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Impact of future climate policy scenarios on air quality and aerosol-cloud interactions using an advanced version of CESM/CAM5: Part I. model evaluation for the current decadal simulations

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HIGHLIGHTS

- CESM-NCSU provides a reasonable representation of the current atmosphere.
- Aerosol-cloud interactions are well simulated in CESM-NCSU.
- Biases in chemical predictions are due to inaccurate emissions, mixing, deposition, and POA volatility.

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ABSTRACT

A version of the Community Earth System Model modified at the North Carolina State University (CESM-NCSU) is used to simulate the current and future atmosphere following the representative concentration partway scenarios for stabilization of radiative forcing at 4.5 W m^{-2} (RCP4.5) and radiative forcing of 8.5 W m^{-2} (RCP8.5). Part I describes the results from a comprehensive evaluation of current decadal simulations. Radiation and most meteorological variables are well simulated in CESM-NCSU. Cloud parameters are not as well simulated due in part to the tuning of model radiation and general biases in cloud variables common to all global chemistry-climate models. The concentrations of most inorganic aerosol species (i.e., SO_4^{2-}, NH_4^+, and NO_3^-) are well simulated with normalized mean biases (NMBs) typically less than 20%. However, some notable exceptions are European NH_4^+, which is overpredicted by 33.0–42.2% due to high NH_3 emissions and irreversible coarse mode condensation, and Cl^-, that is negatively impacted by errors in emissions driven by wind speed and overpredicted HNO_3. Carbonaceous aerosols are largely underpredicted following the RCP scenarios due to low emissions of black carbon, organic carbon, and anthropogenic volatile compounds in the RCP inventory and efficient wet removal. This results in underpredictions of $PM_{2.5}$ and PM_{10} by 6.4–55.7%. The column mass abundances are reasonably well simulated. Larger biases occur in surface mixing ratios of trace gases in CESM-NCSU, likely due to numerical diffusion from the coarse grid spacing of the CESM-NCSU simulations or errors in the magnitudes and vertical structure of emissions. This is especially true for SO_2 and NO_2. The mixing ratio of O_3 is overpredicted by 38.9–76.0% due to the limitations in the O_3 deposition scheme used in CESM and insufficient titration resulted from large underpredictions in NO_2. Despite these limitations, CESM-NCSU reproduces reasonably well the current atmosphere in terms of radiation, clouds, meteorology, trace gases, aerosols, and aerosol-cloud interactions, making it suitable for future climate simulations.

1. Introduction

The study of the future state of the atmosphere is of crucial importance as it will impact human and ecosystem health (Patz et al., 2005; Haines et al., 2006; Moore et al., 2008; Pereira et al., 2010; Shindell et al., 2012; West et al., 2013). However, these studies are limited since the true path of future climate and emissions of air pollutants are unknown and as a result the scientific community relies on many different scenarios to explore the range

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of possible future outcomes. The majority of future air quality studies have used either the older Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) Special Report on Emissions Scenarios (SRES) scenarios or the newer IPCC Fifth Assessment Report (AR5) Representative Concentration Pathway (RCP) scenarios (Fiore et al., 2012 and references therein). IPCC AR4 SRES scenarios are based primarily on socio-economic changes and as such the range in possible futures is described based on assumptions regarding the rate of globalization, population growth, and economic growth, as well as differences in future technology and energy generation (IPCC, 2000). The IPCC AR4 SRES scenarios are a limited projection of the future since none of these scenarios represent the implementation of climate policy initiatives and as a result scenarios with such policies were needed (IPCC, 2007). In a response to this need, the IPCC AR5 RCP scenarios were developed in a parallel process where information is exchanged between disciplines in a rapid manner to develop climate policy scenarios with multiple ways to achieve specific anthropogenic radiative forcing goals (Moss et al., 2008, 2010).

Ultimately, four RCP scenarios were chosen by IPCC AR5 including: a scenario that peaks at approximately 3.0 W m^{-2} and declines to 2.6 W m^{-2} by 2100 (RCP2.6), two stabilization scenarios where radiative forcing stabilizes at target values of 4.5 W m^{-2} (RCP4.5) and 6.0 W m^{-2} (RCP6), respectively, by 2100, and a scenario in which radiative forcing never stabilizes, reaching a value of 8.5 W m^{-2} by 2100 (RCP8.5) (Moss et al., 2010; van Vuuren et al., 2011a). Some commonalities in all scenarios are the introduction of carbon capture and storage technologies (CCS) to reduce global carbon emissions and greater affluence of developing countries that will lead to greater implementation of emissions control policies for atmospheric pollutants (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011a, b). The RCP8.5 scenario provides a pseudo baseline for the other scenarios as it is the scenario reflecting the least climate mitigation due in part to slower economic growth and turnover in technology. As a result, this is the worst case scenario in terms of greenhouse gas (GHG) emissions, as there are minimal controls implemented over energy sector emission of carbon dioxide (CO_2) and methane (CH_4) and increased demand in food supplies from greater populations leads to strong enhancements in nitrous oxide (N_2O) emissions from greater fertilizer use and significant increases in CH_4 emissions from increases in livestock and rice cultivation. Despite representing the worst carbon policy of all RCP scenarios, air pollutants are strongly reduced in RCP8.5 due to assumed successful implementation of current and planned air quality policies and implementation of these policies in developing countries once sufficient affluence is achieved (Riahi et al., 2011). The RCP2.6 scenario is the most optimistic of the RCP scenarios and achieves reduced radiative forcing through reductions in GHGs, largely from the introductions and large scale implementation of CCS systems on fossil fuel related emissions and introductions of alternative energy sources. Some of these climate policies provide additional air quality benefits as the introduction of CCS systems provides additional reductions in SO_2 emissions from coal and the implementation of hydrogen power sources in the transportation sector helps to reduce total non-methane volatile organic compound (TNMVOC) emissions (van Vuuren et al., 2011b). The more optimistic stabilization RCP4.5 scenario also relies strongly on CCS systems to achieve the radiative forcing target but includes greater reforestation as a process to control land use emissions and provide a carbon sink (Thomson et al., 2011). The less optimistic RCP6 scenario is possibly the most interesting pathway from an air quality perspective as Asian emissions in this scenario peak and then decline through the mid-21st century due to rapid expansion in Asian economies, resulting in the largest emissions of some pollutants (e.g., SO_2) under this scenario during the mid-21st century. Another key difference of this scenario compared to RCP4.5 is increases in deforestation and agriculture that drive greater emissions of CH_4 and N_2O that contribute to the larger radiative forcing target (Masui et al., 2011).

The projection of many air pollutants from these RCP scenarios is significantly different from the IPCC AR4 SRES scenarios where pollutant emissions increase mostly due to the lack of policy considerations (van Vuuren et al., 2011a). This results in key differences in future air quality, ecosystem health, and impacts from short lived climate forcers. For example, O_3 under the SRES scenarios is increased substantially in many scenarios (Prather et al., 2003), while O_3 decreases by 2100 in a global sense under all RCP scenarios except RCP8.5 (Lamarque et al., 2011; Young et al., 2013; Kim et al., 2015). Subsequently, radiative forcing from O_3 under the SRES A1B scenario is a projected increase by 2100 (Levy et al., 2008), while all the RCP scenarios except RCP8.5 project decreases in O_3 radiative forcing by 2100 (Stevenson et al., 2013). In terms of aerosols and radiative forcing the SRES A1B scenario predicted decreases in sulfate (SO_4^{2-}) radiative forcing but large increases in black carbon (BC) radiative forcing associated with emissions changes by 2100 (Levy et al., 2008), while under the RCP scenarios the radiative forcing of both SO_4^{2-} and BC decrease by 2100 in response to declining emissions (Lamarque et al., 2011). Commonalities exist in nitrogen deposition between both types of scenario as the A2 scenario shows enhancements in nitrogen deposition largely from increases in oxidized nitrogen from NO emissions (Dentener et al., 2006); while the RCP scenarios have enhanced nitrogen deposition in certain regions largely from increases in agricultural emissions of NH_3 (Lamarque et al., 2011; Shindell et al., 2013).

In this work, a version of the Community Earth System Model version 1.2.2 (CESM1.2.2) is employed in order to simulate the impact of future climate policy scenarios on air quality and aerosol-cloud interactions. This work will be presented in a sequence of two parts. Part I describes model configurations, application, and evaluation. Part II describes the impact of future climate and emission changes on future air quality under the RCP4.5 and RCP8.5 climate policy scenarios. The objective of Part I is to perform decadal simulations of the current atmosphere using emissions from both the RCP4.5 and RCP8.5 scenarios and to compare the state of the atmosphere predicted in these simulations to a current period decadal simulation using more detailed emissions. This will determine how well these scenarios represent the current atmosphere. This work differs from previous studies by providing a comprehensive model evaluation of the current climate as predicted by the RCP scenarios using CESM with advanced treatments for organic aerosol formation and aerosol-cloud interactions.

2. Model configuration, evaluation protocol, and observational datasets

2.1. Model configuration

The CESM1.2.2 model used in this study contains a version of the Community Atmosphere Model version 5.3 (CAM5.3) that has been modified at the North Carolina State University (hereafter CESM-NCSU) (He et al., 2015a, b). Details of the default treatments within CESM1.2.2 are found on the web at http://www.cesm.ucar.edu/models/cesm1.2/tags/index.html#CESM1_2. CESM-NCSU contains several updated treatments for simulation of gases, aerosols, and aerosol and cloud interactions. Gas-phase chemistry is simulated using the modified version of the 2005 Carbon Bond mechanism with global extension (CB05GE) (Karamchandani et al., 2012; He and Zhang, 2014). The version of CB05GE in CESM-NCSU also contains updated reactions for isoprene, toluene, xylene and their products, as well as, the inclusion of benzene, ethyne,