On the response of Indian summer monsoon to aerosol forcing in CMIP5 model simulations

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On the response of Indian summer monsoon to aerosol forcing in CMIP5 model simulations

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Abstract The Indo-Gangetic plains (IGP), which hosts 1/7th of the world population, has undergone significant anomalous changes in hydrological cycle in recent decades. In present study, the role of aerosols in the precipitation changes over IGP region is investigated using Coupled Model Inter-comparison Project-5 (CMIP5) experiments with adequate representation of aerosols in state-of-the art climate models. The climatological sea surface temperature experiments are used to explore the relative impact of the aerosols. The diagnostic analysis on representation of aerosols and precipitation over Indian region was investigated in CMIP5 models. After the evaluation, multi-model ensemble was used for further analysis. It is revealed from the analysis that aerosol-forcing plays an important role in observed weakening of the monsoon circulation and decreased precipitation over the IGP region. The significant cooling of the continental Indian region (mainly IGP) caused by the aerosols leads to reduction in land sea temperature contrast, which further leads to weakening of monsoon overturning circulation and reduction in precipitation.

Keywords Aerosol monsoon interactions · CMIP-5 experiment · IGP rainfall · Aerosol effects

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1 Introduction

The south-west Indian summer monsoon is the most important climate system, which provides about 80 % of the annual rainfall over Indian region. However, summer monsoon rainfall has undergone a weakening tendency, which is attributed by a decreasing south-westerly wind and rainfall during recent decades (Bollasina et al. 2011; Krishnan et al. 2013). Goswami et al. (2006) showed that significant rising trend in frequency and magnitude of extreme rain events and decreasing trend in moderate rain events over central India during monsoon season in last few decades. Thereafter, Rajeevan et al. (2008) showed that inter-annual, inter-decadal and long term trends in extreme rainfall events are modulated by the sea surface temperature (SST) variations over tropical Indian Ocean. The mechanism responsible for the weakening of monsoon circulation and precipitation is an active research topic. The probable causes include natural factors (like solar and internal variability, volcanic eruption etc.) and anthropogenic factors such as green house gases (GHGs), land use and land cover changes and anthropogenic aerosols etc. (Nigam et al. 2013). Li et al. (2010) using coupled climate model showed the role of forcing agents such as GHG, aerosols, ozone, solar variability etc. on decreasing trend in global land monsoon precipitation over the past 50 years.

Ganguly et al. (2012a) suggested that the feedback coupled with SST changes caused by aerosols play more important role than fast response of the aerosols (impact on radiation, clouds and land surface) in shaping the total equilibrium climate response of the monsoon system to aerosol forcing. Ramanathan et al. (2005) demonstrated that the aerosol-induced SST cooling of the Northern Indian Ocean leads to reduced evaporation which in turn leads to weakening of the monsoon circulation and rainfall. On the other hand, Lau and Kim (2006) showed that absorbing aerosols over the Indian region enhance the monsoon circulation and precipitation through aerosol induced tropospheric heating. By using general circulation model, Cherian et al. (2013) demonstrated that, absorbing aerosol induced atmospheric heating and surface cooling leads to stability of the atmosphere, which further leads to reduction in convective precipitation over Indian region. Manoj et al. (2010) have shown the short-term impacts of absorbing aerosols on the monsoon intra-seasonal oscillations due to modification of the lower troposphere meridional temperature gradient. Meehl et al. (2008) discussed about the enhanced precipitation due to absorbing aerosols during pre-monsoon through tropospheric warming and reduction in precipitation during monsoon season due to SST cooling. The role of inter-annual variability of aerosols on regional climate of Indian subcontinent is studied by Sanap and Pandithurai (2014). They emphasized the need for study on aerosol semi-direct effect over the Indian subcontinent. Recently, Vinoj et al. (2014) using global climate model demonstrated that dust aerosol-induced atmospheric warming over Arabian Sea can stimulate atmospheric feedback processes, resulting in enhanced summer monsoon rainfall over central India.

The IGP region is home for about 1/7th of the world population and dominated by the huge amount of anthropogenic activities like biomass and agricultural burning, thermal power plants, industrial emission etc. Regional and seasonal variation of aerosols over Indian region have been studied by Ramachandran and Cherian (2008). They further mentioned that, high population density locations (e.g. IGP, north India) show persistent higher AOD throughout the year due to bio-fuel, fossil fuel, industrial and vehicular emissions. The IGP region is recognized as aerosol 'super hotspot' because of its high aerosol loading and anthropogenic emission (Ramanathan et al. 2007). The study by Nigam et al. (2013) demonstrated an upward trend in precipitation before 1950 and declining trend after 1950 over the IGP region. Their study suggests that the changes in precipitation post 1950 period are partly due to natural variability (statistically linked to Pacific decadal variability) and partly due to anthropogenic changes (aerosols, desertification, GHG etc.). Jha et al. (2013) using standardized precipitation index (SPI) demonstrated significant increasing dryness over four agro-climatic zones of IGP region, which are very much important in terms of future drought management because of its high population density and agricultural activity. Study by Andrews (2013) demonstrated that the relative changes in AOD and aerosol effective radiative forcing (ERF) with respect to pre-industrial period are higher over industrial regions of the world. This study further clarifies that there is decadal upward trend in aerosol loading over the regions of IGP and China. As IGP region is highly dominated by anthropogenic as well as transported aerosols and experienced anomalous changes in hydrological cycle in recent decades, it is essential to study their relative impacts on recent hydro-climate change over the region. For studying the role of aerosols on monsoon, it is essential that representation of aerosol and monsoon processes to be realistically represented in models (Srinivasan and Gadgil 2002; Ganguly et al. 2012b). There have been several studies on the role of aerosol in weakening of the monsoon circulation and precipitation (Menon et al. 2002; Chung and Ramanathan 2006; Ramanathan and Carmichael 2008; Bollasina et al. 2011 and so on). However, present study is different from earlier studies in following ways:

- This is one of the first studies which represent contributory role of 20th century aerosol emissions in decreasing precipitation over IGP region in state of the art climate models.
- CMIP5 model studies with aerosol direct and indirect effect parameterized, which addresses the role of aerosol on Monsoon rainfall (especially over IGP) and circulation with appropriate representation of aerosols.
- The Hansen style experiments (Hansen et al. 2005) with aerosols and control experiment are used here to identify the role of aerosols on Indian monsoon circulation and precipitation.

The diagnostic analysis is performed on aerosol distribution over Indian region (mainly IGP) in CMIP5 models to choose the most suitable model/models for the present study. Analysis was also carried out to investigate how well the south west (SW) monsoon precipitation distribution over Indian subcontinent is simulated among the models. The MME is used for further study, as aerosol and precipitation was found to be comparable with observations. Also, mean monsoon features in MME is verified with observations to assess the robustness of the results. Therefore, in the present study, we examine the response of Indian monsoon circulation and IGP rainfall to aerosol forcing in CMIP5 models with appropriate representation of the aerosol distribution over Indian subcontinent. The datasets, CMIP5 model experiments and methodology is explained in Sect. 2, results from the analysis are documented in Sect. 3 followed by summary and conclusions of the study in Sect. 4.

2 Datasets and CMIP5 model experiments

The monthly mean aerosol optical depth (AOD, at 550 nm wavelength) and other atmospheric variables data for the models mentioned in Table 1 is obtained from http://pcmdi9.llnl.gov/esgf-web-fe/live for present analysis. For validating

Table 1 CMIP5 model details

Model	Institution	Model resolution	Aerosol species	Direct and indirect effects parametrized?	References
HadGEM2-A	Met Office Hadley Centre, UK	1.25° × 1.875°	Sulphate, ammonium nitrate, BC, organic carbon (OC), sea salt, mineral dust	✓	Bellouin et al. (2011)
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence, Australia	T63	Sulphate, BC, OC, sea salt, mineral dust	✓	Rotstayn et al. (2012)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	1.875° × 3.75°	Sulphate, BC, OC, sea salt, mineral dust	✓	Dufresne et al. (2013)
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	T85	Sulphate, BC, OC, sea salt, mineral dust	✓	Watanabe et al. (2010)
MRI-CGCM3	Meteorological Research Institute, Japan	T159	Sulphate, BC, OC, sea salt, mineral dust	✓	Yukimoto et al. (2012)
NorESM1-M	Norwegian Climate Centre, Norway	1.875° × 2.5°	Sulphate, BC, OC, sea salt, mineral dust	✓	Kirkevåg et al. (2013)
GFDL-CM3	Geophysical Fluid Dynamics Laboratory, USA	2° × 2.5°	Sulphate, BC, OC, sea salt, mineral dust	✓	Donner et al. (2011)

the model simulated AOD, we used Moderate Resolution Imaging Spectro-radiometer (MODIS) TERRA satellite derived AOD for the period 2000–2012. The MODIS is a 36 band scanning radiometer onboard NASA's Terra and Aqua satellites (Kaufman et al. 2002; Platnick et al. 2003). We have used Terra MODIS Level-3 monthly data product with 1° × 1° spatial resolution (see link http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_MONTHLY_L3). The MODIS aerosol cloud mask identifies clouds at 0.5 × 0.5 km resolution, but retrieves aerosol at 10 × 10 km resolution. Because of the relative fine resolution of the sensor's pixel size, aerosols can be derived even in partly cloudy situations when there are clouds within the 10 km retrieval box. The details on MODIS aerosol retrievals can be found in Martins et al. 2002 and Remer et al. 2012. Due to the influence of surface reflectivity in MODIS retrievals of AOD and the percentage of retrievals over land is expected to be less and hence the MISR data also used in the present study. The Level-3 monthly data product with 0.5° × 0.5° spatial resolution from Multi-Angle Imaging SpectroRadiometer (MISR) satellite observation of AOD (at 555 nm) for the period 2000–2012 is used for comparing the results. The MISR is an instrument on the Earth Observing System TERRA satellite. The mean sea level pressure and circulation data is obtained from European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis (ERA40) for the period 1980–2010 (Uppala et al. 2005). For precipitation, we used, monthly mean Global Precipitation Climatology Project (GPCP) data, which combines surface observations as well as merged satellite estimates at 2.5° × 2.5° resolution (Huffman et al. 1997). Our study uses 30-year fixed SST experiments performed in seven global climate models (GCMs) as part of the CMIP5 project. In sstClim experiment (control experiment) annual cycle of climatological SSTs and sea ice derived from each model's pre-industrial control run is imposed, while aerosols are set to preindustrial levels. The perturbation experiments, sstClimAerosol is same as sstClim, except emissions of anthropogenic aerosols from year 2000 of the historical experiment in sstClimAerosol experiment is added (see Table 2). More details of CMIP5 simulations are mentioned in Taylor et al. 2012. The difference between sstClimAerosol and control experiment (sstClim) is used to study the response of the aerosol forcing to IGP rainfall, monsoon circulation and related processes.

3 Results

3.1 Model Inter-comparison

For studying the impact of aerosols on climate system using numerical models, it is very much essential that the

Table 2 CMIP5 experiment details

Exp. no.	Short name of exp.	Experiment name	Experiment description	Number of years	Ensemble size
6.2a	sstClim	Control SST climatology	Control run climatological SSTs and sea ice imposed	30	1
6.4a	sstClimAerosol	All aerosol forcing	As in experiment 6.2a, but with aerosols from year 2000	30	1

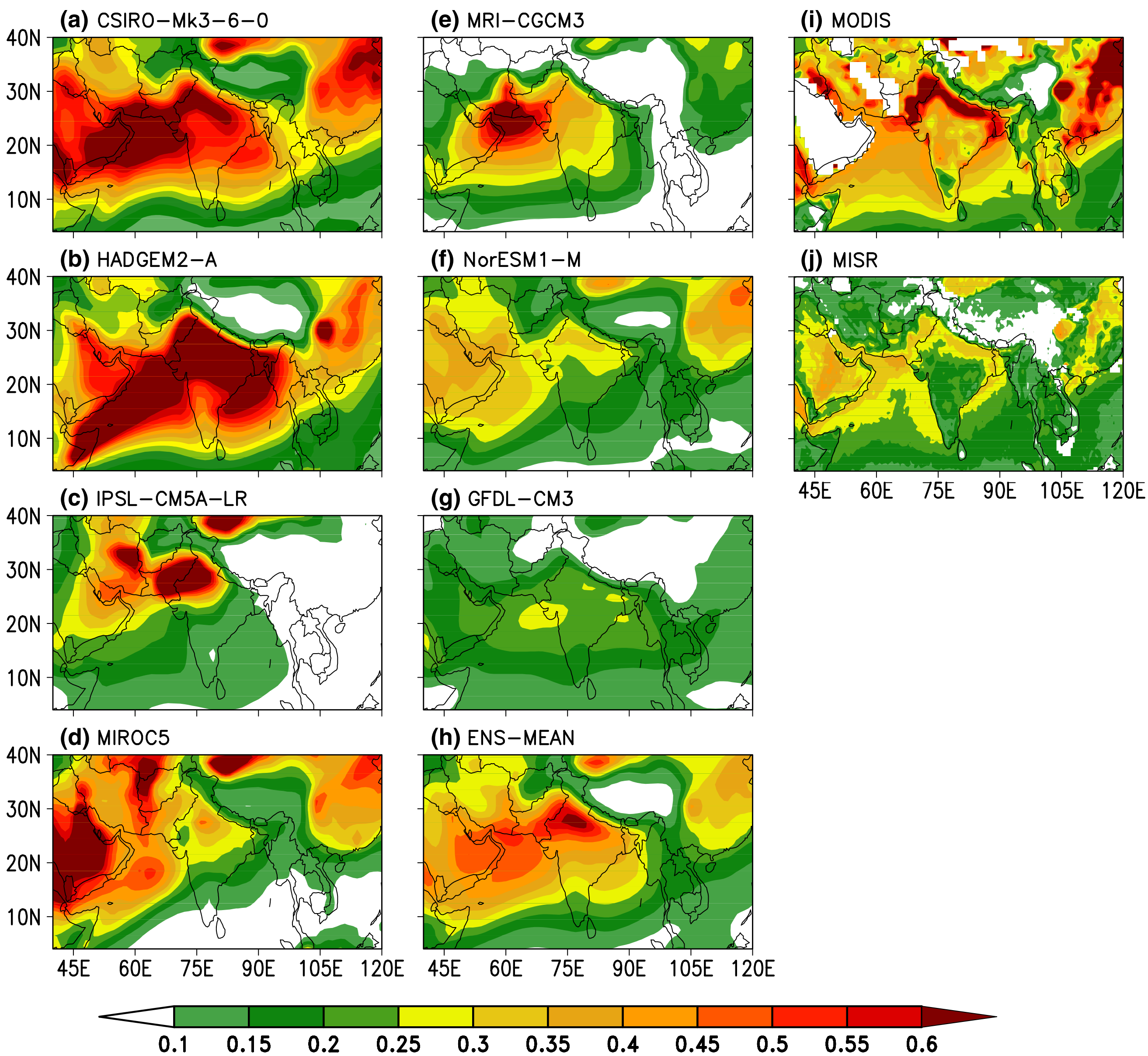


Fig. 1 JJAS AOD climatology for model **a** CSIRO-Mk-3-6-0, **b** HADGEM2-A, **c** IPSL-CM5-LR, **d** MIROC-5, **e** MRI-CGCM3, **f** NorESM1-M, **g** GFDL-CM3, **h** multi-model ensemble. Satellite observed AOD climatology from **i** MODIS and **j** MISR

model should simulate spatial distribution of aerosols and processes realistically well (Ganguly et al. 2012b). The Hansen style (Hansen et al. 2005) climatological SST experiments (see Table 2) are used in the present study. Seven models were participated in these experiments. The brief description of the models used for study is presented in Table 1. The comparison of JJAS mean AOD distribution simulated by these models (along with MME) with MODIS and MISR satellite observations are plotted in Fig. 1. Majority of the models could not simulate the spatial distribution of the AOD appropriately over Indian subcontinent, especially over the IGP region. The JJAS aerosol spatial distribution simulated by HadGEM2-A, CSIRO-Mk3.6.0 is overestimated when compared with MODIS as well as MISR satellite observed AOD, while MME AOD is found to be comparable with MISR satellite derived AOD in terms of magnitudes over Indian region (mainly over IGP region). The latitude-time climatological cross-section of the AOD for CMIP5 models along with satellite observations averaged over the longitude 68°E–98°E is plotted in Fig. 2. The aerosol distribution over Indian region depicts huge variations with latitude. The northern India and IGP region accounts high concentration of aerosols when compared with other parts of the country. The Himalayan mountain barrier helps to trap the aerosols at foothills and region of IGP. The meridional variation and mean annual cycle of the aerosol in HadGEM2-A, CSIRO-Mk3.6.0 and IPSL-CM5A-LR reasonably well compared with satellite observed AOD values (with variation in magnitudes). Rest of the models failed to simulate the acceptable meridional variation and annual cycle of AOD over Indian region.

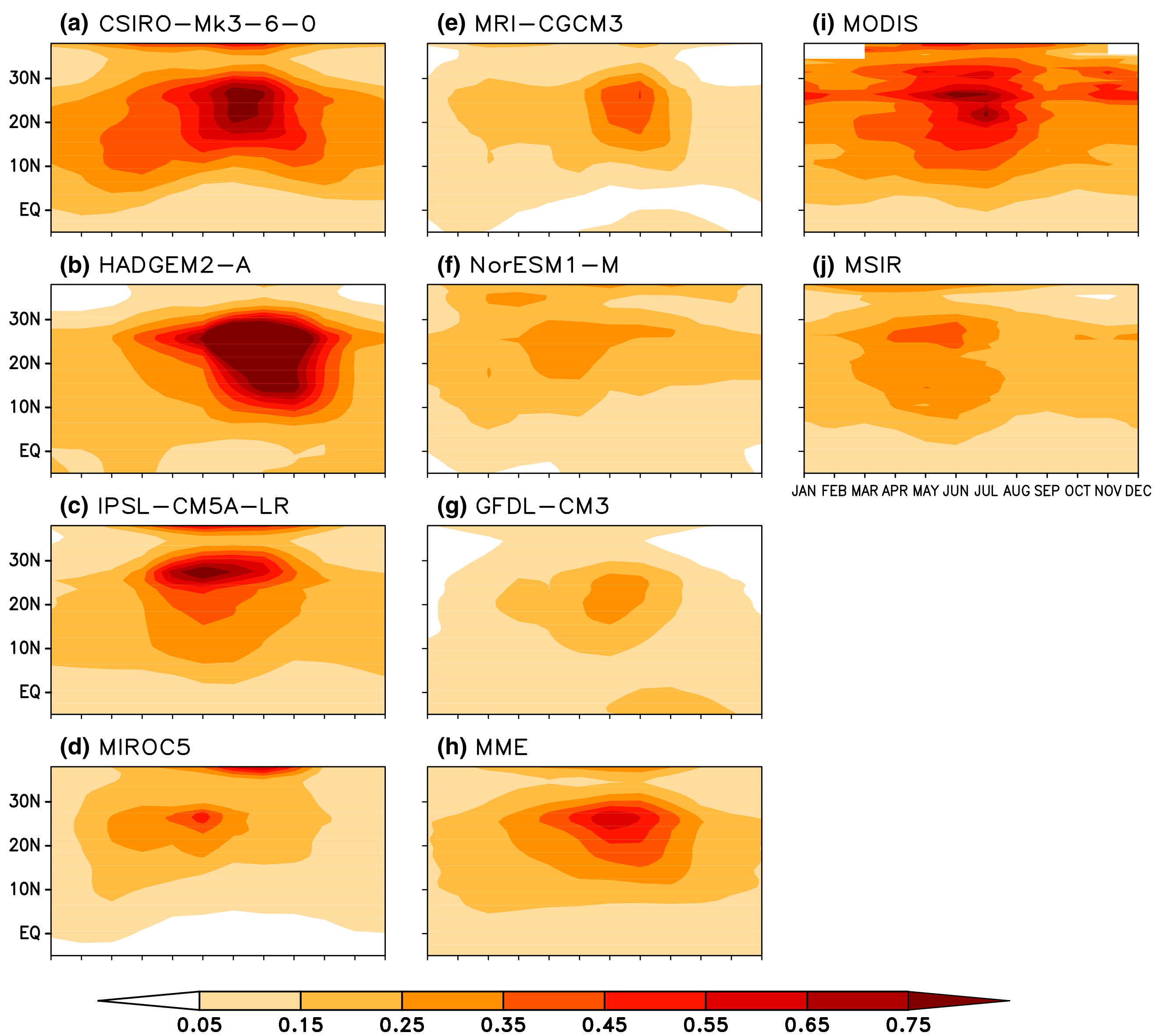


Fig. 2 Latitude-time climatological mean cross-section of aerosol optical depth as simulated in CMIP5sstClim experiment for **a** CSIRO-Mk-3-6-0, **b** HADGEM2-A, **c** IPSL-CM5-LR, **d** MIROC-5, **e** MRI-CGCM3, **f** NorESM1-M, **g** GFDL-CM3, **h** multi-model ensemble, **i** and **j** MODIS and MISR satellite derived latitude-time climatological mean cross-section of AOD

Taylor diagram is used to evaluate the fidelity of the models in simulating the patterns of climatological AOD distribution over the IGP region (with respect to MODIS and MISR AOD; Fig. 3a, b). The Taylor skill is computed over the domain 24°N–30°N and 70°E–90°E. It gives brief statistical information about how well the patterns of correlation, root-mean-square difference (RMSE), and the ratio of variances match between different models (Taylor 2001). The normalized standard deviations for JJAS AOD are represented by the distance from the origin on both sides. Here, models are normalized by the standard deviation of the observed climatology. The distance from the reference point to the plotted point gives the RMSE, which are represented by concentric circles. The plotted point closer to the reference point, lesser will be the RMSE. The correlation between model and climatology is the cosine of the polar angle (i.e., in ideal case, if correlation between the model and observation is 1, then the point will lie on the horizontal axis). Therefore, model simulated variable which has least RMSE, highest correlation coefficient (CC), and normalized standard deviation close to unity considered to be the best. Even though the correlation coefficient between few models and observation is high (For e.g., IPSL-CM5A-LR, GFDL-CM3, MRI-CGCM3), variance is underestimated by all of them as shown in the Taylor diagram with respect to MODIS (see Fig. 3a). The model HadGEM2-A slightly overestimate the variance. The variance was found to be overestimated in CSIRO-Mk3.6.0, HadGEM2-A and MIROC5, while other models display an underestimation in variance, when plotted with respect to MISR observations. However, MME shows a good comparison in AOD values with respect to MODIS as well as MISR.

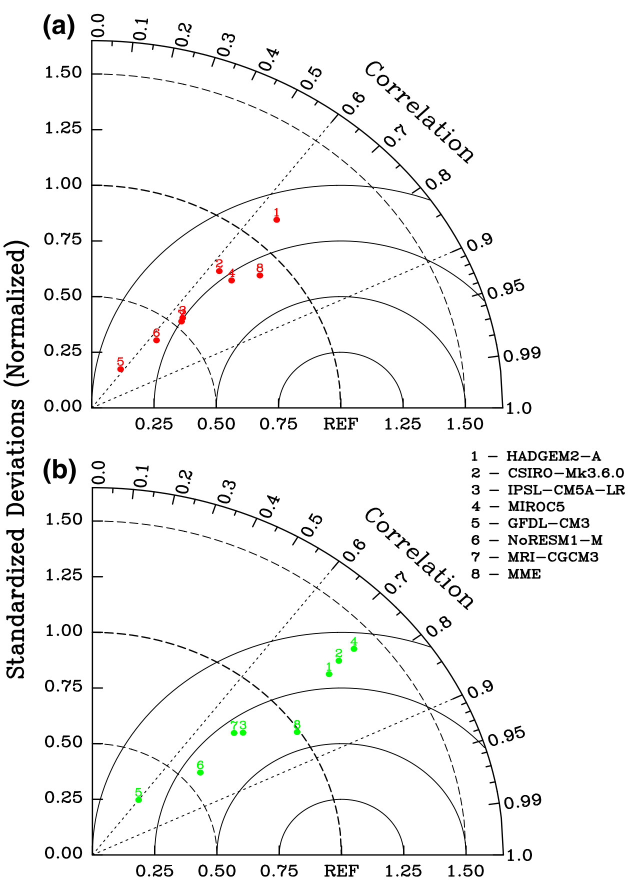


Fig. 3 **a** The Taylor diagram of spatial pattern of JJAS climatological AOD. The Taylor skill is computed over the region 23°N–30°N, 70°E–90°E with respect to MODIS satellite observed AOD, **b** same as (**a**) but, with respect to MISR satellite observed AOD

The better representation of monsoon processes in a model depends on how well the model simulates seasonal mean precipitation as well as annual cycle over the region. Here we examine the capability of the models in simulating the climatological SW monsoon precipitation (June to September, JJAS) and mean annual cycle (see Figs. 4, 5). The spatial pattern of the Indian summer monsoon rainfall (ISMR) as simulated in seven CMIP5 models along with GPCP observed rainfall is presented in Fig. 4. The mean ISMR is overestimated in MIROC5, NorESM1-M, while it is underestimated in CSIRO-Mk3.6.0, IPSL-CM5A-LR and MRI-CGCM3. The GFDL-CM3 simulates precipitation over central India quite well with underestimation in magnitude over Western Ghats. The annual cycle of precipitation over ISMR core region (10°N–30°N, 70°E–100°E) is shown in Fig. 5. The phase of the annual cycle is comparable in HadGEM2-A, GFDL-CM3, NorESM1-M and MME, while it is found to be overestimated in MIROC5 and underestimated in rest of the models. After the above assessment analysis, we decided to select MME for further analysis, as aerosols and precipitation are reasonably well represented in MME over Indian region.

While selecting climate model for studying monsoon, it is also important to examine the representation of mean monsoon characteristics simulated by the model (Srinivasan and Gadgil 2002). The mean monsoon features (mean sea level pressure, 850 and 200 hPa wind) for MME are shown in Fig. 6. The key monsoon features like- south Asian monsoon trough, cross-equatorial and south-westerly flow, upper tropospheric Tropical Easterly Jets (TEJ), Tibetan anticyclone (high) etc. are convincingly well represented by MME (see Fig. 6a–c). The details of the experiments and CMIP5 models used in present study are provided in Tables 1 and 2. The detailed information on CMIP5 model experiment and structure is explained in Taylor et al. 2012. The differences of aerosols (sstClimAerosol) with control experiment (sstClim) are used to find out the relative impact of aerosols forcing on Indian summer monsoon and IGP rainfall.

3.2 Surface temperature and radiation feedback

The atmospheric aerosols reduce an amount of radiation reaching the Earth's surface through scattering and

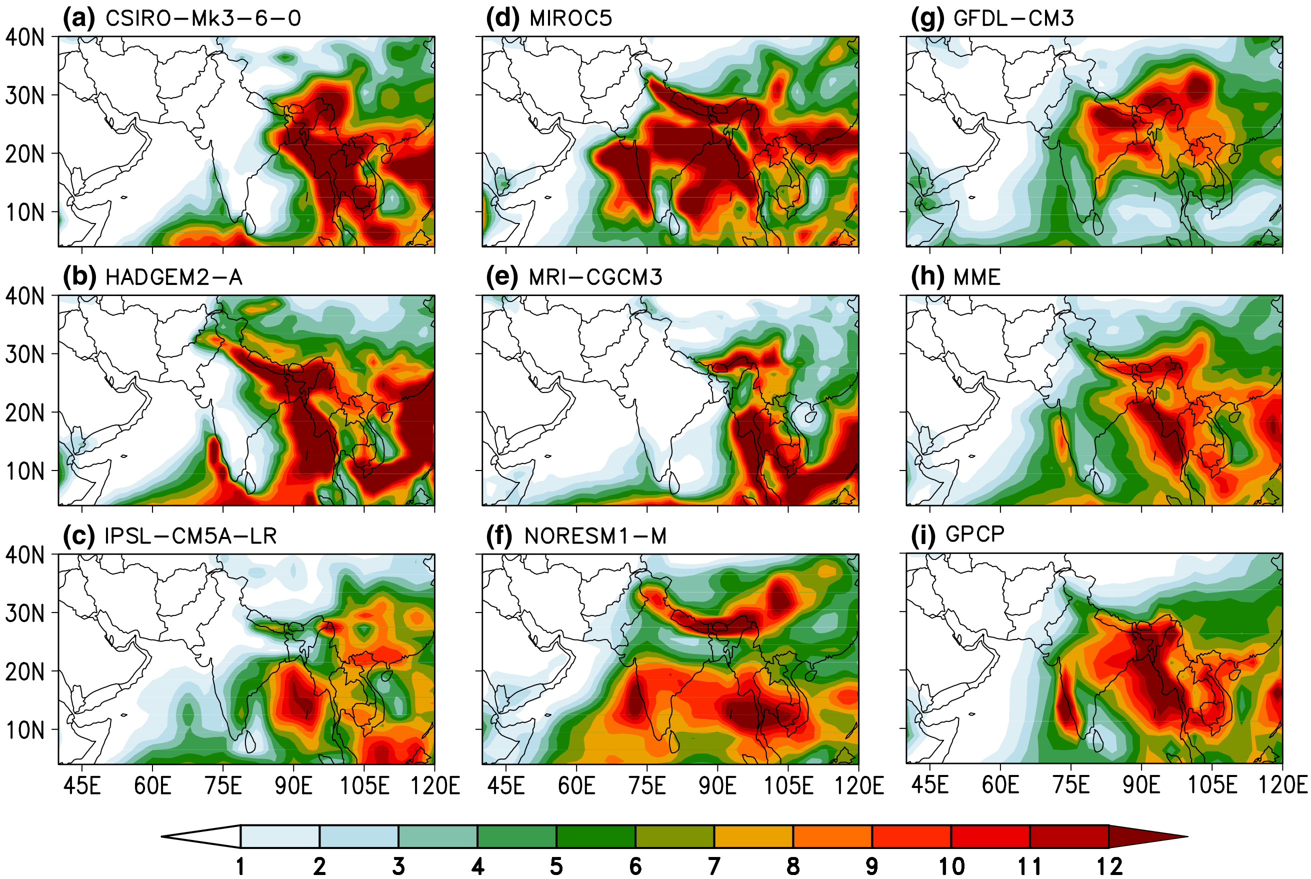
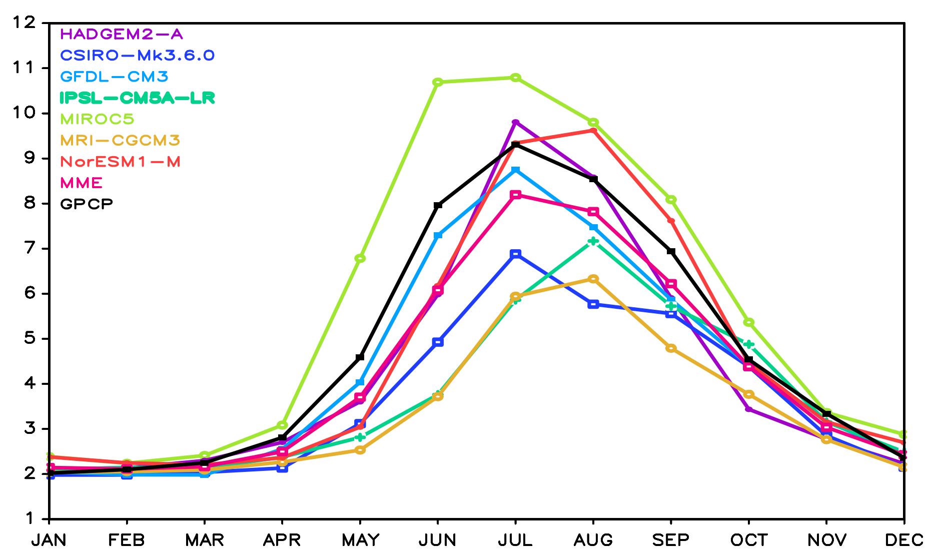


Fig. 4 Southwest monsoon season (JJAS) precipitation climatology for model **a** CSIRO-Mk-3-6-0, **b** HADGEM2-A, **c** IPSL-CM5-LR, **d** MIROC-5, **e** MRI-CGCM3, **f** NorESM1-M, **g** GFDLCM3, **h** multi-model ensemble, **i** same as above but for the GPCP

Fig. 5 The annual cycle of the precipitation simulated by 7 CMIP5 models in sstClim (*control*) experiment over the monsoon core region (10°N–30°N, 70°E–100°E) together with GPCP (*black line*)



absorption. The emissions of the aerosols and its precursors have increased since pre-industrial time due to enormous anthropogenic activities. Aerosols can reduce the solar radiation reaching the surface up to 15–35 W m^{-2} in dry winter monsoon season over Indian Ocean region (Ramanathan et al. 2001). They play a contributory role in reduction of the solar radiation at the surface in addition to clouds so called '*solar dimming*'. The differences of aerosol

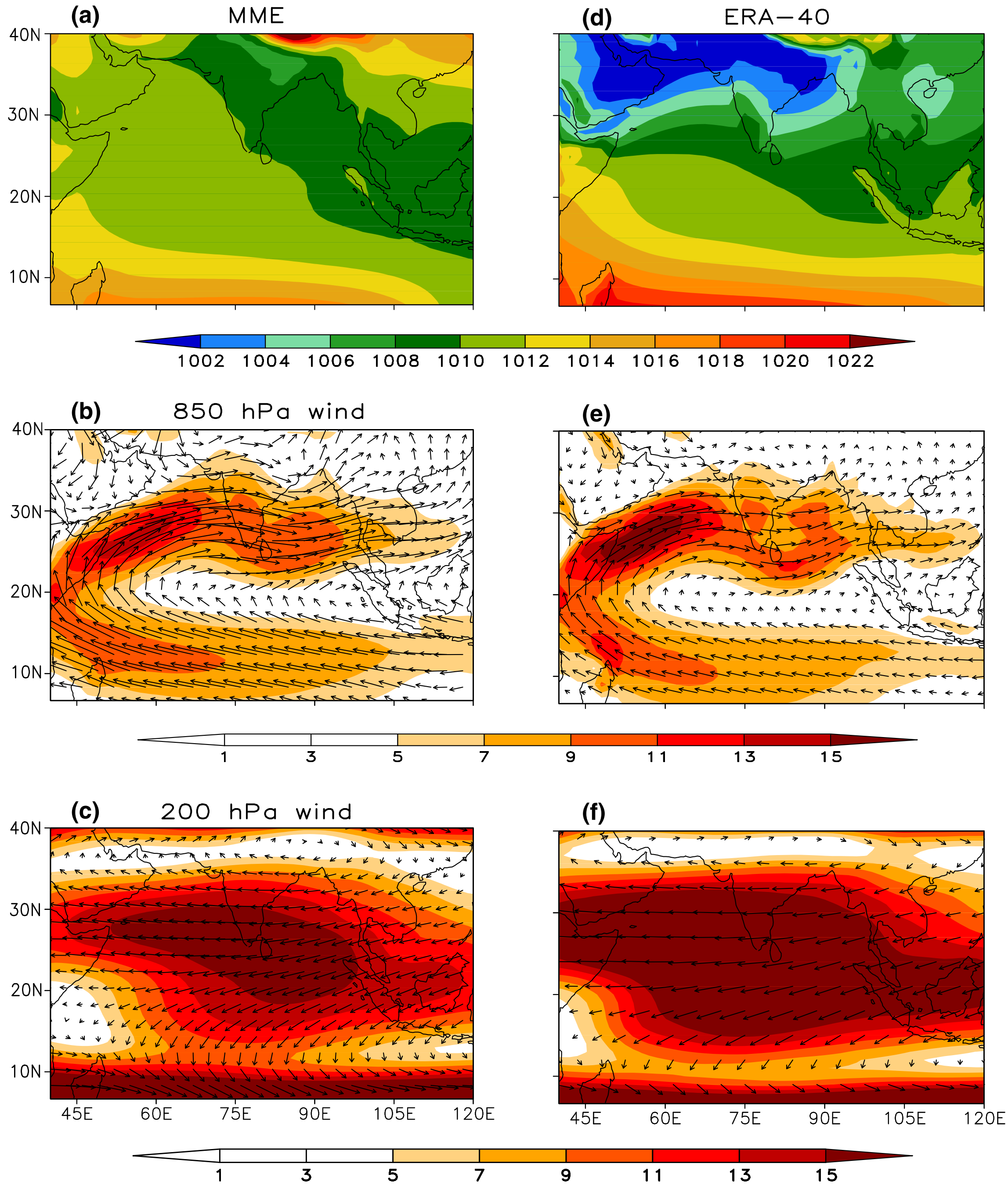


Fig. 6 The spatial maps of mean monsoon (JJAS) fields for multi-model ensemble (MME) **a** sea level pressure in hPa, **b** and **c** 850 and 200 hPa level winds (m/s), (**d**), (**e**), (**f**) same as (**a**), (**b**), (**c**), but for ERA-40 reanalysis

(sstClimAerosol) simulation with control (sstClim) experiment for surface temperature, sea level pressure (SLP), and shortwave downwelling radiation at surface for clear sky are shown in Fig. 7a–c. The widespread significant near surface cooling, decreased surface shortwave downwelling radiation for clear sky, and positive anomalies in SLP have been observed with higher anomalies over northern Indian region. The radiative impact (decreased shortwave at the surface) of the aerosols and its responses to surface temperature and SLP were distinguished from analysis. Earlier studies have shown that cooling trend in surface temperature over northern India and warming trends over the southern part of the country (Kothawale et al. 2012; Srivastava et al. 1992). Krishnan and Ramanathan (2002) demonstrated a cooling over Indian region as much as 0.3 degrees from year 1971. Like temperature trends, spatial

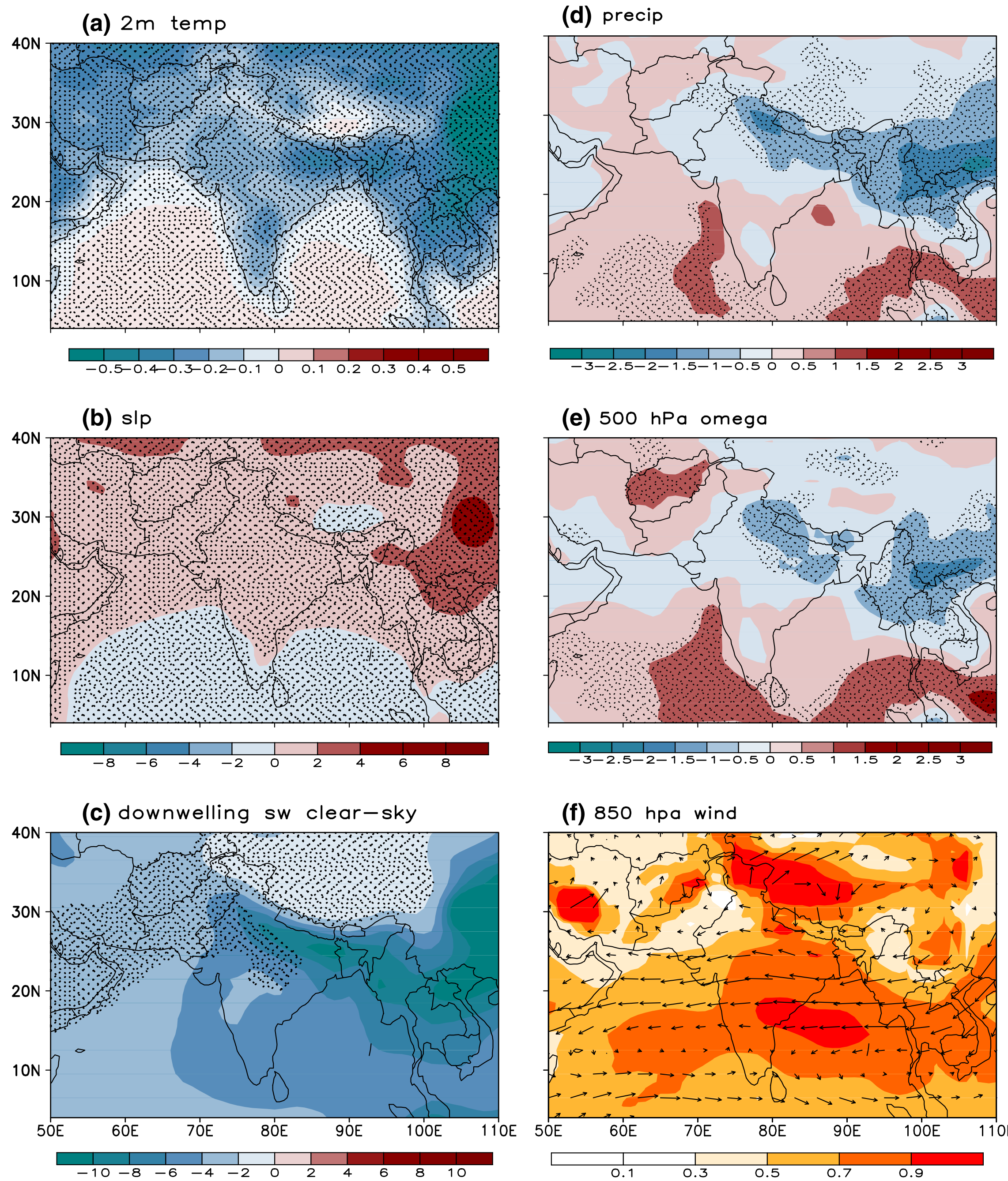


Fig. 7 JJAS anomaly plots of the difference between aerosol and control experiment for MME **a** near surface temperature (~2 m, °K), **b** sea level pressure in hPa, **c** down welling shortwave radiation at the surface for clear sky (W m^{-2}), **d** precipitation in mm/day, **e** vertical velocity field (−omega × 100) at 500 hPa in units of Pa s^{-1}, **f** winds at 850 hPa level in m/s. The stipples represent the regions where, anomalies are at 95 % confidence level based on Student's *t* test

distributions of aerosol show north–south asymmetry over India. Northern Indian region (mainly IGP) is dominated by the local emission as well as transported dust from the adjacent deserts and Middle East countries, hence show higher concentrations of the aerosol as compared to southern Indian region (Manoj et al. 2010; Sanap et al. 2014). Recent studies showed a decreasing trend in precipitation over IGP region (Jha et al. 2013; Nigam et al. 2013). Probable causes for the weakening trend in monsoon circulations and rainfall over Indian region may be attributed to the factors explained in Sect. 1. As aerosols show high emission over northern India with their diverse response to the atmosphere, it is essential to quantify its relative role in recent hydro-climate change over IGP region.

3.3 Monsoon precipitation and circulation changes over Indian region

A remarkable drying trend over IGP region has been observed in last 60 years (Guhathakurta et al. 2011; Nigam et al. 2013; Jha et al. 2013) and possible causes include, natural variability (e.g. Solar and internal variability, volcanic eruptions etc.) as well as anthropogenic factors like GHG, land use and land cover changes, anthropogenic aerosols etc. The greenhouse gases and aerosol forcing respond differently to the ISMR variability. Interestingly, both aerosol and GHG emission is found to be high over the northern Indian region (with high emission over IGP) compared to other part of the country due to intense anthropogenic activities (Garg et al. 2001). In a warming environment, we expect excess rainfall, but precipitation trend over the region is found to be declining in last few decades (Nigam et al. 2013). Therefore, here we study the impact of aerosol forcing on monsoon precipitation and circulation. The trend analysis (1951–2005) of the precipitation over Indian subcontinent with different forcing (historical, historical-natural, anthropogenic, GHG and aerosol) using CMIP5 historical simulations are shown in Figure S1. This analysis is done using coupled CMIP5 simulations and shown here only to discuss the response of each forcing to monsoon precipitation trend. For further details, please see the auxiliary information. However, rest of the analysis is performed by using fixed SST experiment only (i.e. sstClim and sstClimAerosol).

The changes in summer monsoon rainfall, vertical velocity at 500 hPa, and 850 hPa level wind due to aerosol are shown in Fig. 7d–f. The significant negative anomalies in precipitation are observed over the IGP and southern China region (difference between aerosol and control experiment), which are mainly dominated by the high concentration of the aerosols, while southern Indian region show insignificant changes in precipitation (see Fig. 7d). Similarly, vertical velocity at 500 hPa shows downward motion due to aerosols over IGP and western China region (Fig. 7e) during monsoon season, which suggest that the suppressed convection over the region. The changes in JJAS 850 hPa wind shows that the anomalous northeasterly flow (weakening monsoon circulation) in aerosol minus control experiment (see Fig. 7f). This implies that aerosol induced surface radiative changes over aerosol dominant region of IGP and northern India lead to reduction in land–ocean temperature contrast, anomalous suppressed convection over Northern India which, further lead to weakening of the monsoon overturning circulation and precipitation over continental Indian region. While absorbing aerosols can heat up the atmosphere, our study indicates that aerosol cooling effect is dominant over the Indian region (total AOD considered here), which further slows down the upward motion and in turn weakens the monsoon circulation and precipitation.

3.4 Hadley circulation

As monsoon circulation is a convectively coupled phenomenon, strengthening (weakening) in monsoon circulation would entail enhanced (reduced) summertime convection. Therefore, it would be important to know whether the precipitation decrease over the IGP and weakening of low level south-westerly monsoon flow under aerosol forcing is related to a weakening of the large-scale summer monsoon Hadley-type circulation. The negative anomalies for 500 hPa vertical velocity in aerosol minus control experiments showed suppressed convection over Indian region (see Fig. 7e). For further understanding of the large scale changes in monsoon circulation due to aerosol, latitude-pressure monsoon Hadley type circulation is plotted using meridional and vertical velocities (averaged over 60°E–100°E; see Fig. 8). It can be noticed that strong descending branch around 20°N–30°N (latitudinal belt of IGP region), which implies that suppressed monsoon convection (subsidence) over the region (high aerosol loading) and ascending branch of the Hadley circulation is observed over the oceanic tropical convergence zone (TCZ) in aerosol minus control experiment (Fig. 8). The weakening of the monsoon Hadley circulation due to aerosols is clearly evident from the above analysis. Also, the changes associated with Hadley circulation in aerosol corroborate with relative changes in fields like precipitation, 500 hPa vertical velocity and lower tropospheric circulation (see Fig. 7). The weakening tendency of low level westerly, upper tropospheric tropical easterly as well as monsoon Hadley type circulation have been observed in recent decades (Rao et al. 2004; Joseph and Simon 2005; Krishnan et al. 2013). Our analysis suggest that aerosol forcing induced atmospheric feedbacks leads to weakening in monsoon Hadley circulation, which corroborates with observed changes.

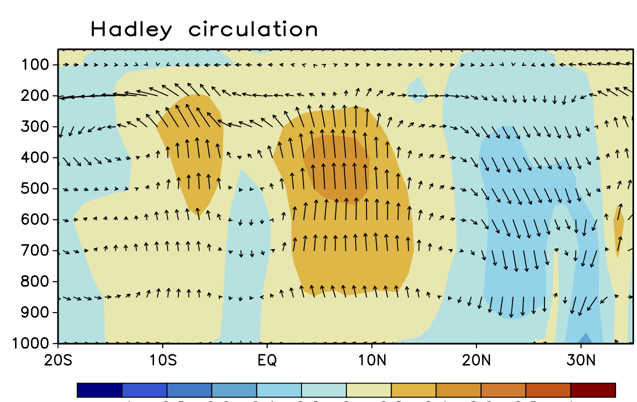


Fig. 8 The latitude-pressure section of monsoon (JJAS) Hadley-type circulation for MME difference between aerosol and control experiment

3.5 Cloud microphysics and future scope

Apart from aerosol direct radiative effects, it can indirectly alter the cloud characteristics and affect the precipitation in different ways. As aerosol act as a cloud condensation nuclei, increase in concentration of aerosol leads to enhancement in cloud brightness (Twomey 1977). The increase in cloud droplets due to aerosols reduce the collision and coalescence rates limiting the growth of the cloud leads to increase in cloud lifetime, decrease in precipitation and radiation reaching the surface of the earth (Albrecht 1989). The absorption of the solar radiation by absorbing aerosols (e.g. soot, BC) can heat up the atmosphere while cooling the surface below thus increasing the stability of lower atmosphere leading to inhibition of convection and reduction in cloud cover (Hansen et al. 1997). The IGP and North-India being a region of high aerosol loading, it is equally important to study aerosol indirect effects in addition to direct radiative effects over a region. Here, we just glimpsed on few relevant microphysical parameters which were available in the CMIP5 experiments. However, it is difficult to conclude or quantify the role of aerosol indirect/semi-direct effect on recent hydro-climate changes over IGP region from the present analysis. Nevertheless, it provides an idea about possible causes. The anomaly maps of the difference between aerosol and control experiment for total cloud cover and condensed water path (CWP) are shown in Fig. 9a, b. The remarkable widespread negative anomaly for cloud cover in aerosol minus control experiment is observed over Northern India and IGP region. The reduced CWP is found over the IGP region due to aerosol, which corroborates the result from cloud cover anomalies. These results reveal the possible role of aerosol indirect/semi-direct effect on changes in precipitation over IGP region in recent decades.

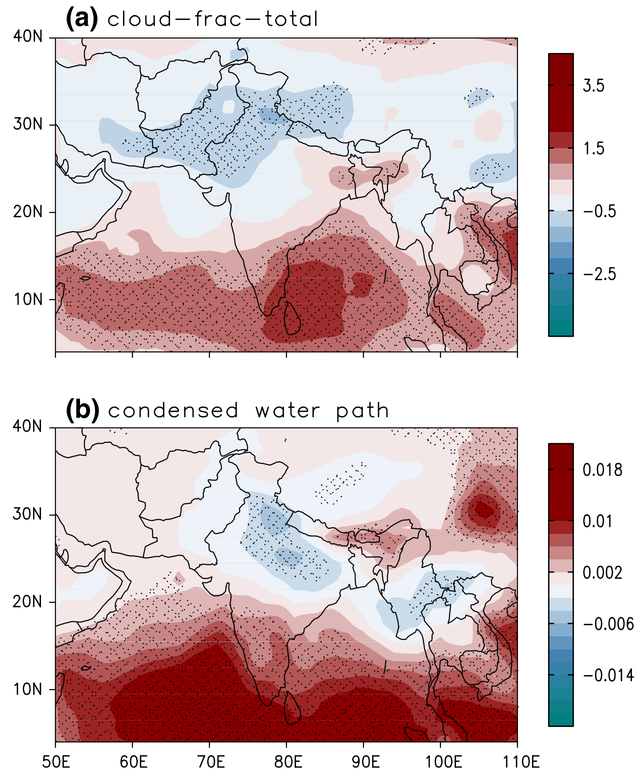


Fig. 9 JJAS anomaly maps of the difference between aerosol and control experiment for MME **a** total cloud fraction (%), **b** condensed water path (Kg m^{-2})

4 Summary and conclusions

Even though there were several studies on role of aerosols on monsoon processes, aerosol forcing responses remains a dominant uncertainty. Previous studies indicate that the role of aerosols on monsoon dynamics is extremely complicated and it is mainly dependent on model, aerosol distribution, how well the aerosol processes specified in models as well as modeling strategies used on spatial and temporal scales (Sajani et al. 2012; Srinivasan and Gadgil 2002; Ganguly et al. 2012b). The influence of aerosols on weakening of the monsoon circulation and precipitation over IGP is examined in present study using fixed SST CMIP5 experiments. The diagnostic analysis for aerosols and precipitation is employed on models in order to choose most appropriate model/models for present study. The MME is used for further study, as aerosol and precipitation was found to be comparable with observations. Also, mean monsoon features in selected models is verified with observations to assess the robustness of the results.

The comparison of aerosol experiment in MME shows that the aerosol forcing plays an important role in weakening of the monsoon circulation and reduction in precipitation particularly over IGP region. The direct impact of aerosols causes significant reduction in summer monsoon precipitation over Indian region (mainly IGP and North India). Aerosol forcing reduces surface solar absorption over aerosol dominant region and impels a preferential cooling, which leads to land–ocean temperature contrast and weakens the monsoon overturning circulation and associated moisture advection into Indian land mass. This further leads to suppressed convection, decreased cloud, precipitation etc. over northern India and IGP region. Observed trend in precipitation also shows decreased precipitation over IGP and North-India in last few decades, despite the fact that GHG level have gone up due to enormous anthropogenic emissions. In a warming environment *'warmer gets wetter'* mechanism does not go well as far as recent trend in Indian monsoon rainfall is concerned (particularly over IGP region).

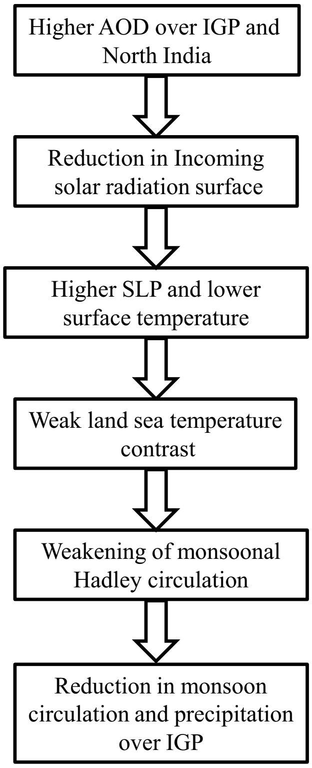


Fig. 10 Schematic of the physical mechanism of aerosol effect on monsoon circulation and IGP precipitation

Here we demonstrate that, aerosol induced changes in monsoon dynamics plays an important role in observed precipitation changes over IGP and North India, as these regions are dominated by high aerosol emission. The physical mechanism demonstrating the role of aerosols on the weakening of monsoon circulation and precipitation over IGP is shown in Fig. 10.

The recent weakening of the precipitation over IGP is partly related with pacific decadal variability (Nigam et al. 2013) and speculated that it is partly due to other external forcing like aerosols and GHGs. Our study suggests that aerosol forcing plays an important contributory role in decreased precipitation over IGP region. However, relative contribution of the other external forcing agents on weakening of monsoon circulation and precipitation over IGP deserves further study. Also, only dynamical response of the aerosol forcing is addressed in the present paper. Nevertheless, the role of aerosols on cloud micro-physics (aerosol indirect and semi-direct effect) is also equally important and deserves further investigation. We hope our ongoing Ganges Valley Experiment (over IGP region) under Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) will definitely help to unravel the issues related to aerosol-cloud-precipitation interactions over IGP region.

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References

Albrecht BA (1989) Fractional cloudiness. Science 245(80):1227–1230

Andrews T (2013) Using an AGCM to diagnose historical effective radiative forcing and mechanisms of recent decadal climate change. J Clim. doi:10.1175/JCLI-D-13-00336.1

Bellouin N, Collins WJ, Culverwell ID et al (2011) The HadGEM2 family of Met Office Unified Model climate configurations. Geosci Model Dev 4:723–757. doi:10.5194/gmd-4-723-2011

Bollasina M, Ramaswamy V, Ming Y (2011) Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science 334(80):502–505. doi:10.1126/science.1204994

Cherian R, Venkataraman C, Quaas J, Ramachandran S (2013) GCM simulations of anthropogenic aerosol-induced changes in aerosol extinction, atmospheric heating and precipitation over India. J Geophys Res Atmos 118:2938–2955. doi:10.1002/jgrd.50298

Chung CE, Ramanathan V (2006) Weakening of North Indian SST gradients and the monsoon rainfall in India and the Sahel. J Clim 19:2036–2045

Donner LJ, Wyman BL, Hemler RS et al (2011) The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3. J Clim 24:3484–3519. doi:10.1175/2011JCLI3955.1

Dufresne J-L, Foujols M-A, Denvil S et al (2013) Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Clim Dyn 40:2123–2165. doi:10.1007/s00382-012-1636-1

Ganguly D, Rasch PJ, Wang H, Yoon J (2012a) Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols. Geophys Res Lett. doi:10.1029/2012GL053043

Ganguly D, Rasch PJ, Wang H, Yoon J-H (2012b) Climate response of the South Asian monsoon system to anthropogenic aerosols. J Geophys Res 117:D13209. doi:10.1029/2012JD017508

Garg A, Shukla PR, Bhattacharya S, Dadhwal VK (2001) Sub-region (district) and sector level SO and NO emissions for India: assessment of inventories and mitigation flexibility. Atmos Environ 35:703–713

Goswami BN, Venugopal V, Sengupta D et al (2006) Increasing trend of extreme rain events over India in a warming environment. Science 314(80):1442–1445

Guhathakurta P, Sreejith OP, Menon PA (2011) Impact of climate change on extreme rainfall events and flood risk in India. J Earth Syst Sci 120:359–373. doi:10.1007/s12040-011-0082-5

Hansen J, Sato M, Ruedy R (1997) Radiative forcing and climate response abstract. We examine the sensitivity of a climate model to a wide range of radiative including changes of solar forcing introduced times the climate response, specifically the global mean temperature change, is se. J Geophys Res Atmos 102:6831–6864

Hansen J, Sato M, Ruedy R et al (2005) Efficacy of climate forcings. J Geophys Res. doi:10.1029/2005JD005776

Huffman GJ, Adler RF, Arkin P, et al (1997) The Global Precipitation Climatology Project (GPCP) combined precipitation dataset. Bull Am Meteorol Soc 78:5–20

Jha S, Sehgal VK, Raghava R, Sinha M (2013) Trend of standardized precipitation index during Indian summer monsoon season in agroclimatic zones of India. Earth Syst Dyn Discuss 4:429–449. doi:10.5194/esdd-4-429-2013

Joseph PV, Simon A (2005) Weakening trend of the southwest monsoon current through peninsular India from 1950 to the present. Curre 89:687–694

Kaufman YJ, Tanré D, Boucher O (2002) In the climate system. Nature 419:215–223

Kirkevåg A, Iversen T, Seland Ø et al (2013) Aerosol–climate interactions in the Norwegian Earth System Model—NorESM1-M. Geosci Model Dev 6:207–244. doi:10.5194/gmd-6-207-2013

Kothawale DR, Kumar KK, Srinivasan G (2012) Spatial asymmetry of temperature trends over India and possible role of aerosols. Theor Appl Climatol 110:263–280. doi:10.1007/s00704-012-0628-8

Krishnan R, Ramanathan V (2002) Evidence of surface cooling from absorbing aerosols. Geophys Res Lett 29:2–5

Krishnan R, Sabin TP, Ayantika DC, et al (2013) Will the South Asian monsoon overturning circulation stabilize any further ? doi:10.1007/s00382-012-1317-0

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

Li H, Zhaou TLC (2010) Decreasing trend in global land monsoon precipitation over the past 50 years simulated by a coupled climate model. Adv Atmos Sci 27:285–292. doi:10.1007/s00376-009-8173-9.1.Introduction

Manoj MG, Devara PCS, Safai PD, Goswami BN (2010) Absorbing aerosols facilitate transition of Indian monsoon breaks to active spells. Clim Dyn 37:2181–2198. doi:10.1007/s00382-010-0971-3

Martins J, Tanré D, Remer L (2002) MODIS cloud screening for remote sensing of aerosols over oceans using spatial variability. Geophys Res 29:3–6

Meehl G, Arblaster J, Collins W (2008) Effects of black carbon aerosols on the Indian monsoon. J Clim. doi:10.1175/2007JCLI1777.1

Menon S, Hansen J, Nazarenko L, Luo Y (2002) Climate effects of black carbon aerosols in China and India. Science 297:2250–2253. doi:10.1126/science.1075159

Nigam S, Zhao Y, Ruiz-Barradas A, Zhou T (2013) The south-flood north-drought pattern over the Eastern China and the drying of the Gangetic plains: observations, simulations and origin. In: Ghil M, Latif M, Wallace M, Chang CP (eds) Climate change: multidecadal and beyond. World press

Platnick S, King MD, Ackerman SA, Menzel WP, Baum BA, Riedi JC, Frey RA (2003) The MODIS cloud products: algorithms and examples from Terra. IEEE Trans Geosci Remote Sens 41(2):459–473

Rajeevan M, Bhate J, Jaswal AK (2008) Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. 35:1–6. doi:10.1029/2008GL035143

Ramachandran S, Cherian R (2008) Regional and seasonal variations in aerosol optical characteristics and their frequency distributions over India during 2001–2005. J Geophys Res 113:D08207. doi:10.1029/2007JD008560

Ramanathan V, Carmichael G (2008) Global and regional climate changes due to black carbon. Nature 1:221–227

Ramanathan V, Crutzen PJ, Kiehl JT, Rosenfeld D (2001) Aerosols, climate, and the hydrological cycle. Science 294:2119–2124. doi:10.1126/science.1064034

Ramanathan V, Chung C, Kim D et al (2005) Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle. Proc Natl Acad Sci USA 102:5326–5333. doi:10.1073/pnas.0500656102

Ramanathan V, Li F, Ramana MV et al (2007) Atmospheric brown clouds: hemispherical and regional variations in long-range transport, absorption, and radiative forcing. J Geophys Res 112:D22S21. doi:10.1029/2006JD008124

Rao BRS, Bhaskar Rao DV, Rao VB (2004) Decreasing trend in the strength of tropical easterly jet during the Asian summer monsoon season and the number of tropical cyclonic systems over Bay of Bengal. Geophys Res Lett 31:L14103. doi:10.1029/2004GL019817

Remer LA, Mattoo S, Levy RC et al (2012) Retrieving aerosol in a cloudy environment: aerosol product availability as a function of spatial resolution. Atmos Meas Tech 5:1823–1840. doi:10.5194/amt-5-1823-2012

Rotstayn LD, Jeffrey SJ, Collier MA et al (2012) Aerosol- and greenhouse gas-induced changes in summer rainfall and circulation in the Australasian region: a study using single-forcing climate simulations. Atmos Chem Phys 12:6377–6404. doi:10.5194/acp-12-6377-2012

Sajani S, Moorthy KK, Rajendran K, Nanjundiah RS (2012) Monsoon sensitivity to aerosol direct radiative forcing. J Earth Syst Sci 121:867–889

Sanap SD, Pandithurai G (2014) Inter-annual variability of aerosols and its relationship with regional climate over Indian subcontinent. Int J Climatol. doi: 10.1002/joc.4037

Sanap SD, Ayantika DC, Pandithurai G, Niranjan K (2014) Assessment of the aerosol distribution over Indian subcontinent in CMIP5 models. Atmos Environ 87:1–15. doi:10.1016/j.atmosenv.2014.01.017

Srinivasan J, Gadgil S (2002) Asian brown cloud—fact and fantasy. Curr Sci 83:586–592

Srivastava HN, Dewan BN, Dikshit SK, Rao P, Singh GS, Rao KR (1992) Decadal trends in climate over India. Mausam 43:7–20

Taylor KE (2001) Summerizing multiple aspects of model performance in a single diagram. J Geophys Res 106:7183–7192

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498. doi:10.1175/BAMS-D-11-00094.1

Twomey S (1977) The influence of pollution on the shortwave albedo of clouds. J Atmos Sci 34:1149–1152

Uppala SM, KÅllberg PW, Simmons AJ et al (2005) The ERA-40 re-analysis. Q J R Meteorol Soc 131:2961–3012. doi:10.1256/qj.04.176

Vinoj V, Rasch PJ, Wang H, et al (2014) Short-term modulation of Indian summer monsoon rainfall by West Asian dust. Nat Geosci. doi:10.1038/NGEO2107

Watanabe M, Suzuki T, O'ishi R et al (2010) Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. J Clim 23:6312–6335. doi:10.1175/2010JCLI3679.1

Yukimoto S, Adachi Y, Hosaka M et al (2012) A new global climate model of the Meteorological Research Institute: MRI-CGCM3; model description and basic performance. J Meteorol Soc Japan 90A:23–64. doi:10.2151/jmsj.2012-A02