

Abstract

Climate-aerosol interactions in India are studied by employing the global climate-aerosol model ECHAM5-HAM and the GAINS inventory for anthropogenic aerosol emissions. Seasonal cycles and spatial distributions of radiative forcing and the temperature and rainfall responses are presented for different model setups. While total aerosol radiative forcing is strongest in the summer, anthropogenic forcing is considerably stronger in winter than in summer. Local seasonal temperature anomalies caused by aerosols are mostly negative with some exceptions, e.g. Northern India in March–May and the eastern Himalayas in September–November. Rainfall increases due to the elevated heat pump (EHP) mechanism and decreases due to solar dimming effects are studied. Aerosol light absorption does increase rainfall significantly in Northern India, but effects due to solar dimming and circulation work to cancel the increase. The total aerosol effect on rainfall is negative when considering all effects if assuming that aerosols have cooled the Northern Indian Ocean by 0.5 °K compared to the equator.

1 Introduction

Aerosols in India have a significant impact on human health, the environment and through their effects on regional climate, on agriculture and other aspects of society. By scattering and absorbing radiation and modifying cloud properties, aerosols can affect heating at different height levels and the hydrological cycle.

Literature results from modeling and measurements consistently report a strong negative aerosol forcing at the surface and strong atmospheric heating in India (Ramanathan et al., 2001, 2007, 2009; Chung and Ramanathan, 2006; Padma Kumari et al., 2007; Niranjana et al., 2007; Ramanathan and Carmichael, 2008; Stier et al., 2007; Marcq et al., 2010; Pathak et al., 2010; Verma et al., 2011). Two main types of mechanisms, by which aerosols influence monsoon rainfall have been proposed. Firstly, solar dimming mechanisms (SDM, Xu, 2001; Chung and Ramanathan, 2006;

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Ramanathan et al., 2005; Lau and Kim, 2010) indicating a reduced north–south temperature gradient slowing down the monsoon circulation and reduced evaporation due to less absorbed sunlight at the surface would both contribute to reduced rainfall. Secondly, the elevated heat pump (EHP, Lau et al., 2006) hypothesis states that atmospheric heating at elevated levels due to light absorption by aerosols increases convection, cloud formation and rainfall. Despite having some observational support (Lau and Kim, 2006, 2010, 2011; Bollasina et al., 2008), the EHP hypothesis has received also controversial responses (Kuhlmann and Quaas, 2010; Nigam and Bollasina, 2010, 2011), a large part, but not all, of them involving aerosol and rainfall properties during March–May, before the monsoon season. The sea surface temperature (SST) gradients take time to adjust to adjust to aerosol forcing and based on simulations coupling an atmospheric model to a slab ocean model, it has been suggested that the slow response through the ocean would be more important for precipitation (Ganguly et al., 2012a, b). Investigating the links from aerosol loading to effects on precipitation is a complex task due to a multitude of relevant, interplaying effects, many of which are non-local in space and time (Lau et al., 2008; Bollasina et al., 2009).

In this article, we study aerosol–climate interactions with help of the global climate–aerosol model ECHAM5–HAM. Our goal is to provide a more detailed breakdown of the spatial distributions and seasonal cycles of the aerosol effects than before. We will separate direct and indirect effects as well as absorbing from scattering and modification of cloud properties. We will investigate the SDM and EHP hypotheses and provide our input to the ongoing discussion, especially regarding the strength of different competing effects and their relative importance during different seasons.

The article is organised as follows: Sect. 2 describes the model, the emission inventory and the simulations done. Section 3 describes aerosol climatology and the comparison with measurements. Section 4 presents radiative forcing in the simulations. Section 5 presents aerosol effects on rainfall, followed by conclusions in the last section.

2 The model, the emission inventories and simulations

The ECHAM5-HAM model (Stier et al., 2005; Roeckner et al., 2006b) is an atmospheric general circulation model (GCM) coupled with an aerosol model simulating five aerosol species in seven log-normal modes. The simulated species are sulfate, black carbon, organic carbon, mineral dust and sea salt. Aerosol transport, chemistry and removal are simulated. The aerosols effect the climate through their impact on shortwave radiation. Optionally, cloud activation by aerosols can be simulated. The model also includes an option of nudging. The model is described in more detail in (Stier et al., 2005) and simulated large-scale aerosol distributions in India and China in (Henriksson et al., 2011), where the model was evaluated against MODIS AOD seasonal cycles and spatial distributions and other measurements and shown to qualitatively reproduce large-scale aerosol properties in India and China. The Ganges valley with large amounts of biomass burning aerosol containing absorbing material was one of the two areas where correspondence with MODIS results was not that good, which could imply that either the simulation or MODIS results or both are inaccurate. For additional model evaluation, we will compare the modeled BC concentrations with those measured in Mukteshwar on the slopes of the Himalayas (29°26' N, 79°37' N), an important area where biomass burning aerosols emitted in the Ganges valley get transported. The Mukteshwar measurement results have been analysed earlier (Hyvärinen et al., 2009; Komppula et al., 2009; Hyvärinen et al., 2011a,b; Neitola et al., 2011) but have not been compared to climate model results before.

The model was run at horizontal resolution T42 (grid-spacing of 2.8°) and 19 levels in the vertical in a hybrid sigma/pressure coordinate system, with the top level at 10 hPa. Sea surface temperatures were prescribed using data for years 2005–2010 from a simulation with the coupled model ECHAM5-MPIOM (Roeckner et al., 2003, 2006a) assuming the IPCC A1B scenario for greenhouse gases (Nakicenovic et al., 2000), and modified further in two of the experiments.

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The use of prescribed SSTs is naturally a limitation of the current study. The difference between simulations with and without anthropogenic aerosols represents only a part of their full climate effect. In principle, the best solution would be to do coupled simulations with ECHAM5-HAM combined with an ocean GCM, but this was not computationally feasible to us. Instead, to get a very rough idea of how aerosol-influenced SST changes might influence the climate response, a simple modification of the SST distribution in the Indian Ocean is included in two of the experiments described below. A model coupled with a mixed layer ocean model would have been available, but it has not been evaluated against aerosol observations and, more importantly, SSTs in such models react only locally and possibly too strongly to radiative forcings (Anonymous Referee #2 (2011), Anonymous Referee #3, 2011). In ECHAM5-HAM coupled with a mixed layer model, unrealistically strong SST gradients have arisen in simulations with very strong aerosol forcing (A.-I. Partanen, personal communication, 2013), which casts doubt on the model's ability to give realistic SST and precipitation responses in the case of strong aerosol forcing over India.

The GAINS (Greenhouse gas–Air pollution Interactions and Synergies) model (Amann et al., 2011); <http://gains.iiasa.ac.at> has been used to determine the anthropogenic emissions in 2005. Globally the GAINS model considers 170 regions. The model includes all major economic sectors, including energy and industrial production, transport, residential combustion, agriculture, as well as waste. In the most detailed level it can calculate emissions for nearly 2000 sector–fuel–emission control technology combinations. The global energy database in GAINS for 2005 uses the most recent statistics from the International Energy Agency (IEA) and EUROSTAT, whereas for agriculture data from FAO (UN Food and Agriculture Organization) is used. The development of the subnational level data relies on national statistics and has involved national experts, including collaboration with TERI (The Energy Research Institute, India) within the GAINS-Asia project (Purohit et al., 2010).

This study utilizes the 2005 emissions of BC, OC and SO₂ as calculated by GAINS for the 23 Indian administrative regions. The provincial level emissions have been dis-

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tributed into RCP (Representative Concentration Pathways) sectors (energy, industry, solvent use, transport, agriculture, cropland burning, residential combustion, and waste treatment) and further spatially allocated into $0.5^\circ \times 0.5^\circ$ longitude–latitude using RCP consistent proxies as used and further developed within Global Energy Assessment project (GEA, 2012).

The energy and domestic sector emissions are resolved on monthly scale. Monthly temporal patterns for the domestic heating and cooking were developed as well by combining the stove use assumptions presented by Streets et al. (2003) with the global gridded temperature fields from the CRU3.0 archive of monthly mean temperatures in 2005 (<http://badc.nerc.ac.uk/data/cru/>) (Brohan et al., 2006).

The international shipping emissions were developed using two data sources: (1) the global shipping from RCP (Eyring et al., 2010; Lamarque et al., 2010), and (2) a separate arctic area emissions database developed by Corbett et al. (2010). Some overlaps between the spatial grids were observed and in those cases the Corbett et al. (2010) emission values were used.

The global and Indian emissions used as input for the climate modelings are presented in the Supplement.

The wildfire emissions are based on GFED 3 emission database (Giglio et al., 2010). To be consistent with the GAINS model emissions, we use the wildfire data for the year 2005. GFED 3 emissions include an agricultural wasteland burning sector, which is also present in the GAINS emissions. However, in this work, the GAINS agricultural waste burning emissions are used. Of natural emissions in the model, mineral dust, sea salt and ocean DMS emissions are calculated online and others are prescribed. Natural emissions from wildfires were taken from the GFED3 inventory (van der Werf et al., 2010), terrestrial biogenic DMS emissions in the model are prescribed according to Pham et al. (1995). SO_2 emissions from volcanoes are based on Andres and Kasgnoc (1998) and Halmer et al. (2002). SO_2 and biogenic POM emissions on Guenther et al. (1995).

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A total of nine simulations were made in this study (Table 1). Five of the simulations (MAIN, ZERO, NOABS, SSTMODIF and NUDGE) were made without aerosol cloud activation. Thus, in these simulations the indirect effect of aerosols is not included, while the direct radiative effects and semidirect effect on cloudiness are considered. The MAIN simulation included anthropogenic emissions based on the GAINS inventory, while in the ZERO simulation, anthropogenic emissions were excluded. The NOABS, SSTMODIF and NUDGE simulations included anthropogenic emissions from the GAINS inventory but differed from the MAIN simulation as follows. First, in NOABS, aerosol single-scattering albedo was set to 1, which eliminates aerosol absorption. The difference between the MAIN and NOABS simulations thus represents the impact of aerosol absorption. Second, in SSTMODIF, SSTs were modified to study the effect of a potential aerosol-induced cooling of the Northern Indian Ocean (NIO) compared to the equatorial Indian Ocean. Based on the observation that equatorial Indian Ocean has warmed, since 1950s, by roughly 0.5 K more than the Northern Indian Ocean (Ramanathan et al., 2005) a negative SST perturbation increasing linearly from 0 K at the equator to 0.5 K at 20° N was added to the baseline SST field. Finally, in the NUDGE simulation, simulated vorticity, divergence, temperature, and surface pressure were nudged towards ERA-INTERIM reanalysis data (Dee et al., 2011).

The remaining four simulations MAIN_ACT, ZERO_ACT, NOABS_ACT, and SSTMODIF_ACT included aerosol cloud activation according to Lin and Leaitch (1997). Otherwise, these simulations were similar to MAIN, ZERO, NOABS and SSTMODIF, respectively. Conducting these simulations both with and without aerosol activation is useful for assessing which aspects of the climate response are robust to changes in model formulation. All simulations were run for the years 2005–2010 (the years are not that important as emissions are at 2005 levels during all years). The first year of each simulation was discarded as a spin-up period when analyzing the results.

3 BC concentrations in Mukteshwar

Emissions of carbonaceous aerosols are more uncertain than those of sulfate aerosols (Ohara et al., 2007; Klimont et al., 2009) and validating the concentrations is thus an essential part of raising confidence in the model results. Figure 1 shows a comparison of simulated daily surface BC concentrations interpolated to Mukteshwar with measurements. The simulation is NUDGE and the year is 2006. The time series follow each other quite well with a minimum in the winter, maxima in the spring and fall and a drop in the monsoon months, although the decrease starts later in the simulation. The precipitation field is not nudged and the discrepancy is most likely due to significantly more wet removal in the real situation. Figure 2 shows multi-year monthly averages of the measured and modeled concentrations for the MAIN_ACT simulation including aerosol cloud activation. In this case, the drop in concentrations in the monsoon months of June and especially July and August are seen also in the simulation, though not as strongly as in the measurements. Modeled concentrations are larger in the winter months January and especially December, while spring and fall maxima are seen both in the simulation and in measurements. In general, BC and OC concentrations are smaller than in the previously published simulations using the REAS emission inventory (Henriksson et al., 2011) due to different emissions and a slightly different model version (we did not track down the detailed reasons behind the discrepancy, but a comparison between the AOD seasonal cycle in previously and presently presented simulations can be found in Fig. S1b).

4 Radiative forcing and temperature response

In this section, we present estimates for aerosol radiative forcing and the surface temperature response in the model. The seasonal cycle of radiative forcing in the simulations with GAINS emissions is shown in Fig. 3 for the top of the atmosphere (TOA) and for the surface in Fig. 4. The radiative forcing gives the instantaneous effect of aerosols

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on radiation; the effect including feedbacks will be discussed below. The anthropogenic forcing can be estimated as the difference between the radiative forcing in a simulation containing anthropogenic aerosols and that in the simulation with natural aerosols only. The natural aerosols are causing total negative radiative forcing to be strongest in the summer, but anthropogenic forcing is much stronger in the winter than in the summer. In the summer months, the Indian average negative forcing is only a few tenths of watts per square meter. Figure 5 shows the spatial distribution of annual-mean anthropogenic forcing.

Figure 6 shows the total radiation (shortwave plus longwave) anomalies, which include also the effect on cloud cover through semi-direct and other feedbacks affecting the radiative balance (neglecting those adopting slowly e.g. due to ocean thermal inertia), in different simulations with GAINS emissions with reference to simulations without anthropogenic emissions. The surface anomalies are negative in all cases and so are the TOA anomalies in the simulation with aerosol cloud activation included, but in the simulation without aerosol cloud activation, the TOA radiation anomalies in the summer are positive.

Figures 7 and 8 show anomalies of the 2 m air temperature in different seasons for the simulations with GAINS emissions both without and with aerosol cloud activation, respectively, with the simulations with no anthropogenic emissions used as reference. Anomalies are similar with and without aerosol activation included and mostly negative, except for Northern India in March–May. A warming tropospheric temperature trend has been observed for these months in the western Himalayas (Prasad et al., 2009), could partly be explained by aerosols according to our results (also see height-resolving plots in the next section) and is argued to be consistent with the EHP hypothesis (Gautam et al., 2009; Lau and Kim, 2010). Prasad et al. (2009) report a positive temperature trend in the winter months, but in our simulations aerosols rather cause cooling in the winter.

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5 Aerosol effects on rainfall

Figure 9 shows the seasonal cycle of rainfall in the area 65–90° E, 20–35° N in the different simulations. It can be seen that the model simulates significantly more rainfall in Northern India when aerosol cloud activation is included compared to when it is not included. Without cloud activation, rainfall in the monsoon months June–August is larger with anthropogenic emissions included than without, smaller than either in the simulation with anthropogenic emissions but without absorption and smallest in the simulation with modified SSTs. With cloud activation included, turning the anthropogenic emissions to zero does not seem to reduce monsoon rainfall, whereas turning off absorption reduces it a lot and modifying the SSTs reduces it somewhat. With cloud activation included, in the months up to May, absorption does not seem to increase rainfall but slightly reduce it, which, if a realistic result, could partly explain controversial responses raised by the EHP hypothesis and resolve the controversy by the explanation of different responses in different times of the year. Nigam and Bollasina (2010) partly use aerosol–rainfall correlations in May in arguments against the EHP hypothesis and Kuhlmann and Quaas (2010) rely on CALIPSO lidar satellite aerosol observations in March–May. Below we will show that cloud cover anomalies are of different sign in pre-monsoon and monsoon months, connected with temperature and humidity responses of the climate to aerosol forcing. When considering all aerosol effects including an assumed relative cooling of 0.5° of the Northern Indian Ocean compared to the equator, the total effect on precipitation in Northern India is about –20%. Based on five-year simulations it is unclear in a statistical significance sense, whether the total aerosol effect on rainfall is an increase or decrease, as anomalies in different months or for the June–August average have different signs in different years (not shown). However, absorption increases rainfall during 5 yr out of 5 in June–August both with and without cloud activation, giving a 97% significance in a binomial significance test for both cases separately.

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Figures 10 and 11 show time-pressure level plots area averaged over the longitude-latitude box 20–35° N, 65–90° E for the aerosol effects on cloud cover and vertical velocity. The simulations with zero anthropogenic emissions and without absorption are taken as reference (Fig. S2 shows the reference without anthropogenic emissions in the case of no cloud activation). In general, the cloud cover and vertical velocity anomalies have a tendency to be of negative sign in March–May, with exceptions, and positive at 100–700 hPa heights, where cloud cover is largest, in June–August. The positive cloud cover anomalies are most distinct when comparing the simulations with GAINS emissions (MAIN and MAIN_ACT) with those without aerosol absorption (NOABS and NOABS_ACT). The corresponding total effect of anthropogenic aerosols (MAIN-ZERO and MAIN_ACT-ZERO_ACT) is smaller. The total effect even becomes negative if the assumed effect of aerosols on SSTs is included for the case with cloud activation (SSTMODIF_ACT-ZERO_ACT).

Further time-pressure level plots are shown in the Supplement, showing specific humidity temperature and relative humidity (Figs. S3–S5). Summarizing the results, aerosols cause warming especially in March–May throughout the troposphere due to reduced cloud cover involving a semi-direct effect. Gautam et al. (2009); Lau and Kim (2010) point out that warmer tropospheric temperatures in the pre-monsoon season are consistent with the EHP hypothesis. In July and August, the surface cools in all simulations as compared to the reference simulations and in some simulations the higher troposphere seemingly warms enough to cause a positive anomaly to the mean vertical motion there. Specific humidity in the troposphere decreases in June–September in the MAIN_ACT and SSTMODIF_ACT simulations, probably largely due to reduced evaporation, but increases during the pre-monsoon months and also in the monsoon months for all the other cases considered. Thus, with enough dimming present in these simulations with cooling by the aerosol indirect effect, reduced humidity due to decreased evaporation could also be an important part of the aerosol effect on rainfall. Relative humidity anomalies follow the cloud cover anomalies quite strongly.

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Figure 12 shows rainfall in more southern parts of India: 10–20° N, 75–80° E. In these parts, there is high rainfall for a longer time during the year and, in contrast to Northern India, more rainfall in the simulations without aerosol cloud activation. Effects of aerosols are somewhat similar, but not the same as in Northern India. Absorption increases rainfall in most months with higher rainfall both with and without cloud activation. Without anthropogenic emissions, the rainfall is clearly decreased without cloud activation and not changed much with cloud activation included. Modifying SSTs decreases the rainfall in both cases, especially when cloud activation is not included.

Yet, one more point we want to make that to our knowledge has not been presented in the literature before: interannual variations in aerosol load and precipitation can cause correlations of different sign in different months. In the area 20–35° N, 65–90° E in some years, winds in May are more westerly, bringing more dust and at the same time, drier air, implying a higher AOD but a lower precipitation, indicating a negative correlation between AOD and precipitation shown in Fig. 13a. At the same time, the correlation is strongly positive in July, shown in Fig. 13b, explained by aerosol hygroscopic growth during years with more precipitation accompanied by a high relative humidity in general and a resulting increased AOD. This is illustrated further in Fig. S7. The interannual variability in aerosol parameters and precipitation is in this case driven by prescribed SSTs and the weather produced by the model.

6 Conclusions

The Indian climate was simulated in a series of nine simulations applying the aerosol-climate model ECHAM5-HAM and the GAINS emission inventory. The model has been evaluated against observed aerosol optical properties and surface concentration measurements earlier. Simulations were performed with and without aerosol cloud activation separately, with and without absorption of shortwave radiation, with and without artificially cooled sea surface temperatures in the Northern Indian Ocean and one simulation was performed using the ERA-Interim reanalysis weather for nudging. Total

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negative aerosol forcing at the TOA was strongest in the summer and anthropogenic forcing, including that of light-absorbing BC, is strongest in the winter. While the Indian average forcing was found negative in all months and all model setups, in the simulation with GAINS emissions and no aerosol cloud activation there were locations with positive mean forcing. In the summer months, the Indian average radiation anomalies at the TOA were positive due to the semi-direct aerosol cloud effect and other effects turning the small negative forcing in to a positive anomaly in the radiative balance. Seasonal temperature anomalies were mainly negative and locally of the order of up to 2°, but especially in the pre-monsoon months of March–May there were local positive anomalies north of 25° N both with and without aerosol cloud activation.

As for rainfall, the model serves as a tool for separately studying different, opposing effects and to study separate mechanisms with, of course, scope for model development and evaluation remaining. Our results provide support for the elevated heat pump (EHP) mechanism, which increases vertical velocity and monsoon rainfall in Northern India. However, circulation changes as well as reduced surface evaporation caused by the aerosols seem to nearly or more than cancel out these effects and the total effect of aerosols on rainfall is negative, reaching ~ 20% with cloud activation considered and sea surface temperatures modified. A small increase or decrease in precipitation in March–May was observed due to absorption, depending on the model setup, connected with decreased cloudiness due to semi-direct aerosol effects during these months. This could help resolve apparent contradictions between different earlier results in the literature. We hope to have contributed significantly to the ongoing discussion about the EHP and SDM mechanisms by making simulations with setups allowing to separately study the effects of aerosol light absorption, total atmospheric effects of anthropogenic aerosols as well as relative cooling of the Northern Indian Ocean assumed to have happened mostly because of aerosols during the past decades. In all, we have presented a model analysis of seasonal cycles and spatial distributions of aerosol radiative forcing and aerosol effects on temperature and precipitation in India.

Supplementary material related to this article is available online at:
[http://www.atmos-chem-phys-discuss.net/13/18031/2013/
acpd-13-18031-2013-supplement.pdf](http://www.atmos-chem-phys-discuss.net/13/18031/2013/acpd-13-18031-2013-supplement.pdf).

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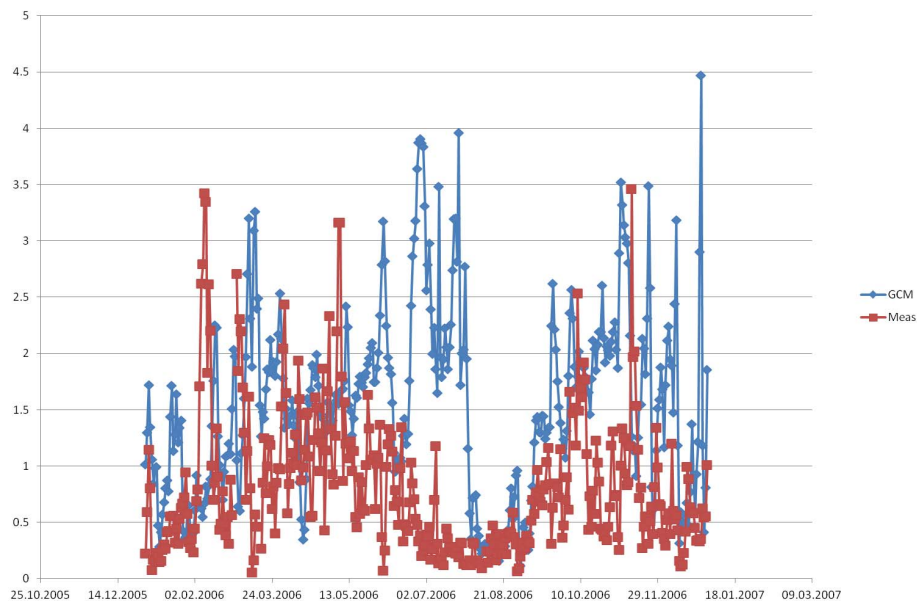


Fig. 1. Surface BC concentration (in $\mu\text{g m}^{-3}$) in Mukteshwar measurements and in the gridpoint nearest to Mukteshwar in the NUDGE simulation, year 2006.

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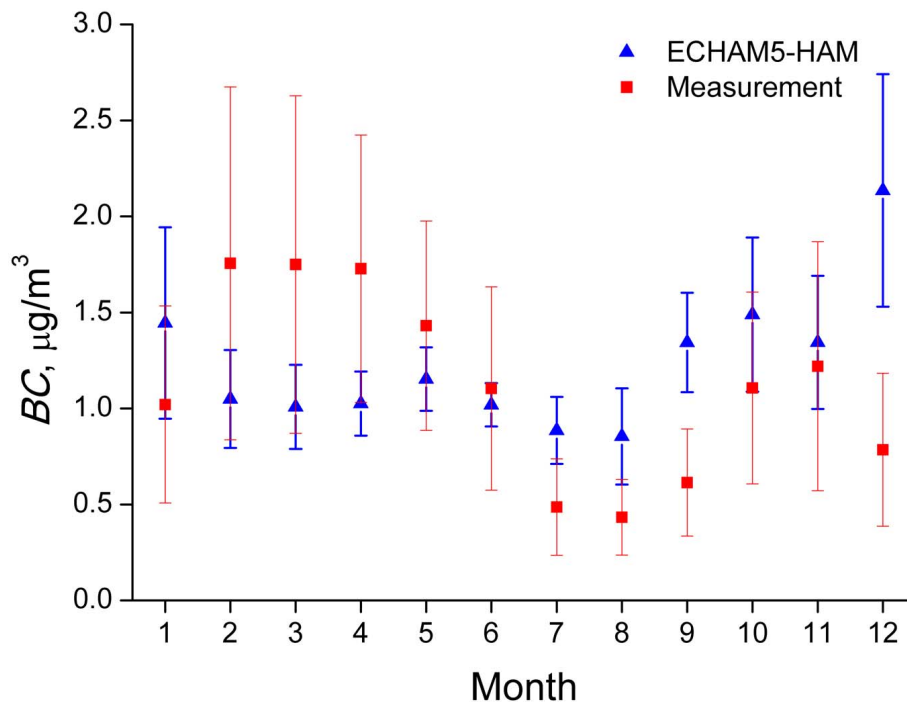


Fig. 2. Surface BC concentration (in $\mu\text{g m}^{-3}$) in Mukteshwar measurements and in the MAIN_ACT simulation with GAINS emissions and aerosol cloud activation, five-year monthly means with variability illustrated by standard deviation of daily values.

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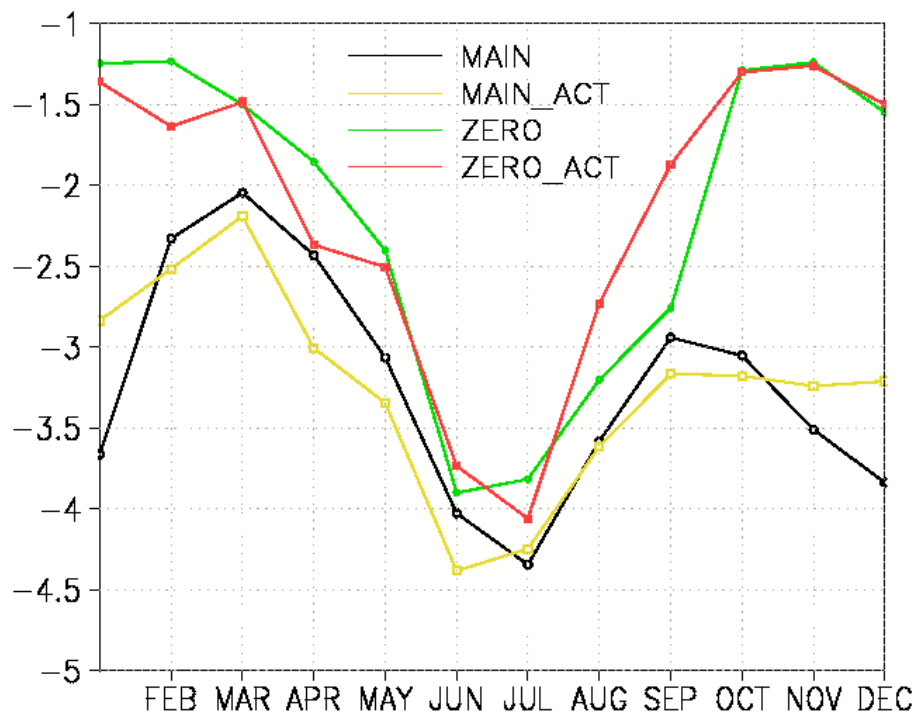


Fig. 3. Five-year monthly mean radiative forcing (in W m^{-2}) in the area $65\text{--}90^\circ \text{E}$, $5\text{--}35^\circ \text{N}$ at the TOA in the MAIN and MAIN_ACT simulations with GAINS emissions without aerosol cloud activation (black) and with aerosol cloud activation (yellow) and in the ZERO the ZERO_ACT simulations without anthropogenic emissions without cloud activation (green) and with aerosol cloud activation (red).

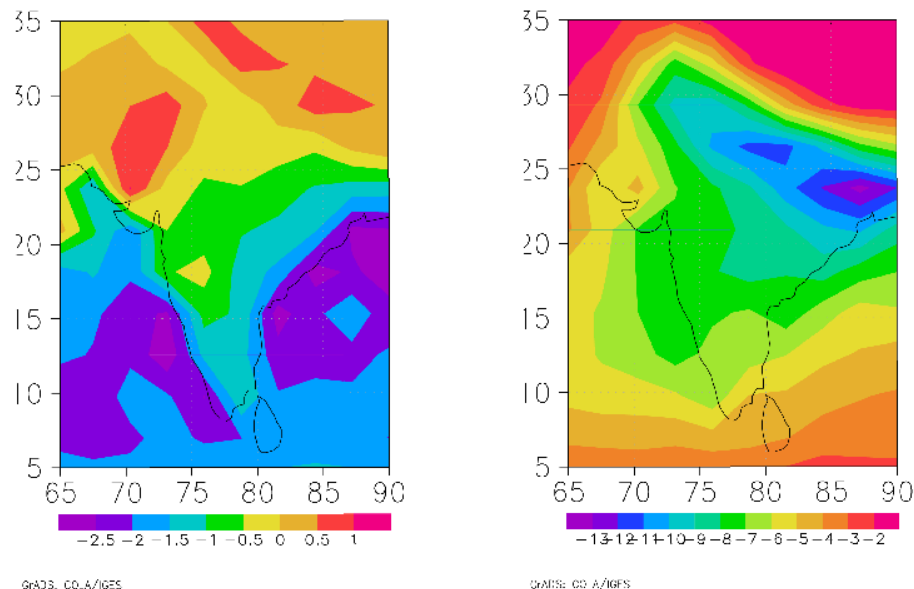


Fig. 5. Five-year average anthropogenic radiative forcing (in W m^{-2}) in the area $65\text{--}90^\circ\text{ E}$, $5\text{--}35^\circ\text{ N}$ in the MAIN simulation with GAINS emissions and without aerosol cloud activation at the top of the atmosphere (left) and at the surface (right).

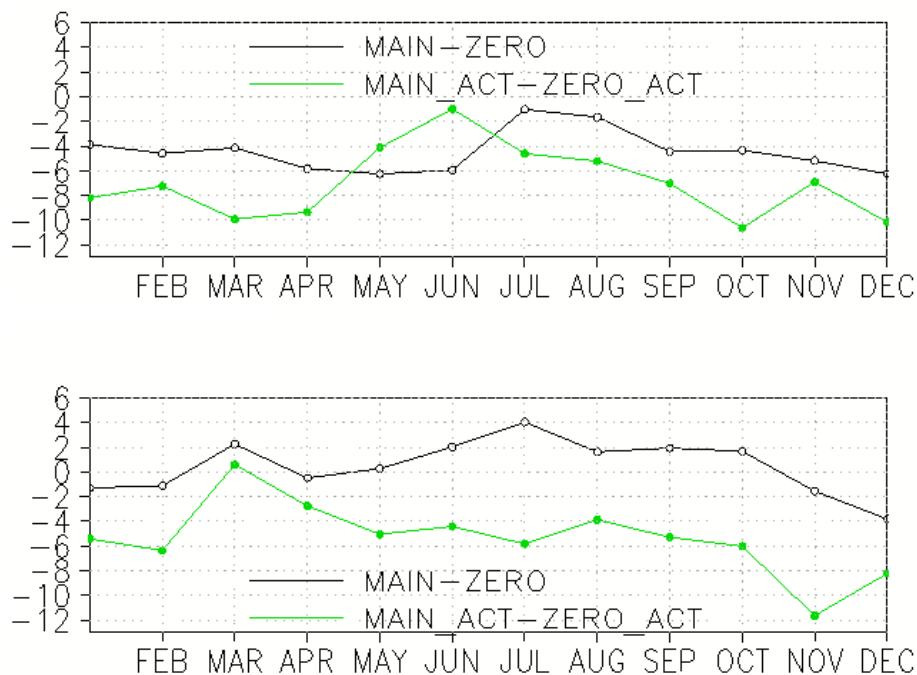


Fig. 6. Five-year monthly mean anthropogenic SW + LW radiation flux anomalies (in W m^{-2}) in the area $65\text{--}90^\circ \text{E}$, $5\text{--}35^\circ \text{N}$ in the MAIN and MAIN_ACT simulations with GAINS emissions **(a)** at the surface and **(b)** at the TOA (black = w/o, green = with aerosol cloud activation).

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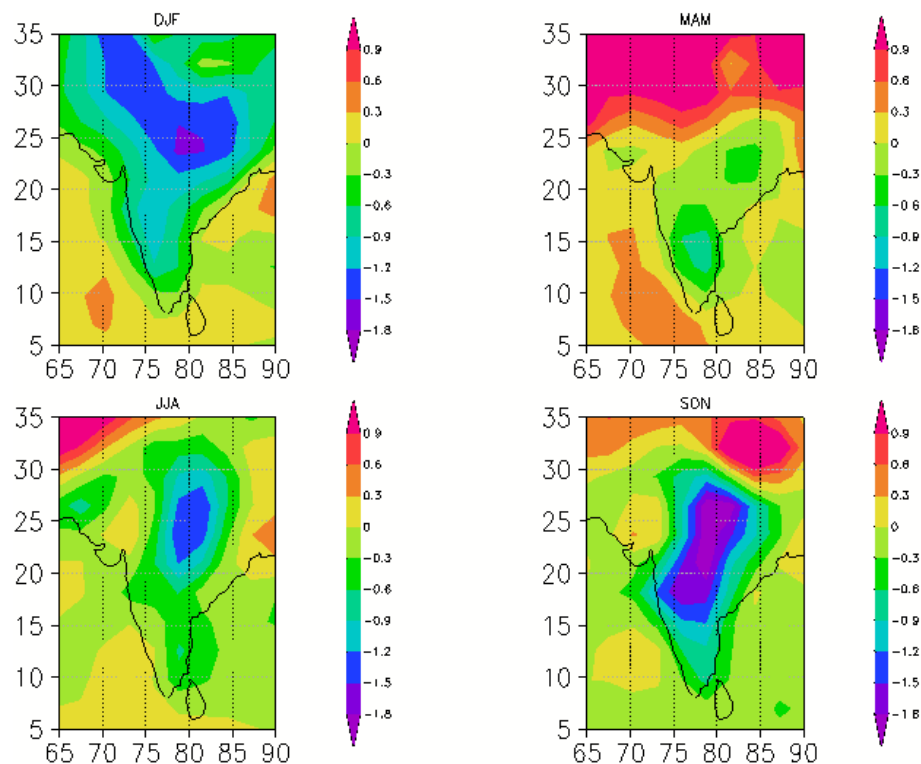


Fig. 7. Five-year seasonal 2 m temperature anomalies ($^{\circ}\text{K}$) in the MAIN simulation with GAINS emissions and without aerosol activation.

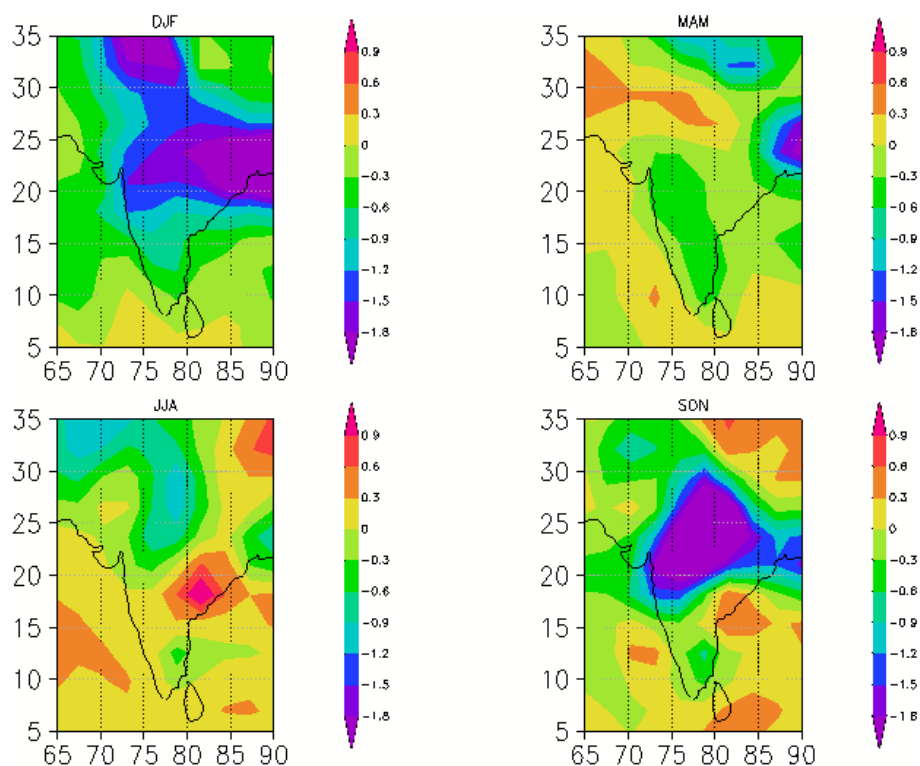


Fig. 8. Five-year seasonal 2 m temperature anomalies ($^{\circ}\text{K}$) in the MAIN_ACT simulation with GAINS emissions and aerosol activation.

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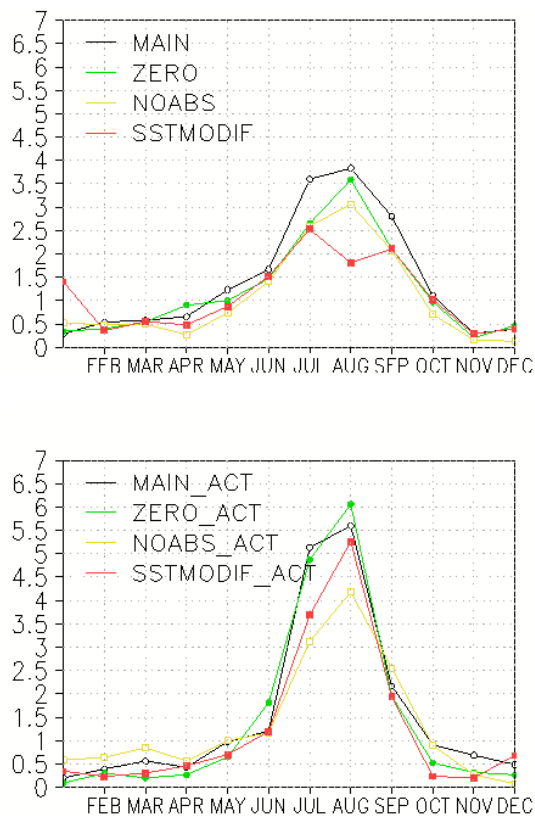


Fig. 9. Five-year monthly mean precipitation (mmd^{-1}) in the longitude-latitude box 65–90° E, 5–35° N for simulations (above) without aerosol cloud activation (black = MAIN, green = ZERO, yellow = NOABS, red = SSTMODIF) and (below) with aerosol cloud activation (black = MAIN_ACT, green = ZERO_ACT, yellow = NOABS_ACT, red = SSTMODIF_ACT).

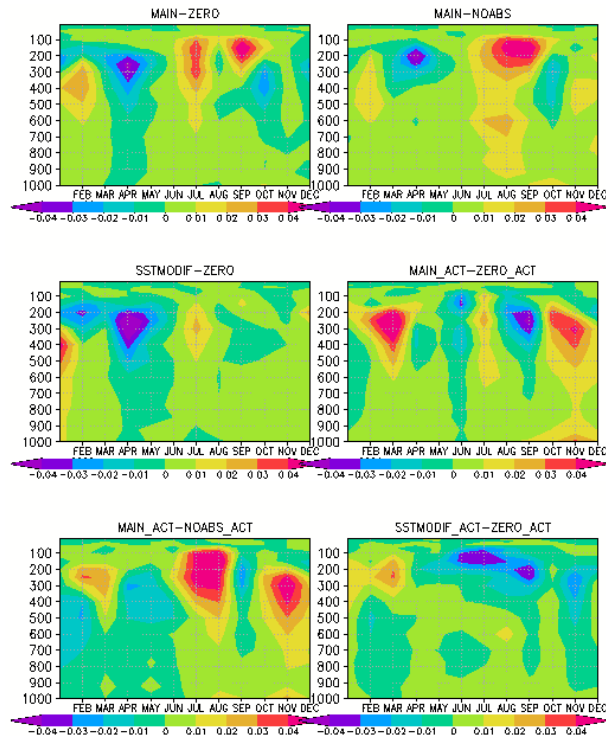


Fig. 10. Cloud cover anomalies at different pressure levels in the different simulations, five-year monthly means.

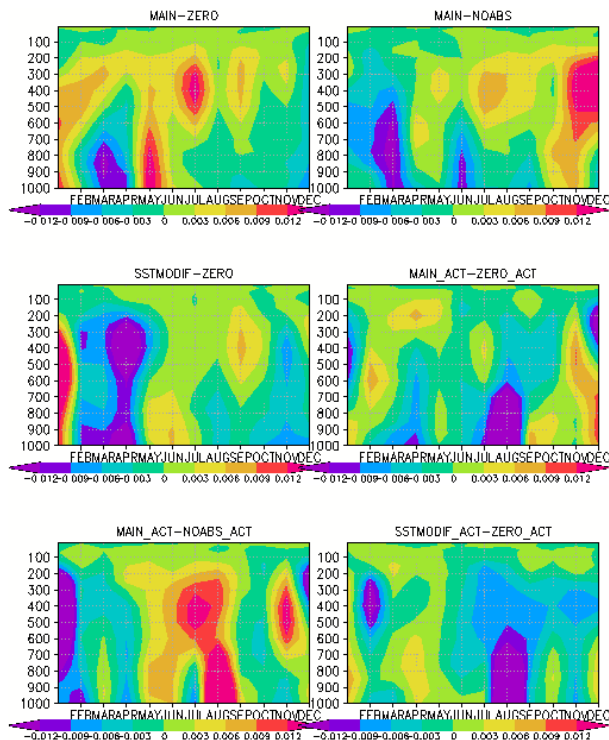


Fig. 11. Vertical velocity anomalies ($-\text{Pa s}^{-1}$) at different pressure levels in the different simulations, five-year monthly means.

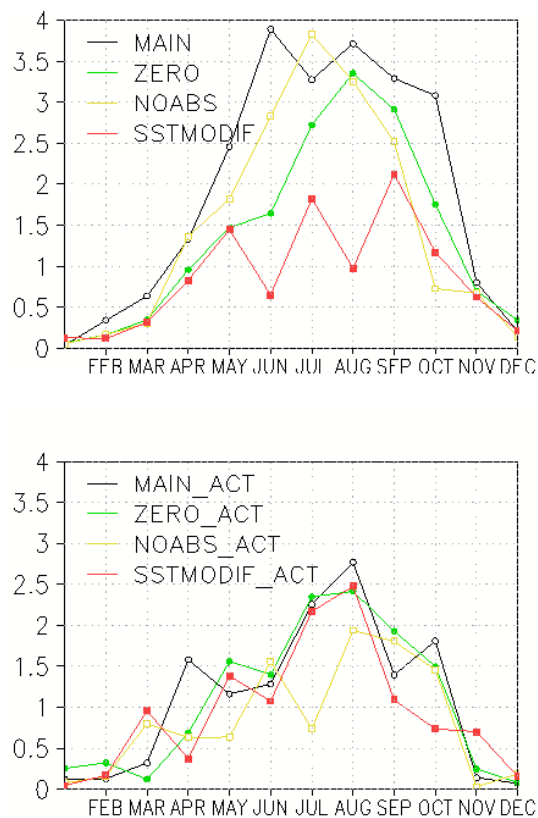


Fig. 12. Rainfall in the area 75–80° E, 10–20° N in the simulations (above) without aerosol cloud activation (black = MAIN, green = ZERO, yellow = NOABS, red = SSTMODIF) and (below) with aerosol cloud activation (black = MAIN_ACT, green = ZERO_ACT, yellow = NOABS_ACT, red = SSTMODIF_ACT), five-year monthly means.

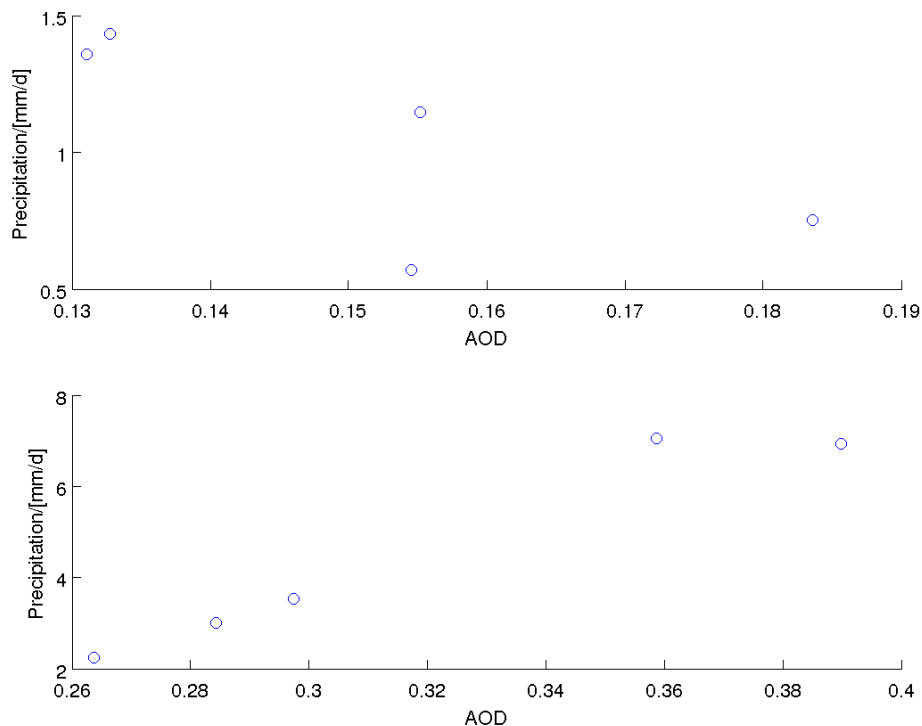
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Fig. 13. Values of mean AOD and mean precipitation for separate years in the area 65–90° E, 20–35° N in May (above) and June (below), MAIN_ACT simulation.