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Potential impacts of aerosol–land–atmosphere interactions on the Indian monsoonal rainfall characteristics

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Abstract Aerosols can affect the cloud-radiation feedback and the precipitation over the Indian monsoon region. In this paper, we propose that another pathway by which aerosols can modulate the multi-scale aspect of Indian monsoons is by altering the land–atmosphere interactions. The nonlinear feedbacks due to aerosol/diffuse radiation on coupled interactions over the Indian monsoon region are studied by: (1) reviewing recent field measurements and modeling studies, (2) analyzing the MODIS and AERONET aerosol optical depth datasets, and (3) diagnosing the results from sensitivity experiments using a mesoscale modeling system. The results of this study suggest that the large magnitude of aerosol loading and its impact on land–atmosphere interactions can significantly influence the mesoscale monsoonal characteristics in the Indo-Ganges Basin.

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1 Introduction

Monsoon systems are important features of the global climate. In this paper, we suggest that aerosols—tiny particles that absorb and/or scatter solar radiation—can impact land–atmosphere interactions and the heavy precipitation episodes and other monsoon characteristics in the Indian region. Atmospheric aerosols can alter the amount of solar radiation reaching the surface and modulate the surface albedo as feedbacks coupled to physical evaporation/transpiration rate and the regional water cycle. Past studies, such as that of Ramanathan et al. (2001a), have presented the hypothesis that due to the direct and indirect aerosol effects, global precipitation and water cycles could be altered.

The surface energy budget can be written as (Pielke 2002):

$$H + LE + LT + G = (1 - A)S + LWD - LWU \tag{1}$$

where H is the sensible heat flux, LE is the physical evaporation, LT is the transpiration, G is the ground heat conduction, A is the albedo, S is the solar irradiance, LWD is the downwelling longwave irradiance, and LWU is the upwelling longwave irradiance. The equilibrium surface temperature results from this balance of heat fluxes. A change in any one of the fluxes will, in general, result in a change in the surface temperature.

The total radiation reaching the Earth's surface can also be recognized as the combination of direct and diffuse radiation. Changes in solar radiation, cloud cover, cloud type, atmospheric trace gases, and aerosols in the atmosphere can affect the radiative forcing and alter the regional climate.

A number of studies (Roderick and Farquhar 2002; Gu et al. 2003; Reichenau and Esser 2003; Niyogi et al. 2004) have conducted analyses of the effect of changes in diffuse and direct radiation on the biosphere. Taking an example of vegetation canopy, the direct beam radiation is intercepted, absorbed, or scattered by leaves at the top of the canopy. The scattered and transmitted irradiance is dispersed as a diffuse component within the canopy, penetrating down to the deeper leaves. Applying this example to the atmosphere, we can develop a 'big-tree' concept similar to the 'big-leaf' approach used in transpiration parameterizations in land-surface models. The atmospheric radiation has to pass through numerous diffusers, such as clouds, haze, and aerosols, which can act like the leaves of a tree canopy. Thus, a radiation beam transmitting through an environment that has more clouds and aerosols will have a higher DDR (diffuse to direct radiation ratio) than that under clear sky conditions. In addition to affecting DDR, clouds and aerosols can also affect surface albedo. Further, DDR and surface albedo are correlated.

2 Aerosol–land–atmosphere feedbacks

Aerosols affect the global irradiance by absorbing and scattering solar radiation. The degree to which this occurs is determined by the chemical characteristics of the particular aerosol, its size distribution, and the amount of aerosols in the atmosphere. Results from observations and model simulations from previous studies will be discussed in this section to highlight the fact that aerosols can have multi-scale

feedbacks on the surface energy balance, land–atmosphere interactions, and precipitation and convection characteristics over the monsoon regions.

2.1 Impact on energy balance and boundary layer processes

Land-use/land-cover change has been identified as a significant forcing that can impact precipitation characteristics (Pielke et al. 2006). Changes in land-surface characteristics can alter the surface Bowen ratio and have a feedback via boundary layer processes. Recent results from field measurements and model analyses suggest that aerosols can have similar impacts on land–atmosphere interactions (by modifying the surface energy balance). Most of these studies have focused on the effects of aerosols and diffuse radiation change on terrestrial carbon fluxes. Since fluxes of carbon dioxide, water vapor, and energy are closely coupled over vegetated areas, we expect that the effect on carbon fluxes exemplifies the role of aerosols in land–atmosphere interactions. Examples of studies that have documented the effects of aerosols/DDR changes on land surface response include those of Hollinger et al. (1994), Roderick et al. (1999), Gu et al. (2003), and Niyogi et al. (2004). The aerosol feedback on carbon fluxes indicates a more vigorous land–atmosphere interaction due to aerosol loading.

The notion of a more efficient landscape under a more diffuse condition is well known to the agricultural community (e.g., Goudriaan 1977). Recent observations on different vegetation landscapes have also revealed that diffuse radiation has a twofold or higher radiation use efficiency (RUE) than direct beam radiation (Gu et al. 2003; Niyogi et al. 2004). For example, Gu et al. (1999) analyzed CO_2 fluxes from two midlatitudinal forests and found that higher DDR with increased cloud cover typically led to more vigorous land–atmosphere interactions. Other field studies (Hollinger et al. 1994) also indicate similar tendencies for enhanced land-surface response under higher diffuse radiation conditions.

Regional studies related to aerosol impacts have focused on assessing the effects of volcanic eruptions. Volcanic eruptions are a major source of aerosols and are capable of ejecting aerosols directly into the stratosphere. Higher DDR values have been reported following an eruption as aerosols scatter incoming solar radiation. Gu et al. (2003) and Farquhar and Roderick (2003) concluded that aerosols released into the atmosphere as a result of volcanic eruptions can also affect the terrestrial carbon cycle through enhanced photosynthesis. A volcanic eruption in the tropics will result in a higher aerosol-induced atmospheric heating than one at the higher latitudes and also in greater temperature gradients between the equator and the poles. Soon after an eruption, the temperature may drop below the cloud layer (Robock 2000; Krakauer and Randerson 2003).

A modeling analysis by Yu et al. (2002) suggests that aerosols can affect the diurnal atmospheric boundary layer (ABL) as a response to altered surface buoyancy flux and the capping inversion. In their analysis, scattering (absorbing) aerosols lowered (increased) the BL temperature, enhanced (weakened) the capping inversion, and reduced (increased) the height of the ABL. Aerosol loadings increased entrainment and, furthermore, drying conditions and reduced surface evaporation caused a decrease in specific humidity. The drying of the ABL is less for wet soils and scattering aerosols. The BL can also dry up due to the hydrophobic properties of absorbing aerosols. Thus, radiative changes, such as those from aerosol loading, can impact the land–atmosphere feedback.

At a regional scale, changes in optical depth and DDR can impact surface evaporation/transpiration rates. Since transpiration is implicitly linked with photosynthesis and the carbon exchange over terrestrial landscapes, changes in the photosynthesis rates and, hence, the regional ecosystem exchange could also translate into changes in the regional water loss via changes in evaporation/transpiration. Chang (2004) and Niyogi et al. (2004) sought to address this hypothesis. Their results indicate that aerosol loading can alter the surface latent heat flux and hence the redistribution of the radiative energy reaching the surface; more specifically, the effect of increasing aerosol loading would cause a relative decrease in the surface latent heat flux. This was confirmed by assessing the effect of aerosol loading on other environmental variables (such as humidity, and air temperature), and a consistent feedback appears to be emerging, that of a reduced latent heat flux with increasing aerosol loading.

There are two potential reasons for the altered surface fluxes and energy redistribution with increasing aerosol loading: (1) an increase in transpiration as a response to increased DDR, and a corresponding smaller decrease in soil evaporation; (ii) an increase in the surface albedo as a feedback of soil moisture and, possibly, wavelength shifts between the incoming and reflected radiation. Both of these effects could be verified with observations and provide evidence that an integrated climate change assessment would need to consider the role of aerosols as a modulator of biogeochemical and land–atmosphere forcing, radiative redistribution of the surface energy fluxes (via Bowen ratio changes), and a potential for warming/cooling as a feedback to the aerosol loading. The uncertainty in the aerosol loading could be more significant in the monsoon regions, where the vegetation has seasonal leaf area changes and there can be complex radiation-temperature-moisture interactions of magnitudes that have not been encountered in previous midlatitude datasets.

2.2 Aerosol impacts on the Asian monsoon region

An important aspect of the radiative effects due to aerosols is the change in surface radiative fluxes that have been observed over the last few decades (1960–1990). This phenomenon, sometimes referred to as ''Global dimming'', refers to the observed decrease in the absorbed solar radiation at several places across the globe and is emerging as an important climate change issue (Pinker et al. 2005). Wild et al. (2005) recently reported a reversal in dimming after 1990 at several locations across the globe, though with continued dimming over some places, notably India (Ramanathan et al. 2005). These may be related to regional disparities in aerosol sources, types, and amounts that in turn modify surface fluxes and precipitation response differently, depending on the region. The majority of the studies dealing with the role of aerosols and cloudiness (which is a dominant mechanism for increasing diffuse radiation) have concentrated on the temperature effects, particularly at the top of the atmosphere (TOA), and radiation-cloud feedback mechanisms. We propose in this paper—largely based on observational and modeling analyses—that the aerosol- and cloud-induced diffuse radiative flux enhancement could have an even more critical impact on the surface energy balance via an increase in the photosynthesis, transpiration, and evaporation rate that can affect monsoon dynamics. The interaction between the aerosols, clouds, and the terrestrial environment can modify the redistribution of the radiative forcing and also affect the integrated climate via

biogeochemical pathways; the consequence would be an impact on the regional climate over the Indian monsoon region.

Aerosols can affect the radiative flux at the TOA and, even more profoundly, at the surface, thereby affecting biospheric processes. Therefore, changes in the diffuse radiation fraction as a result of aerosol loading would appear to have the potential to have an impact on the efficiency of land–atmosphere interactions. Although aerosols are abundant globally, their forcing effects are generally regional when compared to the global forcing effects associated with greenhouse gases (GHGs). Through upper-level jet streams, smaller aerosol particles can travel across continents typically within a week and affect the climate at locations farther than the source regions.

Regional climate model simulations of diffuse radiation due to aerosol changes were performed by Qian et al. (2003) for a region covering China. In general, high AOD values caused negative radiative forcing. The negative radiative forcing ranged from –1 to –14 W m^{-2} in the summer and fall to –1 to –9 W m^{-2} in the spring and winter. The annual average global heating at the TOA, planetary boundary layer (PBL), and surface due to the aerosol direct effect were estimated as –4.5, 5.4, and –9.9 W m^{-2}, respectively (Yu et al. 2004).

Boer et al. (2000) conducted coupled climate model simulations to examine the potential climate effect of GHGs and aerosols. For the winter monsoon period, the GHG experiment alone (doubling CO_2) resulted in a steadily increasing precipitation of about 4% in the future climate; however, when GHG and aerosol effects were both considered, the precipitation decreased by about 4%, which appears to be a response to reduced evaporation and low soil moisture availability (despite reduced evaporation). For the summer monsoon season, both the GHG and GHG with aerosol experiments projected a lowered precipitation: 3% for GHG alone and 5% for GHG with the aerosol effect. Specifically, in the Indian monsoon region, an overall reduction in precipitation was found for the winter monsoon season and increased precipitation was found for the summer monsoon season. Observations also suggest that evaporation is losing its strength in the global water cycle even though regionally, over Asia, evaporation is still relatively unchanged (Peterson et al. 1995). These results were evaluated further by Roderick and Farquhar (2002), who correlated this global decreasing pan evaporation rate to increasing diffuse radiation as a result of cloudiness and aerosols. Wild et al. (2005) recently reported that the decreasing aerosol trend and radiation trend continues most prominently over the Indian monsoon region. The decreasing trend in the pan evaporation and the potential for increased transpiration (Gu et al. 2003; Niyogi et al. 2004) will result in complex water vapor tendencies over the Indian region.

2.3 Impact of aerosol type and climate feedback

The effect of aerosols has only been a recent inclusion in climate studies, and the topic of aerosol type—rather than aerosol loading alone—has received relatively less attention. This lack of data makes a comparison of modeling results challenging, since both aerosol type and loading can affect the results dynamically.

The General Circulation Model (GCM) simulations reported in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) have found an average annual precipitation increase over most of Asia of about 3+/–1% in the 2020s, 7+/–2% in the 2050s and 11+/–3% in the 2080s. Results are however

largely driven by the projected increase in greenhouse gases (GHGs) (Lal et al. 2001). Including GHGs impacts with sulfate aerosol effects results in a lower increase in precipitation: $2 \pm 1\%$ in the 2020s, $3 \pm 1\%$ in the 2050s and $7 \pm 3\%$ in the 2080s (Giorgi and Francisco 2000). Sulfate aerosols can weaken the Asian monsoon if the effect of GHGs are taken into account and can affect the rate of increase in annual precipitation (Lal et al. 1995; Mitchell et al. 1995). The overall effect of the combined aerosol and GHG forcing is partly dependent on the land-ocean distribution of aerosol forcing and aerosol direct and indirect effects (also see Chung and Ramanathan 2006).

Chung et al. (2002) evaluated the effects of absorbing aerosols in the South Asian haze on heat flux changes in the air and at the surface during the winter monsoon. The South Asian haze could heat up the low-level atmosphere by 0.8 K per day. They used the NCAR CCM3 (National Center for Atmospheric Research Community Climate Model, ver. 3) model to find that aerosol effects also enhanced the low-level convergence, causing more convective rainfall and more latent heat release. The increasing precipitation due to the absorbing haze could thus directly affect the monsoon rainfall and be the underlying reason for the drought in Southwest Asia.

Chou et al. (2005) studied the effect of absorbing and scattering aerosols and the local and remote impacts of aerosol forcing using a global model. They concluded that reflecting aerosols have a dominant forcing, while the absorbing aerosols have a relatively less dominant forcing with a complex feedback (but the impact may be almost linear in its magnitude). These researchers further concluded that the reflecting aerosols can be a leading effect in altering tropical precipitation as well as tropospheric temperature.

Menon et al. (2002) conducted a comprehensive study in which they studied the sensitivity of the climate to effects from absorbing aerosols over India and China using observed distributions of aerosol optical depths (AODs) in the Goddard Institute for Space Studies (GISS) SI2000 12-layer climate model. With respect to China, observations over the last few decades indicate increased flooding in southern China and droughts in northern China. These trends were captured by the model only when large amounts of absorbing aerosols were taken into account. Menon et al. (2002) conclude that anthropogenic activities (primarily coal burning) produce absorbing aerosols that can affect the atmospheric circulation and regional climate. Even though the relative mass of black carbon (BC) aerosols is small compared to that of sulfates, they have a strong impact on climate due to their absorbing properties. The thermodynamic effects of changes to the vertical temperature profile (due to atmospheric heating) alter evaporation, latent heat fluxes, atmospheric stability, and the strength of convection. Even though no obvious large-scale climate trends were discernable over India in the Menon et al. (2002) study apart from increased droughts over northern India, changes to the spatial patterns of precipitation for the pre-monsoon season were found to be similar to those reported by Ramanathan et al. (2005), who also conclusively demonstrated that the atmospheric brown clouds can significantly impact on the climate, including hydrology, of the larger Indian monsoon region.

To address the issue over India, Ramanathan et al. (2001a) used a coupled Ocean and Atmospheric GCM (OA-GCM) and performed sensitivity runs to investigate the effects of aerosols over the India/Indian Ocean region during the winter monsoon by changing the single scatter albedo (SSA). For non-absorbing sulfate aero-

sols, the SSA approximated 1, while for BC (absorbing aerosol), the SSA approximated 0.2. Most of the aerosols found in the Northern Hemisphere have a SSA between 0.90 and 0.95 and are expected to result in a negative TOA forcing for SSA > 0.95 and a positive forcing for SSA > 0.85. Results from the Ramanathan et al. (2001a) study indicate values of SSA ranging from 0.85 to 1.0. Over the Indian Ocean region, aerosol layers in the atmosphere caused a divergence in the heating/cooling rates of the lower troposphere (Ramanathan et al. 2001b), decreased the solar radiation reaching the surface, and increased atmospheric heating in the lower 3 km of the atmosphere, thereby resulting in a dynamical response that strengthened the precipitation along the intertropical convergence zone (ITCZ) by 15–30% (Ramanathan et al. 2001a).

Although aerosols have a short lifetime of 2–10 days, they have a strong impact on surface forcing, atmospheric heating, and precipitation. The cooling effects caused by aerosol-cloud interactions (also called the aerosol indirect effect), ranging from -0.5 to -4.4 W m^{-2} are also quite comparable to GHG warming effect (Ramanathan et al. 2001a). The impact of aerosols on the redistribution of the radiation at the TOA is relatively well understood. However, although there have been several studies that examine changes to radiation from the aerosol indirect effects, the feedback of this variability on the ABL and convective processes is still largely unknown. Aerosols could have an even more dramatic effect on surface energy redistribution, and this effect continues to be largely undocumented.

3 Potential feedback/synthesis

The changes in the aerosol loading and associated diffuse radiation/land–atmosphere interactions can alter mesoscale responses. The variations in local to regional to global feedbacks due to aerosol processes can potentially modulate the monsoon characteristics, such as the amounts, distributions, and variability of precipitation.

Figure 1 shows the Moderate Resolution Imaging Spectrometer (MODIS) Terra-based global AOD maps for February, July, and November 2003. The figure illustrates why the aerosol impacts can be significant in the Indian monsoon region. An important feature to note is that during the summer, some of the higher AODs are around China and India when the summer monsoon is active. Thus, the magnitude of aerosol loading by itself could be one factor by which aerosol effects can be considered to be significant in modulating the local and regional scale monsoonal characteristics. Figure 2 shows the relative AOD distribution for different tropical and midlatitudinal sites around the globe. As can be seen, the sites in India (Kanpur)
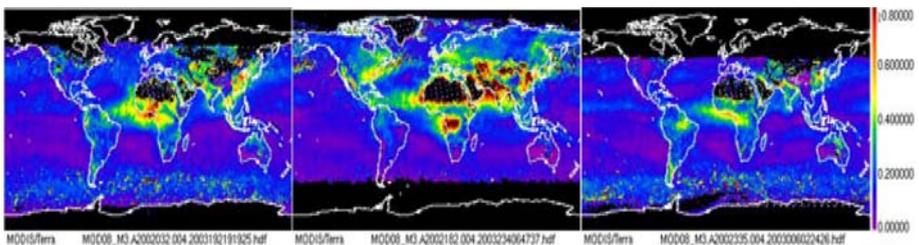
Fig. 1 Moderate Resolution Imaging Spectrometer (MODIS) imagery for aerosol optical depth in 2002. *Left* February, *middle* July, *right* November

Fig. 2 Aerosol optical depth (AOD) cumulative probability plot for: Beijing, China (39° N, 116° E); Walker Branch, Tenn. (*WB*; 35° N, 84° W); Pimal, Thailand (15° N, 102° E); Mukhadan, Thailand (16° N, 104° E); Bondville, Ill. (40° N, 88° W); Barrow, Alaska (71° N, 156° W); Abracos, Amazon, Brazil (10° S, 62° W); Kanpur, India (26° N, 80° E)
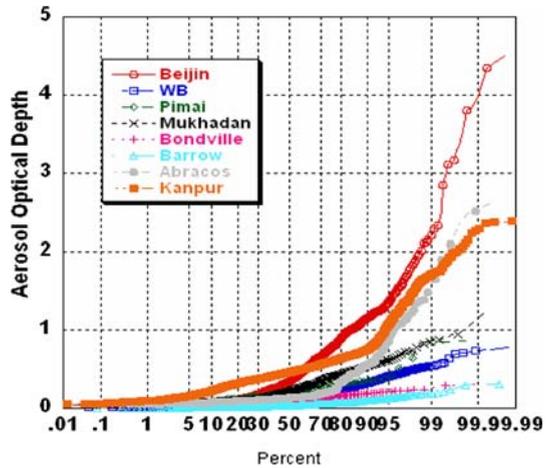
and China (Beijing) consistently show high AOD values. At Kanpur, which is situated in northern India, the AOD values are significantly high and often compare to the highest optical depth values over the United States where the majority of the impacts have been assessed (Fig. 3). One can extrapolate the results to hypothesize that aerosol impacts can significantly affect land–atmosphere interactions and hence influence the precipitation characteristics in the monsoon region. In addition, aerosol impacts on the land surface could be important in modulating the monsoonal characteristics, which are at a high degree of land–atmosphere coupling over the Indian region.

3.1 Aerosol impacts over the tropical land surface

Note that the majority—if not all—of the results are based on data from midlatitude vegetation and that the impact on the vegetation in the arid monsoon domain is

Fig. 3 Aerosol optical depth (AOD) observations from AERONET over Kanpur, India (36° N, 80° E) in 2005
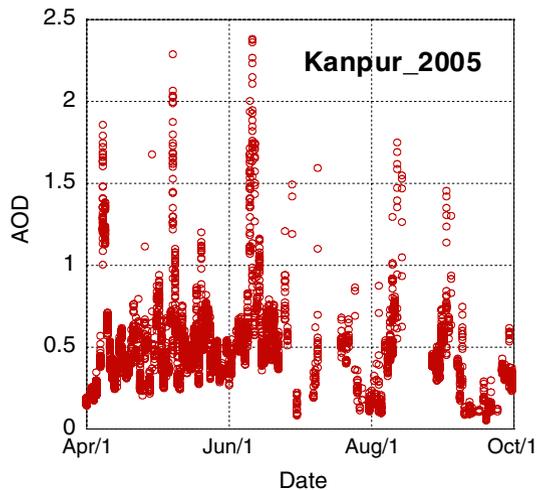
unclear. The impacts of DDR change will be affected by land-surface characteristics. In addition, other factors, such as temperature, moisture, precipitation, and heat fluxes, can influence radiation and have direct or indirect effects on the net ecosystem exchange (NEE) (Gu et al. 2003). However, aerosols could have a similar impact even over the tropical regions. For example, biomass burning as a common practice of land clearing for agriculture is the dominant source of tropospheric aerosols in tropical areas. These aerosols can substantially modulate surface radiative and moisture conditions through their direct and indirect effects (Kobayashi et al. 2004). Because tropical rainforests generally have higher leaf area indices than forests in other climate zones, such as temperate forests, aerosols in moist tropical areas are expected to exert a stronger control on vegetation activities through the diffuse radiation effect than those reported for temperate or boreal forests. For semiarid landscapes in the tropics, the diffuse radiation effect of aerosols may not be as large as those for tropical rainforests because of a reduced leaf area index (LAI), but it can still be significant because leaves and crowns of vegetation in semiarid areas such as tropical savannas tend to be clumped together, thereby creating mutual shading. However, studies in this direction have been rare and are sorely needed.

As shown empirically in Lin et al. (2006), who used datasets available for an entire dry, burning season, aerosols from biomass burning in the Amazon are associated with higher AODs, which resulted in increased rainfall in both 2000 and 2003 as well as increased cloud cover. With enhanced AOD, cloud top temperatures also decreased, suggesting higher cloud tops. These observational results are consistent with previous observational and modeling studies that pointed to dynamical effects from aerosols that invigorate convection, leading to higher clouds, enhanced cloud cover, and more rainfall. Lin et al. (2006) concluded that accelerated forest burning for agricultural land clearing and the resulting enhancements in aerosols and rainfall may even partially account for the observed positive trend in Amazonian precipitation over the past several decades.

3.2 Aerosol–land–atmosphere feedbacks—a proposed framework

The potential aerosol-induced land–atmosphere interactions that can impact the monsoon-precipitation characteristics are presented in Fig. 4. The summer monsoon onset is characterized by northern ITCZ movement, intensity, and structure as well as the associated reversal of synoptic winds. The changes over the monsoon domains in terms of precipitation and temperature characteristics are well known; however, there is now increasing evidence that the regional aerosol loadings also alter with monsoons. As discussed in Ramanathan et al. (2005), the aerosols in the Indian region have a potential for modifying the regional climate, and an additional pathway to these simulated climate changes over the India/Indian Ocean region could be the feedbacks associated with land–atmosphere interactions that are largely ignored in aerosol climate studies (Fig. 4). Aerosols could be transported over the monsoon regions from areas that have frequent biomass burning activity, large amounts of natural dust, or other kinds of trans-boundary pollution (Ramanathan et al. 2005). The resulting aerosol impacts can be classified as cooling (sulfate-dominated) and warming (BC-dominated). For the scenario in which aerosols mainly scatter, enhanced DDR and reduced surface radiation would result. Additionally, studies suggest a narrower cloud droplet spectra and higher cloud liquid water for increased

Fig. 4 Potential aerosol-land-atmosphere interactions and surface, convection, and precipitation feedbacks in the monsoonal systems. *CAPE* Convectively available potential energy, *PBL* planetary boundary layer, *DDR* diffuse to direct radiation ratio, *LAI* leaf area index, *ITCZ* intertropical convergence zone

amounts of reflecting aerosols. As a feedback to the altered radiation, land surface can show enhanced transpiration and lowered evaporation, which can lead to a lower air temperature and modified humidity levels in the surface and at the boundary layer. The changes in radiation and temperature can also modify the surface energy balance or Bowen ratio and cause stronger land–atmosphere coupling, suppression of regional soil moisture, and a higher surface and TOA albedo. It is expected that these feedbacks will lead to a lower convectively available potential energy (CAPE), suppress rain, and alter the monsoon characteristics via modified regional precipitation patterns.

When aerosols are largely absorbing, a simplified perspective suggests a warmer boundary layer with higher albedo that modifies cloud cover and impacts on the boundary layer moisture. This could lead to a shallower boundary layer. As a feedback, this is also expected to alter the surface energy balance and the land–atmosphere coupling, atmosphere convection, and associated rainfall characteristics (Pielke et al. 2002). These responses can have regional differences depending both on the aerosol types and the land-surface characteristics. For grass/croplands, it is expected that the transpiration feedback is largely seasonal and will be a function of leaf area changes. The shallower roots of the vegetation in such regions, in tandem with LAI variability, can suppress soil moisture recycling. This can also impact on

the surface albedo and BL CAPE and, more importantly, on the convective inhibitions (CIN), which can lead to altered rainfall characteristics. For woody vegetation with deeper roots and a more uniform LAI, there is a higher potential for water recycling. Overall, lower surface albedo and higher CAPE would also be found in these regions, both of which are the drivers in modifying regional precipitation characteristics and the intensity of monsoonal rainfall. The feedbacks and pathways discussed here are presented as a possible example; there are numerous nonlinear feedbacks that can occur and will impact on this multi-scale monsoonal system.

3.3 Model radiation—optical depth sensitivity analysis

To test this aerosol-radiation-induced land–atmosphere impact, we conducted a sensitivity study using a mesoscale model to simulate a convective rain event over the Indian monsoon region. We selected May 29–30, 2004, which shows a high aerosol concentration location as per the AERONET and MODIS data over India (not shown). Satellite intra-red imagery reveals that the monsoon is active and that ITCZ cloud bands are visible over the northern part of India. Some severe thunderstorm formation is also seen ahead of the ITCZ, particularly along the eastern part of India and Bangladesh, Bay of Bengal region. Three simulations were conducted to test the sensitivity of changes in radiative feedback over the Indian monsoon region; these are summarized in Fig. 5. The mesoscale model [Weather Research and Forecast (WRF) model] was run at a 30-km grid spacing and 31 vertical levels. Other model configurations included the Noah land surface model, MRF boundary layer scheme, and the Kain Fritsch cumulus parameterization. The model was initialized using NCEP (National Centers for Environmental Prediction) reanalysis, and the boundary conditions were updated every 3 h. The control case simulated the event realistically (Fig. 5a), and results compared well with NCEP reanalysis as well as with satellite imagery over the region, which showed mesoscale convection and rain over the eastern part of India and over Bangladesh/Bay of Bengal. To assess the sensitivity of monsoonal land–atmosphere interactions to radiative feedbacks, three simulations were conducted: (1) Rapid Radiative Transfer Model (RRTM scheme, control); (2) Eta operational radiation scheme (GFDL); (3) 25% increase in optical depth in the RRTM scheme. A comparison of (1) and (2) was expected to enable extraction of the effect of change in the radiative scheme, while runs (1) and (3) were expected to show the effect of increased aerosol loading (optical depth).

The results from these three simulations are summarized here. First, the results suggest that the overall rainfall distribution from the three simulations is quite similar, while the intensity is different. This is expected since the rainfall distribution is a result of the synoptic setup, while the intensity is impacted by mesoscale processes. The difference in the RRTM and GFDL simulations shows that the discrepancy in rainfall is approximately 200–300 mm in the core of the high precipitation region (along the Bay of Bengal, Bangladesh, eastern India region). For this area, the cloud water mixing ratio difference is about 4 g kg^{-1}, and the CAPE difference is about 800 J Kg^{-1}. Over the region with a high aerosol concentration, the vertical velocity difference is found to be around 4 m s^{-1}. The difference between the control and the optical depth sensitivity run yields a water vapor mixing ratio difference of about 0.4 g kg^{-1}. The difference in the two simulations is much
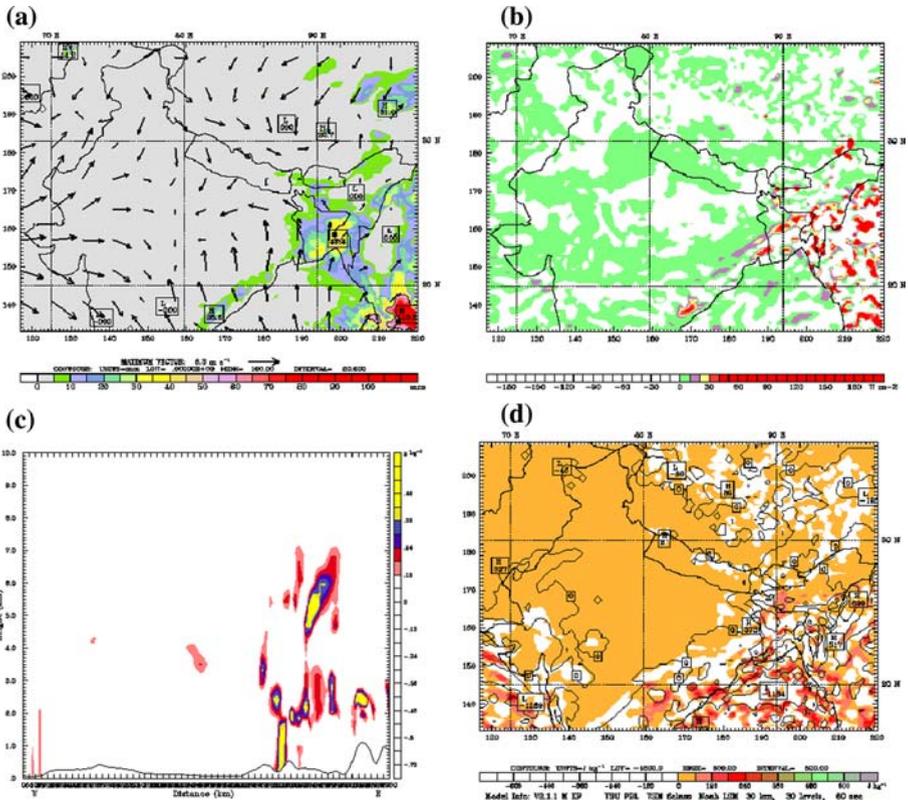
Fig. 5 **a** Total rain and the surface wind circulation for the control case. **b** Control minus modified optical depth simulation for surface latent heat flux. **c** Vertical structure of the simulated water vapor mixing ratio. **d** CAPE. The optical depth impacts are seen both at the surface and the troposphere for the region with mesoscale convection and rainfall. Model results are valid at 00UTC May 30, 2004

less in the areas with rainfall and around the ITCZ, and differences are more prominent over the high aerosol concentration region in the northern part of India where the two cases simulate significantly different weather conditions. The model which simulated CAPE and the surface vapor mixing ratio distribution shows a spatial variation of about 100 J kg^{-1} in CAPE and 23 g kg^{-1} in the vapor mixing ratio due to changes in optical depth. A synopsis of the model results (and differences) are summarized in Fig. 5. Figure 5a shows the precipitation from the control run, while Fig. 5b shows the difference between the control and effect of increased AOD on LHF. There are significant LHF differences that are seen as convection bands. The impacts of these differences are not restricted to the surface but can also be distributed vertically throughout the lower troposphere and impact on the heat and moisture transfer (Fig. 5c). This interaction further impacts the convergence pattern and convective potential (and CAPE), as is seen in Fig. 5d, which shows the differences in the simulated CAPE for the control and high AOD situations. In summary, even this limited sensitivity study enables significant conclusions to be

drawn: (1) a high aerosol concentration associated with different radiative forcing physics can significantly change the amount (intensity) of rainfall; (2) the main impact of aerosol induced land–atmosphere interactions was visible in CAPE and the surface fluxes (and moisture). More detailed studies are necessary to analyze the feedback in the land–atmosphere processes over the Indo-Gangetic plain.

4 Conclusions and future directions

Aerosols are abundant over the Indian monsoon region. Prior studies have shown that aerosols can affect the regional climate by affecting the cloud-radiative processes. In this study, we propose that aerosols can also have a profound impact on the Indian monsoon region by affecting the land–atmosphere interactions and regional coupling. This in turn can have a feedback on boundary layer response, regional convection, and the intensity/distribution of monsoonal precipitation.

Our results also provide the basis for future research which should be directed towards studying the coupled land-surface-aerosol-boundary layer cloud chemistry problem using a combination of column models, mesoscale systems, regional climate models as well as GCMs. It is also anticipated that field programs, such as those from the upcoming atmospheric brown cloud field program (Ramanathan et al. 2005), will provide important information on the underlying processes.

Some of the topics that need to be targeted include: (1) a further understanding of the role of aerosol loading as well as aerosol speciation on the BL response in order to critically evaluate the results obtained from modeling studies; (2) the impact of aerosol changes on tropical (including semiarid regions) BLs, since most of the results and findings have to be extrapolated from midlatitudes; (3) the aerosol impacts for different seasons; that is, the summer versus the winter monsoon as well as active versus break monsoon periods; (4) the effect of the vertical gradient of aerosol forcing (cooler surface with warmer BL, or warmer surface with cooler BL) rather than the column-integrated AOD impacts; (5) methods for assimilating satellite AODs and radiation products for understanding the aerosol–land–atmosphere interactions; (6) assessment of the coupling between aerosols and cloud properties (micro and macrophysical), and the mesoscale convection due to differential heating resulting from both gradients in surface and BL fluxes from surface landscape heterogeneity and to aerosol plumes.

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