Easy Aerosol - a modeling framework to study robustness and sources of uncertainties in aerosol-induced changes of the large-scale atmospheric circulation

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1 Synopsis

Recent climate modeling studies illustrated the potential of aerosols to change the large-scale atmospheric circulation, and with this the global patterns of precipitation. It remains unclear, however, to what extent the proposed aerosol-induced changes reflect robust model behavior or are affected by uncertainties in the models' treatment of physical processes, most notably those related to moist phenomena. "Easy Aerosol" addresses these questions by subjecting comprehensive atmosphere general circulation models to the same set of idealized "easy" aerosol perturbations that are designed based on a global aerosol climatology and mimic the gravest mode of the anthropogenic aerosol. This document discusses the motivation of Easy Aerosol, describes the aerosol perturbations, and defines the experimental protocol.

2 Motivation

Atmospheric aerosols and their effect on climate and climate change have since long been a focus of climate and atmospheric sciences. Traditionally, aerosol research centered on how aerosols affect Earth's energy budget and surface temperatures through aerosol-radiation (ARI) and aerosol-cloud interactions (ACI). As these interactions depend on details of the aerosols' radiative and chemical properties, large efforts have been undertaken to map the presence of aerosols in Earth's atmosphere and to develop analogously comprehensive and complex descriptions of aerosols in climate models. In recent years, however, an increasing number of studies emphasized that the climatic impact of aerosols is not limited to surface temperatures. Indeed, due to their spatial variability, aerosols form localized patterns of heating and cooling through which they can cause substantial changes in the large-scale atmospheric circulation and distribution of precipitation (Wang, 2013). Several observed circulation changes have been attributed to aerosols. Specifically, it has been suggested that aerosols were fundamental to temperature oscillations in the North Atlantic (Booth et al., 2012), changes in the Southeast Asian monsoon (Bollasina et al., 2011), and southward shifts of the tropical rainbelt (Hwang et al., 2013). Moreover, aerosols might alter the frequency and severeness of extreme events through their effect on the background atmospheric flow (Petoukhov et al., 2013).

Substantial uncertainties in aerosol-climate interactions remain. These uncertainties presumably arise both from the way aerosols are represented in models, and from the way the atmospheric circulation responds to aerosols. Advancing our understanding of aerosol-climate interactions therefore requires us to separate the uncertainties related to the aerosol representation from those related to the response of the circulation. While projects such as AeroCom have extensively studied the former source of uncertainty (e.g., Stier et al., 2012), Easy Aerosol tackles the latter. Although the CMIP5 experiments *sstClimAerosol* and *sstClimSulfate* (Taylor et al., 2012) could serve as a starting point for at least some of the questions addressed by Easy Aerosol, Easy Aerosol compares aerosol-induced circulation changes in a manner that would not be possible with the CMIP5 experiments. This is not only because in Easy Aerosol models will use exactly the same aerosol perturbation, sea-surface temperatures, and sea-ice fractions, but also because Easy Aerosol takes into account changes in sea-surface temperatures.

3 Aim

Easy Aerosol aims to identify to what extent suggested aerosol-induced circulation changes are robust across climate models and which differences in the models' treatment of physical processes limit robust behavior. To this end, Easy Aerosol subjects comprehensive atmosphere general circulation models to a set of idealized "easy" aerosol perturbations. Easy Aerosol regards aerosols as agents of atmospheric and surface heating or cooling, and as such focuses on aerosol-radiation interactions. Easy Aerosol neglects aerosol-cloud interactions because the varying levels of how models currently represent these interactions would obstruct to distill robustness and differences in aerosol-radiation interactions. While one might expect that models should respond similarly to the same heating anomaly, differences in the models' circulation and interactions with other parametrized processes, most notably clouds and convection, may dominate the response and lead to non-robust circulation changes. Therefore, Easy Aerosol will help to pinpoint and interpret sources of model uncertainty and to judge what level of complexity in the representation of aerosols is needed and sensible in the light of other currently existing model limitations.

Easy Aerosol is organized within COOKIE&CREAM (Stevens et al., 2012) and the WCRP Grand Challenge on Clouds, Circulation and Climate Sensitivity (Bony and Stevens, 2012), which aim to improve understanding of the coupling between clouds, water vapor and the large-scale circulation. Easy Aerosol also maintains discussions and actively seeks input from the AeroCom, GeoMIP and ACCMIP communities.

4 The Easy Aerosol perturbations

Current atmosphere models do not only differ in the amount of aerosols they use but also in their level of representation of these aerosols (Myhre et al., 2013). To overcome the associated difficulties when comparing aerosol-induced large-scale circulation changes across different models, Easy Aerosol applies a set of idealized "easy" aerosol perturbations that are designed based on the aerosol climatology MACv1 of Kinne et al. (2013) and are meant to capture the gravest mode of the anthropogenic aerosol. Easy Aerosol focuses on shortwave aerosol-radiation interactions. Aerosol-cloud interactions are not taken into account as these remain poorly understood and the way these effects are entered into models would largely determine the results. Nonetheless one could imagine repeating Easy Aerosol with the Twomey effect at some later date given a suitable climatology of cloud-condensation nuclei, as this type of aerosol-cloud interaction can be reasonably well modeled. The Easy Aerosol perturbations are constant in time and, except for total aerosol optical depth, are independent of wavelength. They are defined in terms of analytical expressions, which facilitates their model implementation.

4.1 Horizontal distribution of total aerosol optical depth at 550 nm

Fig. 1 shows the geographical distribution of total anthropogenic aerosol optical at 550 nm and year 2000 from MACv1, τ_{550}, as well as its meridional and zonal profiles. Easy Aerosol mimics the aerosol preponderance in the northern hemisphere and in the three main emission regions over the US, Europe, and Southeast Asia by means of Gaussian functions. τ_{550} is approximated via a separation ansatz that decouples the zonal and the meridional distributions,

$$\tau_{550}(\varphi, \lambda) = \tau_0 \, a(\varphi) \cdot b(\lambda), \tag{1}$$

where φ and λ denote latitude and longitude. The meridional distribution, a, is modeled as

$$a(\varphi) = \exp\left(-\frac{(\varphi - \varphi_0)^2}{2\sigma_\varphi^2}\right). \tag{2}$$

Analogously, the zonal distribution is modeled by the superpositions of three Gaussians,

$$b(\lambda) = \sum_{i=1..3} b_i \exp\left(-\frac{(\lambda - \lambda_i)^2}{2\sigma_{\lambda,i}^2}\right), \tag{3}$$

with the centers, widths and magnitudes of the plumes chosen such that the zonal profile of Easy Aerosol matches that from MACv1 averaged between 10° S and 80° N.

In addition to the zonal distribution with three plumes, Easy Aerosol applies a zonally-uniform distribution, $b(\lambda) = 1$ (Fig. 2). In the zonal mean the zonally-uniform and three plumes cases exhibit the same total aerosol optical depth. Contrasting the aerosol-induced changes from the zonally-uniform and three plumes cases will allow Easy Aerosol to study to what extent changes of the mean and eddy parts of the circulation are controlled by the zonal aerosol distribution.

Tab. 1 lists the values for the horizontal distribution parameters. Note that τ_0 differs for the zonally-uniform and the three plumes cases as the zonal profile b is not normalized to one.

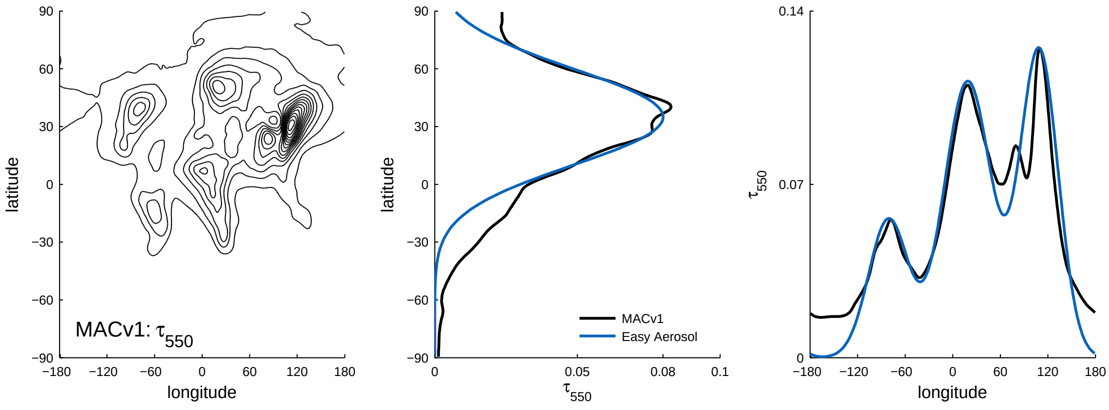

Figure 1 – Annual-mean anthropogenic total aerosol optical depth at 550 nm from MACv1, τ_{550}. Left: geographical distribution in contour intervals of 0.025; lowest contour at 0. Middle: Meridional profile obtained by averaging τ_{550} zonally. Right: Zonal profile obtained by averaging τ_{550} between 80° N and 10° S. The Easy Aerosol fits according to Eqs. 2 and 3 are shown in blue.

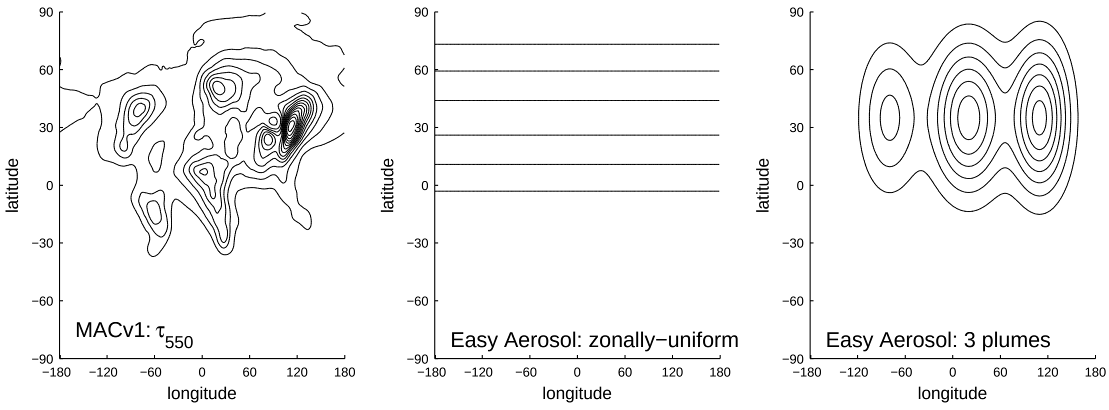

Figure 2 – Left: annual-mean anthropogenic total aerosol optical depth at 550 nm from MACv1, τ_{550}. Middle and right: τ_{550} for the zonally-uniform and three plumes cases of Easy Aerosol. The contour interval is 0.025, with the lowest contour at 0.

Table 1 – Parameters defining the total aerosol optical depth at 550 nm, τ_{550}, for the zonally-uniform and three plumes cases.

	zonally-uniform	three plumes
τ_0	0.08	0.0932
φ_0	35° N	35° N
σ_φ	25°	25°
plume over Europe:		
λ_1	n/a	20° E
$\sigma_{\lambda,1}$	n/a	30°
b_1	n/a	1.8
plume over Southeast Asia:		
λ_2	n/a	110° E
$\sigma_{\lambda,2}$	n/a	24°
b_2	n/a	2.0
plume over the US:		
λ_3	n/a	80° W
$\sigma_{\lambda,3}$	n/a	25°
b_3	n/a	0.9

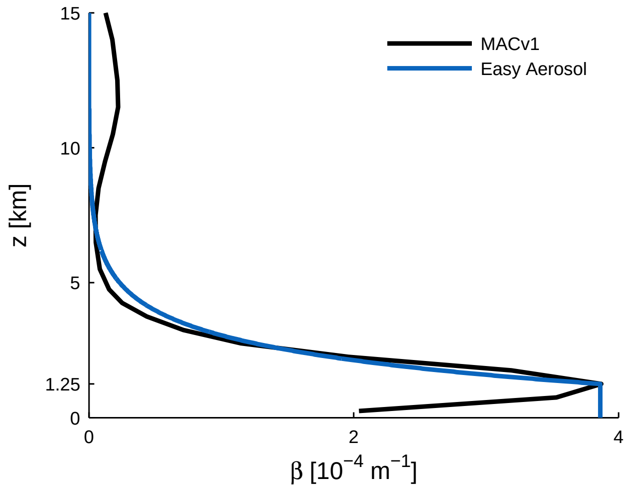

Figure 3 – Vertical profile of the normalized extinction coefficient β in MACv1 and Easy Aerosol.

Table 2 – Parameters defining the vertical profile of the normalized extinction coefficient.

β_0	$0.98657 \cdot 10^{-3}\,\mathrm{m}^{-1}$
c	$0.75 \cdot 10^{-3}\,\mathrm{m}^{-1}$
z_0	$1250\,\mathrm{m}$

4.2 Vertical distribution of total aerosol optical depth at 550 nm

In the vertical, the aerosol distribution is specified by the normalized extinction coefficient, β (units of m^{-1}), shown in Fig. 3. In Easy Aerosol, β is constant from the surface to a height z_0 and decays exponentially above,

$$\beta = \beta_0 \cdot \exp(-c \cdot z_0), z < z_0 \quad (4)$$

$$\beta = \beta_0 \cdot \exp(-c \cdot z), z > z_0. \quad (5)$$

The shape and parameters are chosen to fit the vertical profile of the average extinction profile of MACv1; parameter values are given in Tab. 2. The vertical distribution is the same for the zonally-uniform and three plumes cases.

4.3 Optical properties and Ångström coefficient

The single scattering albedo, the asymmetry factor and the Ångström coefficient are set to globally constant values listed in Tab. 3. The single scattering albedo and the asymmetry factor are independent of the wavelength. The choice of a globally constant single scattering

Table 3 – Optical properties and Ångström coefficient used in Easy Aerosol.

single-scattering albedo	0.926
asymmetry factor	0.65
Ångström coefficient	1.8

albedo and asymmetry factor is motivated by the fact that their time and zonal means were found to vary only marginally with latitude in MACv1. Because the asymmetry factor derived from MACv1 is biased low due to assumptions in MACv1's fitting procedure (S. Kinne, personal communication), Easy Aerosol does not apply the asymmetry factor derived from MACv1 but a higher value of 0.65.

The Ångström coefficient, α, translates the total optical depth at 550 nm, τ_{550}, to the total aerosol optical depth at other wavelengths Λ,

$$\frac{\tau_\Lambda}{\tau_{550}} = \left(\frac{\Lambda}{550\,\mathrm{nm}}\right)^{-\alpha}. \tag{6}$$

When incorporating the wavelength dependence of τ_Λ in models with a high number of shortwave bands like ECHAM6, τ_Λ for a given band can safely be calculated by the above equation and taking Λ as the central wavelength of this band. However, for models with a low number of shortwave bands like LMDz, τ_Λ for a given band should be computed by taking into account the spectral distribution of the solar insolation across this band.

4.4 Impact of Easy Aerosol is limited to aerosol-radiation interactions

The Easy Aerosol should not have any effects beyond its radiative effect. Aerosol-cloud interactions are deliberately ingnored in Easy Aerosol. This means that the Easy Aerosol should not affect the cloud droplet and ice particle number. In ECHAM6, for example, this is guaranteed by making the cloud-droplet number a pure function of pressure and surface (ocean vs. land) such that at a grid box and model level all Easy Aerosol simulations use the same cloud-droplet number. Also, there should be no aerosol surface deposition affecting snow and ice albedo.

4.5 Technical implementation of the aerosol perturbations

To implement the aerosol perturbations, Easy Aerosol provides a Fortran90 module. Based on the geographical location, the lower and upper altitudes of the vertical layers above ground, and the spectral resolution of the shortwave radiation bands the module calculates the aerosol optical properties of each grid box and layer. For the total aerosol optical thickness at 550 nm, τ_{550}, the module uses the central latitude and longitude of a given grid box. In the vertical, the aerosol optical thickness at 550 nm of a given layer is calculated as the vertical integral of the normalized extinction coefficient, β, across that layer, multiplied by τ_{550}. Thanks to the analytical expressions for β in Eqs. 4 and 5, the vertical integral can be evaluated analytically. Because the module was developped for ECHAM6, which has a large number of shortwave bands, τ for a given band is calculated from τ_{550} using the central wavelength of that band in Eq. 6. As noted above, for models with a low number of shortwave bands, the module needs to be adapted to take into account the appropriate wavelengths to calculate τ_Λ, which in general deviate from the central wavelengths.

To verify the correct implementation of the Easy Aerosol perturbations, it is recommended to monitor the changes in the clear-sky shortwave irradiances at the top-of-atmosphere, surface, and inside the atmosphere. These are depicted for reference in Figs. 4 and 5 for the ECHAM6-TNT model and calculated from the difference between the AMIP Easy Aerosol simulations ZONAL and PLUMES and the AMIP aerosol-free reference simulation CLEAN (see Sec. 5). The vertical profile of the aerosol radiative effect at the center of the aerosol perturbation is also provided for reference in Fig. 6.

5 The experimental protocol

The Easy Aerosol simulations closely follow the AMIP protocol of the Coupled Model Intercomparison Project Phase 5. Notwithstanding aerosol changes, the models are driven by observed boundary conditions from 1979 to 2008. These boundary conditions include sea-surface temperatures, sea-ice fraction, total solar irradiance, well-mixed greenhouse gases, ozone and CFCs. The AMIP protocol is chosen because it is used in COOKIE&CREAM, which means that modeling groups that participate in COOKIE can easily participate in Easy Aerosol as well. Simulations entirely devoid of atmospheric aerosols are compared to those in which the Easy Aerosol is the only atmospheric aerosol.

5.1 Simulations with AMIP sea-surface temperatures

The first set of Easy Aerosol simulations uses AMIP sea-surface temperatures. These simulations serve to estimate the adjusted aerosol-radiative forcing. They also allow to isolate how the response to an aerosol perturbation is mediated by other atmospheric quantities such as clouds and water vapor in the absence of sea-surface temperature changes, and how much of the response from more complex model simulations can be explained in terms of the response to the atmospheric heating and changes in the surface energy budget over land.

Robust aerosol-induced circulation changes might be masked by natural variability in the AMIP runs as sea-surface temperatures are held constant. Therefore, simulations with quintupled total aerosol optical depth are also requested.

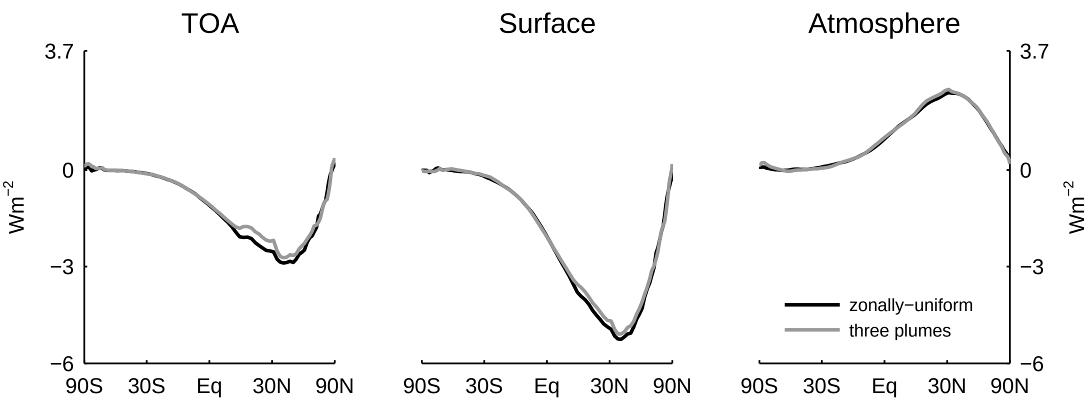

Figure 4 – Time-mean zonal-mean change in clear-sky shortwave irradiances between the aerosol-free AMIP reference simulation CLEAN and AMIP simulations with the zonally-uniform (black; ZONAL) and the three plumes aerosol (gray; PLUMES). In the zonal-mean ZONAL and PLUMES exert the same change.

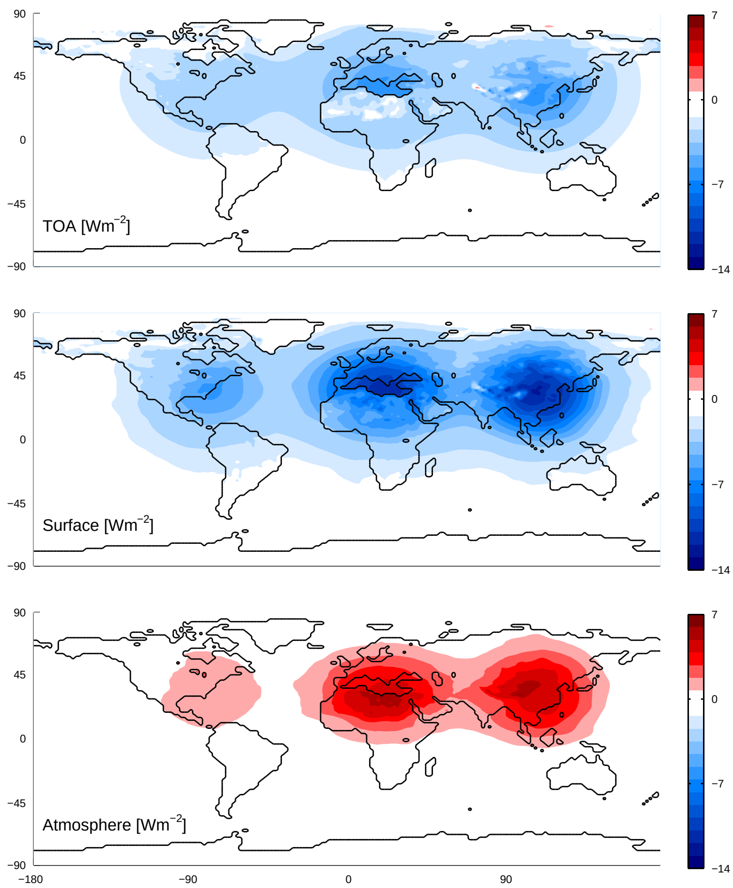

Figure 5 – Time-mean change in clear-sky shortwave irradiances between the aerosol-free AMIP reference simulation (CLEAN) and the AMIP simulation with the three aerosol plumes (PLUMES).

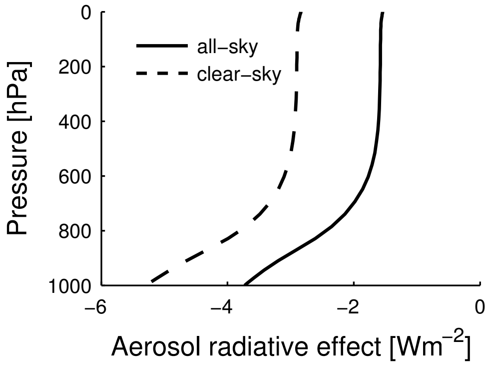

Figure 6 – Time-mean zonal-mean aerosol radiative effect in the ECHAM6 simulation ZONAL at the center of the Easy Aerosol at 35° N for all-sky and clear-sky conditions. The aerosol radiative effect is calculated as the difference in shortwave irradiance between a radiation calculation and a second radiation calculation with aerosol radiative properties set to zero. Downard irradiance is defined as positive.

Table 4 – List of Easy Aerosol simulations.

Experiment	SST	Aerosol	CO_2	Time Period	Output
aerosol-free reference simulation:					
CLEAN	AMIP	none	observed	1979-2008	AMON
simulations with Easy Aerosol perturbations:					
ZONAL	AMIP	zonal	observed	1979-2008	AMON
PLUMES	AMIP	3 plumes	observed	1979-2008	AMON
5xZONAL	AMIP	zonal with 5xτ_0	observed	1979-2008	AMON
5xPLUMES	AMIP	3 plumes 5xτ_0	observed	1979-2008	AMON
ZONAL+ΔSST_{zonal}	AMIP+ΔSST_{zonal}	zonal	observed	1979-2008	AMON
PLUMES+ΔSST_{plumes}	AMIP+ΔSST_{plumes}	3 plumes	observed	1979-2008	AMON

5.2 Simulations with adjusted sea-surface temperatures (AMIP + Δ SST)

To take into account the ocean cooling due to aerosol scattering while keeping the AMIP framework, slab ocean simulations with ECHAM6-TNT were performed. Based on these simulations, the impact of the Easy Aerosol perturbations on sea-surface temperature was estimated and is represented by climatological monthly Δ SST patterns; with one pattern for the zonally-uniform and one pattern for the 3 plumes aerosol. More specifically, the Δ SST pattern for the zonally-uniform aerosol was constructed by subtracting the climatological monthly-mean SST field of a 90 year slab ocean simulation with the zonally-uniform aerosol from the climatological monthly-mean SST field of a 90 year aerosol-free slab ocean simulation, with the first 30 years of the simulations being discarded to remove spinup effects. To avoid inconsistencies with the prescribed sea-ice fraction, SST changes poleward of 65° N are not taken into account. Because a reliable estimate of the SST changes in the southern extra-tropics would require longer slab ocean simulations, we also do not take into account SST changes poleward of 30°S. Lake temperature changes are neglected. The Δ SST pattern for the 3 plumes Easy Aerosol is constructed analogously. The anomaly patterns are provided as netcdf-files on the native ECHAM6 T63 grid; their time-mean geographical distribution is shown in Fig. 7. The ECHAM6 land-sea mask is provided.

5.3 Output requirements

As for COOKIE&CREAM, CMIP5 Amon (Atmosphere monthly) data outputs are requested. The CMOR2 format is preferred, although this is not a requirement to participate in Easy Aerosol. The CMIP5 Aon table is available at `http://cmip-pcmdi.llnl.gov/cmip5/docs/standard_output.pdf` (pp. 24-36). Carbon fields and mole fractions of CH_4, N_2O, O_3 etc. are not requested.

5.4 Ensemble simulations

To facilitate the participation of modeling groups with limited computing resources, no ensemble simulations are requested. However, ensemble simulations with the ECHAM6 model will be performed to study to what extent the aerosol-induced circulation changes are detectable with respect to the model's natural variability. If modeling groups want to contribute ensemble simulations, these simulations will be highly appreciated. For ECHAM6, an ensemble member is created by restarting the model at Jan 1, 1979 from the end (Dec 31, 2008) of another simulation with the same aerosol. This strategy is slightly more involved than other techniques such as small shifts in the start time or short-period changes in horizontal diffusion because the ensemble members can not be generated simultaneously but need to be produced consecutively. However, this strategy has the advantage that slower components like soil moisture can equilibrate, and that the initial conditions of these components do not impact the ensemble. It is therefore recommended for other models as well.

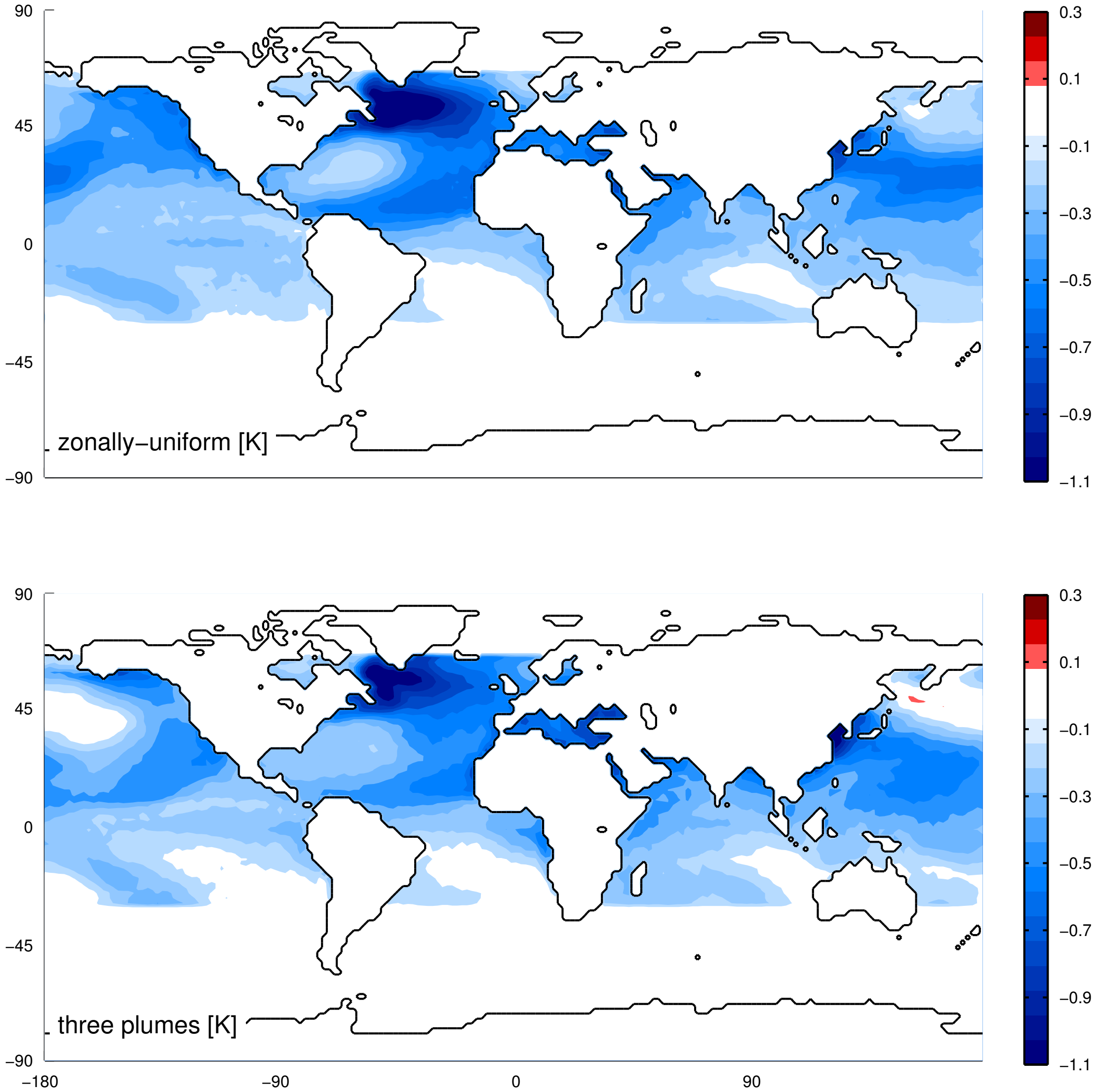

Figure 7 – Time-mean ΔSST patterns for the zonal-uniform and three plumes cases.

6 Contact

Please direct questions to Aiko Voigt (aiko@ldeo.columbia.edu). This document, as well as the files for the Δ SST patterns are available on the website of the WCRP Grand Challenge on Clouds, Circulation and Climate Sensitivity under `http://www.wcrp-climate.org/index.php/gc-clouds-circulation-activities/gc4-clouds-initiatives/gc4-clouds-projects/368-gc-clouds-easy-aerosol`.

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