Reply to Comments on ***"Elevated Heat Pump" Hypothesis for the Aerosol–Monsoon Hydroclimate Link: "Grounded" in Observations?***

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

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Lau and Kim's [2011, hereafter LK11] defense of the Elevated Heat Pump (EHP) hypothesis is weak. *Nigam and Bollasina* [2010, hereafter NB10] have assessed the viability of the EHP hypothesis [*Lau et al.,* 2006; *Lau and Kim,* 2006, hereafter LK06] from a careful review of LK06's own analysis and other related studies since then [e.g., *Bollasina et al.,* 2008; *Gautam et al.,* 2009]. NB10 find little observational evidence for key elements of the EHP hypothesis. In their rejoinder, LK11 do *not* address many of the specific concerns raised by NB10 about the EHP hypothesis. Instead, in their final overall remark, they dwell on the hypothesis's new-found complexity, asserting it to be untestable at the present time in view of limited observational data sets and incomplete treatment of aerosols in climate models.

LK11's response is best summarized in their own words "EHP hypothesis deals with a very complex, system-wide response of the entire monsoon climate system to aerosol forcing." The response is surprising given the authors' previous assertions about the role of specific processes [i.e., *LK06*] and because their hypothesis for aerosol-monsoon link is rooted in a reasonably simple mechanism – one predicated on direct radiative heating by absorbing aerosols. LK11's response can be construed as a broad refrain from verification attempts. LK11, in fact, state as much, "Testing the hypothesis requires coordinated modeling and observation approaches involving multiple models and observational data sets…" In short, testing of the EHP hypothesis must be deferred into the future. We think otherwise.

The scientific method is characterized by development and continual testing and refinement of hypotheses. Hypotheses are tested from verification of their predictions/deductions, an ongoing exercise that leads to the emergence of more viable hypotheses. Hypothesis testing, at least of the core elements, does not require a full set of system observations, only consistency with the known subset. An example in the EHP context is illustrative: The EHP hypothesis has aerosol absorption of shortwave radiation as its key element, one that purportedly leads to rising motions in the Himalayan foothills and solar dimming over the Indo-Gangetic Plains (which supposedly cools the land surface, stabilizing the lower troposphere and limiting convective instability and precipitation). EHP hypothesis would thus predict diminished surface shortwave radiation over the Indo-Gangetic Plains (hereafter IGP) with attendant land-surface cooling (see schematic Fig. 3 in *Lau et al.* [2008]). Unfortunately, neither of the predictions is borne out: Absorbing aerosol (e.g., dust and black carbon) build-up is, in fact, accompanied by increased surface shortwave radiation and land-surface warming [*Bollasina et al.*, 2008; *NB10*]. When predictions cannot be verified, the scientific method calls for hypothesis refinement from the consideration of hitherto excluded effects after corroboration of the basic data. One pertinent effect in this case is the semi-direct effect of absorbing aerosols which leads to reduction in cloudiness with aerosol build-up (as observed) and increased surface shortwave radiation and attendant land-surface warming (both observed, as noted above). This refinement doesn't refute the EHP mechanism as such but indicates its relative insignificance in comparison with other operative effects. The relevance of the aerosol semi-direct effect is manifest given its success in explaining the anomalous states of more climate system variables than the EHP mechanism.

NB10 pointed out several weaknesses in the EHP hypothesis: The principal ones are stated below, followed by key sentences from the LK11 response (in italics), and then our critique.

- May rainfall anomalies in the core aerosol-loading region over the northern IGP (which includes the Himalayan foothills) are found to be weakly negative. LK06 associated aerosol loading with positive rainfall anomalies however and used this link in developing the EHP hypothesis. As noted in NB10, LK06's incorrect association likely resulted from their lack of appreciation of the spatial distribution of rainfall anomalies: they focused on an overlywide longitudinal sector *average*. NB10 show that this sector-averaged anomaly is positive only because of contributions from the far eastern region (i.e., the area between 90º-95ºE, which is not collocated with the core aerosol-loading region). In the remaining sector, including the core aerosol-loading region, the rainfall signal was shown to be negative.

LK11's response (in italics):

- *"First, LK06 never stated that the main rainfall response to EHP is in May."* This is factually incorrect since LK06 state "At the time of the maximum build up of aerosols in May, rainfall is increased over northern India (20º-28ºN) but reduced over central India (15º-20ºN). 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…" We never state the *maximum* response to be in May either. We only stress that the EHP effect should be clearly discernible and large in May, as LK06 itself states.

- "*Second, the EHP is about responses of the entire Indian monsoon system that are non-local in space and time with respect to aerosol forcing."* How do we know? Ascribing such all-inclusive complexity to EHP appears to be a new interpretation since the hypothesis was succinctly stated in LK06: EHP, at least initially, is based on the direct and "local" response to aerosol heating over northern India during May (see Fig. 3a in LK06). The new ascription of complexity can serve only one purpose: rendering the hypothesis untestable using current observations and models.

- *"Third, the correlation maps shown in Fig. 1 of NB, including the increased convection over the Bay of Bengal, as shown in the increased rainfall in Fig. 1a, and the increased low level moisture convergence in Fig. 1f of NB, 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."* Interesting, since Figure 3a in LK06 and related discussion of precipitation anomalies over northern India were actually presented as a *response* to the EHP effect! LK11 do not reveal the basis of their new assertion; as such, it is deemed speculative. On the contrary, NB10 present aerosol-leading regressions in section 3 of their paper, and the similarity of Figs. 1a and 2b therein refute LK11's assertion. Moreover, their Fig. 1 showing *climatological* distribution of aerosol optical depth and rainfall distribution is irrelevant to the discussion at hand, which is focused on interannual variations.

- *"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…"* Expansive zonal averaging is not a minor detail for it leads LK06 to state *"the anomalous deep convection has been set up in May*". The averaging, specifically, precluded LK06 from appreciating the non-collocation of the aerosol loading and enhanced precipitation regions. Besides, what are 'preliminary observations'? LK11 argue that higher resolution rainfall data (e.g. TRMM) is perhaps necessary to firmly establish the presence/absence of positive rainfall anomalies in the Himalayan foothills that lie within the core aerosol-loading region. Yes, such observational data will uncover more structure but the core aerosol-loading zone is wide enough (~8°) in our opinion to be resolved using traditional data sets (e.g., GPCP) and for the sign of the regional rainfall anomaly to be revealed with certitude. LK11's concern on GPCP data resolution is interesting since analysis of the same data set was the basis for several confident assertions in LK06 (and related papers). Besides, the authors' concerns on horizontal resolution are not reflected in their modeling experiments, most of which were conducted using low-resolution models [*Lau et al.*, 2006].

- ○ *"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 aerosol concentration actually peaks in May, i.e., prior to the arrival of monsoon rainfall which decreases aerosol loading by wash-out (the reduction is however not complete; Lau *et al.*, 2008). As for the geographical location, it is the aerosol layer piled-up against the Himalayas that is important in EHP. In any case, the CALIPSO data shown in LK11 is for May only and cannot weigh in on EHP viability as the latter concerns the structure and hydroclimate links of regional aerosol anomalies.

- Aerosol-related temperature changes in May are significant only in the lower troposphere (sfc-700 hPa). We find little evidence for the mid-to-upper tropospheric warming expected from the EHP mechanism [*LK06*; *Gautam et al.*, 2009]. The lower-tropospheric warming is moreover focused over the IGP region, not the Himalayan foothills. Although aerosol absorption of shortwave radiation cannot be ruled out, the surface-trapped vertical structure of aerosol-related diabatic heating and temperature [Fig. 4 (top-right) and Fig. 7 (top panels), respectively in *Bollasina et al.*, 2008] indicates an important role for surface sensible heating in warming the lower troposphere. LK11 have not responded to this concern of ours.

- There is no evidence that aerosol induced "solar dimming" is an influential effect over the IGP region in May observations. According to the EHP hypothesis, such dimming leads to cooling of the IGP, limiting convective instability and rainfall. *Bollasina et al.* [2008] and

NB10 show the absorbing aerosol-related downward shortwave radiation anomaly to be positive! The positive surface shortwave radiation anomaly results from related reduction in cloudiness (i.e., the semi-direct effect; *Bollasina et al.*, 2008), and leads to warming of the land surface (see 2-m air temperatures in Fig. 1e of NB10). There is no sign of any land-surface cooling in observations. The structure and relationship of these anomalies indicates the considerable importance of the aerosol semi-direct effect. Again, solar dimming, if occurring, must be of second-order insignificance in May.

LK11's response (in italics):

- *"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, in the monsoon system response."* Modeling of aerosol effects is rapidly improving but still widely viewed as uncertain [e.g., *CCSP 2009*]. Semi-direct effects have only begun to be modeled and, as such, modeling evidence for or against their importance must be viewed with caution [e.g., *Denman et al.*, 2007; *Allen and Sherwood*, 2010].

- *"The semi-direct 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."* First, the relevance of the semi-direct effect vis-à-vis "solar dimming" is being assessed over the larger IGP, not just northwestern India. Second, it is not the case that cloudiness and rainfall are rare over the larger IGP region in May; pre-monsoon cloudiness is not that uncommon. Instead of anecdotal evidence, we actually show the downward surface shortwave radiation anomaly in *Bollasina et al.* [2008] and

NB10. How does one understand these positive anomalies if the semi-direct effect is viewed as unimportant? Interestingly, LK11 skirt this critical finding of ours in their response:

- *"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 semi-direct effect of aerosols in the dry pre-monsoon season."* Nature is, indeed, complex and LK11 have articulated additional interesting processes. But mere articulation of the same does not explain away some of the EHP weaknesses. It is surprising that LK11 can claim that some process is far more powerful than the semi-direct effect which remains to be adequately modeled. It is noteworthy that we are trying to explain not only a warmer land surface but also more downward surface shortwave radiation and reduced cloudiness.

- *"NB used correlations from observations only to infer causality of the aerosol impact on land surface temperature and convection. This is an unsound approach."* Interestingly, the same method is used by LK06.

- LK11's final remarks are of speculative nature. Our intent was to show how some analysis attributes can sometimes lead to faulty hypotheses, not to discredit modeling results, even inadvertently. Modeling analyses often provide precious insights into coupled processes that cannot be gleaned from observational analyses. However, considering that aerosols have become fully interactive in climate models only recently (in contrast with *Lau et al.'s.* [2006] study where they were externally prescribed), we caution against readily accepting model generated regional aerosol effects, especially when observational evidence seems contradictory.

In summary, *Lau and Kim* [2010] have not addressed *Nigam and Bollasina*'s [2010] specific concerns on the Elevated Heat Pump hypothesis. Critical elements of this hypothesis were examined using a suite of observations in NB10, with the analysis revealing the dominance of the aerosol semi-direct effect (rather than the direct one, as EHP posits) in explaining aerosol-monsoon hydroclimate links over the Indo-Gangetic Plains during northern summer. NB10 find the EHP hypothesis untenable, notwithstanding its new complexity attribute.

Lau and Kim's [2010] defense of EHP is not via rebuttal of the specific concerns noted in NB10 but from invocation of new-found complexity in the hypothesis's cause, with follow-on assertion that the hypothesis is, as such, untestable at the present time in view of limited observational data sets and incomplete representation of aerosol effects in climate models; a proposition, we disagree with.

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