Hindawi Publishing Corporation
Advances in Meteorology
Volume 2013, Article ID 649156, 20 pages
http://dx.doi.org/10.1155/2013/649156

Review Article

Aerosol-Precipitation Interactions over India: Review and Future Perspectives

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Received 2 August 2013; Revised 8 October 2013; Accepted 24 October 2013

Academic Editor: Ana I. Calvo

Atmospheric aerosols can interact with clouds and influence the hydrological cycle by acting as cloud condensation nuclei. The current study reviews the results obtained on aerosol-precipitation interactions over India and the surrounding oceanic regions. An analysis of aerosol and cloud characteristics over the Arabian Sea, India, and the Bay of Bengal during summer monsoon in the last decade reveals large regional, intraseasonal, and interannual variations. Aerosol optical depth (AOD) and aerosol absorbing index (AAI) in 2002 (a drought year) are higher over India when compared to normal monsoon years. Cloud effective radius (CER) and cloud optical thickness exhibit a negative correlation with AOD over India, which agrees well with the indirect radiative effects of aerosols. Over Bay of Bengal CER is positively correlated with AOD suggesting an inverse aerosol indirect effect. In future, observatories to measure aerosol characteristics (amount, size, type, chemical composition, mixing, vertical and horizontal distributions), and cloud properties (number and size) over several locations in India, and intense observational campaigns involving aircraft and ships are crucial to unravel the quantitative impact that aerosols have on Indian monsoon. Satellite remote sensing of aerosol distribution, their chemical composition, microphysical properties of clouds, solar irradiance, and terrestrial longwave radiation is important.

1. Introduction

Aerosols affect the earth-atmosphere radiation budget directly by scattering and absorbing the incoming solar radiation and indirectly by influencing the processes of formation of clouds and precipitation. The properties of cloud get influenced by aerosols through their role as cloud condensation nuclei and/or ice nuclei. Aerosols alter the intensity of solar radiation scattered back to space, absorbed in the atmosphere, and reaching the surface of the earth which is known as *direct radiative effect*. Aerosols indirectly can modify the cloud characteristics and influence precipitation in different ways. Aerosols (a) can increase the lifetime of clouds and reflectivity (albedo) and decrease the precipitation and radiation reaching the surface of the earth (*cloud lifetime effect*), (b) can cause an increase in cloud droplet concentration and a decrease in the cloud effective radii (*cloud albedo effect*), and (c) can absorb the solar radiation, reemit as thermal radiation, and heat the air mass and may cause evaporation of cloud droplets (*semidirect effect*) [1]. The level of scientific understanding of the above processes that contribute to aerosol-cloud-precipitation interactions is very low [1]. The present change in the top-of-the-atmosphere net radiation since 1750 (preindustrial era) due to all aerosol effects (indirect plus direct) estimated by climate models is $-1.2\,\mathrm{Wm^{-2}}$ with a range from -0.2 to $-2.3\,\mathrm{Wm^{-2}}$ [1]. The aerosol effect on precipitation is estimated to be more uncertain with the model predictions varying from no change to a decrease of 0.13 mm/day [1]. The indirect radiative effects of aerosols are more uncertain than the direct radiative effects owing to uncertainties in quantification of aerosol-cloud interactions, model simulation of aerosol and cloud distributions, difficulties associated with evaluation from observations, lack of global measurements, and optical properties of aerosol mixtures [1].

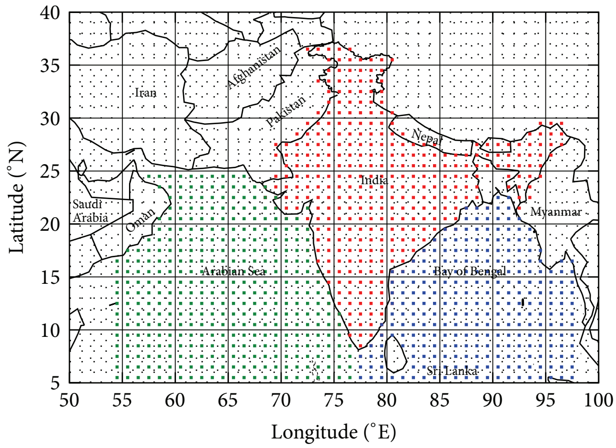

Figure 1: Map showing the study regions (in lat.-lon. grids) of Arabian Sea, India, and the Bay of Bengal.

The Indian subcontinent, apart from being a source region for aerosols, is bordered by densely populated and industrialized areas on the east and western sides from where different aerosol species are produced and transported and is one of the regional aerosol hot spots. The Indian landmass comprises coastal regions, inland plains, semiarid regions, mountains, and plateau regions and experiences tropical and subtropical climatic conditions resulting in extreme temperatures, rainfall, and relative humidity which modulate the aerosol characteristics [2]. The low-level synoptic winds over the Indian subcontinent (Figure 1) during winter (December-January-February (DJF)) are calm, north/northeasterly and are from the polluted northern hemisphere (Figure 2(a)); temperatures are colder and the atmosphere is dry (low relative humidity (RH)). In premonsoon (March-April-May (MAM)) winds originate and travel from/through a less polluted west (arid/marine) (Figure 2(b)). In this season mineral dust gets transported from the adjacent Thar desert and the Middle East to western India [3]. During monsoon (June-July-August-September (JJAS)) the winds are stronger and moist and are from the marine and western regions (Figure 2(c)), and RH is high (>70%). During postmonsoon (October-November (ON)) wind patterns start shifting in direction from southwest to northeast (Figure 2(d)). RH is low (<50%) over west and north India, while RH is higher than 70% over east and south India during postmonsoon.

The Indian summer monsoon and the associated rainfall exhibit wide variability over spatial and temporal scales and comprise interactions between land, ocean (Arabian Sea and Bay of Bengal) (Figure 1), and atmosphere [4]. The summer monsoon rainfall is dependent on a number of factors including sea surface temperature (SST), soil moisture, snow cover, El Nino Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD) and is known to be largely governed by internally driven atmospheric processes caused by the monsoon intraseasonal oscillations [4, 5]. The summer monsoon season extends from June to September and is the principal rainy season in India and accounts for 80% of the total annual rainfall except in Tamil Nadu and Jammu and Kashmir [6]. Over Tamil Nadu, the rainfall is higher during the postmonsoon months of October–December, while in Jammu and Kashmir significant amount of rainfall occurs during January and February. The rainfall over India during the monsoon season exhibits large spatiotemporal variability [6]. The all India mean summer monsoon rainfall calculated from 1871–1994 rainfall data is about 852 mm with a standard deviation of about 85 mm [7]. The rainfall over northeast is more than a factor of two higher than northwest and hilly region [6]. Aerosol characteristics over India were also found to exhibit large spatiotemporal variabilities [2]. Most urban cities in India showed a winter (January) low and a summer (July) high in aerosol optical depths (AODs) [2].

The summer monsoon precipitation over India is not uniform as large-scale interruptions known as monsoon breaks occur over all India during the same time period. An analysis of the break periods during monsoon seasons from 1979 to 2004 showed that this break period can vary from 4 to 20 days [4] at a stretch. During the break period aerosols can build up over a region [8]. The lifetimes of aerosols can increase when precipitation decreases. The fine mode aerosols are more affected by rain than the coarse mode particles leading to a decrease in mid-visible AODs [9]. The drier conditions that exist due to deficient rainfall could facilitate an increase in more light absorbing aerosols (dust and smoke) [10] resulting in higher AODs. Also, these aerosols can get transported to higher heights (2–4 km) because of prevailing strong convection and can give rise to a heating of >0.5 K/day [3] leading to a burn-off of clouds (*semidirect effect*) which can further suppress the rainfall, thus producing a feedback effect.

With such significant spatiotemporal variations in aerosol, cloud characteristics, rainfall, and orography India is an ideal region to undertake aerosol-precipitation interaction studies. The region attains importance because the observed summer monsoon rainfall shows trends that vary spatially and are of different signs [6]. The aerosol impacts on clouds and precipitation over India and the surrounding oceanic regions (Arabian Sea, Bay of Bengal, and northern Indian Ocean) have been investigated mostly using models. A few observational studies connecting aerosols with precipitation also exist. It was demonstrated through model simulations that aerosol absorption can reduce the daytime cloud cover over the Indian Ocean during northeast monsoon [11]. Precipitation over the northern Indian Ocean was found to increase when the forcing due to aerosols measured over the Indian Ocean was input in NCAR CCM3 [12]. GISS GCM simulated an increase in precipitation over India when aerosols with characteristics representative of those measured during the Indian Ocean experiment (INDOEX) were used as input [13]. The Indian summer monsoon rainfall was found to decrease during 1950–2000 when atmospheric brown clouds were introduced in the ocean-atmosphere coupled NCAR model [14]. NCAR CCSM3 simulations showed that aerosols absorbing solar radiation contribute to the decreases in rainfall over parts of India during summer monsoon [15]. GFDL CM3 model simulations which included aerosol-cloud interactions and aerosol mixing effects found a drying trend over central northern

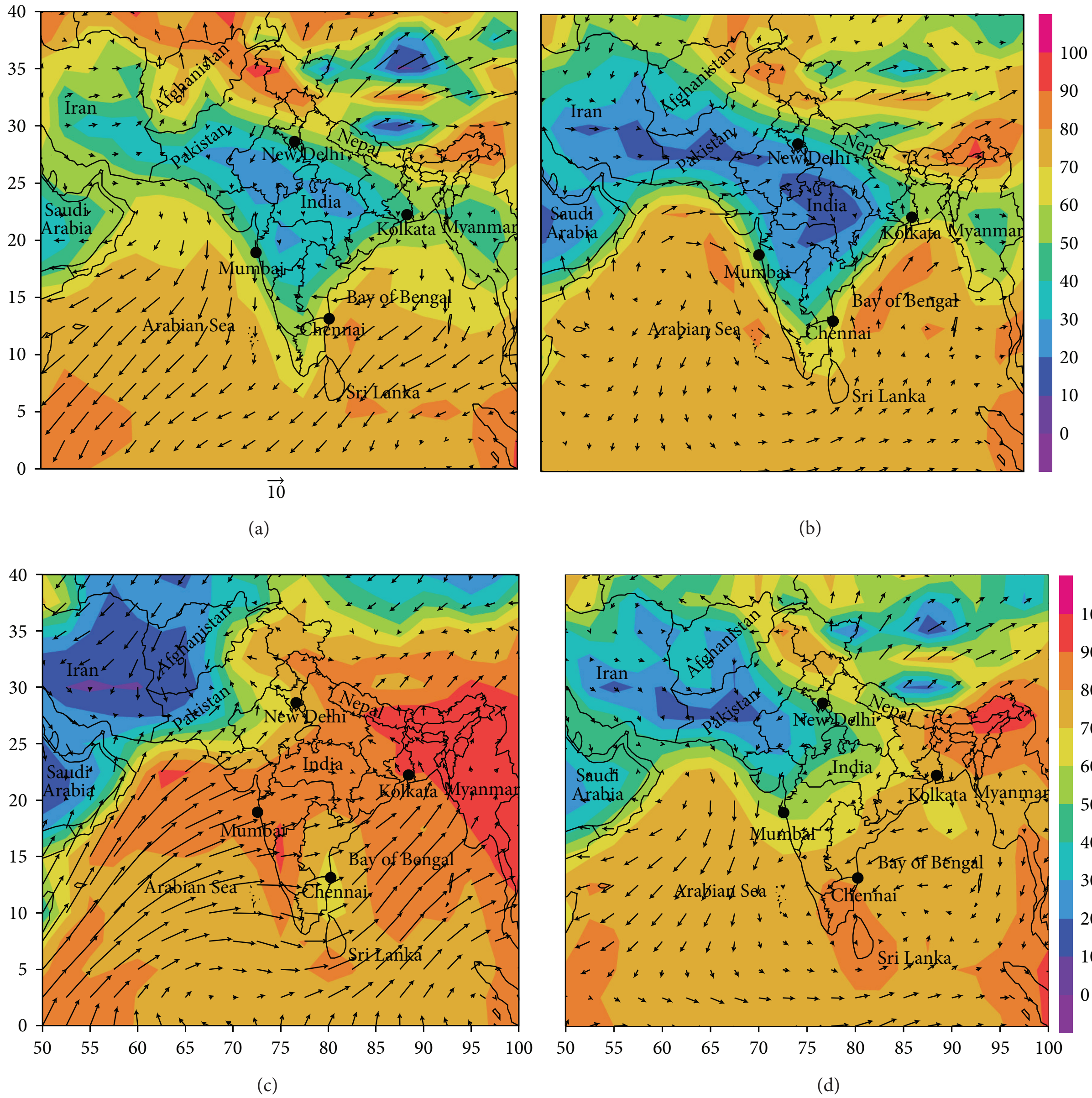

FIGURE 2: Surface level relative humidity (%) and synoptic winds (ms^{-1}) over the Arabian Sea, India, and the Bay of Bengal during (a) winter (DJF), (b) premonsoon (MAM), (c) monsoon (JJAS), and (d) postmonsoon (ON). The shaded contours correspond to relative humidity, on which winds represented by arrows are overlaid.

India [16]. A differential cooling of the source and nonsource regions and a reduction in the land-surface thermal contrast were found to be the main mechanisms for weakening of monsoon circulation [16]. It was also mentioned that in contrast to the earlier studies [14, 15] light absorbing aerosols were found to play a limited role in affecting the multidecadal trend of the monsoon. Recent results using ECHAM5.5 which incorporates aerosol mixing and indirect effects showed that anthropogenic-induced aerosol changes simulate a statistically significant decreasing trend only for the southwest monsoon and only over central northern India [17].

From observations and modeling studies [18, 19] it was shown that Indian subcontinent and surrounding regions are subject to heavy loading of light absorbing aerosols (mineral dust and black carbon) which can advance the monsoon rainy season and result in increased rainfall over the Indian subcontinent. It was hypothesized that the elevated heating due to absorbing aerosols over the Tibetan Plateau and the associated dynamical responses in terms of circulation changes and convection played a significant role in influencing the Indian summer monsoon. Subsequently, [20] suggested that the correspondence between aerosols and rainfall depends on aerosol types, distribution, and radiative properties, which need to be validated by detailed observations. Using remote sensing data and radiative transfer modeling [21] found no strong elevated heating over the Tibetan Plateau which could influence the large-scale monsoonal circulation over India. Reference [22] analyzed the observations on atmospheric dynamics (SST, rainfall anomaly, Indian Ocean Dipole, and ENSO), aerosols (absorbing aerosol index (AAI) and AOD), and outgoing longwave radiation during 2002 and 2003 considering all India (10–35° N, 70–90° E) and northwest India (20–30° N, 70–80°E), respectively, as one grid point. Reference [23] analyzed the MODIS (moderate resolution imaging spectroradiometer) satellite data over the seas adjacent to the Indian subcontinent and investigated the effect of aerosols on the size distribution of cloud droplets and ice crystals. Reference [24] analyzed the AOD variability over the Arabian Sea (10–27° N, 45–75° E) during drought (2002, 2004) and normal years (2001, 2003) of Indian monsoon. Reference [25] studied the zonal mean aerosol and rainfall variability over India (0–40° N, 60–100° E) by considering the study domain as one grid point. Reference [26] investigated the variations of cloud and aerosol properties over the Indian region associated with the active and break spells during monsoon. Using remote sensing data [27] found that light absorbing aerosols play an important role during the transition from break to active spells of the Indian monsoon rainfall by modifying the north-south temperature gradient at lower levels. Based on aircraft observations of aerosols and cloud characteristics of continental cumuli (the fractional coverage of cumuli is small) [28] reported that cloud droplet dispersion should be taken into account in models to estimate the aerosol indirect effect more accurately. Despite a number of modeling and observational studies the impact of aerosols on Indian summer monsoon it is still not clear as to how and which aerosol type can influence the monsoon rainfall.

July is considered as the core rainy month of the southwest monsoon season, as rainfall in July contributes 30% or more to the total rainfall during the season (June-July-August-September) (Table 1). In the present study the interannual and spatial variations in aerosol and cloud characteristics during the last decade (2001–2010) in July and JJAS over the Arabian Sea, India, and the Bay of Bengal (Figure 1) are investigated. The correlations between aerosol and cloud characteristics in the study regions in July and JJAS are derived and presented. The analysis is performed for July and the entire monsoon season separately to determine whether the correlations between aerosols, cloud characteristics, and precipitation observed in the core rainy month of the monsoon season become stronger or weaker when their respective seasonal means are considered or vice versa.

2. Data Sets, Analysis, and Approach

2.1. Aerosol and Cloud Properties: MODIS Terra and Aqua. Data from the moderate resolution imaging spectroradiometer (MODIS) remote sensor on board the two Earth observing system (EOS) Terra and Aqua satellites are used. Level 3 MODIS Collection V5.1 quality assured (QA) monthly average 0.55 μm AOD, cloud effective radius (CER), and cloud optical thickness (COT) at 1° × 1° resolution [29] from 2001 to 2010 are utilized. MODIS level 3 atmospheric products are sorted into 1° × 1° latitude-longitude cells on an equal-angle global grid from level 2 atmospheric products that span over 24 h period [30]. MODIS retrieval algorithms try to match the MODIS observed surface reflectances to a lookup table of precomputed reflectances for a wide variety of commonly observed aerosol conditions [31] over land and ocean. All the data products for 2001 are from Terra only, while from 2002 to 2010 the mean values of data products obtained from Terra and Aqua (launched in 2002) are calculated and utilized. Validation and comparison of AODs retrieved from Terra and Aqua, with ground-based aerosol robotic network (AERONET) sun/sky radiometer measured AODs [32] over the globe, revealed that AODs from Terra and Aqua showed only little differences and agree very well over ocean and land [29]. The algorithms developed to retrieve AODs from MODIS Terra and Aqua were tested and validated with data obtained from airborne imagers [29]. The results of these field tests combined with sensitivity studies suggested that 1σ (standard deviation) of AOD retrievals from MODIS would fall within the expected error bounds of ± (0.05+0.15 AOD) over land and ± (0.03 + 0.05 AOD) over ocean, respectively [29].

Cloud optical properties (CER and COT) retrieved for the combined phase of liquid water and ice cloud drops are used in the present study. The error in MODIS retrieved CER is less than 0.1 μm for a COT of 50, while the error increases to 0.3 μm for an optically thin cloud having an optical thickness of 1 for a CER of 4 μm [33]. The mean error for CER and COT is estimated to be about 13% [34]. Although the absolute errors in individual MODIS retrievals may be significant, the error in the observed relative changes of CER (focus of the current study) is small [23, 35]. Regionally averaged cloud properties derived from MODIS were found to be similar to those diagnosed from ground-based remote sensing data over Southern Great Plains [36] during different seasons. Southern Great Plains is characterized by wide variability in cloud type and surface flux properties and large seasonal variation in temperature and specific humidity [36].

2.2. Absorbing Aerosol Index (AAI): TOMS and OMI. Earth probe total ozone mapping spectrometer (TOMS) measured level 3 1° latitude × 1.25° longitude monthly mean absorbing aerosol index (AAI) data from 2001 to 2004 and monthly level 3 global 1° × 1° gridded AAI from the Aura ozone monitoring instrument (OMI) from 2005 to 2010 are used in the study. AAI is calculated as the difference between the observed and model estimated absorbing and nonabsorbing spectral radiance ratios at 331 and 360 nm. Positive values of AAI (>0.2) represent absorbing aerosols and high negative AAI values (<−0.2) correspond to small nonabsorbing aerosols, that is, pure scattering, while near zero AAI values (±0.2) represent the presence of clouds or larger nonabsorbing particles [37]. The concept of AAI retrieval was developed empirically from TOMS observations [37]. Single scattering albedo (ratio of scattering AOD to the total (scattering + absorption AODs)) obtained from OMI and ground-based AERONET sun photometer observations was found to agree well yielding a root mean square (RMS) difference of 0.03

Table 1: Accumulated rainfall (mm) in July from 2001 to 2010 over the Arabian Sea, all India, and the Bay of Bengal and its mean. Total rainfall during the southwest monsoon season (June-July-August-September) and percentage contribution of July rainfall to total rainfall are given. Percentage difference in July and seasonal rainfall from the mean (2001–2010) for each year and each region is also given. Percentage difference in − indicates % deficit and + denotes % excess with respect to the mean rainfall in July or for the season.

Month/season	Year										Mean
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	
Arabian Sea											
July	78	27	124	80	88	79	90	90	147	155	96 ± 37
Total	277	254	298	328	335	379	570	336	382	545	370 ± 107
July %	28	11	42	24	26	21	16	27	39	28	26 ± 9
% difference in July	−19	−72	+29	−17	−8	−18	−6	−6	+53	+61	
% difference in total	−25	−31	−19	−11	−10	+2	+54	−9	+3	+47	
All India											
July	253	152	278	254	285	277	268	235	290	306	260 ± 43
Total	780	661	819	784	807	848	948	860	741	950	820 ± 88
July %	33	23	34	32	35	33	28	27	39	32	32 ± 4
% difference in July	−2	−41	+7	−2	+10	+7	+3	−10	+11	+18	
% difference in total	−5	−19	0	−4	−2	+3	+16	+5	−10	+16	
Bay of Bengal											
July	244	187	304	201	248	218	232	262	268	275	244 ± 36
Total	887	777	938	848	890	956	1046	946	912	1035	923 ± 81
July %	28	24	32	24	28	23	22	28	29	27	26 ± 3
% difference in July	0	−24	+25	−18	+2	−11	−5	+8	+10	+13	
% difference in total	−4	−16	+2	−8	−4	+4	+13	+2	−1	+12	

for carbonaceous aerosols, while for desert dust aerosols the comparison yielded an RMS difference of 0.02 [37].

2.3. Rainfall: TRMM. The tropical rainfall measuring mission (TRMM) derived level 3 monthly rainfall calculated from the 3-hourly rainfall (mm) data at $1^\circ \times 1^\circ$ latitude-longitude resolution over India and the surrounding oceanic regions (Figure 1) from 2001 to 2010 is used in this study.

2.4. Anomalies. Anomalies in AOD, AAI, CER, COT, and rainfall corresponding to July for each year from 2001 to 2010 and for JJAS are calculated with respect to the 2001–2010 mean of the respective parameters over the Arabian Sea, India, and the Bay of Bengal (Figure 1) and analyzed.

3. Results and Discussion

3.1. Aerosol Characteristics and Rainfall. Monthly (July) and seasonal (JJAS) mean characteristics of aerosols and cloud and rainfall over the study region (Figure 1) are plotted in Figure 3 for the year 2003. 2003 is chosen as it was a normal monsoon year (Table 1). AOD, AAI, and rainfall over India exhibit large spatial variations [2, 6, 38]. AODs were higher in July than in January (winter), April (premonsoon), and October (postmonsoon) (Figure 4) and were lower in northeast India and south India when compared to the other regions in India on an annual scale [2]. AOD, AAI, CER, COT, and rainfall values are higher in July when compared to those in January, April, and October and the monsoon seasonal average (JJAS). During April the Indo-Gangetic Plain is found influenced by emissions from central India from forest fires and open burning of crop waste [38] resulting in higher AAI values (Figure 4(g)). Mineral dust emissions over the northwest and west combined with long range transport of mineral dust from Africa and west Asia (Figure 2(b)) produce higher AAI. During October (northeast monsoon season) the south and eastern India experience rainfall (Figure 4(o)); CER and COT are also high over these regions (Figures 4(m) and 4(n)). High values of AOD, AAI, CER, COT, and rainfall over the Arabian Sea and western India observed in July decrease when seasonal means are considered. In July AODs are higher mainly because of increase in relative humidity which leads to hygroscopic growth of water soluble aerosols [39]. This increase in AOD due to the hygroscopic growth is found to overwhelm the wet removal of aerosols [39]. Towards the end of the summer monsoon season the wind speed and relative humidity decrease (Figure 2); in addition, the winds undergo a transition in direction from southwest to northeast. Thus, the aerosol characteristics show a decrease when averaged over the entire season. These findings give an indication of the variability in AOD, AAI, and rainfall over different regions in India and their interlinks.

At the outset, aerosol characteristics show large regional, intraseasonal, and interannual variations in the last decade (Figures 5, 6, 7, and 8). In the study region AOD anomalies are positive during the 10-year period indicating that the AODs have increased in the last decade over India and the surrounding oceanic regions. AOD anomalies are higher over the Indo-Gangetic Plain (Figures 5 and 6). AOD anomalies are significantly higher during 2002 (Figure 5). Rainfall was

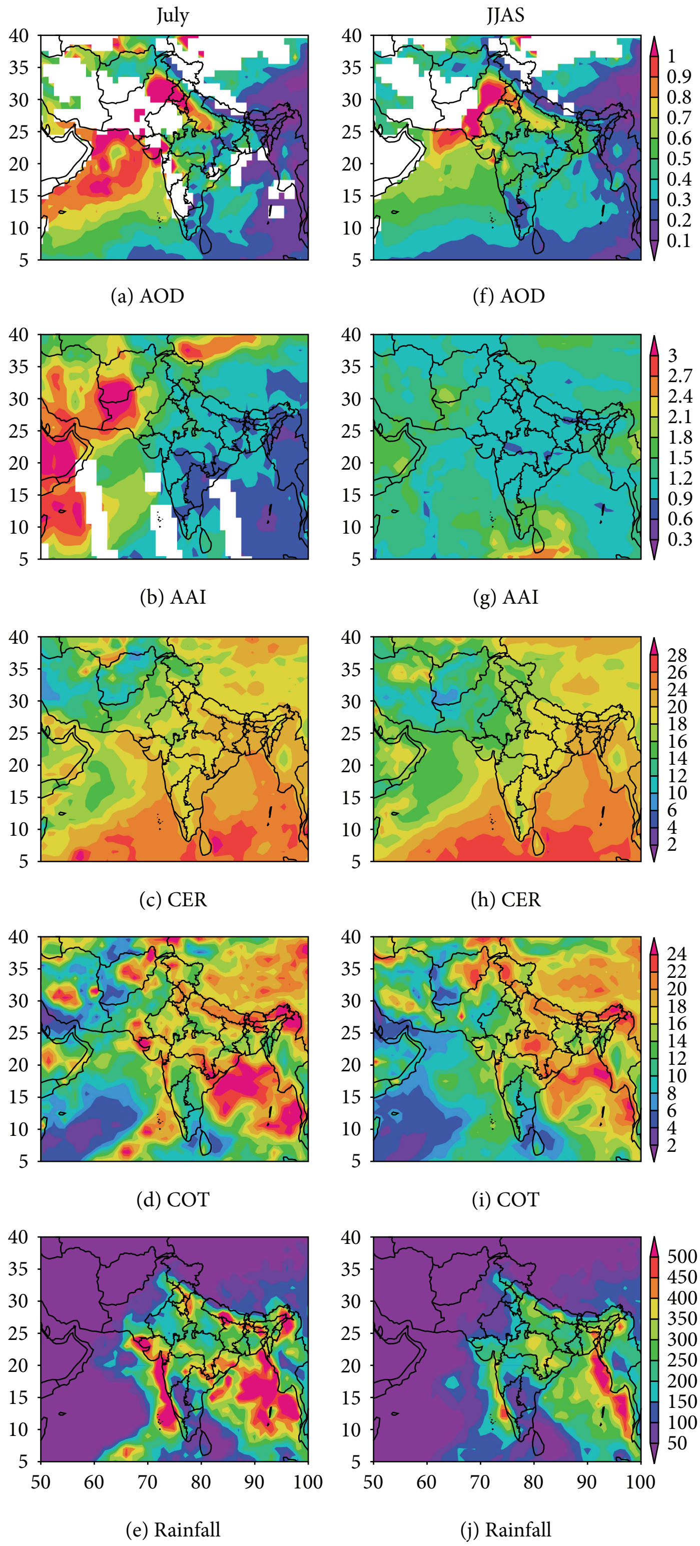

FIGURE 3: ((a), (f)) Aerosol optical depth (AOD), ((b), (g)) absorbing aerosol index (AAI), ((c), (h)) cloud effective radius (CER, μm), ((d), (i)) cloud optical thickness (COT), and ((e), (j)) rainfall (mm) in July and JJAS of 2003, respectively. Aerosol, cloud characteristics, and rainfall for the year 2003 are shown as it was a normal monsoon year.

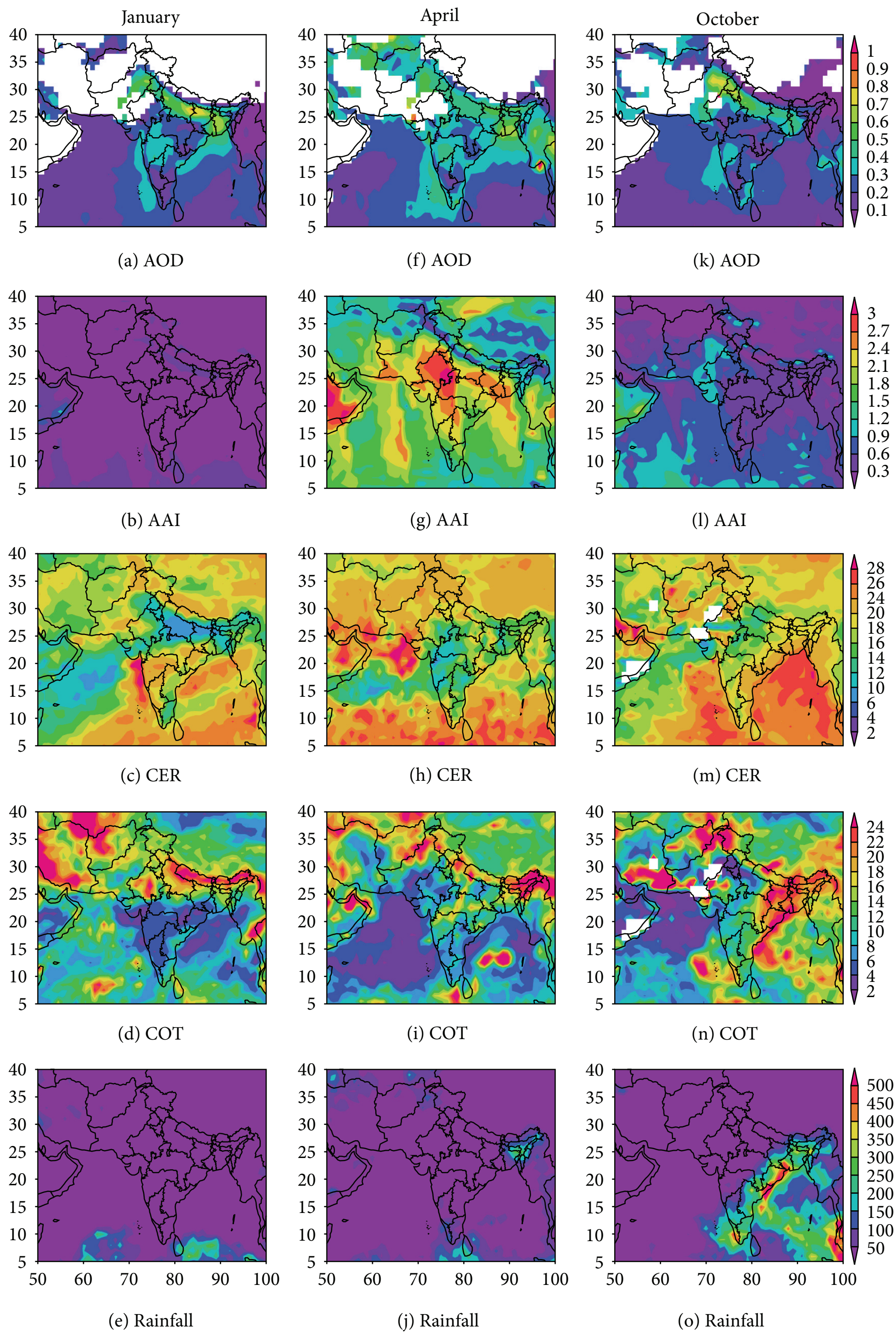

FIGURE 4: ((a), (f), and (k)) Aerosol optical depth (AOD), ((b), (g), and (l)) absorbing aerosol index (AAI), ((c), (h), and (m)) cloud effective radius (CER, μm), ((d), (i), and (n)) cloud optical thickness (COT), and ((e), (j), and (o)) rainfall (mm) in January, April, and October of 2003, respectively, for comparison.

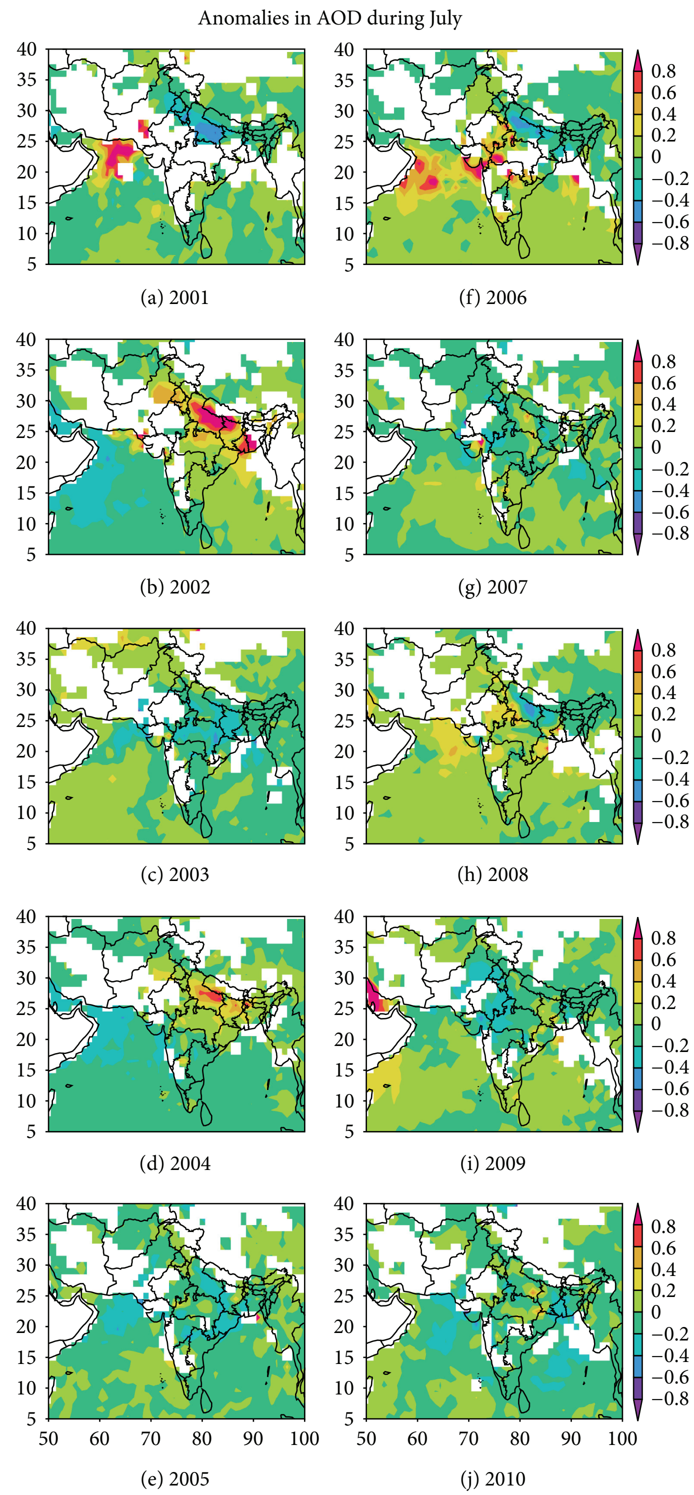

Figure 5: Anomalies in aerosol optical depth (AOD) during July from 2001 to 2010 ((a)–(j)) over the study regions.

significantly lower during 2002 monsoon season (Table 1). The break period in 2002 July was 23 days (5–16 July and 20–30 July) [4]. A longer duration of the drier conditions in July 2002 could have been conducive for raising more dust and smoke as mentioned earlier and resulted in an increase in AOD and AAI (Figures 6 and 8). This is corroborated from the positive anomalies in AOD and AAI and negative anomalies in rainfall over India during the monsoon season of 2002, more significantly in July (Figures 5, 6, 7, 8, 9 and 10).

As most parts of India receive southwest monsoon rainfall in July, AAI values are low owing to wet removal. AAI values are higher than the normal during July 2002 over most parts

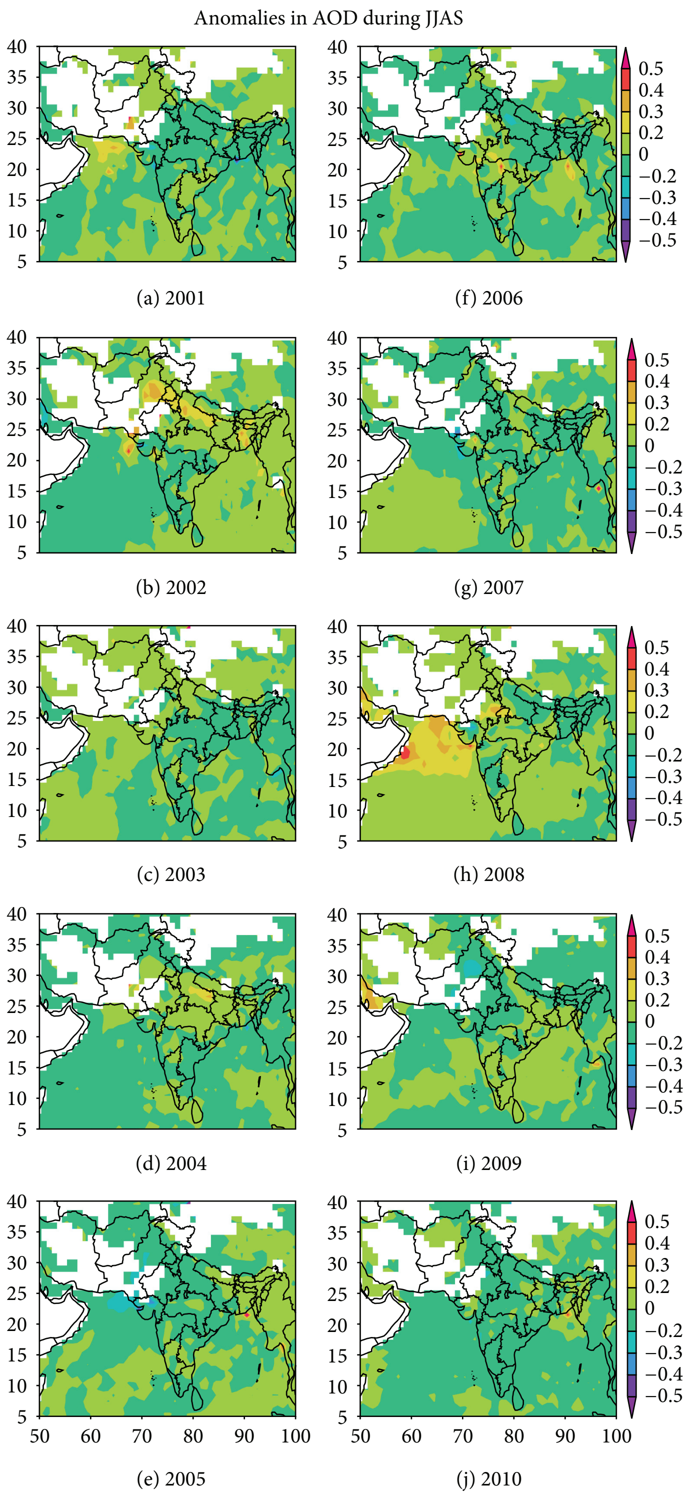

Figure 6: Anomalies in aerosol optical depth (AOD) during the southwest monsoon season (JJAS) in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010 over the Arabian Sea, India, and the Bay of Bengal.

of India (Figure 7). It should be noted that only positive values of AAI which represent absorbing aerosols (mineral dust and carbonaceous aerosols) are used in the study. The dust and carbonaceous aerosol emissions and loading are found to show seasonal and spatial variations across India [38]. Dust emissions were high in the northwest [38] leading to higher AAI values (Figure 7). Thus, these results establish that due to differences in aerosol sources and types (absorbing versus scattering) the inverse relationship between AAI and rainfall can vary (Tables 2 and 3). AAI shows higher

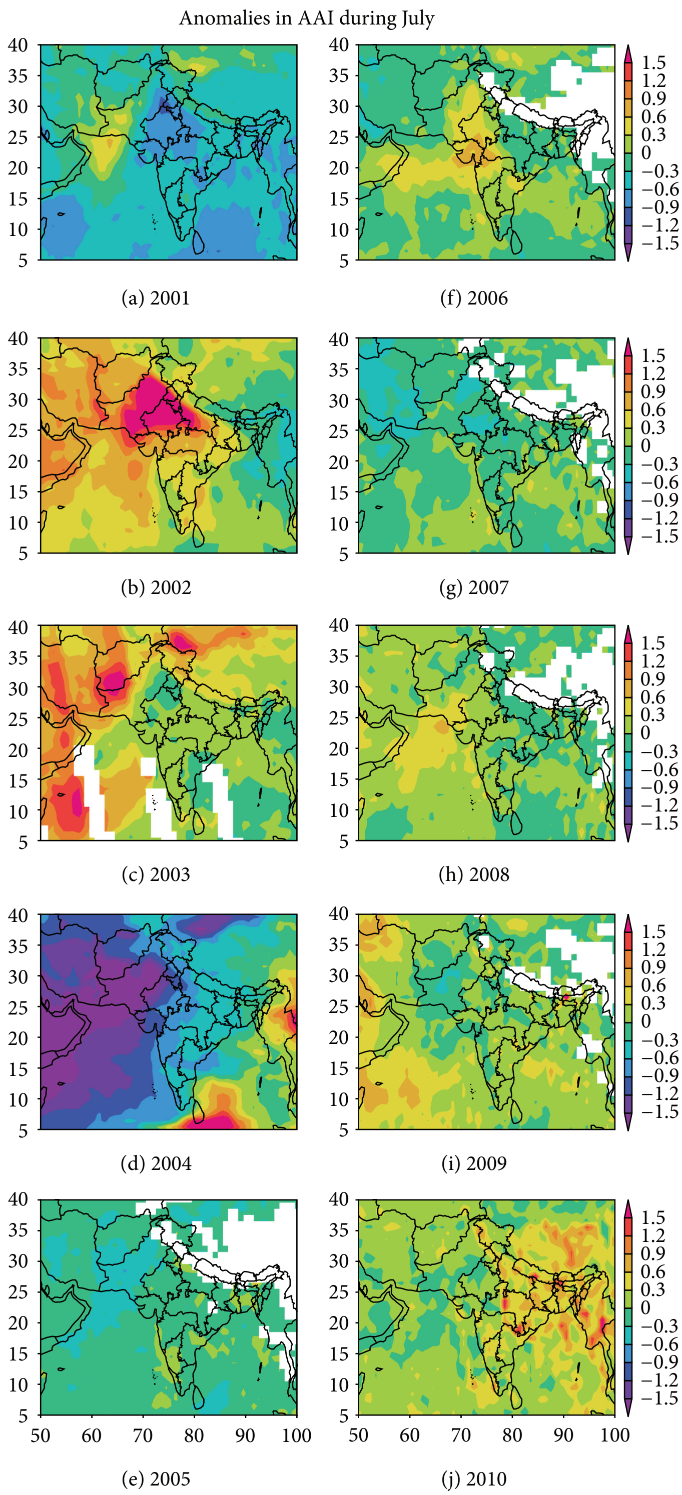

Figure 7: Absorbing aerosol index (AAI) anomalies over the Arabian Sea, India, and the Bay of Bengal during July in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010.

anomalies during July and JJAS, 2010, while no such features are seen in AODs. These interannual variations could lead to lower values of correlation.

3.2. Cloud Characteristics. As aerosols are effective cloud condensation nuclei, the variability in aerosol characteristics is expected to modulate the cloud optical properties such as CER and COT. The precipitation threshold CER is found to be 14 μm [40], and this value has been used as threshold CER in many studies conducted over land and ocean [10, 22, 23]. CER is >14 μm during 2003 (Figure 3) over the study regions and COT is >10 over most of the study region. CER and

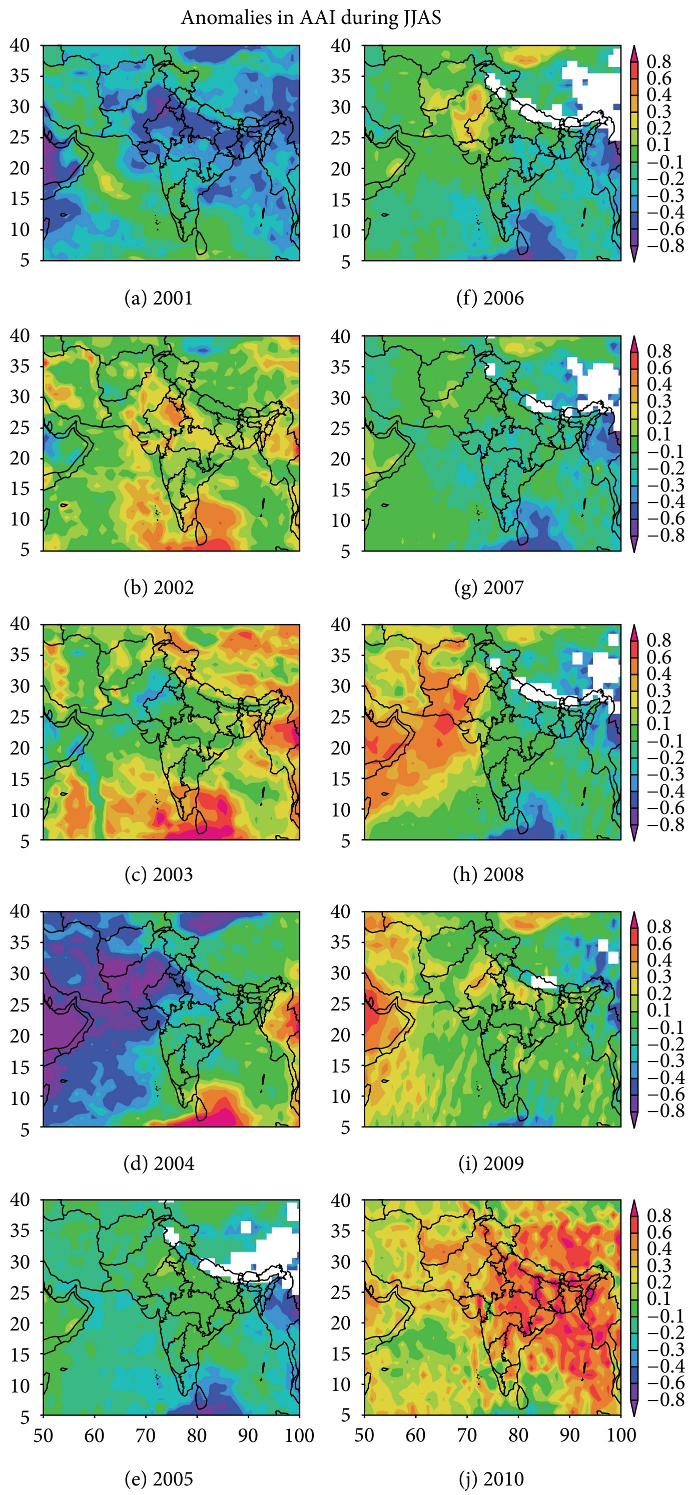

Figure 8: Anomalies in absorbing aerosol index (AAI) during the southwest monsoon season (JJAS) in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010 over the Arabian Sea, India, and the Bay of Bengal.

COT anomalies are significantly lower than the mean in 2002 in July and JJAS over different regions of India (Figures 11, 12, 13, and 14) while AODs and AAI are higher, suggesting an association between aerosols and clouds, and provide an observational evidence for the indirect radiative effect of aerosols on clouds. These results emphasize the fact that when aerosols (especially the absorbers) become abundant, they can decrease the cloud effective radius and decrease the precipitation.

3.3. Correlation between Aerosols, Cloud, and Rainfall. The correlation coefficients obtained based on the correlation

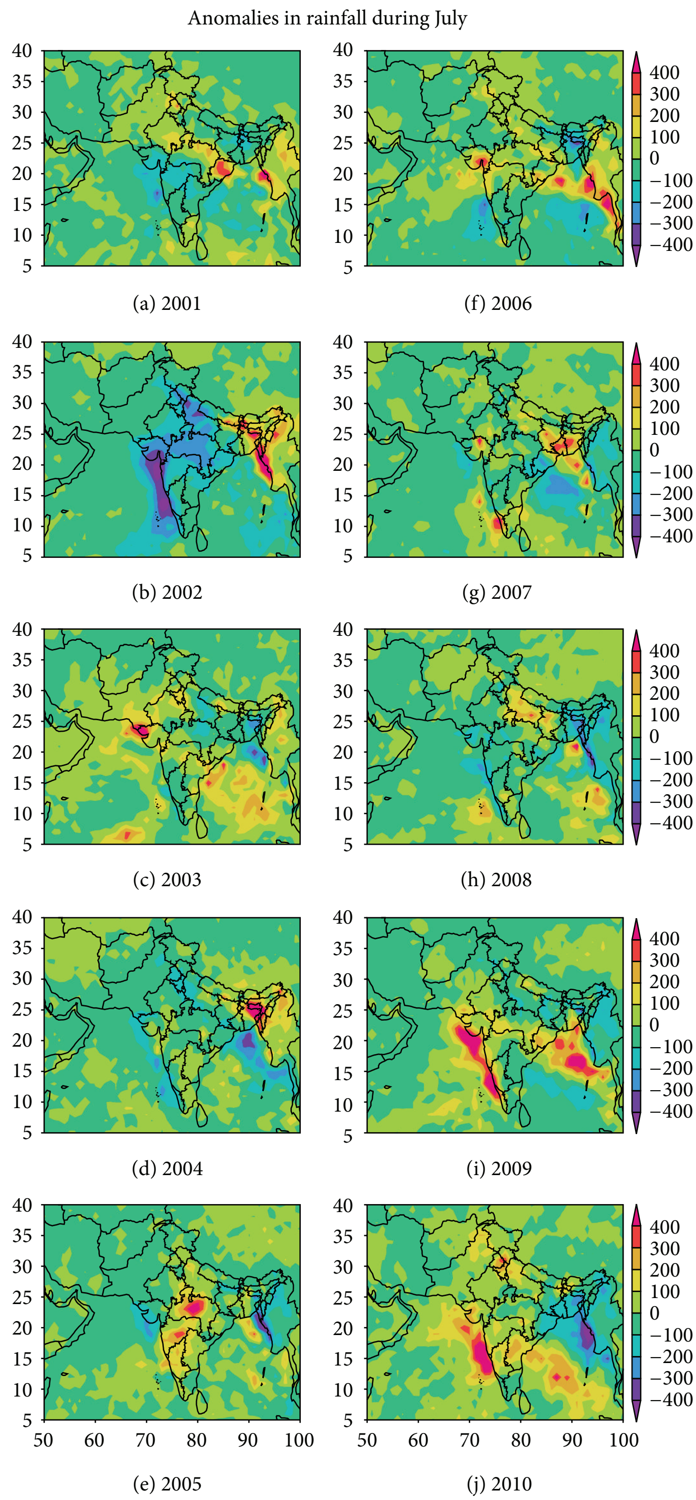

Figure 9: Anomalies in rainfall (mm) over the Arabian Sea, India, and the Bay of Bengal during July in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010.

analysis between AOD, AAI, rainfall, CER, and COT over the Arabian Sea, all India, and the Bay of Bengal on the 10-year time scale (2001–2010) are given in Tables 2 and 3 for July and JJAS, respectively. AOD and rainfall exhibit significant negative correlation over all India and the Bay of Bengal; correlation between the two is positive and low over the Arabian Sea. It is expected that a decrease in AOD will occur during heavy rainfall due to wet removal as seen

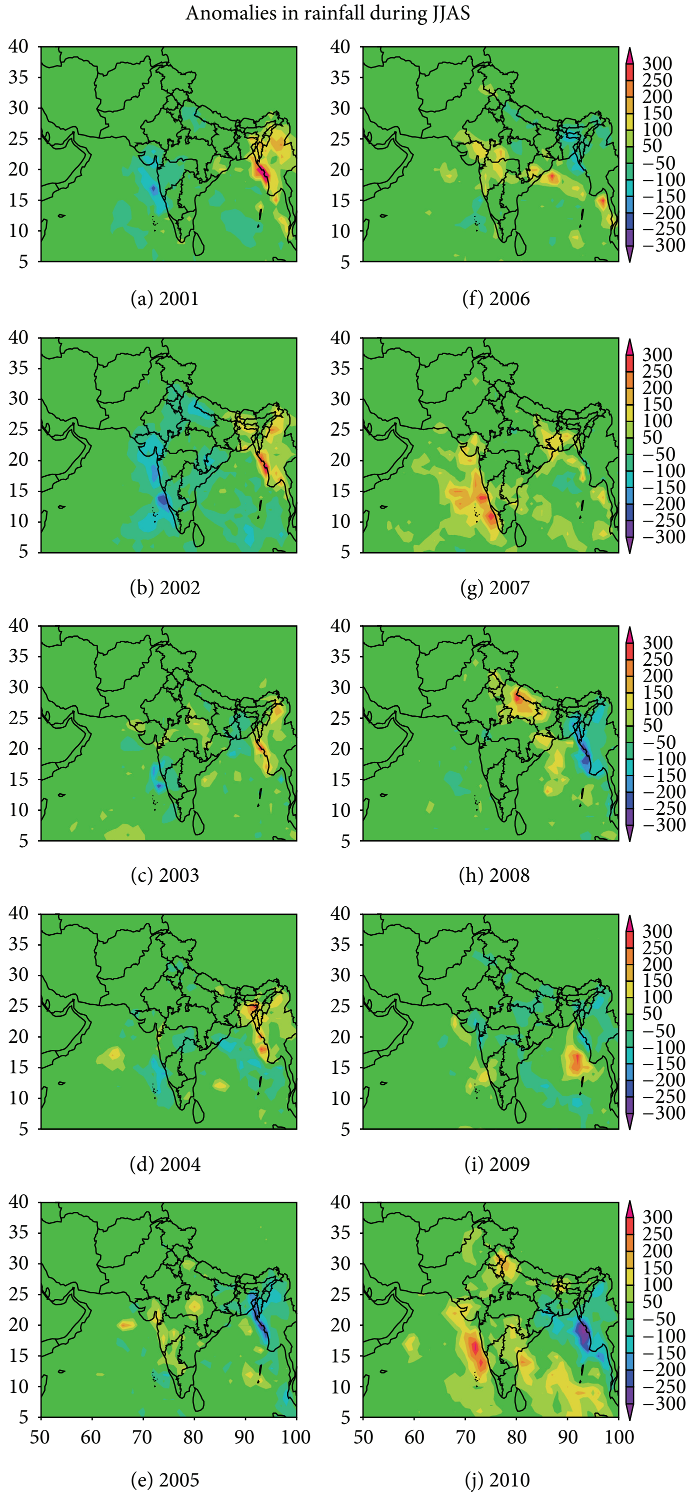

Figure 10: Anomalies in rainfall (mm) during the southwest monsoon season (JJAS) in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010 over the Arabian Sea, India, and the Bay of Bengal.

over all India and the Bay of Bengal. However, a positive correlation between AOD and rainfall anomalies (as seen over the Arabian Sea, Table 2) can arise due to (a) inefficient removal of aerosols by wet deposition, (b) replenishment of aerosols due to natural sources (especially sea salt), and (c) growth of existing hygroscopic (e.g., water soluble) aerosols due to high ambient relative humidity (RH) (exceeding 80%) during summer monsoon. The correlation between AOD

Table 2: Correlation coefficient between aerosol optical depth (AOD), rainfall, absorbing aerosol index (AAI), cloud effective radius (CER), and cloud optical thickness (COT) over the Arabian Sea, all India, and the Bay of Bengal in July between 2001 and 2010. Correlation coefficient (R^2) values ≥0.5 are highlighted in bold.

Region	AOD	Rainfall	AAI	CER	COT
Arabian Sea					
AOD	1.00				
Rainfall	0.23	1.00			
AAI	0.29	0.15	1.00		
CER	0.05	**0.78**	0.29	1.00	
COT	0.47	**0.84**	0.10	**0.52**	1.00
All India					
AOD	1.00				
Rainfall	**−0.78**	1.00			
AAI	0.42	−0.26	1.00		
CER	**−0.72**	**0.78**	−0.39	1.00	
COT	**−0.78**	**0.82**	−0.29	**0.60**	1.00
Bay of Bengal					
AOD	1.00				
Rainfall	**−0.50**	1.00			
AAI	−0.23	0.00	1.00		
CER	0.19	**−0.52**	**0.71**	1.00	
COT	**−0.69**	**0.82**	0.09	−0.34	1.00

Table 3: Correlation coefficient between aerosol optical depth (AOD), rainfall, absorbing aerosol index (AAI), cloud effective radius (CER), and cloud optical thickness (COT) over the Arabian Sea, all India, and the Bay of Bengal during the summer monsoon (JJAS) between 2001 and 2010. Correlation coefficient (R^2) values ≥0.5 are highlighted in bold.

Region	AOD	Rainfall	AAI	CER	COT
Arabian Sea					
AOD	1.00				
Rainfall	−0.09	1.00			
AAI	0.36	0.25	1.00		
CER	0.18	**0.63**	−0.05	1.00	
COT	−0.08	**0.85**	0.00	**0.61**	1.00
All India					
AOD	1.00				
Rainfall	**−0.59**	1.00			
AAI	−0.04	0.16	1.00		
CER	−0.43	**0.90**	−0.07	1.00	
COT	**−0.67**	**0.66**	−0.32	**0.71**	1.00
Bay of Bengal					
AOD	1.00				
Rainfall	**−0.65**	1.00			
AAI	−0.17	−0.14	1.00		
CER	**0.50**	**−0.54**	−0.45	1.00	
COT	−0.08	0.42	−0.45	0.02	1.00

and AAI is positive over the Arabian Sea and all India in July. Averaged over the monsoon season a weak negative correlation exists between AOD and AAI over all India (Table 3). Correlation is negative between AAI and rainfall over all India in July (Table 2), while it is positive for the season (Table 3), though the correlations are weak. A negative correlation suggests that when rainfall is more AAI reduces; a positive correlation between rainfall and AAI indicates that either the near surface aerosols are removed less efficiently or the aerosols could be of scattering type.

Correlation analysis on the 10-year time scale (2001–2010) (Tables 2 and 3) shows that CER and COT exhibit a negative correlation with AOD over India. This feature is different over the Arabian Sea and the Bay of Bengal.

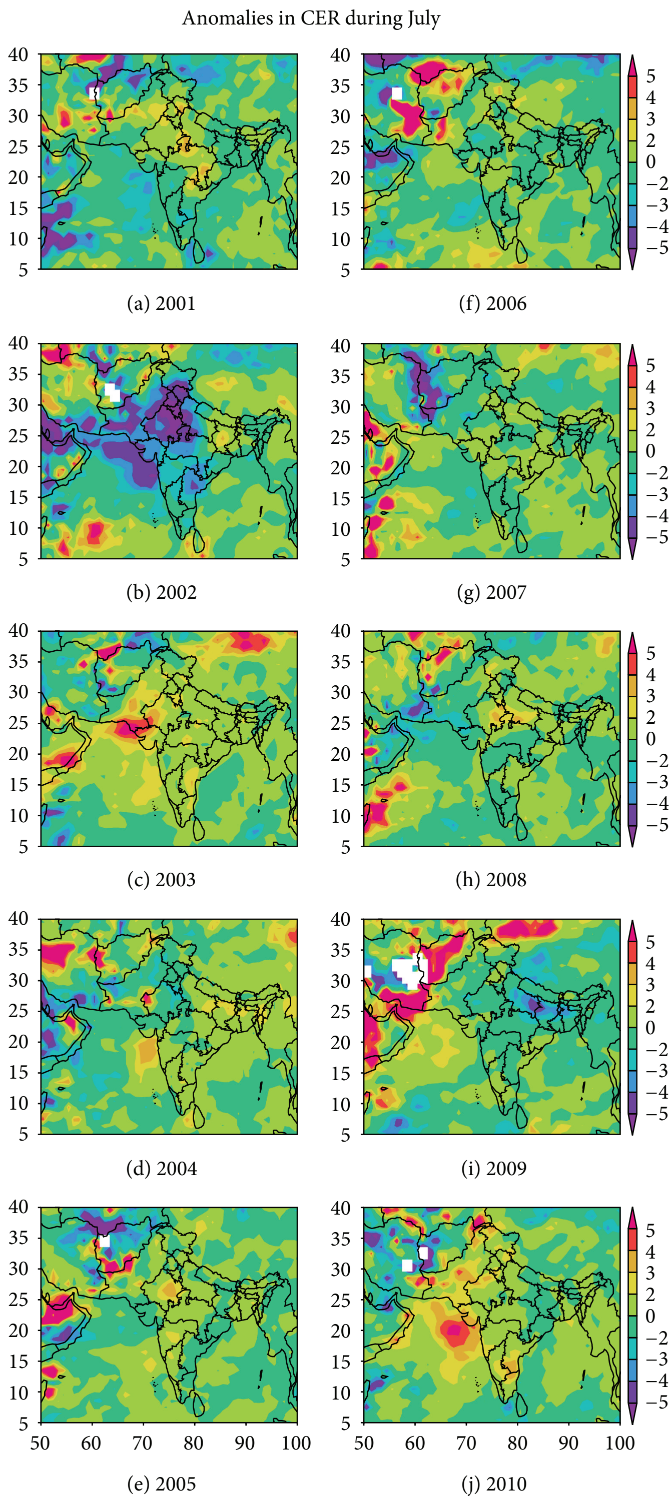

FIGURE 11: Anomalies in cloud effective radius (CER, μm) over the Arabian Sea, India, and the Bay of Bengal during July in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010.

CER and COT show significant positive correlation with rainfall both during July and JJAS over India and the Arabian Sea (Tables 2 and 3). Over the Bay of Bengal CER is negatively correlated with rainfall, while COT is positively correlated. The negative correlation between CER and rainfall could occur due to a combination of variability in meteorological conditions and an inverse aerosol indirect effect caused by heterogeneous ice nucleation [23]. Information on

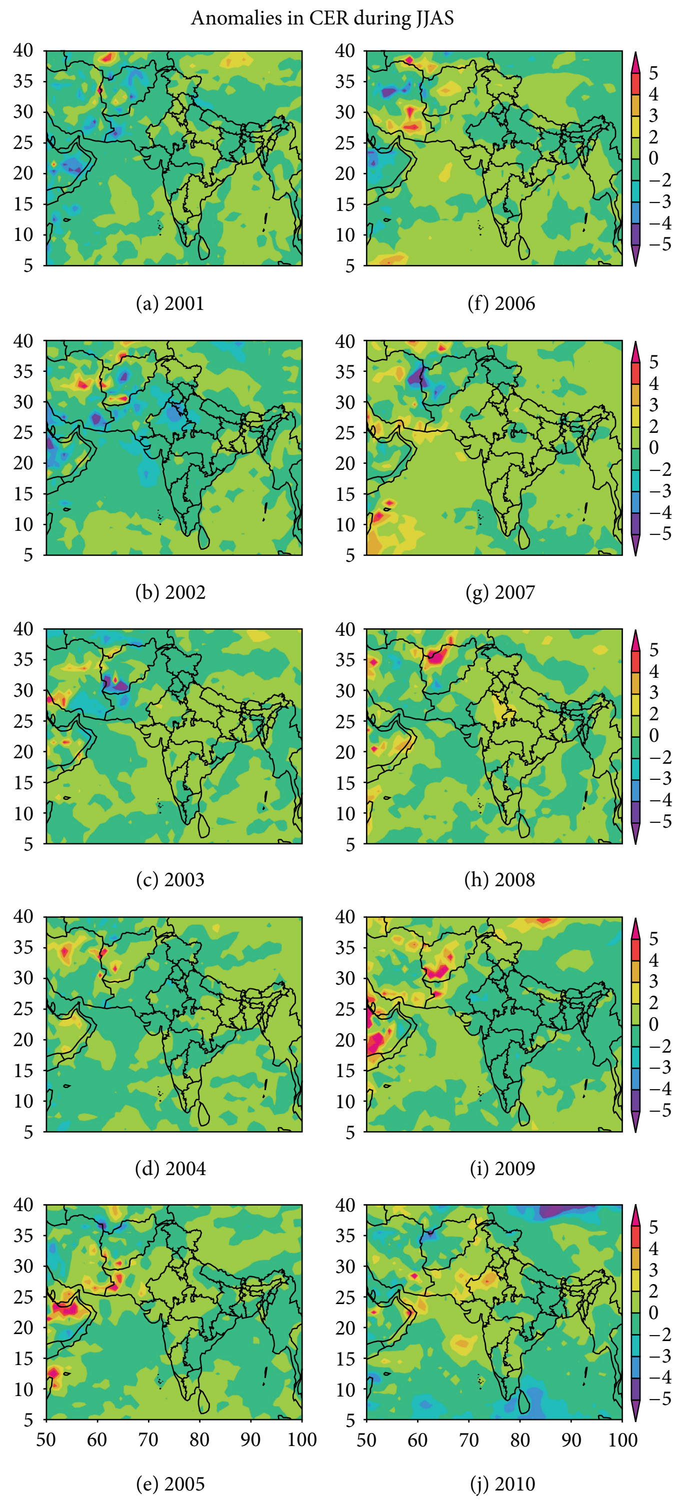

Figure 12: Anomalies in cloud effective radius (CER, μm) during the southwest monsoon season (JJAS) in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010 over the Arabian Sea, India, and the Bay of Bengal.

the variation in CER separately in warm and ice phase clouds is required to examine this effect. The correlation results obtained from the analysis of aerosol-cloud characteristics and rainfall over India and the adjoining oceanic regions agree well with aerosol indirect effects (where CER decreases as AOD and AAI increase [1]). Similar results over the Indian Ocean were obtained by [23]. Further, analysis of aerosol, cloud, and rainfall characteristics over land (India) and

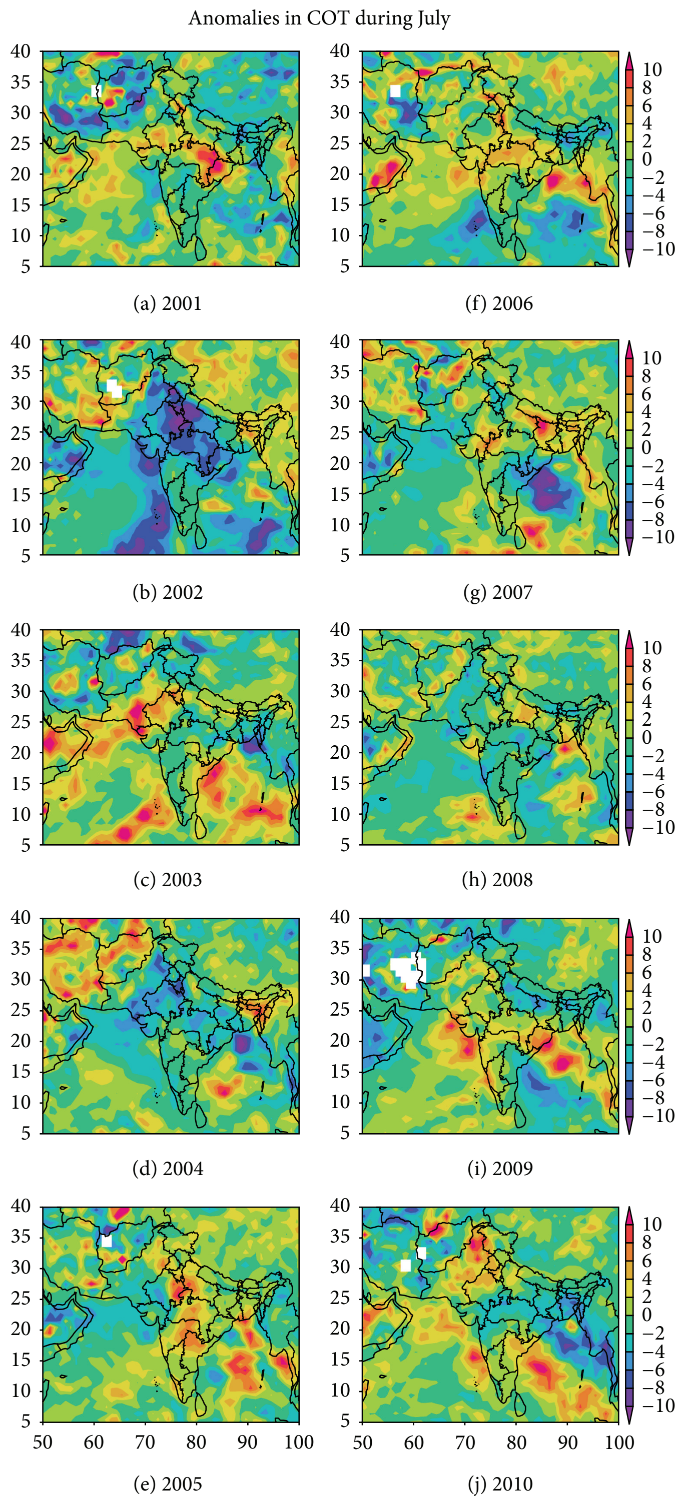

Figure 13: Anomalies in cloud optical thickness (COT) over the Arabian Sea, India, and the Bay of Bengal during July in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010.

the adjacent oceanic regions (Arabian Sea and Bay of Bengal) reveals that the aerosol-cloud interactions and the related aerosol indirect effects can vary on spatial scales.

4. Future Perspectives

It is clear from the above review on aerosol-precipitation interactions that, so far, over India studies linking aerosols

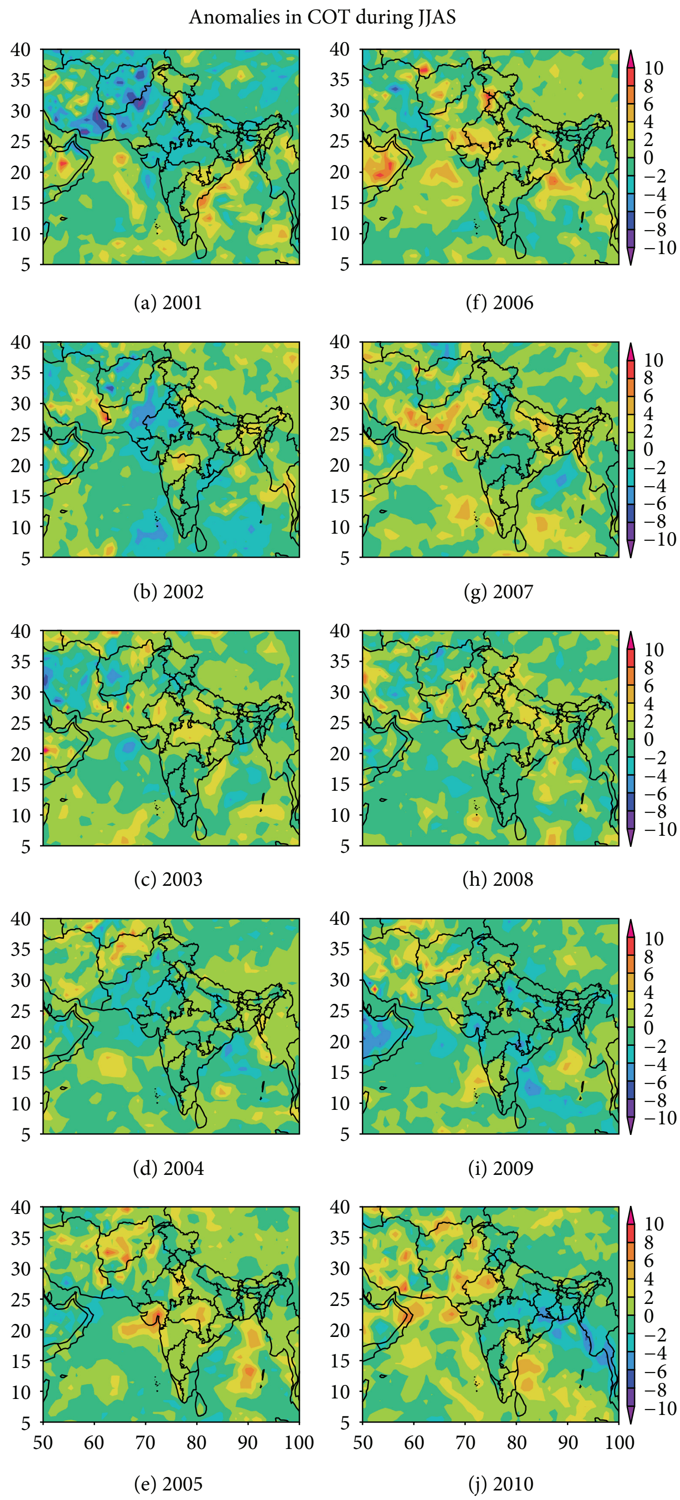

Figure 14: Anomalies in cloud optical thickness (COT) during the southwest monsoon season (JJAS) in (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) 2010 over the Arabian Sea, India, and the Bay of Bengal.

to clouds and precipitation have been performed only using remote sensing data and models which have limitations and uncertainties.

To address the outstanding issues in aerosol-cloud-precipitation interactions and to reduce the uncertainties in indirect radiative effects of aerosols, in future the following should be carried out.

(1) Establish a network of observatories in India and the surrounding oceans, to conduct in situ measurements of chemical composition, size, shape, mixing state of aerosols, and cloud parameters.

(2) Undertake detailed observations on aerosol types, vertical and horizontal distribution of aerosols, mixing of dust and black carbon, and their interannual variations.

(3) Launch satellites to measure aerosol distribution, their chemical composition, microphysical properties of clouds, solar irradiance, and terrestrial longwave radiation.

(4) Conduct intensive campaigns involving aircraft, ship, and land-based observations over different regions of India and the adjoining oceanic regions to measure aerosols and cloud characteristics including the reverse aerosol indirect effect.

The aerosol indirect effects, namely, cloud albedo effect, cloud lifetime effect, and semidirect effect, occur in all clouds (subject matter of the review), while glaciation indirect effect (where an increase in ice nuclei increases the precipitation efficiency) and thermodynamic effect (where smaller cloud droplets delay freezing and produce super-cooled clouds) occur in mixed phase clouds [1]. The aerosol indirect effects that occur in mixed phase clouds can either decrease or increase precipitation [1]. These aerosol indirect effects that occur in mixed phase clouds are also important as their potential magnitude of influence on precipitation is medium [1] and need to be examined in order to reduce the uncertainty in aerosol indirect effect.

These above observations and analysis will determine quantitatively the mixing of aerosols, aerosol types, the role absorbing and scattering type aerosols play in aerosol-cloud-precipitation interactions, and their impact on summer monsoon rainfall over India. The results from these proposed studies will provide hitherto unavailable spatial and temporal distribution of aerosol and cloud parameters, all of which will result in an improved and a more reliable quantification of direct and indirect radiative effects of aerosols.

Acknowledgments

Relative humidity and winds are obtained from NCEP Reanalysis through http://www.cdc.noaa.gov/. Aerosol optical depth (AOD), cloud effective radius (CER), and cloud optical thickness (COT) from MODIS, absorbing aerosol index (AAI) from TOMS and OMI, and rainfall from TRMM are downloaded from GES-DISC, NASA.

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