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Unexpected increasing AOT trends over northwest Bay of Bengal in the early postmonsoon season

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[1] The main point of our study is that aerosol trends can be created by changes in meteorology without changes in aerosol source strength. Over the 10 year period 2000–2009, in October, Moderate Resolution Imaging Spectroradiometer (MODIS) showed strong increasing aerosol optical thickness (AOT) trends of approximately 14% yr^{-1} over northwest Bay of Bengal (BoB) in the absence of AOT trends over the east of the Indian subcontinent. This was unexpected because sources of anthropogenic pollution were located over the Indian subcontinent and aerosol transport from the Indian subcontinent to northwest BoB was carried out by prevailing winds. In October, winds over the east of the Indian subcontinent were stronger than winds over northwest BoB, which resulted in wind convergence and accumulation of aerosol particles over northwest BoB. Moreover, there was an increasing trend in wind convergence over northwest BoB. This led to increasing trends in the accumulation of aerosol particles over northwest BoB and, consequently, to strong AOT trends over this area. In contrast to October, November showed no increasing AOT trends over northwest BoB or the nearby Indian subcontinent. The lack of AOT trends over northwest BoB corresponds to a lack of trends in wind convergence in that region. Finally, December domestic heating by the growing population resulted in positive AOT trends of similar magnitude over land and sea. Our findings illustrate that in order to explain and predict trends in regional aerosol loading, meteorological trends should be taken into consideration together with changes in aerosol source strength.

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1. Introduction

[2] In the developing countries of Asia, Africa, and Latin America significant population growth is observed. In this respect, the demographic situation in the Indian subcontinent is the most pronounced. The Indian subcontinent occupies 2.4% of the world landmass and is home to ∼17% of the world population. In accordance with demographic predictions, India will become the most highly populated country in the world by the year 2030, with a population of over 1.4 billion. By the year 2050, the Indian population could be over 1.6 billion (U.S. Census Bureau, http://www.census.gov/population/international/). The significantly growing population needs increasing transportation, industrial development, and more fuel for domestic purposes. These factors are already causing increasing anthropogenic aerosol emissions and declining air quality [*Di Girolamo et al.* 2004; *Ramanathan and Ramana*, 2005; *Tripathi et al.*, 2005; *Prasad and Singh*, 2007; *Kaskaoutis et al.*, 2011a; *Dey and Di Girolamo*, 2011]. In our previous study [*Kishcha et al.*, 2011] we quantified the effects of urbanization on aerosol optical thickness (AOT) over the Indian subcontinent, averaged separately over regions with differing population densities. The quantification of the effect of urbanization on AOT trends was carried out by analyzing satellite aerosol data every year from 2000 to 2008 from October to February, which is the season of minimal cloud presence and desert dust activity. We have shown that over extensive areas with differing population densities, (1) the higher the averaged population density, the larger the averaged AOT, and (2) the larger the population growth, the stronger the increasing trends in AOT. Over the regions with population density $P > 100$ person km^{-2} (more than 70% of the territory), a population growth of ∼1.5% yr^{-1} was accompanied by increasing AOT trends of over 2% yr^{-1}. The presence of the aforementioned AOT trends is evidence of the current worsening of air quality in the Indian subcontinent over the period under consideration.

[3] Anthropogenic aerosol particles originating in the Indian subcontinent are transported to the surrounding sea

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areas, in accordance with prevailing winds. Aerosol loading over BoB is mainly produced by aerosol transport from highly populated zones and industrial centers located within the Indian subcontinent, mainly in the Ganges basin. This is because of prevailing winds blowing along the Ganges basin in the postmonsoon and winter months [*Di Girolamo et al.* 2004; *Prasad and Singh*, 2007; *Kumar et al.*, 2010]. The aerosol over BoB has been extensively investigated during a number of sea expeditions. Some short-term sea expeditions in BoB focused mainly on aerosol studies in coastal waters [*Ramachandran and Jayaraman*, 2003; *Vinoj et al.*, 2004; *Ganguly et al.*, 2005]. During the ICARB campaign, aerosol over BoB was investigated during the premonsoon season of 2006 [*Moorthy et al.*, 2008]. The Winter-ICARB (W-ICARB) campaign was performed during the winter season 2008–2009 in order to study physical, chemical, and optical properties of atmospheric aerosols over the entire BoB region [*Kumar et al.*, 2010; *Kaskaoutis et al.*, 2011b].

[4] Spatial distributions of long-term AOT trends over south Asia including BoB were examined, using different satellite AOT data sets, by *Mishchenko and Geogdzhayev* [2007], *Zhao et al.* [2008], *Zhang and Reid* [2010], *Kaskaoutis et al.* [2011a], *Dey and Di Girolamo* [2011], and *Hsu et al.* [2012]. Based on AVHRR satellite data, *Mishchenko and Geogdzhayev* [2007] showed significant changes in over-water AOT in the four seasons which occurred between the two periods 1988–1991 and 2002–2005. *Zhao et al.* [2008] studied AOT trends over the whole area of BoB for spring, summer, autumn, and winter, using AVHRR data during the 25 year period 1981–2005. Using Moderate Resolution Imaging Spectroradiometer (MODIS)-Terra Level 2 AOT data, *Zhang and Reid* [2010] analyzed AOT trends over the whole area of BoB for all months during the 10 year period 2000–2009. The spatial distribution of decadal (2000–2009) MODIS Level 3 AOT trends over south Asia including BoB in different months was obtained by *Kaskaoutis et al.* [2011a]. Using MISR aerosol data, decadal (2000–2009) AOT trends over the Indian subcontinent and surrounding sea areas were also estimated by *Dey and Di Girolamo* [2011]. *Hsu et al.* [2012] obtained the maps of SeaWiFS AOT trends for the four seasons from 1998–2010. In the aforementioned studies, increasing AOT trends over northwest BoB were detected, however, the influence of changes in meteorology on these AOT trends was not discussed.

[5] In the current study, we compared AOT trends over northwest BoB and those over the east of the Indian subcontinent during the 10 year period 2000–2009, in the postmonsoon season. Northwest BoB is relatively remote from sources of anthropogenic emissions in the Indian subcontinent, mainly in the highly populated Ganges basin. In the postmonsoon season, one could expect to find AOT trends over northwest BoB not exceeding AOT trends over the Indian subcontinent. However, in the early postmonsoon season (October), strong increasing AOT trends were observed over northwest BoB, in the absence of AOT trends over the Indian subcontinent, including those over the Ganges basin. It should be noted that the authors of the aforementioned previous studies on AOT trends over BoB did not discuss this phenomenon of unexpected increasing AOT trends over northwest BoB in October. The obtained strong AOT trends over northwest Bay of Bengal in October were surprising indeed, and they deserved detailed analysis. Consequently, in the current study, we focused on this specific phenomenon.

2. Method

[6] Following our previous study [*Kishcha et al.*, 2011], we analyzed AOT trends over the east of the Indian subcontinent and northwest BoB using Collection 5 (MOD08_M3–005) of MODIS-Terra Level 3 monthly aerosol data with horizontal resolution 1° × 1°, during the 10 year period 2000–2009.

[7] MODIS is a sensor with the ability to characterize the spatial and temporal characteristics of the global aerosol field. MODIS with its 2330 km viewing swath provides almost daily global coverage. MODIS has separate algorithms for retrieving aerosol products over land and ocean. The MODIS over-ocean algorithm is more accurate than the over-land algorithm: the AOT uncertainty is ±0.03 ± 0.05 AOT over the ocean and ± (0.05 + 15%) over the land [*Remer et al.*, 2005; *Levy et al.*, 2010]. It should be noted that because of sensor degradation, there is a weak (but nevertheless statistically significant) artificial downward trend in MODIS Terra AOT products over the land: MODIS tended to overestimate AOT by ~0.005 before 2004 and to underestimate AOT by a similar magnitude thereafter [*Levy et al.*, 2010]. In addition, *Zhang and Reid* [2010] found an artificial upward trend in MODIS Terra AOT at the rate of 0.01 decade^{-1} over the ocean.

[8] MODIS has quite a limited opportunity to view aerosols if cloud cover is higher than 0.8 [*Remer et al.*, 2008; *Zhang et al.*, 2005]. It means that satellite aerosol retrievals obtained under such overcast conditions are less accurate than AOD obtained when cloud presence is rather low. Moreover, in accordance with *Remer et al.* [2008] and *Zhang et al.* [2005], it is possible that when cloud fraction exceeds 0.8, satellite aerosol retrievals are overestimated because of cloud contamination: the aerosol retrievals interpret, in error, cloud droplets as coarse mode particles. In the current study, the analysis was conducted for the postmonsoon season (October, November, and December), the season of minimal cloud presence and minimal desert dust activity over the region under consideration.

[9] Our investigation was based on the analysis of long-term variations of AOT over three zones 3° × 3° located in northwest BoB (Figure 1). These long-term variations of AOT averaged over northwest BoB were compared with those averaged over land areas in the east of the Indian subcontinent. Figure 1a shows the spatial distribution of 10 year mean AOT over the region under consideration in October, together with the location of zones 3° × 3° in the Bay of Bengal (zone 1 to zone 3) and in the east of the Indian subcontinent (zone 4 to zone 8). In addition, there are two reference zones of the same dimension 3° × 3°, against which the long-term changes in AOT over the Bay of Bengal are compared. The first reference zone (zone 9) is located in the Ganges basin and is centered at the AERONET monitoring site in Kanpur (26.5°N, 80.2°E). We compared long-term variations of MODIS AOT over zone 9 with those of AERONET AOT, using available quality assured monthly Level 2 AERONET measurements in Kanpur from 2001–2009. The second reference zone (zone 10) is located on the

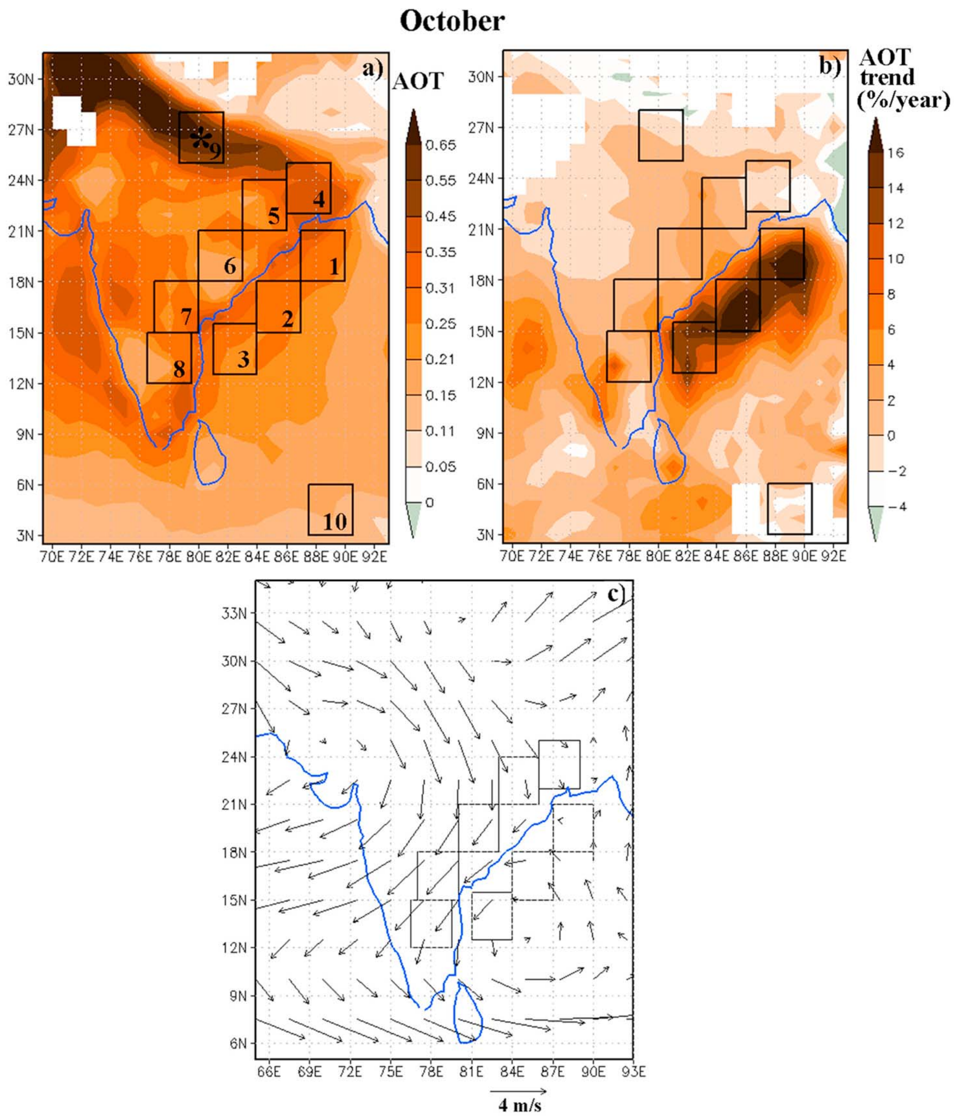

Figure 1. Spatial distributions of (a) the 10 year (2000–2009) mean MODIS AOT and (b) its trends in October. (c) The 10 year mean wind vectors of the 700–850 hPa layer in October. The horizontal vector at the bottom is the scale for wind vectors. The squares show the locations of zones 1 to 10 within the region under consideration. The star in square 9 in Figure 1a designates the location of the AERONET monitoring site in Kanpur.

boundary between the Bay of Bengal and the Indian Ocean, an area which is substantially less polluted than northeast BoB (Figure 1a).

[10] A linear fit was used to determine the resulting trend of aerosol optical thickness for long-term variations (2000–2009) over each of the aforementioned zones, as well as over two joint areas: in BoB (zone 1–3) and in the east of the Indian subcontinent (zone 5–8). The obtained AOT trend values correspond to the slope of the linear fit in percentage form, using as a basis the mean AOT value during 2000–2001 of the particular month. To ensure that the linear fit produces normally distributed residuals, they were required to pass the Shapiro-Wilk normality test [*Shapiro and Wilk*, 1965; *Razali and Wah*, 2011]. If the residuals were normally distributed, they could be used in a *t* test, in order to estimate the statistical significance of a linear fit. The statistical significance of the AOT trend was checked by applying the significance level (p) value, i.e., $p < 0.05$ for statistically significant AOT trends at the 95% confidence level.

3. Results

3.1. AOT Trends in October

[11] According to the spatial distribution of 10 year (2000–2009) mean MODIS AOT in October, over the Indian subcontinent, AOT maximum of 0.72 was observed over the northwest part of the Indo-Gangetic Plain (Figure 1a). This AOT maximum was associated with the impact of crop waste burning on aerosol properties [*Sharma et al.*, 2010; *Venkataraman et al.*, 2006]. *Venkataraman et al.* [2006] mentioned a seasonal cycle in cropland fires with peaks in

Table 1. The 10 Year Mean AOT (τ), Standard Deviation (SD), and Resulting Trends (α) for Long-Term Changes of MODIS AOT Averaged Over the Specified Zones in October[a]

Zone	Geographic Coordinates	τ	SD	α (% yr^{-1})	S-W Test	p
		Bay of Bengal				
1	18°N–21°N, 87°E–90°E	0.29	0.09	14.0	Normal	0.001
2	15°N–18°N, 84°E–87°E	0.27	0.09	16.0	Normal	0.001
3	12.5°N–15.5°N, 81°E–84°E	0.26	0.08	12.0	Normal	0.007
		India Subcontinent				
4	22°N–25°N, 86°E–89°E	0.38	0.05	−0.7	Normal	Not significant
5	21°N–24°N, 83°E–86°E	0.24	0.04	2.5	Normal	Not significant
6	18°N–21°N, 80°E–83°E	0.19	0.04	1.5	Normal	Not significant
7	15°N–18°N, 77°E–80°E	0.26	0.04	2.0	Normal	Not significant
8	12°N–15°N, 76.5°E–79.5°E	0.23	0.06	2.4	Normal	Not significant
		Joint Areas				
1–3		0.27	0.08	14.0	Normal	0.001
5–8		0.26	0.03	2.1	Normal	Not significant
		Reference Zones				
9	25°N–28°N, 78.7°E–81.7°E	0.56	0.07	0.3	Normal	Not significant
10	3°N–6°N, 85°E–88°E	0.14	0.04	−1.6	Normal	Not significant
AERONET site	26.5°N, 80.2°E	0.67	0.16	2.2	Normal	Not significant

[a]The decision based on the Shapiro-Wilk normality test for residuals (S-W test) and the significance level (p) are also displayed. If the p value was too high as compared with the 0.05 significance level, the obtained linear fit was considered as statistically insignificant.

May and October corresponding to the two major harvest seasons in the western Indo-Gangetic plain. *Sharma et al.* [2010] measured AOT and the Angstrom exponent in the Punjab state, India, in October. They showed high values of the Angstrom exponent, which indicated increasing concentrations of fine biomass burning aerosol particles with size less than 1 μm.

[12] Over the Bay of Bengal, the spatial distribution of 10 year mean AOT showed maximum values over zones 1 to 3 in its northwest part, adjacent to the east coast of the Indian subcontinent (Figure 1a). AOT over northwest BoB decreased with descending latitude: AOT of 0.29 over zone 1 was higher than AOT of 0.26 over zone 3 (Table 1). Moreover, as estimated, there was a high correlation of over 0.8 in long-term AOT variations in October during the period under consideration between zones 1 and 2, and also between zones 2 and 3. This suggests that aerosols were mainly transported from zone 4 through zone 1 into zones 2 and 3.

[13] In October, the spatial distribution of AOT trends shows that AOT trends over the northwest BoB exceed those over the Indian subcontinent, including the AOT trends over the Ganges basin (Figure 1b). In particular, insignificant AOT trends were observed over zones 4–8 in the east of the Indian subcontinent, based on MODIS AOT data (Table 1). Moreover, AERONET also showed insignificant AOT trends at the Kanpur monitoring site in October, based on available quality assured monthly Level 2 AERONET measurements in Kanpur during the period under consideration (Table 1). This is in line with *Kaskaoutis et al.* [2012], who estimated AERONET trends at the Kanpur site in different months during the period 2001–2010. It is surprising that in October, in the absence of AOT trends over the east of the Indian subcontinent, strong AOT trends were observed over sea areas in northwest BoB. Over joint zone 1–3, an AOT trend of approximately 14% yr^{-1} was observed (Table 1). This was unexpected because aerosol particles transported over northwest BoB were also transported over the land in the east of the Indian subcontinent. Therefore, the obtained AOT trends over different zones clearly show that in October, long-term changes in AOT over sea areas in northwest BoB were essentially different from those over land areas in the Indian subcontinent.

[14] This difference in AOT trends over land and sea is further illustrated with comparisons between long-term changes of AOT over the two adjacent zones 1 and 4 (Figure 2a). It is seen that at the beginning of the 10 year period under consideration, in October 2000 and 2001, AOT over zone 4 was equal to ~0.36, while AOT over zone 1 was 2 times lower and equal to ~0.19 (Figure 2a). This low AOT over zone 1 corresponded to the aerosol level over the remote zone 10 (Figure 3a). This suggests that at the beginning of the 10 year period under consideration, in October 2000 and 2001, the aerosol transport from the Indian subcontinent to northwest BoB was weak. In subsequent years in October, the AOT difference between zones 1 and 4 gradually decreased. In October 2008 and 2009, AOT over zone 4 was equal to ~0.34, while AOT over zone 1 it was equal to ~0.38 (Figure 2a).

[15] In addition, in order to illustrate the significant AOT trend over zone 1 in northwest BoB, we compared it with the AOT trend over remote zone 10 (Figure 3a). As mentioned, zone 10 is distant from the main anthropogenic sources on the land. Over zone 10, the obtained 10 year mean AOT of 0.14 (Table 1) was close to the regional background AOT level in the Indian Ocean, which is equal to approximately 0.10 at latitude 30°S [*Kishcha et al.*, 2009]. In October 2000 and 2001, AOT over zone 1 was approximately the same as that over zone 10. At the end of the 10 year period, in October 2009, AOT over zone 1 became approximately 2.5 times as high as that over zone 10 (Figure 3a). In contrast to the strong increasing AOT trend over zone 1, over zone 10 the AOT trend was insignificant in October (Table 1). In subsequent months, November and December, 10 year mean AOT over zone 10 remained approximately the same, and AOT trends remained statistically insignificant. This is in

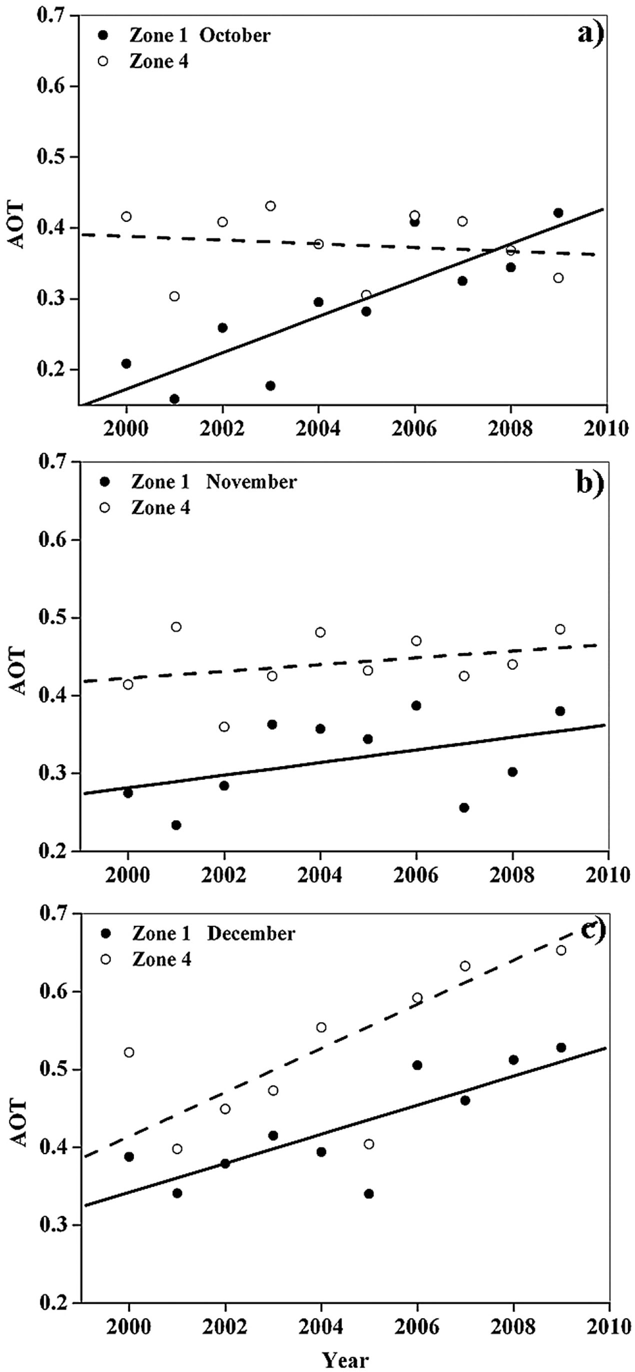

Figure 2. Year-to-year variations of MODIS AOT over zones 1 and 4 in (a) October, (b) November, and (c) December. The straight lines (dashed for zone 4 and solid for zone 1) designate linear fits.

contrast to AOT trends over northwest BoB, as shown in section 3.3.

[16] This comparison between the AOT trend over northwest BoB in October and that over remote zone 10 provides us with evidence that the strong increasing AOT trend over northwest BoB was real and not an artifact. Indeed, if calibration drifts in the MODIS sensor [*Zhang and Reid*, 2010] were causing significant trends in northwest BoB, these drifts would be seen more or less uniformly over the global oceans because sensor calibration is applied uniformly and globally. The fact that zone 10 shows no significant trend in October is evidence that the trends in zones 1–3 are not artifacts from instrument calibration drift.

[17] Using quality assured MODIS Level 2 data, *Zhang and Reid* [2010] found a statistically significant AOT trend of 0.0076 yr^{-1} over the whole geographic area of BoB (10°N–25°N; 78°E–103°E). To compare their MODIS Level 2 AOT trend with that based on MODIS Level 3 AOT data, we also estimated the decadal AOT trend over the same area of BoB and for all months. As shown in Figure 3b, the obtained AOT trend was equal to 0.008 yr^{-1} (approximately 3% yr^{-1}). One can see that the AOT trend over BoB for all months, based on MODIS Level 3 data, was similar to that obtained by *Zhang and Reid* [2010]. This indicates that over BoB, there was no noticeable difference between MODIS Level 3 AOT trends and those of MODIS Level 2, and we can reproduce previously published results.

3.2. Wind Convergence Trends in October

[18] Mean wind distributions, averaged over the 10 year period under consideration, were used in the current study to show aerosol transport from the Indian subcontinent to northwest BoB. NCEP/DOE Reanalysis-2 wind monthly data with horizontal resolution 2.5° × 2.5° were used. The

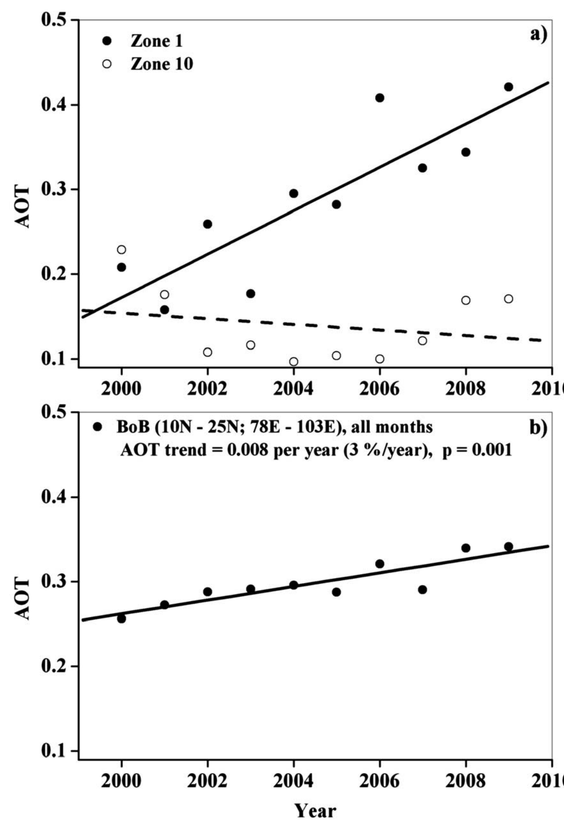

Figure 3. Year-to-year variations of AOT over different zones based on MODIS Level 3 AOT data: (a) Over zones 1 and 10 in October, (b) over the whole geographic area of BoB (10°N–25°N; 78°E–103°E) for all months. The straight lines designate linear fits.

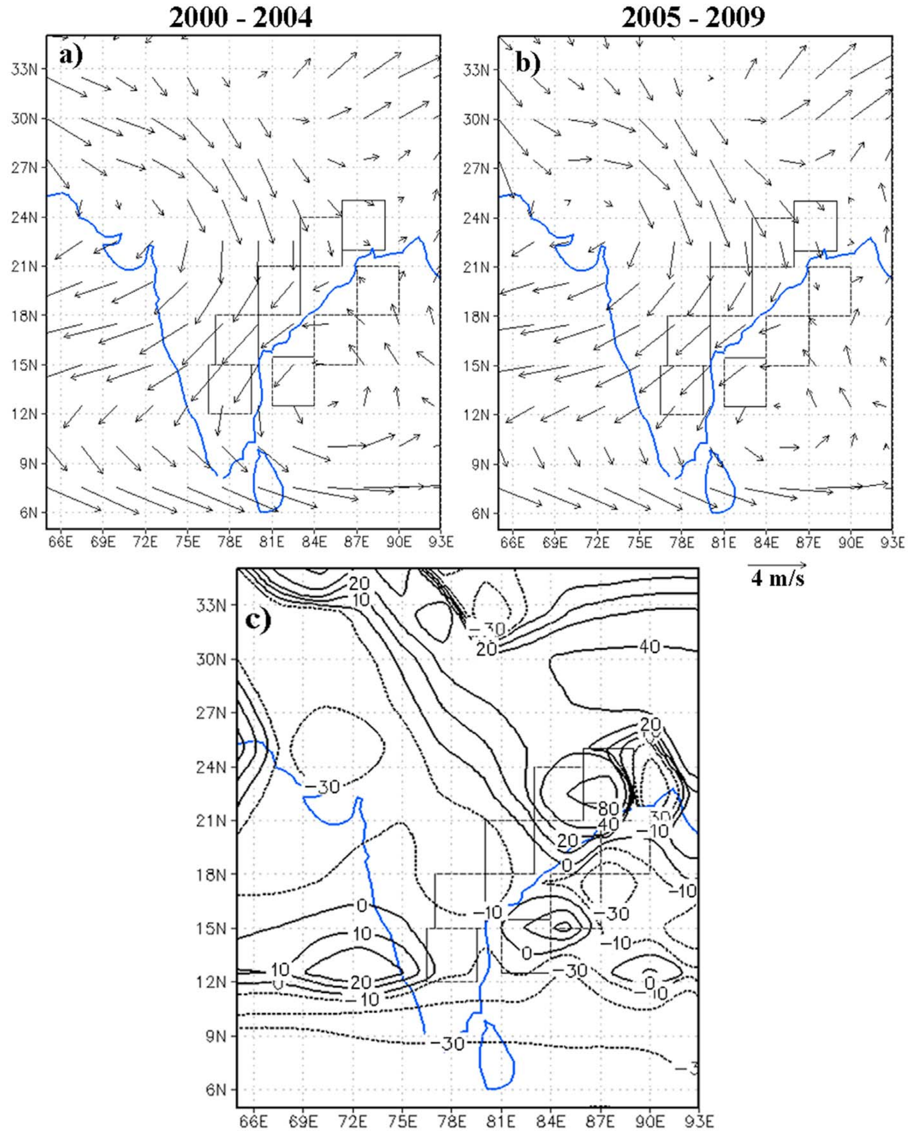

Figure 4. Mean wind vectors of the 700–850 hPa layer in October averaged over the 5 year periods (a) 2000–2004 and (b) 2005–2009. (c) The spatial distribution of wind speed tendency in October: the wind speed tendency corresponds to the difference between wind speeds of the 700–850 hPa layer averaged over the second 5 year period 2005–2009 and wind speeds averaged over the first 5 year period 2000–2004 in percentage form. Here we used as a basis the wind speeds averaged over the period 2000–2004. The horizontal vector at the bottom of Figure 4b is the scale for wind vectors.

wide 700–850 hPa layer is considered as indicative of wind in the lower troposphere, where aerosol transport mainly occurs [*Dunion and Velden*, 2004]. According to mean wind vectors of the 700–850 hPa layer in October, averaged over the 10 year period under consideration, northwest winds dominated the Indian subcontinent to the north from latitude 21°N (Figure 1c). To the south from 21°N, prevailing winds were northeast. Therefore, in October, aerosols from the northwest part of the Indian subcontinent were transported by the prevailing winds through the central regions into the east of the Indian subcontinent. One can see that winds over the east of the Ganges basin (zone 4) were weak (Figure 1c). Those weak winds are still able to transport fine aerosol particles (including biomass burning aerosols from the northwest of the Indian subcontinent) to northwest BoB. In October, winds over the sea in northwest BoB were weaker than those over the land in the east of the Indian subcontinent (Figure 1c). This wind difference between land and sea, when the winds over northwest BoB were weaker than the winds from the east of the Indian subcontinent, resulted in some accumulation of aerosol particles over zone 1.

[19] In order to find out if wind direction had any bearing on the accumulation of aerosols over zone 1, we compared mean wind vectors of the 700–850 hPa layer in October: averaged over the first 5 year period 2000–2004 (Figure 4a) and over the second 5 year period 2005–2009 (Figure 4b). In northwest BoB, wind direction over zones 2 and 3 did not change over the two 5 year periods under consideration.

Winds over zone 1 changed direction in the second period 2005–2009. However, this change is of no great importance as wind speeds over zone 1 were low in these two periods, as compared with winds in the Indian subcontinent. It can be seen that wind direction over the Indian subcontinent did not change in these two periods. At the same time, increasing wind speed was observed over the Indian subcontinent in the second 5 year period 2005–2009 compared to wind in the first 5 year period 2000–2004 (Figures 4a and 4b). In particular, winds blowing along the Ganges basin toward northwest BoB became noticeably stronger, transporting more aerosols into zone 1.

[20] Furthermore, Figure 4c represents the spatial distribution of wind speed tendency in October. The wind speed tendency corresponds to the difference between wind speeds of the 700–850 hPa layer averaged over the second 5 year period 2005–2009 and wind speeds averaged over the first 5 year period 2000–2004 in percentage form, using as a basis the wind speeds averaged over the period 2000–2004. An increasing tendency of over 50% is seen over zones 4 and 5 in the east of the Indian subcontinent (Figure 4c). Contrastingly, a decreasing tendency of approximately −10% was observed over zone 1 in northwest BoB (Figure 4c). Therefore, during the 10 year period under consideration, a strong increasing tendency in wind speed over the land in the east of the Ganges basin was accompanied by a weak decreasing tendency over the sea in northwest BoB.

[21] The aforementioned phenomenon of aerosol accumulation in October was further quantitatively described by means of wind convergence (Figure 5). Wind convergence was defined as

$$C = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

where u and v are the zonal and meridional components of wind. Positive C corresponds to convergence of horizontal winds resulting in the accumulation of aerosol particles. Negative C corresponds to divergence of horizontal winds resulting in the dispersion of aerosol particles. Using NCEP/DOE Reanalysis-2 wind monthly data, the spatial distribution of wind convergence in the 700–850 hPa layer in October, averaged over the first 5 year period 2000–2005, was compared with that averaged over the second 5 year period 2005–2009 (Figures 5a and 5b). One can see that during the first 5 year period, negative C values were mainly observed over zone 1 (Figure 5a). However, during the second 5 year period, over the main part of zone 1, positive C values (wind convergence) were observed. This transition from negative C values to positive ones over zone 1 reveals an increasing trend in wind convergence over the 10 year period under consideration. This increasing trend in wind convergence led to some increasing trend in accumulating aerosol particles over zone 1 and, as a result of the accumulation, to the aforementioned increasing AOT trends there.

3.3. AOT Trends in November and December

[22] In November, two AOT maxima were observed over the Indian subcontinent, based on the spatial distribution of 10 year mean MODIS AOT (Figure 6a). The first AOT maximum was observed over the northwest of the Indo-Gangetic Plain and the second AOT maximum was observed over its central part. According to 10 year mean wind vectors of the 700–850 hPa layer, in November, prevailing winds blowing along the Ganges basin were stronger than the winds in October (Figure 6c). This is illustrated by the difference in wind vectors, obtained by subtracting October 10 year mean wind vectors of the 700–850 hPa layer from those in November (Figure 6d). It is seen that both the increase in wind speed and changes in wind direction in November contribute to intensification of aerosol transport from the east of the Ganges basin (zone 4) to zones 1 to 3 in northwest BoB. This is supported by the fact that the AOT values over zones 1 and 2 in November were higher than those in October (Table 2). In contrast to October, in November the stronger winds were approximately the same over zone 4 in the east of the Ganges basin and over zone 1 in northwest BoB (Figure 6c). Moreover, wind convergence over zone 1 disappeared in November: no wind convergence was observed either during 2000–2004 or during 2005–2009 (Figures 5c and 5d). This fact indicates that in November, conditions were not suitable for the accumulation of aerosol particles over northwest BoB. In the absence of aerosol accumulation, MODIS was able to show similar AOT trends over the east of the Indian subcontinent and northwest BoB, as expected (Figure 6b). Indeed, in November, insignificant MODIS AOT trends were observed over zones 1 and 4 (Figure 2b and Table 2).

[23] In December, the spatial distribution of 10 year (2000–2009) mean AOT over the region under consideration showed that both over the east of the Ganges basin and over northwest BoB, AOT values in December were noticeably higher than those in November (Figure 7a). In particular, in December, AOT values of 0.43 and 0.54 over zones 1 and 4 respectively were higher than those of 0.32 and 0.44 in November (Table 2). The increase in AOT in December compared to that in November was associated with an increase in fossil fuel burning for domestic heating by the growing population [*Kaskaoutis et al.*, 2011a]. December domestic heating by the growing population resulted in a strong decadal AOT trend of 6.1% yr^{-1} observed over zone 4 in the east of the Ganges basin (Table 2).

[24] Prevailing winds in December, blowing along the Ganges basin, were even stronger than those in November (Figure 7c). This is illustrated by the difference in wind vectors obtained by subtracting November 10 year mean wind vectors of the 700–850 hPa layer from those in December (Figure 7d). As seen, changes in wind vectors contribute to further intensification of aerosol transport from zone 4 in the east of the Ganges basin to zones 1 to 3 in northwest BoB (Figure 7c). Similar to November, in December no wind convergence was observed over zone 1 either during 2000–2004 or during 2005–2009 (Figures 5e and 5f), indicating that conditions were not suitable for the accumulation of aerosol particles there.

[25] In the absence of wind convergence trends over zone 1, in December, we expected to find increasing AOT trends over northwest BoB in accordance with the aforementioned increasing AOT trends over the Ganges basin. Indeed, as

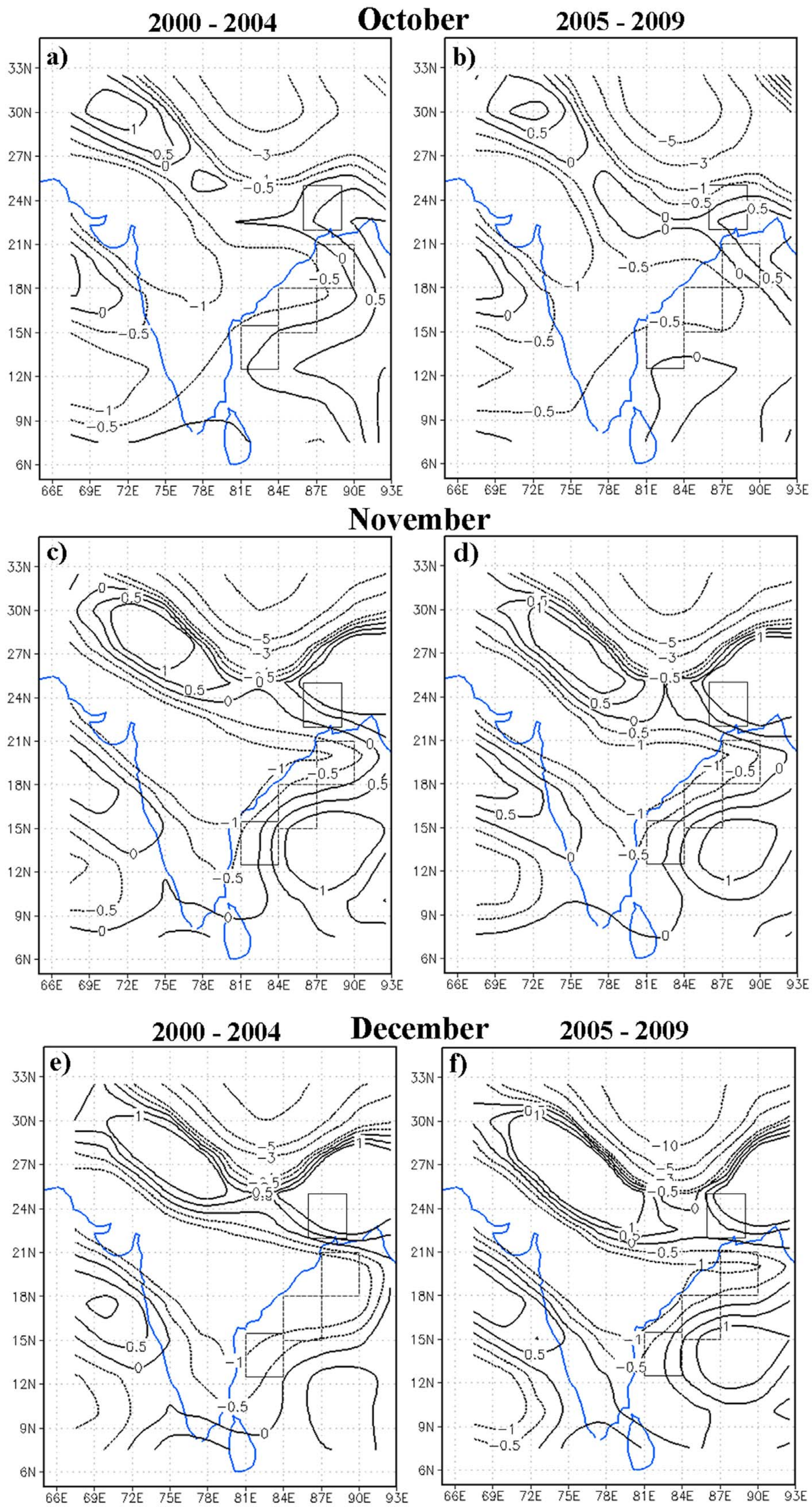

Figure 5. Spatial distributions of 5 year mean wind convergence (10^{-6} s^{-1}) of the 700–850 hPa layer averaged (left) over the first 5 year period 2000–2004 and (right) over the second 5 year period 2005–2009 corresponding to (a and b) October, (c and d) November; and (e and f) December.

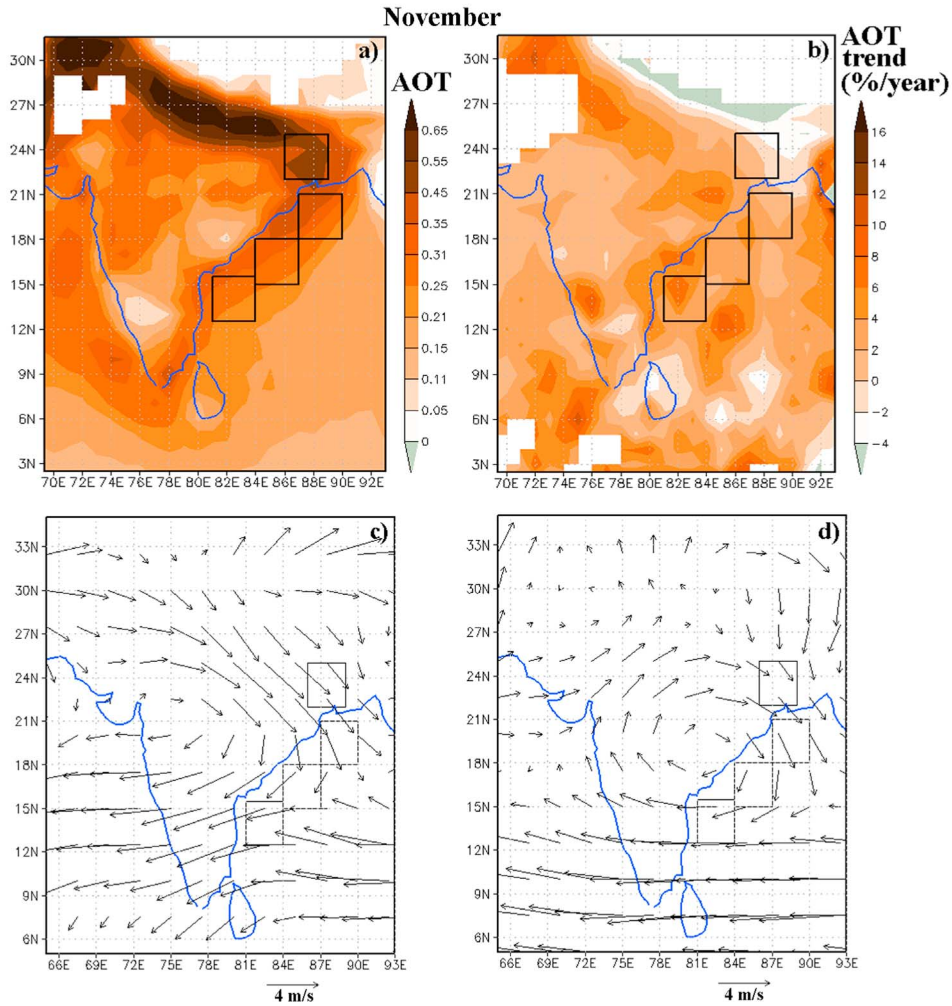

Figure 6. Spatial distributions of (a) the 10 year mean MODIS AOT and (b) its trends in November. (c) The 10 year mean wind vectors of the 700–850 hPa layer in November. (d) Difference in wind vectors obtained by subtracting October 10 year mean wind vectors of the 700–850 hPa layer from those in November. The designations are the same as in Figure 1. The horizontal vectors at the bottom are the scale for wind vectors.

illustrated in Figures 2c and 7b, our expectation were confirmed by increasing AOT trends over northwest of BoB, which did not exceed AOT trends over the east of the Ganges basin.

[26] We compared MODIS AOT trends over zone 9 in the Ganges basin with those based on AERONET measurements at the Kanpur site, located at the center of the same zone 9. In November, both AERONET and MODIS showed statistically insignificant AOT trends (Table 2). In December, AERONET showed an increasing AOT trend of 7.7% yr^{-1} at the Kanpur site, which was twice as high as the AOT trend shown by MODIS over zone 9 (Table 2). There could be two reasons for the differences. MODIS could have underestimated AOT trends over zone 9 in the Indian subcontinent in December. Or, the difference in spatial sampling between MODIS AOT data over zone 9 (a large 3° × 3° area) and AERONET data (point observations) could also contribute to this difference between MODIS AOT trends and those of AERONET AOT.

Table 2. The 10 Year Mean AOT (τ), Standard Deviation (SD), and Resulting Trends (α) for Long-Term Changes of MODIS AOT Averaged Over Specified Zones in November and December and Those of AERONET AOT in Kanpur

Zone	τ	SD	α (% yr^{-1})	S-W Test	p
			November		
1	0.32	0.05	3.2	Normal	Not significant
2	0.29	0.05	3.4	Normal	Not significant
3	0.26	0.04	4.7	Normal	0.040
4	0.44	0.04	1.0	Normal	Not significant
9	0.61	0.10	3.7	Normal	Not significant
AERONET	0.79	0.16	3.5	Normal	Not significant
			December		
1	0.43	0.07	5.1	Normal	0.005
2	0.33	0.06	5.3	Normal	0.010
3	0.29	0.04	4.1	Normal	0.020
4	0.54	0.11	6.1	Normal	0.010
9	0.60	0.07	3.7	Normal	0.003
AERONET	0.78	0.20	7.7	Normal	0.050

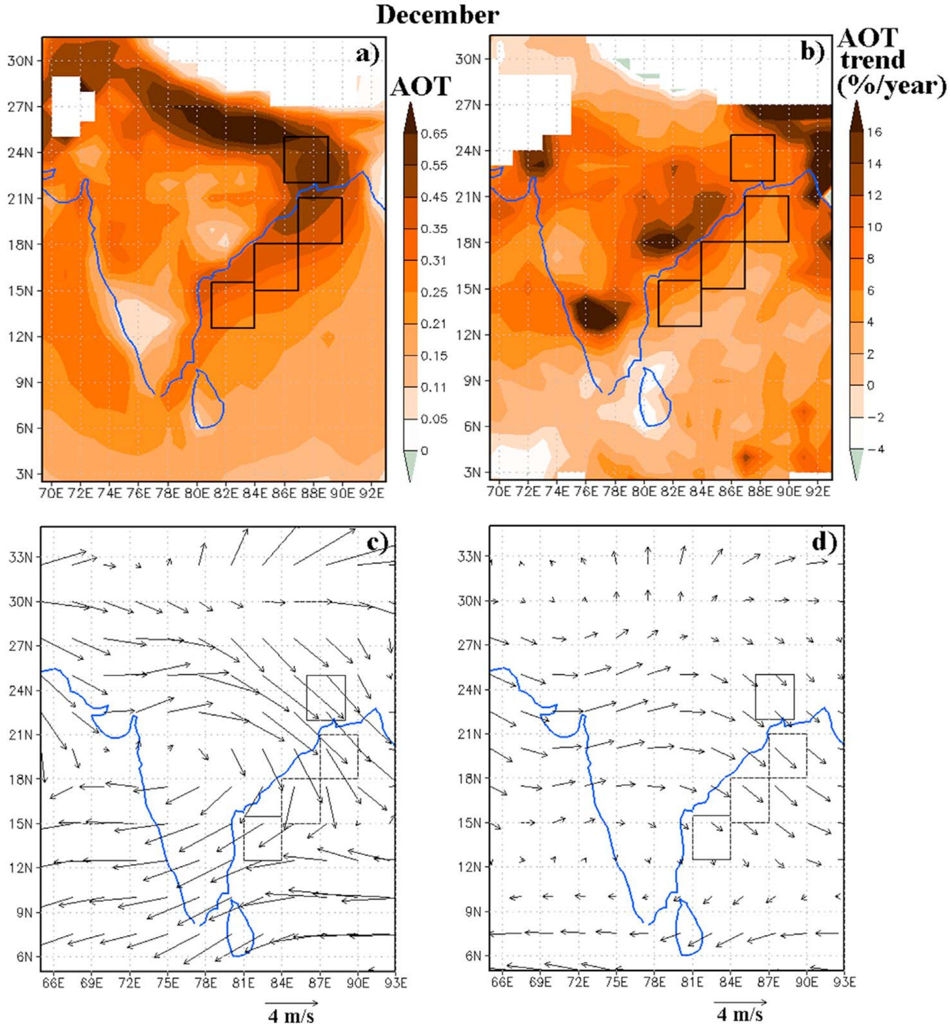

Figure 7. Spatial distributions of (a) the 10 year mean MODIS AOT and (b) its trends in December. (c) The 10 year mean wind vectors of the 700–850 hPa layer in December. (d) Difference in wind vectors obtained by subtracting November 10 year mean wind vectors of the 700–850 hPa layer from those in December. The designations are the same as in Figure 1. The horizontal vectors at the bottom are the scale for wind vectors.

3.4. Correlation Between Year-to-Year Variations of AOT Over Zones 1 and 4

[27] As mentioned, because of prevailing winds blowing along the Ganges basin in the postmonsoon and winter months, aerosol loading over BoB is mainly produced by aerosol transport from highly populated zones and industrial centers located in the Ganges basin [*Di Girolamo et al.* 2004; *Prasad and Singh*, 2007; *Kumar et al.*, 2010]. *Kaskaoutis et al.* [2011a] reported a high correlation between the area-averaged AOT over the Ganges basin for all months during the 10 year period 2000–2009 and those over BoB.

[28] We found, however, that although there is aerosol transport from zone 4 (the east of the Ganges basin) to zone 1 (northwest BoB), the correlation in year-to-year variations in AOT between the two zones differed significantly in different months (Figure 8). Specifically, in October, there was no correlation in AOT between the two zones. This is because a strong increasing AOT trend was observed over

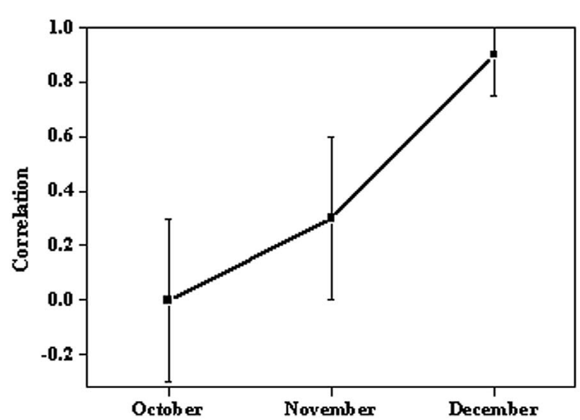

Figure 8. Correlation between year-to-year variations of MODIS AOT over zone 1 and those over zone 4 in October, November, and December. The error bars show the standard error of correlation.

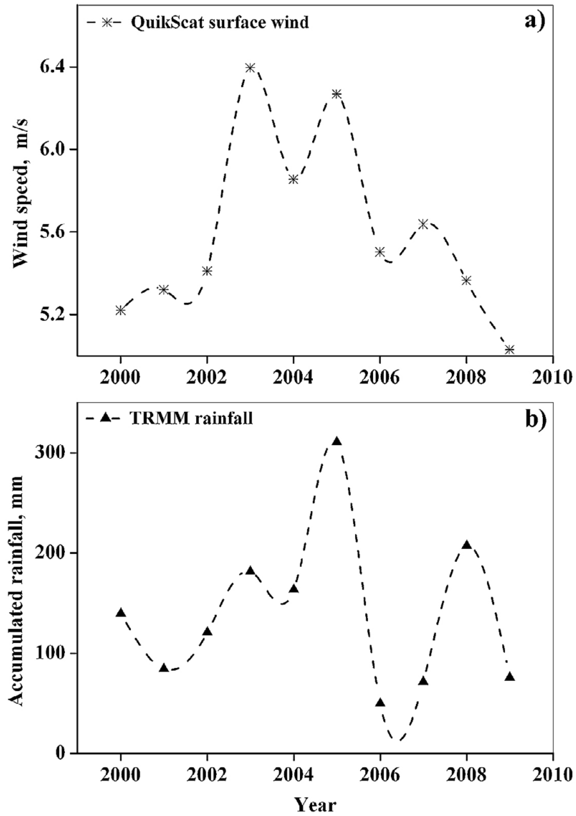

Figure 9. Year-to-year variations of (a) QuikScat surface wind over northwest BoB in October, and (b) TRMM accumulated rainfall over zone 1 in October.

zone 1 in the absence of AOT trends over zone 4 (Figure 2a). As discussed, the strong increasing AOT trend over zone 1 in October can be explained by the effect of wind convergence trends on aerosol accumulation over zone 1. In November, in the absence of wind convergence over zone 1, the correlation in AOT between zones 1 and 4 slightly increased (r = 0.3) (Figure 8). In December, the correlation in AOT between zones 1 and 4 was extremely high (r = 0.9) (Figure 8). This indicates that in the absence of wind convergence over zone 1 in December, the increasing AOT trend over zone 1 was determined by increasing aerosol emissions over the land (Figure 2c).

4. Contribution of Natural Aerosols to AOT Trends Over Northwest BoB

[29] Measurements of aerosol chemical composition over the Bay of Bengal revealed the presence of natural components, such as desert dust and marine aerosols [*Kumar et al.*, 2010]. It was important to estimate a possible contribution of those natural aerosol components to the aforementioned AOT trends over northwest BoB.

[30] As mentioned, the season October–February is the period of minimal dust activity in the Indian subcontinent [*Di Girolamo et al.*, 2004; *Singh et al.*, 2004; *Prasad and Singh*, 2007]. Moreover, the dust presence over northwest BoB is associated with continental outflow from the Indo-Gangetic Plate [*Kumar et al.*, 2010]. This means that the assumed contribution of desert dust to the strong AOT trends over northwest BoB in October should be accompanied by strong AOT trends over the land in the east of the Indian subcontinent, in the same month. However, as seen in Figure 2a, this is not the case. Therefore, desert dust cannot be responsible for the aforementioned strong AOT trends observed over northwest BoB.

[31] In addition, we estimated a possible contribution of marine aerosol, which is produced by breaking waves during whitecap formation [*Lewis and Schwartz*, 2004]. Possible increasing trends in sea surface winds in the Bay of Bengal could result in increasing concentrations of marine aerosols. However, using QuikScat satellite wind measurements, we found that during the 10 year period 2000–2009, there were no increasing trends in sea surface wind speed over northwest BoB (zones 1–3) in October (Figure 9a). The obtained long-term changes in QuikScat sea surface wind speed did not conform to a linear fit (Figure 9a).

[32] Therefore, long-term changes in natural aerosols over the 10 year period under consideration are not likely to be the cause of the obtained strong AOT trends over northwest BoB in October.

5. The Effect of Long-Term Changes in Rainfall Over Northwest BoB on AOT Trends

[33] Northwest BoB (joint zone 1–3) was characterized by the 10 year (2000–2009) mean accumulated rainfall of 183 mm, 124 mm, and 40 mm in October, November, and December, respectively. This was obtained using monthly accumulated Tropical Rainfall Measuring Mission (TRMM) rainfall data from the 3B43V6 archive, on a 0.25° $\times$ 0.25° latitude-longitude grid [*Huffman et al.*, 2007]. The presence of intensive rainfall over northwest BoB in October can produce a significant removal of atmospheric aerosols by wet deposition. One can assume that some noticeable decreasing trend in accumulated rainfall could be responsible for the observed increasing AOT trend over zone 1 in northwest BoB. We found, however, that it is not the case because long-term changes in accumulated rainfall over zone 1 did not show any decreasing trend in October, during the 10 year period under consideration (Figure 9b). The obtained long-term changes in accumulated rainfall did not conform to a linear fit (Figure 9b).

6. Conclusions

[34] The main point of our study is that aerosol trends can be created by changes in meteorology, without changes in aerosol source strength. Although regional long-term AOT trends over south Asia including BoB have been evaluated in previous studies [e.g., *Dey and Di Girolamo*, 2011; *Hsu et al.*, 2012; *Kaskaoutis et al.*, 2011a; *Mishchenko and Geogdzhayev*, 2007; *Zhang and Reid*, 2010; *Zhao et al.*, 2008], those studies did not discuss the phenomenon of strong increasing AOT trends over northwest BoB in October, in the absence of AOT trends over the east of the Indian subcontinent. In the current study, we focused namely on this specific phenomenon and its possible explanation.

[35] The northwest part of the Bay of Bengal is relatively remote from sources of anthropogenic emissions in the

highly populated Indian subcontinent (mainly in the Ganges basin). During the postmonsoon season, prevailing winds transport anthropogenic pollution from the Ganges basin downwind into northwest BoB. Therefore, in the post-monsoon season, over northwest BoB, we expected to find AOT trends not exceeding those observed over the Ganges basin. However, in October, over the 10 year period 2000–2009, in the absence of AOT trends over the east part of the Indian subcontinent, MODIS showed strong increasing AOT trends of approximately 14% yr^{-1} over northwest BoB.

[36] This strong increasing AOT trend over northwest BoB in October could not be an artifact, but a real aerosol trend. Indeed, if this strong increasing AOT trend over northwest BoB was due to calibration drift or other instrument problems, then similar strong artificial trends would be observed over remote zone 10 in BoB. However, as shown in the current study, this is not the case: no AOT trend was observed over zone 10. Therefore, no known artificial AOT trends due to calibration drifts contributed to the AOT trend over zone 10, and, consequently, no artificial trend contributed significantly to AOT trends over northwest BoB. Moreover, over BoB, MODIS Level 3 AOT trends were quite reliable. Using quality assured MODIS Level 2 data, *Zhang and Reid* [2010] found a statistically significant AOT trend over the whole area of BoB for all months. Our comparison showed that the AOT trend over BoB, based on MODIS Level 3 data, was similar to that obtained by *Zhang and Reid* [2010].

[37] In October 2000 and 2001, aerosol loading over northwest BoB was low and corresponded to the aerosol level over remote zone 10 (section 3.1). This suggests that at the beginning of the 10 year period under consideration, aerosol transport from the Indian subcontinent to northwest BoB in October was weak. During the study period, in October, there was an increasing trend in wind convergence over zone 1 in northwest BoB. This led to increasing trends in the accumulation of aerosol particles over northwest BoB, and as a result of the accumulation, to increasing AOT trends over this area. Therefore, unexpected increasing AOT trends over northwest BoB in October, in the absence of AOT trends over the east of the Indian subcontinent, can be understood by analyzing changes in wind convergence.

[38] In contrast to October, in November the stronger winds were approximately the same over the east of the Ganges basin and over northwest BoB, and no wind convergence was observed over northwest BoB. This fact indicates that in November, conditions were not suitable for the accumulation of aerosol particles over northwest BoB. Statistically insignificant AOT trends were observed over northwest BoB and the east of the Indian subcontinent in November. December domestic heating by the growing population resulted in a strong increasing decadal AOT trend of 6.1% yr^{-1} observed over zone 4, in the east of the Ganges basin. In December, we expected to find increasing AOT trends over northwest BoB in accordance with the aforementioned increasing AOT trends over the Ganges basin. Indeed, our expectations were confirmed by increasing statistically significant AOT trends of approximately 5% yr^{-1} over northwest of BoB. These AOT trends did not exceed those over the east of the Ganges basin. The correlation in AOT between zones 1 and 4 in December was extremely high (r = 0.9). This indicates that in the absence of wind convergence over zone 1 in December, the increasing AOT trend over northwest BoB was determined by increasing aerosol emissions over the land.

[39] Our analysis showed that natural aerosols, neither desert dust no sea salt aerosol, are likely to be the cause of the AOT trends over northwest BoB in October. These increased AOT trends over northwest BoB indicate an increase in anthropogenic pollution over the sea. One can suggest that an increase in anthropogenic pollution over northwest BoB could affect atmospheric dynamics, cloud formation processes, and marine life in this area.

[40] Our findings illustrate that in order to explain and predict trends in regional aerosol loading, meteorological trends should be taken into consideration together with changes in aerosol source strength.

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