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Simulated aerosol key optical properties over global scale using an aerosol transport model coupled with a new type of dynamic core

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HIGHLIGHTS

- We simulate aerosol key optical properties using a new aerosol transport model.
- The correlations between model and AERONET are strong for both AOD and AE.
- 82.1% of the simulated AODs agree within a factor of two with the measurements.
- Model underestimates both the global 3-year mean AOD and AE.

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ABSTRACT

Aerosol optical depth (AOD), Ångström Exponent (AE), and single scattering albedo (SSA) simulated by a new aerosol-coupled version of Nonhydrostatic ICosahedral Atmospheric Model (NICAM) have been compared with corresponding AERONET retrievals over a total of 196 sites during the 2006–2008 period. The temporal and spatial distributions of the modeled AODs and AEs match those of the AERONET retrievals reasonably well. For the 3-year mean AODs and AEs for all sites show the correlations between model and AERONET of 0.753 and 0.735, respectively, and 82.1% of the modeled AODs agree within a factor of two with the retrieved AODs. The primary model deficiency is an underestimation of fine mode aerosol AOD and a corresponding underestimation of AE over pollution region. Compared to the retrievals, the model underestimates the global 3-year mean AOD and AE by 0.022 (10.5%) and 0.329 (31.2%), respectively. The probability distribution function (PDF) of the modeled AODs is comparable to that of the retrieved ones, however, the model overestimates the occurrence frequencies of small AEs and SSAs.

1. Introduction

Atmospheric aerosols greatly impact the Earth's climate in many ways, and to date, not all of them are well known. Aerosols are considered to be one of the factors inducing climate change primarily through two effects: (a) a direct effect in which aerosol particles scatter and absorb the solar and thermal radiation (Coakley et al., 1983), and (b) an indirect effect in which they change the microphysical and optical properties of cloud droplets acting as cloud condensation nuclei (Albrecht, 1989).

To evaluate aerosol effects on the climate system, we need to accurately estimate aerosol optical properties, such as aerosol optical depth (AOD), Ångström Exponent (AE), and single scattering albedo (SSA). Aerosol optical properties are determined not only by aerosol amount but also by physical and optical parameters such as size distribution of particles, mixing state of particles, and refractive index (especially for absorbing particles, e.g., soot and dust). These parameters are usually described differently within global aerosol models, and there are large model diversities in aerosol dispersal and consequently optical properties (Textor et al., 2006, 2007). It has become evident that aerosol modeling suffers from both poorly

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Table 1
Particle density, particle radius, refractive index, mass extinction coefficient (β), AE derived from β at 440 and 870 nm, and SSA for dry aerosol as used in the model.

Species	Density (g cm^{-3})	dry particle radius (μm)	Refractive index at 550 nm	β at 550 nm (m^2 g^{-1})	AE	SSA
Sulfate	1.769	0.0695	1.43−10^{-8}i	1.775	2.740	1.000
BC	1.25	0.0118	1.75−0.44i	8.185	1.119	0.323
OC	1.5	0.02	1.53−0.006i	1.062	2.683	0.915
OC/BC (1)	1.473	0.1	1.558−0.063i	5.455	1.520	0.766
OC/BC (2)	1.468	0.1	1.563−0.072i	5.547	1.478	0.741
OC/BC (3)	1.442	0.1	1.588−0.126i	6.036	1.278	0.638
OC/BC (4)	1.462	0.1	1.569−0.085i	5.666	1.426	0.712
OC/BC (5)	1.468	0.1	1.563−0.072i	5.547	1.478	0.741
Dust	2.5	0.13	1.53−0.0055i	2.239	2.811	0.965
	2.5	0.20	1.53−0.0055i	3.809	1.838	0.976
	2.5	0.33	1.53−0.0055i	3.652	0.608	0.972
	2.5	0.52	1.53−0.0055i	2.059	−0.405	0.950
	2.5	0.82	1.53−0.0055i	1.013	−0.348	0.903
	2.5	1.27	1.53−0.0055i	0.687	−0.081	0.876
	2.5	2.02	1.53−0.0055i	0.397	−0.010	0.831
	2.5	3.20	1.53−0.0055i	0.248	−0.047	0.778
	2.5	5.06	1.53−0.0055i	0.155	−0.0530	0.719
	2.5	8.02	1.53−0.0055i	0.089	−0.041	0.652
Sea salt	2.2	0.178	1.50−10^{-8}i	4.257	1.850	1.000
	2.2	0.562	1.50−10^{-8}i	1.715	−0.352	1.000
	2.2	1.78	1.50−10^{-8}i	0.493	0.011	1.000
	2.2	5.62	1.50−10^{-8}i	0.168	−0.078	1.000

Note: OC/BC (1−5) represent the internal mixture of OC and BC for tropical forest fire, other forest fire, fossil fuel, fuel wood, and agriculture source, respectively. The β and SSA for sulfate, BC, OC, OC/BC, and sea salt are calculated from the Mie-scattering theory using a mono-modally lognormal size distribution. The modal radii (r_m) for sulfate, BC, OC, OC/BC, and sea salt are 0.0695, 0.0118, 0.02, 0.1, and 0.114 μm, while the geometric standard deviations (σ_g) are 1.526, 2.3, 1.8, 1.562, and 2.305, respectively. The size distribution for dust aerosol is assumed a bi-modally lognormal distribution with $r_m = 0.202$, 0.994 μm and $\sigma_g = 2.397$, 1.110.

known emission inventories and aerosol physical and optical parameters. Thus, the modeled aerosol properties have to be validated by observations to ensure high confidence in the modeled results.

AErosol RObotic NETwork (AERONET) is to date the most dedicated effort in establishing a global surface network with the purpose of observing aerosol behavior, and its data have been commonly used for model validations. Monthly mean AODs, AEs and SSAs simulated by Spectral Radiation Transport Model for Aerosol Species (SPRINTARS) coupled with an atmospheric general circulation model, MIROC (Model for Interdisciplinary Research on Climate), were compared with the observations collected at dozens of AERONET sites (Takemura et al., 2002). In an attempt to provide an absolute measure for model skill, AODs simulated with aerosol modules of seven global models were compared to the observations from 20 AERONET sites (Kinne et al., 2003). To investigate the ability of the Community Multiscale Air Quality (CMAQ) model to simulate the aerosol distribution in Europe, the modeled results were compared with surface-measured PM10 values and AERONET AODs (Matthias, 2008). Compared to AERONET retrievals, the simulated AODs with a global chemical and transport model (GEOS-Chem) were systematically overestimated over northern Africa and southern Europe (Generoso et al., 2008). Chin et al. (2009) evaluated the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model simulated key aerosol optical parameters against AERONET retrievals at seven different regions worldwide and concluded the model underestimated AODs for biomass burning aerosols by 30–40%.

The SPRINTARS module has also been implemented into the Nonhydrostatic ICosahedral Atmospheric Model (NICAM). The simulated results with a spatial resolution of 7 km were compared with satellite observations, but the period was very limited only during July 1–8, 2006 (Suzuki et al., 2008). In addition, although NICAM model with a coarse spatial resolution of 224 km was also applied for a passive tracer model to simulate CO_2 distribution (Niwa et al., 2011), NICAM + SPRINTARS with a coarse resolution has not been evaluated using ground-based remote sensing measurements. Therefore, we simulate the global temporal and spatial distributions of aerosol characteristics using this new aerosol-coupled version of NICAM and evaluate the simulated aerosol key optical properties with the AERONET retrievals over a total of 196 sites during the period 2006–2008 in this study.

2. Model description, data, and methodology

2.1. Model description

The Nonhydrostatic ICosahedral Atmospheric Model (NICAM) (Tomita and Satoh, 2004; Satoh et al., 2008) is designed to perform cloud-resolving simulations by directly calculating deep convection and meso-scale circulations. It has been used for several types of global cloud-resolving experiments with a horizontal resolution of 3.5 km (Satoh et al., 2008, and references therein), including a realistic simulation of the Madden-Julian Oscillation (Miura et al., 2007). The aerosol module called Spectral Radiation Transport Model for Aerosol Species (SPRINTARS), a global three-dimensional aerosol transport-radiation model (Takemura et al., 2000, 2002, 2009), has been implemented into NICAM (Suzuki et al., 2008). In this aerosol-coupled version of NICAM, the aerosol effects are incorporated into cloud microphysical and radiative transfer processes so that the direct and indirect effects of aerosols are represented (Suzuki et al., 2008, 2011).

We use this new aerosol-coupled model to perform the global simulation with a horizontal resolution of 224 km (a total of 10,242 grid points). The Lorenz grid is used for the vertical grid configuration (Satoh et al., 2008), and there are a total of 40 vertical layers with the top of model located at 40 km. The SPRINTARS uses a single-moment scheme to track only aerosol mass by considering the transport processes including emission, advection, diffusion, and deposition. Bulk aerosol mass of sulfate and carbonaceous aerosols are predicted, whereas sea salt mass is tracked in 4 bins and dust mass is tracked in 10 bins (Takemura et al., 2002). The carbonaceous aerosols include one pure black carbon (BC), one pure organic carbon (OC), and five different internal mixtures of OC and BC according to the carbonaceous aerosols sources (Takemura et al., 2000). Therefore, 22 tracers are used in SPRINTARS to predict the mass of the four aerosol species. The combinations of the aerosol mass and the pre-calculated optical parameters with prescribed size distributions provide the modeled aerosol optical properties. AOD is derived as $\tau = \beta m$, where β is the mass extinction coefficient and m is the aerosol mass. AE represents the spectral change in AOD and is calculated as $-\log(\tau_1/\tau_2)/\log(\lambda_1/\lambda_2)$, where τ_1 and τ_2 represent AODs at wavelengths λ_1 and λ_2, respectively. SSA measures the contribution of scattering to total extinction and is calculated as τ_s/τ, where τ_s is the scattering optical depth. The main model physics used are the k-distribution radiation scheme (Nakajima et al., 2000; Sekiguchi and Nakajima, 2008), the prognostic Arakawa-Schubert type cumulus convection scheme (Arakawa and Schubert, 1974; Pan and Randall, 1998), and the MATSIRO land surface scheme (Takata et al., 2003). NCEP Final (FNL) Operational Global Analysis data are used for the initial and boundary conditions (e.g., SST and sea ice). For proper simulations, the modeled wind, water vapor, pressure and temperature fields are also nudged to the NCEP FNL analysis data with a time-scale of six hours.

The emission inventories of aerosols (primary OC and BC) and aerosol precursors emitted from anthropogenic sources, including fossil fuel combustion and biomass burning, come from the