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Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007

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[1] Fundamental to the onset of the Indian Summer Monsoon is the land-sea thermal gradient from the Indian Ocean to the Himalayas-Tibetan Plateau (HTP). The timing of the onset is strongly controlled by the meridional tropospheric temperature gradient due to the rapid pre-monsoon heating of the HTP compared to the relatively cooler Indian Ocean. Analysis of tropospheric temperatures from the longest available record of microwave satellite measurements reveals widespread warming over the Himalayan-Gangetic region and consequent strengthening of the land-sea thermal gradient. This trend is most pronounced in the pre-monsoon season, resulting in a warming of 2.7°C in the 29-year record (1979–2007), when this region is strongly influenced by dust aerosols at elevated altitudes. The enhanced tropospheric warming is accompanied by increased atmospheric loading of absorbing aerosols, particularly vertically extended dust aerosols, raising the possibility that aerosol solar heating has amplified the seasonal warming and in turn strengthened the land-sea gradient. **Citation:** Gautam, R., N. C. Hsu, K.-M. Lau, S.-C. Tsay, and M. Kafatos (2009), Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007, *Geophys. Res. Lett.*, *36*, L07704, doi:10.1029/2009GL037641.

1. Introduction

[2] The orography of the Himalayas-Tibetan Plateau (HTP), which acts as an elevated heat source, is crucial to the onset and strength of the monsoon, and sets this region apart from other tropical/sub-tropical regimes [*Yanai et al.*, 1992; *Webster et al.*, 1998]. Warm air rising over the landmass throughout the troposphere, in response to the pre-monsoon heating of the HTP, causes the inflow of moist air from the ocean towards the continent. In particular, the middle-upper tropospheric temperature gradient over the HTP and the oceanic region to the south is a strong control of the timing of the onset of the Asian monsoon [*Yanai et al.*, 1992]. Additionally, the Himalayas act as a barrier to the moisture-laden strong monsoon winds, resulting in heavy rainfall over South Asia that forms the bulk of the annual precipitation during each summer, from June through September. The Himalayas also contain the largest ice-covered regions of the Earth's surface outside the poles and their glaciers form a source of major rivers in South Asia, such as the Indus and the Ganges, that serve about 900 million living in the highly fertile Indo-Gangetic Plains (IGP) that encompass parts of northern India, Pakistan and Bangladesh. Along with the monsoon rainfall, rivers originating from the glaciers provide water needed for agriculture which is the mainstay of economy of the South Asian countries.

[3] In recent decades, South and East Asia have witnessed a dramatic increase in atmospheric pollution due to the growing population and energy demands, accompanied by rapid urbanization and industrialization. The influence of absorbing aerosols over these monsoon-dominated regions has been shown to alter long-term rainfall patterns [*Menon et al.*, 2002]. Through general circulation model (GCM) simulations, it has been shown that aerosol-induced surface dimming over the Indian Ocean results in less evaporation from the ocean surface, thereby reducing moisture inflow into South Asia which in turn causes weakening of the monsoon rainfall [*Ramanathan et al.*, 2005]. On the other hand, *Lau et al.* [2006] and *Lau and Kim* [2006] have recently proposed the Elevated Heat Pump (EHP) hypothesis, suggesting that desert dust, mixed with soot aerosols over northern India and the foothills of the Himalayas, may cause enhanced heating in the middle/upper troposphere over southern slopes of the Tibetan Plateau and may further lead to the strengthening of the meridional tropospheric temperature gradient, thus resulting in the advancement of the monsoon rainfall in early summer.

[4] In addition, aerosol solar heating combined with increasing concentrations of greenhouse gases has been modeled in warming the troposphere over Asia [*Ramanathan et al.*, 2007]. In general, the global tropospheric warming, in recent decades, is recognized to be partly of anthropogenic origin as simulated by GCMs [*Hansen et al.*, 2002]. Consistent with model simulations, microwave satellite observations of the free troposphere since 1979 have also shown an upward trend in the tropospheric temperatures associated with global warming [*Mears et al.*, 2003; *Fu et al.*, 2004]. In the context of the strong control of seasonal heating over the HTP on the South Asian monsoon dynamics and the regional hydrological cycle; and in relation with global climate change as well, we examine here tropospheric temperature trends using satellite-borne Microwave Sounding Unit (MSU) data over the Indian Monsoon region from 1979 to 2007, and explore the possible role of aerosol forcing in the observed trends.

2. Data

[5] Since 1979, the MSU has provided an unprecedented measure of global temperatures for several atmospheric layers from the lower troposphere to the stratosphere. As

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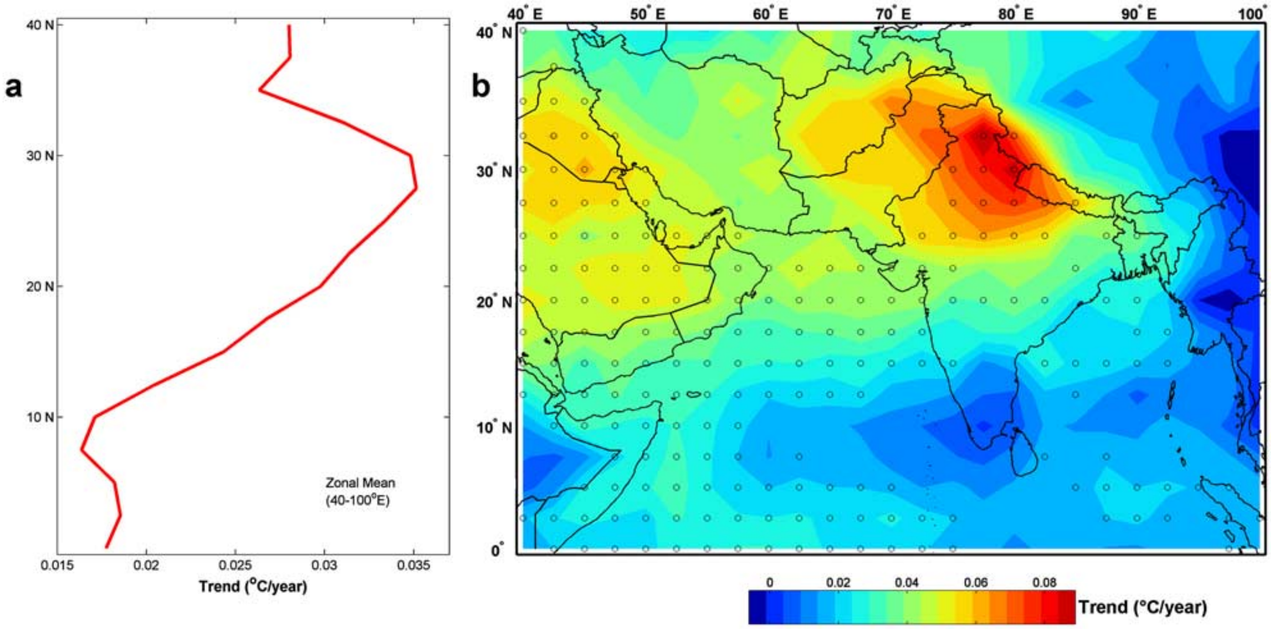

Figure 1. (a) Zonal mean (40–100 °E) latitudinal profile of mid-tropospheric temperature trend for the pre-monsoon season (March–April–May) from 1979 to 2007, and (b) spatial distribution of the mid-tropospheric temperature trend over the Indian Monsoon region in May. Open circles denote significance of linear trends at 95%.

most of the HTP stands over 4 km, tropospheric temperatures over the Himalayan region pertain to the mid-troposphere, corresponding to the 4–7 km atmospheric layer as recorded by the MSU. We adopt the methodology of a previous study [*Fu et al.*, 2004] by applying statistical combinations to different MSU channels in order to minimize the influence of stratospheric cooling on the tropospheric temperature signal. Aerosol products from the Moderate Resolution Imaging Spectroradiometer (MODIS), namely Dark-Target [*Levy et al.*, 2007] and Deep Blue [*Hsu et al.*, 2004], onboard NASA's Aqua satellite, were used to analyze distribution of Aerosol Optical Depth (AOD) over dark vegetated and bright arid/semi-arid regions, respectively.

[6] Solar flux calculations were performed using the Fu-Liou radiative transfer model [*Fu and Liou*, 1993] in conjunction with instantaneous surface pyranometer measurements. In addition, aerosol optical properties from sunphotometer measurements, in central IGP [*Singh et al.*, 2004], were provided as input to the radiative transfer model. Instantaneous temperature profiles from AIRS/AMSU (using microwave retrieval) were also used to infer the influence of aerosol forcing on tropospheric temperatures. Daily profiles for a four-year period from 2003–2006 in May were co-located over sunphotometer measurements and were subsequently grouped in high-dust and low-dust loading days based on the combined information from AOD and Angstrom Exponent (α), which is a first-order indicator of particle size.

3. Results

[7] Figure 1a shows the zonal mean (40–100°E) latitudinal profile of mid-tropospheric temperature trend for the pre-monsoon period of March–April–May from 1979 to 2007. Trends are calculated from the temperature anomaly, i.e., after removing the climatological seasonal mean from the time series. A steep temperature gradient pattern is evident from the equatorial Indian Ocean to the South Asian landmass peaking around 30°N. All individual pre-monsoon months indicate a warming trend, however, we find that the Himalayan-Gangetic region is marked by the strongest positive trend in May, resulting in a statistically-significant warming of 2.7°C in the last three-decade period (at 95% significance using student's *t* test) (Figure 1b). Spatial extent of the warming spans the Himalayas to the western arid regions of Pakistan, Afghanistan, Iran and the Arabian Peninsula with appreciable warming also found over the Hindu-Kush Mountains. Additionally, the northern Arabian Sea is also associated with a larger increase in tropospheric temperatures comparable to that of the arid landmass to its north. On the contrary, regions south of 10°N, experience weak positive-neutral trends, especially over oceanic regions such as the Indian Ocean and the Bay of Bengal. Apart from the emergence of the strengthened land-sea gradient, there is a sharp east-west pattern across the Tibetan Plateau (TP) and the Himalayan region. Most of the TP experiences relatively smaller (positive) warming trends compared to the strong western Himalayan warming. Overall, it is found that the entire South Asian monsoon region has experienced tropospheric warming of 0.87°C during May since 1979.

[8] The land-sea thermal gradient is also governed by the Himalayan snow cover extent in spring and early summer. Since a substantial fraction of solar radiation is required for the melting of snow accompanied by less energy available for heating the underlying ground surface, therefore, in general, excessive snowfall results in colder surface temperatures. Reduced snow cover, on the contrary, is considered to be responsible for stronger land-sea thermal gradient

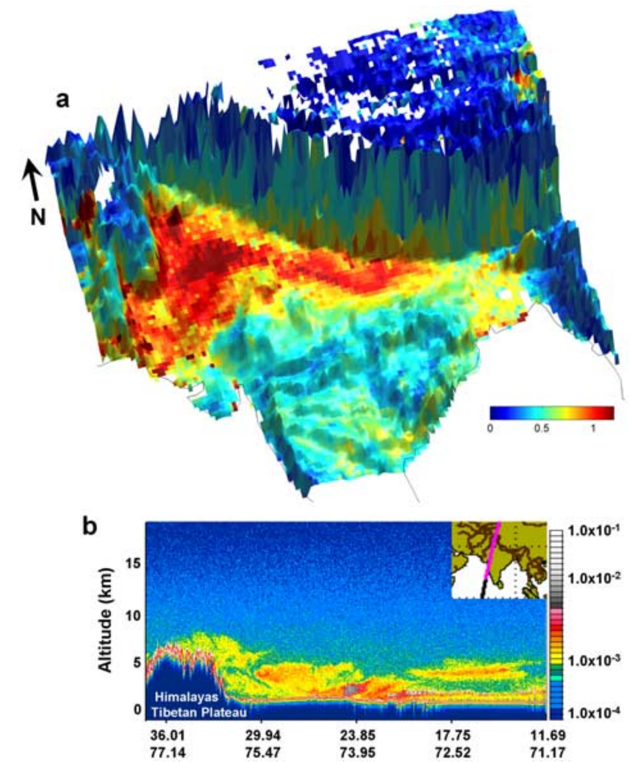

Figure 2. (a) Mean MODIS AOD, during pre-monsoon period 2003 to 2006, projected as a function of surface topography, and (b) CALIPSO backscatter profile from Southern India to the Himalayas, reveals the vertical extent of aerosols at elevated altitudes (>5 km) piling up against the slopes of the Himalayas. Inset image shows the lidar transect on 12 May 2007. Backscatter signal from aerosols usually lie in the Yellow-Red color scale and clouds are marked by pink, grey and white colors.

[*Meehl*, 1994]. Concurrent with the warming trends reported here, a progressive decline in snow cover extent has been observed from satellite data over the HTP annually and in May as well since 1979 [*Goes et al.*, 2005].

[9] The anomalous tropospheric warming, during the pre-monsoon period also marks the period of high dust activity over the Himalayan-Gangetic region that constitutes the bulk of regional aerosol loading, particularly in May [*Singh et al.*, 2004]. During the strong pre-monsoon inflow, dust aerosols are transported from the Northwestern deserts of India/Pakistan and the Arabian Peninsula to the Himalayan-Gangetic region [*Middleton*, 1986; *Prospero et al.*, 2002]. The towering Himalayas form a barrier to the passage of dust storms resulting in the accumulation of dust particles, largely over northwestern India and the foothills of the Himalayas. Dust activity usually starts in March–April and peaks during May, combined with heavy atmospheric pollution over northern India, and results in maximum aerosol loading prior to the monsoon. Due to enhanced convection and large-scale topographic variations in the Himalayan-Gangetic region, aerosols transported with the pre-monsoon winds are vertically advected to elevated altitudes (up to 8 km as shown in recent space-borne lidar measurements and air-mass trajectory simulations [*Liu et al.*, 2008]). The pre-monsoon AOD clearly shows the passage of dust loading over the Thar Desert in Northwestern India/Pakistan and the IGP bounded by the Himalayan-Hindu-Kush Mountains (Figure 2a). The AOD is projected as a function of surface topography in order to distinctly highlight the high aerosol loading (as high as 0.8) at elevated altitudes (>3km) over the foothills of the Himalayas. Vertical extent of aerosols piling up against the slopes of Himalayas, well over 5 km, is also evident from CALIPSO lidar backscatter (Figure 2b). With the arrival of monsoon rain, net aerosol loading significantly drops, due to the aerosol washout from the atmosphere [*Singh et al.*, 2004].

[10] The pre-monsoon aerosols are found to cause significant absorption of sunlight in the atmosphere, about 12% of the incident shortwave solar flux, as indicated by our radiative transfer calculations. The single scattering albedo (SSA), at wavelength 550 nm, from our model simulations was estimated to be 0.88. A close agreement was found in the derived spectral SSA from our model calculations and AERONET with only a difference of 2–3%. The subsequent instantaneous radiative heating caused due to aerosol absorption is estimated to be ~6.5 K/day that peaks around 3.5 km. This aerosol-induced heating appears to extend well into the middle troposphere and results in enhanced heating rates (4.5–2 K/day) in the 4–7 km altitude range. In addition, the response of aerosol solar absorption is also observed in instantaneous temperature profiles from satellite measurements that reveal a temperature increase of 2–2.4 K in the middle-troposphere, i.e. associated with high-dust loading conditions compared to that of low-dust environment. Mean statistics of AOD and α for high and low dust loading conditions are (AOD_{mean} – 1.1, α_{mean} – 0.07) and (AOD_{mean} – 0.68, α_{mean} – 0.87), respectively.

[11] The observed tropospheric warming over the Himalayan-Gangetic region since 1979 is accompanied by an increase in aerosol loading over India during pre-monsoon season, particularly over the desert dust-laden regions with enhanced transport of dust-raising activity into the alluvium of the IGP, as indicated by analysis of Absorbing Aerosol Index (AI) from space-borne Total Ozone Mapping Spectrometer (TOMS) observations in the past two decades (see auxiliary material).[1] 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]. This northward migration of tropospheric temperature anomaly, due to the atmospheric feedback, is clearly observed with respect to the increasing aerosol loading in the spatial distributions of long-term trends derived from the MSU and TOMS observations, respectively.

[12] In addition, we have examined the temporal correlations of temperatures and aerosols using the two satellite datasets over this region. As evident in Figure 3, the increasing aerosol loading over northern India since 1979 is associated with strong inter-annual variations of temperatures, both in middle and lower troposphere, during pre-

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL037641.

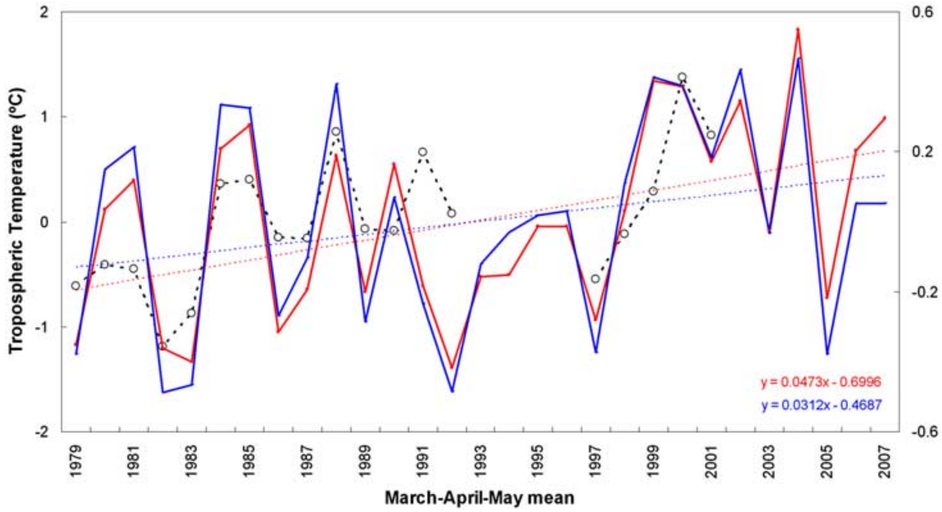

Figure 3. Red and blue curves (solid) show inter-annual variations of temperatures in the middle (4–7 km) and lower (surface-4 km) troposphere, respectively, over northern India (25–35°N, 69–82°E) for March–April–May (MAM) period (mean) from 1979 to 2007. Straight lines (dotted) indicate the linear trends with in the middle (red) and lower (blue) troposphere, respectively. TOMS Aerosol Index variations during MAM over northern India since 1979 are shown by black dashed curve.

monsoon season. Regression analysis including statistical significance tests suggest a strong positive relationship between TOMS AI and mid-tropospheric (4–7 km) and lower-tropospheric (surface-4 km) temperatures with correlation coefficient values of 0.67 and 0.65 (exceeding 95% significance), respectively. It is also discernable that the temperature variations in both middle and lower troposphere follow closely during the pre-monsoon season and the trends are found to be most pronounced in May. Surface temperatures (from NCEP data), on the other hand, in the same spatio-temporal domain, show no significant trend in the past three decades. Although aerosols tend to cool the surface, temperature variations at the surface were not found to be significant (see auxiliary material). It should be noted that apart from aerosol-induced surface dimming effects, there are other important forcings such as due to global warming as well as significant land use/land cover changes that the IGP has witnessed in recent decades. Surface/air temperature variability and trends require further analysis from more reliable ground station datasets. With reference to the stability of the troposphere, the warming of the middle-upper troposphere due to EHP effect would trump the surface cooling (stability) effect at the foothills of the Himalayas and the Tibetan Plateau due to atmospheric dynamic feedback from enhanced convection [*Lau et al.*, 2006]. Overall, we find enhanced warming, both in lower and middle troposphere, during pre-monsoon season, most pronounced in May, which is indicative of a strengthened meridional circulation pattern, consistent with the EHP mechanism.

4. Discussion

[13] We find that the annual mean tropospheric warming is highest over the western Himalayan region, about 1°C for the period 1979 to 2007. Isotopically inferred temperatures from Himalayan ice cores in the past millennium have also indicated warming at elevated sites over the HTP accompanied by increasing dustiness in the 20th century [*Thompson et al.*, 2000]. Dust deposition over snow cover acts to reduce the snow albedo and enhances absorbed solar radiation and snow melt rates [*Painter et al.*, 2007]. In addition to the enhanced tropospheric warming over the western Himalayan region near the snow surface, increasing dustiness could work in concert or independently in the melting the Himalayan snow cover. Although it may appear valid, however, it is not straightforward to attribute the warming as due to increasing aerosol loading, especially the presence of dust aerosols at elevated altitudes as shown here. A causal link in the opposite sense may also exist such that warming of the Himalayas at higher elevations and the subsequent rising motion may lead to enhanced inflow of air-mass from arid landmasses during the pre-monsoon season.

[14] Regardless of the cause, we believe that the warming trends appear to be amplified at elevated altitudes, particularly on a seasonal-to-interannual scale, most likely due to the induced heating of increasing dust transport and anthropogenic emissions in the Himalayan-Gangetic region. In addition, presence of enhanced water vapor, associated with the transport of dust plumes, may also increase radiative heating rates subsequently adding to the net atmospheric warming [*Kim et al.*, 2004]. As the atmosphere warms, its capacity to hold water vapor increases, which in turn provides a positive feedback to the tropospheric warming. Our ongoing work suggests a plausible response of the enhanced warming in May to be associated with an increase of water vapor flux over northern India with strong positive trends of All India Rainfall in June (not shown). The monsoon rainfall variability associated with aerosol-induced heating is a subject of an ongoing study, and will be reported in a separate paper. This paper is focused on enhanced pre-monsoon tropospheric warming over HTP, increased aerosol loading and enhanced water vapor (see auxiliary material) that are physically consistent with the key elements of the EHP effects by dust and soot aerosols

[*Lau et al.*, 2006] and related recent studies [*Lau and Kim*, 2006; *Meehl et al.*, 2008; *Bollasina et al.*, 2008]. In summary, the enhanced warming of the Himalayan-Gangetic region and the relatively smaller positive trend over the Indian Ocean appears to have strengthened the land-sea thermal gradient which may influence the monsoon rainfall variability. Together with the possible alterations to the monsoon dynamics on seasonal-to-interannual time scales, the observed warming at elevated altitudes, if continues, may also have direct implications to the Himalayan glaciers and snowpacks and in turn the hydrological cycle over much of South Asia, which has received growing scientific attention [*Barnett et al.*, 2005].

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References

Barnett, T., J. Adam, and D. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, *438*, 303–309.

Bollasina, M., S. Nigam, and K.-M. Lau (2008), Absorbing aerosols and summer monsoon evolution over south Asia: An observational portrayal, *J. Clim.*, *21*, 3221–3239.

Fu, Q., and K. N. Liou (1993), Parameterization of the radiative properties of cirrus clouds, *J. Atmos. Sci.*, *50*, 2008–2025.

Fu, Q., C. M. Johanson, S. G. Warren, and D. J. Seidel (2004), Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends, *Nature*, *429*, 55–58.

Goes, J. I., P. G. Thoppil, H. do R Gomes, and J. T. Fasullo (2005), Warming of the Eurasian landmass is making the Arabian Sea more productive, *Science*, *308*, 545–547.

Hansen, J., et al. (2002), Climate forcings in Goddard Institute for Space Studies SI2000 simulations, *J. Geophys. Res.*, *107*(D18), 4347, doi:10.1029/2001JD001143.

Hsu, N. C., S.-C. Tsay, M. D. King, and J. R. Herman (2004), Aerosol properties over bright-reflecting source regions, *IEEE Trans. Geosci. Remote Sens.*, *42*, 557–569.

Kim, S.-W., S.-C. Yoon, A. Jefferson, J.-G. Won, E. G. Dutton, J. A. Ogren, and T. L. Anderson (2004), Observation of enhanced water vapor in Asian dust layer and its effect on atmospheric radiative heating rates, *Geophys. Res. Lett.*, *31*, L18113, doi:10.1029/2004GL020024.

Lau, K.-M., and K.-M. Kim (2006), Observational relationships between aerosol and Asian monsoon rainfall, and circulation, *Geophys. Res. Lett.*, *33*, L21810, doi:10.1029/2006GL027546.

Lau, K.-M., M.-K. Kim, and K.-M. Kim (2006), Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau, *Clim. Dyn.*, *26*, 855–864, doi:10.1007/s00382-006-0114-z.

Levy, R. C., L. A. Remer, S. Mattoo, E. F. Vermote, and Y. J. Kaufman (2007), Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance, *J. Geophys. Res.*, *112*, D13211, doi:10.1029/2006JD007811.

Liu, Z., et al. (2008), Airborne dust distributions over the Tibetan Plateau and surrounding areas derived from the first year of CALIPSO lidar observations, *Atmos. Chem. Phys. Discuss.*, *8*, 5957–5977.

Mears, C. A., M. C. Schnabel, and F. J. Wentz (2003), A reanalysis of the MSU Channel 2 tropospheric temperature record, *J. Clim.*, *16*, 3650–3664.

Meehl, G. A. (1994), Influence of the land surface in the Asian summer monsoon: External conditions versus internal feedbacks, *J. Clim.*, *7*, 1033–1049.

Meehl, G. A., J. M. Arblaster, and W. D. Collins (2008), Effects of black carbon aerosols on the Indian monsoon, *J. Clim.*, *21*, 2869–2882.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo (2002), Climate effects of black carbon aerosols in China and India, *Science*, *297*, 2250–2253.

Middleton, N. J. (1986), A geography of dust storms in southwest Asia, *Int. J. Climatol.*, *6*, 183–196.

Painter, T. H., A. P. Barrett, C. C. Landry, J. C. Neff, M. P. Cassidy, C. R. Lawrence, K. E. McBride, and G. L. Farmer (2007), Impact of disturbed desert soils on duration of mountain snow cover, *Geophys. Res. Lett.*, *34*, L12502, doi:10.1029/2007GL030284.

Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill (2002), Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.*, *40*(1), 1002, doi:10.1029/2000RG000095.

Ramanathan, V., C. Chung, D. Kim, T. Betge, L. Buja, J. T. Kiehl, W. M. Washington, Q. Fu, D. R. Sikka, and M. Wild (2005), Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 5326–5333, doi:10.1073/pnas.0500656102.

Ramanathan, V., M. V. Ramana, G. Roberts, D. Kim, C. E. Corrigan, C. E. Chung, and D. Winker (2007), Warming trends in Asia amplified by brown cloud solar absorption, *Nature*, *448*, 575–578, doi:10.1038/nature06019.

Singh, R. P., S. Dey, S. N. Tripathi, V. Tare, and B. Holben (2004), Variability of aerosol parameters over Kanpur, northern India, *J. Geophys. Res.*, *109*, D23206, doi:10.1029/2004JD004966.

Thompson, L. G., T. Yao, E. Mosley-Thompson, M. E. David, K. A. Henderson, and P.-N. Lin (2000), A high-resolution millennial record of the south Asian monsoon from Himalaya ice cores, *Science*, *289*, 1916–1919.

Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari (1998), Monsoons: Processes, predictability, and the prospects for prediction, *J. Geophys. Res.*, *103*, 14,451–14,510.

Yanai, M., C. Li, and Z. Song (1992), Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon, *J. Meteorol. Soc. Jpn.*, *70*, 319–351.

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