

# **Fingerprinting the impacts of aerosols on long-term trends of the Indian summer monsoon regional rainfall**

**by K.M. Lau and K. M. Kim**

## **Popular Summary**

The summer monsoon is the main source of fresh water supply to the vast population of Asia. Recently there have been a growing number of numerical modeling studies indicating significant impacts of dust and black carbon aerosols in altering the Asian summer monsoon rainfall distribution and large scale circulation. Yet studies of long-term rainfall data over Asia have so far shown no clear signals implicating impacts of aerosols. This is partly due to the diverse possible forcing of the monsoon climate, from sea surface temperature anomalies, to Eurasian snow cover to global warming, which tend to confound the aerosol impact signals. In this paper, we used a fingerprinting approach, based on a recent hypothesis of Asian monsoon system response to dust and black carbon forcing, to analyze Indian rainfall and related observations to detect signals of aerosol impacts. We find that increased absorbing aerosols in the Indo-Gangetic Plain in recent decades may have led to long-term warming of the upper troposphere over northern India and the Tibetan Plateau, enhanced rainfall in northern India and the Himalayas foothill regions in the early part (May-June) of the monsoon season, followed by diminished rainfall over central and southern Indian in the latter part (July-August) of the monsoon season. These signals, which are consistent with current theories of atmospheric heating and solar dimming by aerosol and induced cloudiness in modulating the Indian monsoon, would have been masked by conventional method of using all-India rainfall averaged over the entire monsoon season.

**Fingerprinting the impacts of aerosols on long-term trends of  
the Indian summer monsoon regional rainfall**

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## Abstract

In this paper, we present corroborative observational evidences from satellites, in-situ observations, and re-analysis data showing possible impacts of absorbing aerosols (black carbon and dust) on subseasonal and regional summer monsoon rainfall over India. We find that increased absorbing aerosols in the Indo-Gangetic Plain in recent decades may have led to long-term warming of the upper troposphere over northern India and the Tibetan Plateau, enhanced rainfall in northern India and the Himalayas foothill regions in the early part (May-June) of the monsoon season, followed by diminished rainfall over central and southern Indian in the latter part (July-August) of the monsoon season. These signals, which are consistent with current theories of atmospheric heating and solar dimming by aerosol and induced cloudiness in modulating the Indian monsoon, would have been masked by conventional method of using all-India rainfall averaged over the entire monsoon season.

## 1. Introduction

The detection and attribution of long-term trends in regional rainfall over the Indian subcontinent are essential for assessing the consequences of regional climate change, and societal impacts on approximately 1.2 billion people, about one-sixth of the world population. There is now a growing body of evidence, mostly from climate model experiments, suggesting that increased loading of absorbing aerosols (*i.e.*, black carbon, dust, and their mixture) over the India subcontinent may have strong impacts on monsoon rainfall and circulation [Menon *et al.*, 2002; Ramanathan *et al.*, 2005; Lau and Kim, 2006; Lau *et al.*, 2008, 2009; Meehl *et al.*, 2008; Bollasina *et al.*, 2008; Collier and Zhang, 2009; Krishnamurti *et al.*, 2009; Wang *et al.*, 2009]. While the long-term reduction in surface solar radiation associated with increasing aerosol loading due to industrial development and population growth in India, has been documented in many previous studies [Ramanathan *et al.*, 2005; Kumari *et al.*, 2007], results on long-term trends in Indian monsoon rainfall have been varied, depending on the length of the data period, and whether all-India or regional rainfall data were used [Ramanathan *et al.*, 2005; Joseph and Simon, 2005; Goswami *et al.*, 2006; IPCC, 2007; Kumar *et al.*, 2006]. More recently, Dash *et al.* (2009) has subdivided monsoon rainfall into different regions and seasons, and found different trends in different regions and different seasons. Most important, all previous studies of Indian rainfall trend are purely statistical in nature with no attempt at physical attributions. In this study, we use a fingerprinting approach to detect regional and subseasonal trends in Indian monsoon rainfall, with attribution to possible impacts of absorbing aerosols.

Aerosol may reduce Indian monsoon rainfall by cooling the surface via a reduction of solar radiation reaching the earth's surface – the so-called solar dimming effect (SDM), thereby

1 reducing the north-south thermal contrast, resulting in a spin-down of the local monsoon  
2 meridional circulation [Ramanathan *et al.*, 2005]. On the other hand, Lau *et al.* [2006, 2008]  
3 proposed the “elevated heat pump” (EHP) hypothesis which posits that accumulation of dust and  
4 black carbon over the Indo-Gangetic Plain and the foothills of the Himalayas during the pre-  
5 monsoon season, may induce enhanced warming in the middle and upper troposphere and  
6 subsequently lead to increased rainfall over northern India in late spring and early summer. As  
7 a secondary effect, the increased rainfall and associated changes in cloudiness and water cycle in  
8 the early monsoon may be consequential to reduced monsoon rain over all India in late summer.  
9 They argued that the EHP mechanism may be important to monsoon rainfall not only on  
10 seasonal-to-interannual timescales, but also on long-term (decadal and longer) timescales.  
11 Recently, observational studies have showed that a long-term spring warming trend in the upper  
12 troposphere over northwestern India and Pakistan are consistent with the EHP hypothesis  
13 [Gautam *et al.*, 2009; Prasad *et al.*, 2009]. However, the possible regional re-distribution of  
14 rainfall over the Indian subcontinent during different phases of the summer monsoon season and  
15 relationships to SDM and/or EHP effects are still unknown.

## 17 **2. Data and Approach**

18 The datasets used for this study include long-term visibility from New Delhi from the global  
19 surface summary of day data archived at the National Climate Data Center (NCDC), rainfall  
20 from the Global Precipitation Climatology Project (GPCP) for the period 1979-2007, and from  
21 the Indian regional rainfall data from Indian Institute of Tropical Meteorology (IITM), for the  
22 period 1955-2006. The GPCP rainfall is satellite measurement combined with selected rain  
23 gauge data over land (Huffman *et al.* 1997). Also used in the study is the Aerosol Index (AI)

1 from Total Ozone Mapping Spectrometer (TOMS), and from the Ozone Measuring Instrument  
2 (OMI) for absorbing aerosols. The AI is an index that detects the presence of UV-absorbing  
3 aerosols such as dust and soot. It is defined as the difference between the observations and  
4 model calculations of absorbing and non-absorbing spectral radiance ratios. . Positive values of  
5 Aerosol Index generally represent absorbing aerosols (dust and smoke) while small or negative  
6 values represent non-absorbing aerosols [Hsu *et al.*, 1999]. Also used are upper tropospheric  
7 temperature data from the Microwave Sounding Unit (MSU), specifically temperature profile  
8 from MSU channel TTS (Temperature Troposphere/Stratosphere) which corresponds to the  
9 average temperature between 5 to 15 km [Mears and Wentz, 2009] for 1987-2008. Winds from  
10 the National Center for Environmental Prediction (NCEP) reanalysis [Kanamitsu *et al.*, 2002]  
11 will be used to identify associated circulation patterns. These data are used collectively to  
12 establish the fingerprints of aerosol impacts on the Indian monsoon environment. To avoid  
13 confusion, here we define a trend as a monotonic increase or decrease within the data period as  
14 represented by the linear regression for the given data period. This definition leaves the  
15 possibility that a trend unveiled here could be a part of a multi-decadal variation much longer  
16 than the data record we use. The investigation of such long-term variation is outside the scope of  
17 this study.

### 19 **3. Results**

#### 20 *3.1 Increasing absorbing aerosols over the IGP*

21 Growing population and industrialization in recent decades have led to the rapid increase of  
22 atmospheric loading of black carbon over the Indo-Gangetic Plain (IGP) – a densely populated  
23 basin in northern India bounded by the Tibetan Plateau to the north and the Vindhya Range and

1 Chota Nagpur Plateau to the south. In addition, during the months of April through June, the  
2 IGP is buffeted by dusty air masses transported by winds from the Thar Desert in northwestern  
3 India and from deserts in Pakistan, Afghanistan, and as far as the Arabian Peninsula, and North  
4 Africa [Lau and Kim, 2006; Lau *et al.*, 2009]. During the monsoon period (Jun-July), dust  
5 particles continued to be transported into the Indo-Gangetic Plain from the Middle East deserts,  
6 across the Arabian Sea. Dust aerosols transported into the IGP may sweep up the finer black  
7 carbon aerosols, which form a coat over the larger dust particles, making them more absorbing  
8 [Eck *et al.*, 2008; Ramana *et al.*, 2005]. The steady increase in atmospheric loading of  
9 absorbing aerosols over the IGP can be seen in the apparent positive trend of AI over the region,  
10 from TOMS and from OMI (Fig. 1a). Because different instruments are used for different  
11 periods, the statistical significance of the AI trend cannot be established in its own right, and can  
12 only be ascertained based on consistency with independent datasets, as well as physically  
13 consistent with model predicted scenario [Lau *et al.*, 2006]. An alternate measure of  
14 atmospheric loading of aerosols is atmospheric visibility, which is directly a function of solar  
15 attenuation by aerosols free of interference from clouds, and is inversely proportional to the  
16 aerosol optical thickness, i.e., the higher the aerosol loading, the lower the visibility. Long-term  
17 record of visibility is generally available at meteorological stations as a part of the weather  
18 record. A recent study [Wang *et al.*, 2009a] has established that visibility is a useful proxy for  
19 long-term atmospheric aerosol loading both regionally and globally. As a supporting evidence of  
20 the increasing AI trend, the visibility for New Delhi in Fig. 1a (with axis reversed) also shows a  
21 highly significant trend with greater than 99% confidence level (c.l.) of reducing visibility (  
22 increasing aerosol loading), that matches well with TOMS AI trend. The long-term reduction in

visibility is associated with increased attenuation of solar radiation by aerosol, and can be considered as an indication of the SDM effect [Wang *et al.*, 2009a].

### 3.2 Large-scale trend patterns

To identify the spatial fingerprints of aerosol forcing on the large-scale environment, we have computed the linear regressions of the visibility over New Delhi, with a number of large-scale environmental fields over the Indian subcontinent and adjacent areas for the overlapping period. Because of the dominant trend in the visibility data, the regression patterns are mostly a reflection of the long-term trend signals. The upper tropospheric temperature in April-May (Fig. 1b) shows a pronounced warming anomaly over northern India and the Tibetan Plateau, with the center over the northwestern IGP, representing the large-scale initial set-up of the large scale environment associated with increasing aerosols in the IGP, similar to that reported in previous studies [Lau and Kim, 2006; Gautam *et al.*, 2009]. Associated with the warming is a large-scale anticyclone centered over northwestern India at 200 hPa (Fig. 1b), with anomalous easterlies over the Indian subcontinent and the Bay of Bengal. The warming and anticyclonic flow are dynamically consistent with heating initiated by solar absorption by deep layers of absorbing aerosols, and maintained by induced convective and circulation feedback [Lau *et al.*, 2006]. The regressed rainfall pattern shows increased rainfall in May-June over the Bay of Bengal and east coast of Myanmar (Fig. 1c). The increased rainfall extends northwestward along the foothills of the Himalayas over the IGP. A second positive precipitation anomaly is found over the Arabian Sea, off the coast of western India, extending northeastward into northwestern India and the Thar Desert. The rainfall anomalies are associated with increased low-level westerly flow from the Arabian Sea to the southern Bay of Bengal, with a clear northward flow towards the foothills of

1 the Himalayas over northern India. The upper and lower level flow indicated an anomalously  
2 strong easterly vertical wind shear. The large-scale upper tropospheric warming, circulation and  
3 rainfall features are consistent with those of an enhanced Indian monsoon [Webster and yang,  
4 1992; Lau *et al.*, 2000]. These features are also reminiscent of the observed characteristic  
5 patterns associated with the EHP based on interannual variability [Lau and Kim, 2006],  
6 suggesting that a similar mechanism may be at work on longer timescales. In subsequent months  
7 (July-August), the monsoon rainfall shows a general decline over most of the subcontinent,  
8 particularly over northeastern and southern India, with the upper tropospheric anticyclone  
9 disappearing and replacing by an upper-air cyclonic circulation over the Bay of Bengal,  
10 signaling a weakened Indian monsoon in late summer (see Fig. S1 in Supplementary Material  
11 and further discussion).

### 13 *3.3 Regional Indian Rainfall Trends*

14 For the regional India rainfall trend analysis, we use the IITM regional rainfall data. The IITM  
15 data subdivides all-India rainfall into five regions: northwest (NW), west central (WC), central  
16 northeast (CNE), northeast (NE), and peninsular (PN), as shown in Fig. 2a. The total rainfall  
17 increases from south (PN=666 mm) to north (CNE=975 mm). There is a strong contrast in  
18 northern India, with the NE, which is close to the Bay of Bengal, being the wettest (NE=1394  
19 mm), while the northwest region including the Thar Desert, the driest (NW=483 mm). From  
20 Fig. 2b, the time series of all-Indian-monsoon rainfall (AIMR), defined as the mean of all the  
21 regional rainfall averaged over the extended monsoon season JJAS, show large interannual  
22 variability with a slight negative trend of approximately -7.3 mm/decade. However as shown in  
23 Table 1, this trend is statistically insignificant (<90% c.I.).

1  
2 To explore the possible signals in regional rainfall associated with the EHP and SDM effects, the  
3 trends for monthly and bimonthly mean for May through August have been computed for each  
4 region. Since the trends for May and June are similar, as are those for July and Aug, only the  
5 bimonthly mean time series are shown in Fig. 3. The numerical values of the trends and  
6 corresponding statistical significance are summarized in Table 1. For all regions, and time of the  
7 season, the time series show large interannual variability relative to the trend. Trends are  
8 discernable in some, but not all regions. During May-June, all regions, except NE, show positive  
9 trends with NW and CNE which includes the northwest India and the northern central Himalayas  
10 foothills adjoining Nepal shows the most substantial increase ( $> 99\%$  c.l.). These regional  
11 rainfall anomalies are consistent with the positive GPCP rainfall regression pattern over the same  
12 region (see Fig. 1c). In contrast, during July-August negative trends are found in all regions,  
13 except the NE. Here, the most pronounced signals are found in PN ( $>99\%$  c.l.), and in WC  
14 ( $>90\%$  c.l.), which together cover more than half of the area of the subcontinent.

15  
16 Overall, the aforementioned large scale pattern, and regional rainfall signals are consistent with  
17 the EHP and SDM (including induced cloudiness) effects. During the early monsoon season,  
18 absorbing aerosols heat the atmosphere, and excite atmospheric feedback via the EHP, which  
19 beside inducing large-scale rainfall anomalies over South Asia, shifts rainfall to northwestern  
20 and northern India and the Himalaya foothills (Lau and Kim, 2006). This is consistent with the  
21 highly significant positive rainfall trend in NW and in CNE in May-June. While rainfall over  
22 the subcontinent may be heavy during the monsoon season, they occur intermittently, and often  
23 with prolonged break periods in relative small regions compared to the size of continent. As a

1 result, monsoon rain is not necessarily an efficient wash-out agent for atmospheric aerosols. Eck  
2 *et al.* [2008] showed that total aerosol optical depth in July-August over Kanpur which is located  
3 at the center of the IGP can be as high as 0.5-6, only about 30 % reduction from its peak values  
4 in May-June. The unabated loading of absorbing aerosols and increased cloudiness from the  
5 enhanced early monsoon may act in concert to amplify the SDM effect, causing the land surface  
6 to cool anomalously leading to diminished land evaporation and a reduction of rainfall in the late  
7 monsoon season [Meehl *et al.*, 2008; Bollasina *et al.*, 2008; Collier and Zhang, 2009]. The  
8 amplified SDM effect may be reflected in the significant negative trend in PN, and WC regions.  
9 The general pattern of reduced rainfall in late summer (July-August) in the IITM record is in  
10 overall agreement with the regression patterns of GPCP rainfall in July-August (see Fig. S1 in  
11 Supplementary Material).

12  
13 Notice that because of the above subtleties involved in possible aerosol impacts, the regional  
14 rainfall signals will be masked if one uses the AIMR for the extended seasonal means May  
15 through September (MJJAS) or June through September (JJAS), as done in many previous  
16 studies [*e.g.*, Goswami *et al.*, 2006; Chung and Ramanathan, 2006; Naidu *et al.*, 2009]. As  
17 shown in Table 1 (first column), both the MJJAS and the JJAS mean for AIMR (Table 1, first  
18 column) show a slight negative, but insignificant trend. This is because the impact of  
19 absorbing aerosols on rainfall in the early monsoon season (May-June) is masked by the relative  
20 larger magnitude in the negative rainfall anomalies in the peak monsoon season. Separating the  
21 AIMR into early and late monsoon does produce a significant positive (>95%) trend in May-  
22 June and a marginally significant (>90%) negative trend in July-August. As the preceding  
23 analyses suggest, the positive trend in AIMR is mainly contributed by the northwestern and

northern regions, while the negative trend by the central and southern regions. Also can be seen in Table 1 (last two rows), separating by regions but not by early and late season yields no significant rainfall trend. Hence, timing and regional spatial distribution are key to the detection of the aerosol impacts on rainfall over India. Previous studies using traditional seasonal (JJA) or extended seasonal (JJAS) means have indicated that the Indian monsoon has weakened in the last 50 years (Dash *et al.* 2009, Joseph and Simon 2005). As Table 1 indicates, these seasonal mean trends are not significant according to our calculations. Rather, the negative rainfall trends (weakening monsoon) identified by previous studies identified are likely due to rainfall in the late monsoon season (July-August), and confined to peninsular India and western central regions.

#### 4. Concluding remarks

Our results show that the AIMR has a pronounced long-term (45years) positive trend in May-June, with contribution mostly from the northern part of the subcontinent. A significant negative trend in AIMR is found in July-August, with the largest contribution from the central and southern part of the subcontinent. The extended seasonal means (JJAS or MJJAS) used in most previous studies of the Indian monsoon tend to mask the regional and intra-seasonal trend signals, which are essential in identifying the fingerprints of aerosol impacts. The positive rainfall trend in northwestern and northern central India in May-June, is consistent with the increasing trend in absorbing aerosol in the Indo-Gangetic Plain, and the EHP large-scale fingerprints of a warmer upper troposphere, an anomalous anticyclonic circulation over northwestern Indian and the Tibetan Plateau, and a strong easterly vertical shear across the Indian subcontinent, all signaling a strengthened Indian monsoon in May-June. The increased cloudiness from the enhanced rain in the early monsoon season may amplify the SDM effect, and

1 therefore consequential to the reduced monsoon rainfall in July and August. The above signals  
2 are masked by the use of conventional seasonal mean, and all-India monsoon rainfall. We note  
3 also that since aerosol impacts on monsoon rainfall are strongly dependent not only on the  
4 emission sources, but also on transport and deposition by the large-scale circulation, it is likely  
5 that the regional Indian rainfall trends attributed to aerosol effects discussed here may also be  
6 influenced by interactions of anthropogenic forcing and variability stemming from changes in  
7 large-scale circulation from climate change.

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#### Figure Captions

Figure 1 a) Time series of Aerosol Index from TOMS, EPTOMS, and OMI averaged over the Indo-Gangetic Plain [70-90E, 25-35N], in increasing relative unit in the right ordinate and visibility (solid black line) over New Delhi in decreasing relative units in the left ordinate, from 1979-2008. Missing data in AI are indicated by symbol 'X'. Spatial patterns of linear regressions of inverse visibility at New Delhi with b) MSU upper tropospheric temperature ( $^{\circ}\text{C}$ ) and 200hPa wind, and c) GPCP rainfall (mm/day), and 850 hPa winds. Different size green dots indicate different levels of statistical significance in the temperature and rainfall fields. Bold arrows indicate wind signal exceeding the 90% significance level.

Figure 2 a) Geographic distribution of the five rainfall regions and annual rainfall total from the IITM rainfall data, and b) time series of all-India rainfall averaged over June-July-August-September. Solid red line indicates linear regression line.

Figure 3 Time series and linear regression lines (dotted) of each of the five regional rainfall over India for a) May-June (left panels), and for b) July-August (right panels). Units are in mm/day.

Table 1. Linear trend of regional precipitation over India in various seasons for 1961-2006. Bold face types indicate statistically significant trend exceeding 90% level. (\*) and (\*\*) indicate significant trends at 95% and 99% level, respectively.

Season	Precipitation Trend (mm/decade)					
	AIMR	Northwest (NW)	West Central (WC)	Central North-East (CNE)	Northeast (NE)	Peninsular (PN)
May-June	<b>9.8*</b>	<b>11.6**</b>	8.2	<b>19.5**</b>	-4.3	6.6
July-August	<b>-9.6</b>	-7.3	<b>-13.7</b>	-4.0	2.4	<b>-18.2**</b>
MJJAS	-4.0	-2.9	-15.0	13.0	11.5	-13.0
JJAS	-7.3	-5.2	-15.7	5.9	1.5	-14.3

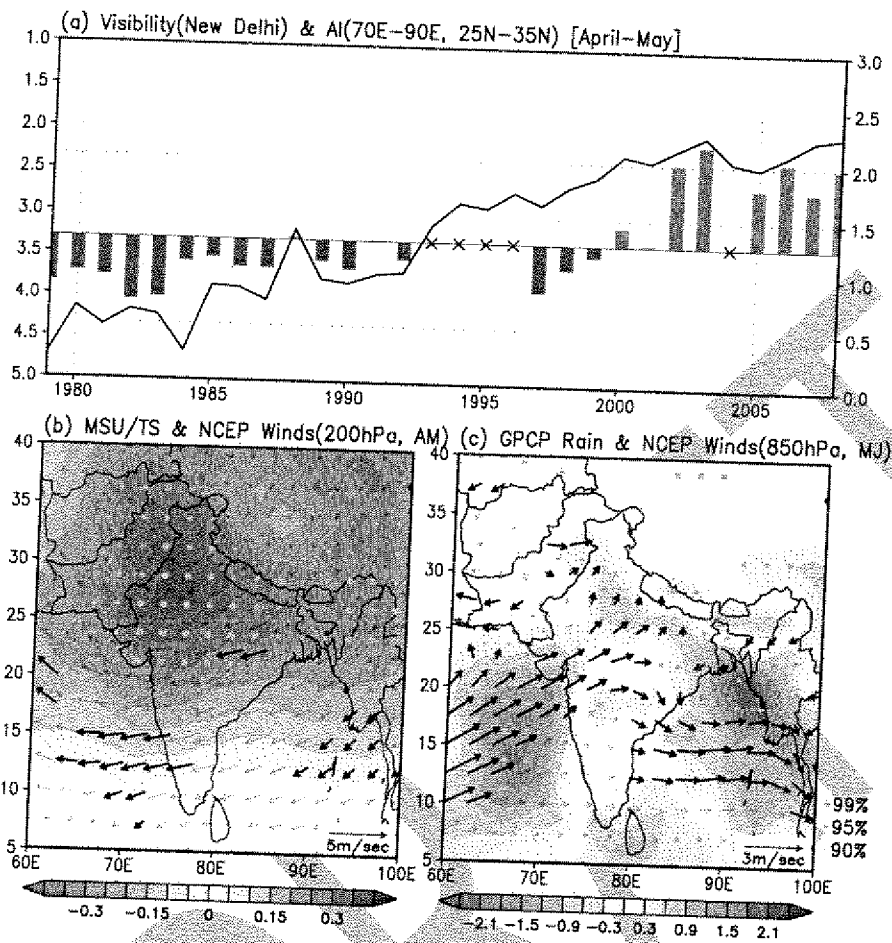


Figure 1

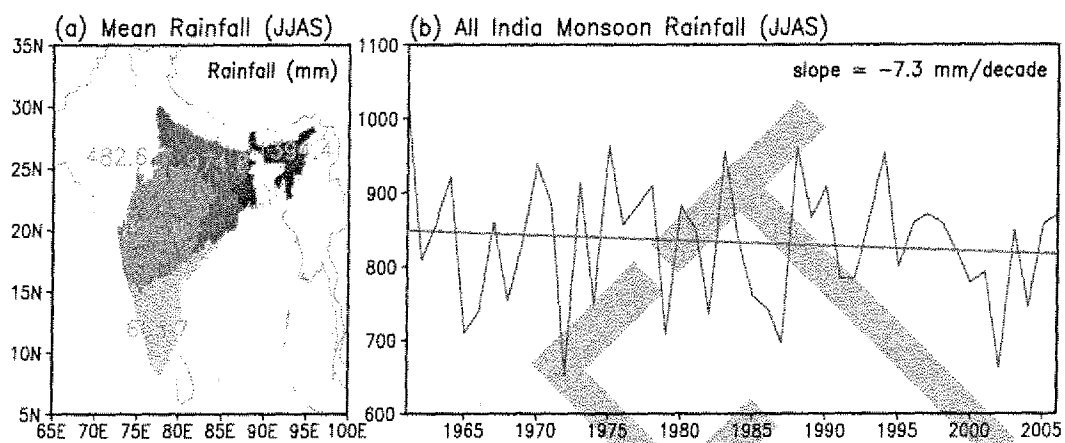


Figure 2

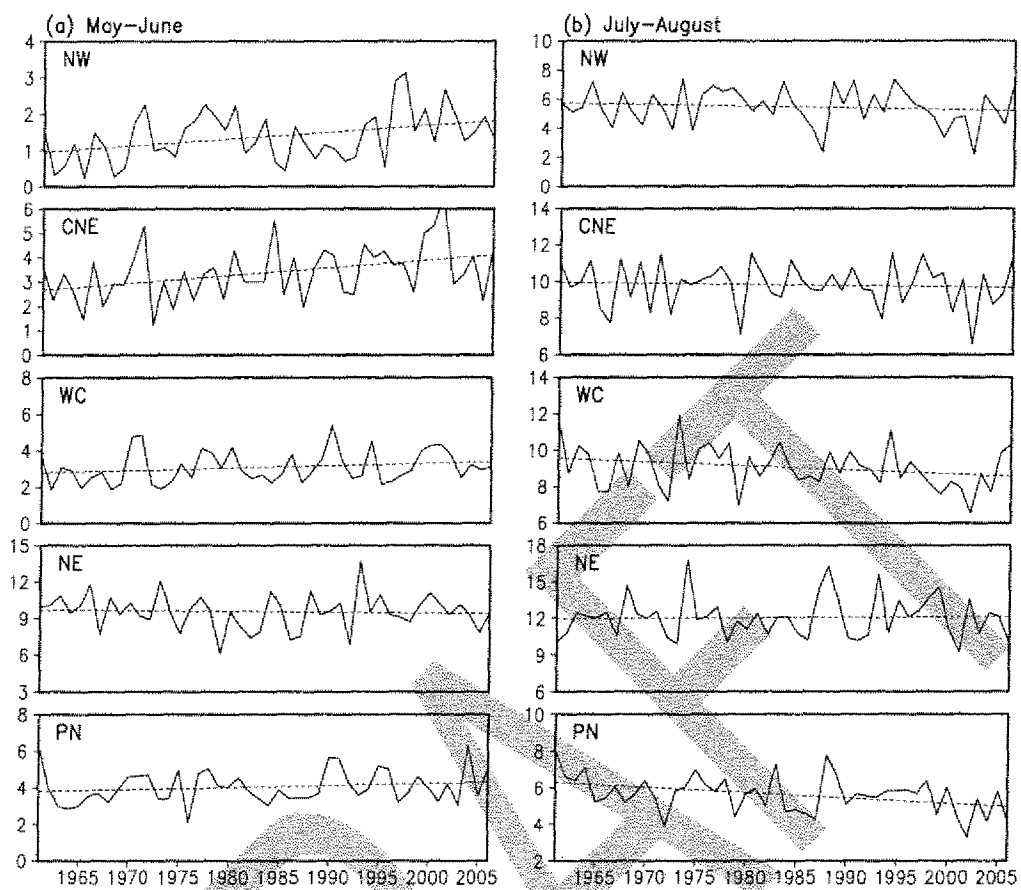


Figure 3

## Supplementary Material

In addition to the key pre-conditioning and feedback associated with the build-up of absorbing aerosols in May-June, the EHP hypothesis also argued that the increased monsoon rainfall and circulation induced by absorbing aerosols in late spring and early summer, may be conducive to a reduction of the monsoon rainfall in the peak monsoon period (July-August) because of increased SDM effect due the increased cloudiness, and changes in the water cycle associated with the strengthening of the early monsoon. Figure S1b shows that in association with an increase aerosol loading (reduction in visibility) over the Indo-Gangetic Plain in April-May, there is an overall reduction in rainfall, most pronounced over the northeastern, northern Bay of Bengal, and southwestern part of the subcontinent. The large-scale upper level anticyclone in April-May (see Fig. 1b) has largely disintegrated, and replaced by an upper level cyclone over the Bay of Bengal, and mostly upper level westerly flow over southern India (Fig. S1a), consistent with the rainfall reduction. It is important to note that because of the dominance of latent heating in the peak monsoon period, the changes in July-August are likely to stem from a subsequent dynamical adjustment of the coupled atmosphere-land-ocean system to the initial aerosol induced responses, and may be subject to additional remote forcing such as sea surface temperature and heat source and sinks outside the domain. This may explain the far less organized rainfall pattern and the upper level and lower level wind circulation compared to those in May-June (See Fig. 1c).

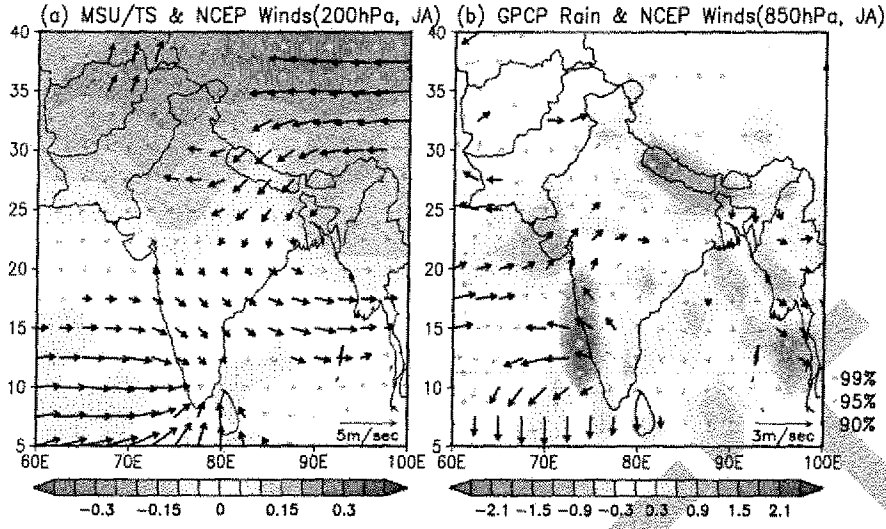


Figure S1 Patterns of linear regression of OMI AI (April-May) with a) MSU upper troposphere temperature and 200 hPa winds for July-August, and b) GPCP rainfall and 850hPa winds for July-August. Different size green dots represent different levels of statistical significance. Bold arrows represent wind anomalies exceeding the 90% significance level.