



**Development and
evaluation of aerosol
physical
parameterizations**

B. Sič et al.

Modelling of primary aerosols in the chemical transport model MOCAGE: development and evaluation of aerosol physical parameterizations

B. Sič, L. El Amraoui, V. Marécal, B. Josse, J. Arteta, J. Guth, M. Joly, and P. Hamer

CNRM-GAME, Météo-France and CNRS, UMR3589, Toulouse, France

Received: 24 February 2014 – Accepted: 16 April 2014 – Published: 29 April 2014

Correspondence to: B. Sič (bojan.sic@meteo.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

This paper deals with recent improvements to the chemical transport model of Météo-France MOCAGE that consists of updates to different aerosol parameterizations. MOCAGE only contains primary aerosol species. We introduced important changes to the aerosol parameterization concerning emissions, wet deposition and sedimentation. For the emissions, size distribution and wind calculations are modified for desert dust aerosols, and a surface sea temperature dependant source function is introduced for sea salt aerosols. Wet deposition is modified toward a more physically realistic representation by introducing re-evaporation of falling rain and snowfall scavenging, and by changing in-cloud scavenging scheme along with calculations of precipitation cloud cover and rain properties. The sedimentation scheme update includes changes regarding the stability and viscosity calculations. Independent data from satellites (MODIS, SEVIRI), the ground (AERONET), and a model inter-comparison project (AeroCom) is compared with MOCAGE simulations and showed that the introduced changes brought a significant improvement on aerosol representation, properties and global distribution. Emitted quantities of desert dust and sea salt, as well their lifetimes, moved closer towards values of AeroCom estimates and the multi-model average. When comparing the model simulations with MODIS aerosol optical depth (AOD) observations over the oceans, the updated model configuration shows a decrease in the bias (from 0.032 to 0.002) and a better correlation (from 0.062 to 0.322) in terms of the geographical distribution and the temporal variability. The updates corrected a strong positive bias in the sea salt representation at high latitudes (from 0.153 to 0.026), and a negative bias in the desert dust representation in the African dust outflow region (from -0.179 to -0.051). The updates in sedimentation produced a modest difference; the bias with MODIS data from 0.002 in the updated configuration went to 0.003 in the updated configuration only without the sedimentation updates. Yet, the updates in the emissions and the wet deposition made a stronger impact on the results; the bias was 0.041 and 0.032 in updated configurations only without emission, and wet deposition

GMDD

7, 2745–2796, 2014

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

updates, respectively. Also, the lifetime, the extent, and the strength of the episodic aerosol events are better reproduced in the updated configuration. The wet deposition processes and the differences between the various configurations that were tested greatly influence the representation of the episodic events. However, wet deposition is not a continuous process; it has a local and episodic signature and its representation depends strongly on the precipitation regime in the model.

1 Introduction

Atmospheric aerosols play a major role in a number of atmospheric processes, and have an important global climate impact (IPCC AR4, 2007). Increased effort has been made in the domain of aerosol modeling as knowledge of their importance has increased (Textor et al., 2006). The goal of the modeling has been to qualitatively and quantitatively represent aerosols in the correct way in order to better understand how aerosols affect atmospheric chemistry, air quality, climate, aviation, visibility, radiative budget and clouds. For this task, it is necessary to develop reliable parameterizations that describe how aerosols are emitted, transported and transformed, and, in the end, removed from the atmosphere. Owing to this drive to improve model representation of aerosols, and due to the complexity of aerosol processes, a large diversity of parameterizations now exists. This variety produces a wide range of model results (Textor et al., 2006). Therefore, the choice, development and validation of used parameterizations are crucial for the performance of the models.

Sources of aerosols are more difficult to define than those of gases (IPCC AR4, 2007). In models, aerosol sources are characterized either by interactive emission parameterizations that depend on soil properties and/or wind intensity – which are, in the case of primary aerosols, generally used for desert dust and sea salt particles – or by existing emission inventories, mainly used for other primary aerosol types. Secondary aerosols are not directly emitted and they originate from gas phase precursors or from reactions between dissolved or adsorbed gases and primary aerosols.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Aerosol deposition is complex and challenging to implement in an accurate way (Rash, 2000; Sportisse, 2007). Removal processes balance against the emission and production processes, and determine the lifetime of aerosols in the atmosphere. They are especially important for species that do not interact chemically (i.e. primary aerosols) because they represent their only available sinks. Mechanisms which remove aerosols are divided in two groups: “wet” deposition (scavenging) processes which take place in the interaction of aerosols with precipitation, and “dry” processes which include gravitational sedimentation (or gravitational settling) and dry deposition by interaction with the surface.

Wet deposition is the most efficient aerosol sink (Pruppacher and Klett, 1997), but it is regionally limited. In wet deposition processes, particles are indirectly transferred to the surface with the aid of precipitation. Inside clouds, in-cloud scavenging (rain-out) occurs. Aerosols can act as condensation nuclei for the formation of water droplets and small cloud particles. When water vapour interacts with their surface, it can start to condensate and allow the cloud droplets to grow. Additional aerosol particles can then be attracted and absorbed into them. When a droplet starts to precipitate, below-cloud scavenging (wash-out) takes place. While falling, a droplet can collide with aerosol particles and collect them from the air. Although less efficient than in-cloud scavenging, below-cloud scavenging is important for both very small and coarse particles (Andronache, 2003). Wet deposition is commonly parameterized by the scavenging coefficient Λ [s^{-1}] where $\frac{dc}{dt} = -\Lambda c$, c is the aerosol concentration. Many methods have been proposed in the literature to estimate the scavenging coefficient (e.g. Sportisse, 2007): more theoretical approaches; semi-empirical parameterizations with detailed modeling of various component processes that are responsible for aerosol deposition; or fully empirical approach with a large number of different proposed formulations can be used.

Aerosols undergo the influence of gravitational forces and tend to fall because their mass is not negligible. Near the surface, the dry deposition process acts together with gravitational sedimentation and it is especially efficient for coarse and very fine particles

(Seinfeld and Pandis, 1998). Particles interact with the surface and objects in a thin layer of air next to the surface: they experience drag, change velocities and fall down. The velocity of dry deposition depends on properties of the surface, aerosols particles, and meteorological parameters (Seinfeld and Pandis, 1998).

Uncertainties in the models do not only come from the different formulations of deposition parameterization. Uncertainties in meteorological fields can also have a significant effect on model performance. Winds control the transport of species and it can influence the interactive emission parameterizations. The humidity determines cloud coverage, rain localization and intensity – which are crucial for wet deposition processes – and hygroscopic particle growth, which is important for the particle settling and visibility.

In the present study we examine all of the above mentioned processes in the chemical transport model (CTM) MOCAGE. The CTM MOCAGE was developed at Météo-France and contributes to a wide range of scientific studies. Its applications, cover both regional and global scales, and extend to: air-quality forecasts, climate-chemistry interactions (Teyssedre et al., 2007; Lamarque et al., 2013), desert aerosol studies (Martet et al., 2009), long-range transport pollution studies (Bousserez et al., 2007), “chemical weather” (Dufour et al., 2005), data assimilation of chemical species (e.g. El Amraoui et al., 2010), troposphere-stratosphere transport (Ricaud et al., 2009; Barré et al., 2012), etc.

Many aerosol processes are highly inter-connected; uncertainties and different formulations of processes lead to a large dispersion of model results as shown in comparative studies (Rash, 2000; Textor et al., 2007). This reveals the importance and complexity of aerosol physical parameterizations. In this paper, we present the recent developments on primary aerosol emissions and physical parameterizations in the CTM MOCAGE. Our main objective is to improve the aerosol representation in the model. To achieve this objective, we will: firstly, reexamine and modify primary aerosol emissions and parameterizations (wet scavenging and sedimentation) in MOCAGE; secondly, study sensitivities to different formulations of the mentioned processes in order to

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



show how different treatments influence the aerosol representation in the model and to which extent their uncertainties affect the model performance; and thirdly, validate the new parameterizations for emissions, wet deposition, and sedimentation in MOCAGE by comparing the model outputs with different satellite and ground observations.

The article is organized as follows. In Sect. 2 we present the general description the model MOCAGE. The aerosol parameterizations in the model and their improvements are presented in details in Sect. 3. Section 4 describes all observational datasets used for comparison with the model. In Sect. 5 we define the model experiments and explain the method used to assess model performance. Results and discussions are presented in Sects. 6 and 7 where we compare MOCAGE results with different independent observations, and evaluate a new set of parameterizations in MOCAGE to estimate their impact on aerosol burden, lifetime, concentration, deposition and optical depth. Section 8 concludes this study.

2 General description of the model

MOCAGE (Modèle de Chimie Atmosphérique à Grande Echelle) is a global chemistry and transport model (CTM) developed in Météo-France. It is used as an operational air quality model simulating gases (Josse et al., 2004; Dufour et al., 2005) and primary aerosols (Martet et al., 2009). It transports atmospheric species by a semi-lagrangian advection scheme (Williamson and Rasch, 1989). Turbulent diffusion is implemented following Louis (1979), and convection following Bechtold et al. (2001). The aerosol dry deposition scheme is described in detail in Nho-Kim et al. (2005). The dynamics within the CTM are forced by ARPEGE meteorological analysis fields (pressure, winds, temperature, specific humidity). ARPEGE is the operational global weather prediction model of Météo-France. The precipitating cloud, precipitation field and liquid water content are calculated in MOCAGE in the same way as in ARPEGE. MOCAGE has 47 vertical hybrid sigma-pressure levels from the surface up to about 5 hPa. The vertical resolution is not uniform; levels are packed more densely near the surface,

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



with a resolution of 40 m in the planetary boundary layer, about 400 m in the free troposphere and about 700–800 m in the upper troposphere and lower stratosphere. In the global configuration, simulations have a horizontal resolution of 2° latitude × 2° longitude.

5 Aerosols in MOCAGE are considered as an external mix of four primary aerosol species: desert dust, sea salt, black carbon (BC) and organic carbon (OC). The particle size distribution is divided across size bins, which are treated as passive tracers: aerosols are emitted, transported and removed from the atmosphere, and no transformations or chemical reactions between the different aerosol species or with gases
10 are allowed. Each of the species has six size bins where we consider only the averaged mass and diameter of particles. The size ranges of bins for all considered aerosol species are shown in Table 1. The number of bins per species is limited to six in order to balance the operational cost and effectiveness. Two of the bins have their limits at 2.5 μm and 10 μm for practical air quality purposes in order to easily integrate the sum
15 of PM_{2.5} and PM₁₀ particles (particulate matter up to 2.5/10 μm in size). The other bin size ranges are distributed in a such manner as to have an optimal aerosol representation considering the initial size distribution and evolution of each aerosol species in the model.

20 Aerosol optical depth (AOD) in the model is calculated at 550 nm using Mie theory with refractive indices taken from the Global Aerosol Data Set (GADS, Koepke et al., 1997) and extinction efficiencies derived with Wiscombe's Mie scattering code for homogeneous spherical particles (Wiscombe, 1980).

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Aerosol parameterizations in the model

3.1 Sedimentation

Gravitational settling of aerosol particles is implemented as described in Seinfeld and Pandis (1998). The settling velocity is based on Stokes law and is a function of particle diameter, particle density, and air viscosity:

$$V_p = \frac{D_p^2 \rho_p g C_c}{18 \mu_a} \quad (1)$$

where D_p is the aerosol diameter [m], ρ_p is the aerosol particle density [kg m^{-3}], g is the gravitational constant [ms^{-2}], μ_a is the dynamical viscosity of air [Pas], and C_c is the slip correction factor which accounts for noncontinuum effects when the particle diameter and the air mean free path are of the same order of magnitude. C_c is defined as (Seinfeld and Pandis, 1998):

$$C_c = 1 + \frac{2\lambda}{D_p} \left[1.257 + 0.4 \exp\left(-\frac{1.1 D_p}{2\lambda}\right) \right] \quad (2)$$

where λ is the mean free path of an air particle [m].

Currently, we calculate the dynamical air viscosity using an assumed value of the kinematic viscosity. In the updated sedimentation calculations, we calculate it by Sutherland's law, an empirical relation connecting dynamical viscosity and temperature (White, 1991):

$$\mu_a = \mu_0 \frac{T_0 + S}{T + S} \left(\frac{T}{T_0}\right)^{3/2} \quad (3)$$

where μ_0 is the reference dynamical viscosity of air at the reference temperature T_0 with values of $\mu_0 = 1.716 \times 10^{-5}$ Pas and $T_0 = 273$ K, and $S = 111$ K is the Sutherland's effective temperature (White, 1991).

Also, in the update to the sedimentation calculations, sedimentation velocity is not allowed to exceed a value equal to a gridbox height per model timestep, to ensure the stability of our explicit sedimentation scheme.

3.2 Wet deposition

The fraction of aerosols removed at each time step by interaction with precipitation (by both in-cloud and below-cloud scavenging) is calculated as

$$F = f_{\text{prec}}(1 - e^{-\Lambda \Delta t}) \quad (4)$$

where F is the fraction of removed aerosols, f_{prec} is the fraction of precipitating cloud cover (the percentage of a cloud coverage in a gridbox where precipitation forms or falls); Λ is the scavenging coefficient [s^{-1}] which describes a rate of loss of particles due to scavenging; Δt is the model time step for scavenging [s].

To better represent the precipitating cloud cover in MOCAGE, we updated the model by adapting a scheme from Giorgi and Chameides (1986) which considers typical conditions in stratiform and convective clouds during the formation of precipitation. To estimate the portion of the sky covered by precipitating clouds, precipitation rates are calculated following Xu and Randall (1996). For stratiform clouds, the fraction of precipitation forming clouds is (we also take all values of quoted parameters from Giorgi and Chameides, 1986, if not stated differently):

$$f_{\text{strat}} = \frac{Q}{(L_{\text{st}} \cdot R_{\text{st}} + Q)} \quad (5)$$

where Q is the rate of precipitation formation [$\text{kg m}^{-3} \text{s}^{-1}$]. L_{st} is the typical liquid water content in precipitation forming stratiform clouds: $L_{\text{st}} = 1.5 \times 10^{-3} \text{ kg m}^{-3}$ from Brost

et al. (1991). It differs from the value originally proposed by Giorgi and Chameides (1986) $L_{st} = 0.5 \times 10^{-3} \text{ kg m}^{-3}$ taken from Pruppacher and Klett (1978). It was corrected by Brost et al. (1991) and later adopted by Jacob et al. (2000) and Liu et al. (2001). R_{st} is the rate constant of conversion of cloud water to precipitation for stratiform precipitation:

$$R_{st} = 1 \times 10^{-4} \text{ s}^{-1}.$$

For convective clouds, the fraction of precipitating cloud cover within a gridbox for any given timestep is:

$$f_{\text{conv}} = \frac{F_0 Q \frac{\Delta t}{t_c}}{Q \frac{\Delta t}{t_c} + F_0 R_{cv} L_{cv}} \quad (6)$$

where F_0 is the maximum cumulus cloud cover assumed in the radiation calculations backed by observations: $F_0 = 0.3$, Δt is the model time step, t_c is the typical duration of precipitation from a cumulonimbus cloud: $t_c = 30 \text{ min}$ (Liu et al., 2001), R_{cv} is the rate constant of conversion of cloud water to precipitation in convective clouds: $R_{cv} = 1.5 \times 10^{-3} \text{ s}^{-1}$, L_{cv} is the typical liquid water content in cumulonimbus clouds: $L_{cv} = 2 \times 10^{-3} \text{ kg m}^{-3}$.

To estimate the scavenging coefficient, many parameterizations have been developed and Sportisse (2007) summarizes them adequately. In our model, the current parameterization for in-cloud scavenging is the Langner and Rodhe (1991) scheme and in this study it will be evaluated against the Giorgi and Chameides (1986) scheme. Besides, in this study we modified and re-evaluated the model's current below-cloud scavenging scheme based on Slinn (1977).

3.2.1 In-cloud scavenging

The in-cloud scavenging coefficient according to Langner and Rodhe (1991) is directly proportional to the precipitation formation rate:

$$\Lambda = \frac{\epsilon Q}{L} \quad (7)$$

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



where L is the liquid water content in the raining cloud [kgm^{-3}], ϵ is the scavenging efficiency of a species uptake during the formation of precipitation. The scavenging efficiencies are based on Kasper-Giebl et al. (2000) where a distinction is made between soluble (aerosol carbon) and insoluble aerosols (sulfates). This scheme is not size dependent.

The parameterization from Giorgi and Chameides (1986), similarly to the Langner and Rodhe (1991) scheme, is neither a particle size, nor a particle type resolved scheme. But, it depends on the type of precipitation by taking into account typical conditions in clouds when precipitation forms. For stratiform precipitation the scavenging coefficient equals:

$$\Lambda = R_{\text{st}} + \frac{Q}{L_{\text{st}}} \quad (8)$$

And for convective precipitation, the scavenging coefficient is:

$$\Lambda = R_{\text{cv}} \quad (9)$$

3.2.2 Rain below-cloud scavenging

Below-cloud scavenging in the model acts in all gridboxes where precipitation falls, but does not form at the considered timestep in the gridbox. The rain below-cloud scavenging coefficient is defined as in Seinfeld and Pandis (1998):

$$\Lambda = \frac{3EP}{2D_d} \quad (10)$$

where E is the collection efficiency of a raindrop to collect a particle during its fall, P is the precipitation rate in precipitating area [$\text{kgm}^{-2}\text{s}^{-1}$], and D_d is the raindrop size [m]. To permit both, rain-out and wash-out, to take place in the same gridbox at the same time, we revised the condition for when and where wash-out occurs, and we now assume that it happens in all regions exactly below the rain-out area.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



We calculate the collection efficiency using Slinn's below-cloud scavenging scheme (Slinn, 1977), described also in Seinfeld and Pandis (1998) and widely used in models (Wang et al., 2010). Slinn's scheme considers collisions between a falling raindrop and an aerosol particle, and accounts for Brownian diffusion, interception and impaction.

5 The collision efficiency is a function of the sizes of raindrops and aerosols, and is expressed as (Slinn, 1977):

$$E = \frac{4}{Re Sc} (1 + 0.4Re^{1/2} Sc^{1/3} + 0.16Re^{1/2} Sc^{1/2}) + 4\phi[\omega^{-1} + (1 + 2Re^{1/2})\phi] + \left(\frac{Stk - Stk^*}{Stk - Stk^* + \frac{2}{3}} \right)^{3/2} \cdot \left(\frac{\rho_d}{\rho_p} \right)^{1/2} \quad (11)$$

where $Re = \frac{D_d V_d \rho_a}{2\mu_a}$ is the Reynolds number of the raindrops based on their radius, $V_d = \frac{D_d^2 \rho_d g C_c}{18\mu_a}$ is the terminal raindrop velocity (expression based on Stokes law) [m s^{-1}], ρ_a and ρ_d are the density of air and water [kg m^{-3}], $Sc = \frac{\mu_a}{\rho_a D}$ is the Schmidt number of the collected aerosol particles, $D = \frac{kT_a C_c}{3\pi\mu_a D_p}$ is the aerosol diffusivity [$\text{m}^2 \text{s}$], k is the Boltzman constant [JK^{-1}], T_a is the air temperature [K], $Stk = \frac{2\tau(V_d - V_p)}{D_d}$ is the Stokes number of the collected particles, $\tau = V_p/g$ is the characteristic relaxation time [s]; $Stk^* = \frac{1.2 + \frac{1}{12} \ln(1+Re)}{1 + \ln(1+Re)}$ is the critical Stokes number; $\phi = D_p/D_d$ is the ratio of diameters of the aerosol particle and the rain droplet; ω is the viscosity ratio of air and water. Considering terminal raindrop velocity, the expression defined above covers only the Stokes flow regime. But, the majority of raindrops falls with velocities out of the Stokes flow regime where inertial forces must be regarded, that is true for $D_d > 2 \times 10^{-5} \text{ m}$ (Seinfeld and Pandis, 1998). The expressions of the raindrop terminal velocity which cover the whole raindrop

size range are based on experimental data. From Brown and Lawler (2003) we use:

$$V_t = \frac{V_d}{1 + 0.17\sqrt{Re}} \quad (12)$$

where V_d is the Stokes flow velocity defined earlier, and Re is the corresponding Reynolds number at the Stokes velocity.

The raindrop size is presumed to be fixed with the value of 1 mm. To examine effects of this assumption we consider raindrops to be also distributed in size. We use the exponential raindrop distribution from Marshal and Palmers (1948).

The first term in the collision efficiency equation (Eq. 11) describes Brownian diffusion and is the most important for the smallest particles ($D_p < 0.2 \mu\text{m}$), while the second and the third term describe interception and inertial impaction which dominate for bigger particles ($D_p > 1 \mu\text{m}$) (Seinfeld and Pandis, 1998).

The scavenging calculated due to diffusion, interception and impaction showed possible underestimation of scavenged quantities when compared with field measurements (Davenport and Peters, 1978; Laakso et al., 2003). Some authors broaden scavenging by including more mechanisms – thermophoresis, diffusio-phoresis, and electric effects (Davenport and Peters, 1978; Chate, 2005; Andronache et al., 2006). Thermophoresis makes particles move along a temperature gradient; diffusio-phoresis makes particles move due to gas concentration gradients (e.g. motion toward the raindrop during condensation); and electric forces make charged particles interact between each other. We included these effects to Eq. (11) as (Davenport and Peters, 1978):

$$\text{Thermophoresis } E_{th} = \frac{4\alpha \left(2 + 0.6Re^{\frac{1}{2}} Pr^{\frac{1}{3}}\right) (T_a - T_s)}{V_t D_d} \quad (13)$$

$$\text{Diffusio-phoresis } E_{df} = \frac{4\beta \left(2 + 0.6Re^{\frac{1}{2}} Sc_w^{\frac{1}{3}}\right) \left(\frac{P_s^0}{T_s} - \frac{P^0 RH}{T_a}\right)}{V_t D_d} \quad (14)$$

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



$$\text{Electrostatic charge } E_{\text{ec}} = \frac{16KC_c a^2 \gamma^2 D_p}{3\pi\mu_a V_t} \quad (15)$$

where $\alpha = \frac{2C_c \left(k_a + \frac{5\lambda}{D_p k_p} \right) k_a}{5P \left(1 + \frac{6\lambda}{D_p} \right) \left(2k_a + k_p + \frac{10\lambda}{D_p k_p} \right)}$, k_a and k_p are the thermal conductivity of air and aerosol particle [$\text{Jm}^{-1} \text{s}^{-1} \text{K}^{-1}$], P is the atmospheric pressure [Pa], $Pr = \frac{c_p \mu_a}{k_a}$ is the Prandtl number for air, c_p is the specific heat capacity of air [$\text{m}^2 \text{s}^{-2} \text{K}^{-1}$], T_s is the temperature at the surface of the raindrop and it is taken to be 1 K less than the air temperature (Slinn and Hales, 1971), $\beta = \frac{T_a D_w}{P} \left(\frac{M_w}{M_a} \right)$, $D_w = 2.1 \times 10^{-5} \left(\frac{T_a}{T_0} \right)^{1.94} \left(\frac{P}{P_0} \right)$ is the water vapor diffusivity (Pruppacher and Klett, 1997), M_w and M_a are the molecular weights of water and air, respectively, $Sc_w = \frac{\mu_a}{\rho_a D_w}$ is the Schmidt number for water vapor in air, P_s^0 and P^0 are the water vapor partial pressures (in [Pa]) at temperatures T_s and T_a , respectively, RH is the relative humidity, K is the Coulomb constant, a is a constant: $a = 0.83 \times 10^{-6}$, γ is the parameter of cloud electricity and it is taken as an averaged value $\gamma = 2$ (Pruppacher and Klett, 1997; Andronache, 2004).

3.2.3 Below-cloud scavenging due to snowfall

We extended the scavenging module by adding snowfall scavenging. Often, precipitation in liquid state at the surface originates from solid state precipitation at higher altitudes. Tests in MOCAGE show that snowfall wash-out occurs in a larger number of gridboxes than rainfall wash-out. Compared to rainfall scavenging, there are less studies of the scavenging due to snowfall and there are wider set of snowfall parameters (due to different types and shapes of snow particles), which lead to larger uncertainties in the aerosol scavenging due to snowfall in the models. Also, snow scavenging efficiencies measured by different authors have a wide range of values: some are similar to those of rainfall, but some are one order of magnitude larger or lower (Sportisse, 2007).

Within MOCAGE, we introduce Slinn's (1982) snowfall scavenging formula, which is one of the most commonly used snowfall parameterizations (Gong et al., 1997; Croft et al., 2009; Zhang et al., 2013). All snow crystals in this study are assumed to be formed by riming. The snowfall below-cloud scavenging coefficient is given as (Slinn, 1982):

$$\Lambda = \frac{\gamma EP}{D_m} \quad (16)$$

where γ is the dimensionless fractional constant (in our case 0.5), D_m is the characteristic volume-to-area length scale (for the rimed crystals $D_m = 2.7 \times 10^{-5}$ m, Slinn, 1982).

Slinn's (1977) formulation is aerosol size and type dependent. The collection efficiency of the snow crystals is:

$$E = \left(\frac{1}{Sc}\right)^\delta + \left[1 - \exp\left[-\left(1 + \sqrt{Re_l}\right)\frac{D_p^2}{l^2}\right]\right] + \left(\frac{Stk - Stk^*}{Stk - Stk^* + \frac{2}{3}}\right)^{3/2} \cdot \left(\frac{\rho_s}{\rho_p}\right)^{1/2} \quad (17)$$

where the exponent δ depends on the snow crystal type, l is the characteristic length of collecting ice filaments, and Re_l is the corresponding Reynolds number; $\rho_s = 100 \text{ g m}^{-3}$ is the density of falling snow. For rimed snow crystals that we consider in the model: $l = 100 \mu\text{m}$, $Re_l = 10$ and $\delta = \frac{2}{3}$ (Slinn, 1977). Since we consider only rimed crystals of a fixed size, terminal settling velocity is considered constant: $V_s = 0.9 \text{ m s}^{-1}$ (Todd, 1964).

3.2.4 Re-evaporation

We introduced precipitation re-evaporation in the below-scavenging module. If the fraction f of precipitation evaporates at one level, then the corresponding $0.5f$ fraction of scavenged aerosols will be released back to the atmosphere. The factor of 0.5 (Liu

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
⏪	⏩
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



et al., 2001) is due to the fact that water molecules are more efficiently released than aerosols. If precipitation evaporates completely, then all scavenged aerosols are released. Sublimation of snowfall is not taken in account, and it is presumed that all solid precipitation would first melt, and then evaporate.

3.3 Emissions

All considered species are emitted as particles, i.e. primary aerosols. For emissions of black carbon and organic carbon we use prepared emission inventories, while for desert dust and sea salt we use online parameterizations.

The organic carbon and black carbon anthropogenic emissions come from the inventory of Lamarque et al. (2010). These monthly defined emissions are based on Bond et al. (2007) and Junker and Louise (2008), harmonized with the reference year 2000, and updated using other studies regarding additional emission sources (coal burning, domestic biofuel, ship tracks). Biomass burning emissions for both organic carbon and black carbon come from the GFEDv3 project (van der Werf et al., 2010). In GFEDv3, the data from biogeochemical modeling and active fire satellites measurements (MODIS and GOES) are combined to a daily state-of-the-art biomass burning emission estimate (Mu et al., 2011). Biomass burning carbon emissions are injected more quickly to higher altitudes compared to other emissions, due to fire induced convection. The maximal injection height depends on fire heat flux and environmental conditions, and varies significantly with latitude. In our model we have defined the maximal injection height in the tropical regions to be 1000 m, in mid latitudes 4000 m, and in the boreal regions 6000 m. Our choice is consistent with Williams et al. (2009).

The black carbon and organic carbon initial size-distribution is defined using a two-mode log normal distribution with the number mode diameters of the two modes as $r_1 = 1.5 \times 10^{-8}$ m and $r_2 = 4 \times 10^{-8}$ m, the geometric standard deviation $\sigma_1 = \sigma_2 = 1.8$, and the mass distribution between modes $\text{frac}_1 = 0.4$ and $\text{frac}_2 = 0.6$ (Dentener et al., 2006).

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.3.1 Sea-salt source function

Monahan et al. (1986) developed a formulation for the production of sea-salt particles resulting from the bursting of wind formed sea surface bubbles. Their semi-empirical formulation depends on the particle size and the intensity of surface winds. Gong (2003) addressed the overestimation of small particles ($D < 0.2 \mu\text{m}$) compared with observations and proposed an improved formulation. The rate of sea-salt particle production (particles $\text{m}^{-2} \text{s}^{-1} \mu\text{m}^{-1}$) became (Gong, 2003):

$$\frac{dF}{dr} = 1.373u_{10}^{3.41}r^{-A}(1 + 0.057r^{3.45}) \cdot 10^{1.607e^{-B^2}} \quad (18)$$

where r is the particle radius at relative humidity of 80 %, u_{10} is the wind speed at 10 m above the surface [ms^{-1}], $A = 4.7(1 + 30r)^{-0.017r^{-1.44}}$ and $B = (0.433 - \log r)/0.433$. Jaeglé et al. (2011) compared modeled data with AOD and sea salt measurements from coastal stations, satellites and ocean cruises, and found that the Gong (2003) function at high wind speeds ($> 6 \text{ms}^{-1}$) overestimates sea-salt concentrations over cold waters, and underestimates them over tropical waters. Their modified sea-salt source function includes a sea surface water temperature dependence (Jaeglé et al., 2011):

$$\frac{dF}{dr} = (0.3 + 0.1T - 0.0076T^2 + 0.00021T^3) \cdot 1.373u_{10}^{3.41}r^{-A}(1 + 0.057r^{3.45}) \cdot 10^{1.607e^{-B^2}} \quad (19)$$

where T is the sea-surface temperature [$^{\circ}\text{C}$]. Currently in MOCAGE, the sea-salt source function proposed by Gong (2003) is used, and the Jaeglé et al. (2011) modification is evaluated in this study. Both of these formulas use particle size at relative humidity of 80 %, and to calculate a dry particle sea salt source function we use Gerber's (1985) hygroscopic growth formula:

$$r = \left(\frac{C_1 r_d^{C_2}}{C_3 r_d^{C_4} - \log \text{RH}} + r_d^3 \right)^{\frac{1}{3}} \quad (20)$$

**Development and
evaluation of aerosol
physical
parameterizations**

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



where r_d is the dry particle radius [cm], RH is the relative humidity in percentage, r is the particle size at the RH relative humidity, and $C_1 = 0.7664$, $C_2 = 3.079$, $C_3 = 2.573 \times 10^{-11}$, $C_4 = -1.424$ are constants valid for sea salt particles. The particle sizes are assumed to be in an equilibrium corresponding with the ambient relative humidity. The hygroscopic growth affects optical properties, sedimentation and dry deposition of sea salt aerosols. Gerber's (1985) relation is not accurate for high relative humidity (Fan and Toon, 2011). Thus, we limit relative humidity to 95% to avoid unrealistic optical depths and deposition.

3.3.2 Desert dust emission schemes

The emission of mineral dust particles in arid zones depends on the surface characteristics and wind intensity. If the wind friction velocity is larger than the erosion threshold velocity for a given particle size and soil properties, particles can be emitted into the atmosphere (e.g. Zhao et al., 2006). A desert dust emission scheme takes into account all of the main processes involved: achievement of the erosion threshold, saltation where particles start to move horizontally, and sandblasting where the fine particles are released from soil aggregates into the atmosphere due to impacts between the saltating particles and the surface.

In MOCAGE, two emission schemes have been implemented: the first one for African and Arabian deserts (Marticorena et al., 1997), and the second one for deserts in Asia (Laurent et al., 2006). The Marticorena et al. (1997) scheme covers Africa, Arabia and Middle East [13–36° N, 17° W–77° E] with the resolution of $1^\circ \times 1^\circ$. The input soil properties and aerodynamical surface parameters are based on available pedological, topographical, geological and climatological data and analysis (Marticorena et al., 1997; Callot et al., 2000). The main sources were from the French National Geographic Institute (IGN) and soviet topographic maps. Laurent et al. (2006) developed the emission scheme for North-East Asia that includes all arid areas in the region 35.5–47° N, 73–125° E. Typical soil characteristics are derived from soil samples (Mei et al., 2004), and statistically analyzed and extrapolated to all known deserts in the

domain. Aerodynamical surface parameters are determined from POLDER-1 surface bi-directional reflectance observations with a resolution of $0.25^\circ \times 0.25^\circ$.

Currently, ARPEGE wind analysis is rebinned to the resolution of the emission schemes with the nearest-neighbor interpolation. In this study we also take into account all adjacent gridboxes with the bilinear interpolation.

The initial emitted size-distribution is a three-mode log-normal distribution composed of fine, accumulation and coarse modes. The currently used size distribution has number median diameters: $r_1 = 1.7 \times 10^{-6}$ m, $r_2 = 6.7 \times 10^{-6}$ m, $r_3 = 14.2 \times 10^{-6}$ m; geometric standard deviations: $\sigma_1 = 1.7$, $\sigma_2 = 1.6$, $\sigma_3 = 1.5$; mass fractions $\text{frac}_1 = 0.3$, $\text{frac}_2 = 0.4$, $\text{frac}_3 = 0.3$; In this study we modified the size distribution following Alfaro et al. (1998) and Crumeyrolle et al. (2011), and our distribution is shifted towards smaller sizes with number median diameters: $r_1 = 6.4 \times 10^{-7}$ m, $r_2 = 3.45 \times 10^{-6}$ m, $r_3 = 8.67 \times 10^{-6}$ m, standard deviations and the mass fractions are the same as above.

4 Observations

To evaluate the performance of the model we use large-scale satellite observations and ground-based photometer data. The MODIS (Moderate-resolution Imaging Spectroradiometer) instruments observe atmospheric aerosols aboard Terra (since 2000) and Aqua (since 2002) from complementary sun-synchronous orbits. We use MODIS Aerosol Optical Depth the Collection 5 retrievals at 550 nm from Terra and Aqua that have predicted uncertainties of $\Delta\tau = \pm(0.03 + 0.05\tau)$ over oceans and $\Delta\tau = \pm(0.05 + 0.15\tau)$ over land (Remer et al., 2005). We start with good-quality global level 3 (L3) daily MODIS data (QA-weighted products) and perform an additional quality control by rejecting all gridboxes with less than 5 observations and more than a 50% cloud fraction. To combine Terra and Aqua observations and to regrid from the original L3 $1^\circ \times 1^\circ$ to MOCAGE $2^\circ \times 2^\circ$ grid we weight data by considering the number of level 2 (L2) observations in each L3 gridbox. The data is processed in this manner to minimize the number of observations that are cloud contaminated and those with statistically low

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



confidence, which often artificially increase AOD (Zhang et al., 2005; Koren et al., 2007; Remer et al., 2008).

AERONET (Aerosol Robotics Network) measures ground-based AOD from hundreds of automated stations with an accuracy of ± 0.01 (Holben et al., 1998). We use L2 daily data from different stations and interpolate it in logarithmic space to 550 nm (to harmonize wavelengths between different stations and with the model) by using available neighboring wavelengths: 440 nm, 500 nm, 675 nm, 870 nm.

Carrer et al. (2010) applied a multi-temporal approach to SEVIRI geostationary observations to derive surface and aerosols properties simultaneously. They retrieved AOD over land using directional and temporal analysis of the signal, opposed to spectral and spatial analysis done in MODIS retrieval (Ichoku et al., 2005). The data covers the SEVIRI field of view with a selected resolution of $1^\circ \times 1^\circ$, which is later regridded to the MOCAGE resolution.

5 Experiment design

We conduct our experiment to test the performance of the model in two main stages. First, we compare model outputs with observations. We define two main model configurations used as reference simulations, and compare them with observations to evaluate the overall impact of the model updates. The reference simulations are called SIM1 and SIM2 and their configurations are presented in Table 2. SIM1 uses the configuration of MOCAGE with the current parameterizations, while, in SIM2 we use the updated parameterizations. Second, we will evaluate the sensitivities of our results to the individual modules updates introduced in this study. To emphasize the separate effects of the parameterization updates, we have implemented different configurations based on the reference simulations. We separately analyze the impact of these updates on the emissions, sedimentation and wet scavenging (in simulations SIM2_EMI, SIM2_SED and SIM2_WDEP in Table 2), and we study the introduction of thermophoresis, diffusio-phoresis and electric effects in the below-cloud scavenging (simulation SIM2_BCPLUS

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



in Table 2). The simulations cover the globe for the year 2007 and use dynamics from 3 hourly meteorological fields from ARPEGE analyses downgraded to the resolution of the model ($2^\circ \times 2^\circ$). We have only primary aerosols in the model. Thus, to compare the model outputs with observations, we focus on the regions where primary aerosols dominate the aerosol optical depth field, and on strong, high concentration aerosol events near the sources where we can presume that the contribution of other aerosols is minimal. Inspecting averaged quantities (annual budget, burden, lifetime, emissions, depositions . . .) is used to evaluate the relative importance of different parameterizations and processes.

6 Results

In this section we compare MOCAGE SIM1 and SIM2 output to independent data. In Fig. 1, SIM1 and SIM2 aerosol optical depth (AOD) fields are compared with global yearly averaged MODIS AOD. Model AOD are only considered in the case of available MODIS observations. Overall, SIM2 shows a significant improvement over SIM1 in terms of AOD; especially in mid to high latitude southern oceans and the African dust outflow region. Near coasts, where the influence from the land is stronger, both model simulations underestimate AOD. This could be due to the absence of secondary aerosols in the model. The effect is more evident near South-East Asia, India, the Arabian peninsula and in Guinea Gulf, and is less pronounced in SIM2 due to the changes in primary aerosol parameterizations. The cause of discrepancy over the Gulf of Guinea is not clear and a similar pattern is observed by Jaeglé et al. (2011) in the GEOS-Chem model. In MOCAGE, it could be due to the missing secondary aerosols, the insufficient biomass-burning aerosol concentration, or possibly the cloud contamination in the MODIS data. Another possibility that is less likely is the inaccurate sea salt emissions due to possible wind errors in ARPEGE analysis, but considering the low wind speeds in the region we do not expect a lot of sea salt particles. In the tropical oceans, compared to MODIS, model AOD shifted from a negative bias in SIM1 to

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



a positive bias in SIM2. The results for SIM2 were significantly better, but the model still overestimates AOD with discrepancies that are larger than the MODIS expected error.

The relationship between model simulations and observations are presented in Fig. 2. This figure confirms the improvement in the AOD field in SIM2 compared to SIM1, but with discrepancies with observations visible in the both simulations. As we performed a strong quality control of the MODIS data, we presume that these discrepancies are related to the model performance. Having in mind also Fig. 1, SIM1 (Fig. 2a) shows strong signatures of overestimated sea salt AOD, a lack of secondary aerosols and an underestimation of desert dust particles. SIM2 (Fig. 2b) has significantly better statistics: a better correlation and smaller standard deviation relative to the observations, but still displays the strong signature of the missing secondary aerosols.

Figure 3 presents the temporal variability comparison of model simulations with MODIS observations over the selected regions, where primary aerosols dominate the AOD throughout the year and which are large enough to cover a statistically meaningful number of observations (usually thousands of observations per day). This figure confirms the positive effect due to the updates in the model parameterizations (statistics of Fig. 3 shown in Table 3). In the Saharan desert dust outflow region over the Atlantic (Fig. 3a), SIM2 agrees better with MODIS than SIM1, but with some underestimation of AOD in both simulations. We improved the intensities of the stronger dust events and overall correlation, and lowered bias from 0.18 in SIM1 to 0.05 in SIM2. Over the tropical waters of the central Pacific, SIM2 shows a slight statistical improvement (Fig. 3b): while SIM2 overestimates (≈ 0.04), SIM1 underestimates AOD (≈ 0.07). In the high-wind South Pacific region (Fig. 3c), SIM2 greatly improves the AOD values (bias reduced by a factor of five – from 0.15 to 0.03). Correlations between the observations and the simulated AOD are smaller than in the other regions, which is possibly due to wind errors present in the ARPEGE analysis for this remote part of the world. However, by taking into account the whole year data, SIM1 correlates better with MODIS than SIM2. The cause is a minimum in AOD in the Southern Hemisphere winter visible in the MODIS data, which is not present in the model. The noted minimum in the data is

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

determined by only a small number of satellite observations (there are even days without observations over the whole region because of high cloudiness). Thus, statistical confidence in the observations over that period is low, but it is possible that the errors in winds and sea surface temperature in the model are responsible for the discrepancy. If we exclude the effect of the observed winter minimum from our analysis, correlations in SIM2 are superior to SIM1, which demonstrates the improvement in the representation of aerosols in this part of the globe.

We also compared the model AOD with the independent dataset from AERONET for 2007 (Fig. 4). AERONET data is very accurate and it is often used for the validation of satellite data (Remer et al., 2005; Kahn et al., 2005; Schuster et al., 2012). However, the horizontal representativity of AERONET data is much smaller compared to that of satellite data. The data is less adapted to make comparisons with the model than satellite data – it is localized in a single spot for each station compared to the $2^\circ \times 2^\circ$ model data. It may be preferable to do multi-year analysis to improve statistics since some stations do not have the whole year record, and observations are especially scarce in the winter time. For our study, we chose the stations with available observations where primary aerosols dominate AOD. The AERONET observations confirmed the findings from the comparison with MODIS (Fig. 4, with statistics shown in Table 3): SIM2 reduced the AOD underestimation in the African dust outflow region (stations on Tenerife and Cape Verde), reduced sea salt overestimation in mid and high latitude regions (Amsterdam Island and Crozet Island), and had a minor impact on the absolute value of the bias – but changed its sign – over tropical regions (Nauru and Tahiti). We noted that AERONET stations on the oceanic islands show smaller AOD values than MODIS.

In Fig. 5 we compare the model simulation with the independent data from SEVIRI. We used the daily averaged only-land SEVIRI data (Carrer et al., 2010) to analyze an AOD field over Europe on a day when several strong primary aerosol events dominated the AOD field: several desert dust plumes visible over southern and central Europe, and sea salt aerosols to the north of the British Isles. In both model simulations, we see the same AOD features, but they differ in intensity. The location and extent of the features

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

in the model correspond well with the SEVIRI field, except that the desert dust plume over Eastern Europe in the model is located more to the South. The AOD in SIM2 are much closer to the SEVIRI data than in SIM1. Low background AOD values in the model reveal a systematic underestimation over continents. This could be due to an absence of secondary aerosols.

Table 4 shows how the MOCAGE simulations compare to data from the AeroCom model inter-comparison (<http://aerocom.met.no/>; Textor et al., 2006, 2007). AeroCom data is not based observations, but it is an independent dataset which indicates how MOCAGE relates to performances of other models. Values from SIM2 compare better to AeroCom ranges, by improving several parameters over SIM1. Emitted quantities fit better in SIM2, and there is an improvement in desert dust and sea salt lifetime as well. Black carbon emissions and burden correspond well to AeroCom, but the lifetime is by a factor of two larger, which could indicate weak wet deposition in the regions of high black carbon concentrations in SIM2. A larger sea salt burden in SIM2 causes longer lifetimes, but it is an improvement over SIM1.

In summary, observations from MODIS, AERONET and SEVIRI showed that changes in the aerosol parameterizations improved the model performance. SIM2 show a significantly better agreement in AOD compared with different types of observations relative to SIM1.

Sensitivity to new parameterization components

The updates to the parameterizations, which are collectively compared to the observations in the section above, have different and separate effects on the model results. In this section we analyze separate impacts of the updates by dividing them into the three most important components: changes in emissions of sea salt and desert dust aerosols, in sedimentation of particles, and in wet deposition. In Fig. 6, simulations SIM2_EMI, SIM2_WDEP, SIM2_SED are compared with the reference SIM2 run. This figure demonstrates that the improvements in the sedimentation make a modest overall change and that the changes to the emissions and wet deposition changes impact

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the results much more strongly. The total annual sedimentation in SIM2 decreased by 22 %, but this change influence AOD only moderately (Fig. 6c). In the atmospheric surface layer, sedimentation acts in conceit with dry deposition, and the impacts due to the changes to each process tend to compensate one another (Table 5).

Figure 6a presents the changes and major improvements in SIM2 that result from the modifications to the emissions compared to SIM2_EMI. The two distinct populations of points in the scatterplot represent overestimated sea salt particles, and underestimated desert dust. In addition, both populations are likely affected by the missing secondary aerosols. In the SIM2 emissions, the desert dust aerosol distribution is shifted towards smaller diameters making the sedimentation process less important for aerosol removal, and consequently their lifetimes are $\approx 50\%$ longer. The sea salt particle emissions in SIM2 are seven times larger than in SIM2_EMI, which makes their burden larger in SIM2. Also, their global distribution changed – there are more particles in low and mid latitudes, which makes their lifetime shorter. Although emitted sea salt quantities hugely vary between different estimates (from 1000–30 000 Tg year⁻¹, Lewis and Schwartz, 2004), emissions in MOCAGE are in agreement with the “best” estimate of Lewis and Schwartz (2004) of 5000 Tg year⁻¹ (estimate uncertainty of the factor of 4) and with AeroCom data (Table 4). Desert dust aerosols are emitted by a factor of 2–3 less in SIM2 than in SIM2_EMI, with the decrease mostly in Asian deserts. The new value agrees better with AeroCom estimate (Table 4). The change of wind interpolation in the desert dust emission schemes more strongly affected Asian desert dust because of the finer resolution of the scheme and the rougher topography present in this region.

Figure 6b shows the impact of the wet deposition changes in the model between the SIM2 and SIM2_WDEP simulations. The two simulations are strongly correlated both temporally and spatially, but they show important differences in AOD. Compared to SIM2_WDEP, the AOD in SIM2 became both larger and smaller in different situations; it decreased and increased depending on location with an overall tendency of weaker wet deposition in SIM2 (also shown in Table 5). Notably, the below-cloud scavenging is stronger in SIM2_WDEP due to the high precipitating cloud fraction in SIM2_WDEP,

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and missing precipitation re-evaporation (which is only introduced in SIM2). The difference is the most pronounced in tropical regions where convective systems are the cause of the majority of scavenging. Re-evaporation of precipitation effectively mitigates the wash-out of aerosols and reintroduces into the atmosphere about 10 % of aerosols. Modifications of the below cloud scavenging scheme also included additional scavenging processes (thermohoretic, diffusiphoretic and electric charge effects) proposed in the literature (Andronache et al., 2006) and which are introduced in the SIM2_BCPLUS simulation. The additional processes moderately changed the efficiency of the below-cloud scavenging (Table 6). Scavenging increased by 5 %, but this only minimally influenced the resulting AOD field.

7 Discussion

The updated parameterizations improve the aerosol representation in the model and agree better with observations independent from one another. Compared to observations the updated model still shows some overestimation over the sea-salt dominated regions, and an underestimation over the Atlantic region affected by the African desert dust outflow. The identified differences in AOD between the model and observations exceed prescribed observation errors and are consistent with the results of other studies: Zhang et al. (2012) with the ECHAM-HAM model compared to MODIS observations, Jaeglé et al. (2011) with the GEOS-CHEM model compared to both MODIS and AERONET observations, Su et al. (2013) using the GOCART model compared to the MODIS/MATCH AOD field. Zhang et al. (2012) found that simulated AOD over sea salt regions was overestimated to a similar degree as with MOCAGE, while Saharan outflow desert dust AOD was overestimated with an absolute difference of greater than a factor of 2. Jaeglé et al. (2012) found that AOD over sea salt regions was underestimated by less than 0.04, and over the African dust outflow region overestimated with the absolute difference greater by factor of 2–3 than as compared to MOCAGE. Su et al. (2013) compared GOCART with assimilated MODIS/MATCH AOD that was

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



“constrained to a large extent by MODIS” and found that AOD over the sea salt regions was overestimated slightly more than in MOCAGE, and AOD over the African dust outflow region was underestimated a little less than in MOCAGE.

We note the similar performances of the present time’s state-of-the-art models as compared to MOCAGE. Regarding this study, the biases could have different causes, and we should concentrate our further model developments to deal with these issues. Concerning desert dust aerosols, the peaks of the most intense desert dust events are well reproduced in MOCAGE, but in days with more moderate dust production we notice weaker model AOD than in the observations. These weaker AOD values over the African dust outflow region were found both near and far to the sources, which hints that emissions of African desert dust may be too small. Wind uncertainties could be important in this region, which could lead to less fugitive sand and dust, or the soil characterization in the scheme might need a refinement (e.g. better resolution, satellite retrieved soil type/properties) (Laurent et al., 2008a, b; Bouet et al., 2012,).

The sea salt discrepancy between MOCAGE and observations is possibly caused by either emissions that are too high, or below-cloud scavenging that is too weak. A high sea salt burden could indicate that the emissions are too high that produce it. Emitted sea salt quantities are in agreement with the AeroCom model average (Table 4), but the very large range in emissions in AeroCom indicates large uncertainties (Textor et al., 2007). Jaeglé et al. (2011) clearly showed the sea salt emission dependency on sea surface temperature, but their parameterization could be model dependent because they derived it by minimizing bias of their model relative to in-situ observations. Models could vary significantly and it might be necessary to separately fit the parameters of the Jaeglé et al. (2013) function to the individual model employed (which Jaeglé et al. (2011) also noted). This idea is supported by results from Spada et al. (2013), who implemented the sea salt function from Jaeglé et al. (2011) in the NMMB/BSC-CTM model and found the sea salt is overestimated in the tropical regions. Still, the parameterization depending on sea surface temperature undoubtedly improved the performance of MOCAGE.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The ratio of wet deposition to the total dry deposition (surface dry deposition + sedimentation) measured on cruise ships is 0.3/0.7 (Jaeglé et al., 2011), which corresponds well to the results from MOCAGE (Table 5). However, the longer mean atmospheric residence time of sea salt particles could indicate that the wet deposition, and in particular below-cloud scavenging, might be underestimated. The below-cloud scavenging is an efficient, episodic process, generally located near to sources, which can strongly influence the residence times of aerosols (Croft et al., 2009), and it is directly proportional to the precipitation intensity. The long lifetime of black carbon aerosols in the model can also indicate that wet deposition – by far the most important sink for black carbon particles (Textor et al., 2006) – could be too weak in MOCAGE. Compared with the data from the Global Precipitation Climatology Project, which is based on ground and satellite observations (Adler et al., 2003), the mean zonal distribution of precipitation in MOCAGE is correctly located, but its intensity is lower for ≈ 25% (Fig. 7). This affects the simulated quantities that are scavenged and could lead to a longer residence time in MOCAGE than in the AeroCom model average.

Updates in the emissions created the largest improvement in our model. But in other studies, uncertainties in the other aerosol parameterizations are found to be bigger than in emissions (Textor et al., 2007). This is backed by the difference in the scavenged aerosols simulated by two different in-cloud scavenging schemes presented in SIM1 and SIM2 that are about 25%. This implies that adding other refinements and aiming for more physically realistic parameterizations would likely further improve the model performance. Inclusion of secondary aerosols will be the most crucial addition, it would make the aerosol family more complete and improve the model performance over regions where secondary aerosols play a major role.

8 Summary and conclusion

In this paper we introduced the improvements to the aerosol module in the chemical transport model MOCAGE and evaluated the impact on aerosol representation,

**Development and
evaluation of aerosol
physical
parameterizations**

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

properties, and global distribution. The ambition was to solve already known model biases and to have more physically realistic aerosol parameterizations. The updates include changes in emissions, wet deposition, and sedimentation. Regarding emissions, we added a sea surface temperature (SST) dependence to the sea salt source function, and adjusted the size distribution (and the wind speed calculation) in the desert dust emission scheme. In the wet deposition scheme we used a new precipitation cloud cover calculation and in-cloud scavenging scheme. We also developed the below-cloud scavenging scheme by revising the calculation of raindrop size and terminal velocity, and by introducing re-evaporation and snowfall scavenging. The sedimentation module update strengthened the performance of the scheme: for example, the model demonstrated better mass conservation. The emission and wet deposition changes produced a stronger impact, while updates in sedimentation produced a less pronounced effect. Emission changes directly influenced known biases of sea salt and African desert dust aerosols, while the impact of wet deposition update is more complex and balanced – depending on the location, it decreased or increased aerosol optical depth (AOD).

We evaluated the impacts of these changes and compared them to observations from satellite sensors (MODIS, SEVIRI), the AERONET stations, and the AeroCom model inter-comparison. Since in our model only primary aerosols are present, we focused the analysis on the regions where mainly primary aerosols dominate AOD. Compared to the model simulation with old parameterizations, we significantly improve agreement with the observations and the AeroCom data. The sea salt and desert dust emitted quantities correspond better to the both estimates from the literature and the model average from the AeroCom project. The shift toward smaller particles in the desert dust size distribution and the modified geographical distribution of sea salt emissions had a positive impact on aerosol lifetimes. We examined the spatial and temporal variability of AOD and showed that the SST dependent emissions solved the strong positive bias in sea salt aerosols in mid to high latitudes that were previously seen in our model. This lead to a lower AOD over these regions and stronger AOD values over the tropics, which better agrees with observations. In the Saharan desert dust

aerosol outflow region, we reduced the bias, and improved the correlation and intensity of the stronger events. Overall, the updates had a positive effect on the correlation with observations.

The results confirmed that large uncertainties in models can come from the use of parameterizations. Significant differences in parameterization formulations lead to big differences in model outputs, as also confirmed in the literature (Textor et al., 2007). Two different in-cloud scavenging schemes used in this study had efficiencies that differed by a factor of 2, and a few changes in different components in our semi-empirical below-cloud scavenging scheme produce very different results in the same scheme.

We found that the introduced updates enhanced the model performance, but some discrepancies with the observations remain: (a) underestimation in the regions where secondary aerosols could have an important impact, (b) some overestimation of sea salt aerosols, and (c) some underestimation of African desert dust aerosols. The future work will address these issues. The inclusion of secondary aerosols in MOCAGE, which is the most important deficiency, is already in progress. The African desert dust emission scheme with a better resolution and satellite derived soil properties could bring better results over the region. Also, the addition of dust emissions in Australia, North and South America would fill the gap in the global dust emissions in the model.

As mentioned, aerosols have both direct and indirect effects on many atmospheric processes that have relevance to research themes in air quality and climate change. The current development is therefore a necessary stepping stone to being able to conduct studies on these important research topics. The mid-term aim, having added secondary aerosols, would be to carry out studies of air quality studies and to determine the human exposure to aerosols. Another aim would be to calculate the aerosol radiative budget. Another possibility would be to improve the representation of aerosols by using data assimilation or data inversion in the cases where the source term is highly uncertain.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Code availability

This paper is based on source code that is presently incorporated inside the Mocage model. The Mocage source code is the property of Meteo-France and CERFACS, and it is based on libraries that belong to some other holders. The Mocage model is not open source and routines from Mocage cannot be freely distributed. Therefore, we cannot provide the code openly to the GMD website.

Acknowledgements. This work is funded in France by Centre National de Recherches Météorologiques (CNRM-GAME) of Météo-France and Centre National de la Recherche Scientifique (CNRS). The authors would like to thank the AERONET PIs and their staff for establishing and maintaining the sites used in this investigation. We acknowledge the MODIS mission team and scientists for the production of the data used in this study. We also acknowledge NASA/Goddard Space Flight Center's Laboratory for Atmospheres for developing and computing GPCP combined precipitation data and NOAA/OAR/ESRL PSD, Boulder, USA for providing it, Lamarque et al. (2010) for the emissions of carbonaceous aerosols and Global Fire Emission Database project for the fire emissions that we used. We thank D. Carrer and his collaborators for developing and providing their SEVIRI retrieved aerosol data.

References

- Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P. P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., and Bolvin, D.: The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present), *J. Hydrometeorol.*, 4, 1147–1167, 2003.
- Alfaro, S. C., Gaudichet, A., Gomes, L., and Maille, M.: Mineral aerosol production by wind erosion: aerosol particle sizes and binding energies, *Geophys. Res. Lett.*, 25, 991–994, 1998.
- Andronache, C.: Estimated variability of below-cloud aerosol removal by rainfall for observed aerosol size distributions, *Atmos. Chem. Phys.*, 3, 131–143, doi:10.5194/acp-3-131-2003, 2003.
- Andronache, C.: Diffusion and electric charge contributions to below-cloud wet removal of atmospheric ultra-fine aerosol particles, *J. Aerosol Sci.*, 35, 1467–1482, 2004.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Andronache, C., Grönholm, T., Laakso, L., Phillips, V., and Venäläinen, A.: Scavenging of ultra-fine particles by rainfall at a boreal site: observations and model estimations, *Atmos. Chem. Phys.*, 6, 4739–4754, doi:10.5194/acp-6-4739-2006, 2006.

Barré, J., Peuch, V.-H., Attié, J.-L., El Amraoui, L., Lahoz, W. A., Josse, B., Claeysman, M., and Nédélec, P.: Stratosphere-troposphere ozone exchange from high resolution MLS ozone analyses, *Atmos. Chem. Phys.*, 12, 6129–6144, doi:10.5194/acp-12-6129-2012, 2012.

Bechtold, P., Bazile, E., Guichard, F., Mascart, P., and Richard, E.: A mass-flux convection scheme for regional and global models, *Q. J. Roy. Meteorol. Soc.*, 96, 869–886, 2001.

Bond, T. C., Bhardwaj, E., Dong, R., Jogani, R., Jung, S., Roden, C., Streets, D. G., and Trautmann, N. M.: Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000, *Global Biogeochem. Cy.*, 21, GB2018, doi:10.1029/2006GB002840, 2007.

Bouet, C., Cautenet, G., Bergametti, G., Marticorena, B., Todd, M. C., and Washington, R.: Sensitivity of desert dust emissions to model horizontal grid spacing during the Bodélé Dust Experiment 2005, *Atmos. Environ.*, 50, 377–380, 2012.

Bousserez, N., Attié, J.-L., Peuch, V.-H., Michou, M., Pfister, G., Edwards, D., Emmons, L., Mari, C., Barret, B., Arnold, S. R., Heckel, A., Richter, A., Schlager, H., Lewis, A., Avery, M., Sachse, G., Browell, E. V., and Hair, J. W.: Evaluation of the MOCAGE chemistry transport model during the ICARTT/ITOP experiment, *J. Geophys. Res.*, 112, D10S42, doi:10.1029/2006JD007595, 2007.

Brost, R., Feichter, J., and Heimann, M.: Three-dimensional simulation of ^7Be in a global climate model, *J. Geophys. Res.*, 96, 22423–22445, 1991.

Brown, P. P. and Lawler, D. F.: Sphere drag and settling velocity revisited, *J. Environ. Eng.-ASCE*, 129, 222–231, doi:10.1061/(ASCE)0733-9372(2003)129:3(222), 2003.

Callot, Y., Marticorena, B., and Bergametti, G.: Geomorphologic approach for modelling the surface features of arid environments in a model of dust emissions: application to the Sahara desert, *Geodin. Acta*, 13, 245–270, 2000.

Carrer, D., Roujean, J. L., Hautecoeur, O., and Elias, T.: Daily estimates of aerosol optical thickness over land surface based on a directional and temporal analysis of SEVIRI MSG visible observations, *J. Geophys. Res.*, 115, D10208, doi:10.1029/2009JD012272, 2010.

Chate, D. M.: Study of scavenging of submicron-sized aerosol particles by thunderstorm rain events, *Atmos. Environ.*, 39, 6608–6619, 2005.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Croft, B., Lohmann, U., Martin, R. V., Stier, P., Wurzler, S., Feichter, J., Posselt, R., and Ferrachat, S.: Aerosol size-dependent below-cloud scavenging by rain and snow in the ECHAM5-HAM, *Atmos. Chem. Phys.*, 9, 4653–4675, doi:10.5194/acp-9-4653-2009, 2009.
- 5 Crumeyrolle, S., Tulet, P., Gomes, L., Garcia-Carreras, L., Flamant, C., Parker, D. J., Matsuki, A., Formenti, P., and Schwarzenboeck, A.: Transport of dust particles from the Bodélé region to the monsoon layer – AMMA case study of the 9–14 June 2006 period, *Atmos. Chem. Phys.*, 11, 479–494, doi:10.5194/acp-11-479-2011, 2011.
- Davenport, H. M. and Peters, L. K.: Field studies of atmospheric particulate concentration changes during precipitation, *Atmos. Environ.*, 12, 997–1008, 1978.
- 10 Dentener, F., Kinne, S., Bond, T., Boucher, O., Cofala, J., Generoso, S., Ginoux, P., Gong, S., Hoelzemann, J. J., Ito, A., Marelli, L., Penner, J. E., Putaud, J.-P., Textor, C., Schulz, M., van der Werf, G. R., and Wilson, J.: Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom, *Atmos. Chem. Phys.*, 6, 4321–4344, doi:10.5194/acp-6-4321-2006, 2006.
- 15 Dufour, A., Amodei, M., Ancellet, G., and Peuch, V.-H.: Observed and modelled “chemical weather” during ESCOMPTE, *Atmos. Res.*, 74, 161–189, doi:10.1016/j.atmosres.2004.04.013, 2005.
- El Amraoui, L., Attié, J.-L., Semane, N., Claeys, M., Peuch, V.-H., Warner, J., Ricaud, P., Cammas, J.-P., Piacentini, A., Josse, B., Cariolle, D., Massart, S., and Bencherif, H.: Midlatitude stratosphere – troposphere exchange as diagnosed by MLS O₃ and MOPITT CO assimilated fields, *Atmos. Chem. Phys.*, 10, 2175–2194, doi:10.5194/acp-10-2175-2010, 2010.
- 20 Fan, T. and Toon, O. B.: Modeling sea-salt aerosol in a coupled climate and sectional microphysical model: mass, optical depth and number concentration, *Atmos. Chem. Phys.*, 11, 4587–4610, doi:10.5194/acp-11-4587-2011, 2011.
- 25 Gerber, H. E.: Relative-Humidity Parameterization of the Navy Aerosol Model (NAM), NRL Report 8956, Naval Research Laboratory, Washington DC, 1985.
- Giorgi, F. and Chameides, W. L.: Rainout lifetimes of highly soluble aerosols and gases as inferred from simulations with a general circulation model, *J. Geophys. Res.*, 91, 14367–14376, 1986.
- 30 Gong, S. L.: A parameterization of sea-salt aerosol source function for sub- and super-micron particles, *Global Biogeochem. Cy.*, 17, 1097, doi:10.1029/2003GB002079, 2003.
- Gong, S. L., Barrie, L. A., and Blanchet, J.-P.: Modeling sea-salt aerosols in the atmosphere: 1. Model development, *J. Geophys. Res.*, 102, 3805–3818, 1997.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A.: AERONET – a federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, 66, 1–16, doi:10.1016/S0034-4257(98)00031-5, 1998.
- 5 Ichoku, C., Remer, L. A., and Eck, T. F.: Quantitative evaluation and intercomparison of morning and afternoon Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol measurements from Terra and Aqua, *J. Geophys. Res.*, 110, D10S03, doi:10.1029/2004JD004987, 2005.
- 10 IPCC: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp., 2007.
- 15 Jacob, D. J., Liu, H., Mari, C., and Yantosca, R. M.: Harvard wet deposition scheme for GMI, Harvard Atmospheric Chemistry Modeling Group, available at: http://gmi.gsfc.nasa.gov/models/jacob_wetdep.pdf (last access: 1 December 2013), 2000.
- Jaeglé, L., Quinn, P. K., Bates, T. S., Alexander, B., and Lin, J.-T.: Global distribution of sea salt aerosols: new constraints from in situ and remote sensing observations, *Atmos. Chem. Phys.*, 11, 3137–3157, doi:10.5194/acp-11-3137-2011, 2011.
- 20 Josse, B., Simon, P., and Peuch, V.-H.: Radon global simulation with the multiscale chemistry transport model MOCAGE, *Tellus*, 56, 339–356, 2004.
- Junker, C. and Lioussé, C.: A global emission inventory of carbonaceous aerosol from historic records of fossil fuel and biofuel consumption for the period 1860–1997, *Atmos. Chem. Phys.*, 8, 1195–1207, doi:10.5194/acp-8-1195-2008, 2008.
- 25 Kahn, R. A., Gaitley, B. J., Martonchik, J. V., Diner, D. J., Crean, K. A., and Holben, B. N.: Multiangle Imaging Spectroradiometer (MISR) global aerosol optical depth validation based on 2 years of coincident Aerosol Robotic Network (AERONET) observations, *J. Geophys. Res.*, 110, D10S04, doi:10.1029/2004JD004706, 2005.
- 30 Kasper-Giebl, A., Koch, A., Hitzenberger, R., and Puxbaum, H.: Scavenging efficiency of “aerosol carbon” and sulfate in supercooled clouds at Mt. Sonnblick (3106 m a.s.l., Austria), *J. Atmos. Chem.*, 35, 33–46, 2000.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Koren, I., Remer, L. A., Kaufman, Y. J., Rudich, Y., and Martins, J. V.: On the twilight zone between clouds and aerosols, *Geophys. Res. Lett.*, 34, L08805, doi:10.1029/2007gl029253, 2007.
- Köpke, P., Hess, M., Schult, I., and Shettle, E. P.: Global Aerosol Data Set, Report no. 243, Max-Planck Institut für Meteorologie, Hamburg, Germany, 44 pp., 1997.
- Laakso, L., Grönholm, T., Rannik, U., Kosmale, M., Fiedler, V., Vehkamäki, H., and Kulmala, M.: Ultrafine particle scavenging coefficients calculated from 6 years field measurements, *Atmos. Environ.*, 37, 3605–3613, 2003.
- Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, *Atmos. Chem. Phys.*, 10, 7017–7039, doi:10.5194/acp-10-7017-2010, 2010.
- Lamarque, J.-F., Shindell, D. T., Josse, B., Young, P. J., Cionni, I., Eyring, V., Bergmann, D., Cameron-Smith, P., Collins, W. J., Doherty, R., Dalsoren, S., Faluvegi, G., Folberth, G., Ghan, S. J., Horowitz, L. W., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Naik, V., Plummer, D., Righi, M., Rumbold, S. T., Schulz, M., Skeie, R. B., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., Voulgarakis, A., and Zeng, G.: The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): overview and description of models, simulations and climate diagnostics, *Geosci. Model Dev.*, 6, 179–206, doi:10.5194/gmd-6-179-2013, 2013.
- Langner, J. and Rodhe, H.: A global three-dimensional model of the tropospheric sulfur cycle, *J. Atmos. Chem.*, 13, 225–263, doi:10.1007/BF00058134, 1991.
- Laurent, B., Marticorena, B., Bergametti, G., and Mei, F.: Modeling mineral dust emissions from Chinese and Mongolian deserts, *Global Planet. Change*, 52, 121–141, 2006.
- Laurent, B., Heinold, B., Tegen, I., Bouet, C., and Cautenet, G.: Surface wind accuracy for modeling mineral dust emission: comparing two regional models in a Bodélé case study, *Geophys. Res. Lett.*, 35, L09804, doi:10.1029/2008GL033654, 2008a.
- Laurent, B., Marticorena, B., Bergametti, G., Léon, J. F., and Mahowald, N. M.: Modeling mineral dust emissions from the Sahara desert using new surface properties and soil database, *J. Geophys. Res.*, 113, D14218, doi:10.1029/2007JD009484, 2008b.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Lewis, E. R. and Schwartz, S. E.: Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models, American Geophysical Union, Washington DC, 2004.
- Liu, H., Jacob, D., Bey, I., and Yantosca, R.: Constraints from ^{210}Pb and ^7Be on wet deposition and transport in a global three-dimensional chemical tracer model driven by assimilated meteorological fields, *J. Geophys. Res.*, 106, 12109–12128, 2001.
- Louis, J.-F.: Parametric model of vertical eddy fluxes in the atmosphere, *Bound.-Lay. Meteorol.*, 17, 187–202, 1979.
- Marshall, J. S. and Palmer, W. M.: The distribution of raindrops with size, *J. Meteorol.*, 5, 165–166, 1948.
- Martet, M., Peuch, V.-H., Laurent, B., Marticorena, B., and Bergametti, G.: Evaluation of long-range transport and deposition of desert dust with the CTM MOCAGE, *Tellus B*, 61, 449–463, doi:10.3402/tellusb.v61i2.16843, 2011.
- Marticorena, B., Bergametti, G., Aumont, B., Callot, Y., N'Doum'e, C., and Legrand, M.: Modeling the atmospheric dust cycle: 2. Simulation of Saharan dust sources, *J. Geophys. Res.*, 102, 4387–4404, doi:10.1029/96JD02964, 1997.
- Mei, F., Zhang, X., Lu, H., Shen, Z., and Wang, Y.: Characterization of MASDs of surface soils in north China and its influence on estimating dust emission, *Chinese Sci. Bull.*, 49, 2169–2176, 2004.
- Monahan, E. C., Spiel, D. E., and Davidson, K. L.: A model of marine aerosol generation via whitecaps and wave disruption in oceanic whitecaps, in: *Oceanic Whitecaps and their Role in Air–Sea Exchange Processes*, edited by: Monahan, E. C. and Niocaill, G. M., D. Reidel Publishing, Dordrecht, Holland, 167–174, 1986.
- Mu, M., Randerson, J. T., van der Werf, G. R., Giglio, L., Kasibhatla, P., Morton, D., Collatz, G. J., DeFries, R. S., Hyer, E. J., Prins, E. M., Griffith, D. W. T., Wunch, D., Toon, G. C., Sherlock, V., and Wennberg, P. O.: Daily and 3-hourly variability in global fire emissions and consequences for atmospheric model predictions of carbon monoxide, *J. Geophys. Res.*, 116, D24303, doi:10.1029/2011JD016245, 2011.
- Nho-Kim, E.-Y., Michou, M., and Peuch, V.-H.: Parameterization of size-dependent particle dry deposition velocities for global modeling, *Atmos. Environ.*, 38, 1933–1942, 2004.
- Pruppacher, H. R. and Klett, J. D.: *Microphysics of Clouds and Precipitation*, Kluwer Academic Publishers, Dordrecht, 1997.
- Rasch, P. J., Feichter, J., Law, K., Mahowald, N., Penner, J., Benkovitz, C., Genthon, C., Giannakopoulos, C., Kasibhatla, P., Koch, D., Levy, H., Maki, T., Prather, M., Roberts, D. L.,

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Roelofs, G. J., Stevenson, D., Stockwell, Z., Taguchi, S., Kritz, M., Chipperfield, M., Bal-
docchi, D., McMurry, P., Barrie, L., Balkansi, Y., Chatfield, R., Kjellstrom, E., Lawrence, M.,
Lee, H. N., Lelieveld, J., Noone, K. J., Seinfeld, J., Stenchikov, G., Schwartz, S., Walcek, C.,
and Williamson, D.: A comparison of scavenging and deposition processes in global models:
5 results from the WCRP Cambridge Workshop of 1995, *Tellus B*, 52, 1025–1056, 2000.

Remer, L. A., Kaufman, Y. J., Tanre, D., Mattoo, S., Chu, D. A., Martins, J. V., Li, R. R.,
Ichoku, C., Levy, R. C., Kleidman, R. G., Eck, T. F., Vermote, E., and Holben, B. N.: The
MODIS aerosol algorithm, products, and validation, *J. Atmos. Sci.*, 62, 947–973, 2005.

Remer, L. A., Kleidman, R. G., Levy, R. C., Kaufman, Y. J., Tanre, D., Mattoo, S., Martins, J. V.,
10 Ichoku, C., Koren, I., Yu, H., and Holben, B. N.: Global aerosol climatology from the MODIS
satellite sensors, *J. Geophys. Res.*, 113, D14S07, doi:10.1029/2007JD009661, 2008.

Ricaud, P., Attié, J.-L., Teyssèdre, H., El Amraoui, L., Peuch, V.-H., Matricardi, M., and Schlues-
sel, P.: Equatorial total column of nitrous oxide as measured by IASI on MetOp-A: implications
for transport processes, *Atmos. Chem. Phys.*, 9, 3947–3956, doi:10.5194/acp-9-3947-2009,
15 2009.

Schuster, G. L., Vaughan, M., MacDonnell, D., Su, W., Winker, D., Dubovik, O., Lapyonok, T.,
and Trepte, C.: Comparison of CALIPSO aerosol optical depth retrievals to AERONET mea-
surements, and a climatology for the lidar ratio of dust, *Atmos. Chem. Phys.*, 12, 7431–7452,
doi:10.5194/acp-12-7431-2012, 2012.

20 Seinfeld, J. H. and Pandis, S. N.: *Atmospheric Chemistry and Physics*, Wiley, New York, USA,
1998.

Slinn, W. G. N.: Some approximations for the wet and dry removal of particles and gases from
the atmosphere, *Water Air Soil Pollut.*, 7, 513–543, 1977.

Slinn, W. G. N.: Estimates for the long-range transport of air pollution, *Water Air Soil Pollut.*, 18,
25 45–64, doi:10.1007/978-94-009-7966-6_4, 1982.

Slinn, W. G. N. and Hales, J. M.: A reevaluation of the role of thermophoresis as a mechanism
of in- and below-cloud scavenging, *J. Atmos. Sci.*, 28, 1465–1471, 1971.

Sportisse, B.: A review of parameterizations for modelling dry deposition and scavenging of
radionuclides, *Atmos. Environ.*, 41, 2683–2698, 2007.

30 Su, W., Loeb, N. G., Schuster, G. L., Chin, M., and Rose, F. G.: Global all-sky shortwave di-
rect radiative forcing of anthropogenic aerosols from combined satellite observations and
GOCART simulations, *J. Geophys. Res.*, 118, 655–669, doi:10.1029/2012JD018294, 2013.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., Berntsen, T., Berglen, T., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Feichter, H., Fillmore, D., Ghan, S., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Horowitz, L., Huang, P., Isaksen, I., Iversen, I., Kloster, S., Koch, D., Kirkevåg, A., Kristjansson, J. E., Krol, M., Lauer, A., Lamarque, J. F., Liu, X., Montanaro, V., Myhre, G., Penner, J., Pitari, G., Reddy, S., Seland, Ø., Stier, P., Takemura, T., and Tie, X.: Analysis and quantification of the diversities of aerosol life cycles within AeroCom, *Atmos. Chem. Phys.*, 6, 1777–1813, doi:10.5194/acp-6-1777-2006, 2006.

Textor, C., Schulz, M., Guibert, S., Kinne, S., Balkanski, Y., Bauer, S., Berntsen, T., Berglen, T., Boucher, O., Chin, M., Dentener, F., Diehl, T., Feichter, J., Fillmore, D., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Horowitz, L., Huang, P., Isaksen, I. S. A., Iversen, T., Kloster, S., Koch, D., Kirkevåg, A., Kristjansson, J. E., Krol, M., Lauer, A., Lamarque, J. F., Liu, X., Montanaro, V., Myhre, G., Penner, J. E., Pitari, G., Reddy, M. S., Seland, Ø., Stier, P., Takemura, T., and Tie, X.: The effect of harmonized emissions on aerosol properties in global models – an AeroCom experiment, *Atmos. Chem. Phys.*, 7, 4489–4501, doi:10.5194/acp-7-4489-2007, 2007.

Teyssède, H., Michou, M., Clark, H. L., Josse, B., Karcher, F., Olivie, D., Peuch, V.-H., Saint-Martin, D., Cariolle, D., Attié, J.-L., Nédélec, P., Ricaud, P., Thouret, V., van der A, R. J., Volz-Thomas, A., and Chéroux, F.: A new tropospheric and stratospheric Chemistry and Transport Model MOCAGE-Climat for multi-year studies: evaluation of the present-day climatology and sensitivity to surface processes, *Atmos. Chem. Phys.*, 7, 5815–5860, doi:10.5194/acp-7-5815-2007, 2007.

Todd, C. J.: A System for Computing Ice Phase Hydrometeor Development, Report ARG 64 Paper 121, Atmospheric Research Group, Altadena, 30 pp., 1964.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), *Atmos. Chem. Phys.*, 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

Wang, X., Zhang, L., and Moran, M. D.: Uncertainty assessment of current size-resolved parameterizations for below-cloud particle scavenging by rain, *Atmos. Chem. Phys.*, 10, 5685–5705, doi:10.5194/acp-10-5685-2010, 2010.

White, F.: Viscous Fluid Flow, McGraw-Hill, New York, USA, 1991.

Williams, J. E., Scheele, M. P., van Velthoven, P. F. J., Cammas, J.-P., Thouret, V., Galy-Lacaux, C., and Volz-Thomas, A.: The influence of biogenic emissions from Africa on tropical

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

tropospheric ozone during 2006: a global modeling study, *Atmos. Chem. Phys.*, 9, 5729–5749, doi:10.5194/acp-9-5729-2009, 2009.

Williamson, D. L. and Rasch, P. J.: Two-dimensional semi-lagrangian transport with shape-preserving interpolation, *Mon. Weather Rev.*, 117, 102–129, 1989.

5 Wiscombe, W.: Improved Mie scattering algorithms, *Appl. Optics*, 19, 1505–1509, 1980.

Xu, K.-M. and Randall, D. A.: A semiempirical cloudiness parameterization for use in climate models, *J. Atmos. Sci.*, 53, 3084–3102, 1996.

10 Zhang, J., Reid, J. S., and Holben, B. N.: An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products, *Geophys. Res. Lett.*, 32, L15803, doi:10.1029/2005GL023254, 2005.

Zhang, K., O'Donnell, D., Kazil, J., Stier, P., Kinne, S., Lohmann, U., Ferrachat, S., Croft, B., Quaas, J., Wan, H., Rast, S., and Feichter, J.: The global aerosol-climate model ECHAM-HAM, version 2: sensitivity to improvements in process representations, *Atmos. Chem. Phys.*, 12, 8911–8949, doi:10.5194/acp-12-8911-2012, 2012.

15 Zhang, L., Wang, X., Moran, M. D., and Feng, J.: Review and uncertainty assessment of size-resolved scavenging coefficient formulations for below-cloud snow scavenging of atmospheric aerosols, *Atmos. Chem. Phys.*, 13, 10005–10025, doi:10.5194/acp-13-10005-2013, 2013.

20 Zhao, T. L., Gong, S. L., Zhang, X. Y., Abdel-Mawgoud, A., and Shao, Y. P.: An assessment of dust emission schemes in modeling east asian dust storms, *J. Geophys. Res.*, 111, D05590, doi:10.1029/2004JD005746, 2006.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Table 1. Bin ranges of individual primary aerosol species present in MOCAGE.

	bin1	bin2	bin3	bin4	bin5	bin6
desert dust (μm)	0.1–1	1–2.5	2.5–5	5–10	10–30	30–100
sea salt (μm)	0.003–0.13	0.13–0.3	0.3–1	1–2.5	2.5–10	10–20
black carbon (μm)	0.0001–0.001	0.001–0.003	0.003–0.2	0.2–1	1–2.5	2.5–10
organic carbon (μm)	0.0005–0.003	0.003–0.1	0.1–0.3	0.3–1	1–2.5	2.5–10

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 2. Description of MOCAGE simulations used in this study.

Simulation	Description
1. SIM1	The reference simulation using the current MOCAGE configuration: the Langner and Rodhe (1991) in-cloud scavenging scheme, Slinn's (1977, 1982) rainfall below-cloud scavenging scheme with fixed raindrop size and Stoke's regime terminal raindrop velocity, Gong's (2003) sea salt emission function.
2. SIM2	The reference simulation using the updated configuration: the Giorgi and Chameides (1986) precipitation cloud cover and in-cloud scavenging scheme, Slinn's (1977, 1982) rainfall below-cloud scavenging scheme modified with the exponential raindrop size-distribution and parameterized terminal raindrop velocity, the precipitation re-evaporation treated in the scavenging scheme, Slinn's (1977) snowfall below-cloud scavenging, Sutherland's law in the sedimentation scheme, the Jaeglé et al. (2011) sea salt source function, the Alfaro et al. (1998) desert dust initial distribution, a bilinear wind interpolation in the two desert dust emission schemes
3. SIM2-WDEP	As SIM2, but wet deposition module as in SIM1
4. SIM2-SED	As SIM2, but sedimentation module as in SIM1
5. SIM2-EMI	As SIM2, but emissions as in SIM1
6. SIM2-BCPLUS	As SIM2 plus thermohoretic, diffusiophoretic and electric charge effects

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 3. Correlation (ρ), absolute bias (Δ) and root mean square error (RMSE) between observations (MODIS and AERONET) and SIM1/SIM2. MODIS regions correspond to Fig. 3a–c, and AERONET sites correspond to Fig. 4a–f.

	SIM1			SIM2		
	ρ	Δ	RMSE	ρ	Δ	RMSE
MODIS						
African dust outflow region	0.76	0.179	0.192	0.797	0.051	0.079
Tropical Pacific	0.647	0.069	0.072	0.689	0.043	0.048
South Pacific*	0.334	0.153	0.185	0.363	0.026	0.057
AERONET						
Tenerife Santa Cruz	0.553	0.065	0.14	0.687	0.015	0.115
Cape Verde	0.587	0.232	0.289	0.632	0.065	0.202
Nauru	0.074	0.07	0.078	0.217	0.062	0.084
Tahiti	0.091	0.020	0.053	0.277	0.074	0.09
Amsterdam Island	0.204	0.104	0.15	0.269	0.052	0.062
Crozet Island	0.076	0.271	0.401	0.181	0.08	0.124

* Statistics calculated excluding the winter months because of very few observations

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Table 4. Globally averaged annual burden, lifetime and emissions in SIM1 and SIM2 for individual aerosols species (DD – desert dust, SS – sea salt, BC – black carbon, OC – organic carbon), compared to data from AeroCom project (Dentener et al., 2006; Textor et al., 2006). For a description of model simulations, see Table 2.

	SIM1			SIM2			AeroCom		
	DD	SS	BC	DD	SS	BC	DD	SS	BC
Burden (Tg)	9.66	9.70	0.24	11.2	34.1	0.34	19.2 ± 40 %	7.52 ± 54 %	0.24 ± 42 %
Lifetime (days)	1.0	3.0	10.1	2.9	1.5	14.2	4.1 ± 43 %	0.5 ± 58 %	7.1 ± 33 %
Emissions (Tgyr ⁻¹)	3476	1180	9.88	1395	8274	8.82	1678	7925	7.7

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Table 5. Globally averaged annual burden, lifetime, emissions, and deposited mass due to wet deposition, dry surface deposition and sedimentation for different aerosol types (DD – desert dust, SS – sea salt, BC – black carbon, OC – organic carbon) in different model simulations to reveal the separate effects of different model updates. For a description of model simulations, see Table 2.

	SIM2				SIM2_SED				SIM2_EMI				SIM2_WETDEP			
	DD	SS	BC	OC	DD	SS	BC	OC	DD	SS	BC	OC	DD	SS	BC	OC
Burden (Tg)	11.2	34.1	0.34	1.74	10.9	32.4	0.34	1.74	14.4	15.5	0.45	1.53	8.9	28.0	0.24	1.21
Lifetime (days)	2.93	1.50	14.2	19.3	2.84	1.43	14.2	19.3	1.51	4.79	16.5	21.0	2.32	1.23	10.1	13.4
Emissions (Tgyr ⁻¹)	1395	8274	8.82	33.0	1395	8274	8.82	33.0	3476	1180	9.89	18.0	1395	8274	8.82	33.0
Dry deposition (Tgyr ⁻¹)	860	2689	3.23	9.71	670	1912	3.23	9.71	1824	344	3.29	4.2	867	2605	2.8	8.1
Sedimentation (Tgyr ⁻¹)	317	3772	0.01	0.06	521	4742	0.01	0.06	1328	318	0.01	0.04	306	3715	0.01	0.05
Wet deposition (Tgyr ⁻¹)	199	1759	5.53	23.2	186	1576	5.53	23.2	305	534	6.4	14.1	184	1908	6.1	25.3

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Table 6. Globally averaged annual burden, lifetime, emissions, and deposited mass due to wet deposition, dry surface deposition, and sedimentation for different aerosol types (DD – desert dust, SS – sea salt, BC – black carbon, OC – organic carbon) in different model simulations to reveal the separate effects of different model updates. For a description of model simulations, see Table 2.

	SIM2				SIM2_BCPLUS			
	DD	SS	BC	OC	DD	SS	BC	OC
Burden (Tg)	11.2	34.1	0.34	1.74	11.1	33.6	0.34	1.72
Lifetime (days)	2.93	1.50	14.2	19.3	2.90	1.48	14.0	19.0
Emissions (Tgyr ⁻¹)	1395	8274	8.82	33.0	1395	8274	8.82	33.0
Dry deposition (Tgyr ⁻¹)	860	2689	3.23	9.71	859	2684	3.22	9.64
Sedimentation (Tgyr ⁻¹)	317	3772	0.01	0.06	317	3766	0.01	0.06
Wet deposition (Tgyr ⁻¹)	199	1759	5.53	23.2	200	1771	5.6	23.2
In-cloud scav. (%/100)	0.75	0.57	0.96	0.97	0.73	0.56	0.94	0.95
Below-cloud scav. (%/100)	0.25	0.43	0.04	0.03	0.27	0.44	0.06	0.05

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

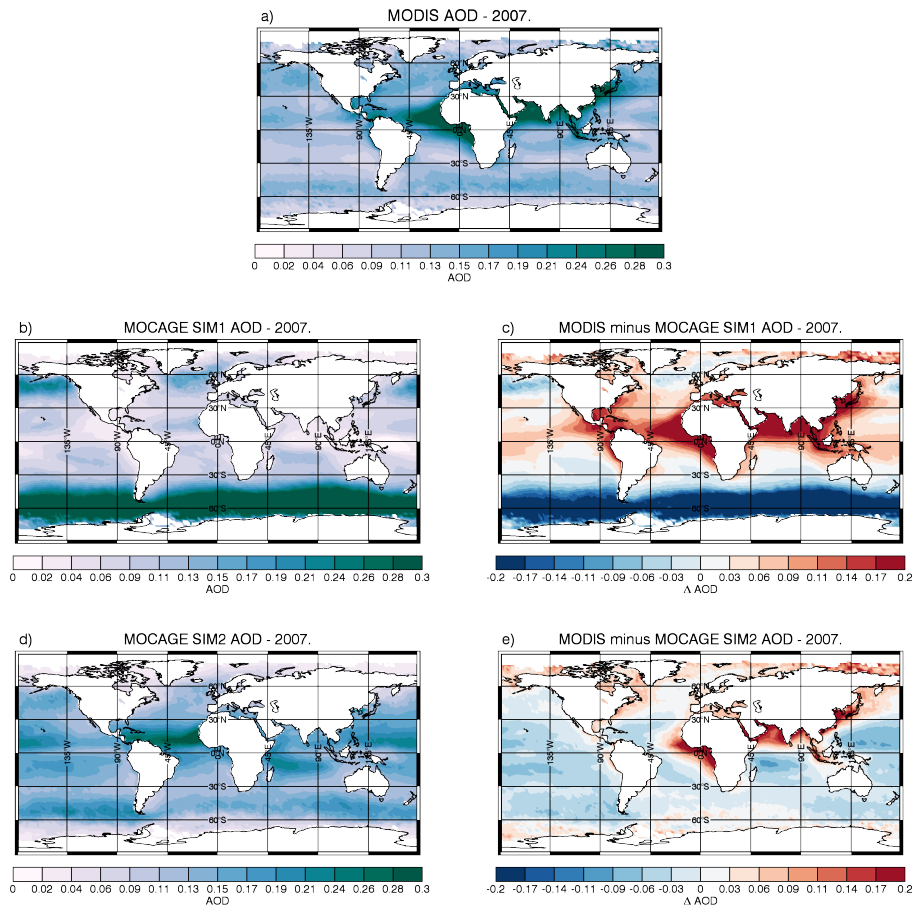


Fig. 1. Global, mean aerosol optical depth at 550 nm for the year 2007 from MODIS (Aqua + Terra) (a), SIM1 (b), SIM2 (d), and the difference between MODIS observations and model simulations (c and e). The descriptions of the model simulations are in Table 2.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

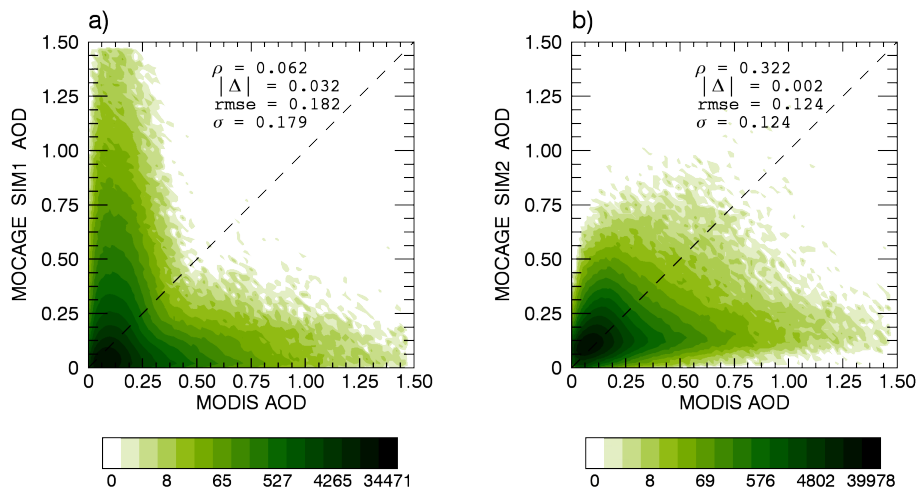


Fig. 2. Scatterplots of aerosol optical depths from MODIS and the simulations: SIM1 (a), SIM2 (b). In each panel, correlation (ρ), absolute bias (Δ), root mean square error (RMSE) and standard deviation (σ) are noted. The descriptions of the model simulations are in Table 2.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

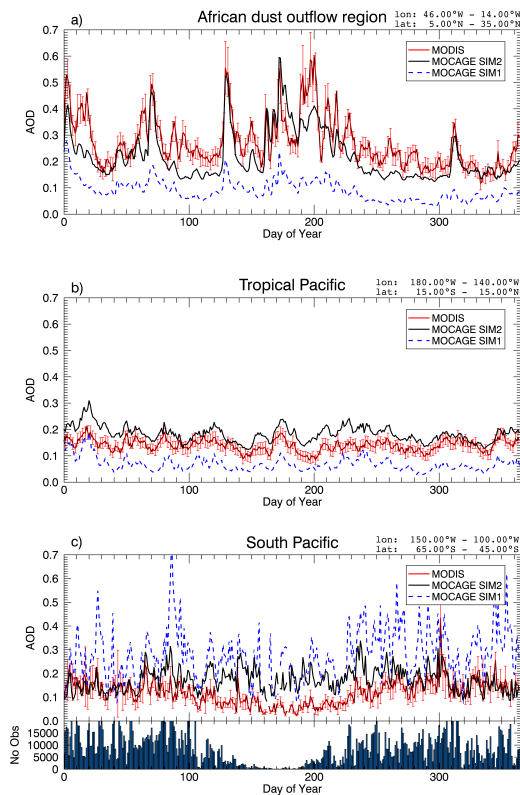


Fig. 3. Time series of aerosol optical depth at 550 nm in 2007 of MODIS (Aqua + Terra) data, SIM1 and SIM2 over: **(a)** the African desert dust outflow region (45–15° W, 5–35° N), **(b)** the tropical Pacific (180–140° W, 15° S–15° N), and **(c)** the South Pacific (150–100° W, 65–45° S). For the South Pacific region, the number of observations over the region is given for each day. Correlation, bias and root mean square error for both SIM1 and SIM2 as compared to MODIS data are given in Table 3. The descriptions of model simulations are in Table 2.

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Development and
evaluation of aerosol
physical
parameterizations

B. Sič et al.

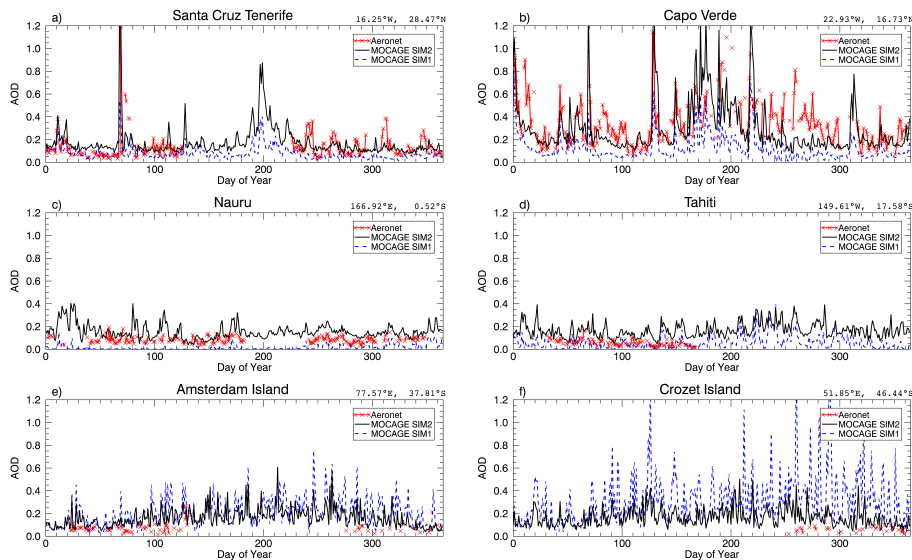


Fig. 4. Time series of aerosol optical depth at 550 nm from the AERONET data, SIM1 and SIM2 for six AERONET stations: Tenerife Santa Cruz (16.25° W, 28.47° N), Cape Verde (22.93° W, 16.73° N), Nauru (166.92° W, 0.52° S), Tahiti (149.61° W, 17.58° S), Amsterdam Island (77.57° E, 37.81° S) and Crozet Island (51.85° E, 46.44° S). Correlation, bias and root mean square error for both SIM1 and SIM2 compared to AERONET observations are given in Table 3. The descriptions of the model simulations are in Table 2.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Development and
evaluation of aerosol
physical
parameterizations

B. Sič et al.

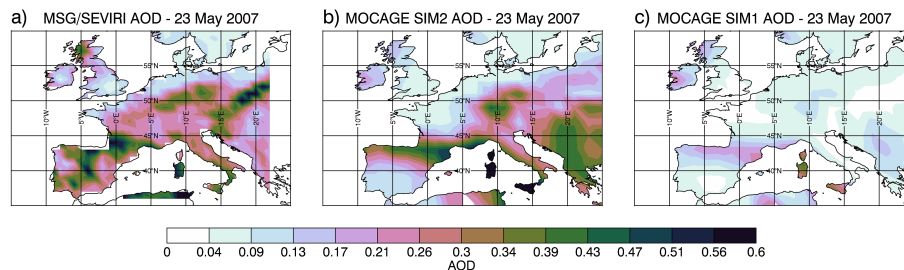


Fig. 5. Aerosol optical depth fields over Europe for 23 May 2007 at 550 nm from SEVIRI (a), SIM2 (b), and SIM1 (c) simulations.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Development and evaluation of aerosol physical parameterizations

B. Sič et al.

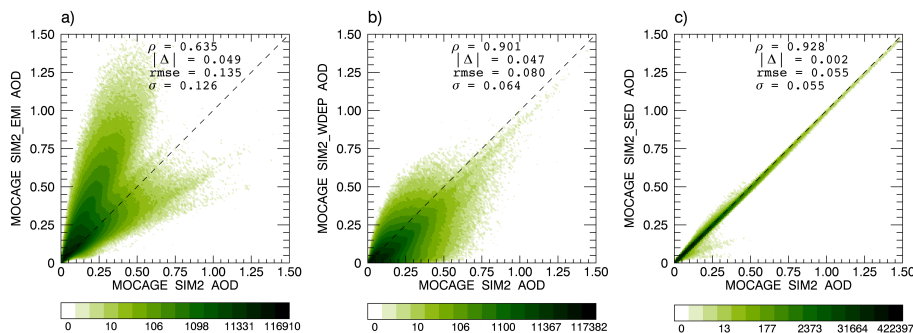


Fig. 6. Scatterplots of aerosol optical depth from the model reference run SIM2 and the simulations: SIM2_EMI (a), SIM2_WDEP (b), SIM2_SED (c). These scatterplots show the impact of different model updates to the model performance. In each panel, correlation (ρ), absolute bias (Δ), root mean square error (RMSE) and standard deviation (σ) are noted. The description of the model simulations is in Table 2.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Development and
evaluation of aerosol
physical
parameterizations**

B. Sič et al.

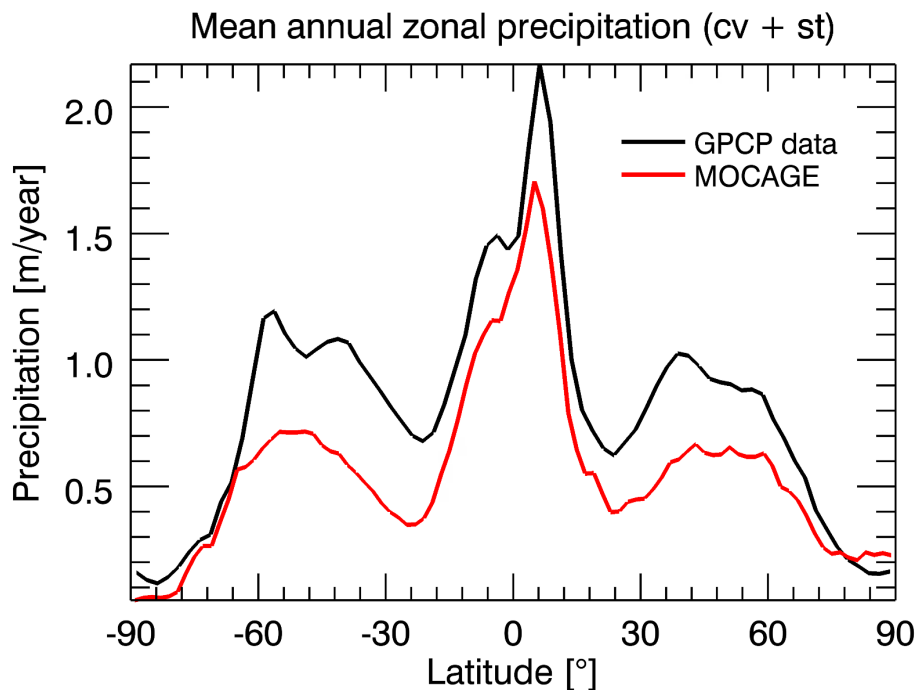


Fig. 7. Mean annual zonal precipitation quantity (combined stratiform (st) and convective (cv) precipitation) from GPCP data and MOCAGE.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)