Atmos. Chem. Phys., 14, 8749–8761, 2014
www.atmos-chem-phys.net/14/8749/2014/
doi:10.5194/acp-14-8749-2014

Atmospheric Chemistry and Physics
Open Access

Investigation of the "elevated heat pump" hypothesis of the Asian monsoon using satellite observations

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Received: 21 January 2013 – Published in Atmos. Chem. Phys. Discuss.: 18 April 2013
Revised: 4 July 2014 – Accepted: 4 July 2014 – Published: 26 August 2014

Abstract. The "elevated heat pump" (EHP) hypothesis has been a topic of intensive research and controversy. It postulates that aerosol-induced anomalous mid- and upper-tropospheric warming in the Himalayan foothills and above the Tibetan Plateau leads to an early onset and intensification of Asian monsoon rainfall. This finding is primarily based on results from a NASA finite-volume general circulation model run with and without radiative forcing from different types of aerosols. In particular, black carbon emissions from sources in northern India and dust from Western China, Afghanistan, Pakistan, the Thar Desert, and the Arabian Peninsula drive the modeled anomalous heating. Since the initial discussion of the EHP hypothesis in 2006, the aerosol–monsoon relationship has been investigated using various modeling and observational techniques. The current study takes a novel observational approach to detect signatures of the "elevated heat pump" effect on convection, precipitation, and temperature for contrasting aerosol content years during the period of 2000–2012. The analysis benefits from unique high-resolution convection information inferred from Meteosat-5 observations as available through 2005. Additional data sources include temperature data from the NCEP/NCAR Reanalysis and the European Reanalysis (ERA-Interim) precipitation data from the Global Precipitation Climatology Project (GPCP), aerosol optical depth from the Multi-angle Imaging Spectroradiometer (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS), and aerosol optical properties from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) aerosol reanalysis. Anomalous upper-tropospheric warming and the early onset and intensification of the Indian monsoon were not consistently observed during the years with high loads of absorbing aerosols. Possibly, model assumptions and/or unaccounted semi-direct aerosol effects caused the disagreement between observed and hypothesized behavior.

1 Introduction

The role of the Tibetan Plateau as an elevated heat source has long been recognized as one of the driving mechanisms of the Asian monsoon (Flohn, 1968; Yeh, 1981; Murakami, 1987; Ueda and Yasunari, 1998). Li and Yanai (1996) observed that the reversal of the meridional temperature gradient due to intense heating over the Tibetan Plateau in springtime coincides with the onset of the monsoon. More recently, the role of aerosols in the monsoon system is gaining attention. The "elevated heat pump" (EHP) hypothesis proposed by Lau et al. (2006) provides a useful framework for such investigations. The basic premise of the hypothesis is that in the pre-monsoon season (March through May), absorbing aerosols such as black carbon from northern India and dust from the deserts of western China, Afghanistan, Pakistan, the Thar Desert, and the Arabian Peninsula stack up against the foothills of the Himalayas in the Indo–Gangetic Basin (IGB) (Fig. 1) and cause anomalous upper-tropospheric warming in the Tibetan Plateau region. It is argued that the warming by aerosol absorption causes the air to rise and act as an "elevated heat pump", drawing in moist air from the Indian Ocean and causing an early onset of the monsoon and intensification of monsoon rainfall. An anomalous sinking motion forms in the southern part of the Indian subcontinent, causing this region to experience dryer-than-normal conditions in the early part of the peak-monsoon season. The potential impact of the absorbing aerosols is magnified in this situation since the mass of the atmosphere above the plateau is roughly

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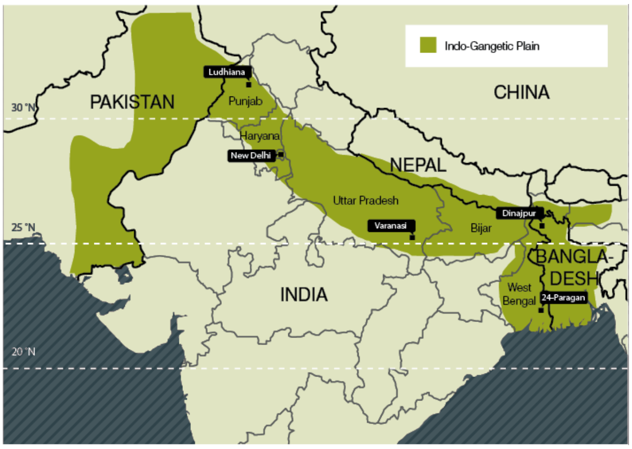

Figure 1. The Indo–Gangetic Basin (from the Australian Centre for International Agricultural Research as provided at: http://aciar.gov.au/files/mn-158/s3_3-gangetic-plain-punjab.html).

half of that near sea level and any heat added warms the air more effectively than over low-level terrain (Yeh, 1981). Impacts on rainfall extend farther than the subcontinent itself, as the heat low established over the Tibetan Plateau by the EHP effect is balanced by an elongated surface high-pressure ridge oriented southwest to northeast from the northwestern Pacific through the northern South China Sea and southern Bay of Bengal into the central Indian Ocean. This pushes the typical *Mei-yu* rain belt northward and suppresses precipitation in the northern Indian Ocean, Eastern China, and the western Pacific, while increasing rainfall totals in central India, the northern Arabian Sea, the northern Bay of Bengal, Central China, and Korea. Observational evidence of the EHP effect presented by Lau and Kim (2006) also indicates an early withdrawal of the Indian monsoon season. These conclusions were reached based on 10-year runs of the NASA finite-volume general circulation model (GCM) with and without aerosol forcing. The authors note that the simulations neglected important processes such as aerosol indirect effects, and, therefore, the findings must be considered suggestive but not conclusive.

Since the initial postulation of the EHP hypothesis, additional investigations on the topic have been initiated (Gautam et al., 2011; Bollasina et al., 2008, 2011; Nigam and Bollasina, 2010, 2011; Kuhlmann and Quass, 2010; Ganguly et al., 2012a, b). Specific studies of aerosol effects on the land–sea temperature gradient and Asian monsoon circulation resulted in somewhat conflicting conclusions. Results from GCM simulations have shown that solar dimming from aerosols can decrease the intensity of the Asian monsoon on multi-decadal timescales because the weakened land–sea temperature gradient in the region can cause the monsoon circulation to shift southward, and because the cooler Arabian Sea has a more limited supply of moisture (Ramanathan et al., 2005; Chung and Ramanathan, 2006). Alternatively, aerosol-induced atmospheric heating has been linked to a strengthening of the monsoon in southern China, northern India, and the Bay of Bengal by impacting circulation patterns, vertical motions, and atmospheric stability (Menon et al., 2002; Lau et al., 2006). Meehl et al. (2008) have shown that the increased meridional temperature gradient due to heating from black carbon aerosols causes an increase in premonsoon rainfall (March through May) but a subsequent decrease in monsoon rainfall during June and July. The same behavior was reported by Collier and Zhang (2009) based on runs of the National Center for Atmospheric Research Community Atmosphere Model (NCAR CAM3) with and without aerosols. Randles and Ramaswamy (2008) found that high loads of absorbing aerosols enhanced the monsoon circulation and precipitation in northwestern India. Vinoj et al. (2014) found a positive correlation between dust and sea salt aerosols over the Arabian Sea and increased monsoon precipitation in central India on a weekly timescale.

Disparities in predicted monsoon behavior have been seen between fixed sea surface temperature (SST) models and coupled ocean–atmosphere models. The model used by Lau et al. (2006) to develop the EHP hypothesis used fixed SSTs and predicted enhanced Asian monsoon rainfall. Similarly, the study conducted by Menon et al. (2002) with a fixed SST model also found increased monsoon precipitation in parts of India and China and decreased precipitation in the northern Indian Ocean. Alternatively, simulations with coupled models by Ramanathan et al. (2005) and Meehl et al. (2008) resulted in less Asian monsoon precipitation. When the SSTs were allowed to respond to the decreased solar radiation in northern India and surrounding waters due to aerosol absorption, the cooler ocean temperatures resulted in reduced precipitation.

In light of conflicting results from multiple investigations of the EHP hypothesis, this study aims to use a new observational approach using relevant information from satellites to revisit the EHP hypothesis.

The data used in this study will be described in Sect. 2. Sections 3 and 4 address methodology and results, respectively. A discussion of results is presented in Sect. 5, and conclusions are given in Sect. 6.

2 Data

2.1 Aerosols

In contrast to previous EHP studies that used the Total Ozone Mapping Spectrometer (TOMS) aerosol index (AI) as an indicator of absorbing aerosols, in this study the aerosol load in the IGB is determined from the aerosol optical depth (AOD) retrieved from the Multi-angle Imaging Spectroradiometer (MISR) (Diner et al., 1989; Bothwell et al., 2002) and is augmented with information from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Kaufman et al., 1997;

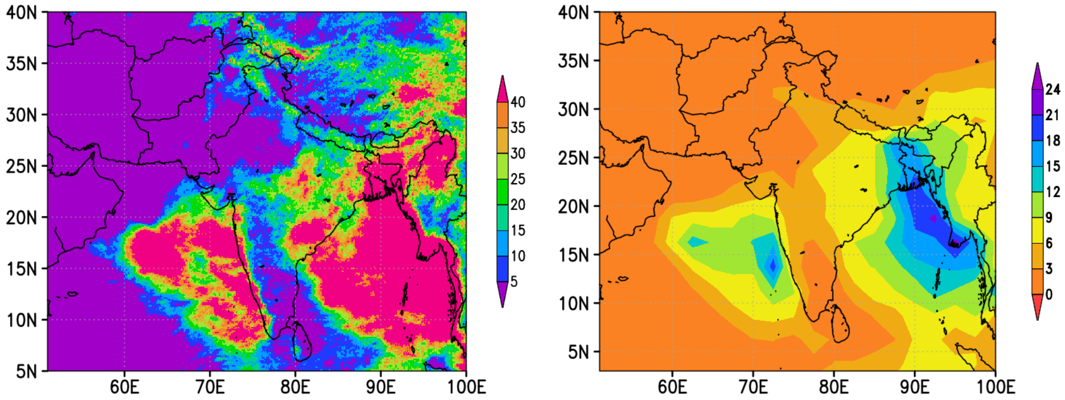

Figure 2. (a) Frequency of occurrence of convection per month derived from Meteosat-5 and **(b)** monthly mean precipitation (mm day^{-1}) from Global Precipitation Climatology Project (GPCP) for June 2003.

Tanre et al., 1997). Retrieval of information on aerosols from TOMS is based on the backscattered radiance measurements in the range of 331 to 380 nm and provides a quantity known as the aerosol index. Theoretical model simulations (Herman et al., 1997; Torres et al., 1998) have shown that the AI depends on AOD, single scattering albedo, and aerosol height. It is a measure of how much the wavelength dependence of backscattered UV radiation from an atmosphere containing aerosols differs from that of a pure molecular atmosphere. Since the underlying Rayleigh scattering in the boundary layer is small, TOMS AI is more sensitive to aerosol loading at upper levels than near the surface. Retrieval of information on aerosols from the MISR and MODIS instruments is based on the reflected radiation and provides information on the total columnar AOD. The quality of the MISR AOD retrievals in the IGB was investigated by Prasad and Singh (2007), who compared AOD estimates from MISR and MODIS to ground-based observations from the Aerosol Robotic Network (AERONET) for the years 2000–2005 and found that MISR retrievals were in closer agreement to ground observations than MODIS, attributable to the multi-angle viewing capabilities of the MISR instrument; however, observations from MODIS are more frequent than those from MISR.

Information on absorbing properties of aerosols comes from a newly developed approach that uses the Goddard Chemistry, Aerosol, Radiation, and Transport Model (GOCART) (Chin et al., 2002) as constrained with Modern-Era Retrospective Analysis for Research and Applications (MERRA) meteorology (Rienecker et al., 2011) (data provide by A. da Silva, personal communication, 2013). GOCART accounts for dust, sea salt, black carbon, organic carbon, and sulfate aerosols. Goddard Earth Observing System-5 (GEOS-5) is the latest version of the NASA Global Modeling and Assimilation Office (GMAO) Earth system model. It contains components for atmospheric circulation and composition, ocean circulation and biogeochemistry, and land surface processes. It also includes modules representing the atmospheric composition, such as aerosols (Colarco et al., 2010) and tropospheric and stratospheric chemical constituents (Pawson et al., 2008). For all aerosol species, optical properties are primarily from the commonly used Optical Properties of Aerosols and Clouds (OPAC) data set (Hess et al., 1998). Daily biomass burning emissions are from the Quick Fire Emission Dataset (QFED) and are derived from MODIS fire radiative power retrievals (Darmenov and da Silva, 2013). The reanalysis has a horizontal nominal resolution of 50 km and 72 layers in the vertical with its top at 85 km.

2.2 Convection and rainfall

High-resolution observations from Meteosat-5 are available until 2005, after which time they were replaced with observations from Meteosat-7. Radiance observations from Meteosat-5 at hourly resolution are used to determine the frequency of occurrence of convection. First, total cloud amounts are derived using a two-channel cloud detection scheme modified from the Clouds from AVHRR (CLAVR) algorithm used for the Advanced Very High Resolution Radiometer (AVHRR) instrument aboard NOAA polar orbiting satellites (Stowe et al., 1999). The algorithm compares 11.5 µm brightness temperature and visible reflectivity to empirically derived cloud thresholds. The cloud detection is first performed at pixel-level resolution (5 km) and then reprojected onto a 0.125° latitude–longitude grid. Details of the algorithm and cloud analyses are given in Wonsick et al. (2009).

Convective cloud determination is based on Meteosat-5 11.5 µm brightness temperature and cloud optical depth as estimated by the University of Maryland Surface Radiation Budget (UMD/SRB) model (Pinker et al., 2003) driven with relevant observations from Meteosat-5. The cloud optical depth threshold for convective clouds is set to 23 as in the International Satellite Cloud Climatology Project (ISCCP) convective cloud algorithm (Rossow and Schiffer, 1991), and the brightness temperature cutoff is 250 K.

The cloud screening method is limited in its ability to accurately detect clouds at night when visible data are unavailable and the algorithm relies solely on the brightness temperature observations. For this reason, cloud data are only calculated where solar zenith angle (the angle between the sun and the pixel zenith) is less than 75°. For the domain of 51 to 136° E longitude, this roughly corresponds to the hours of 00:00–13:00 UTC. The lack of nighttime cloud data does not appear to hamper the analysis for several reasons. Convection is analyzed in a relative sense as high-aerosol years versus low-aerosol years, so absolute values of convection have lesser importance. The percentage of convection missed overnight in the areas of interest is small because convection over land peaks in late afternoon in the Indian monsoon region (Gray and Jacobson, 1977; Dai, 2001; Islam et al., 2004). Frequency of convection patterns derived from Meteosat-5 shows close agreement with rainfall amounts from the Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997), indicating that the patterns capture the situation quite well. A comparison from June 2004 is shown in Fig. 2, and other months were found to be similar.

To enable the extension of the aerosol–rainfall connection to additional years where high-quality information on aerosols is available and where the high-resolution Meteosat-5 data were not available (2006–2012), use was made of the GPCP rainfall product. Although these data have lower resolution than the information from Meteosat-5 and do not differentiate convective precipitation from other forms, they are useful for assessing whether or not total monsoon rainfall is anomalously high during high absorbing aerosol years, as expected from the EHP hypothesis.

2.3 Temperature

Temperature data from the NCEP/DOE-R2 reanalysis (Kistler et al., 2001) and ERA-Interim (Dee et al., 2011) are incorporated into the evaluation of the hypothesis.

3 Methodology

In our study, we examine the MISR and MODIS aerosol records in the IGB for the years 2000–2012 and select years with the highest and lowest load of aerosols, based on AOD. We also establish the absorbing nature of the aerosols as discussed in Sect. 4.1. We assess whether the signatures of upper-tropospheric temperature, convection, and precipitation predicted by the EHP hypothesis are evident in observations during the high-aerosol years in contrast to the low-aerosol years. The following verifiable aspects of the proposed EHP effect are assessed in relation to the aerosol load for each year: (1) the upper-tropospheric temperature in the Tibetan Plateau region during May should be higher in the high-aerosol years due to aerosol absorption of shortwave radiation, (2) convection and precipitation in the foothills of the Himalayas and in northern India should be higher in May during the high absorbing aerosol years due to the early onset of the monsoon, (3) convection and precipitation in southern India should be lower in June in the high absorbing aerosol years due to the northward shift in the subsiding branch of the meridional circulation over India, and (4) convection and precipitation for the peak-monsoon season in the high absorbing aerosol years should be higher than average.

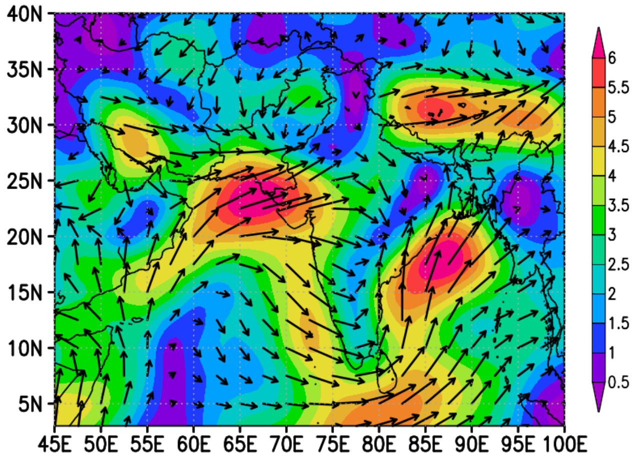

Figure 3. Long-term mean (1968–1996) 1000 mb wind vectors for April from NCEP/NCAR reanalysis. Shading represents wind speed in m s^{-1}.

4 Results

4.1 Aerosol analysis

The plausibility of aerosol transport into the region of interest is evident in Fig. 3, which shows the long-term mean of the general circulation near the surface in April. A relatively strong band of westerlies extends from the deserts of the Arabian Peninsula toward the Indo–Gangetic Basin (IGB) at the base of the Himalayas. A southerly wind from northeast India contributes black carbon from fossil fuel combustion to the aerosol loading in the IGB.

Figure 4 shows the time series of mean AOD in the IGB for the years 2000–2012 from both MISR (top) and MODIS (bottom). The values are calculated by averaging the monthly mean AOD data over the months of March–May in the IGB region as depicted in Fig. 1. The light blue bars show the analysis for the whole IGB region. Differences between the eastern and western sections of the IGB (divided at 82° E) are also illustrated using orange and dark blue color bars, respectively. The magnitudes of the AOD as derived with the two instruments differ, with MODIS reporting mean values near 0.6 compared to the MISR values that are closer to 0.45. However, interannual variability in AOD follows the same

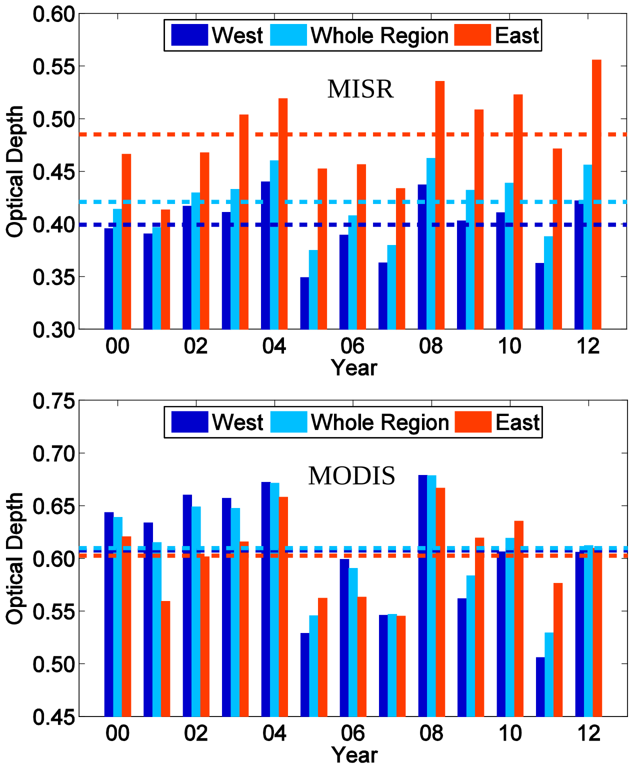

Figure 4. Time series of mean aerosol optical depth at 0.55 nm in the Indo–Gangetic Basin averaged over the months of March–May as derived from MISR (top) and MODIS (bottom). Values are given also for eastern and western portions of the IGB, separated at 82° E. Dashed lines: mean AOD for the region averaged over the months of March–May for the period 2000–2012 for the entire domain and eastern and western portions. Notice the difference in scales on the y axes.

general pattern in each figure. Both data sources agree that the years 2004 and 2008 had the highest springtime aerosol loading over the entire IGB, while aerosol content is much lower in the years 2005, 2007, and 2011; 2012 is also a year of high aerosols according to MISR but not MODIS . For this reason we will categorize 2012 as an uncertain year, but we will still include it in the analysis of the relationship between aerosols and climatic parameters of interest. There is more disagreement between the MODIS and MISR analyses when differences between the eastern and western regions of the IGB are considered. In the MISR data, AOD in the eastern region is consistently higher than in the west. Average values are 0.4 in the west and 0.5 in the east. In the MODIS data, AOD was higher in the west, particularly from 2000 to 2004. After 2004, AOD was more often higher in the east. Over the 13-year period, the mean AOD is roughly 0.6 for both sides of the IGB. Therefore, one side was not consistently higher than the other as seen in the MISR record.

In Fig. 5 we show the spatial distribution of multiyear average (2000–2012) AOD in the IGB region for the months of April (top row) and May (middle row), and the March-April-May average (bottom row) from MISR (left column) and MODIS (right column). As evident, during the buildup phase of April there are more regional differences in the AOD while by May, the entire IGB experiences high aerosol loading.

Since the anomalous warming that initiates the heat pump effect occurs when aerosols increase the air temperature by absorbing solar radiation, there is a need to establish that the aerosols are indeed absorbing (Dey and DiGirolamo, 2010). While a robust data set of aerosol absorbing properties in the IGB is not available, there is ample evidence that absorbing aerosols are present in the region during the pre-monsoon season. For instance, Dey and DiGirolamo (2010) present a detailed analysis of a 9-year (2000–2008) seasonal climatology of size- and shape-segregated AOD and Ångström exponent (AE) over the Indian subcontinent derived from MISR. They introduced indices of aerosol size- and shape-segregated optical depth and their effect on AE that describe the relative seasonal change in anthropogenic and natural aerosols from the preceding season. They report that winter to pre-monsoon changes in aerosol properties are not just dominated by an increase in dust but also by an increase in anthropogenic components, particularly in regions where biomass combustion is prevalent; ∼ 15 % of the AOD over the high wintertime pollution in the eastern Indo–Gangetic Basin is due to large dust particles, resulting in the lowest AE (< 0.8) over India in this season and likely caused by rural activities; while AOD decreases from the Indo–Gangetic Basin up to the Tibetan Plateau, a large peak in AE and the fraction of AOD due to particle radii < 0.7 mm exists in the foothills of the Himalayas, particularly in the pre-monsoon season. Both the dust and smaller-size aerosols from biomass combustion are highly absorbing. We have also analyzed the GOCART–MERRA information on the single scattering albedo (SSA) of the aerosols in the IGB. Figure 6 shows that SSA in the IGB during the pre-monsoon season of the high-aerosol years was overwhelmingly at or below 0.86, indicating the aerosols were mainly of the absorbing type. Values of 0.73 were reported over Bangalore (Babu and Moorthy, 2002), 0.81 over Pune, India (Pandithurai et al., 2004) and 0.91 over the Indian Ocean Experiment (INDOEX) region. Several additional studies ascertain the absorbing nature of the aerosols found over the Indian Continent. Deepshika and Srinivasan (2010) used the Infrared Difference Dust Index (IDDI) to establish the presence of dust in the atmosphere. Large IDDI values were observed even over vegetated regions of India attributed to the presence of transported dust from nearby deserts.

4.2 Upper-tropospheric temperature

According to the EHP hypothesis, in years with high loads of absorbing aerosols, the air above the Tibetan Plateau should undergo anomalous upper-tropospheric warming in May due to absorption of shortwave radiation by aerosols. For the

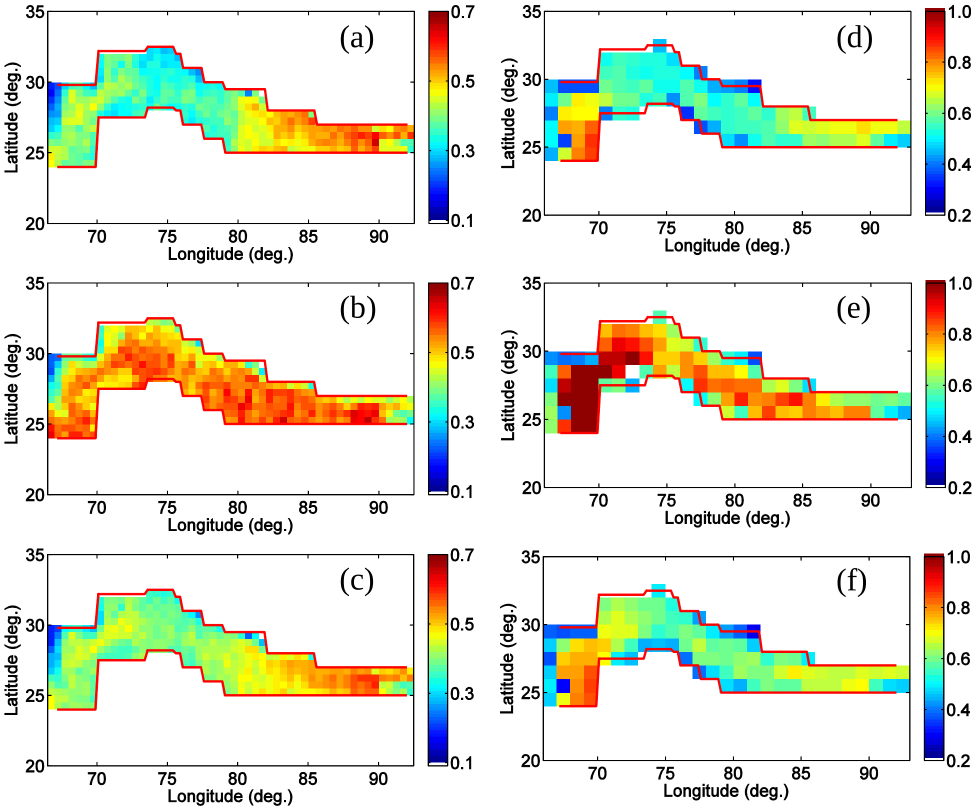

Figure 5. Spatial distribution of multiyear average (2000–2012) AOD in the IGB region for the months of April (top row **a** and **d**), May (middle row **b** and **e**), and the MAM average (bottom row **c** and **f**) from MISR (left column) and MODIS (right column). Notice difference in scales between the MISR and MODIS color bars.

high-aerosol years in our study, we show the latitude–height distribution of temperature anomaly in May from both the European Reanalysis ERA-Interim (ERAi) data set and the NCEP/DOE-R2 Reanalysis (Fig. 7). As in Lau et al. (2006), we averaged the temperature anomaly over the latitude sector 70° E to 100° E. The EHP hypothesis predicts that the largest positive temperature anomalies will occur from 20 to 25° N at and above the 700 mb level, corresponding to the highest concentrations of aerosol in the IGB being drawn northward and upward by the EHP effect. This pattern is seen in 2004; in 2008, the strong warming occurs only above the 300 mb level. In 2012 (the uncertain year), very weak anomalous warming is seen at about 700 mb. Temperature anomalies were also plotted for the low-aerosol years for contrast and are presented in Fig. S1 of the Supplement.

4.3 Convection and precipitation

4.3.1 May

According to the EHP hypothesis, the anomalous warming observed over the Tibetan Plateau should accelerate the monsoon cycle and enhance convection in the foothills of the Himalayas in May during years with high loads of absorbing aerosols. To identify whether enhanced convection in the Himalaya foothills was evident in the form of increased rainfall, we analyzed the monthly mean GPCP rainfall during May for the years 2001–2012 (Fig. 8). Of the three years with highest aerosol load, a fairly low amount of precipitation in the region is seen in 2008 and 2012, while 2004 has more precipitation but is not the highest of all the years investigated.

Lau and Kim (2011) noted that this early signal of the EHP effect may not be detectable with the coarse resolution of the GPCP rainfall analysis and suggested further examination with a data source that could provide more details of the rainfall distribution. Therefore, we further investigated the frequency of convection in the Himalaya foothills with the high-resolution Meteosat-5 observations. The difference in frequency of occurrence of convection in the foothills in May for 2004 (high absorbing aerosol year) minus 2005 (low-aerosol year) is shown in Fig. 9a. Frequency of occurrence of convection is computed for each point in the domain as the number of daytime hours in the month in which cloud top temperature and optical depth meet the convective cloud criteria outlined in Sect. 2.2. Some pockets of more frequent convection are apparent (yellow), particularly in the eastern section of the plateau where AOD is higher in the MISR analysis.

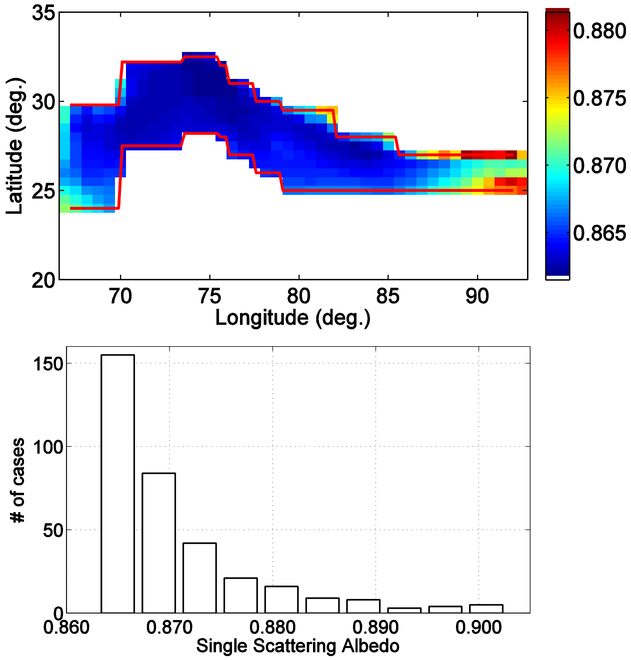

Figure 6. Spatial distribution (top) and frequency (bottom) of single scattering albedo values in the IGB averaged over MAM for the high absorbing aerosol years (2004, 2008, 2012) (from GOCART–MERRA, A. da Silva, personal communication, 2013).

4.3.2 June

By June, the subsiding branch of the meridional circulation that balances the forced ascent in the foothills should be well-established, causing a decrease in convection in southern India in the high absorbing aerosol years. This aspect of the hypothesis is evident in observations of both GPCP precipitation and Meteosat-5 frequency of convection. The difference in frequency of occurrence of convection from Meteosat-5 in June for 2004 (high-aerosol year) minus 2005 (low-aerosol year) is shown in Fig. 9b. This confirms the pattern of less convection in southern India during the high-aerosol year. In general, Fig. 10 shows less rainfall in southern India in the high-aerosol years (2004, 2012, and particularly 2008) compared to most other years.

4.3.3 July

The EHP hypothesis postulates that total amounts of convection and precipitation throughout all of India during the monsoon season will be higher in the high-aerosol years. Therefore, we look at the behavior for July, the month that traditionally produces the bulk of monsoon rainfall. Frequency of occurrence of convection for each July of 2000–2005 is displayed in Fig. 11. The year 2002, an extremely notable drought year (Waple and Larimore, 2003; Bhat, 2006) with a seasonal rainfall deficit of 21.5 %, a result of 56 % below normal rainfall in the month of July, is the only year that had less convection on the Indian subcontinent than the high absorbing aerosol year (2004) (the largest anomalies occurred in the western parts of India). In the longer GPCP rainfall record (shown in the Supplement as Fig. S2), 2004 and 2008 have less rainfall than most other years, particularly over the subcontinent as compared to the Bay of Bengal; 2012 has more convection over land than the other high absorbing aerosol years, but less convection over the Bay of Bengal than any other year except 2010.

5 Discussion

The high spatial and temporal resolution of Meteosat-5 satellite data and long-term record of GPCP rainfall data along with improved aerosol information from sources such as MISR, MODIS, and the MERRA aerosol reanalysis provide a unique opportunity to investigate processes that affect the Asian monsoon. This study exploits these capabilities to apply a novel approach for evaluating the EHP hypothesis. It was found that in some aspects, observations were in agreement with the hypothesis but not in all of them. Specifically, the details are as follows:

1. Strong anomalous warming over the Tibetan Plateau *was observed* in one of the high absorbing aerosol years (2004). In 2008 the anomalous warming occurred only up near the tropopause. In 2012, weak anomalous warming was observed.

2. Enhanced convection in the foothills of the Himalayas in May *was observed* in the high-resolution Meteosat-5 analysis for 2004, but was not evident in the coarse-resolution GPCP data.

3. Suppression of precipitation in southern India in June *was observed*.

4. Total precipitation in July *was not observed* to be consistently higher in the high absorbing aerosol years.

In light of these findings, it is useful to review some of the previous investigations of aerosol impacts on the Indian monsoon.

Lau and Kim (2006) conducted an observational study seeking preliminary validation of the EHP hypothesis. They utilized four high-aerosol years (1980, 1985, 1988, and 1991) and four low-aerosol years (1982, 1983, 1990, and 1992) selected on the basis of the TOMS AI (Hsu et al., 1999) (Fig. S3 in the Supplement). As in the current study, they used rainfall observations from GPCP (Huffman et al., 1997) and temperature and wind fields from the NCEP/DOE-R2 Reanalysis data (Kanamitsu et al., 2002). They composited the data separately for the high- and low-aerosol years (Fig. S3 in the Supplement) and found that the following features were in agreement with the hypothesis during the high absorbing aerosol years: composite rainfall data showed an increase

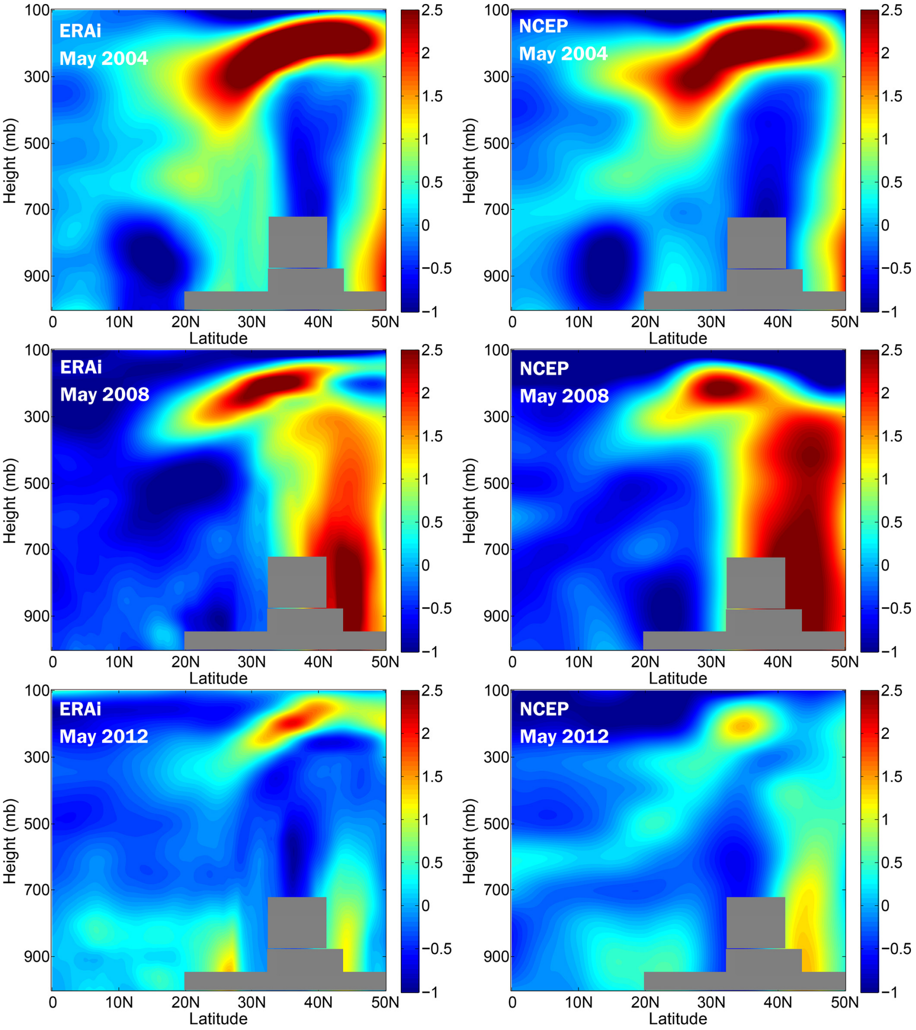

Figure 7. Latitude–height distribution of temperature anomaly (°C) from ERAi (left column) and NCEP/DOE-R2 Reanalysis (right column) over latitude sector 70 to 100° E for May of the high absorbing aerosol years: 2004 (top), 2008 (middle), 2012 (bottom). Gray shaded area is an idealized representation of elevation of the Tibetan Plateau. Anomaly is computed as difference from the mean for the years 1993–2012 for ERAi and 1981–2010 for NCEP/DOE-R2 Reanalysis.

in precipitation in the Himalaya foothills and northern India in the early part of the season, spreading to all of India in June and July; enhanced ascent of warm air along the Himalayan foothills in May was evident in the composite wind fields; statistically significant correlations between high levels of absorbing aerosols and warm upper-tropospheric temperature anomalies in northern India and the Tibetan Plateau were found. The opposite behavior was observed during the low-aerosol years. Since the results of Lau and Kim (2006) differ from the conclusions of this study, it would have been of interest to perform the current analysis for the years used by Lau and Kim (2006). However, the sources of high-resolution cloud and aerosol information chosen for this study were not available until 1998 and 2000, respectively.

Kuhlmann and Quass (2010) investigated the EHP effect using detailed, vertically resolved aerosol information from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data. They found the highest aerosol concentrations in the lower atmosphere with very little aerosol reaching the altitude of the Tibetan Plateau. While peak shortwave heating in the lower troposphere closest to aerosol source regions reached the levels modeled in the Lau et al. (2006) study ($0.2\,\mathrm{K\,day^{-1}}$), elevated heating at the level of the Tibetan Plateau was only $0.05\,\mathrm{K\,day^{-1}}$. Thus, they found no evidence of elevated heating that would be strong enough to influence large-scale monsoonal circulations. Our study partially agrees with their findings; we found that neither the ERAi nor NCEP/DOE-R2 reanalysis data consistently confirmed the existence of anomalous

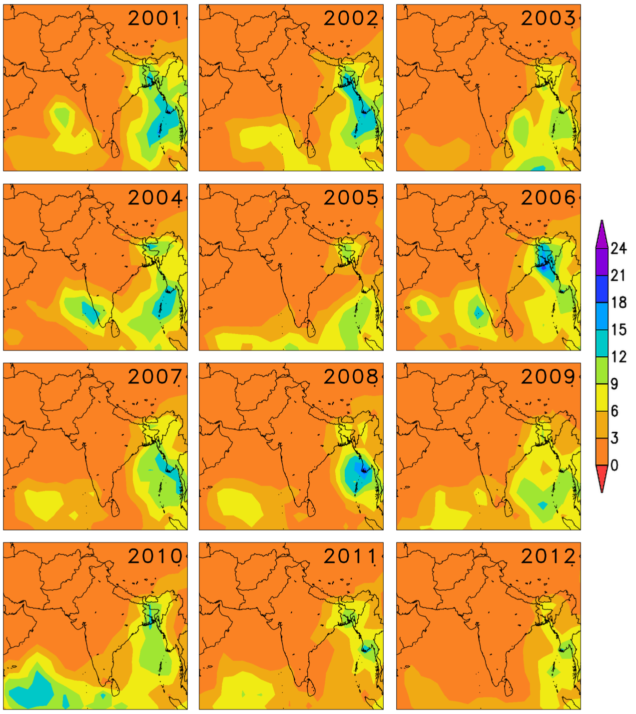

Figure 8. GPCP monthly mean precipitation in May for the years 2001–2012 over the region bounded by 5 to 40° N and 50 to 100° E.

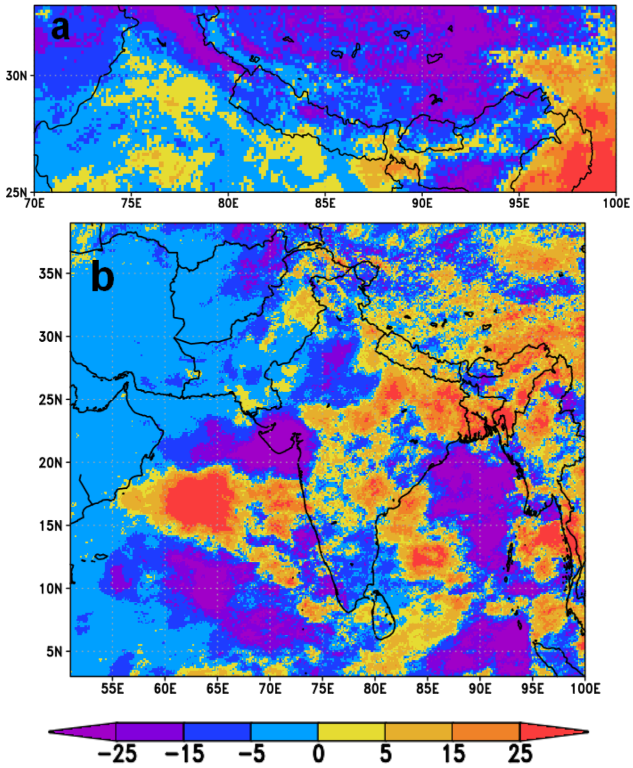

Figure 9. Difference in frequency of occurrence of convection per month for 2004 (high absorbing aerosol year) minus 2005 (low-aerosol year) for **(a)** a detailed view of the Himalaya foothills region in May and **(b)** India and surrounding waters in June.

upper-tropospheric warming above the Tibetan Plateau during the high-aerosol years.

Bollasina et al. (2008) contributed another significant observational study of the EHP hypothesis using a regression of various parameters on the TOMS aerosol index for the years 1979–1992. Their regression of rainfall on the TOMS AI showed a link between high loads of absorbing aerosols and deficient springtime precipitation, which they attributed to dissipation of clouds through the aerosol *semi-direct* effect. Evidence that aerosols can alter cloud characteristics in the Indian monsoon region was provided by Heymsfield and McFarquhar (2001). They analyzed aircraft data from flights made through polluted and clean clouds in the Indian Ocean during INDOEX (Ramanathan et al., 2001) and found a threefold increase in droplet concentrations and a 35 % decrease in droplet effective size in polluted clouds, leading to more rapid dissipation.

Explaining the contrast between their findings and the enhancement of precipitation in the IGB in May observed by Lau and Kim (2006), Bollasina et al. (2008) noted that different mechanisms are at work in the eastern and western parts of the IGB. In the western region, where the aerosol load is highest, precipitation appeared to be subdued by the aerosol semi-direct effect. Some increase in precipitation was seen in the eastern region, where the large-scale circulation flows northward over the Bay of Bengal, picking up abundant moisture and rising orographically when it encounters the Himalayas. The results of Bollasina et al. (2008) suggest that the high loads of absorbing aerosols in the west may affect the large-scale circulation in a manner that enhances this precipitation-producing mechanism in the east. However, the aerosol loading in the east is rather small and does not directly cause rising motion through the EHP mechanism. Furthermore, they assert that since Lau and Kim (2006) used a longitudinal average of precipitation across the IGB, the rainfall reduction in the west was masked by the activity in the east.

The details brought forth by the high-resolution Meteosat-5 data point to the need for further investigation of this concept. Referring back to Fig. 9, it is clear that the most significant increase in convection during the high-aerosol year (2004) occurred in the eastern section of the IGB. The western part of the IGB predominantly showed decreases in convection, or slight increases interspersed with decreases, similar to the observations of Bollasina et al. (2008). Based on Fig. 4, the MISR analysis of AOD showed higher aerosol amounts in the east in 2004 while MODIS observed slightly higher AOD in the west. This makes it difficult to assess the impact of regional differences in aerosol loading on the observed precipitation. A more detailed study, possibly, on shorter timescales, is needed.

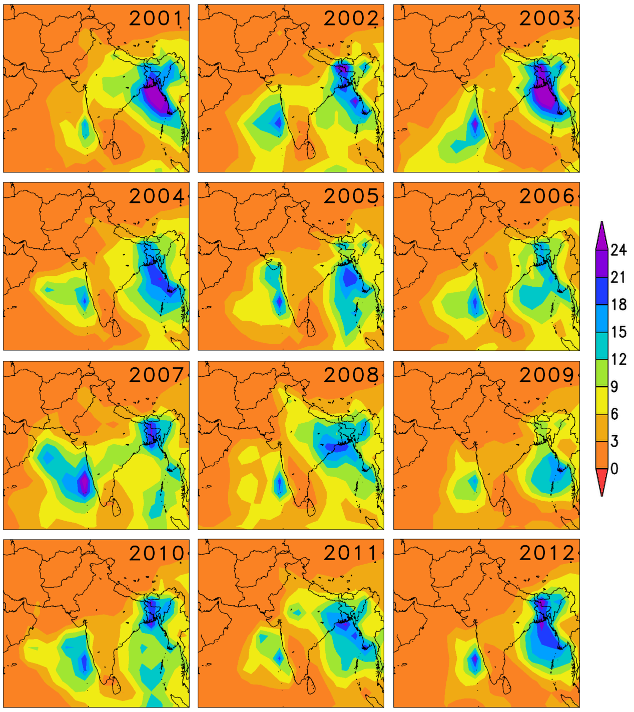

Figure 10. GPCP monthly mean precipitation in June for the years 2001–2012 over the region bounded by 5 to 40° N and 50 to 100° E.

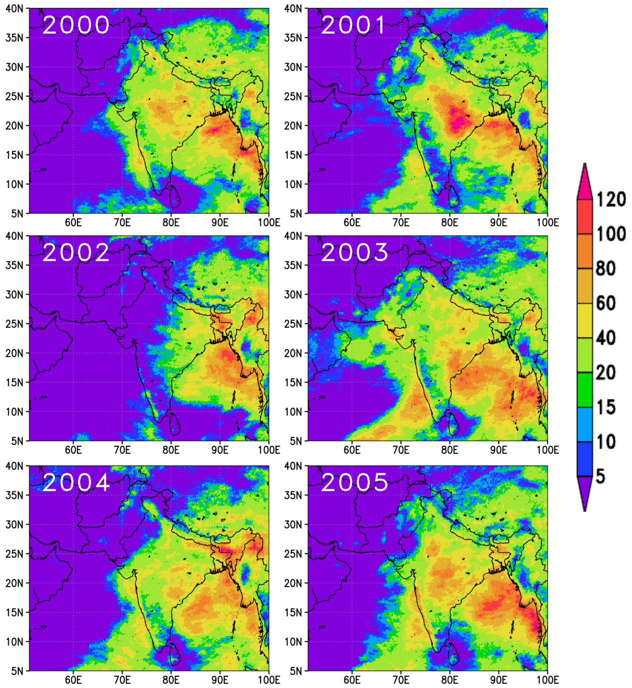

Figure 11. Frequency of occurrence of convection per month for each July between 2000 and 2005.

6 Summary and conclusions

As discussed in Ramanathan et al. (2001), aerosols influence climate *directly* by absorbing and scattering solar radiation within the atmosphere, with carbonaceous aerosols playing a major role in the absorption process (Ramaswamy et al., 2001). Aerosols also influence climate in their role as cloud condensation and ice nuclei (Penner and Novakov, 1996; Haywood et al., 2000) (the first *indirect* radiative forcing), which can lead to a decrease in precipitation efficiency. For instance, Rosenfeld et al. (2001) have documented that urban and industrial air pollution can completely shut off precipitation from clouds that have temperatures at their tops of about −10 °C. Such findings point to the strong connection between aerosols and the hydrological cycle (Ramanathan et al., 2001).

Measurements made during the past 20 years at numerous locations over India indicate that the concentration of aerosols in the Indian region has increased and reached high values (Moorthy et al., 2004; Satheesh, 2012). As part of individual studies and numerous national programs (e.g., Indian Middle Atmospheric Program (IMAP) and the Indian Space Research Organisation – Geosphere Biosphere Programme (ISRO–GBP)), a wealth of information on important aerosol properties such as size, mass concentration, optical depth, and scattering and absorption coefficients have been collected with special attention to black carbon (BC). The National Land Campaign II (LC-II) organized by the ISRO under ISRO–GBP during December 2004 was aimed at characterization of aerosol properties and trace gases across the entire Indo–Gangetic belt. These studies showed the persistence of high-aerosol optical depth and BC concentrations near the surface (Pant et al., 2006; Niranjan et al., 2006, 2007; Moorthy et al., 2005; Ganguly et al., 2005; Nair et al., 2006). It has also been recognized that BC aerosols can contaminate other aerosol species (dust can be coated with BC) or be contaminated by other species, resulting in altered radiative properties and their ability to act as cloud condensation nuclei (Chandra et al., 2004). Because of the complexity of the mixing process, there is still a great degree of uncertainty regarding the hygroscopic properties of BC and their role as cloud condensation nuclei. In the present study a large-scale approach was used to investigate some of the issues identified at local scales; in particular, satellite observations are used that enable us to provide a broader view of aerosol influences over longer timescales than is possible from short-term experiments. In particular, by combining satellite-based information on aerosols and the use of numerical model outputs, it was possible to evaluate the impact of aerosols on the heating of the atmosphere, and by combining information from satellites on aerosols and rainfall, it was possible to address connections between them in areas influenced by conditions in the Indo–Gangetic belt. Below are some findings from our study.

- Our analysis of aerosol characteristics in the IGB based on MODIS, MISR, and MERRA data for a period of

13 years indicates that MODIS and MISR agree on the interannual temporal variation of AOD during springtime, although differences are seen in the spatial patterns from east to west. The MERRA analysis of SSA confirms the absorbing nature of the aerosols in the IGB belt.

- We have investigated whether aerosol absorption causes upper-tropospheric temperature anomalies near the Tibetan Plateau, and found that this was not a consistent feature in any of the high-aerosol years.
- We have demonstrated the need for high-resolution information in addressing aerosol–rainfall issues. For instance, using convection as a proxy to rainfall, enhanced convection and rainfall in the Himalaya foothills during high-aerosol years could be detected in the high-resolution observations from Meteosat-5 but could not be seen in the lower-resolution GPCP rainfall data.

While the Meteosat-5 record ends in mid-2006, geostationary satellite coverage of the Asian monsoon region continued with the replacement of Meteosat-5 by Meteosat-7 in 2006 and by new Indian satellite missions. More detailed information on aerosol absorbing properties in the IGB for the year 2009 has become available from the observing campaigns such as the one coordinated through the Joint Aerosol–Monsoon Experiment (JAMEX) (Lau et al., 2008) as reported on by Gautam et al. (2011). Building on the groundwork set by the current investigation, new advancements in observations will allow many outstanding issues in this region to be addressed. An extended study of the EHP hypothesis that accounts for external influences will also be possible.

The Supplement related to this article is available online at doi:10.5194/acp-14-8749-2014-supplement.

Acknowledgements. This work was supported under NASA grant NNG05GB35G from the Terrestrial Hydrology and Global Water Cycle Program to the University of Maryland and benefited from NASA grant NNX08AN40A from the Science Mission Directorate-Division of Earth Science. The authors wish to thank the staff at the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Archive and Retrieval Facility for providing the Meteosat-5 observations and consulting on the calibration and to Arlindo DaSilva for providing the MERRA aerosol reanalysis data. Thanks are also due to the National Snow and Ice Data Center (NSIDC) at the University of Colorado, Boulder, CO, for providing the IMS snow data, the NASA/GSFC TOMS group for providing the TOMS aerosol data, to NOAA/OAR/ESRL PSD, Boulder, CO, USA, for providing the Reanalysis 2 data, and to NCAR's Data Support Section (DSS) for supplying ERA-Interim data. MISR and MODIS data were downloaded from the Goddard Earth Sciences Data and Information Services Center (GES DISC) Giovanni web site. Sincere thanks are due to the Editor for constructive guidance and to Chuan Li for technical assistance.

Edited by: F. Fierli

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