Observational relationships between aerosol and Asian monsoon rainfall, and circulation

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[1] Preliminary observational evidences are presented showing that the Indian subcontinent and surrounding regions are subject to heavy loading of absorbing aerosols, i.e., dust and black carbon, which possess spatial and temporal variability that are closely linked to those of the Asian monsoon water cycle. Consistent with the Elevated Heat Pump hypothesis, we find that increased loading of absorbing aerosols over the Indo-Gangetic Plain in the pre-monsoon season is associated with a) increased heating of the upper troposphere, with the formation of a warm-core upper level anticyclone over the Tibetan Plateau in April–May, b) an advance of the monsoon rainy season in northern India in May, and c) subsequent increased rainfall over the Indian subcontinent, and decreased rainfall over East Asia in June–July. **Citation:** Lau, K.-M., and K.-M. Kim (2006), Observational relationships between aerosol and Asian monsoon rainfall, and circulation, *Geophys. Res. Lett.*, *33*, L21810, doi:10.1029/2006GL027546.

1. Introduction

[2] Absorbing aerosols such as dust and black carbon are characterized by their ability to heat the atmosphere by absorbing solar radiation. In contrast, non-absorbing aerosols such as sulphate, scatter solar radiation and have relatively weak atmospheric heating effect. Yet, both absorbing and non-absorbing aerosols cause surface cooling by blocking solar radiation from reaching the earth surface. This has been referred to as the ‘‘solar dimming’’ effect [*Stanhill and Cohen*, 2001]. The dimming effect is global even though sources of aerosols are local, because of the abundance and diverse geographic locations of the sources, continuous emission, and long-range transport of aerosols [*Ginoux et al.*, 2001]. In Asian monsoon regions, the dimming effect is especially large due to heavy pollution, and frequent occurrence of dust storms [*Kaiser and Qian*, 2002; *Zhou et al.*, 1994]. Recent atmospheric general circulation model (GCM) experiments have demonstrated significant impacts of aerosols on the Asian monsoon. *Ramanathan et al.* [2005] showed that global dimming causes a long-term (multi-decadal) weakening of the South Asian monsoon by reducing the meridional surface temperature gradient between the Asian land mass and the Indian Ocean. However dimming is not the only mechanism that may affect the Asian monsoon water cycle. *Menon et al.* [2002] found that atmospheric heating induced by increasing loading of black carbon in the Asian monsoon region may be responsible for the long-term dry (wet) pattern over northern (southern) China. More recently, *Lau et al.* [2006] demonstrated that absorbing aerosols (dust and black carbon), may intensify the Indian monsoon through the so-called ‘‘Elevated-Heat-Pump’’ (EHP) effect. While these studies indicate plausible but different scenarios of aerosol impacts, they also suggest that aerosol effects on monsoon water cycle dynamics are extremely complex, and strongly dependent on aerosol distribution and characteristics, as well as on spatial and temporal scales.

[3] In this article, we present preliminary observations of relationship between absorbing aerosols and the monsoon rainfall and circulation that seem to be consistent with the basic premise of the ‘‘EHP’’ hypothesis (See discussion in Section 2). For aerosol data, we use the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI). The TOMS AI is a measure of the wavelength-dependent change in Rayleigh-scattered radiance from aerosol absorption and is especially suitable for detecting the presence of absorbing aerosols above high reflecting surfaces, such as desert, and snow/ice over land [*Hsu et al.*, 1999]. The AI data set is the only multi-year (longer than decade) continuous daily global record for absorbing aerosols, starting in November 1978 and, with the exception of a data gap from May 1993 to August 1996, to the present. For rainfall, we use the Global Precipitation Climatology Precipitation (GPCP) data [*Huffman et al.*, 1997], which combines surface rain gauge data as well as merged satellite estimates covering the period 1979–present. For wind, temperature and moisture, we use the NCEP/DOE-R2 reanalysis data [*Kanamitsu et al.*, 2002].

2. The ‘‘Elevated Heat Pump’’ Hypothesis

[4] To provide the theoretical background of this work, the basic features of the ‘‘Elevated Heat Pump (EHP)’’ hypothesis is briefly discussed here (for details, see *Lau et al.* [2006]). Dust aerosols transported from deserts (Pakistan/Afghanistan, Middle East, Sahara, and Taklamakan) adjacent to the Asian monsoon region accumulate to high elevation against the southern and northern slopes of the Tibetan Plateau (TP), during April through May. Because of the absorption of solar radiation by dust, the atmosphere over northern India and southern TP is heated relative to the region to the south, setting the stage for an anomalous large-scale circulation response. The atmosphere heating by dust over northern India is reinforced by the heavy loading of black carbon from industrial pollution over the Indo-Gangetic Basin (IGB) in northern India. The aerosol-induced heated air rises over the southern slope of the TP, and draws warm and moist low level inflow from the northern Indian Ocean. Over central India, the ‘‘solar dimming’’ effect

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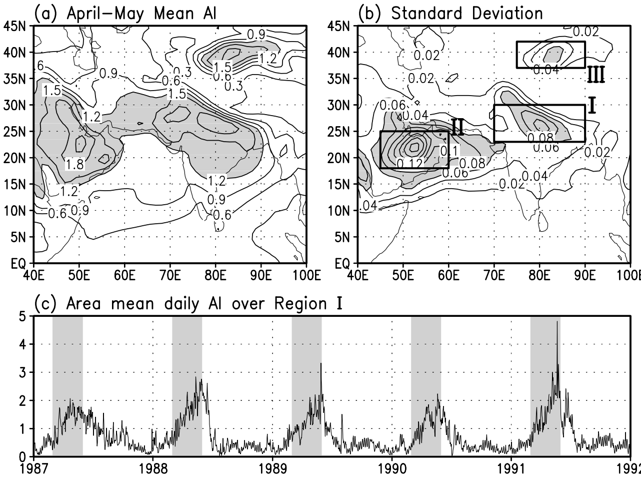

Figure 1. Climatological (1979–2001) distribution of absorbing aerosols over the Indian subcontinent and adjacent areas based on the TOMS Aerosol Index (AI) for April–May showing (a) the bi-monthly mean distribution, and (b) the monthly standard deviation, and (c) Area mean daily AI, and total rainfall (bar charts) over Region I. Key source regions are marked by numbered rectangles in Figure 1b. Shaded columns in Figure 1c mark the March–April–May season. AI is in normalized unit, and rainfall unit is in mm day^{-1}.

produces cooling at the surface relative to the lower troposphere, thus limiting convective instability, and keeping the pre-monsoon atmospheric moisture from rain out. As a result, more warm moist air is drawn into the rising air over northern India, causing a northward shift of the region of maximum convective instability, and spawning deep convection over the foothills of the Himalayas, and the southern portion of the Tibetan Plateau. The deep convection forces more ascent, and further heats the upper troposphere by releasing latent heat of condensation, initiating a feedback process that eventually results in an enhanced local Hadley circulation with rising motion (increased rainfall) over northern India, and sinking motion (reduced rainfall) over the northern Indian Ocean. In June and July, the aerosol loading is reduced due to wet scavenging, but the anomalous deep convection that has been set up in May continues to amplify and strengthens the monsoon meridional overturning through releasing heat of condensation. The EHP essentially holds that absorbing aerosols accelerate physical processes that contribute to the late spring and early summer heating of the troposphere over the TP, which is well known to have a strong impact on the evolution of the Asian monsoon [*Li and Yanai*, 1996].

3. Results

3.1. Variability of Absorbing Aerosols

[5] Figure 1a shows the April–May climatological (1979–1992) distribution of absorbing aerosols from TOMS AI over the greater Indian monsoon region. Three major source regions can be identified: (I) The IGB over northern India, including the Thar Desert (marked by the rectangular box in Figure 1b), (II) Saudi Arabia and Iran/Afghanistan/Pakistan deserts, and (III) Taklamakan desert over Western Asia. The interannual variability of the aerosol loading (Figure 1b) is found to be about 10–15% of the bimonthly mean, and is strongest over the Middle East (Region II), and significant over Region I and III. Much of the aerosols in Region I consist of coarse particles characteristic of dusts transported from Regions II through low level monsoon westerlies [*Miller et al.*, 2004]. The dusts in Region I are coated with black carbon produced from local emissions and become a strong absorber of solar radiation and an efficient source of atmospheric heating [*Singh et al.*, 2004]. Since aerosol emission, concentration, and transport are dependent on the large scale circulation and rainfall, the total dust loading in all three source regions undergo multi-scale variability associated with the monsoon climate system.

[6] Figure 1c shows the AI in Region I, superimposed on the monthly all-India rainfall for years 1987–1991. Most conspicuous is the strong seasonality of the aerosol loading, rising rapidly in boreal spring (March–April–May), peaking near the latter part of May, just before the start of the monsoon rainy season over India, and declining during the summer monsoon and the following seasons. The intraseasonal and interannual variability of aerosol amount are also strong. Since excessive monsoon rainfall is expected to wash out more aerosols, the AI variability may also indicate strength of the monsoon. For example, in 1988, removal of aerosol from the atmosphere is very rapid, with the aerosol reaching minimum levels soon after the excessive rain over all India in June. In contrast, in 1987, the removal of aerosols is relatively slow, consistent with a delayed and weakened monsoon. Previous studies have reported that by all measures, 1988 (1987) was a strong (weak) monsoon year (*Ji and Vernekar* [1997] and many others). This is also obvious from the all-India rainfall shown in Figure 1c. We note from Figure 1c that the build-up of absorbing aerosol is abnormally strong in the spring season leading up to the monsoon season in 1988, and mush less so in 1987. Similarly, in 1991, the all-India rainfall in May increased following a spike in the AI in early May and rain increased further in June following a second spike of AI in late May or early June. These observations are obviously anecdotal, but they do beg the question, whether a strong build up of aerosol in spring can be a contributing factor to an intensification of the monsoon. In the following, we use composite and regression analyses to further explore this question.

3.2. Co-Variability Of Aerosol and Monsoon Rainfall

[7] We have examined the co-variability of aerosol and monsoon rainfall by composite analysis for years of anomalously high, and low AI over Region I, defined by area-mean deviations exceeding one-standard deviation of the year-to-year variability. Four high-AI years (1980, 1985, 1988, 1991) and four low-AI years (1982, 1983, 1990, 1992) were selected. Because the main features for the low and high years were basically similar except for a change in their polarities, only the patterns for the high-AI composite are shown. Here we caution that because of the limited samples of extreme events, and the large interannual variability of the rainfall signal, no meaningful statistical tests can be carried out for the composites. Hence they should be regarded as a collection of case studies. The reliability of the patterns identified will be assessed by their similarity to those obtained from regression analysis where standard

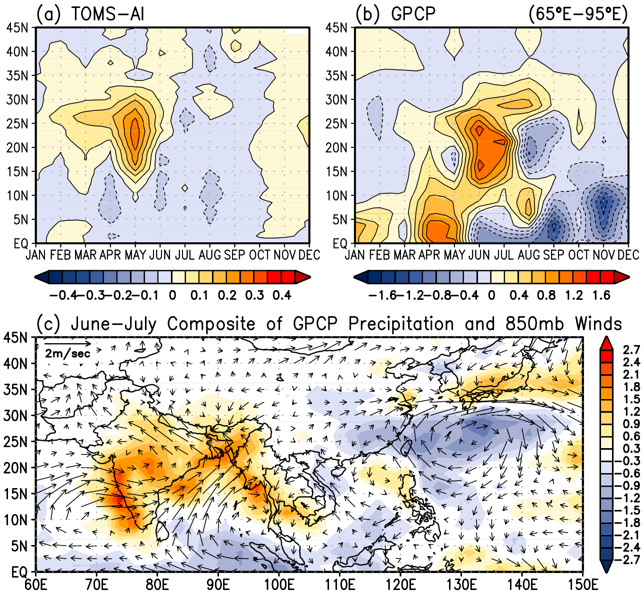

Figure 2. Time-latitude cross-sections showing composite seasonal evolution during year of high loading of absorbing aerosols of (a) the AI anomalies, and (b) the observed rainfall anomalies, and (c) composite of rainfall and 850 hPa wind pattern during years of high AI anomalies. Unit of rainfall is in mm day^{-1}, and wind is m sec^{-1}.

statistical significant test has been applied (See discussion in Section 3d). Figure 2 shows the composite of latitude-time cross sections of AI and rainfall over Region I for the four years of anomalously high AI in April–May. A slow build up of the aerosol beginning from early spring leading to a maximum in mid-May, followed by a rapid removal in June–July–August is noted (Figure 2a). At the time of the maximum build up of aerosol in May, rainfall is increased over northern India (20–28°N) but reduced over central India (15–20°N). The rainfall pattern indicates an advance of rainy season over northern India starting in May, followed by increased rainfall over all-India from June to July, and decreased rainfall in August. The aerosol build-up in May appears to be phase-locked to a northward migration of rainfall anomaly from equatorial oceanic region to the monsoon land region, and an intensification of the monsoon rainfall (15–20°N) in June–July, suggesting that aerosol forcing and response of the monsoon rainfall may be tied to dynamical mechanisms of northward migration of intraseasonal oscillations over the Indian subcontinent (*Lau and Waliser* [2005] and many others). Over the entire monsoon region (0–25°N), the rainy season seems to have advanced with more rain appears in the early, but less rain in the latter, part of the season.

[8] The induced rainfall increase spreads over the entire Indian subcontinent in June–July, with the most pronounced signal over the Western Ghats, and the land region around the Bay of Bengal (Figure 2c). The increased low level flow towards northern India is contributed mostly from the Bay of Bengal, followed by southeasterly flow along the foothills of the Himalayas. The strengthened Indian monsoon is also evident in the anomalous low level westerlies over the Indian subcontinent. Over East Asia and the East China Sea, a large-scale low-level anticyclonic anomaly is found, suggesting an intensification and a westward shift of the Western Pacific Subtropical High. As a result, rainfall over South China is reduced, with the *Mei-yu* rain belt pushed north of the Yangtze and eastward over Japan. This feature is also in agreement with that in model simulations of the EHP effect [see *Lau et al.*, 2006, Figure 6]. However, examination of individual events, and comparing between the high and low AI composites show large variability, indicating that the features over the subtropical western Pacific may be case dependent.

3.3. May–June Transition

[9] As discussed in the previous sections, the build up of absorbing aerosol over the IGB peaks in May, before the onset of the Indian monsoon which generally occurs in mid-June. When the monsoon is in full swing, aerosol effects tend to be diminished, due to wash-out. However, the build up of aerosol up to the onset time, may determine when and where the wash-out occurs. Hence the May-to-June transition is critical in determining the aerosol forcing and subsequent response and feedback of the monsoon water cycle. Figure 3 shows the composites for cross-section of temperature, streamline and rainfall along the longitudinal sector off the Indian subcontinent (65–95°E) for the high-AI events in May and June respectively. As evident in Figure 3a, a high concentration of absorbing aerosols over the IGB in May is associated with an enhanced meridional

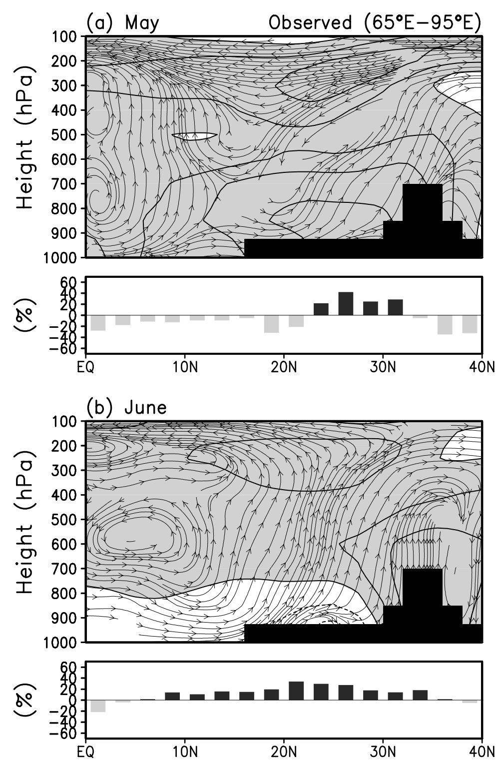

Figure 3. Composite wind, temperature and rainfall anomalies from NCEP/DOE-R2 reanalysis data over the Indian subcontinent sector for high TOMS AI in April–May, for (a) May and (b) June. Contour interval for temperature is 0.2 K. Positive anomalies are shaded. Rainfall anomalies shown in bottom panel are normalized with climatological mean.

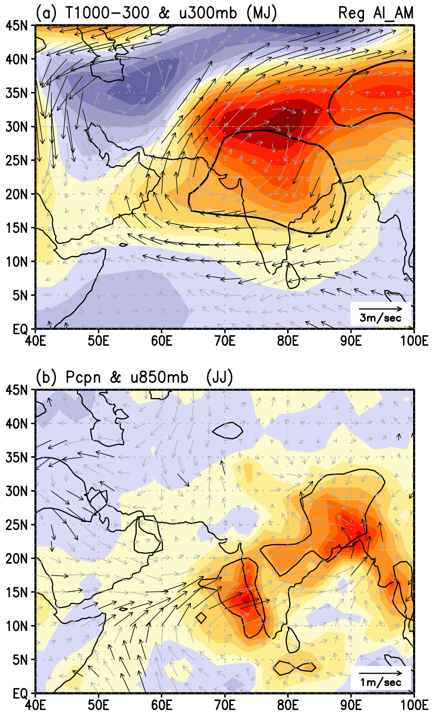

Figure 4. Regression of TOMS AI index over the IGB in April–May with (a) layer-averaged anomalous tropospheric temperature from surface to 300 hPa, and wind at 300 hPa in May–June and (b) anomalous wind at 850 hPa and rainfall in June–July. Regions exceeding 90% significances indicated by thick contours for temperature, and rainfall, and by thick arrows for wind. Contour intervals are 0.05° K for temperature, and 0.2 mm day^{-1} for rainfall.

circulation featuring a thermally direct circulation with mostly positive tropospheric temperature anomalies accompanied by low level onshore flow from the Indian Ocean, with rising motion over the southern slopes of the TP, and increased rainfall over northern India (Figure 3a, bottom panel). In June, the enhanced monsoon circulation is very pronounced, with well defined low-level onshore flow from the Indian Ocean, rising motion over the Indian subcontinent and southern TP, and divergence outflow in the upper troposphere. At this time the positive rainfall anomaly has expanded to the entire Indian subcontinent, and the lower troposphere over the subcontinent cools in association with the increased monsoon rain. These features signal an advance of the monsoon rainy season beginning in May, and intensification of the South Asia monsoon beginning in June, consistent with the EHP mechanism.

3.4. Regression Analysis

[10] To further quantify the relationship between pre-monsoon aerosol-induced tropospheric heating over the Tibetan Plateau and subsequent changes in the monsoon circulation, we have carried out a regression analysis including statistical significance test of monthly mean TOMS AI with temperature and wind from NCEP reanalysis. As mentioned in Section 3b, and confirmed by the regression analysis, the downstream features over East Asia and the East China Sea have large variability and low confidence, we therefore restrict the following analysis and discussion to significant features over the subcontinent of India and the Arabian Sea. Figure 4a shows the lagged regression pattern of layer-averaged (surface to 300 hPa) temperature and 300 hPa wind data for May–June on TOMS AI over the IGB (Region I in Figure 1b) for April–May over the entire domain. It is evident that a build up of aerosol in April–May over the IGB is associated with the development of a pronounced upper level tropospheric warm anomalies, coupled to an anomalous upper level large-scale anticyclone in May–June 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 to 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 northwestern India/Pakistan/region [*Hoskins and Rodwell*, 1995]. At 850 hPa, the regression patterns show general increase in rainfall associated with enhanced convection over India, with the most pronounced increase over the Bay of Bengal, and the western coastal region of India in June–July. At this time, anomalous westerlies are found spanning the Arabian Sea, across the Indian subcontinent, and ending up in a cyclonic circulation over the Bay of Bengal. 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; *Lau et al.*, 2000]. We also found signals, albeit somewhat weak and noisy, indicating an increase in upper tropopsheric water vapor over the Bay of Bengal and the northern Indian Ocean (not shown), consistent with increased "pumping" of moisture into the upper troposphere by the increased convection. Previous studies [e.g., *Gettelman et al.*, 2004] have found significant a relationship between upper tropospheric anticyclone and water vapor over the Tibetan Plateau during the summer monsoon, using satellite and aircraft data. The weak water vapor signal we found may be related to the poor quality of NCEP upper tropospheric water vapor. The linkage of aerosol heating and upper tropospheric water vapor is clearly a subject of future studies related to this work.

4. Concluding Remarks

[11] Our observation results are consistent with the key features of the EHP effect proposed by *Lau et al.* [2006] in showing that the anomalous high concentration of absorbing aerosol during the pre-monsoon season is associated with a) anomalous warming associated with the development of a large-scale anticyclone in the upper troposphere over the Tibetan Plateau in May and June, b) an advance of the monsoon season, with increased rainfall coming to northern India during May, and c) subsequent enhancement of the monsoon rain over India in June–July. Although the present analysis is focused on seasonal-to-interannual time scale, based on ongoing work, the relationships shown may also hold on decadal to climate change time scales reflecting

the increased loading of the black carbon from anthropogenic sources in the IGB. Our results will provide guidance and new avenues for exploring monsoon variability and predictability. Aerosol effects on the monsoon water cycle may be important in years when influence from other controlling factors (sea surface temperature, land surface processes, and internal dynamics) are relative small, or incoherent so that they cancel out. Additionally, aerosol may have amplifying or damping effects when interacting with these factors. Therefore aerosol-monsoon water relationships have to be explored in conjunction with SST, snow cover and other agents of change in future studies.

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