# MACv2.0-SP

## The MPI-M's simple plume parameterization for optical properties of anthropogenic aerosol

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**Abstract** This technical report introduces MACv2.0-SP, the "simple plume" (SP) parameterization for optical properties of anthropogenic fine-mode aerosol that is currently under development at the Max Planck Institute for Meteorology (MPI-M), Hamburg. Four key characteristics of the parameterization guided the code development: (1) computationally efficient code structure, (2) usage of optical properties that can be constrained by observations, (3) flexibility for a variety of applications, and (4) user-friendly module design supporting the implementation into models of different complexity. The mathematical construction of the plumes, their scaling over time, and adaptation to different wavelength are introduced and variables that can be specified by the user are outlined.

## 1 Motivation

State-of-the-art climate models show large uncertainties in the aerosol forcing of the Earth system. Reasons for model diversity include differences in the aerosol parameterization, the background atmospheric state, and the response mechanisms to aerosol perturbations. A key aspect of the latter is believed to be the interaction of atmospheric circulation, clouds and precipitation, which have been identified as one of the grand challenges in climate science. Assessing the relative importance of model differences in circulation and clouds compared to aerosol effects would help to better understand model uncertainty in aerosol forcing.

The new aerosol parameterization “simple plumes” (MACv2.0-SP) for aerosol optical properties is under development at the Max Planck Institute for Meteorology (MPI-M) for use by CMIP6 models participating in the “Radiative Forcing Model Inter-comparison Project” (RFMIP). MACv2-SP represents monthly varying plumes of anthropogenic fine-mode aerosol at and downwind of major source regions. The aerosol parameterization is based on the updated climatology MACv2.0, which uses remote sensing and global aerosol-climate model results of AeroCom to determine the four dimensional distribution of AOD, single scattering albedo and asymmetry parameter. In MACv2.0-SP, this climatology is approximated by functional relationships to derive a computationally efficient, scientifically flexible, and easily applicable parameterization. In the following, the method is introduced.

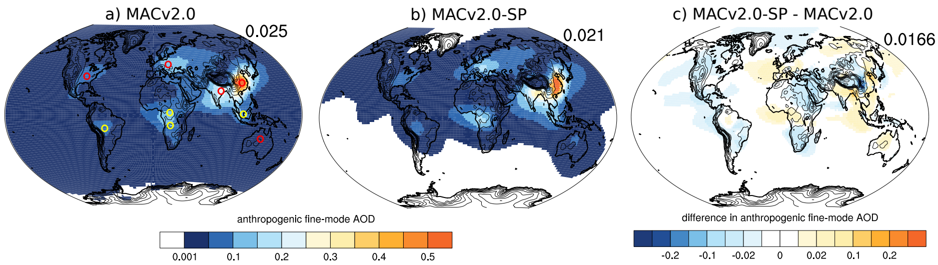


*Figure 1: Global distribution of anthropogenic AOD in MACv2 and MACv2-SP. Shown are the annual mean anthropogenic fine-mode AOD at 550 nm (shaded) of (a) MACv2, (b) MACv2-SP and (c) their differences. The geographical position of the centers of the aerosol plumes for MACv2-SP are indicated in a for regions of industrial pollution (red rings) and regions with additional biomass burning (yellow rings). Number in upper right corners are the globally averaged AODs in a,b and the route mean square difference in c. The orographic height is shown in steps of 500 m (thin contours).*

## 2 Method

The plumes are constructed at nine geographical positions worldwide. The plume centers are defined as regional maxima in the anthropogenic fine-mode aerosol optical depth that have been identified in MACv2.0, shown in Figure 1a. These include five industrial source regions and four areas which are additionally influenced by biomass burning. The regional maxima in AOD at 550 nm are derived from the climatology MACv2.0 that is assumed to be representative for 2005. Each plume is spatially approximated by a superposition of two Gaussian functions for the horizontal distribution and one beta function for the vertical profile. Scaling parameters are applied to vary the AOD over time and adjust the values to different wavelengths. The Angstrom exponent, the single scattering albedo and the asymmetry parameter are prescribed as constant values at 550 nm for each plume. These values are derived from the monthly MACv2.0 climatology for fine-mode AOD by averaging over $20^o$x$20^o$ around the plume centers. The vertical distribution of the scattering properties is achieved through weighting the scattering properties by the vertical profile of aerosol extinction.

### 2.1 Spatial approximations

The horizontal approximation of the anthropogenic AOD is achieved through the superposition of two rotated Gaussian functions. The global $2d$-distribution of the anthropogenic AOD $\tau_{\text{ant}}(x,y)$ at each longitude $x$ and latitude $y$ can be written as:

$$\tau_{\text{ant}}(x,y) = \sum_{i=1}^{9}\sum_{j=1}^{2} a_{ij}\tau_i \exp\left[-\frac{1}{2}\langle \mathbf{x}_i, \mathbf{R}_{ij}\mathbf{A}_{ij}^{-1}\mathbf{R}_{ij}^{-1}\mathbf{x}_i\rangle\right], \mathbf{x}_i = \begin{pmatrix} x - x_i \\ y - y_i \end{pmatrix} \qquad (1)$$

with the number of plume $i$, the number of Gaussian feature $j$ ($i, j \in \mathbf{Z}$), the scaling factor $a_{ij}$ for separating the contribution of the two Gaussian functions

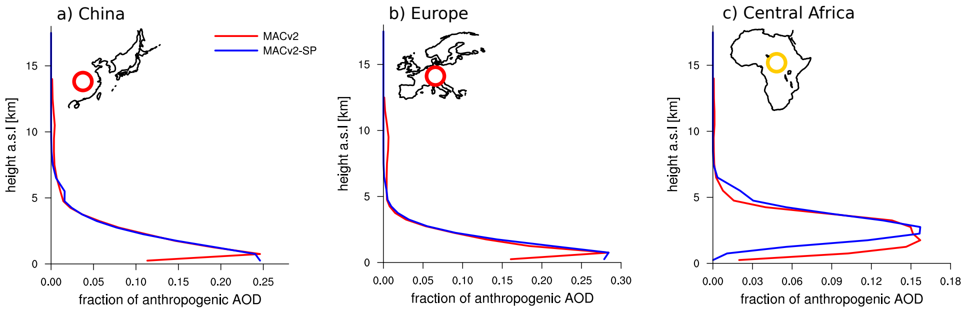


*Figure 2: Vertical profile of fraction of AOD from MACv2.0-SP. Shown are $b_{ik}$ for the Chinese, European and Central African plume.*

to the anthropogenic AOD plume $\tau_i$, and the geographical position ($x_i$,$y_i$) of the plume centers. The scaling factor $a_{ij}$ distributes the anthropogenic AOD across the two Gaussian features. These are plume-dependent fractions that are chosen such that the spatio-temporal pattern of MACv2.0 is reproduced and the maximum AOD of MACv2.0 of the plume center is conserved, i.e., $a_{i1}$ and $a_{i2}$ add to one.

The covariance matrix $\mathbf{A}_{ij}$ describes the horizontal extent of each plume and feature defined by:

$$\mathbf{A}_{ij} = \begin{cases} \begin{pmatrix} \sigma^2_{west,ij} & 0 \\ 0 & \sigma^2_{west,ij} \end{pmatrix}, & \text{if } (x - x_i) \leq 0 \\ \\ \begin{pmatrix} \sigma^2_{east,ij} & 0 \\ 0 & \sigma^2_{east,ij} \end{pmatrix}, & \text{if } (x - x_i) > 0. \end{cases} \tag{2}$$

The standard deviations in x-y directions $\sigma_{ij}$ of the anthropogenic AOD to the east and west of each plume $i$ and each Gaussian feature $j$ serve as tuning parameter. For each plume, one of the Gaussian features is fitted to primarily capture the regional maximum in AOD and is typically rotationally symmetric. The other Gaussian function is modified to capture the zonally and meridionally stretched AOD field that represents the downwind transport. The latter span over elliptic areas with mostly a larger zonal than meridional extent.

The horizontal orientation of the plumes is controlled by the rotation matrix $\mathbf{R}_{ij}$:

$$\mathbf{R}_{ij} = \begin{pmatrix} \cos\theta_{ij} & \text{-}\sin\theta_{ij} \\ \sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix}. \tag{3}$$

The angles $\theta_{ij}$ are tuned for each plume and feature to match the dominant transport pathways as identified by the monthly MACv2.0 climatology. For instance, the mid-latitude plumes point eastward from the centres, motivated by the aerosol transport with prevailing westerlies.

MACv2.0-SP distributes the vertically integrated aerosol optical depth over height by multiplying equation 1 with weights $b_{ik}$. The weights are calculated from a plume-dependent beta-function:

$$b_{ik} = c_i \cdot h_k^{\alpha_i - 1}(1 - h_k)^{\beta_i - 1}, \tag{4}$$

with the normalized height $h_k$ ($h_k \in \mathbf{R}, h_k \in [0,1]$) of the model layer $k$, and the plume-dependent parameters $c_i$, $\alpha_i$, and $\beta_i$ that are tuned to reproduce the vertical distribution of the fine-mode AOD averaged in the surrounding area of $20^o$x$20^o$ of each plume center. The normalized heights and the number of model layers are specified by the user. The weights $b_{ik}$ are implemented such that the total AOD is initially preserved. Grid-boxes below the user-specified orography are assigned extinctions of zero, such that the total AOD is reduced over elevated terrain. Figure 2 shows $b_{ik}$ for three plumes compared to the fractions from MACv2.0. The largest extinction occurs in low-levels for all plumes. Maxima in the tropics, e.g. Central Africa shown in Figure 2c, are shifted to higher altitudes compared to the extra-tropics, e.g. China and Europe (Figure 2a—b), consistent with increasing tropospheric depths towards the equator.

## 2.2 Scaling

Equation 1 is multiplied by scaling variables to adjust the constructed plumes to different times and wavelengths, i.e., the anthropogenic fine-mode AOD $\tau_{ant}$ is determined by:

$$\tau_{\text{ant}}(x,y,k,t,\lambda) = \sum_{i=1}^{9} b_{ik} \sum_{j=1}^{2} a_{ij} w_{ij,mon,year} \tau_i \exp\left[-\frac{1}{2}\langle \mathbf{x}_i, \mathbf{R}_{ij}\mathbf{A}_{ij}^{-1}\mathbf{R}_{ij}^{-1}\mathbf{x}_i\rangle\right]. \tag{5}$$

The scaling variable $w_{ij,mon,year}$ is given by:

$$w_{ij,mon,year} = s_{ij,mon}\, \gamma_{i,year}\, l. \tag{6}$$

The components are the plume-, feature- and month-dependent seasonal factor $s_{ij,mon}$, the plume- and year-dependent annual factor $\gamma_{i,year}$, and the wavelength-dependent factor $l$. These components are introduced next.

### 2.2.1 Seasonal cycle

The seasonality of anthropogenic emissions is approximated by the plume-dependent scaling parameter $s_{i,mon}$, that reads for purely industrial plumes:

$$s_{i,mon} = 1 - \eta_i \cos\left[\left(2\pi\left(f - \frac{mon_i}{12}\right)\right)\right]. \tag{7}$$

The plume-dependent parameter $\eta_i$ is tuned such that the seasonal cycle in $20^o$x$20^o$ grid boxes around the plume centers from MACv2.0 is matched. The fraction of year $f \in [0,1]$ determines the time and the fraction of the year $mon_\mathrm{i}/12$ is the time when the AOD maximum of the plume and Gaussian feature occurs. The values for $mon_i$ are chosen such that the AOD is at maximum in the middle of the month.

The biomass burning plumes have a strong and sharply-defined seasonal cycle that is superimposed onto a constant background. Their seasonal cycles are difficult to approximate with harmonic functions so that the biomass burning plumes in Africa, South America and Southeast Asia are constructed with linear interpolation between prescribed factors per month. For each plume, the factors are the same for their Gaussian features, except in South America and South Africa.

Note that the Central and Southern African plume are situated close to each other. The names refer to their relative position and have no geographical meaning. This plume couple has been introduced to mimic the latitudinal migration of the African biomass burning plume. Figure 3 shows the monthly mean of anthropogenic AOD for illustrating the effect of the seasonal scaling.

### 2.2.2 Annual scaling

The plume-dependent factor $\gamma_{i,year}$ achives an annual scaling of the anthropogenic AOD maximum for 1850 to 2100 for each plume. These factors have been derived from a CMIP5 transient climate simulation of ECHAM5-HAM under the assumption that MACv2.0 is representative for the year 2005. The scaling factor is set to one for 2005, such that $\gamma_{i,year}$ for individual years is derived by:

$$\gamma_{i,year} = \frac{aod_{i,year}}{aod_{i,2005}}, \tag{8}$$

where $aod_{i,year}$ is the mean AOD for single year from the ECHAM-HAM simulation. These values are currently provided in steps of five years and linearly interpolated for years in between. Figure 4 shows the meridional distribution of anthropogenic AOD for different 50-year periods using these derived scaling factors. The long-term evolution can be changed by using other data sets in Equation 8.

Using MACv2.0-SP in some applications requires knowledge of the future evolution of anthropogenic AOD. Results from state-of-the-art aerosol-climate models could be used for deriving the scaling paramter but such simulations might not be available at the time when experiments with MACv2.0-SP will begin. In order to offer an independent solution, the feasibility of using emission instead of AOD in deriving the scaling factor has been explored. Spatial sums of the anthropogenic aerosol emission from NIES $E_{i,year}$ have been used in the ECHAM-HAM simulation and are tested here to derive $\gamma_{i,year}$ following:

$$\gamma_{i,year} = \frac{\sum_{area} E_{i,year}}{\sum_{area} E_{i,2005}}, \tag{9}$$

NIES emissions of SO2 and black carbon have been assumed as sources for anthropogenic aerosol. Different area sizes, namely sub-domains of $20^o$x$20^o$ and

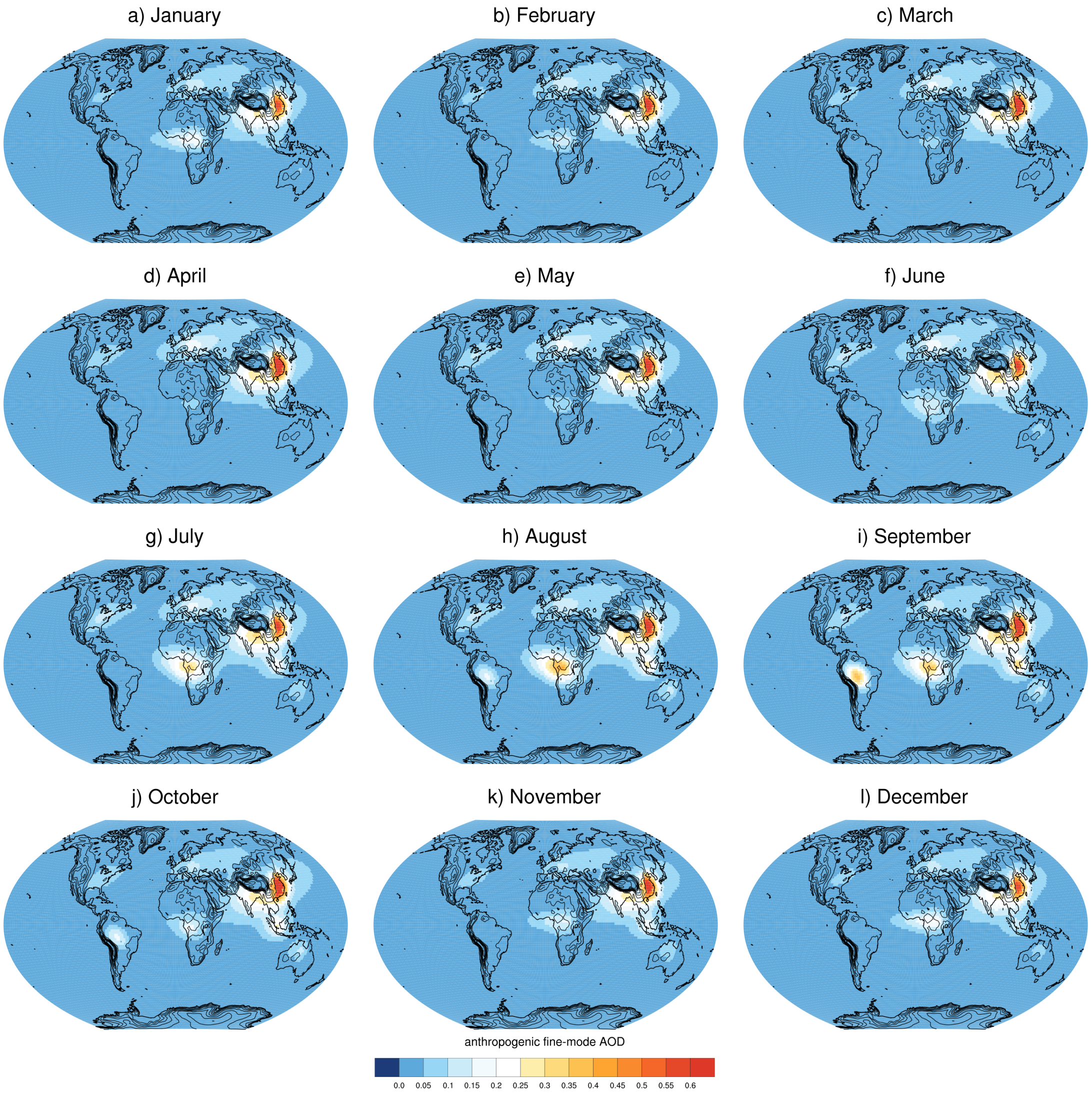


*Figure 3: Anthropogenic AOD from MACv2.0-SP. Shown are monthly means for 2005. The orographic height is shown in steps of 500 m (thin contours).*

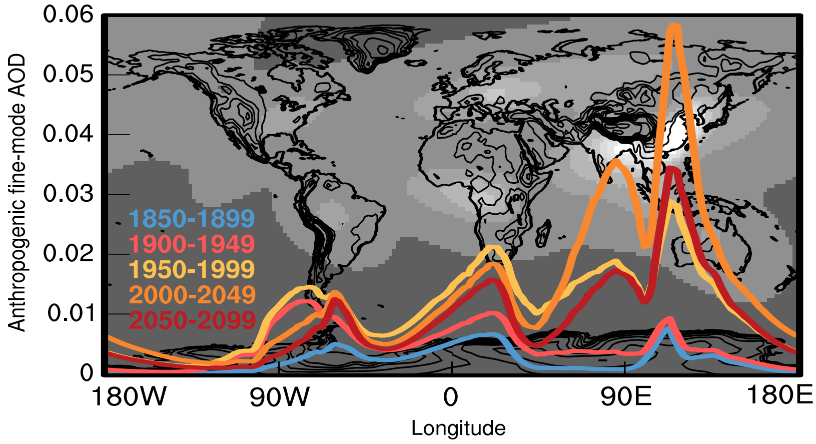


*Figure 4: Meridional means of anthropogenic AOD in MACv2.0-SP. Shown are 50-year means of $\tau_{ant}$ using the annual AOD values from a historical simulation of the aerosol-climate model ECHAM-HAM for deriving scaling factors.*

$10^o$x$10^o$ around each plume center and adjacent grid boxes only, are tested. Figure 5 shows the evolution of the scaling parameter for historical times and suggests that emission could be used for scaling the plume magnitude in MACv2.0-SP. Using the different scaling parameters in MACv2.0-SP gives similar results in global mean AOD, shown in Figure 6.

The year 1850 is chosen as pre-industrial level. The anthropogenic AOD should be set to zero in 1850 for applications of MACv2.0-SP in CMIP6 models because the background aerosol climatology of the models are representative for aerosol loadings that have already been affected by human activity. Moreover, new emission inventories will be available for CMIP6. This requires a revision of the settings for $\gamma_{i,year}$, so that new annual scaling variables will be provided in 2016.

### 2.2.3 Wavelength

MACv2.0-SP adjusts the anthropogenic AOD maximum $\tau_{i,550nm}$ of each plume $i$ to the user-specified wavelength $\lambda$ in nm using:

$$l = exp\left[\alpha \;\; ln\left(\frac{\lambda}{550nm}\right)\right] \tag{10}$$

with the Angstrom exponent $\alpha$ at 550 nm. The latter has been derived from MACv2.0 as means over $20^o$x$20^o$ sub-domains around each plume center.

The scattering properties are adjusted for wavelengths larger than 700 nm only, motivated by the steep increase in aerosol absorption from the visible to the infrared spectral range. For the single scattering albedo $ssa_{i,\lambda}$ of the plume $i$, the approximation for user-specified wavelengths $\lambda$ larger than 700 nm is

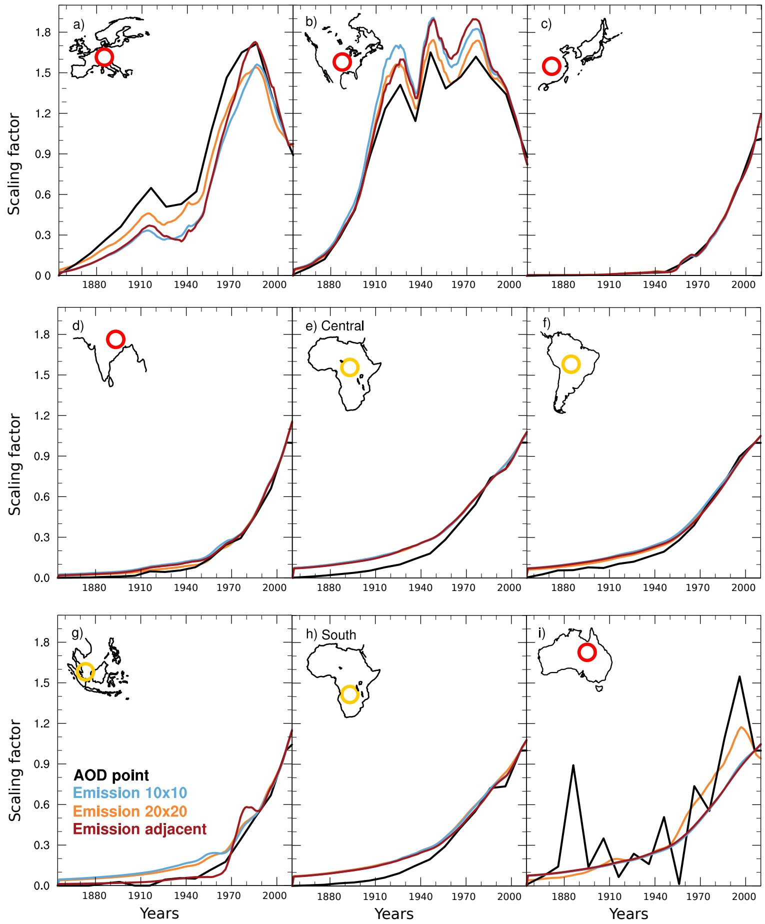


*Figure 5: Regional development of the annual scaling parameter in MACv2.0-SP. Shown is the temporal evolution of $\gamma_{i,year}$ using (black) the annual AOD values from a historical simulation of the aerosol-climate model ECHAM-HAM driven with NIES emissions and (colors) using the NIES emissions with different integration areas for deriving scaling factors directly.*

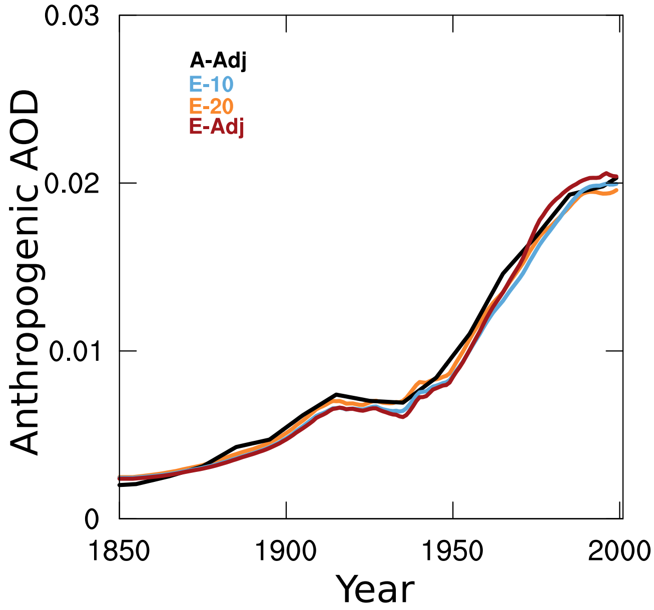


*Figure 6: Evolution of global mean anthropogenic AOD in MACv2.0-SP. Shown is the temporal evolution of $\tau_{ant}$ using $\gamma_{i,year}$ derived from (black) the annual AOD values from a historical simulation of the aerosol-climate model ECHAM-HAM driven with NIES emissions and (colors) using the NIES emissions with different integration areas directly.*

defined as:

$$ssa_{i,\lambda} = \frac{ssa_{i,550nm}\,(r_\lambda)^4}{ssa_{i,550nm}\,(r_\lambda)^4 + r_\lambda(1 - ssa_{i,500nm})},\; r_\lambda = \frac{700nm}{\lambda}. \tag{11}$$

The asymmetry parameter $asy_{i,\lambda}$ is calculated for wavelengths larger than 700 nm using:

$$asy_{i,\lambda} = asy_{i,550nm}\sqrt{r_\lambda}. \tag{12}$$

## 3 Twomey effect

The Twomey effect is parameterized as factor that describes the change in cloud droplet number concentration (CDNC) with changes in fine-mode AOD at 550 nm:

$$\frac{d(CDNC)}{CDNC} = \frac{20\;ln\left(1000\;\left(\tau_{ant} + \tau_{bg}\right) + 3\right)}{20\;ln\left(1000\;\tau_{bg} + 3\right)}. \tag{13}$$

The fine-mode background AOD $\tau_{bg}$ is simplified parameterized as function of longitude, latitude and season:

$$\tau_{bg}(x, y, mon) = \tau_{pl}(x, y, mon) + \tau_{oc} \tag{14}$$

The plume-approximated background $\tau_{pl}$ is derived by repeating the spatial and temporal scaling for prescribed fine-mode background AODs at 550 nm, with

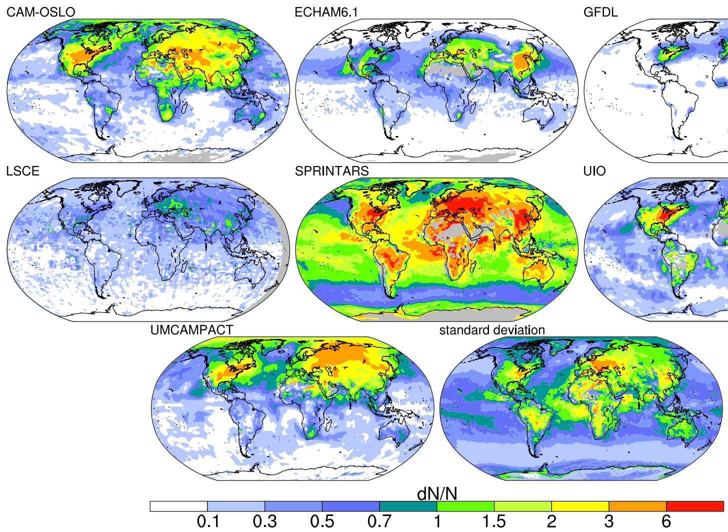


*Figure 7: Global distribution of $d(CDNC)/CDNC$ in AeroCom models. Shown is the annual mean of $d(CDNC)/CDNC$ of different models and their standard deviation at the bottom right. Courtesy Jobst Müsse*

one value for industrial and one for biomass burning regions. These values are set such, that biomass burning regions have a larger background than regions of purely industrial pollution. Sensitivity tests of the impact of the background on the indirect radiative forcing led to the current settings of 0.1 and 0.6, respectively. Regions far from plume centers can not be accurately captured with the plume-approximated background alone. This mainly concerns oceanic regions that motivated the introduction of an additional global background AOD $\tau_{oc}$, that is set to 0.02.

Sensitivity tests suggest that these idealized settings for the fine-mode background give a reasonable estimate of $d(CDNC)/CDNC$, as well as the global mean and pattern of the indirect aerosol forcing calculated with an offline radiative transfer model compared to MACv2.0. The sensitivity tests anticipated to determine settings that yield an indirect aerosol forcing that is plausible rather than reproduces the forcing of MACv2.0. This decision is motivated by large sensitivities of the forcing from MACv2.0 to assumptions made in deriving CDNC, shown in Figure 8, and a large multi-model spread in estimates of $d(CDNC)/CDNC$, shown in Figure 7.

The annual and monthly means of $d(CDNC)/CDNC$ are shown in Figure 9

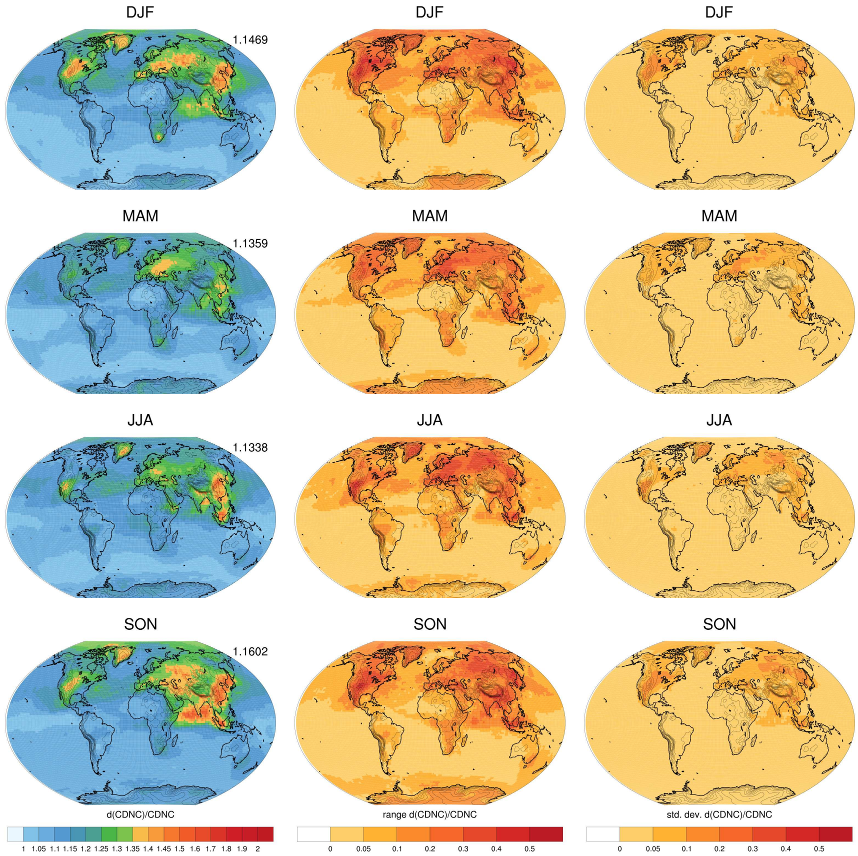


*Figure 8: Seasonal means and sensitivity of $d(CDNC)/CDNC$ in MACv2.0-SP. Shown are (left) seasonal means of $d(CDNC)/CDNC$ of MACv2.0 for 2005. (middle) the range of results and (right) their standard deviation using different assumptions for the CCN activation in MACv2.0.*

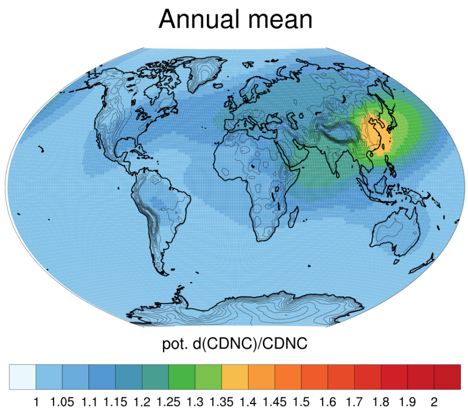


*Figure 9: Global distribution of $d(CDNC)/CDNC$ in MACv2.0-SP. Shown is the annual mean of potential $d(CDNC)/CDNC$ for 2005 based on a fine-mode AOD background of 0.1 for industrial plumes, 0.6 for biomass plumes and 0.02 as global background. The orographic height is shown in steps of 500 m (thin contours).*

and 10, respectively. The associated results for $d(CDNC)/CDNC$ lie within the range of uncertainty from AeroCom models and are not in disagreement with a satellite estimate based on monthly means (courtesy Jobst Müsse and Stefan Kinne). In other applications, the settings could be tuned differently to get other indirect forcing patterns as the magnitude of the Twomey effect remains controversial.

## 4 Using MACv2.0-SP

The fortran module is constructed such, that the user specifies the wavelength, longitude and latitude, time, number of levels, orographic height, absolute and normalized height of model levels and their vertical extent and passes the information to the module. The return values are vertical profiles of aerosol extinction, single scattering albedo and asymmetry parameter as well as the factor for changing the CDNC in the host model. The Angstrom exponent is also returned for validation purposes. The offline driver demonstrates how the input needs to be specified and writes the results to a netCDF file.

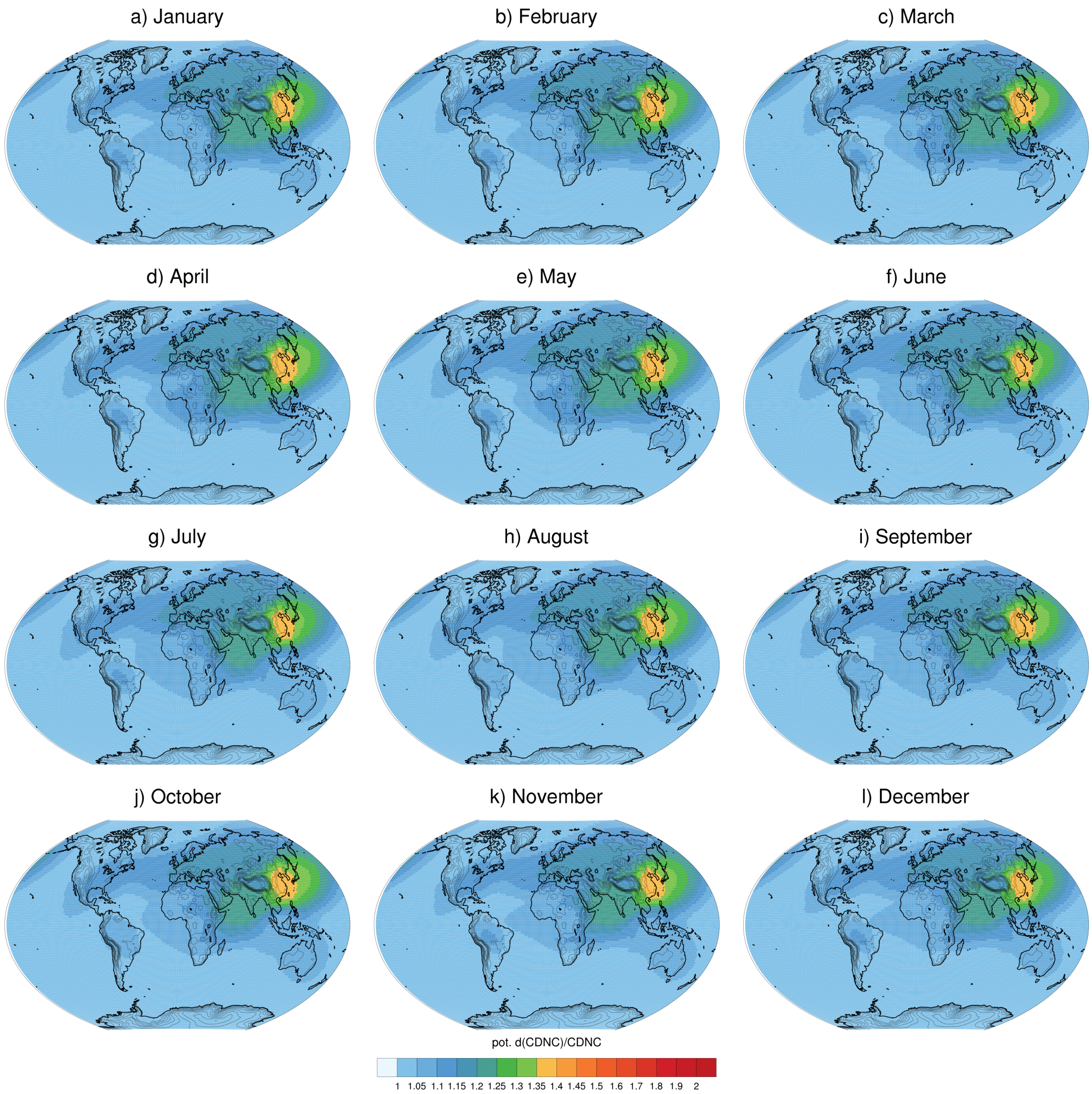


*Figure 10: Global distribution of $d(CDNC)/CDNC$ in MACv2.0-SP. Shown are monthly means for 2005 based on fine-mode AOD backgrounds of 0.1 for industrial plumes, 0.6 for biomass plumes and 0.02 as global background. The orographic height is shown in steps of 500 m (thin contours).*