due to advection of positive temperature anomalies into the model's DWF region.

Finally, OMWG contributed resources towards the integration of the Large Ensemble pre-industrial control simulation with CESM-CAM5.

Paleoclimate Working Group

Development

- Isotope-enabled CESM (iCESM)

The Paleoclimate Working Group development work has revolved around the implementation, spinup, and testing of water ($\delta^{18}O$, δD) and carbon (^{13}C, abiotic and biotic 14C) isotope tracers in the CESM component models. The implementations of the water isotope tracers have been completed for CAM5, CLM4, POP2, and RTM and are being tested and tuned in both uncoupled and coupled simulations. The implementation into CICE4 is ongoing and the porting, testing, and validation of stable water isotope code from CLM4 to CLM4.5 will start this fall. The implementations of the carbon isotope tracers have been completed for POP2, POP2-BGC, and CLM4.5. Results from the first simulations with these new isotope tracers have been presented at numerous meetings and the CESM tutorial and are currently being written up for publication.

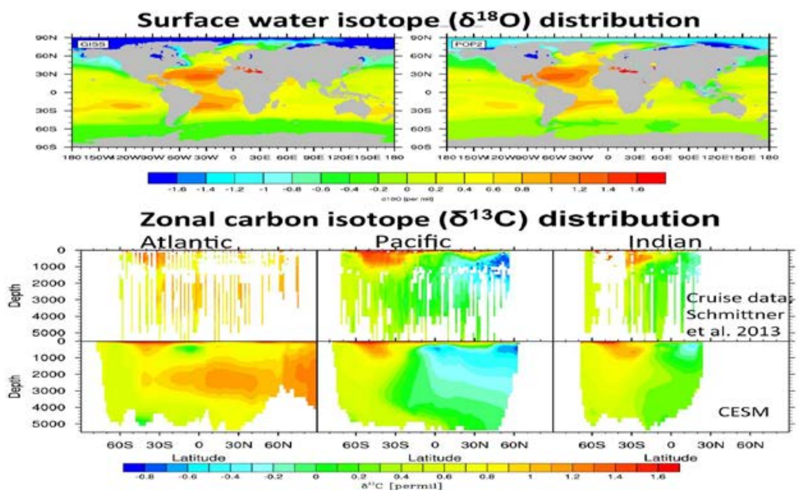

Figure: Both water and carbon isotope simulations show good agreement with observations. The water isotope simulation is from a fully coupled run, with water isotopes in the atmosphere and ocean. The carbon isotope simulation is from an ocean-only (C-compset) simulation.

Production

- DECK runs

We have completed the additional CMIP6 DECK (Diagnosis, Evaluation, and Characterization of Klima) simulations (PI, abrupt 4xCO2, ramped 1% CO2) that correspond to the Last Millennium CESM(CAM5) configuration and resolution as a prerequisite to submitting the Last Millennium Ensemble to the CMIP6 archive. These DECK runs will be posted on the ESG and released this December along with the Last Millennium ensemble runs.CESM-CISM simulationsWe completed a PMIP3-LIG time slice simulation for 128 thousand years ago. This simulation used CESM(CAM5)-1 degree coupled to CISM1 (one-way coupling; no feedbacks of ice sheet changes on CESM). This experiment had promising results with strong warming in northern Greenland and reduced ice thickness over all but central Greenland. The capability of two-way coupling of CESM(CAM5) and CISM1 became available for testing this summer and is currently being evaluated for the LIG and the mid-Pliocene (3 million years ago).

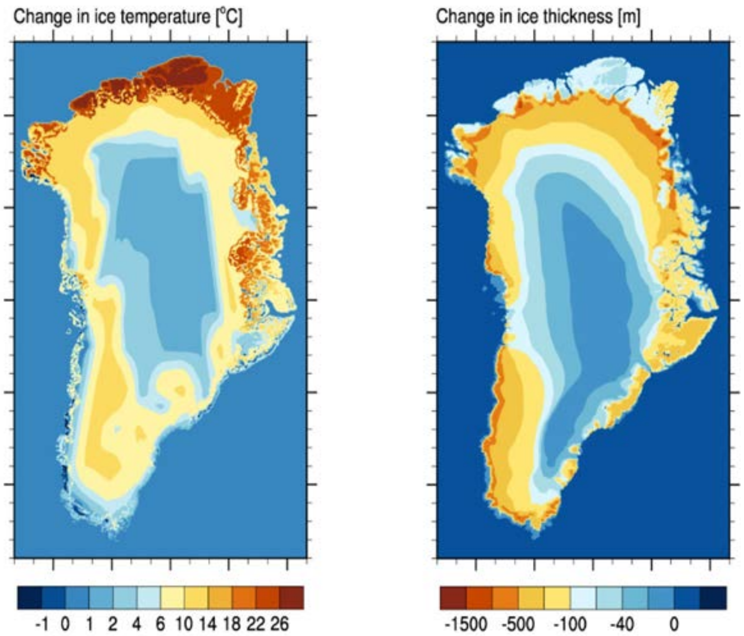

Figure: Changes in Greenland ice sheet temperature and thickness for LIG orbital forcing as compared to Preindustrial as simulated by CESM coupled one-way to CISM1.

- PlioMIP

We postponed additional PlioMIP simulations until the PlioMIP2 time-slice protocols are released at the end of 2014. As PlioMIP2 will include a preferred paleogeography that diverges from modern, with a closed Bering Strait and the West Antarctic Ice Shelf (WAIS) replaced by open ocean, we are completing a 500-year CCSM4 (0.9x1.25_gx1) PlioMIP1 sensitivity simulation with no WAIS. This simulation in conjunction with the already-completed standard PlioMIP1 experiment and a sensitivity simulation with the Bering Strait closed will allow evaluation of differences in paleogeography from modern that will need to be considered when assessing the PlioMIP2 simulations as an analogue for the future.

Polar Climate Working Group

Polar Climate Working Group simulations utilizing CSL resources from September 2012 to September 2014 have included both development and production experiments to improve the understanding of and model representation of high-latitude climate processes in CESM. Many of these activities are ongoing.

Development

- General sea ice model improvements – Efforts to improve the sea ice model in CESM CICE have focused mostly on merging and testing the latest version of the code (CICE5) and on assessing and fixing bugs. Simulations and analysis are ongoing.
- Influence of sub-grid scale sea ice heterogeneity on ocean mixing – We have examined the influence of sea ice heterogeneity on ocean mixing. Specifically, CSL resources have been used to modify the CESM to explicitly send the sub-gridscale fluxes to the ocean model and perform sub-grid ocean boundary layer depth calculations for each under-ice (and open-water) regime. Simulations and analysis are ongoing.
- Improved lidar simulator and Assessing Arctic cloud nucleation schemes – We have implemented and tested an improved version of the lidar simulator and evaluated different mixed-phase ice nucleation schemes. Analysis of these simulations has revealed that CESM1/CAM5 has

compensating biases between cloud albedo and surface snow albedo. Although the mixed-phase ice nucleation schemes improved surface climate, top-of-atmosphere fluxes remain due in part to an increase in high-level clouds. Results are summarized in English, J. M., Kay, J. E., Gettelman, A., Liu, X., Wang, Y., Zhang, Y. and H. Chepfer, (2014), Contributions of clouds, surface albedos, and mixed-phase ice nucleation schemes to Arctic radiation biases in CAM5, J. Climate, doi: http://dx.doi.org/10.1175/JCLI-D-13-00608.1

- Snow parameterization sensitivity experiments – Work utilizing previous PCWG CSL resources has shown the role of snow in modulating winter ice growth is an important element in accurate simulation of ice growth. During this CSL, we have performed experiments to assess the model sensitivity to parameter values that influence the properties of snow on sea ice. Results are summarized in Blazey, B. A., Holland, M. M., and Hunke, E. C. (2013): Arctic Ocean sea ice snow depth evaluation and bias sensitivity in CCSM, The Cryosphere, 7, 1887-1900, doi:10.5194/tc-7-1887-2013.

Production

- Influence of the cryosphere on radiative fluxes in CESM – We evaluated the instantaneous cryosphere shortwave radiative influence in CESM. We incorporated a diagnostic feature in the model that ascertained the contributions of sea ice, terrestrial snow, and glaciers in present-day climate, also considering the interaction with clouds on shortwave radiation. This study allowed us to compare model behavior with observational assessments, and enabled us to conduct a 100 year RCP8.5 scenario to evaluate the diminishing albedo feedback of a warming cryosphere. Results are summarized in: Perket, J., Flanner, M. G. and J. E. Kay (2014), Diagnosing Shortwave Cryosphere Radiative Effect and 21st Century Evolution in CESM, J. Geophys. Res., doi: 10.1002/2013JD021139
- Southern Ocean climate feedbacks – We ran simulations to identify processes controlling Southern Ocean (30–70°S) absorbed shortwave radiation (ASR) in CESM. Both sea ice loss and cloud liquid water content changes were found to be important. More broadly, thermodynamics (warming and near-surface stability), not poleward jet shifts, were found to control 21st century Southern Ocean shortwave climate feedbacks. Results are summarized in: Kay, J. E., B. Medeiros, Y.-T. Hwang, A. Gettelman, J. Perket, and M. G. Flanner (2014), Processes controlling Southern Ocean shortwave climate feedbacks in CESM, Geophys. Res. Lett., 41, doi:10.1002/2013GL058315.
- Sea ice predictability – We produced CESM seasonal outlooks for September sea ice. These are published online as a part of the Sea Ice Outlook at http://www.arcus.org/sipn/sea-ice-outlook. We have also performed sensitivity experiments in which we tested the dependence of perfect-model predictability on snow-on-sea ice cover in the Arctic. A manuscript on this research is in preparation. Finally, we assessed initial-value sea ice predictability within the context of the CESM large ensemble. This includes integrations to explore the influence of long-term sea ice loss and the role of ocean initialization on seasonal to interannual predictability characteristics of sea ice. These integrations are currently being analyzed.
- Complementary runs for the CESM large ensemble project (a cross working group community project) – Multi-century long model runs are needed to statistically characterize internal climate variability and the climate response to external forcing. Measuring internal climate variability is critical for climate change detection and attribution studies, especially for extreme events. PCWG CSL resources were used to extend CESM large ensemble members from 2081-2100 and to extend the 1850 coupled control simulation to 1000 years. Results are described in: Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J., Bates, S., Danabasoglu, G., Edwards, J., Holland, M. Kushner, P., Lamarque, J.-F., Lawrence, D., Lindsay, K., Middleton, A.,

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- The patterns of ocean heat uptake and changes in atmospheric circulations – We have investigated the interactions between oceanic circulations, ocean heat uptake, and atmospheric circulations in global warming scenarios. As a starting point, we alter the mixed-layer depth over Southern Ocean in the slab ocean version CESM to look at the global influence of Southern Ocean heat uptake. Our preliminary results show that the delayed warming over Southern Ocean has an effect on the changes in Southern Hemisphere storm tracks, the shift of tropical rain belt and the strength of Walker Circulation. Simulations and analysis are ongoing.

Societal Dimensions Working Group

Development

In the IAM area, simulations supported development of improved representations of land use and land cover change, relative to the representation used in CMIP5 experiments (Lawrence et al., 2012). The focus was on development of the representation of agriculture in the Community Land Model (CLM) in order to support the assessment of climate impacts on agriculture and land use. Six new crop types were added to CLM-crop, including tropical crops (filling a gap in the ability of CLM to be applied to global agriculture studies). Initial simulations were performed with CLM4.5 to evaluate crop yields for each crop globally. These simulations will be the basis of NCAR's contribution to the Agricultural Model Intercomparison and Improvement Project (AgMIP) over the next two years, in particular to its Global Gridded Crop Model Intercomparison (GGCMI). Computing time remaining in the IAM allocation will be used to continue AgMIP simulations.

Planned work on secondary and disturbed forests using CLM with Ecosystem Dynamics (ED) was postponed since ED did not become available in time. Instead, simulations investigated the differences between the biogeophysical and carbon/nitrogen cycle responses to land use and land cover change in CLM4 and CLM4.5, both offline and fully coupled. These runs were carried out with both Development and Production allocations for IAM-related simulations. Understanding these responses is critical to evaluating the conditions under which IAM-CESM coupling is important, and to anticipating what types of future land use scenarios are likely to lead to significant climate impacts. The simulations provided insight into systematic biases and behavior of both versions of CLM and were used to inform regional land cover change simulations that were carried out for Tropical, Temperate, Boreal and Global deforestation experiments as well as for Global afforestation experiments. The simulations were presented at a CMIP6 meeting at the Aspen Global Change Institute and will help inform the design of both Land Use and Scenario MIPs as part of CMIP6.

In the Water topic area, the simulations were aimed at improving CESM hydrology by reducing model uncertainty and bias. The SDWG simulations addressed three of the four priority areas are aligned with the recommendations outlined in the WUCA “Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change” (OICM) report. The first of the three focused on the development and enhancement of global climate model ensembles. The water utility industry requested a significant increase in number ensemble members for climate simulations in order to increase the confidence in the range of model predictions, particularly over the next 50 years. The CESM 8.5RCP Large Ensemble community project was able to complete its simulations without the use of the SDWG allocation, so this time was shifted to carrying out the 4.5RCP medium ensemble described below. The second involved improved use of observations to constrain climate model projections. The OICM assessment recommended developing and applying methods to use observations of past climate and the emerging climate change signal to narrow the range of climate model projections. In the absence of a proven climate data assimilation capability, the SDWG supported the Last Millennium Community Project through the support of two of the 1000+ year paleoclimate simulations. The Last Millennium ensemble study has been quite successful with 30 simulations completed for 850-2005AD with CESM1.1 at f19_g16 resolution. The SDWG provided the computing time for one full-forcing ensemble member that output at the temporal frequency required by WRF and other regional models. These simulations just finished and post-processing has started. Finally, the third experiment focused on improved seasonal and decadal prediction. The CMIP5 represented the start of a global coordinated effort to achieve climate prediction as part of the climate modeling capability. The SDWG enabled Joe Tribbia's group to carry seasonal (6 month) forecasts for every year, month sequence in the period 1981-2004 to determine forecast spread and model bias for these time scales as part of the larger NMME project. These are 1 degree, fully coupled runs from CESM1.2. The second part of this experiment will involve daily runs with additional output for broader community analysis. The high-resolution community simulations, designed to provide relevant hydroclimate variables for downscaling and decision-making, were merged with the precipitation validation production experiment goals and are described below.

Production

A substantial portion of the supplementary allocation of computing received by the SDWG in 2014 was used to contribute to the production of an ensemble of simulations of RCP4.5 in order to support work on avoided impacts as part of the project on Benefits of Reduced Anthropogenic Climate changE (BRACE) involving NCAR and seven university partners. The recently completed 10 member medium ensemble is an initial condition ensemble of RCP4.5 future simulations to act as a companion to the existing 30 member CESM Large Ensemble, which uses RCP8.5. A further 5 members are planned to be completed under the CVCWG allocation in the near future. The ensembles together provide a well sampled comparison between a high emission future and a moderate mitigation case. The new ensemble will allow both theoretical studies on the interaction of climate variability and the forced climate trajectory as well as societally relevant impact assessments which require a thorough sampling of internal variability in both mitigated and unmitigated futures.

The water production experiments focused on simulating the impacts of climate change on important precipitation hydrologic systems, namely American monsoon and droughts in the American southwest) and providing relevant hydroclimate variables for downscaling and decision-making. The second theme was initially proposed as a development activity. Discussions with SDWG water sector stakeholders representing the water utility industry and federal water agencies showed that there was little interest in the proposed CESM 1° simulations and they requested that high-resolution global and downscaled regional model simulations that better link the CESM climate model resolution to their decision scales. The initial high-resolution runs with the 0.25degree CAM show improved characteristics and mechanisms of resolution sensitivity of aerosol, cloud, and precipitation. While the transport climatology remains similar to the lower resolution simulations, much more realistic simulations of tropical cyclone numbers and filamentary structure of aerosol and precipitation in high-resolution simulation, producing extreme pollution and precipitation (atmospheric river) event of interest to water utility stakeholders. In place of the CESM 1° simulations, regional downscaled 4-km WRF simulations driven by CESM, are being run over the CONUS to examine how different climate scenarios affect the terrestrial water cycle, with attention given to the extremes of floods and droughts. These simulations add a climate perturbation signal to the ERA-interim reanalysis data to provide the initial and boundary conditions for the retrospective/control simulation. The climate change perturbations were obtained from two sets of the

CMIP5 multi-model ensemble (including 6 CESM members) mean monthly fields. One is over 1970-1999 of the 20th century experiments, and the other over 2070-2099 of the RCP8.5 emission scenario experiments. These simulations are in progress at this time.

Software Engineering Working Group

During the past CSL proposal cycle starting in 2012, the CESM development allocation was used to successfully produce the following 11 CESM model releases to the user community:

- CESM 1.0.z series – code base used for the CMIP5 simulations
    - CESM 1.0.4 - February 2012;
    - CESM 1.0.5 - February 2013 (added support for Yellowstone);
    - CESM 1.0.6 - May 2014
- CESM 1.1.z series - introduced new infrastructure support for component sets and resolutions
    - CESM 1.1.0 - November 2012
    - CESM 1.1.1 - February 2013 - added support for Yellowstone
    - CESM 1.1.2 - July 2013
- CESM 1.2.z series - targeting new development versions leading to CESM2, in particular support for CLM4.5 and CAM5-spectral element
    - CESM 1.2.0 - June 2013
    - CESM 1.2.1 - December 2013
    - CESM 1.2.2 - June 2014
- Special release versions only supported on Yellowstone for these specific community projects
    - CESM1_1_2_LENS - Large Ensemble Community Project special release
    - CESM1_1_2_LM - Last Millennium Community Project special release

These releases account for out-ofthe-box support for new computational platforms, bug fixes, and new support for model configurations, both for the CMIP5 release code base and for new development versions. Extensive testing was required for all the development versions leading up these releases.

The allocation was also utilized to bring many new capabilities into the model system, resulting in numerous new development versions of the system. The scripts and associated testing framework continued to be expanded in order to provide both expert and novice CESM users with the ability to create numerous out-of-the box experiments that utilized the new model capabilities and at the same time could easily be load balanced in order to run both efficiently and with optimal throughput on Yellowstone. The allocation was also used to continue the expansion of support for new CESM model grids (particularly refined spectral element grids and MPAS grids) within the system and to target the support for much higher resolution model grids.

Development cycles were utilized to create a new statistical verification methodology to rapidly verify if model software or compiler changes resulted in a new model climate. Whereas past verification techniques required multi-century coupled simulations, we have introduced a much less costly and parallelizable code verification technique based on an ensemble-based statistical approach which requires only short integrations of the model. We have used CSL development resources to create and routinely test this methodology on each new model snapshot, as well as continuing to develop a more rigorous selection of fields to examine that are most likely to be sensitive to model departures. Moreover, this utility is also being leveraged to determine if lossy data compression algorithms, which significantly reduce the volume of output simulation data, are acceptable for routine production simulations.

The CSL SEWG development allocation is currently being leveraged to incorporate major science and infrastructure changes across the CESM system as part of constructing intermediate development versions leading to CESM2. Each model snapshot that is created along the way will require hundreds of system tests in order to ensure model robustness and also as well as to determine the optimal processor layout for various new scientific configurations that will be supported.

Whole Atmosphere Working Group

In the previous development cycle WACCM had several major accomplishments. On the production side, WACCM participated in several model intercomparison projects (MIPs). These included specific projects for stratospheric and tropospheric chemistry, solar variability and geoengineering as well as also contributing to the general CMIP5 climate assessment process. On the development side, WACCM continued development of the solar physics version of the model (WACCM-X) development of new detailed physics (WACCM-CARMA) and simplified and efficient chemistry (WACCM-SC) versions of the model. These activities with references are listed below.

Production

WACCM Participation in MIPs: In the past 2 years WACCM has been used in several different MIP projects. WACCM is a significant part of the Chemistry Climate Model Initiative (CCMI), the outgrowth of the CCMVal model intercomparison project for the stratosphere. WACCM is now run routinely with a coupled ocean/ice and with full stratospheric and tropospheric chemistry. CCMI delivered its first set of simulations in 2014. As a complement to CCMI, WACCM was part of the SPARC lifetimes assessment of long lived species in the stratosphere, such as Chloro-fluorocarbons (CFCs). WACCM also participated in SOLARIS, an intercomparison of models to understand the solar cycle, and in GeoMIP, a project to understand the impacts of 'geo-engineered' stratospheric sulfate.

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Development

WACCM-X for Solar Physics: WACCM now has a version that extends up to 500km (standard WACCM top is 140km, standard CAM top is 60km). Extending a model up to the thermosphere has been an ongoing task. WACCM-X was released to the community in the last CSL cycle. Initial development of ionospheric physics has been completed. WACCM-X has been coupled to the SE dynamical core and has been used for high resolution experiments to explore how the upper atmosphere is forced by waves from the lower atmosphere.

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WACCM-CARMA advanced aerosol physics: WACCM also includes options for a detailed treatment of aerosol microphysics, which has been used for a variety of studies of the importance of particulates in the upper atmosphere. These include ongoing work on stratospheric sulfur impacts, as well as explorations of dust, particulates from meteors (and the general effects of meteor impacts on climate) and detailed ice nucleation on cirrus clouds.

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Specified Chemistry WACCM (SC-WACCM): A version of WACCM with simplified chemistry (specified chemistry) has been developed to enable efficient studies of stratospheric and mesospheric dynamics. This model version has been extensively evaluated against the full version of WACCM.

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