Dust impacts on radiative effects of black carbon aerosol in Central Asia

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Abstract. The radiative effect of mineral dust and black carbon aerosol are investigated with aerosol-climate model simulations with fixed sea surface temperatures as boundary condition. The semi-direct effects of the absorbing aerosol are assessed as the residual between the total direct radiative effect and the instantaneous direct radiative effect of the aerosol species. For Central Asia the presence of mineral dust aerosol below a black carbon aerosol layer enhances the positive radiative effect of the black carbon aerosol.

1 Introduction

Atmospheric aerosol particles impact the atmospheric radiation budget directly and indirectly by modifying cloud microphysical properties. Both natural and anthropogenic aerosol species are relevant regarding interactions of aerosol and climate [1]. While aerosol radiative forcing usually refers to the radiative effect of anthropogenic aerosols in comparison to pre-industrial conditions, the aerosol radiative effect is due to aerosol species from both anthropogenic and natural sources. The effective radiative forcing of aerosols includes both the instantaneous forcing by aerosols and the so-called rapid adjustment of the atmosphere to aerosol forcing. This adjustment is mainly a consequence of heating rate changes from aerosol absorption and may impact atmospheric stability or cloud cover. Such adjustments are also named "semi-direct" effects. Absorbing aerosol types that cause semi-direct effects are black carbon (BC) particles and mineral dust. BC particles are strongly absorbing in the solar spectral range and cause a positive atmospheric direct radiative forcing at the top of atmosphere (TOA). BC is primarily emitted by combustion of fossil fuels or biomass including vegetation fires. While anthropogenic BC from fossil fuel burning usually remains within the boundary layer, BC from vegetation fires can be released several kilometers into the atmosphere and is subject to long-distance transport. The upper limit of estimates of the overall direct radiative effect for BC aerosol from both natural and anthropogenic sources is as high as +0.9 Wm^2 [2].

Mineral dust from dry and unvegetated surfaces is also a partly absorbing aerosol type that may cause semi-direct effects. Due to their large particle sizes dust particles have not only a shortwave but also an radiative effect in the terrestrial spectral range [3]. Mineral dust is mostly a natural aerosol type. The northern hemispheric dust belt reaches from the Sahara over the Arabian Peninsula to the desert areas in Central Asia and China.

Aerosol semi-direct effects can be different. Possible effects are for example a reduction of vertical mixing as consequence of boundary layer stabilization [4], shifts of the inter-tropical convergence zone due to asymmetric absorbing aerosol forcing, or strengthening the southeast Asian monsoon circulation (e.g. [5]). Huang, *et al.* [6] found in a model study an increase in low cloud cover over oceans and some land regions, i.e. a negative semi-direct effect. However, the effects of absorbing aerosols on cloud cover and thus on temperature changes can be opposing, thus the semi-direct effect is difficult to quantify on a global scale. Estimates of the radiative forcing due to the semi-direct effect range from -0.4 to +0.1 Wm^{-2}. Local values of -9.5 to +11 Wm^{-2} have been estimated [7].

In this study we estimate the semi-direct aerosol effects by decomposing radiative forcing estimates from a global aerosol-climate model into direct, indirect and semi-direct forcings as in [8]. In that study it has been shown that the positive direct instantaneous and semi-direct radiative effects of BC are more positive when forcing by mineral dust aerosol is considered together with the BC forcing, as the comparably bright dust aerosol enhances the positive BC forcing. This effect was mainly evident in the Sahel region and the tropical Atlantic. Here we focus on the Central Asian region where the effect of the dust on the semi-direct absorbing aerosol effect is evident in the seasonal rather than the annual means.

2 Methods

We investigate the semi-direct effects (or rapid adjustments) of the absorbing aerosol types BC and mineral dust within the global aerosol-climate model

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ECHAM6-HAM2 [9] (version echam6.3-ham2.3) at a resolution T63 and 47 vertical levels. ECHAM6 is the atmospheric general circulation model developed by the Max Planck Institute for Meteorology (MPIM) in Hamburg, Germany [10]. The aerosol module HAM (Hamburg Aerosol Model) predicts the evolution of an aerosol ensemble considering the species sulfate, black carbon (BC), organic carbon, sea salt, and mineral dust. The aerosol size spectrum is described by seven internally mixed log-normal modes (Nucleation mode, soluble (mixed) and insoluble Aitken, accumulation and coarse modes). Atmospheric radiative transfer is computed based on compounds present in the atmosphere and their related optical properties.

The radiative effects of absorbing aerosols were evaluated with four model experiments, summarized in Table 1. Each model simulation was averaged for 8 years (2003-2010). Sea surface temperatures were held fixed. The direct radiative and semi-direct radiative effects and radiative forcing by aerosol were computed with the method used in Ghan, *et al.* [11]. Radiative fluxes at the top of the atmosphere (TOA) are diagnosed as net solar and thermal fluxes and include scattering and absorption by clouds and aerosol particles. The direct radiative effect (DRE) of an aerosol type (BC, dust) is computed as difference between the radiative fluxes at TOA for the model simulation including the aerosol species and the simulation excluding this aerosol type. The instantaneous direct radiative effect (IDR) by the individual aerosol species is computed by double calls to the radiation routine. This diagnoses the instantaneous radiative effect without influencing the atmospheric conditions. The semi-direct effect (SDE) is subsequently calculated as residual of the direct radiative and the instantaneous radiative effect. The indirect effects of the aerosol particles on cloud microphysical properties are not considered here. The model simulations that are a subset of the simulations described in [8] are listed in Table 1.

Table 1. List of model experiments.

Experiment	Aerosol types
Base	All
noBC	excluding BC aerosol
noDust	excluding mineral dust
noAbs	excluding BC and dust

3 Results

The absorbing aerosol optical depth has been evaluated against OMI retrievals in [8].

Figures 1 and shows the results for TOA IDR and SDE of BC without considering dust aerosol forcing, computed as difference of the forcing results for the experiments noABS-noDust for northern hemisphere summer (JJA).
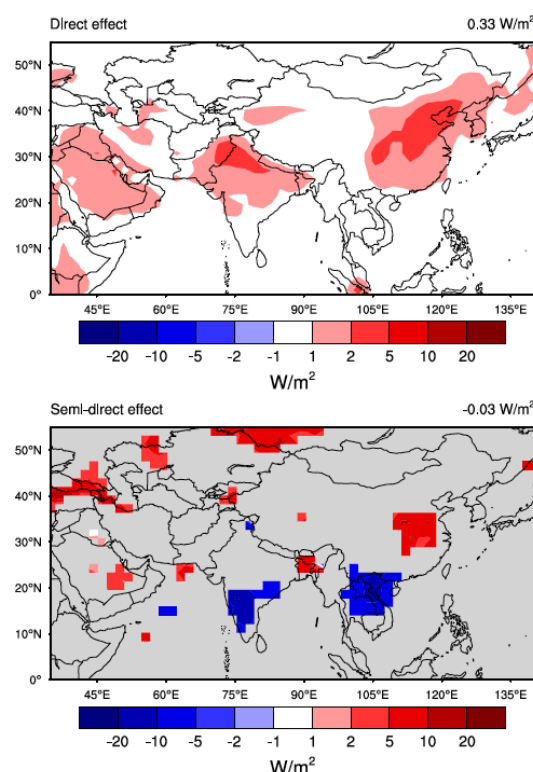

Fig. 1. (Top): Instantaneous BC radiative effect (IDR) at TOA for JJA calculated from noABS-noDust. (Bottom): semi-direct effect (SDE) of BC at TOA. Dust forcing is not considered Grey areas indicate regions where the results are not statistically significant at 95% level.

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The IDR of BC is positive and reflects the regions with highest BC loading in eastern Asia and northern India. Regionally positive forcing up to 5 Wm^{-2} is calculated. The semi-direct effect is positive for eastern Asia but negative in south India (not at the location of the maximum forcing), primarily due to an enhancement in cloud cover. The direct and semi-direct effects are positive in Central Asia, however the results for the semi-direct effect are not statistically significant in most locations.
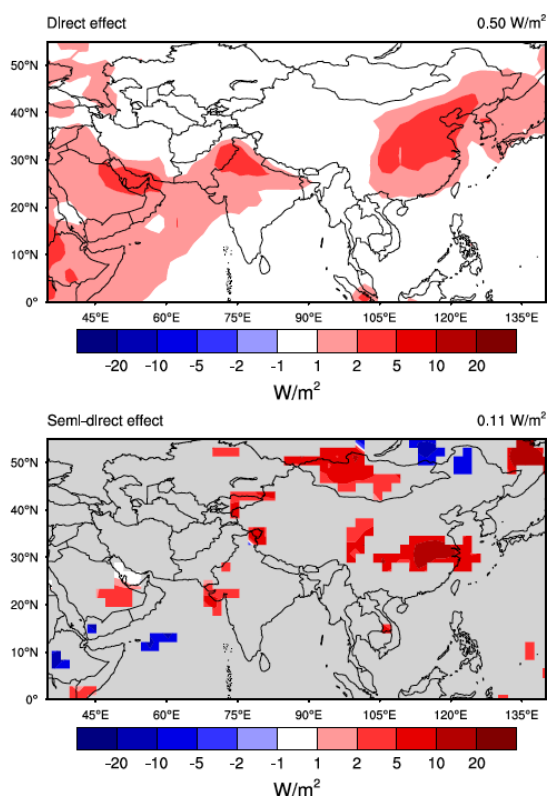
Fig. 2. As Fig. 1, but for noBC-BASE, including the dust in the computation of the radiative effect.
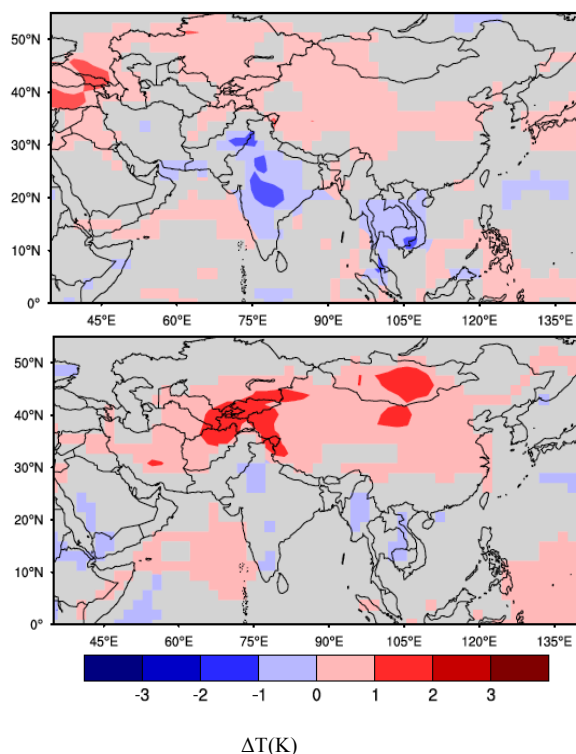

Fig. 3. 2m temperature difference due to BC forcing for noABS-noDust (top) and noBC-BASE (bottom) including the mineral dust effect.

If dust is included (Figure 2) the BC forcing is more positive for both IDR and SDE. The increase in

IDR is a direct consequence of the increase in reflectivity due to the relatively brighter dust above the darker surface. The SDE is more positive in Central Asia as consequence of cloud reduction, and in East Asia it is nearly twice as high compared to the IDR.

Changes in 2-m surface temperature as consequence of BC forcing with and without considering dust aerosol are shown in Figure 3. The temperature change patterns follows mostly the SDE rather than the IDR forcing patterns. When dust is considered, significant warming of more than 1 K is simulated in Central Asia in JJA, while the cooling as consequence of cloud enhancement is reduced over the Indian subcontinent. While the semi-direct effect and temperature change due to the effect of mineral dust itself (not shown) is small in this region, the effect of BC is more positive when the brighening by dust is taken into consideration.

4 Conclusions

The results of aerosol-climate model simulations presented in this study suggest that the presence of mineral dust may enhance the radiative effect due to BC absorption. In the model this effect enhances the warming due to BC aerosol in Central Asia in the northern hemisphere summer months. However, the overall effect is uncertain and may be model-dependent as simulated aerosol and cloud distributions contain uncertainties and the results may differ for different model sensitivities.

In these simulations the presence of mineral dust is also counteracting the effect of the strengthening of the Indian monsoon by BC heating. However the model results presented here are simulated with fixed sea surface temperatures as boundary condition, while such effects should rather be investigated within a fully coupled atmosphere-ocean climate model. For the interior of the continent the results are less impacted by potential sea surface temperature changes and may be more robust.

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