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Local and remote impacts of direct aerosol forcing on Asian monsoon

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ABSTRACT: The impact of heating by black carbon aerosols on Indian summer monsoon has remained inconclusive. Some investigators have predicted that black carbon aerosols reduce monsoon rainfall while others have argued that it will increase monsoon rainfall. These conclusions have been based on local influence of aerosols on the radiative fluxes. The impact of aerosol-like heating in one region on the rainfall in a remote region has not been examined in detail. Here, using an atmospheric general circulation model, it has been shown that remote influence of aerosol-like heating can be as important as local influence on Indian summer monsoon. Precipitation in northern Arabian Sea and north-west Indian region increased by 16% in June to July when aerosol-like heating were present globally. The corresponding increase in precipitation due to presence of aerosol-like heating only over South Asia (local impact) and East Asia (remote impact) were 28 and 13%, respectively. This enhancement in precipitation was due to destabilization of the atmosphere in pre-monsoon season that affected subsequent convection. Moreover, pre-monsoon heating of the lower troposphere changed the circulation substantially that enabled influx of more moisture over certain regions and reduced the moist static stability of the atmosphere. It has been shown that regional aerosol heating can have large impact on the phase of upper tropospheric Rossby wave in pre-monsoon season, which acts as a primary mechanism behind teleconnection and leads to the change in precipitation during monsoon season. These results demonstrate that changes in aerosol in one region can influence the precipitation in a remote region through changes in circulation.

KEY WORDS monsoon; aerosols; remote-impact; GCM; Rossby-wave; radiation; precipitation

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1. Introduction

Aerosols can have a large impact on local and global climate and at the same time cause local air pollution. In this respect, they are different from carbon dioxide which has an impact on climate but does not directly cause air pollution. Carbonaceous aerosols, which primarily consist of black carbon and organic carbon, absorb and reflect radiation in the shortwave range of the electromagnetic spectrum, and thus heat the atmosphere and cool the surface. Observations and data from three-dimensional aerosol transport models show that absorbing aerosols like carbon primarily reside below 700 hPa level in the atmosphere (Satheesh *et al.*, 2006; Moorthy *et al.*, 2009). This lower tropospheric heating and surface cooling in presence of absorbing aerosols can alter the circulation pattern and precipitation.

The role of aerosols to change climate can be either through its interaction with radiation (called the direct effect) or due to its capability to change cloud microphysical properties (called the indirect effect). Several previous studies have shown that both the above mentioned processes can alter the hydrological cycle over different regions of the world (Krishnamurti *et al.*, 2009). Persistent lower tropospheric heating by absorbing aerosols can have a significant impact on circulation patterns of the atmosphere. Chung *et al.* (2002) used an atmospheric general circulation model (GCM) with prescribed sea surface temperature (SST) to find the effect of anthropogenic aerosols on precipitation over south Asia. In their study, pre-monsoon precipitation increased due to stronger meridional temperature gradient with aerosols in the model. Menon *et al.* (2002) found a reduction of precipitation over north Indian Ocean when an atmospheric GCM was forced with radiative effects of carbonaceous aerosols over south Asian region. Chakraborty *et al.* (2004) used an atmospheric GCM with aerosol forcing obtained from INDOEX (Indian Ocean Experiment) field campaign to show that the change in precipitation during monsoon season due to aerosols depend on the cumulus scheme used in the model. The impact of black carbon aerosols on tropical convection and climate has been studied by Wang (2004, 2009). Using a three-dimensional interactive aerosol-climate model, Wang (2004) found that net change in radiation at the top of the atmosphere due to black carbon aerosols could be three times to its own radiative forcing due to changes in cloud amount. Later studies by the author have observed a shift of

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the zonal mean ITCZ towards the heating region by the aerosols (Wang, 2009; Wang *et al.*, 2009).

Ramanathan *et al.* (2005) and Chung and Ramanathan (2006) showed that in presence of air–sea coupling black carbon aerosols over India can increase (reduce) pre-monsoon (monsoon) precipitation due to cooling of the ocean surface. While investigating the impact of aerosols on intertropical convergence zone (ITCZ), Chung and Seinfeld (2005) and Allen and Sherwood (2011) have found that the radiative impact of black carbon aerosols is to shift ITCZ northward. On the contrary, Kristjansson *et al.* (2005) have noticed southward movement of ITCZ due to black carbon aerosols in their model simulations. Gu *et al.* (2006) have also found decreased precipitation in ITCZ due to aerosols.

Lau *et al.* (2005) and Lau and Kim (2006) highlighted the importance of elevated heating by aerosols to explain changes in rainfall during south-west monsoon over south Asia. However, this hypothesis was later challenged by Nigam and Bollasina (2010). Meehl *et al.* (2008) showed that the effect of black carbon is to reduce Indian monsoon precipitation due to decreased meridional surface temperature gradient. Collier and Zhang (2009) have shown that monsoon precipitation over central India decreases during June to July on account of reduction in near-surface temperature in presence of black carbon aerosols. Recently Bollasina and Nigam (2009), using observed data set, have pointed out that absorbing aerosols can modify the hydroclimate over Indo-Gangetic plane significantly by changing cloudiness and precipitation. Bollasina *et al.* (2011) showed that inclusion of anthropogenic aerosols in a coupled model could reproduce the observed decreasing trend in precipitation over central India. Table 1 lists all the above-mentioned modelling studies using aerosols and their primary findings related to precipitation over Indian region. A comprehensive review on the radiative impacts of black carbon aerosols can be found in Zhang and Wang (2011).

Most of the above studies looked at the change in precipitation and circulation due to local aerosol radiative forcing. Aerosols can have remote impacts on climate due to persistent change in atmospheric heating pattern that can tend to change circulation (Wang, 2007).

In many parts of the world aerosols are being reduced on account of attempts to reduce air pollution. What will be the impact of reduction in air pollution in one region on the climate of nearby regions? In this article, we try to address the question of local and remote impact of carbonaceous aerosols on Indian summer monsoon using an atmospheric GCM. Although absorbing aerosols can cool the ocean surface and thus change monsoon precipitation, understanding such changes in coupled climate models is difficult due to complexity in air–sea interactions. Here, we have deliberately used an atmospheric GCM to assess the local and remote impacts of heating by carbonaceous aerosols. This will enable us to understand the effect of reduction in aerosols in other parts of the world on rainfall and circulation in India. We also examine what impact the reduction in black carbon aerosols in India would have on the Indian Summer Monsoon. The results from such experiments can throw light on the effect of changing atmospheric heating pattern on circulation. The article is organized as follows. The next section describes the aerosol forcing used in the model. Sections 3 and 4 describe the model used and experimental setup. The results are discussed in Section 5, followed by the major conclusions of this study.

2. Aerosol forcing

The atmospheric and surface radiative aerosol forcing used in this study were compiled by Takemura *et al.* (2002) using a global three-dimensional model that includes observed sources, sinks, and transport of aerosol by winds. In their aerosol transport model, Takemura

Table 1. Previous studies on the radiative effects of aerosols on precipitation.

Authors	Model type	Primary findings
Chung *et al.* (2002)	AGCM	Enhancement (reduction) in pre-monsoon (monsoon) precipitation
Menon *et al.* (2002)	AGCM	Reduction (enhancement) of precipitation over north (peninsular) India
Chakraborty *et al.* (2004)	AGCM	Change in precipitation dependent on cumulus scheme
Wang (2004)	AGCM	Change in radiative fluxes are higher if aerosols are allowed to change cloud properties
Wang (2009)	AGCM	ITCZ shifts towards the maximum heating location
Gu *et al.* (2006)	AGCM	ITCZ weakens
Lau *et al.* (2005)	AGCM	Enhancement of monsoon precipitation
Ramanathan *et al.* (2005)	CGCM	Cooling of ocean surface reduces monsoon precipitation
Chung and Seinfeld (2005)	AGCM-MLOM	ITCZ shifts northward
Allen and Sherwood (2011)	AGCM-SOM	ITCZ shifts northward
Kristjansson *et al.* (2005)	AGCM-SOM	ITCZ shifts southward
Chung and Ramanathan (2006)	CGCM	Monsoon precipitation weakens due to decreased meridional SST gradient
Meehl *et al.* (2008)	CGCM	Monsoon precipitation weakens due to decreased meridional SST gradient
Bollasina *et al.* (2011)	CGCM	Anthropogenic aerosols decrease precipitation over central India

et al. (2002) estimated sources of carbonaceous aerosols from forest fires, fossil fuel consumption, fuel wood consumption, agricultural waste combustion and gas to wood conversion of terpene. Monthly black carbon emission data set was generated using a combination of that from FAO (1997) and from the Global Emission Inventory Activity (GEIA) database of biomass burning (Cooke and Wilson, 1996). The details of the aerosol transport model along with emission sources can be found in Takemura (2002). The data was available as monthly mean atmospheric and surface forcing all over the globe from different components of aerosols as well as their combined forcing. In this study, we used radiative forcing by carbonaceous aerosols to evaluate its impact on precipitation and circulation over South and East Asia. The forcing was obtained (in W m^{-2}) at the top of the atmosphere and at surface. The model was forced with these values (details in Section 4). This study does not take into account the indirect effect of aerosols, which will be addressed in future correspondence.

Figure 1(a) shows the annual mean atmospheric forcing for 1998 due to carbonaceous aerosols (all types including black and organic species). The absorbing nature of such aerosols in the shortwave range of the electromagnetic spectrum makes the atmospheric forcing primarily positive. In other words, the net effect of carbonaceous aerosol is to heat up the atmosphere. The magnitude of this forcing exceeds 7 W m^{-2} over south-western Asia and eastern Asia. The large region of positive forcing over the Indo-Gangetic plain and over eastern parts of China are major features of this annual mean forcing. The annual mean surface forcing by carbonaceous aerosols is cooling by almost the same magnitude (not shown).

Figure 1(b) and (c) shows the seasonal variation of monthly mean atmospheric and surface radiative forcing averaged over south Asia (60–100°E, 5–40°N) and east Asia (100–135°E, 20–45°N), respectively. Mean atmospheric forcing due to carbonaceous aerosols show a peak during the pre-monsoon season over south Asia. Carbon is the main contributor to total atmospheric forcing over this region in this period. Forcing decreases sharply as the monsoon sets over India during June and has a minimum in October. Carbonaceous aerosols dominate the surface radiative forcing over the Indian region (Figure 1(b)), and show the opposite sign and trend compared to atmospheric forcing. Over East Asia, the peak forcing is during February to April. Aerosol

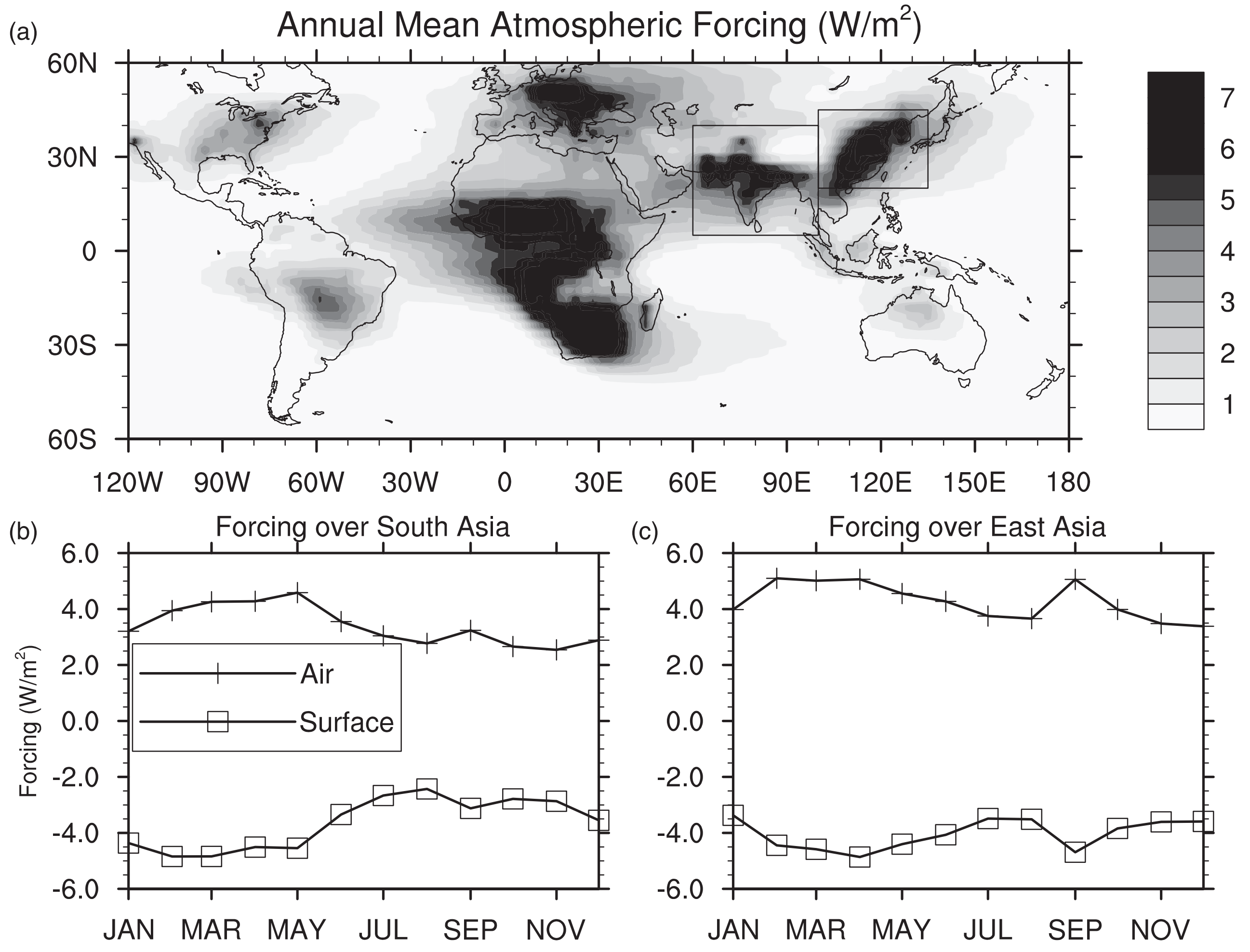

Figure 1. Heating due to carbonaceous aerosols prescribed to the model. (a) Annual mean atmospheric forcing; (b) Monthly mean atmospheric and surface forcing over South Asia and (c) over East Asia (The regions are shown in panel a).

radiative forcing decreases with the commencement of rain during May over this region. There is a sharp increase during post monsoon season in September that is comparable to the pre-monsoon values. The atmospheric heating and surface cooling by carbonaceous aerosols will be termed as aerosol-like heating in this article.

3. Model details

We have used the National Centre for Medium Range Weather Forecast (NCMRWF) model for our study. This atmospheric GCM is a version of the original global spectral model of NCEP (Sela, 1982). The model has triangular truncation at 80 waves in horizontal and 18 vertical levels. The equivalent horizontal dimensions are 256 grids in east–west and 128 grids in north–south, which corresponds to about 1.41 × 1.41 degree resolution near the Equator. To resolve the boundary layer and tropopause, vertical levels are relatively denser near the surface and tropopause. Simplified Arakawa Schubert (SAS) scheme was used for convection parameterization (Grell, 1993). The atmospheric model was coupled to a land surface model that calculates surface fluxes and soil moisture, among other parameters. This model showed good performance in simulating Indian summer monsoon while forced with observed SST (Chakraborty *et al.*, 2002, 2004, 2006, 2009) and therefore can be used for sensitivity studies with good confidence.

4. Experimental setup

The original version of the model did not include aerosol radiative heating. Simulations with the original version of the model will be termed as NoHt in this study.

Next, we have modified the model to introduce direct radiative heating effects from carbonaceous aerosols estimated by Takemura *et al.* (2002). This is a one-way interaction where the aerosol-like heating are allowed to modify model temperature however the model is not allowed to change the aerosol-like heating rate (e.g. scavenging effect of precipitation can reduce amount of aerosols and thus change the heating rate). However, since the modulation of shortwave radiative fluxes due to aerosols obtained from monthly mean data Takemura *et al.* (2002) has seasonality (Figure 1(b) and (c)), this forcing can be considered as representative during different months of the year.

The carbonaceous aerosols affect heating rate of the lower troposphere in the model (below 0.7 sigma level) since most of the aerosols are present below that layer (Satheesh *et al.* 2006). The surface forcing was used to modify the surface heating rate in the model over land. The data was available at 2.8 × 2.8° horizontal resolution. We have used the TOA and surface forcing for this study. The forcing was interpolated linearly to model run time from monthly mean data set. This approach was similar to that used in Chakraborty *et al.* (2004).

To understand the impact of carbonaceous aerosols on Indian summer monsoon, we have conducted sensitivity experiments using the above mentioned configuration. At first, the effect of heating by global distribution of carbonaceous aerosols was introduced in the model (will be termed as HtGlb in this study). In the next set of experiments aerosols were removed from south Asia (60–100°E, 5–40°N) and East Asia (100–135°E, 20–45°N). These experiments will be termed as NoHtSA and NoHtEA, respectively in this article. They were compared with HtGlb and were useful to understand the effect or reduction of aerosols over certain regions.

One set of complimentary experiments was performed where carbonaceous aerosols are present only over south Asia and east Asia region. These simulations will be termed as HtOnlySA and HtOnlyEA, respectively in this paper. These experiments were compared to the NoHt experiment to understand the effect of aerosol-like heating only over certain locations. Table 2 list of all the experiments performed in this study.

In all cases, ensemble simulations were performed using five different initial conditions corresponding to 00 GMT of 1–5 January 1998 for each experiment. Initial conditions were obtained from NCEP/NCAR reanalysis project. The surface boundary conditions over ocean were obtained from monthly mean data of Reynolds *et al.* (2002) and were interpolated to the model run time. Daily outputs were obtained from January to September for each member. Ensemble mean results corresponding to the five members of each experiment (1–5 January initial conditions) are presented in this article.

5. Results

Figure 2 shows June to September 1998 mean precipitation over south Asia from Climate Prediction Center Merged Precipitation Analysis (CMAP) observations and ensemble mean model simulation without any aerosol-like heating (NoHt). Note that the model is able to capture precipitation maximum over northern Bay of Bengal, western parts of the Western Ghats Mountains and over

Table 2. List of all the experiments performed in this study.

Experiment name	Description
NoHt	Aerosol-like heating not present
HtGlb	Aerosol-like heating present all over the globe
HtOnlySA	Aerosol-like heating present only over south Asia
NoHtSA	Aerosol-like heating absent over south Asia
HtOnlyEA	Aerosol-like heating present only over east Asia
NoHtEA	Aerosol-like heating absent over east Asia

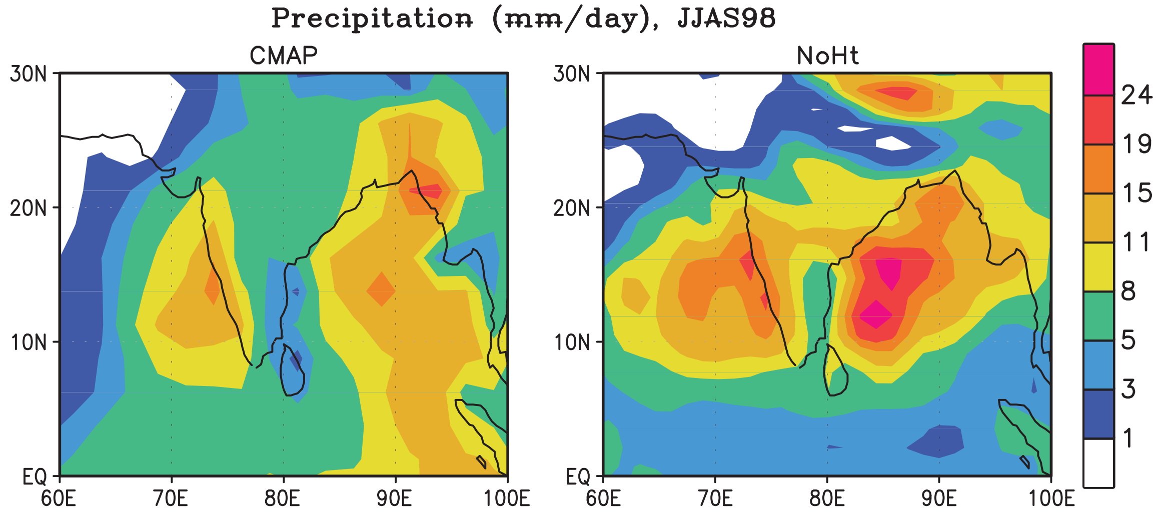

Figure 2. Mean precipitation during June to September 1998 from CMAP estimation and simulation of the model without any aerosol-like heating (NoHt).

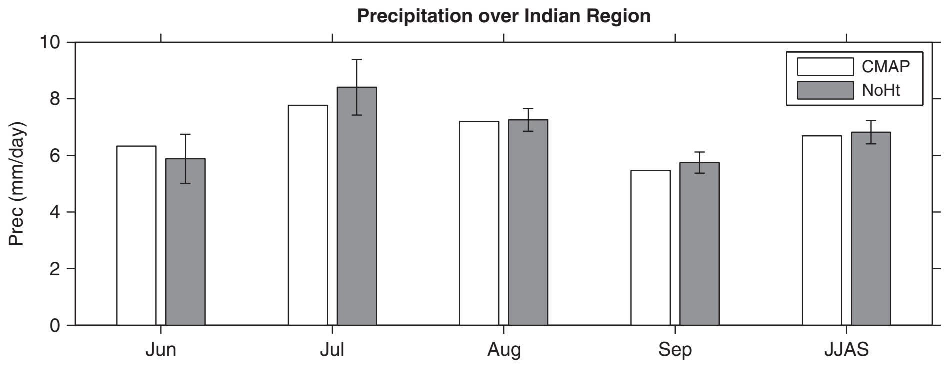

Figure 3. Monthly mean precipitation over the Indian region (70°–90°E, 8°–28°N, land) from CMAP estimation and model simulation without any aerosol-like heating (NoHt). One standard deviation among the model ensemble members are shown as error bars in the figure.

central India. Although model simulated precipitation near the foothills of the Himalayas are lower than the observations, the overall spatial pattern is comparable to that observed.

Figure 3 shows monthly variation of precipitation over Indian region (70–90°E, 8–28°N, land) from observational estimates from CMAP and ensemble mean simulation of the model without any aerosol-like heating (NoHt). One standard deviation of the ensemble members is shown as error bars in the figure. Highest error in NoHt simulation was found in June and July. These early monsoon months were also associated with highest standard deviation between the ensemble members. June is the onset month of Indian summer monsoon and a few days difference in onset date within the ensemble can produce a large variation in average precipitation during that month. Standard deviation in August and September and seasonal mean (JJAS) were within 0.5 mm day^{-1}. Figures 2 and 3 and previous studies using this model (Chakraborty *et al.*, 2002, 2009) show that the NoHt simulation of the model closely follows the observed monthly variation of seasonal precipitation and its spatial structure over the Indian region. Therefore, it should be possible to perturb the model to study the impact of aerosol-like heating on monsoon precipitation.

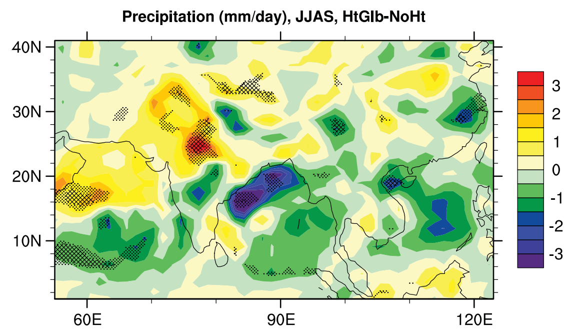

Figure 4. Change in precipitation in June to September due to aerosol-like heating over the entire globe (HtGlb) as compared to no-heating (NoHt). Regions where the differences are significant at more than 90% (95%) level using a *t*-test are marked with dots (cross).

5.1. Aerosol-like heating all over the globe

Figure 4 shows the change in precipitation over south and east Asian monsoon regions during June to September due to heating induced by carbonaceous aerosols over the entire globe. Places where the difference is significant at more than 90% (95%) level (calculated using a t-test) are marked by dots (cross). The major changes are seen over northern Arabian Sea and northwestern parts of Indian subcontinent. Seasonal mean increase in precipitation over these regions was more than 0.75 mm day^{-1}. We also note that the effect is less on East Asian precipitation than that over South Asia. In Figure 4, we also find that there is a decrease in rainfall over Bay of Bengal when aerosol-like heating was imposed in the model.

We examine changes in moist static stability of the atmosphere to understand the changes in Indian summer monsoon precipitation. Neelin and Held (1987) had discussed the relationship between moist static stability and convection. They have shown that an increase in the moist static energy of the lower and middle troposphere leads to an increase in precipitation. The moist static energy (h) is defined as:

$$h = C_p T + Lq + gz \quad (1)$$

where T is the temperature (in K), q, the specific humidity (in kg kg^{-1}) and z, the height of the atmospheric layer (in meters). C_p is the specific heat at constant pressure, L, the latent heat of evaporation and g, the acceleration due to gravity.

Vertical moist-static stability (VMS) is defined as

$$VMS = h_{top} - h_{bot} \quad (2)$$

where,

$$h_{top} = \frac{1}{P_{\mathrm{mid}} - P_{\mathrm{top}}} \int_{P_{\mathrm{top}}}^{P_{\mathrm{mid}}} h \ \mathrm{d}p$$

$$h_{bot} = \frac{1}{P_{\mathrm{bot}} - P_{\mathrm{mid}}} \int_{P_{\mathrm{mid}}}^{P_{\mathrm{bot}}} h \ \mathrm{d}p \quad (3)$$

In our study P_{bot}, P_{mid} and P_{top} are taken as surface pressure, 550 and 100 hPa, respectively. An increase in moist static energy in the lower troposphere results in the reduction of vertical static stability (Neelin and Held, 1987) leading to an increase in precipitation. Zhang (1994) and Nanjundiah (2000) have shown that the changes in precipitation in GCM are associated with changes in vertical stability. Nanjundiah and Srinivasan (1999) have also shown that precipitation changes over the Pacific Ocean between El-Nino and La-Nina can be understood in terms of changes in vertical stability of the atmosphere.

Figure 5(a) shows the change in VMS during the pre-monsoon season (March to May) due to aerosol-like heating all over the globe (HtGlb) as compared to no-heating (NoHt). Sign of change in VMS is homogeneous over large regions in pre-monsoon months. The western parts of India, northern Arabian Sea and southwest Bay of Bengal show decrease in VMS. The value of this decrease exceeded 0.6 kJ kg^{-1} over northwestern parts of the Indian subcontinent. VMS increased over the southern parts of the Arabian Sea, eastern India and east Asia including the north China Sea by as much as 0.3–0.8 kJ kg^{-1}. The corresponding change in precipitation during the first half of monsoon season (June to July) is shown in Figure 5(b). We have considered the first half of the season to assess the impact of pre-monsoon conditioning of the atmosphere on early monsoon convection. Once convection starts, it changes the thermodynamic and dynamic states of the atmosphere and therefore can have a different response as compared to the first half. Figure 5 shows that change in precipitation during June to July closely correspond to changes in VMS during March-May. An increase in VMS over south Arabian Sea during March to May resulted in a decrease in precipitation during June to July season. And a decrease in VMS over northern Arabian Sea increased precipitation in this regions. It can also be noticed that the decrease in precipitation over east Asia during June to July seen in

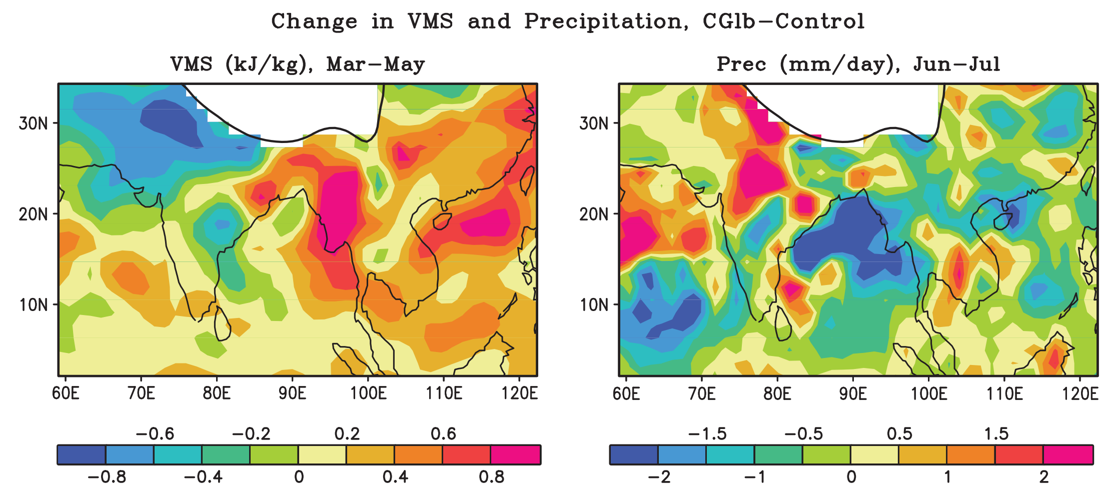

Figure 5. (a) Change in vertical moist static stability during the pre-monsoon season (March to May); and (b) change in precipitation during the first half of monsoon season (June to July) due to aerosol-like heating over the globe (HtGlb). The 3.5 km orographic height is shown as thick black contour.

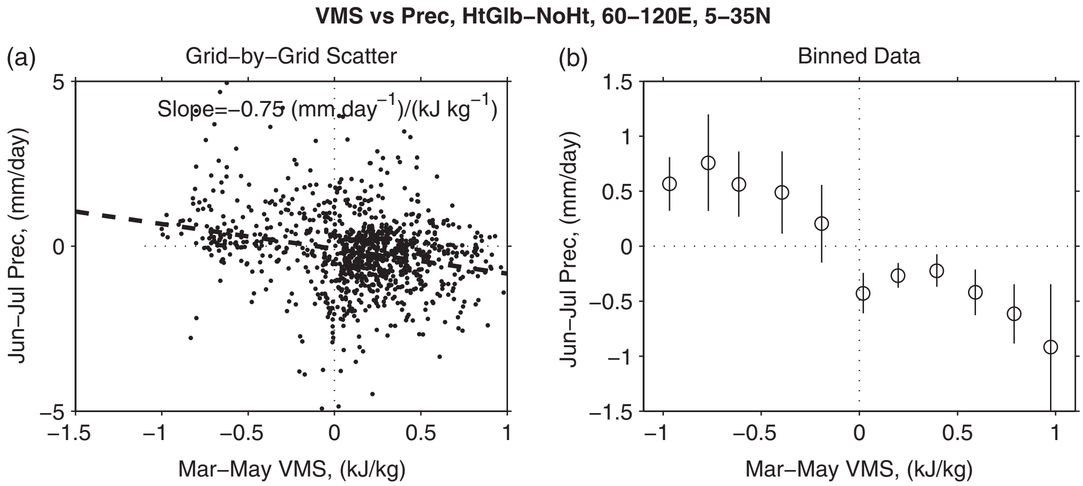

Figure 6. Relationship between change in moist static stability during the pre-monsoon season (March to May) and change in precipitation during the first half of the monsoon season (June to July) over 60°–120°E, 5°–35°N due to carbonaceous aerosol forcing over the globe: (a) Grid-by-grid scatter plot. The slope of the linear regression fit between the points is −0.75 (mm day^{-1})/(kJ kg^{-1}). (b) Data binned at every 0.2 kJ kg^{-1} VMS range. The 95% confidence intervals are shown as vertical lines.

Figure 5(b) can be explained by the increase in VMS in pre-monsoon season over this region.

A grid-by-grid scatter plot of VMS (in March to May) *versus* precipitation (in June to July) over 60–120°E, 5–35°N is shown in Figure 6(a). A negative correlation between pre-monsoon VMS and early monsoon precipitation can be noticed here. The relationship between these two parameters shows that in general a decrease (an increase) in VMS is precursor to an enhancement (a reduction) in precipitation. About two third of the points in this figure are on the second and fourth coordinates where changes in VMS and precipitation have opposite signs. A least-square linear fit between these two parameters is indicated by the thick-dashed line. The slope of this line is −0.75 (mm day^{-1})/(kJ kg^{-1}). This implies that an increase of 1 kJ kg^{-1} in VMS in during March to May leads to a decrease in rainfall of 0.75 mm day^{-1} in June to July rainfall. In Figure 6(b) we have averaged the data (of Figure 6(a)) at every 0.2 kJ kg^{-1} bin of VMS. Circles indicate the averaged values and 95% confidence bands on the average are shown as vertical lines. Note that the negative correlation between change in pre-monsoon season VMS and early-monsoon season precipitation seen in Figure 6(a) is retained in the binned data set.

5.2. Aerosol-like heating over south Asia

In this section, the impacts of regional aerosols are investigated by sensitivity experiments which selectively remove or retain aerosol-like heating over south Asia. These experiments are useful to examine the impact of clean air laws that might be implemented in some of the countries in this region.

Figure 7(a) shows the spatial pattern of change in precipitation in June to July due to removal of aerosol-like heating from south Asia (NoHtSA) as compared to heating over the entire globe (HtGlb). Regions where the

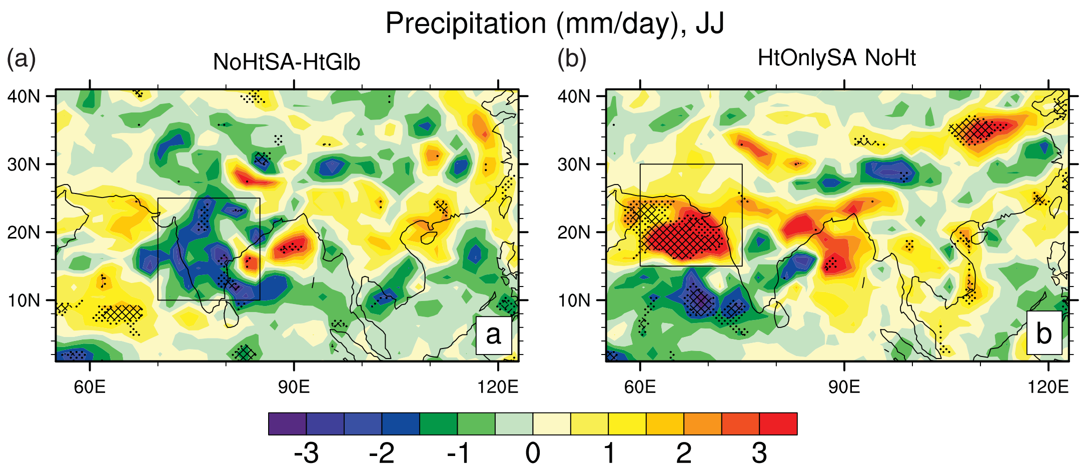

Figure 7. Change in precipitation in June to July for (a) no aerosol-like heating over south Asia (NoHtSA) as compared to heating everywhere (HtGlb); and (b) aerosol-like heating only over south Asia (HtOnlySA) as compared to no heating (NoHt). Regions where the differences are significant at more than 90% (95%) level using a t-test are marked with dots (cross).

differences are significant at more than 90% (95%) level using a t-test are indicated by dots (cross). Decrease in precipitation with large magnitude and coherent spatial pattern over Indian land and south Bay of Bengal is seen when aerosol-like heating is removed from this region. Precipitation increased significantly (90% level) over southern Arabian Sea and northern Bay of Bengal.

Change in June to July mean precipitation in the complementary set of experiments, when aerosol-like heating was introduced only over south Asia (HtOnlySA) and compared to no aerosol-like heating (NoHt), is shown in Figure 7(b). Precipitation increased by about 2 mm day^{-1} over large portions of northern Arabian Sea and Bay of Bengal, including the core-monsoon zone over India. Precipitation decreases over south Arabian Sea, south peninsular India and over north-east Indian region. Most of the changes over Arabian Sea were significant at more than 95% level.

The above figure shows that when aerosol-like heating is present (absent) only over south Asia, there is an increase (decrease) in precipitation over most of the Indian region. This indicates a northward shift of the ITCZ in presence of aerosol-like heating. This result is consistent with previous studies by Chung and Seinfeld (2005) and Allen and Sherwood (2011).

Figure 8 shows the area mean change in vertical profiles of moist-static energy over south-central Indian region (70–85°E, 10–25°N; panel a) and over north-west Indian region (60–75°E, 15–30°N; panel b) during pre-monsoon season (March to May) in the above mentioned sets of experiments. Also shown are the changes in temperature term of the MSE equation (Cp T) and moisture term of the MSE equation (Lq) to highlight the differences in temperature and moisture. Changes in VMS and precipitation during this period are indicated as numbers at the top-right corner of respective panels. When aerosol-like heating was removed from south Asia (NoHtSA), pre-monsoon temperature in most of the lower troposphere decreased as compared to the simulation with global distribution of aerosol-like heating (HtGlb). This was due to the removal of heating from lower troposphere (below 700 hPa). Lower tropospheric moisture has also decreased in the NoHtSA experiment and as a result the MSE decreases by 0.3–0.9 kJ kg^{-1} over this region. This increases the VMS and reduces subsequent monsoon precipitation (Figure 7).

When aerosol-like heating were introduced only over south Asia (HtOnlySA), temperature increased in the most of the lower troposphere over south west Indian region (Figure 8(b)) as compared to no aerosol-like heating experiment (NoHt). This was due to the combined effect of surface cooling by aerosols and atmospheric heating below about 700 hPa. Pre-monsoon lower tropospheric moisture was also increased over this region when aerosol-like heating was included. The combined effect was to increase MSE of the lower troposphere and decrease MSE in the upper troposphere (due to decrease in temperature). This reduces VMS by 0.6 kJ kg^{-1} that was instrumental in increasing precipitation in early monsoon season (June to July; Figure 7(b)). The reason behind this change in moisture is investigated below through lower tropospheric winds and balance of atmospheric moisture flux.

5.3. Changes in lower tropospheric circulation

Changes in 850 hPa vector wind during March to May due to removal of aerosol-like heating from south Asia (NoHtSA) as compared heating all over the globe (HtGlb) is shown in Figure 9(a). Anomalous north-easterly winds are noticed over Arabian Sea, Bay of Bengal and equatorial Indian Ocean. This could be responsible for decreased moisture flux over the Indian region.

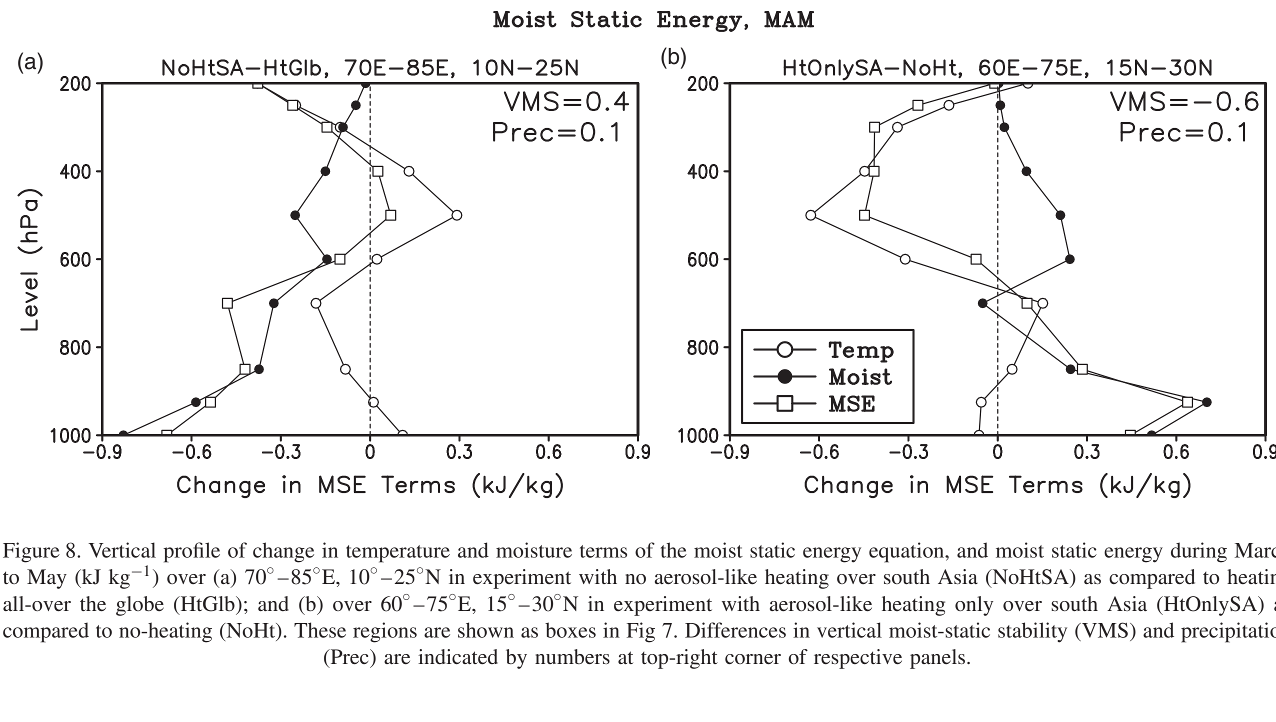

Figure 8. Vertical profile of change in temperature and moisture terms of the moist static energy equation, and moist static energy during March to May (kJ kg^{-1}) over (a) 70°–85°E, 10°–25°N in experiment with no aerosol-like heating over south Asia (NoHtSA) as compared to heating all-over the globe (HtGlb); and (b) over 60°–75°E, 15°–30°N in experiment with aerosol-like heating only over south Asia (HtOnlySA) as compared to no-heating (NoHt). These regions are shown as boxes in Fig 7. Differences in vertical moist-static stability (VMS) and precipitation (Prec) are indicated by numbers at top-right corner of respective panels.

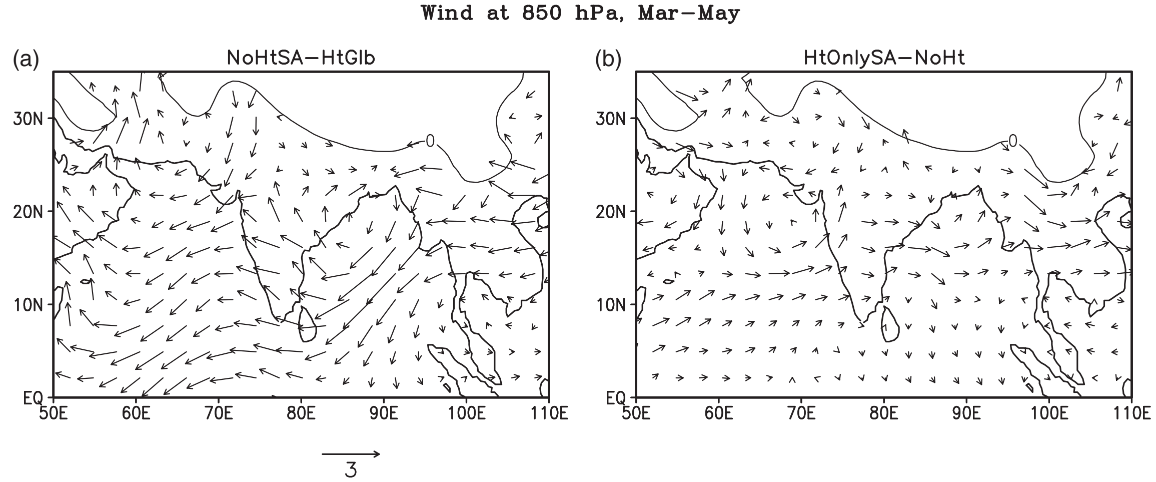

Figure 9. Change in vector wind at 850 hPa during March to May due to (a) no aerosol-like heating over south Asia (NoHtSA) as compared to heating everywhere (HtGlb); and (b) aerosol-like heating only over south Asia (HtOnlySA) as compared to no heating (NoHt).

When carbonaceous aerosols are present only over south Asian region, substantial increase in south-westerlies (2–3 m s^{-1}) at 850 hPa is seen over north Arabian Sea near the west coast of India (Figure 9(b)). This could bring more moisture into land and enhance precipitation subsequently. These results show that effect of aerosol-like heating is to increase southwesterly winds to the south-west of the heating region.

5.4. Moisture budget

The vertically integrated moisture budget was estimated using the following equations. The moisture balance equation for a volume (a grid in the model or observational data at a particular vertical layer) can be written as

$$\frac{d\rho_v}{dt} = \frac{\partial \rho_v}{\partial t} + \vec{V}.\vec{\nabla}\rho_v = S \quad (4)$$

where, ρ_v is the density of water vapour, $\vec{V}$, the three-dimensional velocity field and S, the source term. The second term of the left hand side represents advection of moisture. Integrating over a volume V, applying vector identity and using Gauss divergence theorem the above equation becomes

$$\int_V \frac{\partial \rho_v}{\partial t}\ dV + \int_A \rho_v \vec{V}.\widehat{n}\ \mathrm{d}A = \int_V S\ \mathrm{d}V = E - P \quad (5)$$

where A is the area bounding the volume V of an atmospheric column, and $\widehat{n}$, the unit vector perpendicular to the elemental area dA, E, the evaporation and P, the precipitation. The first term of the left hand side is the rate of change in total column precipitable water. The second term can be written as four individual terms along the four walls of a rectangular region, which when divided by total area of the region, gives net advection of moisture out of the control volume in kg m^{-2} s^{-1}. In our following analysis, the sign convention is such that a positive moisture flux represents net increase in moisture over the region.

Figure 10 shows the change in moisture flux and related parameters over south-central Indian region (70–85°E, 10–25°N) due to removal of aerosol-like heating from south Asia, and over north-west Indian region (60–75°E, 15–30°N) due to inclusion of aerosol-like heating only over south Asia. When aerosols were

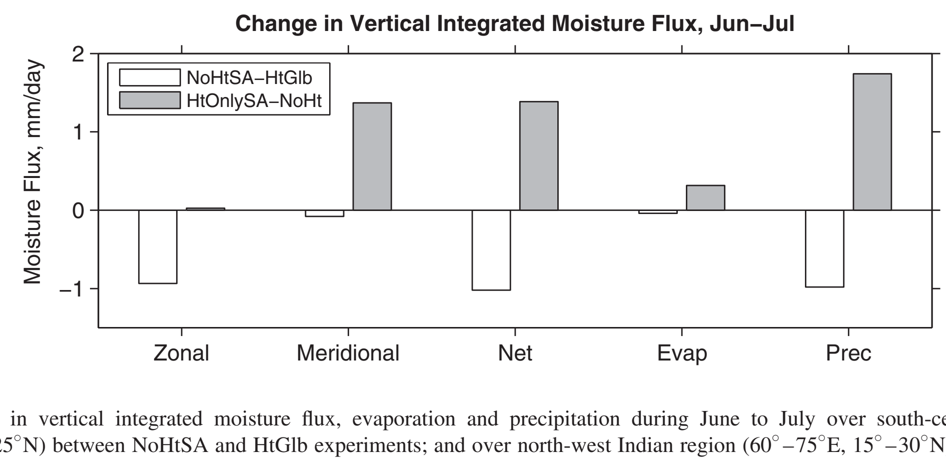

Figure 10. Change in vertical integrated moisture flux, evaporation and precipitation during June to July over south-central Indian region (70°–85°E, 10°–25°N) between NoHtSA and HtGlb experiments; and over north-west Indian region (60°–75°E, 15°–30°N) between NoHt and HtOnlySA experiments.

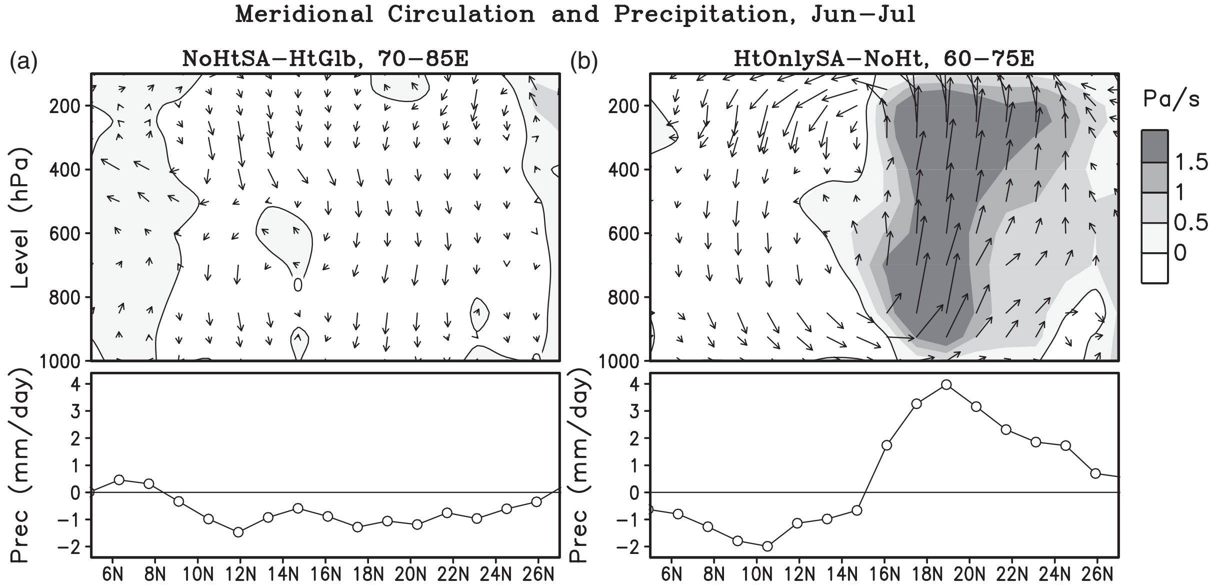

Figure 11. Change in vertical pressure velocity (Pa s^{-1}) and meridional velocity (m s^{-1}) along (a) 60°–80°E during June to July in experiment with no aerosol-like heating over south Asia (NoHtSA) as compared to heating all-over the globe (HtGlb); and (b) along 60°–75°E in experiment with aerosol-like heating only over south Asia (HtOnlySA) as compared to no-heating (NoHt). Sign of pressure velocities are reversed so that positive values indicate upward motion. Lower panels show change in precipitation along the same longitude belt for corresponding experiments of the top panels.

removed from south Asia, net zonal inflow of moisture decreased by about 1 mm day^{-1} over this region. There was no significant change in meridional moisture flux or evaporation. The net moisture flux, therefore, was decreased by 1 mm day^{-1} and reduction in precipitation was also of the same magnitude.

On the contrary, when aerosol-like heating was present only over south Asia, net meridional moisture flux into north-west Indian region increased by more than 1 mm day^{-1} as compared to no-heating experiment (NoHt). There was no significant change in zonal moisture flux in this case. Evaporation increased by about 0.3 mm day^{-1} and the net effect was to increase the precipitation by about 1.8 mm day^{-1}.

5.5. Changes in meridional circulation

Figure 11(a) shows the change in June to July mean vertical pressure velocity (shaded) and changes in meridional circulation (vector) along 70–85°E due to removal of aerosol-like heating from south Asia (NoHtSA) as compared to heating all over the globe (HtGlb). Also shown, in the panel below, the change in precipitation along the same longitude belt as a function of latitude. The sign of the pressure velocity was reversed such that a net reduction means increase in upward motion and an enhancement means decreased upward motion. Note that largest decrease in upward motion north of 15°N was due to removal of aerosol-like heating from this region.

When aerosol-like heating was present only over south Asia, there are two centres of large relative upward motion in the lower and upper troposphere compared to NoHt experiment. Compensating downward motion is noticed south of 15°N where there is a reduction in precipitation. This shows that presence of aerosol-like heating can induce changes in local Hadley cell that can be instrumental in regional redistribution of precipitation. Therefore, the northward shift in ITCZ shown in Figure 7(b) was due to an enhancement of precipitation near locations of maximum aerosol heating and corresponding subsidence of air south of the region that suppresses convection. This result is similar to that obtained by Krishnamurti *et al.* (2009) using MODIS (The Moderate Resolution Imaging Spectroradiometer) observed aerosol forcing in the GSFC (Goddard Space Flight Center) GCM. Recently, Bollasina *et al.* (2011) have also shown that anthropogenic aerosols can change meridional circulation over south Asian monsoon region. Another study by Krishnan *et al.* (2013) shows relationship between strength of Hadley circulation and south Asian monsoon under global warming scenario. Therefore, it can be concluded that local Hadley cell can have substantial impact in determining the spatial distribution and intensity of monsoon precipitation over Indian region, as shown in Figure 11.

5.6. Impact on phase of upper Tropospheric Rossby wave

In this section, we examine the effect of aerosol-like heating in modifying the upper tropospheric Rossby wave. Liu *et al.* (2004) have shown that diabatic heating can have large impact on subtropical anticyclones. Joseph and Srinivasan (1999) found that Indian summer monsoon is negatively correlated with 200 hPa meridional wind of pre-monsoon season (May) over the Indian longitudes. Hu *et al.* (2005) noticed that there exists a high correlation between wave activity at 200 hPa and Indian summer

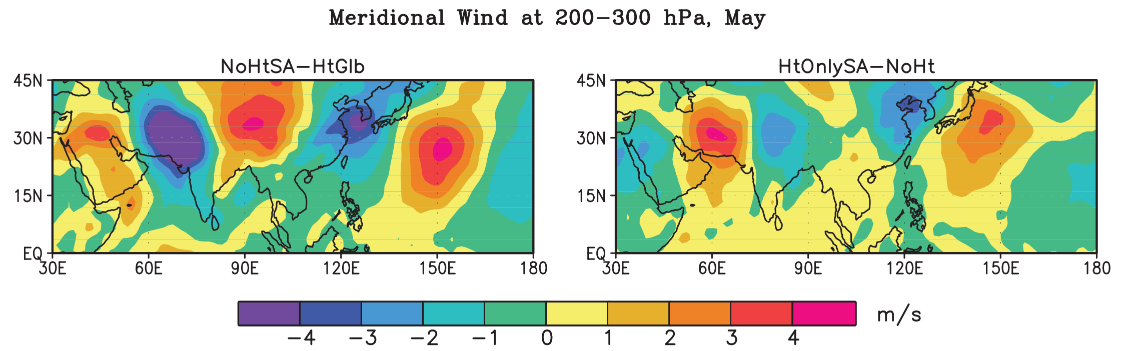

Figure 12. Difference in meridional wind at 200–300 hPa in May between (a) HtGlb and NoHtSA and (b) NoHt and HtOnlySA depicting the impact of aerosol-like heating over south Asia on phase of Rossby wave.

monsoon rainfall. Ding and Wang (2007) have found that summer Eurasian wave train can have interaction with Indian summer monsoon on intraseasonal time scale through passage of consequent cyclonic and anti-cyclone waves at 200 hPa. A recent study by Yun *et al.* (2010) have found high temporal correlation between a certain phase of upper tropospheric Rossby wave and diabatic heating over Indian monsoon region.

Figure 12(a) shows the change in 200–300 hPa meridional wind in May on account of removal of aerosol-like heating from south Asia (NoHtSA) as compared to heating all over the globe (HtGlb). The change signifies shift in upper tropospshereic Rossby wave in the pre-monsoon month. The resultant anomalous cyclonic circulation over Indian region can induce anomalous downward velocity and reduce precipitation. With aerosol-like heating present only over south Asia (HtOnlySA) there is an anomalous anti-cyclonic motion over north-west Indian region at this level when compared to no-heating experiment (Figure 12(b)). This anti-cyclonic motion enhances divergent flow and upward motion below this level, which further can favour monsoon precipitation.

5.7. Aerosol-like heating over East Asia

The remote impact of aerosol-like heating was examined by removing heating from east Asia (NoHtEA) and keeping heating only over east Asia (HtOnlyEA). Figure 13(a) shows the change in precipitation during June to July as a result of removing aerosol-like heating from east Asia as compared to heating everywhere (HtGlb). Even when heating was present over the Indian region in both the experiments, there was a large coherent region of negative precipitation anomaly over north and south India, and over Arabian Sea. However, precipitation increased over east Asia due to removal of aerosol-like heating over the same region.

Figure 13(b) shows difference in precipitation between HtOnlyEA and NoHt experiments in June to July. Precipitation increased over north Arabian Sea and north Bay of Bengal due to introduction of aerosol-like heating only over East Asia. Similar to the response of local aerosol-like heating over south Asia (Figure 7(b)), precipitation decreased over south Arabian Sea creating a north–south dipole in anomaly pattern.

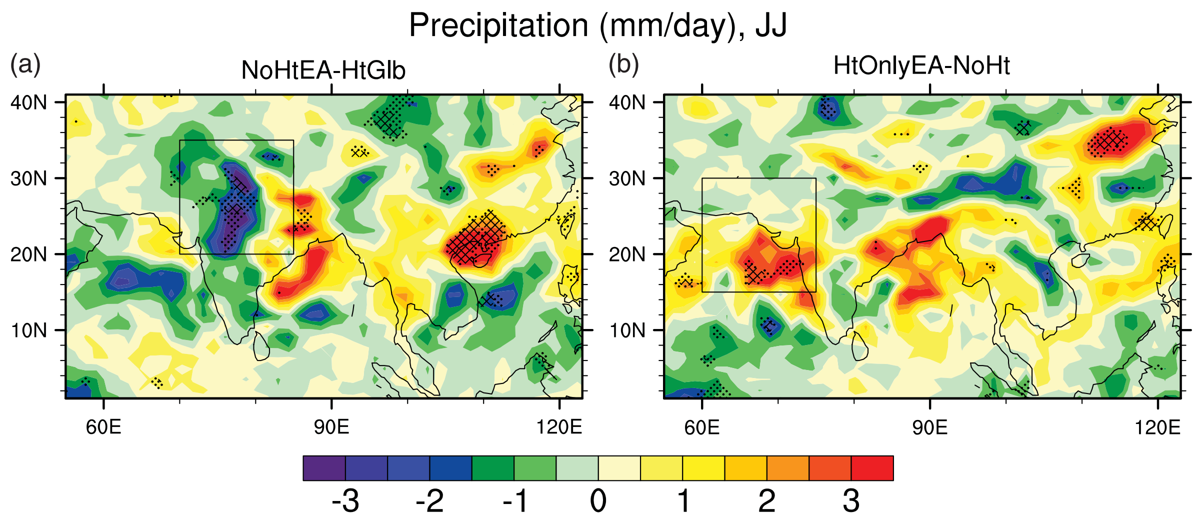

Figure 13. Change in precipitation in June to July for (a) no aerosol-like heating over east Asia (NoHtEA) as compared to heating everywhere (HtGlb); and (b) aerosol-like heating only over east Asia (HtOnlyEA) as compared to no heating (NoHt). Regions where the differences are significant at more than 90% (95%) level using a *t*-test are marked with dots (cross).

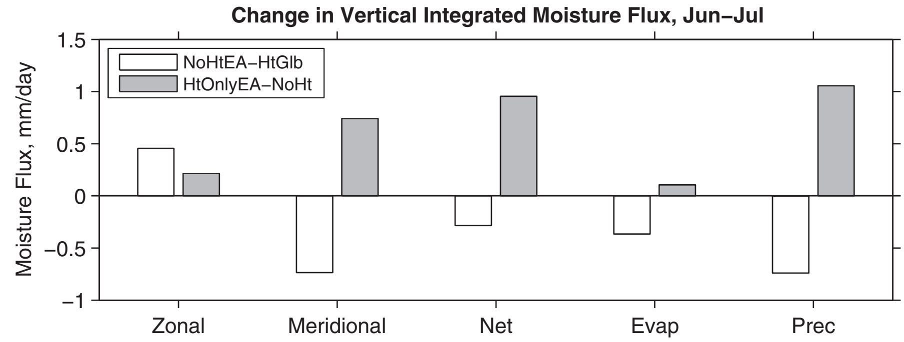

Figure 14. Change in vertical integrated moisture flux, evaporation and precipitation during June to July over north-central Indian region (70°–85°E, 20°–35°N) between NoHtEA and HtGlb experiments; and over north-west Indian region (60°–75°E, 15°–30°N) between HtOnlyEA and NoHt experiments.

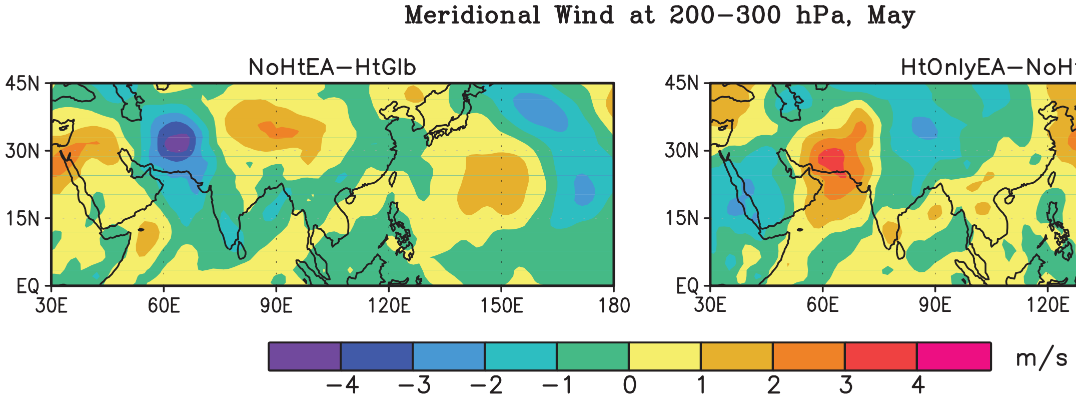

Figure 15. Difference in meridional wind at 200–300 hPa in May between (a) HtGlb and NoHtEA and (b) NoHt and HtOnlyEA depicting the impact of aerosol-like heating over East Asia on phase of Rossby wave.

To understand reasons behind these changes, we have chosen two areas where changes are large and significant, one over north-central Indian region (70–85°E, 20–35°N) and another over north-west Indian region (60–75°E, 15–30°N). These regions are indicated on Figure 13. Moisture budget analysis over these two regions is shown in Figure 14. Note that decrease in precipitation over north-central Indian region due to removal of aerosol over east Asia was on account of decrease of net meridional moisture flux and evaporation. This was unlike the removal of aerosol-like heating from south Asia which decreased zonal moisture flux to reduce precipitation over south-central India. However, the increase in precipitation over north-west Indian region was due to increase in meridional moisture flux, similar to that in Figure 10.

Figure 15 shows the change in 200–300 hPa averaged meridional wind during May in the above mentioned experiments. When aerosol-like heating was removed from East Asia, shift of upper tropospheric Rossby wave was such that it created an anomalous cyclonic motion over north Indian region. This induced additional subsidence over that region and help decreased precipitation as was seen in Figure 13(a). However, introduction of aerosol-like heating over East Asia caused shift in Rossby wave such as to increase the strength of the upper level anticyclone and increase ascent over the Indian region. This helped increase precipitation in HtOnlyEA experiment as compared to NoHt seen in Figure 13(b).

6. Conclusions

This study used a global atmospheric GCM to find the proximate and remote impacts of prescribed radiative heating due to carbonaceous aerosols on Indian summer monsoon. Radiative effects of carbonaceous aerosols were obtained from data compiled by Takemura *et al.* (2002) for the year 1998. This kind of non-interactive prescribed heating by aerosols reduces the complexity of aerosol–atmosphere interactions (which are present in fully interactive models). The amplification of feedback errors in aerosol concentration, precipitation and circulation are thus avoided by such a prescription. Moreover such experiments are ideal to study the response of the atmosphere to various kinds of forcing (idealized and observed, caused by various processes).

Several perturbed experiments were performed to study the impact of such prescribed radiative forcing. At first aerosol-like heating was introduced only over South Asia and the impact was compared with no-heating experiments. The results show that aerosol-like heating over south Asia can increase precipitation over most of northern India, Arabian Sea and Bay of Bengal. However,

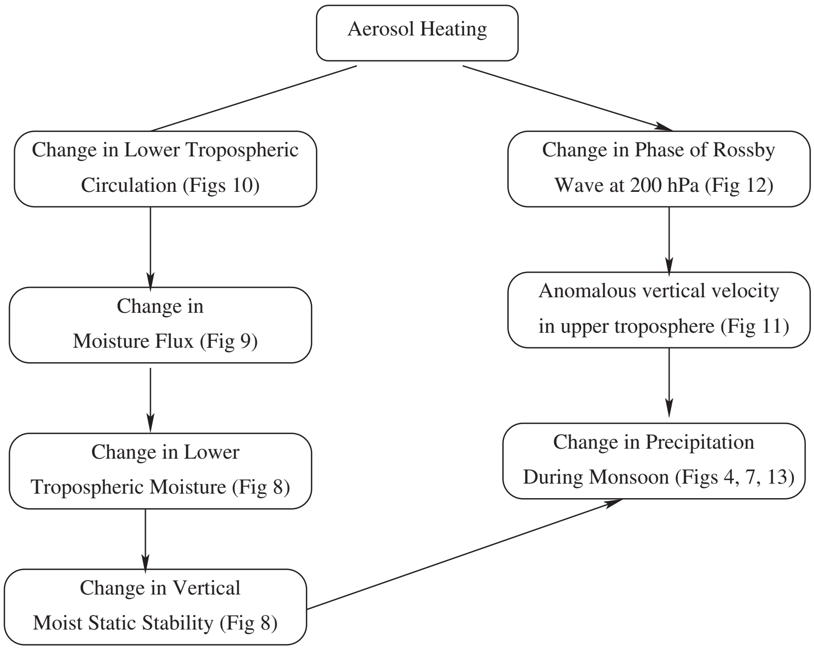

Figure 16. Mechanisms those help enhancement of summer monsoon precipitation over south and east Asia due to local and remote carbonaceous aerosol forcing in the lower troposphere.

precipitation was reduced over southern Arabian Sea, which indicates a northward shift in the ITCZ over this region. In the next set of experiments, aerosol-like heating was removed from south Asia and the results were compared with the experiments with aerosol-like heating everywhere over the globe. It was noticed that due to the removal of local heating, precipitation during monsoon season decreases over most of the Indian land region. The changes in both of these sets of experiments were attributed to changes in pre-monsoon moist static stability of the atmosphere. This in turn was related to change in circulation due mainly to pre-monsoon heating that helped increased net moisture flux into this region.

The remote impacts of radiative forcing by carbonaceous aerosols over east Asia on Indian monsoon were examined by retaining or removing aerosols from East Asia. When aerosol-like heating were present only over East Asia, precipitation over northern Arabian Sea and Bay of Bengal increased as compared to no-heating all over the globe. This change was coherent in space over a large region. In the complementary set of experiments, when aerosol-like heating were removed only from over East Asia, precipitation over Indian region reduced substantially. Both the above-mentioned results signify the influence of remote aerosol-like heating on Indian summer monsoon. It was found that the shift in the phase of Rossby wave at 200 hPa and lower tropospheric moisture were responsible for the remote influence of aerosols like heating on south Asian monsoon.

This study shows that remote impacts of carbonaceous aerosols can be as important as local impacts. Two different mechanisms were suggested for changed precipitation over the south Asian region due to carbonaceous aerosol forcing (Figure 16). These are (1) changes in moist static stability of the atmosphere in the pre-monsoon season on account of change in circulation in the lower troposphere that changes influx of moisture; and (2) change in the upper tropospheric Rossby wave in pre-monsoon season that can pre-condition the atmosphere for changed precipitation during monsoon season.

The experimental results performed in this study also provide an insight into various scenarios based on implementation of clean-air laws in different countries of South and East Asia. Further study is required to compare these results using atmosphere–ocean coupled models and interactive aerosol models.

Acknowledgements

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