Improved Dust Representation and Impacts on Dust Transport and Radiative Effect in CAM5

Ziming Ke1,2, Xiaohong Liu1, Mingxuan Wu3, Yunpeng Shan3, and Yang Shi1

1Department of Atmospheric Sciences, Texas A&M University, College Station, TX, USA; 2Atmospheric, Earth, & Energy Division, Lawrence Livermore National Laboratory, Livermore, CA, USA; 3Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, WA, USA

Abstract Dust transport and spatial distribution are poorly represented in current global climate models (GCMs) including the Community Atmosphere Model version 5 (CAM5). Particularly, models lack explicit representation of super-coarse dust, which may have important implications for dust radiative forcing and impacts on biogeochemistry. A nine-mode version of the modal aerosol model (MAM9) has been developed to address these issues. In this new aerosol scheme, four dust modes have been designed to treat dust particles of sizes up to 20 μm. The MAM9-simulated results are compared with those from the default four-mode version of MAM (MAM4) and also with the in situ surface measurements of dust concentration and deposition flux, satellite-retrieved dust extinction profile, and in situ vertical measurements of dust concentrations from the NASA Atmosphere Tomography Mission (ATom). Overall, MAM9 improves the dust representation in remote regions while maintaining reasonably good results near the dust source regions. In addition, MAM9 reduces the fine dust burden and increases the coarse dust burden globally. The increased coarse dust burden has slightly increased the dust direct radiative effect by 0.01 W m⁻² while it enhanced dust indirect radiative effect by 0.36 W m⁻² globally.

Plain Language Summary Dust aerosol is the most abundant aerosol in the atmosphere. Although the current CESM-CAM5 model can capture some dust aerosol distribution features, the long-distance dust transport and coarse dust burden have been poorly represented. To address these issues, we have developed the nine-mode version of the modal aerosol model (MAM9) and implemented it to CESM-CAM5.4. The MAM9 has four dust modes to enhance the size resolution of dust in the model. The standard deviation in each mode is reset based on observational data. Also, dust and sea salt aerosols in our MAM9 are separated into different modes to reduce the wet scavenge across the Pacific and Atlantic Oceans. These changes improved dust transport in remote regions compared with MAM4. Moreover, the changes warm up the simulated atmosphere through the dust direct and indirect radiative effects.

1. Introduction

Mineral dust is one of the most abundant aerosol species by mass in the atmosphere and has broad impacts on the Earth system (Kok et al., 2017). The source regions of mineral dust are mostly arid or semiarid regions where the vegetation cover is sparse, and soils are easily erodible. When the wind blows over the soil, the dust particles are emitted into the atmosphere (Kok, 2011; Kok & Renno, 2009). Unlike sulfate aerosols, dust particles not only scatter solar radiation, but also absorb solar and terrestrial radiation when their size is larger than micrometer scale. Therefore, the direct radiative effect (DRE) of dust particles, which is the instantaneous radiative impact of all atmospheric dust particles on the Earth’s energy balance (Heald et al., 2014) could be close to a neutral or slightly warming effect (Kok et al., 2017). In terms of aerosol indirect effects, dust particles are observed to participate in cloud formation by serving as cloud condensation nuclei (CCN) and thus may alter the optical properties and the lifetime of clouds (Ansmann et al., 2009). In mixed-phase clouds, dust particles can form ice crystals via the heterogeneous ice nucleation by serving as ice nucleating particles (INP) resulting in a net positive cloud radiative effect (Murray et al., 2012; Y. Shi & Liu, 2019). Dust particles as INPs can compete with homogeneous nucleation for the formation of cirrus clouds and affect ongoing terrestrial radiation (Cziczo & Froyd, 2014). When dust particles fall from the atmosphere, the deposition over snow or ice surfaces can increase the surface albedo and enhance the snow melting rate (Painter et al., 2007). When it deposits over remote oceans, it can be an important source of nutrients to sustain ocean primary production (Ghan et al., 2012; Liu et al., 2012). Therefore, it is of great importance to represent the dust lifecycle accurately in Earth system models.
In recent decades, efforts have been made to represent the dust life cycle in global climate models (e.g., Ginoux et al., 2000; Li et al., 2021; Liu et al., 2012; Mahowald et al., 2014; Scanza et al., 2015; Zender, Bian, et al., 2003). Considerable uncertainties have been found in simulated dust concentrations, deposition fluxes, and optical properties (e.g., Huneeus et al., 2011; Kok et al., 2018; Pu and Ginoux, 2017; M. Wu et al., 2020). As pointed out in these studies, the dust transport in climate models can contribute significant biases to the simulated results. In particular, there are distinct differences in simulated dust properties in the same climate model under different aerosol model configurations (Liu et al., 2012; M. Wu et al., 2020).

The Community Earth System Model version 1 (CESM1) is a state-of-art model simulating the complicated interactions of different components in the Earth system (Hurrell et al., 2013). Its atmosphere component is the Community Atmosphere Model version 5 (CAM5) (Neale et al., 2010), in which two versions of the modal aerosol module (MAM) are introduced to represent the processes and properties of atmospheric aerosols in 2012 (Ghan et al., 2012; Liu et al., 2012). The three-mode version of MAM (MAM3) is the default in CAM5, including the Aitken, accumulation, and coarse aerosol modes. A more complicated version, the seven-mode version of MAM (MAM7) has been developed as an option to represent the aerosol size distributions in more detail but at an increased computational cost. Dust simulations in both MAM3 and MAM7 can capture the observed general pattern of global dust distributions, which feature as high dust burdens at source regions (e.g., Sahara Desert in North Africa, Central Asia, and Australia desert) and gradually reduced burdens toward remote regions (e.g., tropical Atlantic Ocean, North Pacific Ocean, and Antarctica) (Liu et al., 2012; M. Wu et al., 2020). MAM3 tends to overestimate observed dust surface concentrations in regions close to the sources while underestimating in remote regions (Liu et al., 2012). Compared to the Aerosol Comparisons between Observations and Models (AEROCOM) Phase 1 models, MAM3 produces a lower dust lifetime. MAM7 simulates higher dust surface concentrations in remote regions compared to MAM3 results due to higher fine dust emission partition (0.13 vs. 0.011, Table 1). However, this dust emission partition results in the high ratio of fine dust to total dust in the atmosphere (Ghan et al., 2012; Liu et al., 2012), contradicting to 0.035–0.057 estimated by Kok et al. (2017).

The four-mode version of MAM (MAM4) is the updated aerosol model since CAM5.3 and is the default in CAM6, which adds primary carbon mode into MAM3 to enhance the carbonaceous aerosol representation (Liu et al., 2016). As MAM4 does not change the dust configuration compared to MAM3, its results in terms of dust aerosol are comparable to MAM3 results. Study finds that MAM4 underestimates the dust concentrations over the Pacific Ocean and the Arctic regions by comparing the model results with CALIPSO-retrieved dust extinction and dust surface concentration measurements in the Arctic (M. Wu et al., 2020). Moreover, recent studies (Adebiyi & Kok, 2020; Kok et al., 2018) suggest that most of the current climate models underrepresent the coarse (diameter greater than 5 μm) and extra coarse dust (diameter greater than 10 μm) burden in the atmosphere and thus miss out the dust warming effect up to 0.15 W·m⁻².

To improve the representation of dust aerosols, particularly dust transport in remote regions and extra coarse dust, this study develops a nine-mode version of MAM (MAM9) for CAM5. MAM9 is based on MAM7 but adds two more coarse dust modes (Table 1). The fine dust, coarse dust 1, coarse dust 2, and extra coarse dust modes have size ranges of 0.1–1, 1–5, 5–10, and 10–20 μm, respectively. In Section 2, we provide a detailed introduction to MAM9, as well as the data sets used to validate the MAM9. In Section 3, we show the results of MAM9 in comparison to MAM4 and the AEROCOM dust observational data set, CALIPSO dust extinction, and the ATom observed dust concentrations. Furthermore, the dust direct radiative effect is discussed. In Section 4, we summarize our findings.

### 2. Model, Parameterization, and Observation Data

The model used in this study is the NCAR Community Atmosphere Model (CAM), version 5.4, running at 0.9° × 1.25° horizontal resolution with 56 vertical levels. This version is based on the released version 5.3 (Neale et al., 2010), and includes the same deep and shallow convection schemes, cloud macrophysics, and radiation calculations as CAM5.3 (Bogenschutz et al., 2018). The changes from CAM5.3 to CAM5.4 include an upgrade of...
cloud microphysics scheme for prognostic precipitation (Gettelman & Morrison, 2015), improved cirrus ice and mixed-phase cloud ice nucleation (X. Shi et al., 2015; Wang et al., 2014), and four-mode version of modal aerosol model (Liu et al., 2016).

2.1. MAM Dust Scheme

In the CAM5 framework, three modal aerosol models have been developed to meet various climate simulation demands. The three-mode version, MAM3, includes the Aitken, accumulation, and coarse aerosol modes with size ranges of 0.01–0.1, 0.1–1, and 1–10 μm, respectively. Fine and coarse dust particles are divided into the accumulation and coarse modes. The seven-mode version, MAM7, includes the Aitken, accumulation, primary carbon, fine sea salt, coarse sea salt, fine dust, and coarse dust modes. In this version, the size range for the fine and coarse dust mode is 0.1–2 and 2–10 μm. The fine dust mode size range in MAM7 is increased compared to the accumulation mode dust size range in MAM3, while the dust emission rate surges to 13%, compared to 1.1% in MAM3 accumulation mode (Liu et al., 2012). This increment of fine size dust emission rate can lead to overestimating the fine dust burden, which contradicts observations (Kok et al., 2017). The four-mode version, MAM4, adds primary carbon mode into MAM3 to enhance the carbonaceous aerosol representation (Liu et al., 2016). The dust configurations, including size range and emission partition, are similar to MAM3. The dust settings details in MAM3, MAM7, and MAM4 are summarized in Table 1.

The new MAM9 scheme is developed and implemented into CAM5 in this study, based on the previous MAM7 framework (Liu et al., 2012), which includes seven aerosol modes: Aitken, accumulation, primary carbon, fine sea salt, coarse sea salt, fine dust, and coarse dust modes. MAM9 expands the MAM7’s two dust modes into four modes while leaving the other five modes unchanged. The new four dust modes are fine dust, coarse dust 1, coarse dust 2, and extra coarse dust modes. The size ranges for these four dust modes are 0.1–1, 1–5, 5–10, and 10–20 μm, respectively (Table 1). For the fine dust mode, the geometric standard deviation (STD) is set to 2.0 in MAM9 instead of 1.8 in MAM7 and MAM4, while the STD values in the three coarse modes are 1.6 instead of 1.8 used in MAM7 and MAM4 (Table 1). This change is based on the in situ observations of coarse dust size distributions in remote regions (Porter & Clarke, 1997).

In CESM1, dust emission fluxes are calculated based on Zender, Bian, et al. (2003) and Zender, Newman, et al. (2003) in the Community Land Model version 4 (CLM4) and transferred into CAM5. The emitted dust size range is from 0.1 to 10 μm, without considering dust particles with sizes greater than 10 μm in MAM3 and MAM7. The total dust emission is further partitioned into different dust modes based on the specified ratios (Table 1). In MAM3, 1.1% of total dust emission mass is released in the accumulation mode, while 98.9% is released in the coarse mode. In MAM7, the values are 13% and 87%, respectively.

In this study, the ratios for fine dust mode, coarse dust mode 1, coarse dust mode 2, and extra coarse dust mode are 0.011, 0.365, 0.625, and 0.898, respectively. The first three ratios are based on Albani et al. (2014), which divided dust emission into four bins based on the fragmentation scaling theory (Kok, 2011). Here, we merge their second and third bins into our coarse dust 1 mode. The extra coarse dust emission ratio is based on Kok et al. (2017) and Huang et al. (2021), which summarized the dust mass emission rate at different size ranges. In these studies, the dust mass emission rate within the 10–20 μm size range is 0.898 of that within the 0.01–10 μm size range. Therefore, we set our extra coarse dust emission ratio to 0.898, so that the sum of the ratios for the first three modes equals one.

The default aerosol dry deposition scheme in CAM5 is based on Zhang et al. (2001) (hereafter referred to as Z01), while the new dry deposition scheme used in this study follows Petroff & Zhang (2010) (hereafter referred to as PZ10), which has been implemented in CAM5 by M. Wu et al. (2018). Compared to the default scheme Z01, the PZ10 predicts a lower dry deposition velocity for Aitken and Accumulation modes aerosols but a slightly higher dry deposition velocity for coarser aerosols (particle diameter greater than one μm) (M. Wu et al., 2018). As most dust particles are in coarse modes, we expect that the PZ10 scheme overall slightly reduces the dust surface concentration and burden compared to the default Z01 scheme. However, it would increase particle surface concentrations over snow and ice in remote regions where fine dust is dominant.

In CAM5, the cirrus cloud nucleation scheme includes the competition between the heterogeneous nucleation particles (coarse mode dust) with the homogeneous nucleation sulfate aerosols for available water vapors (Liu &
Penner, 2005). In this study, we also use the preexisting ice option (X. Shi et al., 2015) to modulate the ice formation in the cirrus cloud. For dust impact on mixed-phase clouds, we use the classical nucleation theory (CNT) scheme for heterogeneous ice nucleation, which counts for the coarse dust as INPs.

The default CAM5 model uses OPAC optical parameters (Hess et al., 1998) for dust, which are outdated and were accidentally included (Albani et al., 2014). This study uses the dust optics information updated by Albani et al. (2014), which also is the default dust optical file in CAM6. In the current CESM framework, the optical property files for each aerosol mode used for the RRTMG scheme are calculated offline based on the properties of each species in the mode and the mode size range following the method introduced by Ghan and Zaveri (2007). As MAM9 includes the extra coarse dust, we produced the offline optical file for this mode.

In this study, we use F_2000_CAM5 component to set up our model. The detailed configuration is CAM5 physics, CLM4 physics with Satellite Phenology (SP), prescribed sea ice, and prescribed ocean SST as 2000 climatology. In the atmosphere model, the U and V winds are nudged to MERRA2 data every three hours, which constrain the atmospheric winds, humidity, and convection. The PFT, LAI, and canopy height are prescribed through SP in the land model. We conduct two groups of model experiments: the first group covers the time period from 2004 to 2009 and the second group from 2016 to 2017. In each group, the CAM5-MAM4 configuration is set as the control run and the CAM5-MAM9 configuration as the sensitivity run. In the first group of experiments, the first two years are used as model spin-up and the 2007–2009 model results are compared with the AeroCom dust observational data set, and CALIPSO dust extinction data set. To compare model results with the ATom observational data set, daily outputs are conducted in the second group of experiments. Horizontal winds are nudged to the MERRA2 Reanalysis for all the model experiments.

### 2.2. Dust Extinction Data

The Cloud—Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on board the Cloud—Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) provide global vertical aerosol extinction and backscatter coefficients based on six different aerosol types, including clean continental, clean marine, dust, polluted continental, polluted dust, and smoke (Winker et al., 2009). Its level 3 products provide 1° x 1° monthly aerosol extinction profiles. In this study, we only use the dust aerosol type (and refer to it as L3 dust extinction data below), which has a good agreement with observations in the dust source regions (Amiridis et al., 2013). Luo, Wang, Zhang, et al. (2015) and Luo, Wang, Ferrare, et al. (2015) improved the CALIOP dust and thin ice cloud detection algorithm. The derived dust extinction profiles enhanced the data performance over the weak dust source regions, transport areas, and in the upper troposphere. Hereafter, we refer to it as the Luo dust extinction data. H. Yu et al. (2015) improved the CALIOP dust detection under cloud-free conditions to improve data in the dust transport regions. Based on this method, M. Wu et al. (2019) derived the globally dust extinction profiles from 2007 to 2009. Hereafter, we call it as the Yu dust extinction data. Overall, the L3 data have better quality in the dust source regions, especially over the Sahara Desert, while the Luo and Yu data are more sensitive to dust in the remote regions. As each data set has its own advantages and uncertainties, we include all the three data sets in the comparison with our model results.

### 2.3. Dust AeroCom Data

The dust surface concentration and deposition flux data are from AeroCom Benchmark Data website (https://aerocom.met.no/data). These data are collected by different projects and organized by Huneeus et al. (Huneeus et al. (2011). The surface concentration data contains 27 sites (Table 2) and 20 of them have long-term monthly measurements and are managed by the Rosenstiel School of Marine and Atmospheric Science at the University of Miami (Arimoto et al., 1995; Prospero et al., 1989; Prospero, 1996). These sites are designed to be located at source and remote regions to reflect large-scale dust transport pattern. The dust concentrations are derived from measured aluminum concentrations assuming an Al content of 8% in soil dust or from the weights of filter samples ashed at 500°C after removed soluble components with water (Huneeus et al., 2011; Prospero, 1999). Data at site 8 and 12 have been measured in 2000, while all others 25 sites are measured over 1983–1996. In this study, we organized the 27 sites into 6 regions to study the dust transport features across the Atlantic and Pacific Ocean and over Arctic and Antarctic regions (Table 3). The deposition flux data includes data derived from iron deposition measurements by assuming a 3.5% iron content in dust.
and data measured from sediment traps by the Dust Indicators and Records in Terrestrial and Marine Paleoenvironments (DIRTMAP) database (Tegen et al., 2002). These data sets are heavily used to evaluate model dust representation (Albani et al., 2014; Liu et al., 2012; Mahowald et al., 2009; M. Wu et al., 2020).

| Site | Longitude | Latitude | Observation | MAM4 | MAM9 |
|------|-----------|----------|-------------|------|------|
| 1    | −179.20   | −8.50    | 0.20        | 0.0089 | 0.013 |
| 2    | −177.35   | 28.22    | 0.72        | 0.44  | 0.82  |
| 3    | −170.58   | −14.25   | 0.16        | 0.016 | 0.018 |
| 4    | −159.75   | −21.25   | 0.11        | 0.034 | 0.052 |
| 5    | −159.33   | 3.92     | 0.10        | 0.020 | 0.039 |
| 6    | −157.70   | 21.33    | 0.73        | 0.27  | 0.50  |
| 7    | −80.25    | 25.75    | 4.59        | 1.70  | 2.96  |
| 8    | −80.25    | 25.75    | 3.76        | 1.70  | 2.96  |
| 9    | −64.87    | 32.27    | 3.36        | 0.77  | 1.21  |
| 10   | −64.05    | −64.77   | 0.03        | 0.00011 | 0.00050 |
| 11   | −62.51    | 82.49    | 0.36        | 0.0068 | 0.050 |
| 12   | −59.62    | 13.15    | 15.54       | 10.90 | 16.07 |
| 13   | −59.43    | 13.17    | (old)16.15  | 10.90 | 16.07 |
| 14   | −58.30    | −62.18   | 0.61        | 0.00043 | 0.00073 |
| 15   | −20.17    | 63.24    | 5.94        | 0.082 | 0.083 |
| 16   | −16.50    | 28.30    | 30.18       | 19.16 | 24.41 |
| 17   | −9.85     | 53.32    | 1.01        | 0.29  | 0.31  |
| 18   | 29.50     | −16.00   | 10.53       | 0.61  | 0.78  |
| 19   | 62.50     | −67.60   | 0.10        | 0.00040 | 0.00024 |
| 20   | 126.48    | 33.52    | 14.14       | 15.37 | 23.72 |
| 21   | 128.25    | 26.92    | 8.37        | 4.39  | 8.35  |
| 22   | 132.90    | −12.70   | 4.03        | 19.83 | 22.19 |
| 23   | 144.68    | −40.68   | 1.48        | 1.71652 | 2.04 |
| 24   | 162.33    | 11.33    | 0.24        | 0.1111 | 0.19 |
| 25   | 166.95    | −0.53    | 0.10        | 0.00786 | 0.014 |
| 26   | 167.00    | −22.15   | 0.17        | 0.58429 | 0.69 |
| 27   | 167.98    | −29.08   | 0.84        | 0.69689 | 0.86 |

Note. The concentration unit is μg/m³.

(Mahowald et al., 2009) and data measured from sediment traps by the Dust Indicators and Records in Terrestrial and Marine Paleoenvironments (DIRTMAP) database (Tegen et al., 2002). These data sets are heavily used to evaluate model dust representation (Albani et al., 2014; Liu et al., 2012; Mahowald et al., 2009; M. Wu et al., 2020).

| Location                                | Site number | Observation | MAM4 | MAM9 |
|-----------------------------------------|-------------|-------------|------|------|
| Atlantic Transport Source Region        | 16          | 30.18       | 19.16 | 24.41 |
| Atlantic Transport Downwind Region      | 7, 8, 9, 12, 13 | 8.68       | 5.19  | 7.85  |
| Pacific Transport Source Region         | 20, 21      | 11.26       | 9.88  | 16.03 |
| Pacific Transport Downwind Region       | 2, 6        | 0.73        | 0.36  | 0.66  |
| Arctic                                  | 11, 15      | 3.15        | 0.044 | 0.066 |
| Antarctic                                | 10, 14, 19  | 0.25        | 0.00031 | 0.0012 |

Note. The concentration unit is μm/m³.
2.4. Atmospheric Tomography Mission Dust Measurement

The NASA Atmospheric Tomography Mission (ATom) mission (https://espo.nasa.gov/atom) measured atmospheric gases and aerosols over the Pacific and Atlantic Oceans by using the DC-8 aircraft (Brock et al., 2021). During 2016–2018, four flight campaigns were conducted over ~84°N to ~86°S over the Pacific, Atlantic, Arctic, and Southern oceans for four different seasons. In the first two campaigns, ATom-1 (July 29—23 August 2016) and ATom-2 (January 26—21 February 2017), the mass concentration of dust particles with size range from 0.1–4 μm was measured by the NOAA Particle Analysis by Laser Mass Spectrometry (PALMS) (Froyd et al., 2019). There are 11 flights in the ATom-1 and 11 flights in the ATom-2 period. In both periods, dust concentrations from north to south across the Pacific Ocean and from south to north across the Atlantic Ocean were measured, as well as measurements in the high-latitude regions. In this study, we organize the measurement data into the Pacific Ocean segment, the Atlantic Ocean segment, and the Arctic segment. The simulated daily output of dust concentration along ATom flight track is used for the comparison. In other words, the ATom data are averaged into model 3D grids. In the Pacific and Atlantic Ocean segments, we average the observed and simulated data in each 30-degree latitude wide region and plot the vertical profiles of the dust concentrations against the altitude (pressure levels). In the Arctic segment, the ATom 1 and 2 data are compared with simulated data separately to show the seasonality of the Arctic dust (Figures 6–8).

3. Results

3.1. Comparison of Dust Surface Concentrations Between Model Results and in Situ Measurements

The 2007–2009 annual averaged dust surface concentrations from the MAM4 and MAM9 simulations are presented in Figure 1. The MAM4 simulation (Figure 1a) shows that dust concentrations are mostly abundant near the dust source regions: North Africa, Middle East, Central Asia, northwest China, and the Rocky Mountain

![Figure 1. Comparison of dust surface concentrations. Color shading indicates dust concentrations with unit μg/m³, for panel a to c. Panel a is for annual mean dust surface concentrations from the MAM4 simulation while Panel b is for dust concentrations from the MAM9 simulation. Panel c is for observed dust surface concentrations from the AEROCOM data set. Panel d is the relative difference between MAM9 and MAM4 dust results, in which color shading represents the ratio of difference (MAM9 minus MAM4) to MAM4.](image-url)
regions in the Northern Hemisphere (NH), and Australia, the southwest coast of Africa, and the east coast of South America in the Southern Hemisphere (SH). The dust transport follows prevalent wind directions, which are from east to west in the tropics and from west to east in midlatitudes. Therefore, North African dust blows to the Gulf of Mexico and Central America, while dust particles originating from Central Asia and northwest China travel across the northern Pacific to North America. These features are similar to many previous studies (Ghan et al., 2012; Liu et al., 2012; M. Wu et al., 2019).

However, the MAM4 simulation still has large biases compared to observed surface dust concentrations (Figure 1c and Table 2). Low biases are prevalent in two important dust transport pathways, from North Africa to Central America and from northwest China to North America, and in the polar regions: Arctic and Antarctic. Along the pathway of dust transport from the North Africa to Central America, there are six observational sites: one near the North African coast (site-16 in Table 2) and five near the Central American west coast, including site-7, -8, -9, -12, and -13 (Table 2). The site-7 and -8 as well as site-12 and -13 are very close to each other, which makes them indistinguishable from each other in Figure 1. The site-16 has an annual mean value of 30.175 μg/m³ (in red color) while the downwind sites record lower values ranging from 3.76 to 16.15 μg/m³. In the MAM4 simulation, the dust concentration at site-16 is 19.16 μg/m³ (in orange color) and the concentrations at the five Central American sites are from 0.76 to 10.91 μg/m³, indicating that the biases are more significant in the downwind region. Along the dust transport pathway from northwest China to North America, there are two sites near the east coast of China (site-20 and -21) with observed dust concentrations of 14.14 and 8.37 μg/m³, respectively, compared to the MAM4 results of 15.37 and 4.40 μg/m³, respectively. The two sites in the midlatitudes of Pacific islands (site-2 and site-6) have dust concentrations of 0.72 and 0.73 μg/m³, respectively, while the corresponding MAM4 values are 0.44 and 0.27 μg/m³. In the Arctic region (above 60°N), there are two sites (site-11 and -15) near Greenland with dust concentrations of 0.36 and 5.9 μg/m³, respectively, compared to 0.007 and 0.08 μg/m³ in the MAM4 results. In the Antarctic, there are three sites: site-10, -14, and -19 with observed dust concentrations of 0.03, 0.61, and 0.1 μg/m³, respectively, while the MAM4-simulated values are 0.0001, 0.0004, and 0.0004 μg/m³, respectively, indicating the low biases by 1–3 orders of magnitudes.

In comparison, the MAM9 simulation generally has higher dust surface concentrations and has better agreement with observations. On the dust transport pathway from North Africa to Central America, the annual mean value at site-16 (near source) is 24.4 μg/m³, compared to 19.2 μg/m³ from the MAM4 simulation and is comparable to the observed value of 30.18 μg/m³ although still a little too low. At the downwind of this pathway, the average value of the five sites (site -7, -8, -9, -12, and -13) is 7.85 μg/m³, compared to the observed average of 8.68 μg/m³ and the MAM4 average value of 5.19 μg/m³, showing the improvement at the downwind sites. On the pathway from northwest China to North America, the average value in two Asian coastal sites (site-20 and -21) are 16.03 μg/m³ from MAM9 compared to 11.3 μg/m³ from the observation and 9.88 μg/m³ from MAM4, while the average value

Figure 2. Observed dust surface concentration against model results. Color shading indicates results from different models. Site locations are shown in Figure 1c. The x-axis is observed concentration, while the y-axis is model results. The MAM4 results are shown in black dots while the MAM9 results are shown in red dots.
in two Pacific islands (site-2 and -6) is 0.66 μg/m³ from MAM9 compared to 0.73 μg/m³ from the observation and 0.36 μg/m³ from MAM4. These comparisons suggest that MAM9 can better simulate the dust surface concentrations along the two major dust transport pathways, especially at the downwind sites.

In the Arctic, the average dust concentration in the two sites (site-11 and -15) in MAM9 is 0.07 μg/m³. Although it is a strong increase compared to 0.04 μg/m³ in MAM4, it is still one order of magnitude lower than the observed value of 3.15 μg/m³. In the Antarctic sites (site-10, -14, and -19), the model-simulated dust concentrations are too small, 0.001 (MAM9) and 0.0003 (MAM4), compared to the observed value of 0.25 μg/m³. The regional average dust concentrations from MAM4 and MAM9 and from observations are given in Table 3.

The overall model performance against the observations is shown in Figure 2. The MAM9 results are higher than the MAM4 results for most of the observational data. Here, we consider a simulated result acceptable if it is within a factor of 10 difference from the observational value. By this definition, 21 out of 27 points simulated by MAM9 are in the acceptable range, while only 18 out of 27 points simulated by MAM4 are in the acceptable range. Importantly, the mean value of all the observations is 4.58 μg/m³, and the mean value of all the MAM9 points is 4.61 μg/m³, compared to the mean of 3.32 μg/m³ of all the MAM4 points. Therefore, in terms of dust surface concentrations, the MAM9 results are reasonably well and significantly improve the agreement with the observations compared to the MAM4 results.

Besides the general increase of dust concentrations in MAM9, stronger increases occur over the Arctic and Antarctic regions, where changes are broadly between one to ten times (Figure 1d). This is mainly due to the low concentrations in MAM4 and the enhanced transport and weaker dry deposition in MAM9 over ice surfaces. The latter also improves the black carbon concentrations in the Arctic regions in a previous study (M. Wu et al., 2018). However, the MAM9 increase in dust concentrations in the Greenland region is not strong enough to reproduce the observed value, which could be partly due to a lack of local dust sources in high latitudes (Kylling et al., 2018; Y. Shi & Liu, 2019). In the Antarctic, the MAM9-modeled dust concentrations are much still lower than the observations, which could be due to a lack of local sources and/or the too weak transport of dust from the low latitudes to SH high latitudes.

To analyze the impact of the dry deposition scheme on surface concentration, we use the MAM9 with PZ10 scheme as control run (MAM9PZ10), which is our standard MAM9 simulation, while using the MAM9 with Z01 scheme as test run (MAM9Z01). Simulations are conducted under same configurations with nudged U and V. The simulated results in the period of 2007–2009 are compared and shown in Figure S1 in Supporting Information S1. Overall, the MAM9PZ10 simulated slightly lower surface concentration (~0.38%) compared to MAM9Z01. The impact of the PZ10 scheme on dust concentration over the ocean is very limited. The relative changes are smaller than 5% for the most places. However, the MAM9PZ10 simulated up to 20% higher surface concentration over Antarctic and Greenland. This is in line with our expectation in Section 2.1 and agrees with M. Wu et al. (2018), which suggests that the PZ10 scheme could enhance the fine aerosol particle concentration over snow and ice surface, while slightly suppressing the coarse aerosol particle concentration in general.

Furthermore, we have evaluated the contribution of the extra coarse dust to the global surface concentration. We use the MAM9 with extra coarse dust as a control run (M9PM20), which is our standard MAM9 simulation, while using the MAM9 with only PM10 dust as test run (M9PM10). The simulated results in the period of 2007–2009 are analyzed and shown in Figure S2 in Supporting Information S1. Overall, the inclusion of the 10–20 μm dust has enhanced the global dust surface concentrations by 4.97%. But this enhancement is mainly in source regions. In the downwind regions like d, e, and f (defined in Figure 1d), the concentrations' increase is less than 10% compared to M9PM10. Therefore, the results suggest that the simulated improvements in the remote regions are mainly from narrowed geometric standard deviations for the coarse dust modes and the separation between dust and sea salt. Over the Arctic and Antarctic region, the contribution from PZ10 is not negligible. Near the source regions, the inclusion of the 10–20 μm dust is important.

As mentioned in Section 2.3, dust concentrations' data have been measured over 1983–1996, while the model-simulated data based on 2007–2009 meteorology conditions. A recent study shows that the global near-surface dust concentrations decreased by 1.2% per year over 1984–2012 (Shao et al., 2013), mainly due to the climate parameter changes (e.g., rainfall) in North Africa, Northeast Asia, South America, and South Africa regions. Therefore, the low bias of dust concentration simulated by the model over tropics and middle latitude could partially attribute to the climate inconsistency between the observational period (1983–1996) and simulation period (2007–2009). Furthermore, high-latitude (>50°N and >40°S) dust sources are missing in the current
CAM5 dust emission scheme. A study (Bullard et al., 2016) finds that these sources contribute at least 80–100 Tg (~5%) of dust to the Earth system. Thus, improving the dust emission scheme to include the high-latitude dust sources would enhance the model-observation comparison over Greenland, Iceland, and Antarctic regions.

### 3.2. Comparison of Dust Deposition Flux Between Model Results and Observations

Figure 3 shows the comparison of model-simulated annual dust deposition flux with the observation data collected by AeroCom data platform (Huneeus et al., 2011). We categorize the sites into five regions: Pacific, Atlantic, Antarctica, Arctic, and continents. The Arctic is for the sites with latitudes greater than 60°N while the Antarctica is for the sites with latitudes south of 55°S. The Pacific and Atlantic are for the sites in the ocean islands and away from continents. The continents are for the sites in the major continents (except the polar regions) and also close to the dust source regions. As shown in Figure 3, dust deposition fluxes in the continents are generally greater than those in other regions. Both the MAM4 and MAM9 results can reasonably agree with the observations except at a few sites. The added extra coarse dust mode (10–20 μm) in MAM9 increases the modeled deposition flux and improves the model agreement with the observations. There are three sites in the Atlantic region and the averaged results are improved in MAM9 compared to MAM4. In the similar way, MAM9 also improves the model results in the Arctic and Antarctica regions.

### 3.3. Comparison of Dust Extinction Profile Between Model Results and Satellite Data

In this subsection, we compare the model-produced dust extinction with satellite retrievals along two major dust transport pathways: the first one in the NH midlatitudes from Central Asia dust source regions across the Pacific Ocean to North America, and the second one in the tropics from North African desert across the Atlantic Ocean to Central America. Three CALIOP dust extinction data sets are used in this study, which are retrieved based on different methods (Luo, Yu, and L3). The details of these data sets are introduced in Section 2.2. As each data set has its own advantages and uncertainties, we include them to quantify the range of satellite retrieved dust extinction. MAM4-and MAM9-simulated dust extinction results are compared with these three satellite data sets to evaluate the model performance. Both model results and satellite retrievals covering the time period from 2007 to 2009 are used in the analysis.

For the first transport pathway, we break it down into six regions of interest and all of them have the same size: 30-degree width in both latitude and longitude. These regions have the same latitude band from 20 to 50°N and the longitude ranges from east to west are 60–90°E, 90–120°E, 120–150°E, 150–180°E, −180 to 150°W, and 150 to 120°W, respectively, from region a to f shown in Figure 1d. The comparisons of dust extinction profiles for the six regions are shown in Figure 4.

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**Figure 3.** Observed and simulated annual mean mineral dust total (dry plus wet) deposition flux (g m⁻² yr⁻¹). The observational data were collected by Mahowald et al. (2009). The left panel shows the comparison between MAM4 results and observations, while the right panel shows the comparison between MAM9 results and observations.
Region a is the source region in this dust transport pathway including the Taklamakan and Gobi Deserts. The satellite-measured dust extinction profiles are close to each other with some discrepancies between 800 and 1000 hPa. The extinction values are high from 0.02 to 0.1 km\(^{-1}\) near surface. The simulated dust extinction profiles lie within the range of the satellite data below 500 hPa, indicating reasonable simulations of the dust emission and vertical transport. Above 500 hPa altitudes, the simulated values are higher than the satellite retrievals. The close agreement between MAM9 and MAM4 results suggests that the additional extra coarse mode dust (10–20 μm) in MAM9 has little impact on the dust extinction and both MAM9 and MAM4 results agree well with the satellite retrievals. Although 10–20 μm dust has strong emission rate, the large size particles, whose surface area to mass ratio are low, have little impact on particle extinction. Therefore, we see MAM4 and MAM9 has similar vertical profiles over the source regions. Both simulations use the same dust emission tuning factor that let the AOD in the dust region close to the satellite observation. This setting causes the simulated dust extinction like the observed values below 500 mb. Above 500 mb, model simulated high dust extinction compared to satellite-derived values, probably due to the inefficient wet removal in the CAM5 model that leads to a high bias of the aerosol concentration in the upper troposphere (Shan et al., 2021).

Region b is mainly the East Asian continent and the downwind region off the deserts with some local weak dust sources. The decay of dust extinction is expected during the dust transport. The Yu and Luo extinctions show slight increases compared to region a while the L3 extinction even increases between 900 and 1000 hPa. Thus, the three satellites' data shows large differences and the L3 extinction is much larger than the Luo and Yu extinctions below 500 hPa altitude. The MAM9 result is slightly larger than the MAM4 result, indicating that the decay of MAM9 dust extinction is slower than that of MAM4. In general, both MAM9 and MAM4 results are within the range of the three satellites' retrievals.

Regions c and d are over the western Pacific and dust extinction keeps decaying. The MAM9 and MAM4 results are in line with the Luo and Yu data in region c and the difference between MAM9 and MAM4 is increased in region d. Region e is over the eastern Pacific, which is far from the dust source region and dust extinction is much smaller compared to that in the source region a. Between 500 and 1000 hPa, the MAM4 result is much smaller than the satellite retrievals while the MAM9 result improves the agreement with the satellite data especially with Luo and Yu data. Region f contains mostly the eastern Pacific and west coast of North America. There is no obvious decay of the dust extinction compared to region e in both model results and satellite data, and some dust sources over North America may help to sustain the dust extinction. Again, the MAM9 result is greater than the MAM4 result and agrees better with satellite retrievals. In summary, MAM9 and MAM4 reproduce the dust extinction profile reasonably well in the dust major source regions, where there is no significant difference between MAM9 and MAM4 results. Along the transport pathway, the MAM9 dust extinction has a better agreement with the satellite data, and decays slower than the MAM4 dust extinction.

To further investigate the dust transport process across the northern Pacific Ocean, the dust mass budgets from MAM4 and MAM9 are shown in Tables 4 and 5, respectively. In the two source regions (a and b), MAM9 produces more dust burden than MAM4, especially in region b, where the dust burden in MAM9 is 82% higher than that in MAM4. The dust emission of MAM9 is double than that of MAM4 due to the extra coarse mode dust in 10–20 μm range. Although there is a large amount of emissions for the extra coarse mode dust, it does

| Table 4 |
|---|
| The MAM4 Dust Budget in Regions Across the Northern Pacific Ocean |
| MAM4 Pacific | Region a | Region b | Region c | Region d | Region e | Region f |
| Emission (Tg/yr) | 341.10 | 306.60 | 1.16 | 0.00 | 0.00 | 0.00 |
| Burden (Tg) | 1.40 | 0.99 | 0.24 | 0.05 | 0.02 | 0.02 |
| Wet Dep. (Tg/yr) | 49.90 | 45.63 | 12.27 | 1.30 | 0.42 | 0.18 |
| Dry Dep. (Tg/yr) | 190.81 | 140.59 | 10.90 | 0.81 | 0.27 | 0.16 |
| Wet Dep. Lifetime (Day) | 10.21 | 7.92 | 7.28 | 15.06 | 21.72 | 33.27 |
| Dry Dep. Lifetime (Day) | 2.67 | 2.57 | 8.19 | 24.22 | 33.26 | 37.62 |
| Accumulation Mode Burden (Percentage) | 0.03 | 0.03 | 0.04 | 0.06 | 0.08 | 0.10 |
| Coarse mode Burden (Percentage) | 0.97 | 0.97 | 0.96 | 0.94 | 0.92 | 0.91 |
not increase the dust extinction (Figure 4) and only contributes to ~17% of dust burden in the source regions (Table 5). In the fine dust mode (0.1–1 μm), MAM9 and MAM4 have similar emissions but MAM9 has a larger standard deviation, resulting in less fine dust burden (1.8% compared to 3.2% in Tables 4 and 5). Recent studies suggest that GCMs produce more fine dust compared to observations (Adebiyi & Kok, 2020; Kok et al., 2017).

Most of the dust burden in MAM9 in region a and b is attributed to coarse 1 and coarse 2 modes, which contribute more than 80% of the total dust burden (Table 5). The coarse dust modes in MAM9 have a lower standard deviation of 1.6 compared to 2.0 in MAM4, reducing the dry deposition rate in these modes.

### Table 5

**The MAM9 Dust Budget in Regions Across the Northern Pacific Ocean**

| MAM9 Pacific | Region a | Region b | Region c | Region d | Region e | Region f |
|--------------|----------|----------|----------|----------|----------|----------|
| Emission (Tg/yr) | 712.08 | 669.59 | 2.28 | 0 | 0 | 0 |
| Burden (Tg) | 2.03 | 1.80 | 0.41 | 0.11 | 0.06 | 0.04 |
| Wet Dep. (Tg/yr) | 50.08 | 42.66 | 12.54 | 2.04 | 0.70 | 0.31 |
| Dry Dep. (Tg/yr) | 513.29 | 446.69 | 20.36 | 1.12 | 0.41 | 0.30 |
| Wet Dep. Lifetime (Day) | 14.77 | 15.41 | 11.97 | 19.02 | 28.95 | 45.72 |
| Dry Dep. Lifetime (Day) | 1.44 | 1.47 | 7.37 | 34.48 | 49.71 | 47.47 |
| Fine Dust burden (Percentage) | 1.81 | 1.76 | 2.55 | 3.31 | 3.76 | 4.08 |
| Coarse1 Dust Burden (Percentage) | 44.77 | 43.98 | 56.13 | 64.13 | 67.68 | 69.80 |
| Coarse2 Dust Burden (Percentage) | 36.69 | 36.83 | 33.63 | 29.40 | 26.71 | 24.89 |
| Extra Coarse Dust Burden (Percentage) | 16.73 | 17.43 | 7.69 | 3.18 | 1.85 | 1.23 |

**Figure 4.** Dust extinction profiles from Central Asia across the Pacific Ocean to North America. The gray solid lines show dust extinction from Luo’s data, the gray dashed lines show dust extinction from Yu’s data, and the black solid lines show dust extinction from CALIPSO L3 data. The red lines are results derived from the MAM9 simulation and blue lines are from the MAM4 simulation. The regions (a–f) are shown in Figure 1d in solid boxes.
In the remote regions (d, e, and f) over the Pacific Ocean, dust burdens in MAM9 are two times of those in MAM4, while the contribution from the extra coarse mode becomes smaller (1.2% in region f). The dry/wet deposition rates decrease together with the burden. The dry or wet deposition lifetime, defined as burden divided by deposition rate, is a measure of how quickly the current burden is totally removed from the atmosphere if dry or wet deposition acts. Longer lifetimes mean a weaker removal. The MAM9 gives longer dry and wet deposition lifetimes than the MAM4. The longer dry deposition lifetime for MAM9 is expected as its smaller standard deviation in coarse dust modes, while the reason for the longer wet deposition lifetime in MAM9 is due to the separation of dust and sea salt aerosols in the coarse modes. Mixing dust and sea salt aerosols within the same coarse mode in MAM4 increases the dust hygroscopicity and thus enhances the wet removal of dust particles.

Despite the improvement made by MAM9, there is still a gap between observations and modeling results, over regions e–f. A possible reason for the low bias is the lack of local dust sources. For example, the dust sources in Alaska and the west coast of Northern America are missing in the current model (Figure 1). Improving the dust source map would reduce this low bias.

For the second pathway, we break it down into six regions of interest and all of them have the same size: 30° bands in both latitude and longitude. The regions have the same latitude range from 0 to 30°N and the longitude ranges from east to west are 60 to 30°E, 30 to 0°E, 0–30°W, 30–60°W, 60–90°W, and 90–120°W, respectively from region g to l, as shown in Figure 1d. The mean of the three years 2007–2009 are analyzed. The results in these six regions are shown in Figure 5.

The panels g and h for Figure 5 correspond to the dust source regions over Saharan desert and Middle East. The Yu and Luo’s data are generally close to each other and have larger values than the L3 data above 500 hPa level, while having smaller values than the L3 data below 700 hPa level. The MAM4 and MAM9 profiles are close to each other and have larger values than the three CALIPSO data sets over 500 hPa while they are in between the three CALIPSO data sets below 700 hPa level. Again, the too large model results over 500 hPa can be due to the

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Same as Figure 4 except for dust extinction profiles from across the Africa to Central America. The panels g to l show the dust extinction for regions g to l in Figure 1d in dashed boxes.
convectional wet removal issue discussed in P. Yu et al. (2019) and Shan et al. (2021). Dust emissions in the MAM9 extra coarse dust mode do not increase the dust extinction, as MAM9 and MAM4 results are very similar below 300 hPa level.

The panels $i$, $j$, and $k$ are for the dust transport regions from the African continent to Central America and the Caribbean Sea. In panel $i$, the MAM4 and MAM9 results are still close to each other because half of the region $i$ (Figure 1d) is the desert. In panel $j$ and $k$, both the MAM9 and MAM4 results indicates a faster decay of extinction compared to the CALIPSO data, but the MAM9 decay is slower than that of MAM4, indicating a better simulation of dust transport by MAM9 than MAM4. In panel $l$, the CALIPSO data show dust extinction comparable with panel $k$. However, the model shows the continual decay as the MAM9 and MAM4 dust extinctions are much weaker than the observation data.

The dust mass budget for MAM4 and MAM9 in the six regions are summarized in Tables 6 and 7, respectively. In the source regions $g$, $h$, and $i$, MAM9 has more emissions than MAM4 because it includes the extra coarse dust mode (10–20 μm). These extra emissions do not contribute much to the dust extinction as shown Figure 4 and have limited contribution to the dust burden (12–15%) in these three regions. Dust dry deposition in MAM9 is also stronger in these regions as extra coarse mode dust particles fall off faster. In regions $j$ and $k$, dust transports across the Atlantic Ocean and arrives in Gulf of Mexico. The MAM9 dust burden is twice that of MAM4 dust burden in region $k$ (0.15 vs. 0.07 Tg) and the MAM9 dry and wet deposition lifetimes are longer than those of MAM4. The dry deposition lifetime increase in MAM9 is due to the smaller standard deviation in the coarse modes and the wet deposition lifetime increase can be due to the separation of dust and sea salt aerosols in the coarse modes, which reduces the dust hygroscopicity and thus the wet removal of dust particles. In region $l$, the model shows small dust emissions in this region, but it is not sufficient to enhance the dust burden as shown in the satellite data.

| Table 6 |
| The MAM4 Dust Budget in Regions Across the Tropical Atlantic Ocean |

| MAM4 Atlantic | Region $g$ | Region $h$ | Region $i$ | Region $j$ | Region $k$ | Region $l$ |
|---------------|------------|------------|------------|------------|------------|------------|
| Emission (Tg/yr) | 602.18     | 595.92     | 347.56     | 0.00       | 0.00       | 0.002      |
| Burden (Tg)    | 3.77       | 5.19       | 2.78       | 0.44       | 0.07       | 0.01       |
| Wet Dep. (Tg/yr) | 72.58     | 180.97     | 74.52      | 26.88      | 6.94       | 0.66       |
| Dry Dep. (Tg/yr) | 375.50    | 471.37     | 245.91     | 16.55      | 2.82       | 0.58       |
| Wet Dep. Lifetime (Day) | 18.96  | 10.47      | 13.62      | 6.01       | 3.74       | 7.23       |
| Dry Dep. Lifetime (Day) | 3.66    | 4.02       | 4.13       | 9.77       | 9.20       | 8.27       |
| Accumulation Mode Burden (Percentage) | 3.35 | 3.61       | 3.84       | 6.24       | 8.86       | 9.85       |
| Coarse mode Burden (Percentage) | 96.65 | 96.39      | 96.16      | 93.76      | 91.14      | 90.15      |

| Table 7 |
| The MAM9 Dust Budget in Regions Across the Tropical Atlantic Ocean |

| MAM9 Atlantic | Region $g$ | Region $h$ | Region $i$ | Region $j$ | Region $k$ | Region $l$ |
|---------------|------------|------------|------------|------------|------------|------------|
| Emission (Tg/yr) | 1211.60   | 1239.90    | 752.60     | 0.00       | 0.00       | 0.001      |
| Burden (Tg)    | 4.97       | 7.58       | 4.19       | 0.73       | 0.15       | 0.03       |
| Wet Dep. (Tg/yr) | 84.39     | 194.25     | 98.92      | 35.13      | 12.81      | 1.58       |
| Dry Dep. (Tg/yr) | 932.20    | 1125.90    | 626.40     | 22.40      | 4.33       | 1.05       |
| Wet Dep. Lifetime (Day) | 21.51  | 14.25      | 15.47      | 7.59       | 4.30       | 5.99       |
| Dry Dep. Lifetime (Day) | 1.95    | 2.46       | 2.44       | 11.89      | 12.72      | 9.04       |
| Fine Dust burden (Percentage) | 1.92  | 2.08       | 2.24       | 3.55       | 4.67       | 5.35       |
| Coarse1 Dust Burden (Percentage) | 46.94 | 49.68      | 51.30      | 67.88      | 75.24      | 74.52      |
| Coarse2 Dust Burden (Percentage) | 36.14 | 35.44      | 34.39      | 26.66      | 19.73      | 18.19      |
| Extra Coarse Dust Burden (Percentage) | 15.00 | 12.80      | 12.06      | 1.92       | 0.36       | 1.95       |
3.4. Comparison Between Model Results and ATom Dust Measurement

Figure 6 depicts the comparison of modeled and ATom-measured dust concentrations against atmospheric pressure over the Pacific Ocean from 60°S to 60°N by the ATom-1 and ATom-2 projects. The ATom-1 measurements were conducted in the NH summer (July–August 2016). The measurements show comparable dust concentrations in both hemispheres with respect to the latitude (i.e., higher in the low latitudes and lower in the high latitudes). The model reasonably simulates the dust concentrations in the high latitudes (panels a and d) but does a poor job in the low latitudes (panels b and c). In the low latitudes, both MAM4 and MAM9 underestimate dust concentrations by more than one order of magnitude. In the Southern Hemisphere, this underestimation may be due to the dust soil erodibility map used in this study, which is introduced by Zender, Newman, et al. (2003). Kok et al. (2014) shows that this dust erodibility map underestimates dust emissions in the Southern Hemisphere. M. Wu et al. (2020) suggests that the CAM6 using different soil erodibility map by Ginoux et al. (2001) has improved the dust concentration comparison in the Southern Hemisphere. In all the four panels, the model tends to overestimate the dust concentrations above 500 hPa level, which is likely related to the aerosol convective wet removal mentioned in Section 3.3.

The ATom-2 measurements were conducted over the Pacific Ocean during the NH winter. During this period, the ATom measurements depict higher dust concentrations compared to the ATom-1 period in the NH, while there are no significant changes in the SH. The MAM9 results agree well with the ATom-2 data in terms of both magnitude and vertical distributions, except in panel f, where the measurement data were limited. This suggests that MAM9 significantly improves the dust simulation by the model.

In the Atlantic segment (Figure 7), MAM9 and MAM4 poorly simulate the SH dust vertical profiles in both periods (panel a, b, e, and f), suggesting the biases related to dust emissions as discussed in a previous study (M. Wu et al., 2020). In the NH, the MAM9 improves the agreement with observations. Overall, the model simulates the dust concentrations better over the Pacific Ocean than over the Atlantic Ocean.

In the Arctic segment, the ATom measurements display a strong seasonality of dust concentrations near the surface. In summer (ATom-1, Figure 8a), dust concentration slightly decreases from 200 to 700 hPa but
increases sharply from 700 to 900 hPa. The model captures the trend between 200 and 700 hPa, but fails to do so between 700 and 900 hPa, suggesting that the model may miss the local dust source in the high latitudes (Y. Shi et al., 2022), which can be important in the summer after surface snow and ice melt. In contrast, the local dust source has little contribution during the winter, as land surface is covered by snow, and dust long-range transport is the sole source for the Arctic dust. During this period, MAM9 improves the dust vertical profile with enhanced dust transport from the lower latitudes.

3.5. Global Dust Burden and Lifetime

The global dust budgets simulated by MAM4 and MAM9 are summarized in Tables 8 and 9. For the three-year averages (2007–2009), MAM4 simulates the global dust burden at 21.8 Tg with the dust lifetime of 2.8 days,
which are similar to the results produced by MAM3 (Liu et al., 2012) and MAM4 (Liu et al., 2016; M. Wu et al., 2020). Most of the burden is from the coarse mode, 20.96 Tg, compared to 0.82 Tg from the accumulation mode dust. For the accumulation mode dust, the primary removal process from the atmosphere is the wet removal, while for the coarse mode, the primary removal process is the dry deposition due to the increase of dust sizes. The spatial distribution of dust column burden (vertically integrated) concentrations by MAM4 is shown in Figure 9a. The dust column burden concentrates over the source regions, such as Northern Africa, Middle East to Central Asia, Australia, Rocky Mountain regions in North America, and the Andes Mountain area in South America. Dust also transports to the remote regions over the tropical Atlantic Ocean and Northern Pacific Ocean as we discussed in Section 3.3.

Overall, the global dust burden increases to 31.4 Tg in MAM9, around 50% increase compared to MAM4. The burden mainly resides in the coarse dust 1 and 2 modes, as well as in the extra coarse dust mode. The lifetime of the extra coarse dust mode is less than half day, 0.48 days. The lifetimes of the coarse mode 1 and 2 are 5.89 and 1.98 days, respectively. These results agree well with the other GCM study (Kok et al., 2017). Dry deposition is the main removal mechanism for all the coarse dust modes, while wet removal dominates in the fine dust mode.

The spatial distribution of dust column burden concentrations by MAM9 is shown in Figure 9b and the relative difference between MAM9 and MAM4 are shown in Figure 9c. MAM9 increases the dust burden concentrations over the Pacific and the Atlantic Ocean as we discussed in Section 3.3. Also, the dust burden concentrations are enhanced over the Rocky Mountains, Andes Mountains, and associated downwind regions. In the high-latitude regions, the dust burden concentrations are increased in the Arctic while reduced in the Antarctic.

Figure 9. Global distribution of dust column burden concentrations (mg m^{-2}) from (a) MAM4 and (b) MAM9. Panel c is the relative difference in percentage of dust column burden concentrations between MAM9 and MAM4.
3.6. Dust Direct and Indirect Radiative Effect

In this study, the MAM4 and MAM9 experiments simulated global-averaged AOD over 2007–2009 are 0.119 and 0.123, respectively, in line with the 0.126 measured by MODIS over 2003–2012 (Mao et al., 2014). The Dust AOD simulated by MAM4 and MAM9 experiments over 2007–2009 are 0.020 and 0.025, respectively. These values are lower than observational-based estimation, 0.03, but in line with AeroCom model median value, 0.023 (Ridley et al., 2016).

The dust direct radiative effect (DRE) and indirect radiative effect (IRE) at the top of the atmosphere (TOA) in 2007–2009 were diagnosed based on the method introduced by Ghan (2013). The global annual mean MAM4 results are summarized in Table 10. The dust shortwave effect is −0.33 W m\(^{-2}\), longwave effect is 0.092 W m\(^{-2}\), and the net effect is −0.24 W m\(^{-2}\). The negative sign means a cooling effect at TOA. This agrees with the other GCM results summarized by IPCC report (2013), −0.1 (−0.3 to +0.1) W m\(^{-2}\), and other studies (Albani et al., 2014; Kok et al., 2017; Scanza et al., 2015) (Table 12). As dust particles in MAM4 are relatively small, the dust net radiative effect in both accumulation and coarse modes are negative. Spatially, the negative net radiative effect is prevailing, and the net positive radiative effect is limited over dust source regions (e.g., Sahara deserts and Middle East) and the Arctic. The reason for the regional positive radiative effect is due to the dust particles aloft over land surface brighter than dust, such as deserts and sea ice/snow surface.

The global annual mean dust DRE by MAM9 is summarized in Table 11. The net radiative effect is −0.23 W m\(^{-2}\), which is 0.01 W m\(^{-2}\) warmer than MAM4. The longwave DRE contributes to this warming effect. The shortwave radiative effect is −0.35 W m\(^{-2}\), which is 0.02 W m\(^{-2}\) colder than that of MAM4 and the longwave radiative effect is 0.13 W m\(^{-2}\), which is 0.04 W m\(^{-2}\) warmer than that of MAM4. The first two dust modes, the fine dust and coarse dust 1, have dust particle sizes smaller than 5 μm, resulting in net negative radiative effects, while the coarse dust 2 and extra coarse modes with particle sizes greater than 5 μm have net positive radiative effects. This change of dust radiative effect with particle size qualitatively agrees with previous studies (Kok et al., 2017, 2018). However, because of the shorter lifetime and lower particle numbers in coarser dust modes, their warming effect is limited. As the model increases the global dust burden from 21.8 Tg in MAM4 to 31.4 Tg (Tables 8 and 9), this implies that the dust DRE is not proportional to the dust burden. In this study, the extra coarse mode dust burden (4.1 Tg) is larger than the estimate of 3 Tg by Kok et al. (2017), and the coarse dust (≥5 μm) burden, 15.01 Tg, is close to the estimate of 17 Tg by Adebiyi and Kok (2020). However, the longwave dust DRE in our model does not increase from MAM4 to MAM9 as much as expected. This may be due to differences in model dust optical properties.

The spatial distribution of difference between the MAM9 and MAM4 dust DREs is shown in Figure 10c. The positive value dominates especially over the dust source regions, the northern Euro-Asia continent, Arctic, and most of oceans. The warming effect over Africa, Middle East, and northern Euro-Asia continent is attributed to
The coarse dust 2 and extra coarse dust modes (Figures 11c and 11d). Although the extra coarse mode has a short lifetime and limited transport, it has a strong DRE over continents. The coarse dust 1 and 2 modes have a warming effect over dust source regions and the Arctic.

The impacts of the dust difference between MAM9 and MAM4 on clouds and related indirect radiative effect are summarized in Figure 12. Because dust particles are important ice nuclei, the enhancement of the dust transport has enhanced cloud ice water path by 0.024 g/m² and reduced cloud liquid water path by 0.11 g/m² globally. The increase of ice water path is noticeable over the tropics and middle to high latitudes in the Southern Hemisphere. In contrast, the ice water path declines over the middle to high latitudes in the Northern Hemisphere. Figure 13 shows that the ice number concentration above 300 hPa (cirrus clouds) has been enhanced globally. The ice number concentration between 500 and 300 hPa (mixed-phase clouds) has been suppressed in the Northern Hemisphere by comparing MAM9 with MAM4. Because the cirrus cloud heterogeneous ice nucleation is only associated with coarse mode dust in the current model (Liu et al., 2007), the enhanced coarse mode dust burden in MAM9 contributes to the increase in cirrus cloud ice. Meanwhile, the fine and coarse mode dust particles participate in the mixed-phase cloud ice nucleation process. Generally, the fine mode dust has a higher number concentration than the coarse mode dust in remote regions due to its smaller size and longer lifetime. Because the MAM9 implementation has reduced the fine mode dust burden compared to MAM4 (Tables 8 and 9) due to a greater STD value in the fine dust mode (2.0 in MAM9 vs. 1.8 in MAM4), the mixed-phase cloud ice nucleation has been suppressed by MAM9, especially in the Northern Hemisphere. It is evident by recent studies that highlight the importance of the mixed-phase cloud ice nucleation associated with dust particles in the Northern Hemisphere (Y. Shi and Liu, 2019; Villanueva et al., 2021). Overall, the dust enhancement introduced by MAM9 warms up the atmosphere by 0.36 W/m² (Figure 12c), and the warming coincides with the cirrus cloud ice enhancement (Figure 13).

### 4. Summary and Conclusions

In this study, we developed the MAM9 aerosol module to improve the dust representation in CAM5. MAM9 is based on MAM7 and has nine aerosol modes, including accumulation, Aitken, primary carbon, fine sea salt, coarse sea salt, fine dust, coarse dust 1, coarse dust 2, and extra coarse dust modes. The size ranges for the four dust modes are 0.1–1, 1–5, 5–10, and 10–20 μm and the standard deviation for the four modes are 2.0, 1.6, 1.6 and 1.6, respectively, based on dust measurements in Hawaii (Porter & Clarke, 1997). The dust emission ratios for these four modes are 0.011, 0.364, 0.625, and 0.898. The sum of dust emission ratios for the first three modes equals to one and this partitioning is based on a previous CAM dust study (Albani et al., 2014). The partitioning

| Table 10 | Dust Direct Radiative Effect (W m⁻²) at the Top of the Atmosphere (TOA) From MAM4 |
|----------|---------------------------------|
|          | SW | LW  | Net   |
| Accumulation Mode | −0.086 | 0.0046 | −0.082 |
| Coarse Mode | −0.24 | 0.087 | −0.15 |
| All Dust | −0.33 | 0.092 | −0.24 |

| Table 11 | Dust Direct Radiative Effect (W m⁻²) at the Top of the Atmosphere (TOA) From MAM9 |
|----------|---------------------------------|
|          | SW | LW  | Net   |
| Fine Dust | −0.043 | 0.0036 | −0.039 |
| Coarse Dust 1 | −0.28 | 0.070 | −0.20 |
| Coarse Dust 2 | −0.032 | 0.038 | 0.0070 |
| Extra Coarse | 0.0046 | 0.010 | 0.015 |
| All Dust | −0.35 | 0.13 | −0.22 |
for the extra coarse dust mode is derived from the dust emission ratio of PM10 to PM20 by Kok et al. (2017). Additionally, we adopted the improved dry deposition scheme based on the previous work of M. Wu et al. (2018), by which the dry deposition velocity over ice and snow surface is improved for aerosol particles in the 0.1–1 μm size range.

To investigate the effect of these changes, we conducted nudged CAM5-MAM9 and CAM5-MAM4 simulations for two time periods: 2005–2009 and 2016–2017. The 2005 to 2009 simulations are used to perform the comparison between model results and climatological observational data sets. The 2016 to 2017 simulations are used to

|                | All-sky SW DRE     | All-sky LW DRE     | All-sky net DRE      |
|----------------|--------------------|--------------------|----------------------|
| AEROCOM        | −0.65 (−0.93 − 0.22) | 0.18 (0.10−0.26) | −0.46 (−0.78 − 0.03) |
| Kok et al. (2017) | −0.47 (−0.81 − 0.07) | 0.28 (0.18−0.55) | −0.20 (−0.48−0.20)  |
| MAM4           | −0.33              | 0.09               | −0.24                |
| MAM9           | −0.35              | 0.13               | −0.23                |

Note: The median and the 95% confidence interval are shown as obtained in AEROCOM ensembles and in Kok et al. (2017). The AEROCOM ensemble results is from Figure 4 in Kok et al. (2017).

Figure 10. Global distribution of dust direct radiation effect (W m$^{-2}$) from (a) MAM4 and (b) MAM9. The panel c is for the difference between MAM9 and MAM4.
compare model results to dust concentration data obtained by the NASA ATom mission. The MAM9 results have better agreement with observations than the MAM4 results in terms of dust surface concentration and deposition flux. Including the extra coarse dust (10–20 μm) in the model does not lead to overestimations of dust concentration and flux globally, even in the dust source regions. The dust surface concentration and deposition flux in the remote regions are significantly improved in MAM9, while they are still underestimated over the Arctic and Antarctic. By comparing to the three dust extinction data sets derived from the CALIPSO satellite, the MAM9 notably enhances the dust extinction vertically over the Northern Pacific Ocean and the tropical Atlantic Ocean with no obvious overestimations in the source regions. Using the ATom aircraft measurements as a comparison, the MAM9 has a better performance than MAM4 in the NH, while both have difficulties to accurately simulate the dust in the SH, which may be attributed to the soil erodibility map used in CAM5 (C. Wu et al., 2016). Overall, the finer partitioning of dust modes and the lower standard deviation values used in the coarse dust modes led to the better simulation of dust transport from source to remote regions in MAM9.

Recent studies highlight that current GCMs underestimate the coarse dust while overestimating the fine dust in the atmosphere (Adebiyi & Kok, 2020; Kok et al., 2017, 2018). In this study, the inclusion of extra coarse dust (10–20 μm) produces 4.11 Tg dust burden in the atmosphere (Table 9), which is comparable to the estimate of 3 Tg by Kok et al. (2017). If we use the coarse dust definition in Adebiyi and Kok (2020) (diameter ≥5 μm), the MAM9 dust scheme produces 15.01 Tg dust burden (Table 9), which is also comparable to the estimate of 17 Tg by Adebiyi and Kok (2020). The finer dust partitioning in the PM10 size range and the inclusion of dust particles in the 10–20 μm size range improve the model’s representation of the coarse dust.

Dust particles with size smaller than 5 μm tend to have a cooling effect at TOA while those with size greater than 5 μm tend to have a warming effect. In our study, the fine dust and coarse dust 1 modes have net DREs of −0.039 and −0.21 W m⁻², respectively, while the coarse dust 2 and extra coarse dust modes have net DREs of 0.0067 and 0.015 W m⁻², respectively (Table 9). It suggests that the dust DRE becomes more positive as dust size increases. Compared to the MAM4 results, MAM9 reduces the total dust DRE at TOA from −0.24 to −0.23 W m⁻². Although the difference in the absolute value is rather small, the total dust DRE attributed to different dust size ranges has significantly changed. First, as there is less fine dust (0.1–1 μm) in MAM9, 0.68 Tg (MAM9) versus 0.82 Tg (MAM4), the dust net cooling effect at TOA is reduced by 0.043 W m⁻². Second, dust in the size

Figure 11. Global distribution of dust direct radiation effect (W m⁻²) from MAM9 by (a) fine dust mode, (b) coarse dust mode 1, (c) coarse dust mode 2, and (d) extra coarse dust mode.
Figure 12. The impacts of dust on clouds between MAM9 and MAM4. The panel $a$ and $b$ is the difference of ice water path and liquid water path, while the panel $c$ is the difference of dust indirect effect.

Figure 13. The impact of the dust changes on cloud ice number concentrations by comparing MAM9 with MAM4. The cloud ice number concentration is the grid-averaged value (AWN in the model output).
range of 1–10 μm shows a stronger cooling effect in MAM9 than in MAM4 (−0.20 vs. −0.15 W m⁻²). This may be due to the longer lifetime of dust in the coarse mode 1, which has the largest burden and relatively smaller size among all the coarse dust modes. The net DRE of this mode at TOA is negative. More study is needed to appropriately determine the dust emission partitioning between the coarse dust mode 1 and 2. Third, the extra coarse dust mode in MAM9 accounts for 0.015 W m⁻² DRE at TOA, which is smaller than 0.03 W m⁻² estimated by Kok et al. (2017), although the burden of extra coarse dust is higher than the mean value estimated by Kok et al. (2017). Also, the dust longwave radiative effect accounts for 0.13 W m⁻² at TOA in MAM9 compared to 0.092 W m⁻² in MAM4. This 0.04 W m⁻² increase in warming is smaller than the 0.1 W m⁻² warming effect caused by reducing the fine dust and inclusion of the extra coarse dust estimated by Kok et al. (2017). In summary, the increased coarse dust burden does not strongly increase the dust warming effect from MAM9 compared to MAM4.

In the current CAM5 model, dust particles are all considered as spherical particles. Previous studies (Huang et al., 2021; Kok et al., 2017) suggest that the spherical particle assumption may not be appropriate, and assuming dust as aspherical particles would change the dust’s optical properties. It is true when the dust particles are dry in the atmosphere. In this case, the aspherical dust assumption can prolong the coarse dust lifetime, and the model can emit fewer finer dust particles to achieve similar global dust AOD. Therefore, the model would show less dust cooling effect but more dust warming effect. However, when dust particles are traveling over oceans, soluble aerosols (e.g., sulfate) and water may coat on dust particles that can dramatically change the particles’ shape. In this case, the spherical particle assumption may not be a questionable assumption. Therefore, more investigations and observations are needed to improve our understanding of the shape of dust particles in the atmosphere.

Future studies are needed to investigate the impact of coarse dust on regional climate, such as its potential effects on surface albedo via the snow darkening effect (Rahimi et al., 2019; C. Wu et al., 2018). MAM4 and MAM9 overestimate the dust concentration over 300 hPa, and this overestimation could be related to the representation of aerosol convective scavenging in CAM5. Future model development will implement the modifications of aerosol convective scavenging introduced by Shan et al. (2021). Finally, improving the understanding of impact of the dust asphericity on model performance including dust lifetime, burden, and optical properties will be important.

**Data Availability Statement**

The MAM9 codes and related data can be accessed through NCAR Cheyenne Supercomputer, /glade/u/home/zke3/scratch/MAM9_code_sharing. The simulation data and all codes can be accessed in Github: https://github.com/keziming/CAM5.4-MAM9.
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