Possible influences of air pollution, dust- and sandstorms on the Indian monsoon

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Introduction

In Asian monsoon countries, such as China and India, human health and safety problems caused by air pollution are becoming increasingly serious, due to the increased loading of atmospheric pollutants from waste gas emissions and from rising energy demand associated with the rapid pace of industrialization and modernization. Meanwhile, uneven distribution of monsoon rain associated with flash floods or prolonged drought, has caused major loss of human life and damage to crops and property with devastating societal impacts. Historically, air-pollution and monsoon research are treated as separate problems. However recent studies have suggested that the two problems may be intrinsically linked and need to be studied jointly (Lau et al., 2008).

Fundamentally, aerosols can affect precipitation through radiative effects of suspended particles in the atmosphere (direct effect) and/or by interfering and changing the cloud and precipitation formation processes (indirect effect). Based on their optical properties, aerosols can be classified into two types: those that absorb solar radiation, and those that do not. Both types of aerosols scatter sunlight and reduce the amount of solar radiation from reaching the Earth's surface, causing it to cool. The surface cooling increases atmospheric stability and reduces convection potential.

Absorbing aerosols, however, in addition to cooling the surface, can heat the atmosphere. The heating of the atmosphere may reduce the amount of low clouds by increased evaporation in cloud drops. The heating, however, may induce rising motion, enhance low-level moisture convergence and, hence, increases rainfall. The latent heating from enhanced rainfall may excite feedback processes in the large-scale circulation, further amplifying the initial response to aerosol heating and producing more rain.

Additionally, aerosols can increase the concentration of cloud condensation nuclei (CCN), increase cloud amount and decrease coalescence and collision rates, leading to reduced precipitation. However, in the presence of increasing moist and warm air, the reduced coalescence/collision may lead to supercooled drops at higher altitudes where ice precipitation falls and melts. The latent heat release from freezing aloft and melting below implies greater upward heat transport in polluted clouds and invigorate deep convection (Rosenfeld et al., 2008). In this way, aerosols may lead to increased local convection. Hence, depending on the ambient large-scale conditions and dynamical feedback processes, aerosols' effect on precipitation can be positive, negative or mixed.

In the Asian monsoon and adjacent regions, the aerosol forcing and responses of the water cycle are even more complex. Both direct and indirect effects may take place locally and simultaneously, interacting with each other. In addition to local effects, monsoon rainfall may be affected by aerosols transported from other regions and intensified through large-scale circulation and moisture feedback. Thus, dust transported by the large-scale circulation from the adjacent deserts to northern India may affect rainfall over the Bay of Bengal; sulphate and black carbon from industrial pollution in central, southern China and northern India may affect the rainfall regime over the Korean peninsula and Japan; organic and black carbon from biomass burning from Indo-China may modulate the pre-monsoon rainfall regime over southern China and coastal regions, contributing to variability in differential heating and cooling of the atmosphere and to the land-sea thermal contrast.

During the pre-monsoon season and monsoon breaks, it has been suggested that radiative forcing by absorbing aerosols have nearly the same order of magnitude as the forcing due to latent heating from convection and surface fluxes. The magnitude of the total aerosol radiative cooling due to sulphates and soot is of the order of 20-40 W/m2 over the Asian monsoon land region in the pre-monsoon season (Sikka, private communication), compared to about 1-2 W/m2 for global warming. However, the combined forcing at the surface and in the atmosphere, including all species of aerosols, and details of aerosol mixing, and impacts on the energy and water cycles in the monsoon land regions, are not well known.

Recent studies of aerosol effects on the Asian monsoon

Many recent papers have documented variations in aerosol loading, surface cooling and their possible relationships with rainfall in the monsoon regions of India and East Asia (Krishnan and Ramanathan, 2002; Devara et al., 2003; Cheng et al., 2005, Prasad et al., 2006; Nakajima et al., 2007; George et al., 2008; and many others). Modelling studies have suggested that aerosol in the atmosphere can affect the monsoon water cycle by altering the regional energy balance in the atmosphere and at the Earth's surface and by modulating cloud and rain processes (Rosenfeld, 2000; Ramanathan et al., 2001; Li, 2004). However, depending on the experimental design, the spatial and temporal scales under consideration, the aerosol forcing and representation of aerosol and rainfall processes used, models have produced results that vary greatly from each other.

Using a global weather prediction model, Iwasaki and Kitagawa (1998) found that aerosol effect may reduce the land-sea thermal contrast and lead to suppression of the monsoon of East Asia, significantly delaying the northward advance of the Meiyu front over eastern Asia. Menon et al. (2002) suggested that the long-term drought over northern China and frequent summer floods over southern China may be related to increased absorption and heating by increasing black carbon loading over India and China. Ramanathan et al. (2005), using aerosol forcing derived from atmospheric brown clouds (ABC) field experiments, suggested that aerosol-induced cooling decreases surface evaporation and reduces the north-south sea surface temperature gradient over the Indian Ocean, leading to a weakened monsoon circulation. Lau et al. (2006) and Lau and Kim (2006) found that abundant amount of dust aerosols from the Thar Desert and the Middle East deserts are transported into northern India, during the pre-monsoon season (April through early June) Forced by the prevailing wind against the steep topography of the Himalayas, the dust aerosols pile up against the foothills and spread over the Indo-Gangetic Plain (IGP). The thick layer of dust absorbs solar radiation and acts as an additional elevated heat source for the Asian summer. The airborne dust particles become even more absorbing when transported over mega-cities of the IGP and coated by fine black carbon aerosols from local emissions (Prasad and Singh, 2007).

The combined heating effect due to dust and black carbon may excite a large-scale dynamical feedback via the so-called "elevated-heat-pump" (EHP) effect (Lau et al., 2006). The effect amplifies the seasonal heating of the Tibetan Plateau, leading to increased warming in the upper troposphere during late spring and early summer, subsequently spurring enhanced monsoon rainfall over northern India during June and July. Wang (2007) found similar results, indicating that global black carbon forcing strengthens the Hadley cell in the northern hemisphere, in conjunction with an enhancement of the Indian summer monsoon circulation. Meehl et al. (2008) and Collier and Zhang (2008) showed that India rainfall is enhanced in spring due to increased loading of black carbon but the monsoon may subsequently weaken through induced increased cloudiness and surface cooling. Bollasina et al. (2008) suggested that aerosol influence on the large-scale Indian monsoon circulation and hydro-climate is mediated by the heating/cooling of the land surface over India, induced by the reduction in precipitation and cloudiness accompanying increased aerosol loading in May.

The wealth of new results on aerosol effects on the monsoon water and energy cycle from observations and modelling studies can be as confusing as they are informative. This is partly due to the complex nature of the aerosol-monsoon interaction and partly because the study of aerosol-monsoon interaction is just beginning as an interdisciplinary science The effects of aerosols on precipitation processes are strongly dependent, not only on the aerosol properties but also on the dynamical states and feedback processes in the coupled ocean-atmosphere-land system. To understand a particular aerosol-rainfall relationship, therefore, the background meteorological conditions affecting the relationship must first be understood.

In this article, we present basic patterns of aerosol and monsoon seasonal and interannual variability, focusing on the Indian monsoon. We use the 2008 season as an example to discuss possible impacts of aerosols on, and feedback from, the large-scale South Asian monsoon system in the context of forcing from the ocean and the land. These results will help in developing observation requirements, new concepts and ideas for further in-depth joint aerosol-monsoon studies.

Aerosols and the monsoon system

Global aerosol "hotspots"

Aerosol-induced atmospheric feedback effects are likely to be most effective in aerosol "hotspots", which are characterized by heavy aerosol loading, adjacent to regions of abundant atmospheric moisture, i.e. oceanic areas of tropical forests. Figure 1 shows the latest version of the global distribution of aerosol optical depth from MODIS (moderate resolution imaging spectro--radiometer) for 2005 (Hsu et al., 2004). The aerosol hotspots vary geographically with the season; some regions exhibit all-year-round activity. Major hotspots for different seasons include:

March-April-May: the southern Saharan desert, West Africa and the mega-cites of the Indo-Gangetic Plain of northern India, East Asia and South-East Asia;

June-July-August: the Sahel and central West Africa, the Arabian Sea, the Indo-Gangetic Plain, the Indian subcontinent and East Asia;

September-October-November: the Amazon, West Africa, South Africa, the Indo-Gangetic Plain and East Asia;

December-January-February: West Africa, the Indo-Gangetic Plain and East Asia.

It is apparent from Figure 1 that the Saharan desert, West Africa, East Asia and the Indo-Gangetic Plain are all-year-round aerosol hotspots, linked geographically to major monsoon regions. The vast Saharan desert is situated northwards of the rainbelt of the West African monsoon. The East Asia monsoon region coincides with the industrial mega-city complex of China and is downwind of the Gobi and Taklamakan Deserts. The Indo-Gangetic Plain is a mega-city complex, downwind of the Thar and Middle East deserts. These regions are affected by monsoon rains and droughts, as well as major industrial pollution and desert sand- and dust-storms. In the remainder of this article, we shall focus on aerosols in the Indo-Gangetic Plain and the Arabian Sea region, and their possible impacts on the Indian summer monsoon.

The Indo-Gangetic Plain in northern India is an aerosol "super-hotspot", hosting the world's highest population density and concentration of coal-firing industrial plants. Most of the aerosols are the absorbing species—black carbon from coal and biofuel burning, biomass burning and dust. During the northern spring and early summer, these aerosols are blown from the Thar Desert and the Middle East deserts by the developing monsoon westerlies. As shown in Figure 1(b), very high concentrations, as indicated by large aerosol optical thickness, are found over the northern Arabian Sea from July to August. Aerosols mixed with atmospheric moisture during the pre-monsoon months are found in the form of haze and smoke—so-called atmospheric brown clouds (ABC) (Ramanathan and Ramana, 2005).

Aerosol-monsoon rainfall seasonal cycle

The co-variability of absorbing aerosols and rainfall over the Indian subcontinent can be seen in the climatological (1979-2003) time-latitude section of the Total Ozone Mapping Spectrometer-Aerosol Index (TOMS-AI), and Global Precipitation Climatology Project rainfall (Figure 2). TOMS-AI measures the relative strength of absorbing aerosols based on absorptivity in the ultraviolet spectrum and are the only global, long-term, daily satellite data avail-able for the period 1979 to 2005, with a data gap, from 1993-1996. The increase in atmospheric loading of absorbing aerosols, primarily from dust, with some contribution from black carbon, from April to June in northern India (>20°N), preceding the northward movement of the monsoon rainband, is very pronounced. The reduction of aerosols, due to rain wash-out during the peak monsoon season (July-August), is also evident. Clearly, both aerosols and rainfall are related to the large-scale circulation that controls a large part of the seasonal variation. The high aerosol region in northern India in June and July actually overlaps with the rain area, indicating the possibility that aerosols may interact with clouds and rain in this area and not be totally washed out by monsoon rains, due to the rapid re-build up from local emissions and transports from outside the region.

Additional details of aerosol characteristics can be deduced from the monthly distribution of rainfall, aerosol optical depth and Ångstrøm exponent of aerosol from the single-site AERONET observations (Holben et al., 1998) at Kanpur (26.47°N, 80.35°E) located within the Indo-Gangetic Plain, near the boundary of the wet and dry zones (Figure 3). The aerosol optical depth has a double maximum in the annual cycle, i.e. a strong semi-annual component (Figure 3(a)). The first peak is associated with the building-up of absorbing aerosols during May and June, before the peak of the monsoon rain during July and August. Even during the rainfall peak, the background aerosols, while reduced from their maximum peak value (~0.8), are still found to be very high (~0.5-0.6), indicating that not all aerosols are washed out by the monsoon rain. Heavy rain occurs in small regions for short periods of days during the monsoon season, while dust aerosols are spatially widespread. Aerosol burden can rapidly increase in a few days or even hours after major monsoon rain events from local emissions and dust transport from adjacent desert regions. In addition, during monsoon breaks when monsoon rainfall diminishes, aerosols can continue to build up to high concentrations. The second aerosol optical depth peak during November-January is likely to be caused by the build-up of atmospheric brown clouds from industrial emission and bio-fuel burning, favoured by stable meteorological conditions associated with subsiding air-mass and lack of rainfall which prevail over northern India during the winter monsoon (Ramanathan and Ramana, 2005). Hence, the semi-annual cycle may be largely a reflection of the seasonal variations of the meteorological condition.

The bulk properties of the aerosols can be inferred from the variations of the Ångstrøm exponent (Figure 3(b)). The Ångstrøm exponent is a measure of the spectral dependence of the optical thickness, which is inversely proportional to the size of the particle. The lower Ångstrøm exponents found during April-June indicate coarse particles (effective particle radii >1 μm) absorbing aerosols such as dust. The higher values in November-January signal fine aerosols (effective radii <1 μm) from industrial pollution, which is likely to consist of a mixture of absorbing (black carbon) and non-absorbing (sulphate) aerosols. Because of the prevailing subsiding conditions over the Indo-Gangetic Plain during the winter monsoon, it is possible that the fine particles are more confined to the atmospheric boundary layer and below clouds. Hence, they are not detected by TOMS-AI. This may account for the absence of a second peak in TOMS-AI. More detailed analyses are required to confirm this conjecture. Both the aerosol optical depth and the Ångstrøm exponent indicate large interannual variability, as is evident in the large monthly standard deviation.

Characteristic large-scale circulation pattern associated with EHP

As noted previously, a steady build- up of absorbing aerosols begins in April-May before the monsoon rains. Figure 4(a) shows the statistical regression pattern of May-June layer-averaged (surface to 300 hPa) temperature and 300 hPa wind from approximately 20 years of TOMS AI for April-May over the Indo-Gangetic Plain. A build up of aerosol in April-May over the Indo-Gangetic Plain is associated with the development in May-June, of a pronounced large-scale upper level tropospheric warm anomaly, coupled with an anomalous upper-level large-scale anticyclone over northern India and the Tibetan Plateau, with strong northerlies over 75-90°E, 20-25°N, and easterlies across the Indian subcontinent and the Arabian Sea at 5-20°N. The large-scale warm-core anticyclone associated with increased aerosol appears to be coupled with an upper level cold-core cyclone situated to its northwest. The dipole pattern is consistent with Rossby wave response in temperature and wind to increased diabatic heating over India and the Bay of Bengal and reduced heating in the north-western India/Pakistan/ region (Hoskins and Rodwell, 1995). At 850 hPa (Figure 4(b)), the regression patterns show a general increase in rainfall associated with enhanced convection over north-eastern India at the foothills of the Himalayas, with the most pronounced increase over the Bay of Bengal and the western coastal region of India in June and July. North-western India, Pakistan and the northern Arabian Sea remain dry. Anomalous westerlies are found spanning the Arabian Sea, crossing the Indian subcontinent and ending up in a cyclonic circulation over the Bay of Bengal. The enhanced westerlies will transport more dust from the Middle East across the Arabian Sea to the Indian subcontinent. Throughout the May-June-July period, the large-scale circulation patterns in the upper and lower troposphere imply a large increase in the easterly wind shear and a deepening of the Bay of Bengal depression. Both are signals of a stronger South Asian monsoon (Webster and Yang, 1992; Goswami et al., 1999; Wang and Fan, 1999; and Lau et al., 2000). These large-scale circulation patterns are characteristic of the impacts of absorbing aerosols on the Indian monsoon.

The 2008 Indian Monsoon

In this section, we use the 2008 Indian monsoon as an example for a discussion of possible relationships of monsoon rainfall to the large- scale ocean-atmosphere forcing and to aerosols. The Indian summer monsoon in 2008 is somewhat weaker than normal, following the La Niña condition in the tropical Pacific. However, highly anomalous and persistent wetter-than-normal conditions are found in northern India, along the foothills of the Himalayas, and drier-than-normal conditions over central and southern India, the Arabian Sea and Bangladesh (Figure 5(a)). In addition, an east-west dipole rainfall pattern is found over the southern Indian Ocean between the Equator and 10°S. While the east-west dipole in rainfall may be related to the Indian Ocean Dipole (IOD) (Saji et al., 1999 Webster et al., 1999), the reason for the persistent rainfall anomaly in northern India is not known. The low-level circulation show strong easterlies connecting the Indian Ocean Dipole and rainfall dipole over the southern Indian Ocean. Strong south-westerlies are found over the Arabian Sea, and western India, heading towards the foothills of the Himalayas. The rainfall deficit over western and southern India appears to be related to a large-scale cyclone over the northern Arabian Sea and an anticyclonic flow over southern

India and the southern Bay of Bengal. The sea-surface temperature (SST) is anomalously low over the entire Arabian Sea and the Bay of Bengal and the northern Indian Ocean (Figure 5(b)). Such a widespread, below-normal sea-surface temperatures would have caused a weakened Indian monsoon, although the cooling over the northern Arabian Sea may also be the signal of a strengthened monsoon. An east-west dipole in sea-surface temperatures in the southern Indian Ocean is found, possibly a footprint of the Indian Ocean Dipole, and is most likely the underlying reason for the east-west rainfall dipole in the southern Indian Ocean. However, the persistent rainfall anomalies over northern India cannot be explained directly by the Indian Ocean Dipole conditions, as land precipitation over India has little correlation with large-scale oceanic forcing such as the Indian Ocean Dipole and El Niño/Southern Oscillation (ENSO). It is possible that the rainfall anomaly may be related to an extra-tropical cyclonic stationary pattern established over northern India or to the westward extension of the monsoon trough from southern China. This remains to be demonstrated.

Possible impacts of desert dust on Indian monsoon rainfall anomalies in 2008

In this section, we examine the aerosol distribution and possible signals of aerosol impacts on the 2008 Indian monsoon. Figure 6(a) shows the MODIS image of dust and clouds over the Indian monsoon region on 18 June 2008. The large cloud cluster over north-eastern India is related to enhanced convection associated with heavy monsoon rainfall along the foothills of the Himalayas near Nepal. The cloud clusters off the coast of the southern tip of the subcontinent and over the Bay of Bengal are associated with enhanced rainfall anomalies found in those regions. Most striking is the strong contrast between the dry, dusty north-west India/Pakistan and northern Arabian Sea compared to the wet (convectively active) north-eastern India and Bay of Bengal. Large dust loading can be seen over the northern Arabian Sea and western India. The dust and cloud streaks signal a prevailing southwesterly monsoon flow over north-western Arabia. The heavy dust loading is persistent throughout June and part of July as is evident in the distribution of anomalous aerosol optical depth for June-July 2008 (Figure 6(b)). Centres of high aerosol optical depth are found over the northern Arabian Sea and north-west India/Pakistan region, with a secondary centre over eastern India and the Bay of Bengal. There is a strong east-west contrast over the Indo-Gangetic Plain, reflecting the dry region to the west and wet regions to the east. As evident in the Calipso lidar backscatter, the dust layers extend from the surface to more than 4-5 km over a large area from Pakistan/Afghanistan to the northern Arabian Sea (Figure 7, top panel). The dust particles are lifted to high altitudes by wind forced against the steep topography, with highest concentration at 4 km and above, over land. Over the ocean they appear in layers below and above the boundary layer. Below the boundary layer, the dust may be mixed with sea-salt aerosols. Further east, the thick layer of mixture of dust and aerosol from local emissions extending to 5 km are clearly visible over the Indo-Gangetic Plain and central India, extending from the foothills of the Himalayas (Figure 7, bottom panel).

The dust loading over northern India has been steadily building up since April 2008. Back trajectory calculations show that, during April 2008 (Figure 8(a)), most of the aerosols found at low level (850 hPa) at Kanpur, located near the boundary of the wet and dry zones in the Indo-Gangetic Plain, are transported from dust lifted to a high elevation (above 600-400 hPa) over the Afghan and Middle East deserts, with some from low-level transport over the Arabian Sea (Figure 8(b)). In June (Figure 8(c)), the transport is shifted to the northern Arabian Sea, and is found mostly at low levels (below 800 hPa), consistent with the establishment of the low-level monsoon south-westerlies over the Arabia Sea and north-western India. In July (Figure 8(d)), the trajectories still indicate some south-westerly inflow into Kanpur, but it is mostly confined to north-western India and Pakistan, where the trajectories indicate strong re-circulation defined by the local topography.

Based on previous modelling studies, we speculate that the above-normal dust aerosols over the Arabian Sea, north-western India and Pakistan absorb solar radiation and thereby heat the atmosphere. The dust aerosols reduce the incoming solar radiation at the surface by scattering and absorption, while longwave radiation from dust warms the surface and cools the atmosphere. Previous studies have shown that the aerosol-induced atmospheric heating is of the order of +20 to +25 W/m2 and the surface cooling is of comparable magnitude over the Arabian Sea and the Indian Ocean (Satheesh and Srinivasan, 2002; Podgorny and Ramanathan, 2001). We note that the cooling of the Arabian Sea and Indian Ocean already began in February/March 2008, before the dust loading increased. Hence, the cooling by aerosols is most likely a signal of a local effect superimposed on a large-scale ocean cooling that is already underway, due to other factors. The cooling of the Arabian Sea increases atmospheric stability, and reduces precipitation. However, dust aerosols, possibly in combination with local black carbon emissions, accumulated over northern India and in the foothills of the Himalayas in May-June, provided an elevated heat source. Figure 9(a) shows the temperature anomaly at the upper troposphere and the circulation at 300 hPa. The presence of the large-scale warm-core anticyclone and the strong easterly flow over northern India is remarkably similar to the characteristic circulation pattern associated with the EHP (see Figure 4). The circulation pattern at 850 hPa (Figure 9(b)) also resembles the EHP pattern, indicating a partial strengthening of the monsoon flow over north-western India and central India and increased moisture in the upper troposphere (600-300 hPa).

A further signature of the elevated heat pump effect can be seen in the north-south cross-section of meridional flow and temperature anomalies from the Tibetan Plateau to southern India (75-85°E). Above-normal warming is found over the Tibetan Plateau and cooling near the surface and the lower troposphere in the lowlands of the Indo-Gangetic Plain and central India. Enhanced rising motion is found over the southern slopes of the Tibetan Plateau and return sinking motions over southern India (Figure 9(c)). The meridional motion shows a bifurcation in the lower troposphere near 15-20°N, featuring sinking motion presumably associated with aerosol-induced cooling, and rising motion, which merges in the middle and upper troposphere with the ascending motion over the foothills of the Himalayas. The lower-level inflow brings increased moisture to the southern slopes of the Himalayas, increases the monsoon low-level westerlies over central India and upper level easterlies over the southern Tibetan Plateau (Figure 9(d)). Here, the meridional circulation is likely to be forced by convection initiated by atmospheric heating by dust and amplified by positive feedback from low-level moisture convergence and ascending air in the dust layer. While the above are not definitive confirmation of impacts of absorbing aerosols, the large-scale circulation features are consistent with the EHP effect, including the amplified warming of the upper troposphere over the Tibetan Plateau, cooling near the surface and an increase in monsoon flow with increased rainfall over northern India.

Conclusions

The results shown here suggest that aerosol and precipitation in the monsoon area and adjacent deserts are closely linked to the large-scale circulation and intertwined with the complex monsoon diabatic heating and dynamical processes during pre-monsoon and monsoon periods. The deserts provide not only the large-scale radiative forcing but also dust particles that are transported into monsoon regions, interfering with, and possibly altering, the evolution of monsoon circulation and rainfall. Because coupled atmosphere-ocean-land dynamical processes are the primary driver of the Asian monsoon, extreme care must be exercised in identifying aerosol-rainfall relationships that are truly due to aerosol physics and do not arise because both aerosol and rainfall are driven by the same large-scale dynamics. The 2008 Indian monsoon appears to have the telltale signs of impacts by absorbing aerosols but further studies must be conducted to determine the details of the aerosol forcing and response of the monsoon water cycle and relative roles compared to forcing from coupled atmosphere-ocean-land processes.

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Figure 1 — Global distribution of MODIS aerosol optical depth at 0.55 μm showing aerosol hotspots for (a) March-April-May; (b) June-July-August; (c) September-October-November; and (d) December-January-February 2005

Figure 2 — Latitude-time climatological mean cross-section of (a) aerosol optical depth of absorbing aerosols based on TOMS-AI; and (b) GPCP pentad rainfall

Figure 3 — AERONET observations of climatological (2001-2006) (a) aerosol optical depth and (b) Ångstrøm exponent at Kanpur, India. The solid curve indicates monthly mean rainfall in mm/month.

Figure 4 — Characteristic anomalous large-scale meteorological features associated with the elevated heat pump effect, based on regression of TOMS-AI during April-May with (a) tropospheric temperature and 300 hPa wind in May-June; and (b) rainfall and 850 hPa wind

Comment: Please reduce the size of figure further to show color bar.

Figure 5 — Anomaly patterns of (a) rainfall and 850 hPa wind (m s-1) and (b) sea-surface temperature (°C) during June-July 2008. The anomaly is defined as a deviation from an eight-year climatological mean (2000-2007).

Figure 6 — MODIS (a) visible image showing distributions of clouds and dust over the Indian subcontinent and adjacent oceans; (b) aerosol optical depth distribution.

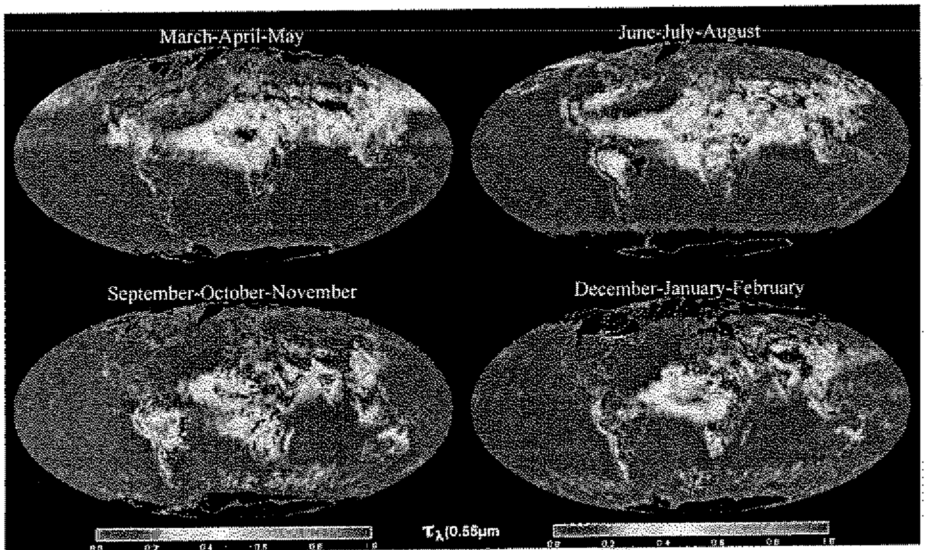
Figure 7 — Calipso backscatter showing depth and relative concentration of aerosol layer along meridional cross-section over (a) Pakistan and the Arabian Sea; (b) the Indo-Gangetic Plain and the Himalayas. Color scheme: Red=high, yellow=medium, green=low concentration, grey=clouds. Numbers on abscissa represent north-latitude and east-longitude.

Note from editor: this is the legend I would like to have expanded to explain the colour coding currently contained in the key which we can't use.

Figure 8 – Seven-day back trajectories showing possible sources and transport routes from adjacent deserts for air mass observed at 850hPa over Kanpur for 11days, starting from (a) 15Apr, (b) 15May, (c) 15June and (d) 15 July 2008. Height (in hPa) of tracer is shown in color.

Figure 9 – Observed spatial distributions of June 2008 anomalies for (a) mean tropospheric temperature ($^{\circ}$ C) and 300hPa winds(m s^{-1}); (b) mean 600-300 hPaspecific humidity, 850hPa winds and meridional vertical cross-sections over northern India and the Himalayas (75-85E); of (c) v-w streamline and temperature; and (d) zonal winds (contour) and specific humidity (shading).

Figure 1


March-April-May
June-July-August
September-October-November
December-January-February
τ_λ(0.55μm

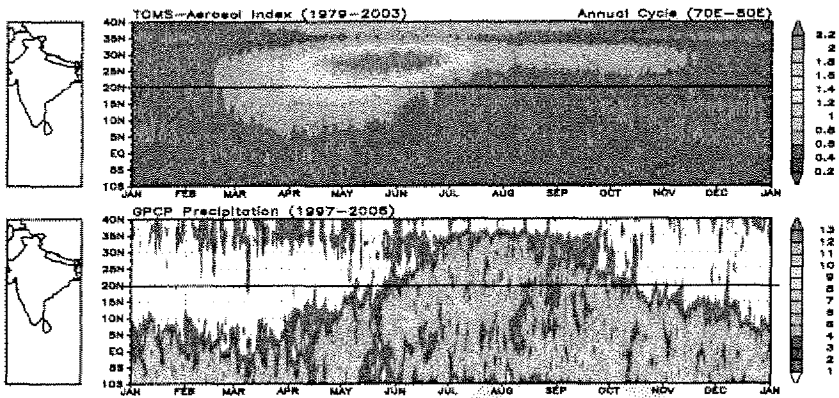


Figure 2

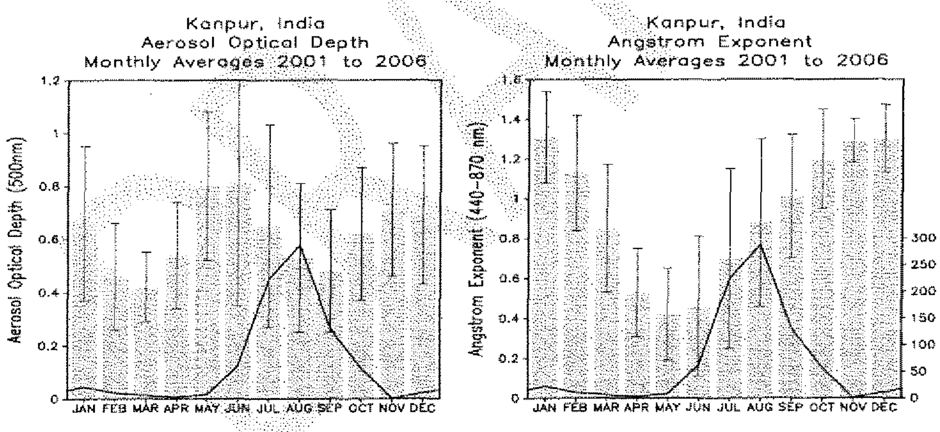


Figure 3

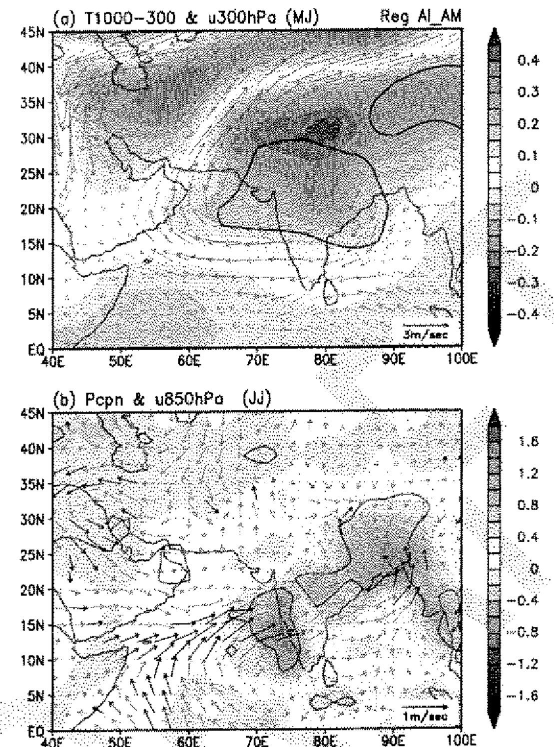


Figure 4