The Whole Atmosphere Community Climate Model
Version 6 (WACCM6)

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Abstract. The Whole Atmosphere Community Climate Model version 6 (WACCM6) is a major update of the whole atmosphere modeling capability in the Community Earth System Model (CESM), featuring enhanced physical, chemical and aerosol parameterizations. This work describes WACCM6 and some of the important features of the model. WACCM6 can reproduce many modes of variability and trends in the middle atmosphere, including the Quasi-Biennial Oscillation, Stratospheric Sudden Warmings and the evolution of Southern Hemisphere springtime ozone depletion over the 20th century. WACCM6 can also reproduce the climate and temperature trends of the 20th century throughout the atmospheric column. The representation of the climate has improved in WACCM6, relative to WACCM4. In addition, there are improvements in high latitude climate variability at the surface and sea ice extent in WACCM6 over the lower top version of the model (CAM6) that come from the extended vertical domain and expanded aerosol chemistry in WACCM6, highlighting the importance of the stratosphere and tropospheric chemistry for high latitude climate variability.
1. Introduction

Simulating the climate system means more than just simulation of the surface climate and the troposphere. For example, the climate and chemistry of the stratosphere may also affect the surface, by changing surface forcing through the climatology of water vapor and ozone [Solomon et al., 2010], by stratospheric aerosol loading [Mills et al., 2016], or dynamical interactions between the stratosphere and troposphere with impacts all the way to the surface [Baldwin and Dunkerton, 2001]. In addition to surface climate variables such as temperature and precipitation, the climate system includes chemical reactions that impact humans and ecosystems through the oxidizing capacity of the troposphere, including near surface and tropospheric ozone [e.g., Lefohn et al., 2018]. Changes in chemistry and dynamics also affect absorbed radiation through the stratospheric ozone layer [World Meteorological Organization, 2010]. Stratospheric ozone changes are the premier example of the influence of stratospheric composition on climate [e.g., Son et al., 2010] and air quality [Hodzic and Madronich, 2018]. Finally, the dynamics of the sun may affect the atmosphere, particularly the upper atmosphere (from the mesosphere to thermosphere to ionosphere). Periods of extreme solar activity can affect the near space environment and impact electrically sensitive human structures from power grids to electronic devices, mediated through solar impacts with the upper atmosphere.

Simulating the earth system and its impacts on human health and ecosystems requires the use of comprehensive simulations that can represent the physical, dynamical and chemical climate of the whole atmosphere. Such models are now becoming commonplace in climate simulations [Marsh et al., 2013], and may be necessary to improve under-
standing and predictability of the lower atmosphere [Thompson et al., 2002; Charlton-Perez et al., 2013]. This work documents a major upgrade to the Whole Atmosphere Community Climate Model (WACCM) in the Community Earth System Model version 2 (CESM2), or CESM2-WACCM. Section 2 describes CESM2-WACCM, which is also known as WACCM6. Section 3 describes the available model configurations, and Section 4 the specific simulations used in this study. Section 5 presents WACCM6 simulations, Section 6 describes differences between WACCM and CAM versions and Section 7 presents conclusions.

2. Model Description

This section documents the important features and changes to WACCM since WACCM4 [Marsh et al., 2013].

2.1. Physical Atmosphere

WACCM6 is the whole atmosphere version of the Community Atmosphere Model version 6 (CAM6), described by Neale et al. [2019]. Unlike in previous versions of CESM, WACCM6 is identical to CESM2-CAM (also known as CAM6) in the range of processes that are parameterized. The only exception is the representation of parameterized gravity waves (see below). A summary of the current parameterizations for CAM6 and WACCM6 clouds and aerosols is contained in Table 1. These are detailed further below as applied to WACCM6, and also in Neale et al. [2019] as applied to CAM6.

Table 1 describes the different versions of WACCM starting with WACCM4, described by Marsh et al. [2013]. WACCM-CCMI was developed for the Chemistry Climate Modeling Initiative (CCMI) and features updated tropospheric and stratospheric chemistry.
WACCM5 [Mills et al., 2017] is based on WACCM4 chemistry, but with updated physical parameterizations following Neale et al. [2010], and features adjustments to the physical parameterizations and gravity wave schemes (see below), as well as updated stratospheric prognostic aerosols [Mills et al., 2016]. WACCM5 also transitions to higher horizontal and vertical resolution. WACCM-CCMI emphasized the evolution of chemistry, and WACCM5 the evolution of dynamics. WACCM6 combines the new aspects of both models with additional updates for CESM2.

2.2. Gravity Wave Drag

In addition to the orographic gravity wave drag parameterization that is identical between CAM6 and WACCM6, WACCM6 includes a non-orographic gravity wave drag parameterization following Richter et al. [2010] with separate specification of frontal and convective gravity wave sources. Two main adjustable parameters in the frontal gravity wave source specification have been changed since WACCM4 due to the increased horizontal resolution in WACCM6: the frontogenesis threshold in WACCM6 is set to 0.108 $K^2 (100 \text{ km})^{-2} \text{ h}^{-1}$ and the source stress of frontally generated waves is set to $\tau_b = 3 \times 10^{-3} \text{ Pa}$. These parameters are the same as those used in Mills et al. [2017] for WACCM5.

In order to obtain an internally generated QBO with a reasonable period, a scaling factor of 0.25 was applied to the depth of heating in the deep convective parameterization (which reduces the effective phase speeds of convectively generated gravity waves), and the efficiency of convectively generated waves was changed to 0.4 [Mills et al., 2017].

Updated orographic schemes were implemented in WACCM6 for Planetary Boundary Layer (PBL) form drag and Orographic Gravity Waves (OGW). The updated PBL form drag scheme is that of Beljaars et al. [2004]. The updated OGW scheme incorporates
near surface nonlinear drag processes following Scinocca and McFarlane [2000] and uses a feature-based algorithm to derive forcing data based on Bacmeister et al. [1994].

2.3. Solar and Geomagnetic Forcing

For almost all model configurations, WACCM6 uses the recommended CMIP6 solar and geomagnetic forcing as described in Matthes et al. [2017] and available via http://solarisheppa.geomar.de/cmip6. The solar spectral irradiance used to calculate heating and photolysis rates are averages from two semi-empirical models: version 2 of the Naval Research Laboratory model (NRLSSI2, Coddington et al. [2015]) and a composite of two Spectral And Total Irradiance REconstruction (SATIRE) models [Yeo et al., 2015].

For photoionization and heating rates at wavelengths shorter than Lyman-α, WACCM6 uses the parameterization of Solomon and Qian [2005], that takes as input the $F_{10.7}$ index. Geomagnetic variability affects the flux of energetic particles that precipitate into the atmosphere, ionizing and possibly dissociating major species. Ion-pair production rates (IPR) by galactic cosmic rays, solar protons and medium-energy electrons are also prescribed following Matthes et al. [2017]. IPRs are specified on pressure levels and geomagnetic L-shell, which are interpolated to the WACCM6 geographic grid. For all schemes other than the MAD scheme described below, IPR rates are converted into rates of production for odd-hydrogen and odd-nitrogen species following Jackman et al. [2009].

For lower-energy electrons that precipitate in the auroral regions, WACCM6 continues to use the parameterized auroral oval model of Roble and Ridley [1994], the implementation of which in WACCM is described in Marsh et al. [2007]. This model takes as input hemispheric power ($HP$) that is assumed to be related to the $Kp$ geomagnetic index.
through the following revised relationship:

\[ HP(GW) = 16.82 e^{0.32Kp} - 4.86 \quad Kp \leq 7 \]
\[ = 153.13 + 73.5(Kp - 7.0) \quad Kp > 7 \]

In the pre-industrial control simulations, the solar and geomagnetic forcing are an average over the period 1850 to 1873. For transient simulations, solar and geomagnetic forcing are linearly interpolated at each model time step from daily averaged data. The model is capable of taking higher frequency forcing files, should the scientific application demand it (e.g., the modeling of solar storms).

It should be noted that beginning January 1, 2015, solar forcing data are projections based on historical solar cycles rather than from observations. It is for this reason that in non-CMIP6 simulations that are nudged to reanalysis (see Section 3), WACCM6 uses only irradiance fluxes from NRLSSI2, which are updated routinely and available from National Centers for Environmental Information (dataset doi:10.7289/V51J97P6).

### 2.4. Chemistry

WACCM6 is designed to represent a full suite of chemical constituents. It shares the 4 mode Modal Aerosol Model (MAM4, Liu et al. [2016]; Mills et al. [2016]) with CAM6, but adds chemistry (explicitly calculating the oxidants which are specified in CAM6).

The baseline chemical mechanism contains reactions relevant for the whole atmosphere: Troposphere, Stratosphere, Mesosphere and Lower Thermosphere (TSMLT), described by Emmons et al. [2019]. Three additional chemistry schemes are available: a Troposphere and Stratosphere (TS) scheme, a Middle Atmosphere (MA) scheme with a reduced set
of tropospheric reactions, and the same MA scheme with the addition of D-region ion chemistry (MAD).

Here we describe the TSMLT mechanism used in WACCM. This is a superset of all the other mechanisms, except that it does not contain detailed D-region ion chemistry (see below). The chemical species within this mechanism include the extended Ox, NOx, HOx, ClOx, and BrOx chemical families, along with CH$_4$ and its degradation products. In addition to CH$_4$, we also include N$_2$O (major source of NOx), H$_2$O (major source of HOx), plus various natural and anthropogenic precursors of the ClOx and BrOx families. This mechanism also includes primary non-methane hydrocarbons and related oxygenated organic compounds. The chemical processes have evolved from previous versions [e.g., Kinnison et al., 2007; Emmons et al., 2010; Lamarque et al., 2012; Marsh et al., 2013; Tilmes et al., 2016], and are summarized in detail in Emmons et al. [2019]. Reaction rates are updated following JPL 2015 recommendations [Burkholder et al., 2015]. The current mechanism includes a new detailed representation of secondary organic aerosols (SOAs) based on the Volatility Basis Set (VBS) approach from major anthropogenic and biogenic VOC precursors [Tilmes et al., 2019; Hodzic et al., 2016]. The WACCM mechanism includes a total of 231 solution species, 583 chemical reactions broken down into 150 photolysis reactions, 403 gas-phase reactions, 13 tropospheric and 17 stratospheric heterogeneous reactions. The photolytic calculations are based on both inline chemical modules and a lookup table approach [Kinnison et al., 2007]. The chemical mechanism includes two very short-lived halogens: CHBr$_3$ and CH$_2$Br$_2$. The surface mole fraction for these two species is set to 1.2 pptv (i.e., 6 pptv of total bromine). This approach adds an additional \(~5\)pptv of inorganic bromine to the stratosphere. The heterogeneous
reactions use aerosol surface area density (SAD) derived from MAM4 [Mills et al., 2016].

The tropospheric heterogeneous reactions take four aerosol types into account (i.e., sulfate, black carbon, particulate organic matter and secondary organic aerosol). The stratosphere heterogeneous reactions occur on three aerosol types (i.e., sulfate, nitric acid trihydrate, and water-ice). The liquid binary sulfate aerosol SAD is derived from MAM4, but modified in very cold regions (<200K) using the Aerosol Physical Chemistry Model [Tabazadeh et al., 1994] to represent supercooled ternary solution (STS) aerosols. WACCM6 uses CMIP6 specified mixing ratios for greenhouse gases [Meinshausen et al., 2017], reactive gases and aerosols from anthropogenic sources, including aircraft NOx [Hoesly et al., 2018] and biomass burning [vanMarle et al., 2017]. Biogenic emissions are calculated online in CLM with MEGANv2.1 [Guenther et al., 2012]. Lightning NOx emissions are interactive, and total ∼3-4 TgN/year.

The water-ICE and nitric acid trihydrate (NAT) SAD approach is described in Kinnison et al. [2007] with updates listed in Solomon et al. [2015]. The chemical mechanism includes 9 chemical tracers (SF6, O3S, E90, AOA_NH, AOA1, AOA2, ST80_25, NH5, NH50). These tracers are described in Tilmes et al. [2016]. The mesosphere and lower thermosphere (MLT) chemistry component of WACCM6 includes the species and reactions described in Marsh et al. [2007]. The radiatively active gases in WACCM include H2O, O2, CO2, O3, N2O, CH4, CFC12, aerosols, and an ‘equivalent CFC11’ (CFC11eq), which includes radiative effects of CFC11 along with a scaling to reflect other CFCs and HFCs [Meinshausen et al., 2017].

The gas phase chemistry of the MA chemical scheme is closest to the chemical scheme used in WACCM4. It includes two additional species not present in WACCM4. These
species are the metastable states O+ (2D) and O+ (2P), which are important for the ener-
getics of the thermosphere but do not have any impact on composition or chemistry in
the lower atmosphere. As with all schemes, the rate coefficients have been updated to
JPL-2015.

The middle atmosphere D-region (MAD) chemical scheme, that adds negative ion and
cluster ion chemistry, was first implemented in WACCM4 and is described in Verronen
et al. [2016]. Since version 3 of WACCM, the chemical scheme has solved for the densities
of 5 ions and electrons that make up the E-region ionosphere [Marsh et al., 2007]. The
MAD scheme adds 15 positive and 21 negative ions, and addresses several deficiencies in
the mesosphere that occur when only E-region ions are considered. The first is that the
dominant negative charge carriers are no longer electrons below 75 km, but negative ions
such as Cl− (HCl), HCO3− and NO3− (HNO3). The negative charge is balanced not by O2+ and
NO+, as in the E-region, but by proton hydrates (H+(H2O)n=3,4,5). This, in theory,
should yield a better representation of electron density throughout the mesosphere. The
second improvement is that production of odd-hydrogen (H, OH) and odd-nitrogen (N,
NO) from ionization by energetic particles is no longer parameterized but flows through
the complex chemistry following the ionization of the major species (N2, O2). It includes
the chemistry that produces the enhanced levels of HNO3 observed in the polar middle
stratosphere following a solar storm that are not seen in simulations with the MA scheme
[e.g., Orsolini et al., 2018].

2.5. Prognostic stratospheric aerosols

WACCM6 features prognostic stratospheric aerosols. As described by Mills et al. [2016],
the modal aerosol model, MAM [Liu et al., 2012, 2016] has been modified to change
the mode widths and allow growth of sulfate aerosol into the coarse mode (MAM4).

This is important to properly represent aerosol sources in the stratosphere, including volcanic emissions, and natural background emissions of carbonyl sulfide (OCS), which form the stratospheric aerosol layer. Historical variability in OCS is included as a time-varying lower boundary condition [Montzka et al., 2004]. SO$_2$ emissions from volcanic eruptions are derived from version 3.11 of Volcanic Emissions for Earth System Models [VolcanEESM, Neely and Schmidt, 2016, ]. To account for the self-lofting of aerosols due to in situ absorption of longwave radiation, we impose a maximum altitude of 20 km for eruptions inputting more than 3.5 Tg of SO$_2$. This adjustment affects 4 eruptions in the historical period of simulation (1850-2014): Krakatau (1883), Agung (1963), El Chichón (1982), and Pinatubo (1991). To account for the loss of sulfur on ice and ash as observed in the initial 10 days following the 1991 Pinatubo eruption, we scale the mass input to the model by a factor of 5/9 from eruptions estimated to have emitted more than 15 Tg of SO$_2$. This adjustment affects 2 eruptions: Krakatau (1883), and Pinatubo (1991). The rationale for these altitude and mass adjustments is discussed further in Mills et al. [2016]. For each day of eruption, SO$_2$ emissions occurs over 6 hours from 1200 to 1800UT.

A complete table of volcanic eruptions and emissions parameters is included as metadata in the VolcanEESM netCDF file used for historical simulations, which is publicly available from the CESM2 inputdata repository.

Following CMIP6 guidance [Eyring et al., 2016], we include in pre-industrial control simulations background volcanic aerosol at a level to match average radiative forcing over the historical simulation (i.e. 1850-2014 mean). Our pre-industrial control simulations therefore include constant SO$_2$ emission rates time-averaged from all eruptions over the
historical period. SO$_2$ emissions from volcanic eruptions are zeroed below the tropopause in pre-industrial simulations.

### 2.6. Secondary Organic Aerosols

In addition to the updated prognostic stratospheric aerosol scheme in WACCM6, for configurations that include comprehensive tropospheric and stratospheric chemistry, WACCM6 includes an interactive Secondary Organic Aerosol (SOA) approach based on the Volatility Bin Set (VBS), following the approach described by Hodzic et al. [2016].

Gas phase semi-volatile SOA components (SOAG) are formed from anthropogenic and biomass burning precursor emissions at the surface, as well as from biogenic emissions from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.1 [Guenther et al., 2012]. In addition to the traditional SOA precursors such as isoprene, monoterpenes, aromatics and short-chain VOCs, the updated mechanism also includes the long-chain n-alkanes (C$_{\geq}$12) that are not included in the standard emission inventories, and that were added as co-emitted species with primary organic carbon emissions from fossil-fuel and biomass burning sources. This approach is more interactive than earlier approaches since the formation of organic SOA interacts with changes in the land model and climate variables. In addition, the new SOA approach includes a more comprehensive description of processes including the water solubility of intermediate organic vapors that determines their dry and wet deposition, formation of SOA by the uptake of glyoxal SOAGs into aqueous aerosols [Knote et al., 2014], and photolytic removal of particulate SOA Hodzic et al. [2015]. In addition to the basic scheme in WACCM6, the model can be run with an extended scheme, where source contribution of different precursor emissions from biomass burning, fossil fuel and biogenic emissions to SOA can be identified.
3. Configurations

The basic configuration of WACCM6 features $\sim 1^\circ$ (0.9$^\circ$ latitude x 1.25$^\circ$ longitude) horizontal resolution using the Finite Volume dynamical core [Lin and Rood, 1997]. WACCM6 has 70 levels in the vertical from the surface to 6x10$^{-6}$ hPa ($\sim$140km). By contrast, CAM6 has 32 levels with a top at 3.6 hPa. Notably, CAM6 and WACCM6 share the same vertical level structure up to the 87 hPa level.

WACCM6 has several different baseline configurations as illustrated in Table 2. The Free Running (FR) configuration features one of the chemistry packages (TSMLT, TS, MA, MAD) described in Section 2.4. The baseline is TSMLT: full chemistry from the troposphere through the lower thermosphere. Free Running WACCM6 configurations can be run with specified sea surface temperatures (SST) and sea ice distribution (called 'FW' case simulations) or fully coupled to active ocean and sea ice model components ('BW' case) [Marsh et al., 2013]. These simulations can be configured for specific years with annually repeating boundary conditions, such as the BW1850 configuration, or using time-dependent boundary conditions for greenhouse gas concentrations, aerosols, volcanic eruptions (BWHIST), solar variability and in the case of FW simulations, specified historical sea surface temperatures (FWHIST). WACCM6 always runs with an interactive land surface model (the Community Land Model version 5, or CLM5).

WACCM6 can also be run in a nudged, or Specified Dynamics (SD) configuration (FWSD). For SD simulations, winds and temperatures are relaxed to a specified set of data, typically another model or a reanalysis system. Commonly, the NASA Goddard Earth Observation System (GEOS) model analyses, Modern-Era Retrospective analysis for Research and Applications (MERRA) [Rienecker et al., 2011] or MERRA2 Molod et al.
[2015] are used. This SD version is effective for reducing climate noise, eliminating biases in winds and/or temperatures and reproducing the chemical response to specific events or for specific times, such as comparison to specific field programs or individual observations. WACCM6-SD configurations typically use a vertical level structure taken from the source nudging data.

As described in Smith et al. [2014], WACCM can also be run with Specified Chemistry (SC). In WACCM6-SC simulations (compset FWscHIST), radiatively active chemical species (like Ozone) are prescribed, typically from a WACCM6 run with interactive chemistry, while all other CAM6 and WACCM6 parameterizations for clouds are interactive. The aerosol model is also reduced in complexity for WACCM6-SC, using CAM6 aerosols (simplified SOA and prescribed stratospheric aerosols). WACCM6-SC is an efficient model useful for dynamical studies. An example of the use of WACCM6-SC for understanding dynamical and chemical effects are provided in Section 6.

For comparison, we also perform CAM6 simulations with specified SST and ice (FHIST). CAM6 has the same physical parameterization suite as WACCM6 minus the frontal and convective gravity wave drag schemes, with a lower top, loss of several upper atmosphere processes, fewer levels, and no chemistry. CAM6 is essentially WACCM6-SC with a lower lid (and without the convective and frontal gravity waves). Comparisons between WACCM6, WACCM6-SC and CAM6 can illustrate the impact of chemistry-climate coupling (WACCM6 v. WACCM6-SC), the impact of the broader vertical range (WACCM6-SC v. CAM6) or both (WACCM6 v. CAM6).
Finally, WACCM6 now has the option to run with a more complete thermosphere and ionosphere, with a lid near 500km. This extended version, or WACCM-X, currently is coupled to WACCM4 physics and is described in a companion paper by Liu et al. [2018].

4. Simulation Description

Results documented below (Section 5) are based on the simulations with WACCM6 listed in Table 2. All are at 0.9°x1.25° horizontal resolution and 70 vertical levels, with TSMLT chemistry, and all are coupled actively to the CLM5 land model. Fully coupled WACCM6 in CESM2 (BW1850) is run first for a long control run representing pre-industrial conditions and starting from a 200 year control simulation with CAM6. Then three ‘BWHIST’ simulations with transient forcing from the Coupled Model Intercomparison Project round 6 (CMIP6) [Eyring et al., 2016] from 1850–2014 are initialized from year 56, 61 and 70 of this run. WACCM6 is also run with prescribed SST and sea ice distribution and CMIP6 forcing for greenhouse gases and aerosols over the period from 1950-2014, initialized with land and atmospheric initial conditions from BHIST simulations (FWHIST). WACCM6-SD (FWSD) is a specified dynamics simulation forced with MERRA2 analysis over the more recent period when comprehensive satellite data is available (1980 to 2014) to examine chemistry with dynamic variability prescribed from the historical atmosphere (as conditioned by a reanalysis system). WACCM6-SC (FWscHIST) is run with specified SSTs and chemical fields from the FWHIST simulations.

5. Results
Here we present key results from WACCM6, focusing on the stratosphere. The overall WACCM6 tropospheric climatology and climate are described in Section 6 with a comparison to CAM6. CAM6 climatology is more fully described by Neale et al. [2019].

5.1. Climatology/Annual cycle

WACCM6 is able to effectively simulate the zonal winds from the surface through the mesosphere. Figure 1 illustrates the December, January, February (DJF) and June, July, August (JJA) WACCM6 FWHIST climatological zonal wind, and compares it to European Center Interim (ERAi) reanalysis [Dee et al., 2011]. There are ∼5 m s\(^{-1}\) biases in S. Hemisphere winter zonal wind in the lower stratosphere, but, in general, the mean wind speeds compare well to reanalyses. Biases would be expected to become larger with altitude. WACCM6 is able to simulate the seasonal variation of the stratospheric polar jets.

WACCM6 is also able to effectively simulate the temperature structure from the surface through the mesosphere. Figure 2 illustrates DJF and JJA WACCM6 FWHIST climatological temperature compared to ERAI [Dee et al., 2011]. Seasonal mean tropical tropopause temperatures are within ±2K of the reanalysis. There are winter time biases in the S. Hemisphere temperature in the lower stratosphere, consistent with the zonal wind biases (Figure 1). WACCM6 also has a cold summer mesopause at ∼85km with temperatures close to 140K, similar to observations.

The winter (JJA) seasonal temperature biases over the South Pole in Figure 2d increase and propagate downward in spring, as illustrated in Figure 3. These biases result from remnants of the winter jet in the lower stratosphere persisting too late. The biases occur late enough in the spring that they do not impact lower stratosphere southern polar
springtime ozone depletion (see below). This bias reflects a delayed breakdown of the southern hemisphere polar vortex relative to observations [Butchart et al., 2011].

The annual cycle of tropical stratospheric water vapor is illustrated in Figure 4, with a representation of the water vapor ‘tape-recorder’ [Mote et al., 1996]. WACCM6 is compared to an observational climatology from the AURA Microwave Limb Sounder (MLS, [Waters et al., 2006; Read et al., 2007]), illustrated in Figure 4B. The tape recorder vertical propagation speed based on tracer contour advection is slightly faster and shifted slightly upward relative to observations (Figure 4A). The amplitude of the tape recorder is well represented, with a 0.25–0.5ppm high (moist) bias in WACCM6. Specified Dynamics (SD) simulations (Figure 4C) have a slightly lower velocity but higher bias than either free running fixed SST (FR AMIP, Figure 4D) or free running coupled (FR COUPLED, Figure 4E) simulations. Free running coupled simulations (Figure 4E) have small biases in value or amplitude relative to MLS. We will discuss differences between WACCM6 (solid lines in Figure 4A) and WACCM4 (dashed lines in Figure 4A) in Section 6.

WACCM6 also does a good job at reproducing the distribution of ozone in the stratosphere. This will be discussed in more detail in analysis of the evolution of stratospheric ozone over the late 20th century in Section 5.3.

5.2. Variability

One of the major features of intraseasonal variability in the stratosphere is Northern Hemisphere Stratospheric Sudden Warmings (SSWs) which can have impacts all the way down to the surface [Baldwin and Dunkerton, 2001]. In this case we define an SSW by a period when the 10 hPa zonal mean zonal wind at 60°N is < 0 m/s (i.e. eastward) following Charlton and Polvani [2007]. Figure 5 indicates that the coupled (Figure 5A)
and historical fixed SST or AMIP (Figure 5B) WACCM6 ensembles are able to capture the frequency of SSWs averaged over 40 years (1975–2014). The ensemble mean frequency (black bars) is close to observations. The AMIP simulations have too few SSWs in February, and too many in March (Figure 5B) while coupled cases (Figure 5A) also have too few SSWs in January and February. The high March frequency may be a result of a late bias in the spring polar vortex break up, but it is also clear from the spread among WACCM ensemble members that the observed record is likely subject to considerable sampling uncertainty. The total winter frequency is 0.60 warmings per year in NCEP, with 0.52 per year for the historical SST and 0.72 per year for the coupled model, neatly bracketing the observations. Few WACCM4, the frequency of occurrence of SSWs was 0.46 per year with a range across ensembles of 0.33 to 0.53 per year [Marsh et al., 2013].

WACCM6 is also able to simulate, albeit imperfectly, the Quasi-Biennial Oscillation (QBO) (Figure 6), the equatorial zonal wind propagation which in observations has an average period of ~28 months. Similar to WACCM5 [Mills et al., 2017], WACCM6 simulates a reasonable QBO with 70 levels in a free running configuration, but the amplitude in the lower stratosphere is too weak and disappears completely below 20km. The average QBO period calculated using fourier analysis is 29 months for WACCM6 (fixed SST), 27 months for WACCM6 (coupled ocean) compared to 28 months for ERAI reanalysis. The QBO does not extend low enough in the stratosphere (Figure 6B and C) compared to observations (Figure 6A). This deficiency is due to the relatively coarse vertical resolution in the lower stratosphere in this version of the model. More realistic downward propagation of the QBO can be obtained in WACCM with increased vertical resolution [Garcia and Richter, 2018].
WACCM6 does not perform as well in reproducing the semi-annual oscillation in stratospheric and lower mesospheric zonal wind at higher altitudes except at the stratopause, as illustrated in Figure 7, which compares model winds at the Equator with winds derived from SABER satellite data [Smith et al., 2017]. The timing of the SAO minimum winds at solstices in the upper stratosphere is well produced, and is driven primarily by horizontal advection of zonal mean momentum that varies with seasonal changes in the Brewer-Dobson circulation. However, wind variations in the mesosphere simulated by WACCM6 are overall much weaker than those deduced from observations. This may be due to a deficiency in forcing by tropical waves, and could also be a result of coarse vertical resolution. There is not currently an observational base to determine whether the waves driving winds in the tropical upper stratosphere and lower mesosphere are small-scale gravity waves or larger-scale waves, such as equatorially trapped Kelvin waves.

WACCM6 represents impacts of both large (e.g. Pinatubo, 1991) and many small-to-moderate (e.g. 2005–2014) eruptions. Figure 8 shows simulated and observed Stratospheric Aerosol Optical Depth (SAOD) from 1980-2015 at different locations corresponding to ground-based lidar observations using a backscatter-to-extinction ratio of 50. WACCM6 with prognostic stratospheric sulfur is able to produce the correct SAOD from volcanic eruptions over most latitudes. There are some differences in the tropics (Mauna Loa) during the volcanically quiescent period of 1997-2004, and in the Southern Hemisphere (Lauder) during the recent period of small-to-moderate eruptions.

5.3. Trends

WACCM6 is able to reproduce the evolution of the ozone layer, including the Southern Hemisphere polar ‘ozone hole’ [World Meteorological Organization, 2010], as illustrated
in Figure 9. The observations lie within the range of variability spanned by the historical coupled and fixed SST (AMIP) simulations. The SD simulations with imposed variability (purple in Figure 9) are able to reproduce the interannual variability seen in observations (black in Figure 9). Variability at both poles (Figure 9A and B) is reproduced, including low ozone events in the N. Hemisphere (Figure 9B). There are some biases in mid-latitudes in free running simulations (Figure 9C and D), which are not seen in SD simulations. Larger biases occur in the tropics (Figure 9E).

The reason for the tropical differences is related to tropical upwelling, illustrated in Figure 10, and consistent with Figure 4. In the 20°S-20°N region, the vertical velocity is larger for pressures greater than 50 hPa for the coupled case, the free running (AMIP) case than the SD case. Since the lower stratosphere is dynamically controlled, the vertical velocity will impact the Total Column Ozone (TCO). The larger vertical velocities in the lower stratosphere are expected to be associated with reduced ozone due to vertical advection of ozone poor air from the troposphere. The difference in vertical velocity would result in more O$_3$ in the SD case than free running for pressures greater than 50 hPa. The opposite is the case for pressures between 50 and 10 hPa, broadly consistent with the representation of tropical upwelling between the two cases. Tropical anomalies (Figure 9E) will affect the mid-latitudes (Figure 9C and D) as well as the near global (60°S–60°N) TCO (Figure 9F).

Globally averaged surface temperature in the WACCM6 fully coupled simulations for the historical period (1850-2014) are compared to observations and CAM6 simulations in Figure 11. Both WACCM6 and CAM6 are able to reproduce the observed historical evolution of global mean surface temperature anomalies. Notably, WACCM6 global mean
surface temperature does not have a different mean (not shown) or global variability than CAM6 simulations. Note how in the first 80 years of this record from 1850-1930 or so, when radiative forcing was dominated by volcanic eruptions, both CAM6 and WACCM6 track much of the observed decadal variability, indicating that it was likely forced variability, and associated with volcanoes. Also note that there is a spread of variation of volcanic response in WACCM6 to large volcanoes such as Krakatoa in 1883. Volcanic SAOD is shown on the top of Figure 11. The CESM2 historical ensemble used volcanic forcing equal to the average of the 3 CESM2-WACCM ensemble members.

Figure 12 illustrates stratospheric temperature trends from WACCM6 historical AMIP simulations compared to Stratospheric Sounding Unit (SSU) and the advanced Microwave Sounding Unit (MSU) temperatures [Randel et al., 2017]. As with WACCM4 [Randel et al., 2017, Fig. 1], WACCM6 is able to capture stratospheric temperature trends from 1980–2014. WACCM6 has a slightly better representation of the temperature response to the 1991 Mount Pinatubo eruption. As noted by Randel et al. [2017], temperature trends are a combination of effects from ozone depletion and recovery, and increasing greenhouse gases, which WACCM6 captures well. Variability is forced from volcanic eruptions and the tropospheric El Niño Southern Oscillation (ENSO), which is imposed on the WACCM historical AMIP simulations with observed SSTs.

6. Difference between WACCM Versions and Configurations

Figure 11 illustrates transient differences in global mean temperature anomalies between CAM6 and WACCM6 simulations. Table 3 illustrates differences in global mean climate metrics between different configurations for the historical period (2000–2014) as well as overlapping observations. Here we compare both CAM6 and WACCM6, as well as the
previous version of WACCM, WACCM4-CCMI. Table 3 also shows pre-industrial (PI, from B1850 simulations) values from WACCM6, CAM6 and WACCM4.

6.1. WACCM6 v. CAM6

WACCM6 and CAM6 have very similar climates defined by their top of atmosphere energy budget and cloud radiative effects. WACCM6 of course provides significantly more fidelity in the stratosphere as it represents the meridional overturning circulation of the stratosphere fully, as well as full tropospheric and stratospheric chemistry, with interactive oxidants and ozone. Differences between WACCM6 and CAM6 are thus a combination of differences due to the different lid and upper atmospheric processes with the differences in chemistry and aerosols [Emmons et al., 2019]. The tropospheric physical processes are the same between WACCM6 and CAM6. We discuss these differences below, and also refer to a WACCM-SC (Specified Chemistry) simulation where appropriate to help distinguish dynamical from chemical and aerosol processes.

There are several climate differences between CAM6 and WACCM6. In the clear sky, there is a -2Wm$^{-2}$ top of model difference in both the SW net flux (FSNTC) and LW net flux (FLNTC) in WACCM6 v. CAM6. This is likely due to absorption of radiation occurring above the model top of CAM, despite an effort to parameterize this absorption in CAM. Additional discussion is found in Tilmes et al. [2019].

Table 3 also indicates a 1 Wm$^{-2}$ magnitude increase in SW (negative) and LW (positive) cloud forcing (SWCRE and LWCRE) in WACCM. This comes from high clouds in the tropics, where there is an increase in high cloudiness (CLDHGH) at the edges of the tropics, and an increase in ice mass (TGCLDIWP) and overall ice crystal number. This would appear to be a result of an increase in accumulation mode sulfate in the tropics.
causing increased homogeneous nucleation of cirrus ice crystals. The increased sulfate is from (a) DMS (dimethylsulfide) sources and (b) stratospheric volcanic sulfate in WACCM6 which are not present in CAM6. CAM6 takes in prescribed surface area densities of sulfate from WACCM6, but not the actual sulfate which can impact tropospheric clouds.

There are also small increases in high latitude Northern Hemisphere shortwave cloud forcing (SWCRE) in WACCM6 over CAM6, due to increases in cloud droplet number from increased East Asian aerosol burdens which extend into the Arctic (see Tilmes et al. [2019] for details). Aerosol lifetimes also differ in the tropics in WACCM6 due to differences in tropospheric chemistry and removal of oxygenated organics.

CAM6 and WACCM6 have similar pre-industrial (1850) annual mean Sea Ice Extent (SIE), but the SIE is much less than WACCM4 (Table 3). The main difference in SIE between CAM6 and WACCM6 is in summer when the WACCM6 simulations have much less melt, but the annual mean SIE is not very different. As a result, there are larger differences between CAM6 and WACCM6 in pre-industrial Sea Ice Volume (SIV) in Table 3. Ice sticks around for the subsequent winter and then the ice is thicker.

In coupled WACCM6 historical simulations (BWHIST), the recent 20th Century warming makes these differences more apparent (Figure 13). WACCM6 has higher September NH SIE than CAM6, in better agreement with observations (Figure 13A). WACCM and CAM NH SIE are close in March (the month of maximum sea ice, Figure 13A). WACCM annual NH sea ice volume (Figure 13B) is dropping slightly faster than observations, while CAM6 has lower ice volume, but a decline rate is similar to observed. WACCM6 is a bit colder than CAM in the 1960-1980 period, and warming up faster. Analysis (not shown) indicates that in 2000-2014, there is less downward surface SW and LW in WACCM6,
and that this happens because of slightly higher LWP (in winter around the ice edge, in
summer over the ice). Higher LWP in WACCM6 than CAM6 results from higher aerosol
number. The higher aerosol number increases cloud condensation nuclei and cloud drop
number, resulting in smaller drops that do not precipitate as readily. Thus the tropo-
spheric aerosol chemistry impacts Arctic sea ice.

WACCM6 and CAM6 climate variability metrics are also very similar, with very few
statistical differences. WACCM6 however does have better high latitude surface pressure
variability, as illustrated in Figure 14. Other ensemble members are similar. WACCM6
has improved Northern Hemisphere high latitude surface variability by this metric com-
pared to CAM6, despite the same vertical resolution in the troposphere. Area-weighted
pattern correlations and Root Mean Square (RMS) differences for the standard deviation
of sea level pressure were calculated between observations (ERA Interim and 20th Cen-
tury reanalyses) and 3 ensemble members for WACCM6 and CAM6 historical coupled
experiments. December – February pattern correlations are as high for WACCM6 (0.96)
as for other reanalyses (0.95-0.96) and higher than for CAM6 (0.95-0.93). RMS differences
are 0.10-0.12 for other reanalyses relative to ERA, 0.11-0.12 for WACCM6 and 0.12-0.14
for CAM6 ensemble members. This variability improvement is present across 3 WACCM6
20th Century ensemble members compared to 9 CAM6 ensemble members. The differ-
ence is likely related to slight changes in the Northern Annular Mode (NAM) pattern
in the stratosphere, and indicates the importance of resolving stratospheric variability.
Experiments with WACCM-SC (no chemistry) look similar to WACCM6, indicating that
chemical-climate interactions and aerosol differences are not the cause. However, in a
WACCM6 experiment without convective gravity waves, high latitude variability looks
more like CAM6, indicating that momentum forcing of the stratosphere is likely important.

Improvements in tropospheric variability can also be seen in a metric of atmospheric blocking. Figure 15 illustrates a longitudinal index of blocking frequency as determined using the method of D’Andrea et al. [1998] which considers reductions in the meridional gradient of 500-hPa geopotential height below a threshold (-5 m deg\(^{-1}\)) to indicate blocking. Figure 15 illustrates the blocking frequency from CESM1 (LENS, 35 simulations), CESM2-CAM6 (5 simulations) and CESM2-WACCM6 (3 simulations). CESM2 is better at many locations than CESM1. March–May (MAM) is better than December–February (DJF) for all versions. In common with many CMIP5 models [Dunn-Sigouin and Son, 2013], CESM2 still has a DJF bias over the Atlantic, but there are improvements in CESM2 near the Greenland blocking ‘bump’ at 30°W in March–May, particularly in WACCM6. WACCM6 is also considerably better than CAM6 in the Pacific sector during DJF. Internal variability however is significantly greater than in the Atlantic sector.

6.2. WACCM6 v. WACCM4

Table 3 highlights several important differences in the climate of WACCM6 v. WACCM4. The tropospheric cloud radiative forcing (SWCRE and LWCRE) is lower, and closer to observations (CERES-EBAF). WACCM6 has higher cloud fraction (closer to obs) with reduced LWP, which is also more in line with observations where available (global values are not available). These results are consistent with improvements in CAM6 over CAM4 (see Neale et al. [2019] for details).
For Pre-Industrial (1850) control climates, WACCM6 has higher global mean precipitation, but very similar surface Temperature (Table 3). The global sea ice extent in WACCM4 [Marsh et al., 2013] is 20% higher than WACCM6 or CAM6.

WACCM6 and WACCM4 do a good job of reproducing tropical tropopause temperatures, but WACCM6 has a warmer summer tropopause temperature and increased annual cycle amplitude. WACCM4 (dashed lines in Figure 4A) has a faster tape recorder propagation speed in the mid stratosphere for free running simulations than WACCM6 (solid lines in Figure 4A). WACCM6 does a good job of reproducing the speed of the tape recorder compared to observations, with some vertical shifts. However, WACCM6 has a 0.5 ppm positive bias in summer, depending on the simulation (a coupled case looks better than the fixed SST case in Figure 4).

As noted in discussion of Figure 5, WACCM6 has slightly higher frequency of occurrence of SSWs than WACCM4, due to more late winter (March) warmings when compared to [Marsh et al., 2013, , Figure 3],

Finally, WACCM4 did not have an internally generated QBO, but it was forced to observations, while WACCM6 has an internally generated QBO (Figure 6).

7. Summary and Conclusions

WACCM6 represents the state of the art in simulation of the middle atmosphere up through the mesosphere. WACCM6 is available in several different configurations, and can be run fully coupled in CESM2, with fixed SSTs, or even with specified dynamics to produce observed dynamical variability. WACCM6 can also be run without full chemistry if just dynamical interactions are desired. WACCM-X [Liu et al., 2018] is a variant of WACCM that goes all the way to 500km, and represents additional thermosphere and
ionospheric processes, with physical parameterizations for the lower atmosphere lagging one generation behind WACCM6.

WACCM6 is able to reproduce the observed climatology of temperatures, winds and trace constituents such as water vapor and ozone in the middle atmosphere. WACCM6 is able to reproduce stratospheric variability from SSWs, the response to volcanic eruptions, the QBO and long term secular trends in the middle atmosphere. Biases in temperatures, winds and water vapor are small, and smaller than previous versions of WACCM. Volcanic emissions are fully prognostic from gas phase through stratospheric aerosol, improving temperature response to volcanic eruptions. Despite temperature biases in spring and early summer in the S. Hemisphere polar stratosphere, WACCM6 is able to reproduce the evolution of 20th and 21st century ozone. There are some biases in the tropics likely due to the speed of tropical upwelling.

WACCM6 features exactly the same lower atmosphere physical parameterizations as CAM6, making it very useful for comparable studies of the model top, as well as the impact of chemistry/aerosols in the troposphere and stratosphere. CAM6 uses specified stratospheric aerosol from WACCM6, as it was found that without interactive oxidants (OH), the lifetime of stratospheric SO$_2$ under high loading was different (and not correct). The present day climate of WACCM6 is nearly identical to CAM6 global mean variables, with similar trends over the 20th century in surface temperature. There are some differences due to absorption and scattering above the CAM6 top in WACCM6, and due to different evolution of tropospheric aerosols with the full tropospheric chemistry of WACCM6, that alters aerosol lifetime, particularly for organic aerosols. This can impact regional climate [Tilmes et al., 2019] as well as sea ice. Thus tropospheric chemistry and
aerosols can significantly impact Arctic climate, improving sea ice extent and volume in WACCM6 over CAM6.

Finally, there are some indications that the stratosphere can improve climate variability, even at the surface. High latitude variability in WACCM6, in particular the standard deviation of winter sea level pressure, is lower in WACCM6 than in CAM6, in better agreement with observations. This extends to WACCM-SC without chemistry, and seems to be related to gravity wave momentum in WACCM6. Blocking frequency is also closer to observed in WACCM6 than CAM6. This indicates that stratospheric dynamical processes are important for high latitude tropospheric variability. Thus stratospheric dynamics can improve high latitude climate variability.

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Table 1. Parameterizations in different versions of WACCM. References are as follows:

HB: Boville et al. [2006], Hack: Hack [1994], MG2: Gettelman and Morrison [2015],
CLUBB: Bogenschutz et al. [2013]; Larson et al. [2002], ZM: Zhang and McFarlane [1995],
ZM*: Zhang and McFarlane [1995]; Neale et al. [2008], MAM3: Liu et al. [2012]; Mills
et al. [2016], MAM4: Liu et al. [2016]; Mills et al. [2016], RRTMG: Iacono et al. [2008];
Mlawer et al. [1997], CAMRT: Collins et al. [2002], UW: Park and Bretherton [2009],
Park: Park et al. [2011], WMO 2010: World Meteorological Organization [2010], JPL-
06, JPL-11, JPL-15: Burkholder et al. [2015], CMIP5 RCPs: Meinshausen et al. [2011],
CMIP6: SSPs Meinshausen et al. [2017], 2-product: Heald et al. [2008], SOAG: Liu et al.
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Table 2. WACCM/CAM Configurations used in this paper, including cost (CPU-hours) of the model.

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Figure 1. WACCM6 (FHIST) simulation zonal wind for (A) DJF and (B) JJA. Contour interval of 10 m s\(^{-1}\). Differences between WACCM and ERA-Interim Reanalysis for (C) DJF and (D) JJA. Contour interval of 2.5 m s\(^{-1}\).
Figure 2. WACCM6 (FHIST) simulation temperatures for (A) DJF and (B) JJA. Contour interval of 10K. Differences between WACCM and ERA-Interim Reanalysis for (C) DJF and (D) JJA. Contour interval of 2K.
Figure 3.  WACCM6 (FWHIST) simulation (A) Climatological (1980–2010) S. Hemisphere Polar Cap (90–59°S) temperature evolution. Contour interval of 10K. (B) Difference v. MERRA2 reanalysis. Shaded differences are not significant at the 95% level based on a t-test. Contour interval of 2K.
Figure 4. A) Tape recorder velocity (mm/s) averaged over 2005-2014 from MLS Satellite observations (black), Specified dynamics WACCM (SD-Red), Free running specified SST WACCM6 (FR AMIP-blue) and fully coupled WACCM6 historical run (FR COUPLED-Green). WACCM6 solid lines, WACCM4 dashed lines. B) Composite MLS water vapor annual cycle showing the ‘tape recorder’ of low and high water vapor being advected in the vertical circulation of the stratosphere. C-E) composite water vapor annual cycles (contour shading) with MLS annual cycle (white contours). C) Specified dynamics WACCM6 (SD), D) Free running specified SST WACCM6 (FR AMIP) and E) Fully coupled WACCM6 historical run (FR COUPLED).
Figure 5. N. Hemisphere Winter SSW frequency by month for A) Coupled (BWHIST) and B) Historical specified SST or AMIP (FWHIST) WACCM6 simulations (gray shading=ensembles, black=mean), and NCEP reanalyses (red).
Figure 6. Monthly average zonal wind from 10°S–10°N in (A) European Center Reanalysis (ERAI), (B) WACCM6 Historical simulation with historical SSTs and (C) Fully Coupled WACCM6 historical simulation illustrating the Quasi-Biennial Oscillation.
Figure 7. Monthly average zonal wind from 10°S–10°N in A) SABER Satellite observations, B) Fully Coupled WACCM6 historical simulation (BWHIST) and C) WACCM6 specified SST simulation (FWHIST) illustrating the Semi-Annual Oscillation.
Figure 8. 5-day averaged SAOD (above model tropopause) from coupled (blue) and AMIP (red) ensembles compared to lidar observations (green, black, yellow). (a) Ny Alesund (78.9°N, 11.9°W) above 10 km (black, Ridley et al. [2014]) (b) Tomsk (56.5°N, 85.0°E) 15-30 km 10-day averages from Jan 1986 to Dec 2014 (black, Zuev et al. [2017]), and 12-30 km 10-day averages from Jan 2006 to Dec 2013 (green) (c) Geesthacht (53.4°N, 10.4°E) above the tropopause (black with 1-σ error bars, Ansmann et al. [1997]) (d) Tsukuba (36.1°N, 140.1°E) 15-30 km monthly averages from Apr 1982 to Dec 2014 (yellow circles), above the tropopause monthly averages from Nov 1988 to Dec 2014 (black, Sakai et al. [2016]), and above the tropopause daily from Jan 2008 to Jul 2013 (green) (e) Mauna Loa (19.5°N, 155.5°W) above the tropopause (black), Hofmann et al. [2009] (f) Lauder (45.0°S, 169.7°E) monthly averages from Nov 1992 to Dec 2014, 16.5-33 km (yellow) and above the tropopause (black) Sakai et al. [2016].
Figure 9. Total column ozone (in Dobson Units: DU) from WACCM6 coupled simulations (blue), specified SST (FWHIST) simulations (green), specified dynamics simulation (purple), and observations (black). Individual points are symbols, mean across ensembles solid line. A) October 90-60°S, B) March 60-90°N, C) Annual 65-35°S, D) Annual 35-60°N, E) Annual 20°S-20°N and F) Annual 60°S-60°N.
Figure 10. Tropical (20S-20N) averaged upwelling ($W^*$: TEM residual vertical velocity in mm/s). WACCM6 coupled simulations (FRb, blue), specified SST simulations (FRf, green), specified dynamics simulation with MERRA2 winds and temperatures (SD-MERRA2, purple).
Figure 11. Global mean surface temperature anomalies with respect to the 1920-1980 average with 5 year smoothing. Blue: mean of 10-member CESM2 historical ensemble (blue shading shows the ensemble spread). Three CESM2-WACCM historical ensemble members are red (001), orange (002), and green (003) curves. Observed temperatures from Hadley Centre-Climatic Research Unit Version 4 (HadCRUT4) infilled with kriging [Cowtan and Way, 2014] (black solid). Goddard Institute for Space Studies (GISS) Surface Temperature Analysis [Hansen et al., 2010] (black dashed). Top curves are a stratospheric aerosol optical depth index (1.15 - 2 x global average) for each CESM2-WACCM ensemble member.
Figure 12. A) MSU and SSU weighting functions from Randel et al. [2017] B) Global average temperature timeseries from three WACCM6 specified SST (FWHIST) ensembles convolved with SSU or MSU weighting functions (red). SSU or MSU observations (black).
Table 3. WACCM and CAM Simulation global averages compared to observations from historical (FHIST) simulations. Observations: CLDTOT (total cloud cover), CLDHGH (cloud cover for p<400 hPa), CLDLOW (cloud cover for p>700 hPa) from CLOUD-SAT+CALIPSO joint data product. Fluxes are compared to CERES EBAF 2.4 [Loeb et al., 2009] for Shortwave/Longwave Net at Top of atmosphere for all sky (FSNT, FLNT), clear sky (FSNTC, FNTC). Cloud Radiative Effects are the difference (LWCRE=FLNT-FLNTC and SWCRE=FSNT-FSNTC). Liquid and Ice Water Path (LWP, IWP) are compared to Microwave (liquid) and CloudSat (ice) observations. For Pre-Industrial (PI) 1850 control simulations, variables are surface temperature (Ts), precipitation rate (Precip), Sea Ice Extent (SIE) and Sea Ice Volume (SIV).

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Figure 13.  A) Arctic Sea Ice Extent in March (dashed) and September (solid). B) Arctic annual mean Sea Ice Volume. WACCM6 (black), CAM6 (grey). National Snow and Ice Data Center (NSIDC) ice extent satellite observations (red) [Fetterer et al., 2017] for A) and Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) ice volume estimate (red) [Schweiger et al., 2011] for B).

Figure 14. Interannual standard deviation of December-February averaged Sea Level Pressure (hPa) from A) ERA 20th Century Reanalysis B) WACCM6 coupled historical simulation ensemble member and C) CAM6 coupled historical simulation ensemble member.
Figure 15. Northern Hemisphere Blocking Frequency defined following D’Andrea et al. [1998]. Observations (black), CESM1 (blue), CESM2-CAM6 (Red) and CESM2-WACCM6 (green) for (A) December–February (DJF), (B) March–May (MAM). Averages are 1979-2005 from daily data and the shading is the full range of each ensemble set.