Comment on "'Elevated heat pump' hypothesis for the aerosol-monsoon hydroclimate link: 'Grounded' in observations?" by S. Nigam and M. Bollasina

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[1] In their recent paper, *Nigam and Bollasina* [2010] (hereinafter NB) claimed to have found observational evidences that are at variance with the elevated heat pump (EHP) hypothesis regarding the possible impacts of absorbing aerosols on the South Asian summer monsoon [*Lau et al.*, 2006; *Lau and Kim*, 2006]. We found NB's arguments and inferences against the EHP hypothesis flawed, stemming from their own out-of-context interpretation of the hypothesis.

[2] NB argued that the simultaneous negative correlation of aerosol with rainfall, and correlations with other quantities in May, are evidence against the EHP hypothesis. Their argument cannot be justified. First, *Lau and Kim* [2006] (hereinafter LK06) never stated that the main rainfall response to EHP is in May. Second, the EHP is about responses of the entire Indian monsoon system that are nonlocal in space and time with respect to the aerosol forcing. As shown in Figure 4 of LK06, while the aerosol anomalies are strongest in April–May, the strongest rainfall response is in June–July, with the enhanced rainfall fed by an induced thermally driven circulation which brings additional moisture from the ocean to the Indian subcontinent. Third, the increased rainfall over the Bay of Bengal as shown in Figure 1a of NB and the increased low-level convergence in Figure 1f of NB do not necessarily reflect responses associated with EHP but rather the large-scale circulation that provides the buildup of the aerosols before the onset of the monsoon rainfall over India. Because aerosol can only accumulate where there is little or no washout by rain, the negative correlation is a necessary condition for increased atmospheric loading of aerosols. For the same reason, the spatial distributions of rainfall and aerosol generally are offset with each other, i.e., high aerosol in regions of low rainfall. This is evident in Figure 1, which shows the climatological mean of the MODIS aerosol optical depth (AOD), and TRMM rainfall over India in May. The maximum AOD is found over the Indo-Gangetic Plain and the desert regions of northwest India and Pakistan. A narrow strip of light-to-moderate rainfall is found over the Himalayan foothills of central and northwestern India, immediately northward of the AOD maximum. The regions over northwestern India and Pakistan, where NB found the largest negative aerosol-rainfall correlation, are largely devoid of rainfall in the premonsoon month of May! This makes the rainfall correlation meaningless. In May, the rainfall over the Bay of Bengal is associated with the development of the early monsoon depression, and monsoon onset over Southeast Asia and the South China Sea [*Lau et al.*, 1998]. The related convection has more to do with the structure of the large-scale circulation that leads to the increased aerosols over northwestern India, and the Indo-Gangetic Plain, but not the EHP response.

[3] NB make many misleading statements and unjustifiable claims regarding the EHP. The major ones are as follows.

[4] 1. NB contended that "EHP" is rooted in "expansive" zonal averaging. This is untrue. The EHP is rooted in numerical model experiments, as well as preliminary observations, aimed at describing the three-dimensional response of the monsoon rainfall and circulation to absorbing aerosols. NB paid too much attention to a minor detail in the latitude-time plot in Figure 2b of LK06, which served only as an introduction to the EHP concept. We agree that the enhanced convection over the Bay of Bengal in May noted by NB might have contributed to increased rainfall in northern India noted by LK06 and thereby masked possible rainfall signal over the Himalayas in northern and northwestern India. However, the possible enhancement of rainfall over the foothills of the Himalayas in May is only a possible early signal which is important for the local population but not critical to the entire outcome of the EHP. We submit that such an increase is still not proven by either NB or LK06, because of the use of coarse resolution GPCP rainfall data set in both analyses. To detect the early response of rainfall in May, there is a need to use high-resolution rainfall data such as TRMM (see Figure 1) as well as in situ observations with high temporal resolution to resolve the orographically generated rainfall along the narrow strip over the Himalayan foothills, downstream of the increased low-level meridional flow toward the foothills.

[5] 2. The buildup of aerosols and induced rainfall are not just along the Himalayan foothills, nor are they limited to

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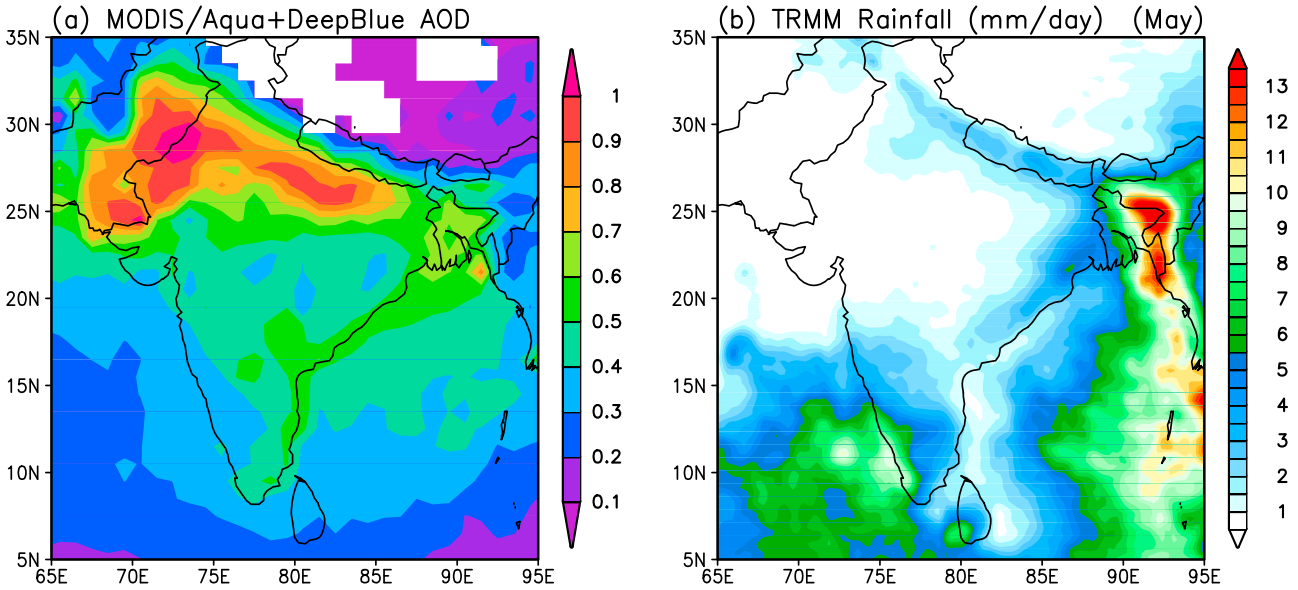

Figure 1. Spatial distribution of the climatological mean (a) aerosol optical depth from MODIS/Aqua combined with the Deep Blue product over bright surface and (b) TRMM rainfall for May. The periods used to calculate climatology are 2003–2009 for AOD and 1998–2009 for TRMM rainfall.

the month of May only, as incorrectly stated by NB. The EHP emphasizes radiative forcing provided by the deep layer of aerosol trapped over the entire Indo-Gangetic Plain and India subcontinent against the foothills of the Himalayas in late spring (April–May) up to the onset of the monsoon in mid-June, leading to the response of the entire monsoon system subsequently. Since the publication of LK06, data from the Cloudsat-Calipso satellite (see Figure 2) clearly show the buildup of a deep layer of aerosol up to the top of the Himalayas foothills, stretching over hundreds of kilometers over the Indo-Gangetic Plain to southern India. The cloud-free sky condition over northern India is also clearly depicted in Figure 2. Such dry condition is also quite typical over northwestern India during the premonsoon period, extending into late June and early July.

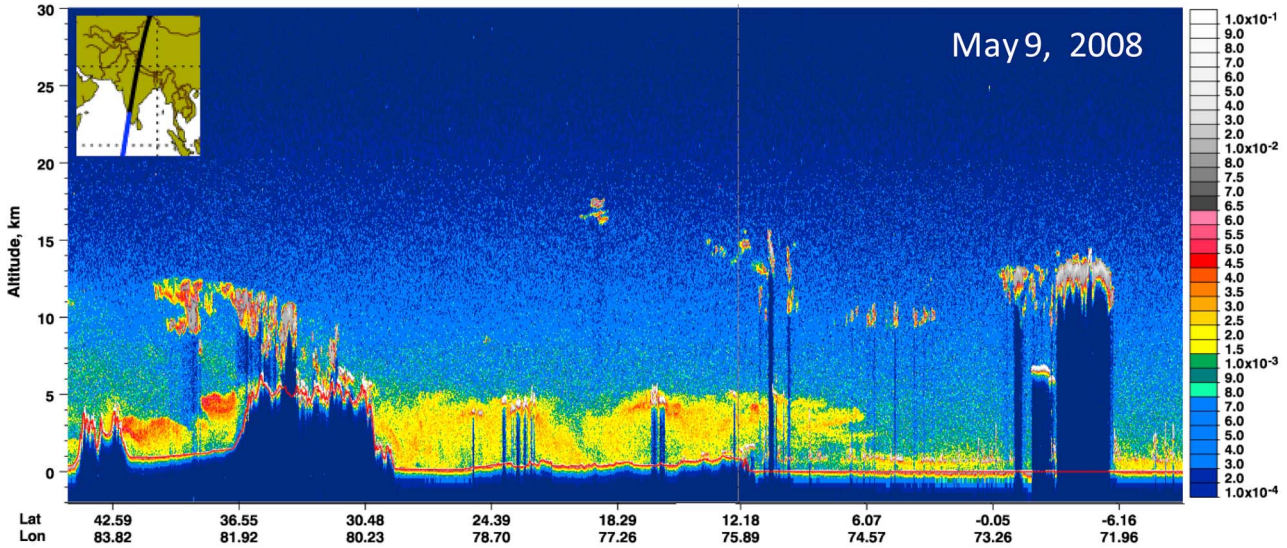

Figure 2. Vertical profile of the total attenuated backscattering coefficients (sr^{-1} km^{-1}) at 532 nm by aerosols along a Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation/Cloud-Aerosol Lidar with Orthogonal Polarization (CALIPSO/CALIOP) transect (see insert) over the India subcontinent on 9 May 2008. The aerosol backscattering signals are obstructed by clouds and are only retrievable under clear sky condition. Yellow to red colors below approximately 5 km indicate increasingly strong backscatter by aerosols. Patchy features near 10 km or above indicate clouds.

[6] 3. NB contended that semidirect effects of aerosols are important in altering monsoon rainfall. Semidirect effects including increased stability from atmospheric heating and evaporation of cloud droplets were included in the GCM experiments [*Lau et al.*, 2006], and those simulations showed little to no impact, compared to the EHP, in the monsoon system response. The semidirect effect is minimal in May because cloudiness and rainfall over northwestern India are rare at that time, and the land is already strongly heated by the incoming solar radiation. While the shielding of solar radiation by aerosol tends to cool the surface, longwave radiation by dust can also cause surface heating, especially at night. The model experiments of *Lau et al.* [2006] showed that EHP-induced condensational heating and atmospheric feedback, initiated by radiative heating of the deep layer of absorbing aerosols, is a far more powerful mechanism than the semidirect effect of aerosols in the dry premonsoon season.

[7] 4. NB used correlations from observation only to infer causality of the aerosol impact on land surface temperature and convection. This is an unsound approach. As pointed out earlier, it is more likely that both aerosols and the rainfall patterns in May are largely driven by sea surface temperature and/or other large-scale forcing. Indeed, NB acknowledged that such a possibility cannot be ruled out. Atmosphere-land interactions were included in our GCM experiments and no doubt played a role, as part of the EHP system-wide response, mostly through induced cloudiness changes accompanying the dynamic feedback. We would like to point out that the EHP was not based on an observation-only argument. It was first proposed based on unambiguously designed model experiments [*Lau et al.*, 2006] that provided the basis for causality of the EHP. While LK06 provided preliminary confirmation and support from large-scale observations, many aspects of EHP remained untested. It is common knowledge that model physics have deficiencies, and observations have biases and/or lack spatial or temporal resolution. Therefore, testing of the EHP requires a combination of modeling and observational studies [see *Lau et al.* [2008] for a full discussion). LK06 used this time-honored practice for hypothesis testing, while NB argued strongly about inferring causality from correlations based only on limited observations.

[8] Further, NB stated that because of uncertainty in model physics, models can provide only limited insights on the impact of aerosols on summer monsoon, implying that all model results are not trustworthy. We strongly disagree with such an assessment. The uncertainties in model physics apply mostly to indirect (microphysics) effects which are not included in most GCMs used to study effects of absorbing aerosols on the hydrological cycle. However, direct (radiative) effects, including the semidirect effect, are well represented in these GCMs [e.g., *Menon et al.*, 2002; *Lau et al.*, 2006; *Roeckner et al.*, 2006; *Meehl et al.*, 2008; *Randles and Ramaswamy*, 2008; *Collier and Zhang*, 2009; *Wang et al.*, 2009]. The differences in model responses to aerosol heating were mostly due to the uncertainties in the aerosol distribution (both vertical and horizontal), aerosol optical properties and states of internal mixing of aerosols. Some models included pure black carbon; others included a mixture of dust and black carbon. Some included aerosol-dynamics interaction; others did not. Therefore, one must keep these different forcing and responses in mind while interpreting model results and not reject model results outright because of differences among them. While these model results differ in details, one common theme linking them is that radiative heating of the atmosphere by absorbing aerosols is crucial in enhancing the transport of moisture from ocean to land, and modifying the monsoon rainfall and large-scale circulation, depending on the nature and buildup of the absorbing aerosols. This common theme is consistent with the basic premise of EHP. Given the uncertainties and short records of aerosol data, we maintain that results from well-designed model experiments are valuable in helping to interpret observational findings, especially with respect to establishing causality. Clearly, more coordination of modeling with observation efforts is needed to better interpret different findings.

[9] In summary, we stress that the EHP hypothesis deals with a very complex, system-wide response of the entire monsoon climate system to aerosol forcing. Testing the hypothesis requires coordinated modeling and observation approaches involving multiple models (including high-resolution regional model) and data sets covering the premonsoon (aerosol buildup) as well as the monsoon periods (main rainfall response). For observations, specifically, we need better measurements of (1) a variety of physical quantities, including the vertical and horizontal extent of dust and black carbon, their mixing states and associated physical and optical properties, and (2) the detailed transport processes that lead to the aerosol buildup over the Indo-Gangetic Plain and accumulation to high elevations in April–May and up to the onset of the monsoon in mid-June. The main response of the monsoon including rainfall and large-scale should be evaluated after the monsoon onset in mid-June to the end of the monsoon season. The complexity of aerosol-monsoon interactions and many confounding factors that may influence the outcome of aerosol impacts on monsoon rainfall, as well as challenges for field observation and validation of various model hypotheses, have been carefully considered and discussed in detail by *Lau et al.* [2008].

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