"Elevated heat pump" hypothesis for the aerosol-monsoon hydroclimate link: "Grounded" in observations?

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[1] The viability of the elevated heat pump hypothesis, a mechanism proposed by Lau and Kim (2006) for absorbing aerosols' impact on South Asian summer monsoon hydroclimate, is assessed from a careful review of these authors' own analysis and others since then. The lack of appreciation of the spatial distribution of the aerosol-related precipitation signal over the Indian subcontinent, its east–west asymmetric structure, in particular, apparently led to the development of this hypothesis. Its key elements have little observational support, and the hypothesis is thus deemed untenable. Quite telling is the observation that local precipitation signal over the core aerosol region is negative, i.e., increased loadings are linked with suppressed precipitation and not more as claimed by the hypothesis. Finally, motivated by the need to address causality, the analysis of contemporaneous aerosol-monsoon links by Bollasina et al. (2008) is extended by examining the structure of hydroclimate lagged regressions on aerosols. It is shown that findings obtained from contemporaneous analysis can be safely interpreted as representing the impact of aerosols on precipitation, not vice versa. The possibility that both are shaped by a slowly evolving, large-scale circulation pattern cannot however be ruled out.

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1. Introduction

[2] One of the areas of the world with high aerosol concentration is South Asia. The contribution of absorbing aerosols to the long-term change in summertime rainfall over the Indian subcontinent has been investigated by *Chung et al.* [2002], *Menon et al.* [2002], *Ramanathan et al.* [2005], *Chung and Ramanathan* [2006], *Lau et al.* [2006], *Meehl et al.* [2008], *Randles and Ramaswamy* [2008], *Collier and Zhang* [2009], and *Sud et al.* [2009]. The interannual variability of aerosol concentration and related summer monsoon rainfall variations has also been analyzed (e.g., *Lau and Kim* [2006] (hereafter LK06) and *Bollasina et al.* [2008] (hereafter BNL08)).

[3] Atmospheric general circulation models and observational analyses have both been deployed to understand aerosol-monsoon interaction. Modeling studies are insightful because of their ability to associate cause and effect in context of modeling experiments, but some caution is necessary as model simulations are known to have significant biases in the climatological distribution and evolution of monsoon precipitation [e.g., *Dai*, 2006; *Bollasina and Nigam*, 2008]. Furthermore, aerosol effects are only partially represented in many models [e.g., *Kiehl*, 2007], often with large uncertainties [e.g., *Kinne et al.*, 2006]. It is expected that aerosols-clouds-precipitation processes and interactions will be greatly improved in the next generation of climate models [e.g., *Ghan and Schwartz*, 2007]. Observational studies, on the other hand, analyze a realistic system but characterization of the pertinent process sequence remains challenging on account of the myriad of feedbacks in the climate system. The influence of large-scale circulation on both aerosol distribution and regional hydroclimate also confounds efforts to elucidate the aerosol impact mechanisms [*Bollasina and Nigam*, 2009].

[4] Several pathways have nonetheless been proposed for aerosol's influence on monsoon hydroclimate:

[5] 1. Anomalous heating of air due to shortwave absorption by black carbon aerosols, which enhances regional ascending motions and thus precipitation in atmospheric general circulation models [*Menon et al.*, 2002; *Randles and Ramaswamy*, 2008].

[6] 2. Modulation of the summertime meridional sea surface temperature (SST) gradient in the Indian Ocean from reduced incidence of downward shortwave radiation in the northern basin in the preceding winter/spring. *Ramanathan et al.* [2005] and *Chung and Ramanathan* [2006] showed that aerosol-induced weakening of the SST gradient (leading to weaker summer monsoon rainfall) more than offsets the increase in summertime rainfall resulting from the "heating of air" effect in a coupled ocean-atmosphere model, leading to a net decrease in summer monsoon rainfall in the latter half of the 20th century. The study of *Meehl et al.* [2008], also with a coupled model but with a more comprehensive treatment of aerosol-radiation interaction, supports the findings by

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Ramanathan et al. on the effect of black carbon aerosols on the Indian summer monsoon rainfall.

[7] 3. Modulation of the meridional tropospheric temperature gradient from anomalous accumulation of absorbing aerosols against the southern slopes of the Himalayas in the pre-monsoon period. The elevated diabatic heating anomaly from aerosol absorption of shortwave radiation ("elevated heat pump," hereafter EHP; *Lau et al.* [2006]; LK06) over the southern slopes of the Tibetan plateau in April–May reinforces the climatological meridional temperature gradient and leads to monsoon intensification in June–July in this scheme.

[8] 4. Anomalous heating of the land surface by aerosol-induced reduction in cloudiness (the "semidirect" effect) and the attendant increase in downward surface shortwave radiation. Stronger heating of the land surface in May generates greater ocean-atmosphere contrast and thus more monsoon rainfall in June in this posited mechanism [*Bollasina et al.*, 2008]. The importance and potential impacts of aerosol-land-atmosphere interactions on the Indian monsoon have been summarized by *Niyogi et al.* [2007] and *Pielke et al.* [2007].

[9] It is interesting that none of the mechanisms except the last one consider aerosol effects on cloudiness (other than those due to attendant heating and circulation changes). The first three pathways are primarily rooted in the aerosol's direct effect on shortwave radiation: tropospheric absorption and surface dimming over both land and ocean. The impact on cloudiness can, perhaps, be neglected in winter when the central and northern Indian subcontinent is relatively cloud-free but not in late spring and summer when cloudiness tracks monsoon development. Climate models are still ill equipped in dealing with the complexities of aerosol-cloud interaction (reckoned important in summer) and can thus provide limited insight on the net effect of aerosols on summer monsoon hydroclimate and the related impact mechanisms. The indirect effect is not well understood and thus inadequately represented. As for the semidirect effect, it is likely under-represented due to uncertainties in aerosol distribution and optical properties and potential misrepresentation of related cloud responses.

[10] A key objective of the present study is to examine the viability of the interesting EHP mechanism. LK06 investigated the link between absorbing aerosols and summer monsoon rainfall and circulation in an observational analysis, targeting the effects of the pre-monsoon aerosol loading over the Indo-Gangetic Basin (IGB). Using composite and regression analysis keyed to the Total Ozone Mapping Spectrometer (TOMS) aerosol index (AI) averaged over the IGB, the authors posit that piling up of absorbing aerosols (i.e., dust and black carbon) along the Himalayan foothills and southern slopes of the Tibetan Plateau during April–May leads to diabatic heating of the lower to midtroposphere from aerosol absorption of solar radiation. The heated air over the southern slopes of the Tibetan Plateau rises, drawing warm and moist low-level inflow from the northern Indian Ocean. Aerosol extinction (due to absorption and scattering) of solar radiation, the "solar dimming" effect, is moreover reckoned to produce surface cooling over central India, with the resulting increased stability leading to rainfall suppression there. A large-scale response, including a regional meridional overturning circulation with rising motion (and increased rainfall) in the Himalayan foothills and northern India and sinking motion over the northern Indian Ocean, is then envisioned (see section 2 in LK06 for more discussion). The EHP hypothesis has recently motivated a NASA field campaign involving ground and remote observations in the IGB and Himalayan-Tibetan regions.

[11] A careful review of LK06 and other analyses since then [BNL08; *Gautam et al.*, 2009] however reveals that the EHP hypothesis is not grounded in observations. The study of BNL08, observationally based on and similar to that of LK06 in many respects, indicates in particular that the EHP mechanism is rooted in the expansive zonal averaging employed in the study by LK06. Such overly wide averaging is without basis because the western and eastern sectors of the averaged region have oppositely signed hydroclimate signals, leading to spurious collocation of aerosol loading (concentrated in the western sector) and the dominating hydroclimate signal (of the eastern sector). The EHP hypothesis has other difficulties as well, all discussed below.

[12] Another objective of this study is to extend the analysis of aerosol-monsoon links by BNL08 that emphasized the aerosol semidirect effect and attendant heating of the land surface. The EHP hypothesis, in contrast, highlights the direct effect of aerosols and related cooling (heating) of the land surface (atmosphere). The contemporaneous analysis by BNL08 for late spring is complemented here by displaying the aerosol-monsoon links with aerosol leading, which provide further insights into cause and effect, albeit cursorily in view of the monthly analysis resolution. The article is organized as follows: section 2 articulates the perceived difficulties with the EHP hypothesis vis-à-vis observations, whereas section 3 presents key results from the analysis of aerosol-monsoon links. Concluding remarks follow in section 4.

2. Difficulties With the EHP Hypothesis

[13] To critique the observational basis for the EHP hypothesis, we first reproduced LK06 analysis before assessing its sensitivity to some attributes. The EHP hypothesis lacks observational support in our opinion for the following reasons:

[14] 1. LK06, unfortunately, did not show the IGB AI-related precipitation footprint in May when aerosol concentration is at its peak. The lack of appreciation of the precipitation distribution, primarily zonal, with decreased rainfall over western-central India (where aerosol is concentrated) and increased rainfall over northern Burma and the far eastern Indian state of Assam (Figure 1a) (Figure 1 shows the May regressions/correlations on the May IGB AI. The May index was chosen for consistency with the study by BNL08, but one could have as well chosen the April–May average IGB AI to be fully consistent with that of LK06. The May precipitation regressions on the latter are indistinguishable from those in Figure 1a.), must have allowed LK06 to entertain EHP-type notions, we surmise. Had the authors realized that the IGB AI rainfall regressions in the aerosol-loading region that includes Himalayan foothills (box I in Figure 1b in the study of LK06; green-sided rectangle in Figure 1a in this study) are weak and that too of opposite sign (i.e., rainfall reduction) in May, they may have shied away from proposing the EHP hypothesis. (The EHP signal should be manifest in the monthly average as the contributing pro-

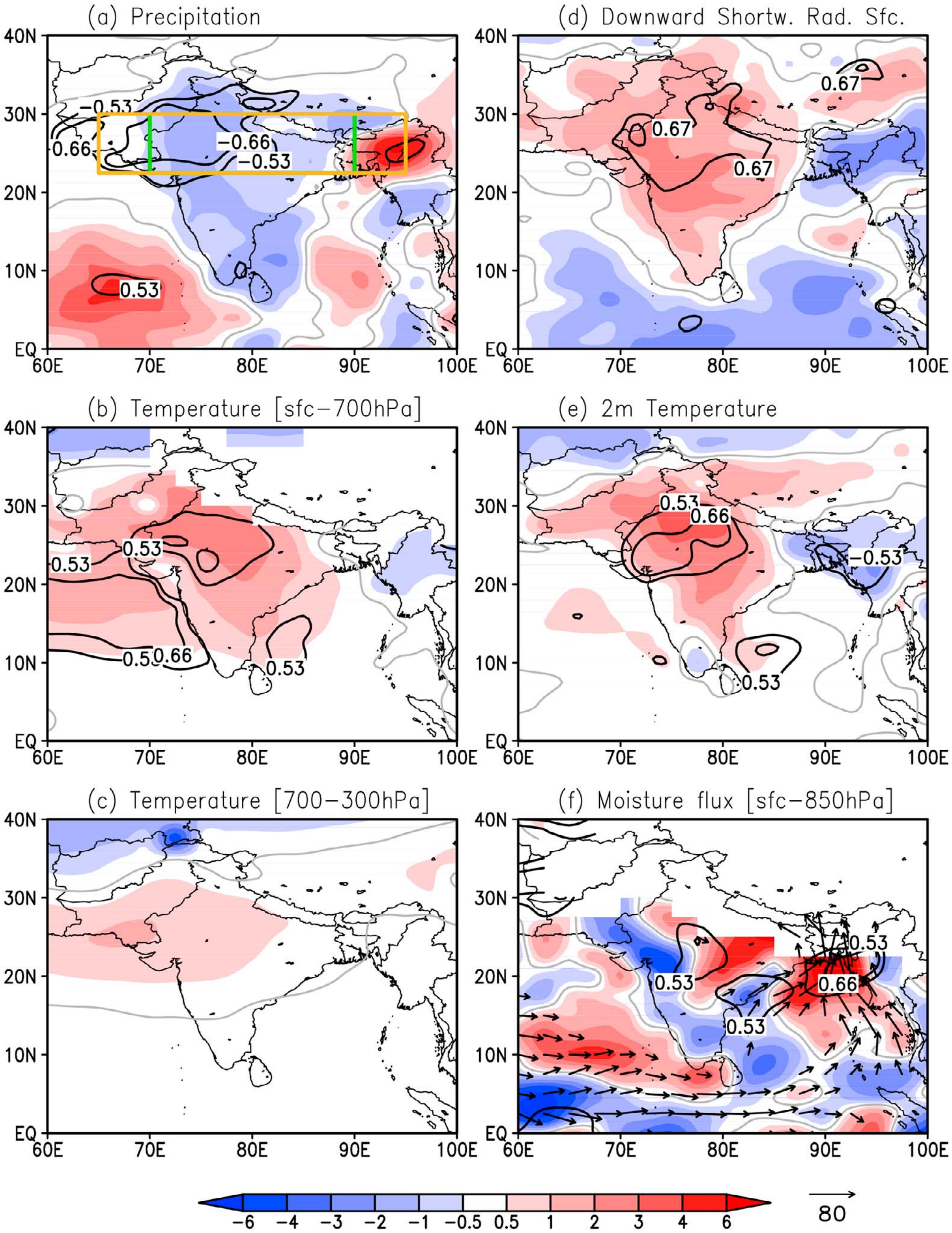

Figure 1. May contemporaneous regressions (shaded, with the gray line indicating the zero contour) and correlations (black contours) on the TOMS AI time series averaged over the area (70°E–90°E, 22.5°N–30°N, green rectangle in Figure 1a; the box I domain in the study by LK06) of (a) precipitation (mm d^{-1}, from the Global Precipitation Climatology Project); (b) surface–700 hPa average temperature (°C, from the European Centre for Medium-Range Weather Forecasts reanalysis, ERA-40); (c) 700–300 hPa average temperature (°C, from ERA-40); (d) downward shortwave radiation at the surface (0.1 × W m^{-2}, from the ISCCP flux data set); (e) 2-m air temperature (°C, from ERA-40); and (f) moisture flux (Kg m^{-1} s^{-1}; vectors, values below 20 Kg m^{-1} s^{-1} have been masked out) and its convergence (Kg m^{-2} s^{-1}; shaded, positive values representing convergence) mass weighted and vertically integrated between the surface and 850 hPa. The time series were not detrended before computing the correlations, to closely compare with maps in the study by LK06. Data are for the period 1979–1992, except radiation, which is only available from 1984. Correlations are only shown in terms of the 95% and 99% significance levels (±0.53 (±0.67) and ±0.66 (±0.79), respectively). Inconsistency in the AI time series after 1992 restricted the correlations to the 14 year period considered here. Green and yellow rectangles in Figure 1a denote the regions (70°E–90°E, 22.5°N–30°N and 65°E–95°E, 22.5°N–30°N, respectively) used by LK06 to define the AI time series (their Figure 1c) and for displaying cross sections of composite anomalies (their Figures 2b and 3), respectively.

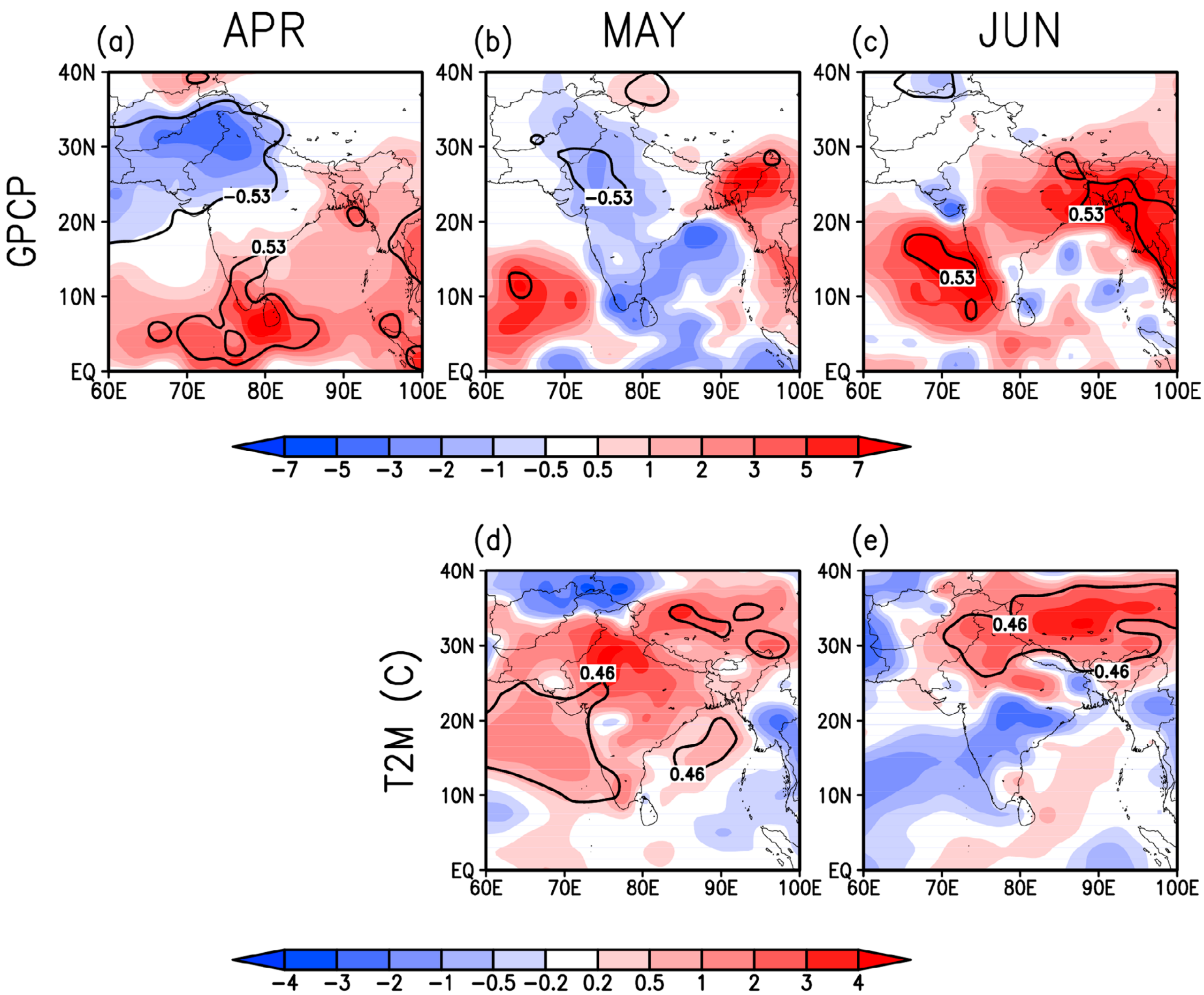

Figure 2. (top) GPCP precipitation (mm d^{-1}) regressed on the TOMS April AI time series (averaged over the same points highlighted in Figure 1a in the study by BNL08) for (a) April, (b) May, and (c) June. The ±0.53 contour line shows the 95% confidence level. (bottom) 2-m air temperature (T2M, °C; data from ERA-40) regressed on the April AI time series for (d) May and (e) June (the ±0.46 contour line show the 90% confidence level). Data are for the period 1979–1992. Both data were detrended before computing the regressions.

cesses operate on shorter time scales.) The May rainfall signal of a more geographically focused AI time series (defined by solid dots in Figure 1 in the study by BNL08) is also very weak in the Himalayan foothills and northeastern India, with rainfall suppression again indicated (Figure 3 in the study by BNL08).

[15] 2. A figure that plays a key role in the formulation of the EHP hypothesis is Figure 2 in the study by LK06: Figures 2a and 2b depict the monthly evolution of sector-averaged aerosol and precipitation anomalies as a function of latitude. The anomalies are from composites keyed to the IGB AI. On the basis of this figure, misleading for reasons discussed next, LK06 (section 3.2) conclude that “At the time of the maximum build up of aerosol in May, rainfall is increased over northern India (20°N–28°N) but reduced over central India (15°N–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.” This incorrectly drawn conclusion is the backbone of the EHP hypothesis. Figure 2b, in particular, is misleading in context of this hypothesis because an overly wide longitudinal sector average (65°E–95°E) is displayed (the sector is marked in yellow in Figure 1a). Such extensive averaging is misleading as it suggests spatial collocation of aerosol loading and enhanced precipitation, when, in fact, there is little overlap among them: Precipitation is enhanced in the very narrow sector to the far right (90°E–95°E) and not at all in region I (70°E–90°E); see Figure 1a. A similar reasoning can be applied to Figure 3a in the study by LK06: Enhanced meridional motion and subsequent upward velocity are actually observed only eastward of 90°E (Figure 1f of the present work), which is a very narrow band compared to the range of longitudes included in the average. Figures 2b and 3a in LK06 thus do not provide observational evidence for the EHP hypothesis, contrary to claims. Examination of the IGB AI-related May precipitation anomaly

(Figure 1a) shows clearly that rainfall does not increase over Northern India (where aerosol loadings are largest); it is, in fact, suppressed. LK06 obtain a precipitation increase only because their overly wide averaging masks the suppressed precipitation over North India favoring the large precipitation increase farther to the east.

[16] 3. The EHP hypothesis is predicated on the piling up of absorbing aerosols against the southern slopes of the Himalayas and over southern Tibetan plateau. The core of the May aerosol standard deviation is however located not over elevated terrain but well south of the Himalayan range (Figure 1b in the study by BNL08 and Figure 1b in that of LK06).

[17] 4. An important element of the EHP hypothesis is the diabatic heating of the troposphere above elevated terrain. Citing *Gautam et al.* [2009], "According to the EHP hypothesis, aerosol forcing resulting from absorption of solar radiation due to enhanced build-up of dust aerosols in May, mixed with soot from industrial/urban pollution over the IGP, may cause strong convection and updrafts in the middle-upper troposphere resulting in positive tropospheric temperature anomalies northward, most pronounced over the southern slopes of the TP and the Himalayas [*Lau et al.*, 2006; *Lau and Kim*, 2006]." The AI-related tropospheric (1000–300 hPa layer average) warming (Figure 4a in the study by LK06) is, of course, not evidence of this (although it is taken as such in the study by *Gautam et al.* [2009]) as the displayed warming signal lags AI by 1 month in the LK06 figure. The IGB-AI related contemporaneous (May) warming in the lower (surface–700 hPa) and upper troposphere (700–300 hPa) is shown in Figures 1b and 1c, respectively. Correlation analysis shows only the former to be significant. In neither case, however, positive temperature anomalies are found northward of the core aerosol loading region and certainly not above the 700 hPa level. As discussed later, the lower tropospheric warming arises from the warming of the land surface, as evident from the vertical structure of the AI-related temperature signal (Figure 7 in the study by BNL08).

[18] 5. The EHP hypothesis posits that rainfall enhancement is confined to the foothill region because aerosol-induced "solar dimming" leads to the cooling of the Indo-Gangetic Plains, limiting convective instability. There is no evidence for this in observations. To the contrary, the AI-related downward shortwave radiation anomaly (Figure 1d) (The downward surface shortwave radiation is from the International Satellite Cloud Climatology Project (ISCCP) FD SRF data set [*Zhang et al.*, 2004]. The field is generated by NASA's Goddard Institute of Space Studies (GISS) general circulation model using ISCCP cloud fields and the GISS aerosol climatology. As shown in Figure 9 in the study by BNL08, this analysis of surface shortwave radiation compares favorably with the Global Energy and Water Cycle Experiment's Surface Radiation Budget diagnosis [*Gupta et al.*, 1999].) is positive over much of the subcontinent, leading to a warmer land surface. Other factors, e.g., advection, may contribute as well. The associated 2-m temperature anomaly (Figure 1e) reflects the modulation of insolation. The "solar dimming" feature of the EHP hypothesis was perplexing to begin with, as detection of "solar dimming" is far more challenging in late spring and early summer when cloudiness variations can be confounding. Observational evidence shows an unambiguous warming of the land surface in May when aerosol loading is anomalously high, attesting to the dominance of the aerosol semidirect effect (or decreased cloud cover) over any "solar dimming" because of aerosol extinction.

[19] 6. Recently, *Gautam et al.* [2009] have correlated the lower and upper tropospheric temperature anomalies over Northern India in March–May with the concurrent AI over the region (their Figure 3), finding significant correlations (~0.65). This correspondence however cannot be considered evidence for the EHP hypothesis any more than it can for the aerosol semidirect effect. As discussed above (and in Figure 9 in the study by BNL08), the AI-related signal in downward surface shortwave radiation is positive over the subcontinent, leading to surface (and lower tropospheric) warming, providing forceful evidence for the dominance of the semidirect effect.

[20] 7. The noncollocation of the aerosol loading and rainfall enhancement regions in May is concerning in context of the EHP hypothesis, as noted above. A more reasonable and straightforward explanation for increased rainfall over northeastern India is orographic uplift of the moisture laden air from the Bay of Bengal. The southerly flow is generated as part of the anomalous low-level cyclonic circulation (Figure 1f), anchored by land surface heating (Figures 1b and 1e) and resulting low pressure over the subcontinent. [More generally, the aerosol loading and rainfall enhancement/suppression regions need not be collocated as the aerosol impact is often generated from induced regional circulation anomalies.]

[21] The EHP hypothesis is not without conceptual difficulties as well. For instance, if aerosol-induced rising motions were to lead to local rainfall enhancement in the foothill region, aerosol washout would rapidly occur. The EHP would then serve as an aerosol self-limiting mechanism in the Himalayan foothills, limiting its efficacy in impacting summer monsoon evolution over the larger subcontinent.

3. Aerosol-Leading Hydroclimate Links

[22] The contemporaneous analysis of aerosol-monsoon hydroclimate links for May reported in the study by BNL08 precludes attribution of cause and effect. One interpretation of the findings, as discussed in section 5 of that paper, could have been that aerosol loading responds to concurrent rainfall variations due to washout effect, which is not an unreasonable proposition. This possibility was however ruled out in the study by BNL08 by additional analysis in which the April AI over the Indo-Gangetic Plain (IGP) was regressed on May and June's precipitation and circulation. Although discussed to some extent, the lagged regression patterns were not displayed in the study by BNL08, leading to some lingering concerns on causality.

[23] Monthly lagged regressions on the IGP aerosol index (defined as in the study by BNL08) can be insightful provided that the AI itself is autocorrelated on time scales longer than a month. Figure 1f in the study by BNL08 shows the autocorrelation structure of both April and May indices. The indices are significantly correlated (~0.6), indicating anomaly persistence longer than 1 month. Figure 2 in the study by BNL08 provides context for the multimonth time scale by showing how "aerosol events" over the Indo-Gangetic Plain can be generated in the pre-monsoon period from advection

of dust and pollutants by the prevailing low-level westerlies, i.e., by a process other than local precipitation which operates on much shorter time scales.

[24] The contemporaneous and lagged precipitation regressions on the April IGP AI are shown in Figures 2a–2c. Close comparison with Figure 3 in the study by BNL08 (top row; contouring and shading intervals are identical) indicates striking similarity between the contemporaneous and 1 month aerosol-leading regressions of May precipitation (BNL08, Figure 3 (top left) and Figure 2b, respectively). The east–west asymmetry, in particular, is well captured in the aerosol-leading regressions. The similarity extends to the June precipitation patterns: the 2 month lagged regressions on the April AI and the 1 month lagged regressions on the May AI. The April and May IGP AI regressions of the May 2-m air temperature also exhibit notable similarity (Figures 2d–2e and BNL08, Figure 8 (top left), respectively), indicating coherent development of surface warming and the dominance of the aerosol semidirect effect over the direct one.

[25] The extensive similarity between the aerosol-leading and contemporaneous regressions of precipitation along with evidence for the multi-month duration of aerosol episodes in the pre-monsoon onset period should address the causality issue. The findings of BNL08 obtained from contemporaneous analysis thus represent the impact of aerosols on precipitation, not vice versa.

4. Concluding Remarks

[26] The study seeks to ascertain the viability of the EHP hypothesis, a mechanism proposed by LK06 for absorbing aerosols' impact on South Asian summer monsoon hydroclimate. A careful review of the analysis by LK06 and others since then [*Bollasina et al.*, 2008; *Gautam et al.*, 2009] reveals that the EHP hypothesis is not grounded in observations. A lack of appreciation of the spatial distribution of the aerosol-related May precipitation signal over the Indian subcontinent, its east–west asymmetric structure, in particular, as reflected in gross zonal averaging (65°E–95°E) of the signal in the study by LK06 (Figure 2b) led to this hypothesis.

[27] We show that key elements of the EHP hypothesis have no basis in observations and the hypothesis is thus deemed untenable:

[28] 1. The core of the May aerosol standard deviation is located not over the southern Himalayan slopes or elevated terrain but southward over the northern Indo-Gangetic Plain.

[29] 2. Aerosol-related downward surface shortwave radiation and 2-m air temperature signals are positive over the core region and the northern subcontinent, i.e., increased loadings are associated with more surface insolation and a warmer land surface (not a colder one, as per EHP hypothesis). This indicates the dominance of the aerosol semidirect effect over the direct one (solar dimming).

[30] 3. More importantly, the concurrent local precipitation signal over the core aerosol region in May is negative, i.e., increased loadings are linked with suppressed precipitation (not more, as claimed by the EHP hypothesis).

[31] 4. Aerosol-related tropospheric warming is confined to the lower troposphere. Sensible heating from the land surface is, perhaps, most important (see Figure 8 in the study by BNL08).

[32] 5. The EHP hypothesis has a self-limiting element. If aerosol-induced rising motions were to lead to local rainfall enhancement in the foothill regions, as claimed, aerosol washout would occur, limiting its intensity and large-scale influence.

[33] 6. The EHP hypothesis can perhaps be mimicked by atmospheric models, but this cannot be an indication of its relevance in nature as the representation of aerosol indirect and semidirect effects in models mentioned above is primitive. Observational analysis is, of course, not without its own uncertainties.

[34] Finally, we extend the analysis of contemporaneous aerosol-monsoon links reported in the study by BNL08 by examining the structure of the 1 and 2 month aerosol-leading regressions on hydroclimate. The extension is motivated by the need to address causality. The extensive similarity between the aerosol-leading and contemporaneous regressions on precipitation along with evidence for the multimonth duration of aerosol episodes in the pre-monsoon period suggest that the BNL08 findings obtained from contemporaneous analysis represent the impact of aerosols on precipitation, not vice versa.

[35] The possibility that both aerosol and precipitation anomalies, in turn, are shaped by a slowly evolving, large-scale circulation pattern cannot presently be ruled out, in part because current atmospheric models and observational analyses are unable to tease apart regional feedbacks from the large-scale influence. Some caution is thus warranted in the interpretation of aerosol mechanisms, as further discussed in the study by *Bollasina and Nigam* [2009].

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