Comments on "The "Elevated Heat Pump" hypothesis for the aerosol-monsoon hydroclimate link: "Grounded" in observations?" by S. Nigam and M. Bollasina

by

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In their recent paper, *Nigam and Bollasina* [2010, hereafter 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 a lack of understanding and an out-of-context interpretation of the hypothesis.

NB argued that the simultaneous negative correlation of aerosol with rainfall, and correlations with other quantities in May as evidences against the EHP hypothesis. They cannot be more wrong in that argument. First, *Lau and Kim* [2006, hereafter, 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 non-local in space and time with respect to the aerosol forcing. As shown in Fig.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 correlation maps shown in Fig. 1 of NB, including the increased convection over the Bay of Bengal is not the response to EHP but rather represents the large-scale circulation that provides the build-up of the aerosols, *before* the onset of the monsoon rainfall over India. Because aerosol can only accumulate where there is little or no wash-out 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 Fig. 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 Himalayas 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 pre-monsoon 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 the 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 the northwestern India, and the Indo-Gangetic Plain, but not the EHP response.

In NB, there are many misleading statements on the EHP, and unjustifiable claims. The major ones are:

a. NB contended that "EHP" is rooted in "expansive" zonal averaging. This is completely untrue. The EHP is rooted in numerical model experiments, as well as from preliminary observations, aimed at describing the three-dimensional response of the monsoon rainfall and circulation to absorbing aerosols. NB nit-picked on a minor detail in the latitude-time plot in Fig. 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 in 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 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 dataset used 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 Fig. 1), as well as in-situ observations with high temporal resolution to resolve the orographically generated rainfall along the narrow strip over the Himalayas foothills, downstream of the increased low-level meridional flow towards the foothills.

b. The buildup of aerosols and induced rainfall are not just along the Himalaya foothills, nor are they limited to 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 against the foothills of the Himalayas in the 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 Fig. 2) clearly shows the build-up of deep layer of aerosol up to the top of the Himalayas foothills, stretching over hundreds of kilometers over the Indo-Gangetic Plain. The clear sky condition over northern India is also clearly depicted in Fig. 2. Such dry condition is also quite typical over northwestern India during the pre-monsoon period.

c. NB contended that semi-direct effects of aerosols are important in altering monsoon rainfall. Semi-direct 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 impacts compared to the EHP. The semi-direct effect is minimal, because cloudiness and rainfall over northwestern India are rare in May, 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. Energetically, EHP induced condensation heating, initiated by radiative heating of the deep layer of absorbing aerosols, is a far more powerful mechanism than the semi-direct effect of aerosols in the dry pre-monsoon season.

d. NB used correlations 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 driven by sea surface temperature, and/or other large-scale forcing. Indeed, NB acknowledged that such 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 like to point out that the EHP was proposed based on a combination of unambiguously designed model experiments [*Lau et al.*, 2006] which provided the basis for causality of the EHP, and thereafter it found preliminary confirmation and support in large-scale observations in LK06. 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. It is puzzling that NB opted to abandon such time-honored practice for hypothesis testing, and argued so strongly about inferring causality from correlations based on limited data sets.

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 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 semi-direct effect are well represented in these GCMs [Menon *et al.*, 2002; Lau *et al.*, 2006; Roeckner *et al.*, 2006; Meehl *et al.*, 2008; Randles and Ramawamy 2008; Collier and Zhang 2008; Wang *et al.*, 2009 and others]. 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 to 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 build-up 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 interpreting observational findings, especially with respect to establishing causality. Clearly, more coordination of modeling with observation efforts is needed to better interpret different findings.

In summary, we stress that EHP hypothesis deals with a very complex, system-wise 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 datasets covering the pre-monsoon (aerosol build up) as well as the monsoon periods (main rainfall response). For observations, specifically we need better measurements of 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; the large scale transport that leads to their build-up over the Indo-Gangetic Plain and accumulation to high elevations, in April–May and up to the onset of 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. In these regards, NB completely missed the mark!

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Figure Captions

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.

Figure 2. Vertical profile of the total attenuated backscattering coefficients (sr^{-1} km^{-1}) at 532nm by aerosols along a 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.

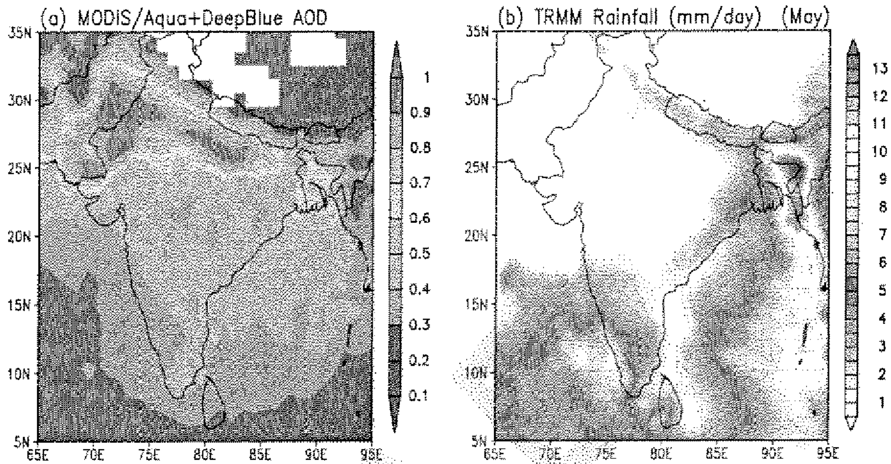
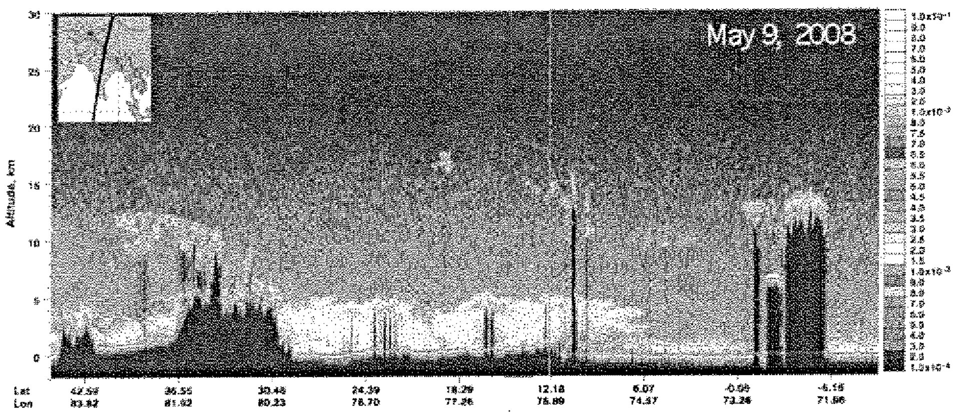


Figure 1. Spatial distribution of the climatological mean a) aerosol optical depth (non-dimensional unit) from MODIS/Aqua combined with the Deep Blue Product over bright surface and b) TRMM rainfall (mm day^{-1}) for May. The periods used to calculate climatology are 2003-2009 for AOD and 1998-2009 for TRMM rainfall.



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