Reply to comment by K. M. Lau and K. M. Kim on "'Elevated heat pump' hypothesis for the aerosol–monsoon hydroclimate link: 'Grounded' in observations?"

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[1] *Lau and Kim*'s [2011] (hereinafter LK11) defense of the elevated heat pump (EHP) hypothesis is unsubstantiated. *Nigam and Bollasina* [2010] (hereinafter NB10) have assessed the viability of the EHP hypothesis [*Lau et al.*, 2006; *Lau and Kim*, 2006] (hereinafter 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 emphasize 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.

[2] 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 moreover suggest that testing of this complex EHP hypothesis must await further model development and acquisition of observational data, for they state, "Testing the hypothesis requires coordinated modeling and observation approaches involving multiple models (including high-resolution regional model) and data sets covering the pre-monsoon (aerosol buildup) as well as the monsoon periods (main rainfall response). For observations, specifically, we need better measurements of a variety of physical quantities. …" While we agree with the need for additional modeling and observations, we find the current data sets already sufficient for evaluation of the basic elements of the EHP hypothesis.

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[3] 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 Figure 3 of *Lau et al.* [2008a]). Unfortunately, neither of the predictions is borne out: Absorbing aerosol (e.g., dust and black carbon) buildup is, in fact, accompanied by increased surface shortwave radiation and land-surface warming [*Bollasina et al.*, 2008] (also 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 semidirect effect of absorbing aerosols which leads to reduction in cloudiness with aerosol buildup (as observed) and increased surface shortwave radiation and attendant land-surface warming (both observed, as noted above). This refinement does not refute the EHP mechanism as such but indicates its relative insignificance in comparison with other operative effects. The relevance of the aerosol semidirect effect is manifest given its success in explaining the anomalous states of more climate system variables than the EHP mechanism.

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

[5] 1. 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 by NB10, LK06's incorrect association likely resulted from their lack of appreciation of the spatial distribution of

rainfall anomalies: they focused on an overly wide 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 90°E and 95°E, 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.

[6] LK11's response is as follows: "First, LK06 never stated that the main rainfall response to EHP is in May."

[7] This is factually incorrect since LK06 state that "At the time of the maximum build up of aerosols 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…." 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 themselves state.

[8] LK11 state that "Second, the EHP is about responses of the entire Indian monsoon system that are nonlocal in space and time with respect to aerosol forcing."

[9] How do we know? Ascribing such all-inclusive complexity to EHP appears to be a new interpretation, since the hypothesis was succinctly stated by LK06: EHP, at least initially, is based on the direct and "local" response to aerosol heating over northern India during May (see Figure 3a of LK06). The new ascription of complexity can serve only one purpose: rendering the hypothesis untestable using current observations and models.

[10] LK11 continue, "Third, the correlation maps shown in Figure 1 of NB, including the increased convection over the Bay of Bengal, as shown in the increased rainfall in Figure 1a, and the increased low-level moisture convergence in Figure 1f of NB, is not the response to EHP but rather represents the large-scale circulation that provides the buildup of the aerosols, before the onset of the monsoon rainfall over India."

[11] This is interesting, since Figure 3a of 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 Figures 1a and 2b therein refute LK11's assertion. Moreover, their Figure 1 showing climatological distribution of aerosol optical depth and rainfall distribution is irrelevant to the discussion at hand, which is focused on interannual variations.

[12] LK11 further state that "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…"

[13] Expansive zonal averaging is not a minor detail for it leads LK06 to state that "the anomalous deep convection has been set up in May." The averaging, specifically, precluded LK06 from appreciating the noncollocation of the aerosol loading and enhanced precipitation regions. Besides, what are "preliminary observations?" LK11 argue that higher-resolution rainfall data (e.g., TRMM) are 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 regarding GPCP data resolution is interesting since analysis of the same data set was the basis for several confident assertions by LK06 (and related papers). Besides, the authors' concerns about horizontal resolution are not reflected in their modeling experiments, most of which were conducted using low-resolution models [*Lau et al.*, 2006].

[14] LK11 assert that "The buildup of aerosols and induced rainfall are not just along the Himalayan foothills, nor are they limited to the month of May only, as incorrectly stated by NB…."

[15] The aerosol concentration actually peaks in May, i.e., prior to the arrival of monsoon rainfall which decreases aerosol loading by washout (the reduction is however not complete [*Lau et al.*, 2008b]). 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 by LK11 are for May only and cannot weigh in on EHP viability as the latter concerns the structure and hydroclimate links of regional aerosol anomalies.

[16] 2. Aerosol-related temperature changes in May are significant only in the lower troposphere (surface to 700 hPa). We find little evidence for the mid-to-upper tropospheric warming expected from the EHP mechanism (LK06) [also *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 (Figure 4 (top right) and Figure 7 (top), respectively, from *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.

[17] 3. 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 semidirect effect [*Bollasina et al.*, 2008]), and leads to warming of the land surface (see 2 m air temperatures in Figure 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 semidirect effect. Again, solar dimming, if occurring, must be of second-order insignificance in May.

[18] LK11 respond that "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."

[19] Modeling of aerosol effects is rapidly improving but still widely viewed as uncertain [e.g., *Climate Change Science Program*, 2009]. Semidirect 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].

[20] LK11 report that "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."

[21] First, the relevance of the semidirect 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; premonsoon cloudiness is not that uncommon. Instead of anecdotal evidence, we actually show the downward surface shortwave radiation anomaly from *Bollasina et al.* [2008] and NB10. How does one understand these positive anomalies if the semidirect effect is viewed as unimportant? Interestingly, LK11 skirt this critical finding of ours in the following.

[22] LK11's response is that "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."

[23] 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 semidirect 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.

[24] LK11 claim that "NB used correlations from observations only to infer causality of the aerosol impact on land surface temperature and convection. This is an unsound approach."

[25] Interestingly, the same method is used by LK06.

[26] 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.

[27] In summary, *Lau and Kim* [2011] 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 by NB10, with the analysis revealing the dominance of the aerosol semidirect 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.

[28] *Lau and Kim*'s [2011] 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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