CESM

Community Earth System Model

CSL Accomplishments Report
(4/1/11 – 6/30/12)

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Atmosphere Model Working Group

The Atmosphere Model Working Group (AMWG) has continued to utilize CSL resources for climate model development, assessment of physical and dynamical atmospheric processes and increasing model resolution for regional climate science. Simulations using these resources have led to significant accomplishments in atmosphere modeling. Chief among these accomplishments is the advancement of the latest version of the Community Atmosphere Model, version 5 (CAM5). A version of the model was finalized for use in simulations to be submitted to the CMIP5 project. This included numerous climate simulations with the final CAM5.1 version of the model physics and at 1° resolution. The atmosphere and coupled simulations from this configuration represent a significant improvement compared to both equivalent CAM4 simulations and lower resolution 2° simulations. The combination of new loud-aerosol-radiation process representations in CAM5 and the increased horizontal resolution leads to the most skilled reproduction of the observed 20th century global temperature record of any current versions or predecessors of CESM.

Global high resolution simulations resolving grid-scales of 25 km have been tested using CAM5 and show many realistic characteristics in the simulation of high impact weather. Simulated Atlantic tropical cyclones exhibit realistic vertical structures, storm tracks and distribution of storm strengths, including category 5 storms. Importantly, for climate change applications, inter-annual storm number counts vary in agreement with observations. The potential role of condensate loading, a previously ignored effect in CAM, has been shown to have a significant impact in high resolution simulations. In response, a condensate loading scheme has been implemented into the CAM finite volume dynamical core which decreased average tropical cyclone storm strengths, but reduced the number of spurious high-precipitation grid-scale events.

Proposed new model configurations for a 2012 release have been significantly advanced toward that goal. Firstly, a version of CAM5 that employs a prescribed version of the Modal Aerosol Model (MAM) reduces the relatively expensive computational cost of CAM5 by a factor of two. Many of the desirable improvements in the climate simulation seen in predicted aerosol version of CAM5 are retained and so ultimately this development will enable CESM users with limited resources to use the most scientifically advanced version of CAM. Secondly, long control coupled integrations of CAM5 using the computationally scalable spectral element dynamical core (CAM-SE) produce a climate that is comparable to CAM5 simulations with the CMIP5 version of CAM5. Using the CAM5-SE configuration the specification of the orography surface boundary conditions has also been completely rewritten in order to more robustly partition resolved and sub-grid scales at any particular resolution. This will be a particularly important new functionality for alternate dynamical core computation grids and regionally refined resolution global simulation grids. CAM5 and WACCM climate simulations show significant sensitivity to the specification of sub-grid scales due to the gravity wave drag and turbulent mountain stress parameterizations and being able to correctly specify the transfer of orographic scales from the sub-grid to the resolved scales as resolution increases is an important achievement.

Significant progress has been made on the implementation of a number of improvements to the representation of physical processes in CAM. The cutting edge UNIfied CONvection Scheme (UNICON) is now fully implemented in CAM and AMWG plans to replace the existing separate deep and shallow convection parameterization schemes in a future model version. UNICON is a unique achievement in CAM. Developed from first principles it represents the entirety of unresolved moist asymmetric turbulence from the earth's surface to the tropopause. Most importantly it will replace the robust, but ageing Zhang McFarlane deep convection scheme, with the capability of working more continuously across the large range of current and potential future CAM grid resolutions. Additional new physical representations have been implemented in CAM and progressed to the point of providing viable climate simulations. The Cloud Layers Unified By Binormals (CLUBB) is an assumed PDF method designed to represent both dry and moist turbulence in the atmosphere. It has the potential to replace major components of the existing physical parameterizations including the boundary layer, shallow convection and large-scale cloud, in a more unified framework.

The existing CAM5 physics representations have also been further developed and validated. The Morrison Gettelman (MG) microphysics is now provided with a more robust and portable code structure. This has enabled it to be more easily ported to alternate climate model codes. It is currently implemented or being implemented in several other IPCC class atmosphere models including the GFDL and NASA-GEOS models. More recent ice nucleation parameterizations have been added to CAM5 and the uncertainties of ice clouds and radiative forcing determined. Upper tropospheric temperature and humidity distributions remain some concern in CAM5, but a comprehensive evaluation of cirrus cloud properties based on available observations has led to improved implementation methodologies using the MG microphysics.

Progress has been made in analyzing the differences in mean climate and sensitivity between CAM4 and CAM5 model versions. Climate sensitivity and cloud feedback analysis show that changes in cloud frequency of occurrence and microphysical states in mid-latitude regions can account for the major difference in climate sensitivity. The full implementation of the CFMIP Observational Simulator Package (COSP) has enabled a more robust evaluation of cloud properties in CAM based on remote instrument simulator diagnostic forward models that are now integral to the model code. COSP analysis of climate simulations clearly shows the variation of global cloud occurrence frequency and optical depth is more realistic in CAM5. The COSP diagnosis capability will be a more reliable tool for future CAM model development and analysis than existing diagnostic interpretations of remotely sensed cloud properties.

Initialized CAM hindcast simulations based on the Cloud-Associated Parameterization Testbed (CAPT) have provided significant insight into the mechanisms of the CAM physics. Stratocumulus cloud simulations are much improved in CAM5 and they no longer exhibit the pervasive low cloud-base characteristics seen in CAM4. In the hindcasts this is clearly seen as a rapid collapse of cloud base and an unrealistic separation of the centers of cloud condensate and cloud fraction with time. With CAM5 realistically initialized states are more readily retained with time, implying the mean climate simulations are representing stratocumulus cloud more realistically. Dependencies of physical parameterization timescales and timesteps have also been shown to be significant in high-resolution CAPT hindcasts. This continuing activity shows the importance of these dependencies on spurious near grid-scale circulations that occasionally lead to unrealistically intense precipitation rates and vertical velocities.

Finally, experiments that extend application capabilities in CAM have been very successful, leading to new research efforts. This includes the impact of aircraft contrail emissions on local cloud fields and ultimately its net impact on the on the local and global radiation budget as well geo-engineering sensitivity experiments via the injection of aerosol particles into the lower stratosphere.

Biogeochemistry Working Group

Biogeochemistry working group made several accomplishments using CSL computing resources. The primary accomplishments fall into the following four categories: coupled carbon-climate model sensitivity experiments; ocean biogeochemical development; the incorporation of a new prognostic wildfire scheme into CLMCN; and land cover change sensitivity experiments.

The first category of experiments were RCP and 1% CO_2 ramping experiments that were performed to satisfy our obligations related to our participation in CMIP5 and to help us analyze carbon-climate feedbacks. These experiments are currently being analyzed for conference presentations and manuscript preparation and submission.

The ocean biogeochemical development experiments have focused on incorporating ocean acidification feedbacks and exploring fast spinup techniques.

The prognostic wildfire parameterization development focused on the implementation of a new fire parameterization in CLMCN and its effects on the carbon cycle. The new parameterization includes human management influences on wildfires, especially human ignition of fires during land clearing and slash-and-burn agriculture. The parameterization had been developed and tested in another model, and the current project examined parameterization behavior in CLMCN.

The land cover change sensitivity experiments examined the effects of land cover change on the carbon cycle and climate. One set of experiments looked at land use carbon emission for the RCPs, compared the simulated CLMCN land use emission to independent estimates provided for each RCP, and devised model changes to correct deficiencies in the simulations. A second set of experiments examined the sensitivity of climate to imposed land cover change for pre-industrial and present-day. These experiments complimented previous such simulations using CAM3.5 and CLM3.5

The above experiments have been performed in the first 9 months out of the 15 month allocation period. Experiments that we anticipate running in the remainder of the allocation period include: initial coupled experiments with the CESM1-(CAM5,BGC) configuration; additional 20C and RCP coupled experiments to facilitate further feedback analysis of the BGC CMIP experiments; and further ocean biogeochemical development focused on incorporating improved remineralization schemes to reduce our oxygen minimum zone bias, ocean acidification feedbacks, and fast spinup techniques.

Chemistry Climate Working Group

The main accomplishments from the Chemistry-Climate Working Group under the CSL Science allocation can be summarized as:

- CAM-chem development, release and documentation

CAM-chem, as implemented in CAM4, is now available in the released CESM. This version can use the online meteorology or the specified dynamics (using analyses from meteorological centers, NASA GMAO in particular). In addition, tropospheric and tropospheric-stratospheric chemistry packages are released and documented in Lamarque, J.-F et al. CAM-chem: description and evaluation of interactive atmospheric chemistry in CESM. *Geosci. Mod. Dev. Discuss*., 4, 1–80, 2011. This model was also used in Hess, P. G. and Zbinden, R.. Stratospheric impact on tropospheric ozone variability and trends: 1990–2009, *Atmos. Chem. Phys. Discuss*., 11, 22719-22770, doi:10.5194/acpd-11-22719-2011.

- Simulations in support of IPCC AR5

  In order to define the evolution (1850-2100, all RCPs) of atmospheric composition, nitrogen deposition and dust and black carbon deposition on snow/ice, we have performed CAM-chem simulations with tropospheric and stratospheric chemistry, driven by CCSM3 simulations. All these are discussed in Lamarque et al. Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.*, 10, doi:10.5194/acp-10-7017-2010, 7017-7039, 2010 and Lamarque et al. Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. *Climatic Change*, doi:10.1007/s10584-011-0155-0, 2011. In addition, in collaboration with P. Cameron-Smith (Lawrence Livermore National Lab), M. Prather (UC Irvine) and P. Hess (Cornell), we have performed 3 1850-2005 CESM simulations with interactive chemistry (superfast chemistry). This will be discussed in a paper led by P. Cameron-Smith.

- Simulations in support of GeoMIP and ACCMIP

  In support of the Geo-engineering Model Intercomparison and Atmospheric Chemistry and Climate Model Intercomparison Projects (both in support of IPCC AR5), the Chemistry-Climate working group has performed a variety of simulations (CAM-chem and CCSM4). These simulations are being analyzed and will be used in a variety of publications.

- Halogen chemistry

  In collaboration with A. Saiz-Lopez (Toledo, Spain), we have developed a version of CAM-chem with a full representation of halogen chemistry (Bromine, Chlorine and Iodine) for the troposphere. Results from those simulations are discussed in Ordóñez, C et al. Bromine and iodine chemistry in a global chemistry-climate model: Description and evaluation of very short-lived oceanic sources. *Atmos. Chem. Phys*. *Discuss*., 11, 27421-27474, 2011 and Saiz-Lopez, A. et al., Estimating the climate significance of halogen-driven ozone loss in the tropical marine troposphere. *Atmos. Chem. Phys*. *Discuss*., 11, 32003-32029, 2011.

Climate Change Working Group

Model runs for the Geoengineering Model Intercomparison Project (GeoMIP)

During 2011 several geo-engineering experiments (solar reduction and emissions of sulfate in the lower stratosphere) were performed under the GeoMIP (Geoengineering Model Intercomparison Project) umbrella, organized by A. Robock (Rutgers). We started with 1deg CAM4 simulations, which are complementary to Phil Rasch's simulations with CAM5 physics. The following GeoMIP experiments were performed with 0.9x1.25° B-case CAM4. These simulations do not include any chemistry:

- 1850 4xCO2 baseline experiment, 1 ensemble, 50 years
- 1850 4xCO2 solar dimming, 2 ensembles, each 75 years
- 1850 1%CO2 ramp-up, 1 ensemble, 50 years
- 1850 1%CO2 ramp-up solar dimming, 2 ensemble, each 70 years
- RCP4.5 G3solar, 3 ensembles, each 70years (2020-2090)

A second set of experiments include tropospheric and stratospheric chemistry and are designed to investigate the impact of solar dimming on stratospheric and tropospheric chemistry and climate for future atmospheric conditions. The experiments are complementary to RCP4.5 G3 solar experiments (above). The following GeoMIP experiments were performed with 0.9x1.25° B-case CAM4Chem trop/Mozart:

- RCP4.5 background, 3 ensembles, each 70 years, ongoing
- RCP4.5 3G solar, 3 ensembles, each 70 years, ongoing

All experiment results will be submitted to the GeoMIP data base.

Model runs to study the impact on the Southern Annular Mode (SAM) of increasing CO2

Perturbation experiments with the CAM3 and CAM4 were undertaken and established that the poleward shift in the Southern Annular Mode (SAM) under future climate change can be driven by both tropical and extratropical SST changes. This is in contrast to results from previous research and with the ACCESS model where increasing tropical SSTs led to an equatorward shift in the SAM and Southern Hemisphere jet. These results were presented at the IUGG (June 2011) and WCRP Open Science Conference (October 2011). Additional experiments with atmospheric heating are underway to understand the mechanisms behind these model differences.

Complete the full suite of CMIP5 experiments

The CVCWG completed NCAR's core CMIP5 experiments, by completing the following simulations:

- The fixed SST 1xCO_2 (150 years)
- The fixed SST 4xCO_2 (150 years)
- Contribution to a set of large ensembles with CCSM4 - simulations run from 2006 to 2100 using forcings defined by the RCPs

Results from the full set of CMIP5 experiments with CCSM4 have been described in a number of the CCCM4 special collection papers, and have included, for example, two papers on the monsoon circulations in CCSM4, a paper on possible future changes to ENSO, several papers looking at aspects of climate sensitivity and high latitude climate change, and an overview paper presenting results from the CCSM4 CMIP5 climate change experiments. From that latter paper, it was shown that by following the

RCP2.5 scenario, the lowest of the four new RCP scenarios run with CCSM4, global warming is kept below 2C above pre-industrial values, a widely cited goal to avoid the most serious impacts associated with climate change. Thus, with aggressive mitigation, global warming can be stabilized, compared to less aggressive mitigation scenarios such as the high scenario RCP8.5 where warming is ongoing and large. Other features of the climate system response to increasing GHGs in the RCP scenarios were shown in CCSM4, such as the future behavior of the meridional overturning circulation (MOC). It weakens with increasing CO_2 at the end of the 20th century and early 21st century, mostly recovers by 2200 in the lower RCP scenarios, but eventually mostly dies out in the high scenario (RCP8.5) after 2200 and shows no signs of recovering at 2300 (see Figure 1).

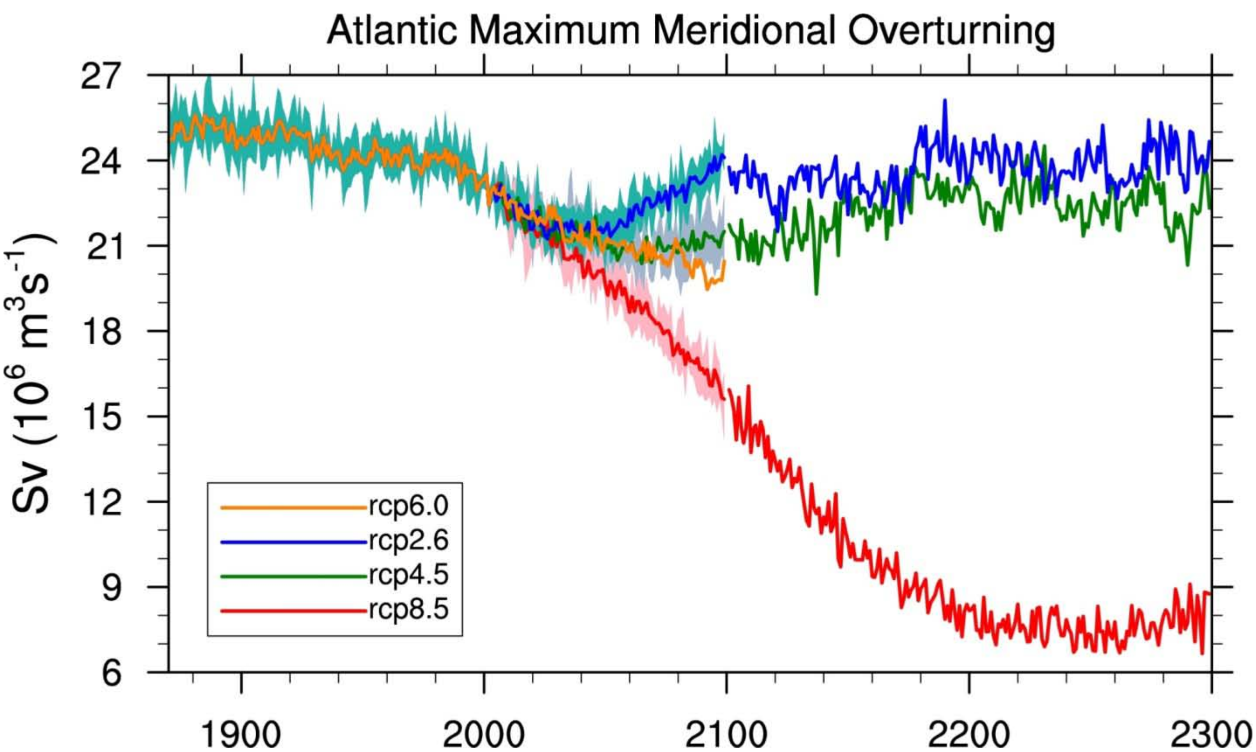

Figure 1.

Climate Variability Working Group

A major accomplishment of the Climate Variability Working Group during the CSL allocation period Dec 2010 – Jun 2012 was the completion of four manuscripts for the *Journal of Climate* CCSM4 Issue, all of which are now in press. These include:

"Tropical Atlantic Oceanic Variability in the CCSM4" by Munoz, E., W. Weijer, I. Wainer, S. Grodsky, M. Goes, and S. C. Bates.

"*ENSO and Pacific Decadal Variability in Community Climate System Model Version 4"* by Deser, C., A. S. Phillips, R. A. Tomas, Y. Okumura, M. A. Alexander, A. Capotondi, J. D. Scott, Y. -O. Kwon, and M. Ohba.

"Will there be a Significant Change to El Nino in the 21st Century?" by Stevenson, S., B. Fox-Kemper, M. Jochum, R. Neale, C. Deser, and G. Meehl.

"The Madden Julian Oscillation in CCSM4" by Subramanian, A. C., M. Jochum, A. J. Miller, R. B. Neale, and D. E. Waliser.

Additional accomplishments include the CAM4 (1 degree configuration) simulations outlined in the CVWG CSL proposal, many of which are still in progress. Specifically: a 500-year integration of CAM4 (1 degree configuration) coupled to the Slab Ocean Model (SOM) for investigation of climate variations due exclusively to thermodynamic air-sea interaction; 5 member ensembles of AMIP-style integrations with observed time-varying SSTs during 1900-2010 prescribed globally, prescribed within the tropics only (and climatological SSTs elsewhere or coupled to the SOM elsewhere), and prescribed within the tropical eastern Pacific ocean only and coupled to the SOM elsewhere. One additional AMIP-style integration was a 5-member ensemble with CAM3 at T42 resolution with observed sea ice concentrations prescribed during 1979-2010 for investigation of the atmospheric/climate response to observed Arctic sea ice conditions. All of the integrations listed above are available to the community through the Climate Variability Working Group web page and the ESG.

Land Ice Working Group

- *Surface mass balance of the Greenland ice sheet: CMIP5 simulations with CESM*

Miren Vizcaíno (Utrecht Univ.) has tested CESM's new ice-sheet component by performing three long simulations: pre-industrial, 20th century, and RCP 8.5. These are BG simulations (fully coupled, including a dynamic Greenland ice sheet) with an interactive carbon cycle. Coupling between CLM and CISM is one-way; that is, CLM computes the ice-sheet surface mass balance (SMB) used to force CISM, but CLM's surface topography and landcover types do not evolve. The grid resolution is 0.9x1.25^{o} for the land/atmosphere and 1^{o} for the ocean/sea ice. The SMB is computed for 10 elevation classes in CLM and then downscaled to the 5-km ice-sheet grid. The glacier mask and topography in CLM were recently improved by replacing the original dataset by data from Bamber et al. (2001). To spin up the carbon cycle and the CLM glacier snowpack, we blended output from a B1850 run with output from an IG1850 run forced by atmospheric data from the 1° CCSM4 pre-industrial control (MOAR).

The simulated surface mass balance for the Greenland ice sheet during 1850-2005 is 404±115 Gt yr^{-1}. Figure 1 shows the time series of integrated SMB. A linear fit of the data gives a trend of -0.48 Gt yr^{-2}; the trend pattern is shown also in Figure 1. The net SMB becomes more positive in the accumulation area as a result of increased snowfall, but becomes more negative in most of the ablation area because of increased summer melting. The simulated SMB for 1958-2005 is 400±120 Gt yr^{-1}, which compares well with estimates from regional models (e.g.,RACMO, 1958-2007, 469±41 Gt yr^{-1}, Ettema et al. 2009). Figure 2 compares the surface mass balance maps for CESM and RACMO. The location and width of ablation zones are well captured by CESM. We are now analyzing results from the recently completed RCP8.5 simulation.

- *Validation of the Community Ice Sheet Model (CISM)*

Charles Jackson and Gail Gutowski (Univ. of Texas) have worked on testing CISM as a component of CESM. The goal has been exercise the code and to initialize and validate the model with CESM preindustrial climate, so that CISM can be used for a variety of science applications. This is one of the first attempts to couple a dynamic ice sheet model to a climate model using a surface-energy-balance scheme (rather than a positive-degree-day method) to compute the ice-sheet SMB. Working with LIWG software engineer William Sacks and others from NCAR, we have resolved a number of technical issues. For example, we have (1) defined a model grid that is consistent among CESM, CISM, and boundary condition fields being used by the SeaRISE sea-level assessment project, (2) implemented an IG configuration procedure using 3-hourly pre-industrial MOAR data to estimate the SMB in different elevation classes, and (3) created a standalone "TG" configuration of CESM that allows the ice-sheet model to be forced with previously generated SMB data. With the TG configuration we have reduced the coupling frequency to 1x a year, decreasing the simulation time by orders of magnitude and allowing multi-millennial ice-sheet integrations. We then began testing various combinations of model parameters (in particular, basal traction and internal viscosity) to determine a configuration that optimizes the steady-state simulation of the Greenland ice sheet when forced with a surface mass balance from CLM. We are now working on branching CISM integrations so that we can integrate CISM longer than the 9999-year CESM time limit. These validation studies will continue through summer 2012.

References

Bamber, J. L., S. Ekholm, and W. B. Krabill (2001), A new, high-resolution digital elevation model of Greenland fully validated with airborne altimeter data, *J. Geophys. Res.*, **106**, 6733–6745.

Ettema, J., M. R. van den Broeke, E. van Meijgaard, W. J. van de Berg, J. L. Bamber, J. E. Box, and R. C. Bales (2009), Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, *Geophys. Res. Lett.*, **36**, L12501, doi:10.1029/2009GL038110.

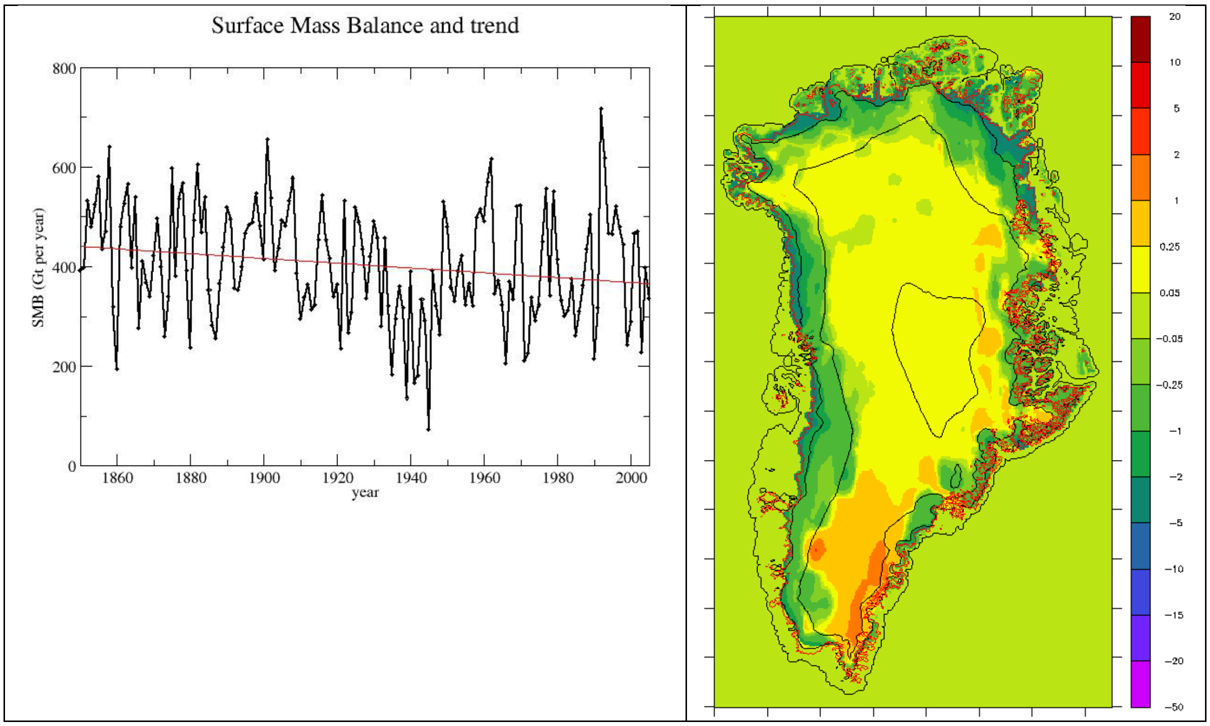

Figure 1. Left: Integrated surface mass balance (Gt yr-1) and trend (red line) for the Greenland ice sheet. Right: Map of the trend for 1850-2005 (mm yr^{-2}).

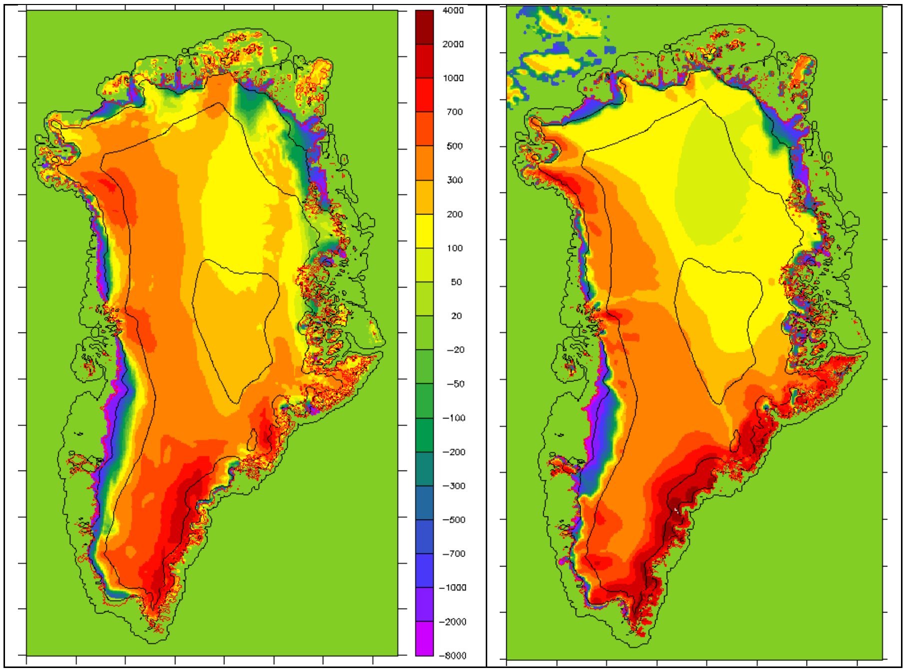

Figure 2. Surface mass balance (mm yr^{-1}) of the Greenland ice sheet as simulated by CESM (left) and RACMO (right) for the periods 1958-2005 and 1958-2008, respectively.

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 development of CLM4.5. Since CESM1 and CLM4 were released, several model development projects have been conducted that were aimed at reducing biases seen in CLM4 or at introducing new functionality that was not completely ready for CLM4. CLM4.5 will represent a significant advance over CLM4. Model parameterization development and improvement and new capability activities undertaken during this CSL period include

- Vegetation processes - photosynthesis and canopy radiation, including multilayer canopy radiation
- Cold region hydrology - ice impedance, new snow cover fraction parameterization, perched water table
- Soil biogeochemistry - vertically resolved soil carbon and nitrogen pools and revised lake and crop models.
- Methane emissions from wetlands
- Prognostic wetland distribution and surface water store
- Dynamic landunits
- High resolution capabilities – high resolution input datasets and testing, high resolution River Transport Model
- Ecosystem Demography - dynamic vegetation approach that is a statistical approximation of an individual-based forest simulation model

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. Participation in the TRENDY land carbon model intercomparison project. 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.
- 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.
- Crop-climate interactions - CAM4/CLM4CNcrop simulations documenting influence of interactive crop management on both biogeophysical and biogeochemical land-atmosphere interactions.
- Vegetation phenology – Assessment of trends in phenological events such as the onset of the growing season and autumn senescence and a changing Arctic climate. Preliminary results indicate that in the 20th century, several Arctic regions have seen a statistically significant increase of half a day per decade in the autumn senescence date and an increase of almost a day per decade in growing season length. In 21st century climate projections, the onset of the growing season advances by nearly one day per decade, the autumn senescence date is delayed by almost two days per decade, and the overall growing season increases by almost three days per decade.
- TRENDY MIP project – model intercomparison studies of global and regional carbon cycle response to historic climate change, CO_2 fertilization, and land cover/land use change.

Ocean Model Working Group

In support of our model development activities, the OMWG completed the implementation and testing of a new near inertial wave mixing parameterization as well as a new parameterization that considers the effects of sea-ice heterogeneity on ocean vertical mixing. Both of these parameterizations were developed in collaboration with the university community as part of our working group's Climate Process Team activities. Preliminary simulations with both show some modest improvements in model solutions in comparison with observations. Also, implementation of an anisotropic formulation for mesoscale eddies has been progressing. We used some resources to verify the successful code separation of the mesoscale and submesoscale parameterizations.

The OMWG continued to maintain and extend the Coordinated Ocean-ice Reference Experiments (COREs) interannually varying atmospheric forcing data sets. These data are now internationally used to force ocean – sea-ice coupled simulations. In particular, we extended the data to the end of 2007, incorporated some new corrections, and included an interannual river runoff data set. We conducted various experiments to test the new data sets and produced ocean and sea-ice solutions for community use. Moreover, in response to the OMWG community requests, we created a new component set that uses these interannual data as an out-of-the-box CESM configuration for ocean-only or ocean – sea-ice simulations.

We performed a set of exploratory ocean – sea-ice coupled simulations to assess the impacts of some mesoscale and vertical mixing parameters on ocean ventilation and boundary layer depths. This work is aimed at addressing low ventilation and shallow boundary layer depth biases of our model simulations, particularly evident in ideal age, oxygen, and carbon fields. This work is still ongoing.

We continued to support and improve the ocean data assimilation work. For expedited completion of some of the decadal prediction simulations for the 2000-2005 period, we used some of our computational resources to perform ocean data assimilation so that ocean initial conditions could be provided for these decadal prediction simulations. This is work in collaboration with the Data Assimilation Research Testbed of CISL. In addition, these simulations represent CESM's contributions to the CMIP5 decadal prediction simulations.

Finally, we note that the studies with the Regional Ocean Modeling System (ROMS) have also been progressing with some preliminary integrations. A new version of the ROMS has been created for the coral triangle region and very initial tests are underway.

Paleoclimate Working Group

Paleoclimate Working Group simulations have included experiments to test new isotope and geotracer capabilities in the CESM ocean model, to develop a bulk aerosol parameterization for pre-Quaternary simulations, to provide appropriate temporal resolution history files for regional modeling, and to understand the climate system functioning under changed past forcings. These are outlined below.

- Sea-ice-modulated ideal age in POP2
  A modified IAGE (which we named VAGE) module has been developed and tested for paleoclimate simulations. IAGE in POP2 is set to zero at the surface regardless of whether sea ice exists or not, which is unrealistic and causes inconsistency with observations in paleoclimate simulations.VAGE, however, is not reset whenunder sea ice. Results show that VAGE is very sensitive to the setup of surface horizontal mixing time scale.

- Implementation of water isotope tracers in POP2
  The first benchmark for implementation of water isotope tracers in POP2 has been successfully completed. A new passive tracer module for $\delta^{18}O$ has been tested using the GISS $\delta^{18}O$ data as the surface-restoring field. The POP2 results compare well to the full 3D GISS dataset. This water tracer module is now being tested with more realistic forcing using isotopic water fluxes from an isotope-enabled CAM. The next step is to extend the tracer to δD and couple to an isotopic-enabled CAM5.

- Bulk aerosol prescription for pre-Quaternary simulations
  Development work was completed to test and evaluate a new, realistic methodology for deep time paleoclimate aerosol prescriptions. This technique includes running the bulk aerosol model (BAM) package in CAM.

- Extension of CMIP5 simulations for regional modeling applications
  High temporal resolution MOAR simulations were completed for the last 30 years of the CCSM4 (**0.9x1.25_gx1)**CMIP5 LGM and Mid-Holocene simulations. These simulations provide the model data needed for community users to force regional models such as WRF.

- Pre-Quaternary simulations
  A high-resolution PETM (Palocene-Eocene Thermal Maximum, 55Ma) atmosphere-only simulation was completed using the finite volume, half-degree (0.47x0.63) configuration of CAM4. The model was forced with sea surface temperature data interpolated from a previously completed fully coupled CCSM3 (T31x3) PETM experiment. A fully coupled CCSM4 Permian/Triassic low-resolution simulation (T31x3) was alsocompleted.

- PlioMIP simulations
  Two 500-year CCSM4 (0.9x1.25_gx1) mid-Pliocene (3 million years ago) simulations have been completed: the standard PlioMIP experiment plus an additional simulation with the Bering Strait closed (suggested by some geological evidence). PlioMIP is designed to explore feedback mechanisms that may have contributed to the significantly warmer temperatures in the North Atlantic and Arctic and smaller polar ice sheets suggested by the data. In addition to CESM, nine modeling groups are participating in PlioMIP.

- PMIP3 Last Interglacial(LIG) simulations
  As part of the PMIP3, a series of CCSM3 T85x1 simulations were extended to 350 years for three intervals in the last interglacial period: 130ka (with and without a West Antarctic Ice Sheet), 125ka, and 120ka (ka: kyrs before present). These simulations are allowing us to compare models in their responses at high-latitudes to the orbital obliquity maximum (130ka) and near precession optimum for ITCZ shift, ENSO and tropical monsoons (*125ka*).These experiments also form the basis for our proposed CSL transient simulation of the LIG.

- Atlantic Meridional Overturning Circulation (AMOC) evolution

  Simulations were completed with CCSM3 to understand the impact of North Atlantic – GIN Sea exchange on the AMOC's deglacial evolution. Results show that after an AMOC shutdown, this oceanic exchange is the dominant influence on convection restarting in the GIN Sea and subsequentAMOC overshootshown in various proxy reconstructions.

Polar Climate Working Group

Polar Climate Working Group simulations utilizing CSL resources from 4/1/11 to 6/30/12 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:

1) General sea ice model improvements. Efforts to improve the sea ice model in CESM CICE have focused mostly on enhancements and bug fixes for releases. Major enhancements that have been incorporated include: radiative forcing diagnostics to allow for on the fly computation of the radiative impact of aerosols and ponds, Gregorian calendar, multi-instance capability for data-assimilation / interactive ensembles and CICE on new grids (e.g., finite volume, unstructured grids).

2) Influence of sub-grid scale sea ice heterogeneity on ocean mixing. Resources have been used to examine the influence of sea ice heterogeneity on ocean mixing for a collaborative Climate Process Team (CPT) project. The sea ice model includes a sub-gridscale ice thickness distribution such that five different ice-ocean fluxes and a single open-water flux are computed for each grid cell. These can vary quite dramatically given that the ice growth rate (and hence brine rejection) depends strongly on ice thickness. This could have implications for ocean mixing in ice-covered seas with feedbacks to the sea ice and climate. In order to test this influence, CSL resources have been used to modify the CESM system 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 have been performed to develop and test this implementation, to diagnose its influence in ice-ocean hindcast simulations and examine the effects in fully coupled integrations. Simulations and analysis are ongoing.

3) Representing sub-grid scale ocean biogeochemistry in ice-covered waters. Comparisons of predicted chlorophyll concentrations with satellite estimates over the Arctic Ocean indicate that CESM1 has more than double the observed amount of phytoplankton biomass on an annual mean basis. Sensitivity experiments were performed, in which the representation of photosynthesis under partially ice-covered grid cells was changed so as to respect non-linearities inherent in biological rate processes. Results from these experiments demonstrate improved chlorophyll distributions and bloom timing. Future work will formalize these changes in the CESM code and a lead to a manuscript (Long et al. in preparation).

Long, M. (in prep) Modeling photosynthesis in ice covered waters, *Geophys. Res. Let.*

4) Hindcast sea ice simulation sensitivity tests. The Common Ocean Reference Experiment version 2 (CORE2) dataset is the latest version of atmospheric variables used to force standard ice-ocean hindcast or 20th century simulations. This dataset has been constructed using a combination of atmospheric re-analysis, satellite and other observational datasets. However, due to the sparseness of data in the polar regions, there are significant errors in temperature, incoming longwave radiation, and specific humidity that lead to very thin, unrealistic sea ice conditions in the Arctic. Work is underway to adjust these variables, based on limited surface observations, to improve this bias in the sea ice hindcast simulations using CESM. A series of experiments with adjusted forcing show 50 cm improvements is sea ice thickness errors. Additional experiments in progress looking at surface albedo adjustments are expected to improve this bias further.

Production:

1) Arctic freshwater cycle. Following earlier work on the Arctic freshwater cycle with the CCSM3 (Holland et al. 2006, Jahn et al. 2010), the freshwater budget of the 20th and 21st century ensemble simulations from the CCSM4 were analyzed. It was found that the freshwater budget shows a better agreement with observations in the CCSM4 compared to the CCSM3, partially due to the addition of an opening in Nares Strait, which leads to a better representation of the split between the freshwater export east and west of Greenland. Results from the Arctic freshwater budget analysis were included in two special issue CCSM4 papers (Jahn et al., 2012, in press; Vavrus et al., 2012, in press). A publication on the details of the freshwater budget changes in the 21st century and their impact on the deep convection in the North Atlantic in all ensemble members from the four different RCPs is in preparation (Jahn et al., in preparation)."

Jahn, A. and Coauthors, (2012), Late 20th century simulation of Arctic sea ice and ocean properties in the CCSM4. *J. Climate*, in press.

Vavrus, S. J. and Coauthors (2012), 21st-century Arctic climate change in CCSM4. *J. Climate*, in press.

2) Arctic sea ice sensitivity to changing snow conditions. Using 20th century hindcast results, the depth of snow on ice in the Arctic ocean was validated. Resources were used to perform simulations designed to test the sensitivity of the ice cover to biases in snow depth and density identified in hindcast simulations. These Slab ocean model (SOM) simulations revealed high sensitivity to snow depth biases, leading to a short wave albedo feedback with the atmosphere. Results of this validation were presented (Blazey et al 2011), and a manuscript documenting these results is in preparation (Blazey et al, in preparation). In addition, the results of these simulations form the body of a doctoral dissertation, currently in preparation (Blazey, B. in preparation).

Blazey, B., M. Holland, J. A. Maslanik, 2011, Sensitivity of CICE/CESM Arctic ice extent and characteristics to a seasonal evolution of snow density and snow depth biases, Poster session presented at Fall meeting of the American Geophysical Union, San Francisco, CA.

Blazey, B. M. Holland, M. Holland, J. A. Maslanik, Arctic Ocean on ice Snow Depth in CICE/CCSM: Validation and Sensitivity, in preparation

Blazey, B. The role of snow cover in modeling the Arctic ice in CICE/CCSM: validation, sensitivity, and implications, PhD Dissertation, University of Colorado, Boulder, in preparation

3) Sea ice predictability. A number of sea ice seasonal forecasting systems in use apply ice-ocean hindcast integrations forced by historical atmospheric conditions. This does not allow for critical ice-atmosphere feedbacks, which could modify the sea ice evolution on seasonal timescales. CSL resources have been used to examine the importance of these feedbacks on sea ice predictability characteristics. In particular, initialized ice-ocean forecast ensemble simulations have been performed with CCSM4 in which the ensemble is created by using atmospheric forcing from different years of a 20th century CCSM4 simulation (much like what is done in several sea ice forecasting systems in use). The predictability characteristics in these simulations are being compared to the inherent predictability obtained from fully coupled CCSM4 initialized ensemble integrations to determine the role of ice-atmosphere coupling on ice predictability. Analysis of these runs is ongoing.

4) Changing seasonality of Arctic nutrient cycling. Simulations performed under 21st century forcing scenarios have been analyzed to determine the impact of shifting seasonality on carbon and nutrient cycling in the Arctic Ocean. This work has demonstrated that while pan-Arctic primary productivity is likely to increase with sea ice decline, export of organic material from the surface ocean to depth (i.e. the "biological pump") becomes less efficient. Algal community composition is sensitive to changes in light distributions; under future scenarios small phytoplankton become more prevalent at the expense of diatoms. These changes, in addition to warmer sea surface temperatures, lead to tighter trophic coupling in the surface ocean, reducing export ratios. Results were presented at two conferences. Further work will examine mechanisms contributing to model biases in Arctic Ocean biogeochemical fields. Manuscripts describing this work will follow, pending a more credible Arctic simulation.

5) Contribution to CCSM4 large-ensemble. PCWG CSL resources were used to complete 6 of 30 members for the CCSM4 large ensemble (1970-2005, 30 members). The runs are now complete and analysis of them is just beginning. There is discussion about extending them to 2050 if CSL resources are available through the end of the POP.

<u>Additional publications based on PCWG CSL resources:</u>

1) New shortwave radiative transfer scheme in CCSM4. Holland et al. (in press) document the incorporation of a new shortwave radiative transfer scheme and the capabilities that this enables in the CCSM4 sea ice model. CSL resources were used to implement and test the climate impact of the new scheme. The new scheme uses inherent optical properties to define scattering and absorption characteristics of snow, ice and included shortwave absorbers and explicitly allows for melt ponds and aerosols. The deposition and cycling of aerosols in sea ice is now included and a new parameterization derives ponded water from the surface meltwater flux. Taken together, this provides a more sophisticated, accurate, and complete treatment of sea ice radiative transfer.

Holland, M. M., D. A. Bailey, B. P. Briegleb, B. Light, and E. Hunke, 2011: Improved sea ice shortwave physics in CCSM4: The impact of melt ponds and aerosols on Arctic sea ice. J. Climate (in press).

2) Atmospheric boundary layer response to 2007 observed Arctic sea ice loss. Raeder et al. (revised) and Kay et al. (2011) use short-term atmospheric forecasts enabled by atmospheric data assimilation with DART to investigate the atmospheric boundary layer response to prescribed observed 2007 sea ice loss. Seasonal variations in the response were documented as Raeder et al. (revised) focused on the December 2007 response, while Kay et al. (2011) focused on July 2007 and September 2007 response. PCWG CSL resources were used to run the short-term forecasts, while computing resources from the DART project were used to run the assimilations and produce initial conditions.

Kay, J. E., Raeder, K., Gettelman, A. and J. Anderson (2011): The boundary layer response to recent Arctic sea ice loss and implications for high-latitude climate feedbacks, J. Climate, doi:10.1175/2010JCLI3651.1

Raeder, K., Anderson, J. L., Collins, N., Hoar, T. J., Kay, J. E., Lauritzen, P. H., and R. Pincus, (revised), DART/CAM: An Ensemble Data Assimilation System for CESM Atmospheric Models, J. Climate.

3) Arctic climate response to idealized greenhouse gas increase in CCSM4 and CESM-CAM5. Kay et al. (revised) used PCWG CSL resources to extend existing CESM experiments and add additional diagnostics needed for evaluation of the Arctic climate response to an idealized greenhouse gas forcing. In slab ocean model (SOM) experiments, local radiative feedbacks, not atmospheric heat flux convergence, were found to the dominant control on the Arctic surface response. Though increased ocean northward heat transport enhanced Arctic sea ice extent loss, the representation of atmospheric processes

(CAM4 vs. CAM5) had a larger influence on the equilibrium Arctic surface climate response than feedbacks due to dynamic ocean circulation.

Kay, J. E., Holland, M. M., Bitz, C., Blanchard-Wrigglesworth, E.,Gettelman, A., Conley, A., and D. Bailey (2012): The influence of local feedbacks and northward heat transport on the equilibrium Arctic climate response to increased greenhouse gas forcing in coupled climate models, J. Climate, revised.

Software Engineering Working Group

Under the CSL development allocation, the Software Engineering Working Group (SEWG) has focused on producing a successful update release for CESM1, CESM1.0.3, in June 2011, and on continuing to enhance the code, scripts and testing infrastructure to support carrying out the long-term simulations that are part of the CMIP5 experimental suite.

The SEWG CSL development allocation was also utilized to bring many new capabilities into the model system, resulting in numerous new development versions of the system. The development code base now supports the ability to run multiple instances of a given component using the single executable. This capability is now being utilized to carry out DART data assimilation work with 80 instances of CAM and CLM running concurrently. The development allocation was also used to support completely new model grids within the system and to target the support for much higher resolution model grids. In particular, the CESM system can now support running CLM, CAM, and prescribed CICE on any grid, including unstructured refined grids. A new tool chain was also implemented that permits the calculation of necessary mapping files and boundary datasets as part of a pre-build step that can be leveraged to explore new grids not officially supported by the model system. In addition, the coupling infrastructure was improved to handle the flexible transfer of new fields between components that could be specified at run time, rather than at compile time. The scripts and associated testing framework continued to be expanded in order to provide both expert and non-expert 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 the target platform.

The Software Engineering Working Group CSL development allocation is also being utilized to provide a CESM1 release update (CESM1.0.4) this February that will include support for the new WACCMX (a thermosphere/ionosphere extension of WACCM) along with bug fixes and machine updates. It will also be leveraged to provide a major science release, CESM1.1, targeted for late May. The creation of both of these releases will require running hundreds of system tests in order to ensure model robustness as well as to determine the optimal processor layout for various new scientific configurations that will be supported.

Whole Atmosphere Working Group

- *Completion of CMIP5 simulations*
  We completed our suite of WACCM4 simulations as part of CMIP5. We completed two ensembles of 3 simulations using RCP8.5 and RCP3-PD. In each ensemble, one realization covered the period 2005-2100, and two realizations covered 2005-2050. We similarly extended one of our RCP4.5 realizations from 2050-2100, and the other two from 2050-2065, to include the full recovery of the Antarctic ozone hole.

  We also completed a suite of low-top CCSM4 simulations with WACCM settings for turbulent mountain stress, for direct comparison of the effects of the representation of the stratosphere on climate simulations. These simulations included 24 years of an 1850 control, a 20^{th} Century (1850-1955) run, and 3 runs covering 1955-2005. In addition, we did one 1955-2005 simulation using prescribed O3 from WACCM4 calculations. A paper on our CMIP5 simulations, including detailed comparisons with these low-top CCSM4 calculations, is in preparation.

- *SC-WACCM development*
  In response to community interest expressed at our February 2011 working group, we have developed and released a specified chemistry version of WACCM4. This version avoids chemical calculations by using pre-calculated values of ozone and other radiatively important gases from full WACCM4 runs, reducing the computational cost by a factor of 2.7. We have released an SC-WACCM compset for present-day conditions, which is being used for dynamical studies.

- *Nuclear winter simulations*
  We have updated simulations of the climatic consequences of a regional nuclear war, following on the work of Mills *et al.* (2008). Using WACCM4 coupled to a full ocean, we have completed an ensemble of 3 simulations covering 10 years following a nuclear war between India and Pakistan. We have shown that 5 Tg of black carbon produced by subsequent firestorms would not only produce a global ozone hole, but would cool global surface temperatures by 2.3K, which is twice as much cooling as predicted by Robock *et al.* (2007), a study which did not include the impacts on stratospheric ozone. Further, we find this level of cooling persists 10 years after the conflict, when the cooling calculated by Robock *et al.* had diminished by more than half. A paper on these results is in preparation.

- *Improvements in WACCM microphysics*
  We have integrated the Community Aerosol and Radiation Model for Atmosphere (CARMA) microphysics package into WACCM, including integration with RRTMG radiation package. Using WACCM/CARMA, we have developed several science models, including meteor smoke, polar mesospheric clouds, sulfate aerosols, and soot aerosols.

- *Improvements in model stratospheric heterogeneous chemistry*
  The WACCM4 heterogeneous chemistry module was updated, tested, and released (CESM1.0.3) using the specified dynamics option. Comparison of the model results to Aura MLS observations for specific winter / spring periods were completed for ground truth for adjusting of parameters (particle densities, super situation thresholds, settling velocity size distribution widths, etc.) that affect ozone depletion, dehydration, and denitrification processes. Several papers are currently in preparation (e.g., Brakebush *et al.*, 2012).

- *Evaluation VSL halogen impacts on ozone*
  Short-lived halogen species (i.e., organic and inorganic gases with lifetimes of less than 0.5 years) have recently been shown to be important catalysts of ozone loss and methane oxidation in the marine boundary layer. Tropospheric ozone, the oxidizing capacity of the troposphere, and the lifetime of methane in the atmosphere are affected and therefore this process is important for understanding anthropogenic climate change. In addition, short-lived bromine compounds may contribute substantially to stratospheric ozone loss. The emissions and chemistry of these processes have been added to WACCM and evaluated. Two publications exist from this work (Saiz-Lopez *et al.*, 2011; Ordonez *et al*., 2011).

- *Temperature and wind bias in the Southern Polar Stratosphere*
  Prototypical study has been conducted using SC-WACCM (WACCM with specified chemistry) to examine the effects of inertial gravity wave (IGW) forcing on the polar stratospheric dynamics. The simulation shows that IGW breaking in the southern polar stratosphere slows down the winter jet, so that the breakdown of the polar vortex occurs much earlier than previous model results. Accordingly, polar stratospheric temperature is increased and the Brewer-Dobson circulation is enhanced. This study therefore demonstrates that missing gravity wave forcing in the stratosphere is probably responsible for the cold temperature and strong jet bias in the southern polar stratosphere.

- *"World avoided" study*
  Completed simulations of "world avoided" scenarios using free-running WACCM coupled to the ocean. The world avoided scenario is meant to simulate the effects of unrestricted growth of halogen compounds, as might have occurred in the absence of the Montreal Protocol. The results confirm the mid-21st century ozone layer collapse documented earlier by Newman *et al*. (2009) and, in addition, they show significant tropospheric climate changes due to the greenhouse effects of the halogens. Initial results were presented at the IUGG Assembly in Melbourne, Australia (July 2011). A paper is currently in preparation.

- *Study SSW, blocking and their relationship*
  Documented the climatology of SSW and blocking in WACCM, and the relationship between the two. The model reproduces the main observed features, as documented in the article by de la Torre *et al*. (in press).

- *Integration of WACCM-X in CESM*
  WACCM-X (WACCM with thermosphere and ionosphere extension with model top at exobase, ~500 km) has now been integrated into the CESM1, and will be released in February 2012 as part of CESM1.0.4 after the software testing is completed. This model self-consistently resolves the thermospheric major and minor neutral species, five main ion species, thermospheric wind and thermal structures. The model also parameterizes ion drag and auroral processes.

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