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INVESTIGATION OF PERMANENT AEROSOL SOURCE REGIONS OVER ASIA USING MULTI-YEAR MODIS OBSERVATIONS

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Key words: aerosols, multi-year aerosol variation, MODIS, aerosol source regions, dust and pollution.

ABSTRACT

This work examines the permanent aerosol source regions over Asia by analyzing 7-years data of aerosol optical thickness (AOT) product from MODerate Imaging Spectroradiometer (MODIS) onboard Aqua and Terra satellites. The analysis is carried out by taking the average AOT map during the years 2002-2008 over the region in different seasons, in which the permanent source regions will appear pronounced whereas the locations influenced by transport or any emissions that last for shorter time period will be smoothened. The results show four such main permanent source regions. Angstrom Exponent (AE) aerosol product is used to infer about the possible type and size of aerosols over the source regions. The average AOT trends over the source regions in different seasons during 2002-2008 are examined and the results are discussed based on the corresponding variations of meteorological parameters derived from National Center for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) reanalysis data. In addition, the trends in AOT variation during the period 2002-2008 over certain selected stations over the area are also discussed.

I. INTRODUCTION

Aerosols, with life time of a few days, not only affect the regions where they are generated, but also could get transported to long distances and influence the radiation budget over remote locations, and pose health risks (Mian Chin et al., 2007). One of the main challenges in modelling climate variation is to account for the forcing from aerosols, which is dynamic and variable in space and time (Ichoku et al., 2002). Thus, it is very important to know their sources as well how the emissions are distributed. With the advantage of satellite remote sensing, it is possible to gather aerosol information over a global scale and the MODerate Imaging Spectroradiometer (MODIS) onboard Aqua and Terra satellites in particular have provided tremendous amount of data with which one could study the aerosol characteristics at desired locations (Kaufman et al., 1997; Chu et al., 2002; He et al., 2012). Several investigators have used the MODIS aerosol products to quantify the aerosol variation and the corresponding seasonal characteristics in different regions (Tanr et al., 1997; Chu et al., 2003; Lesins et al., 2006; Jones et al., 2007; Remer et al., 2008; Alam et al., 2010; 2011; He et al., 2012; Anderson et al., 2013; Ramachandran et al., 2013; Zheng et al., 2013).

In addition to inferring the aerosol properties, MODIS observations have the potential to identify and monitor regions that continually load aerosols into the atmosphere. Rapid industrial growth and economic activities have earned Asia, which also hosts several desert regions, the bad reputation as a major source of dust and pollution. Such emissions are shown to be transported to large distances, reaching Europe and North America. During the transport, the aerosol particles could undergo mode mixing, which modifies their nature and characteristics and could make their impact often severe (Shaw et al., 1980; Uematsu et al., 1983; Jaffe et al., 1999; Chun et al., 2001; Husar et al., 2001; Liang et al., 2004; Eck et al., 2005; Kim et al., 2005; Heald et al., 2006; Kim et al., 2007). While such studies provide information about the transport of the aerosols and how they get mixed with other air-masses en route, identifying the source regions as well as monitoring the nature of emission from the sources over the course of time is also necessary.

This paper focusses on identifying regions in Asia that load aerosol particles continuously to the atmosphere and to understand how the nature and amount of loading from such regions evolve in different years and to study the impact of the emissions from these regions over nearby locations. Though several attempts have been made to quantify the aerosol

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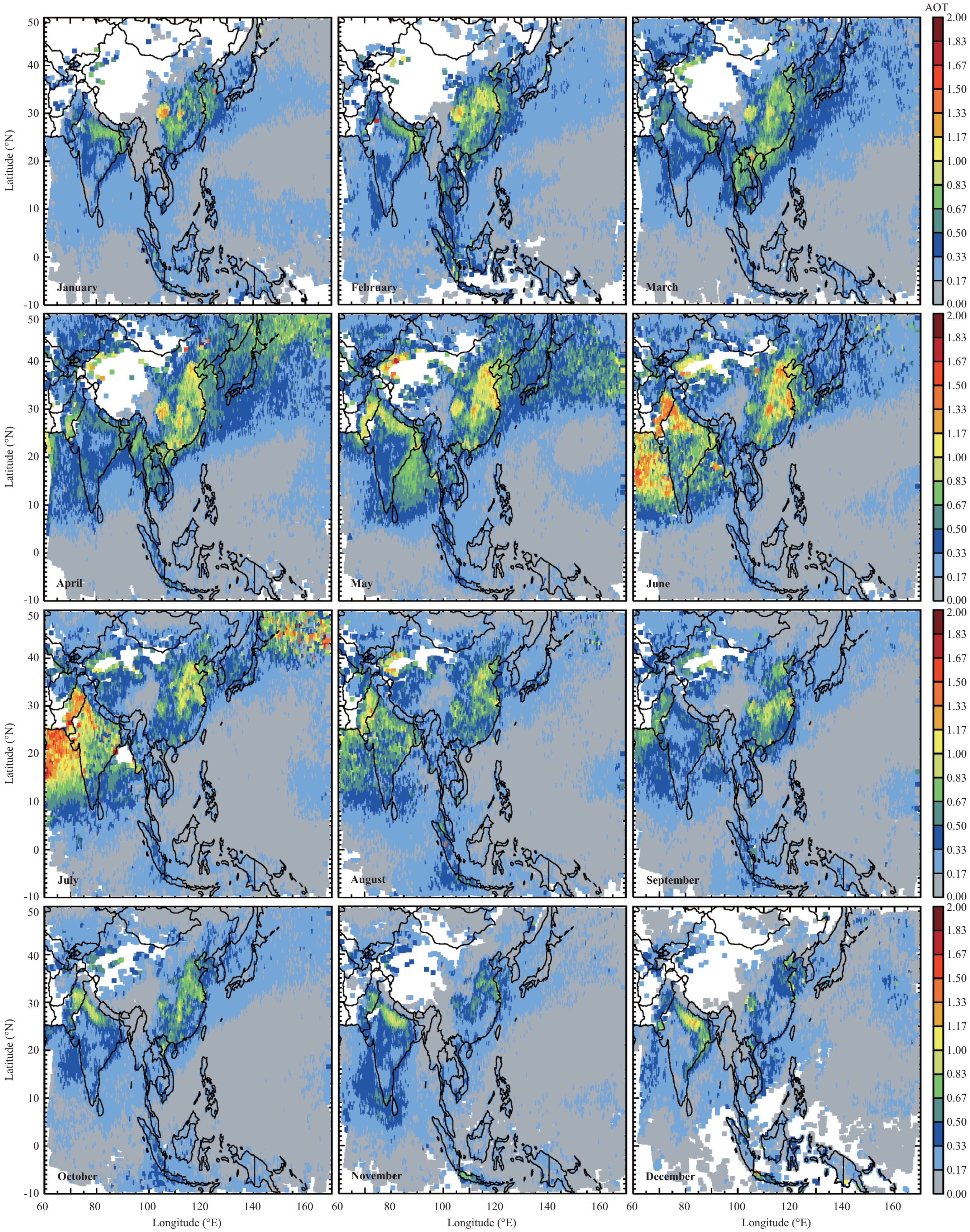

Fig. 1. The study area together with the monthly mean MODIS AOT at 550.0 nm in the year 2008.

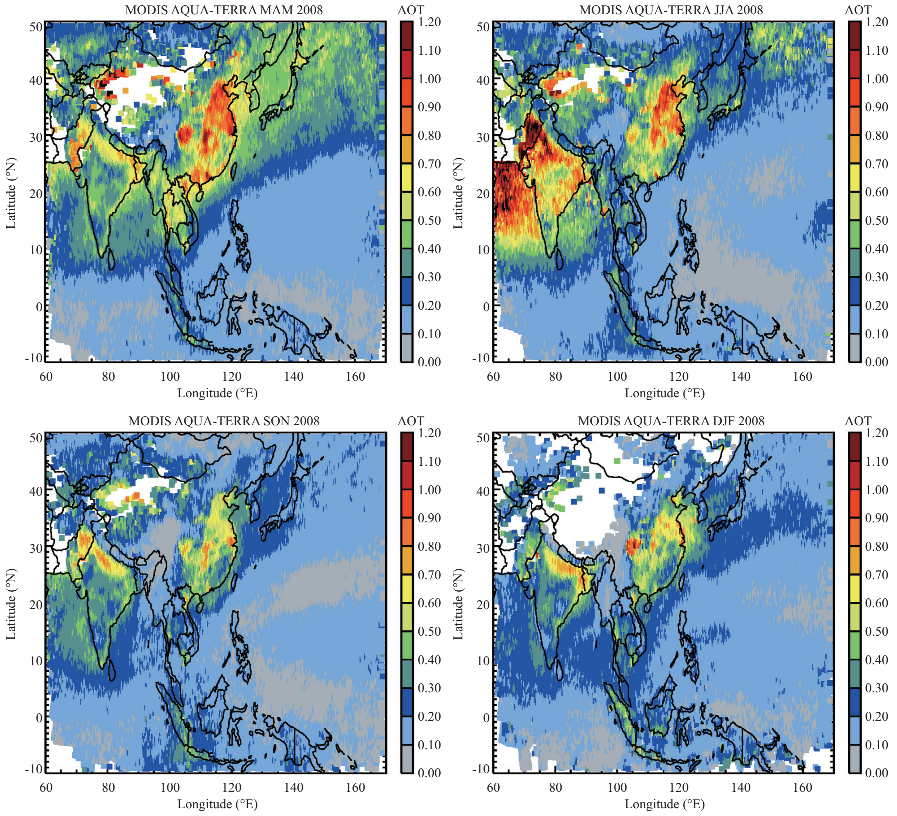

Fig. 2. Seasonal AOT values over the study area in 2008.

variation over selected locations within Asia (Lelieveld et al., 2001; Qian et al., 2002; 2004; Wang et al., 2004; Eck et al., 2005; Kim et al., 2005; Kim et al., 2007; Wang et al., 2011; He at al., 2012; Zheng et al., 2013), and several measurements made at European and American continents have traced back the enhanced levels of aerosols to the sources in Asia mentioned above, there has been no attempt so far to identify permanent aerosol source regions over Asia using satellite remote sensing. In this work, the MODIS aerosol products during 2002-2008 are used to classify the locations with significant aerosol production that persists in multi-year averaging. Such source locations in different seasons are investigated and the aerosol properties as well as the trends during 2002-2008 are discussed. The results are compared with the corresponding trends in meteorological parameters over the source regions derived from National Center for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) reanalysis data. Further analysis is also carried out to provide the trend in aerosol variation during 2002-2008 over certain selected stations in southeast Asia, and the observed results are discussed based on the influence from the source regions. Similar approach could be adopted over other regions using satellite observations.

II. PERMANENT SOURCE REGIONS

The MODIS level 2.0 aerosol products Aerosol Optical Thickness (AOT) and Angstrom Exponent (AE) during the years 2002-2008 are used for the study. The daily AOT observations at 550.0 nm over the region within 10°S-50°N latitudes and 60-170°E longitudes are combined together to generate monthly mean, and also seasonal aerosol maps. The selected study area that include several aerosol source regions in Asia could be noted from Fig. 1, which also gives the monthly mean AOT values in 2008. The AOT values in each season in the 7 year period are averaged together to identify the regions that persist in the multi-year mean. The seasonal mean AE values over the region are examined to understand the size information of the aerosols, which also indicate the possible particle type.

It can be seen from Fig. 1 that the largest AOT values are seen over the Indian continent and the Arabian ocean regions to the west of India in the months of June-July. Another region with prominent AOT values is the eastern parts of China during April-July. The northern part of India shows presence of significant amount of aerosols in almost all the months. Similarly, except in November-December months, the eastern parts of China also reveal larger values of AOT, compared to the rest of the area. The monthly variation reveals that maximum aerosol loading occurs over the selected area in the summer months. Fig. 2 displays the seasonal mean values over the study area, where it can be seen that the monthly patterns in general appear in the seasonal means also, suggesting that the emissions occur on most of the days considered for the

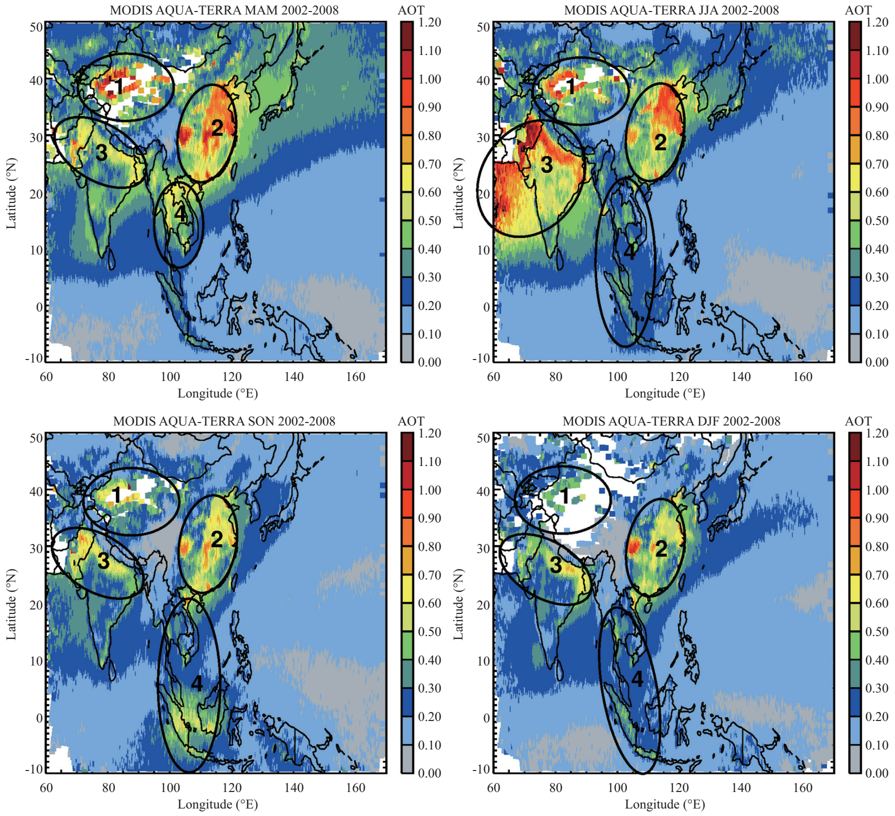

Fig. 3. Seasonal mean AOT values during the years 2002-2008. The regions that persist in the multi-year average are circled with the numbers representing the corresponding region name.

average. North and East parts of China, as well as India appear to be the regions with significant amount of AOT in all seasons.

In order to verify if the regions of larger AOT values over the study area also persist in multi-year averaging, the mean of AOT values in each season during the years 2002-2008 are plotted in Fig. 3. It can be seen that there are mainly four regions with pronounced AOT values in all seasons; (1) the region at North and North-West of China and South of Mongolia, (2) Eastern part of China, (3) North-East of Indian continent, and (4) parts of Thailand, Vietnam and Indonesia, though of slightly lesser magnitude. The four regions, which persist in the 7 year average in all seasons and appear significant with respect to the surrounding areas, are termed as permanent aerosol source regions. These regions thus contribute to majority of the aerosol loading over the area, which gets transported to nearby locations or countries as well as to other continents, affecting the air quality and contributing to climate changes.

In addition to identifying the source regions, it is important to understand what type of particles are loaded into the atmosphere from these sources, and if there is any change in the type of the particles in different seasons. For this purpose, the multi-year average AE values in each season over the same area are given in Fig. 4. For region 1, AE values are not available for winter, but in other seasons it is mostly about 0.5-0.8, reaching as high as 1.0 at certain locations. In region 2, the AE values are different in different seasons. In spring and winter, the values are mainly between 0.5 and 1.0, except at the southern parts of the region where it reaches about 1.5. Largest AE values occur in summer months, in the range 1.2-1.8. In autumn, values from 0.6 to 1.6 could be seen, with lower values in the northern half and larger values to the south. The AE values in region 3 are more-or-less similar to that in region 1, falling in the range 0.5-1.0 in all the seasons. By contrast, region 4 shows larger AE values in all seasons with values greater than 1.5.

To further understand the nature and magnitude of aerosol loading during the study period, the mean AOT in each season over the four regions from 2002-2008, is plotted in Fig. 5. The mean value is calculated by taking the average of all available AOT data within a latitude-longitude of grid of ±0.5°, centered over each of the source regions marked in Fig. 3. The figure shows how the aerosol loading over the source regions has changed over a period of 7 years. It can be seen that the aerosol loading in region 1 shows an increasing trend in spring and the change is rapid during 2006-2008 with an increase by a factor of about 2.7. In other seasons there is no overall significant increasing or decreasing trend. For region 2, increasing trends could be seen in spring, autumn and winter, where the change is pronounced in spring with the AOT in 2008 approximately becoming twice its value in 2003. The

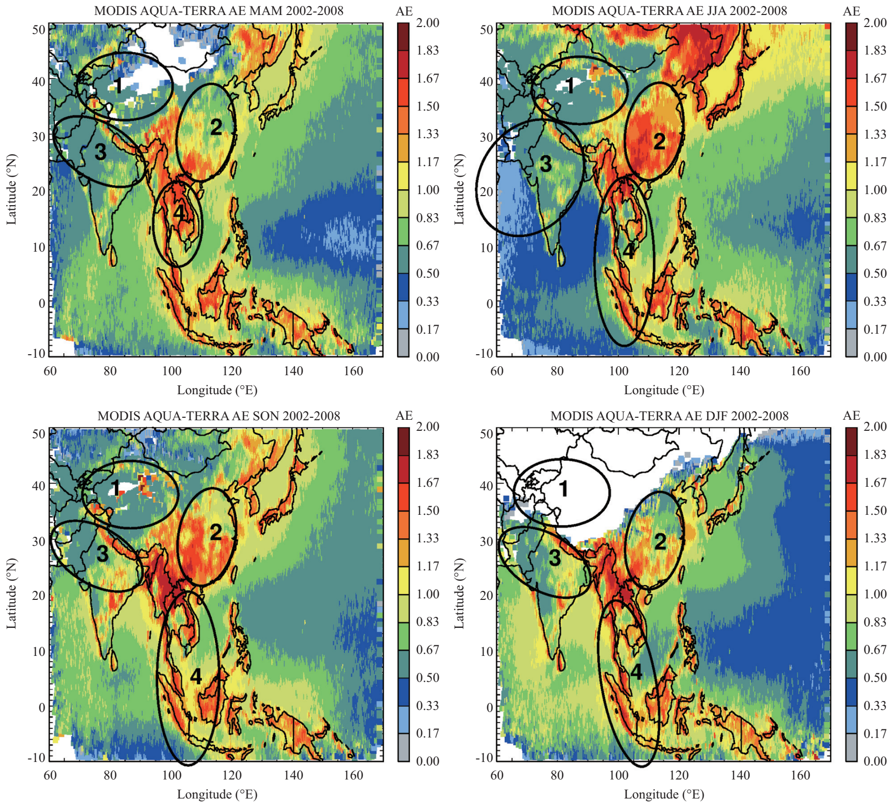

Fig. 4. Seasonal mean AE values during the years 2002-2008. The regions identified in Fig. 3. are over plotted here.

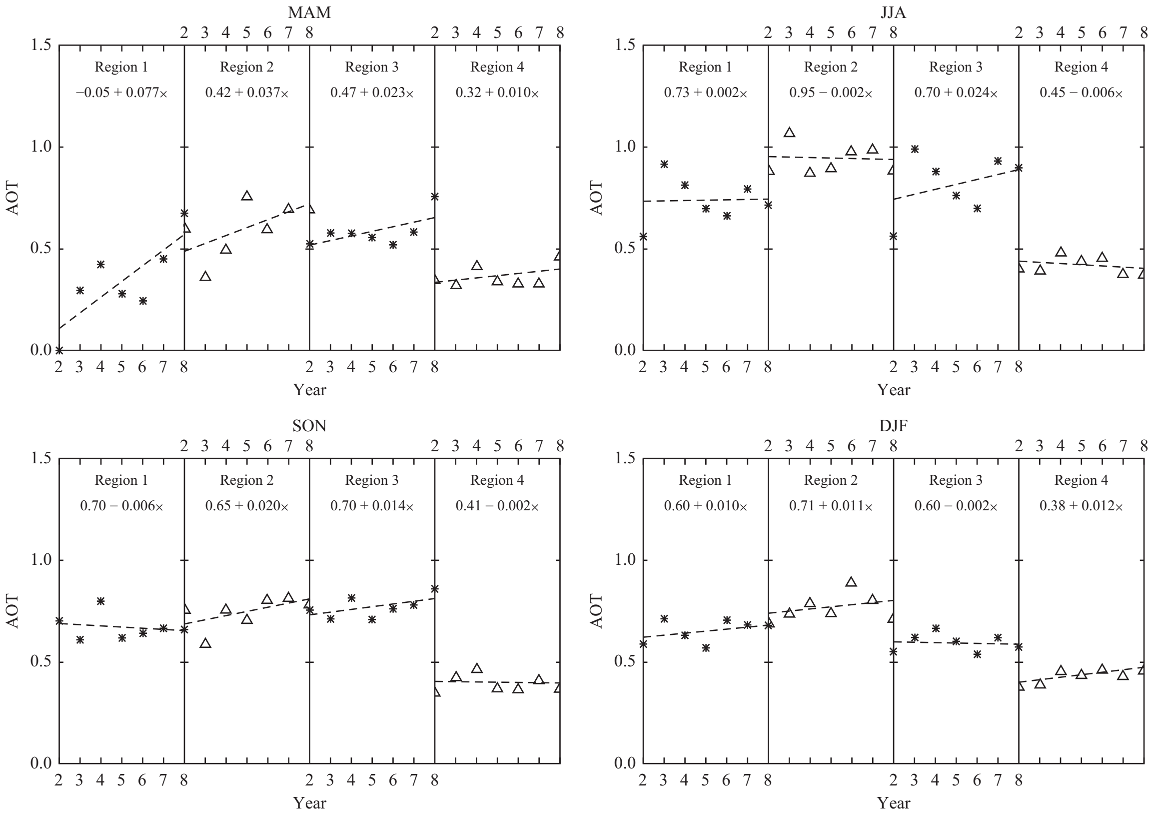

Fig. 5. Mean AOT variation within ±0.5° latitude/longitude grid centered over the permanent source regions during 2002-2008.

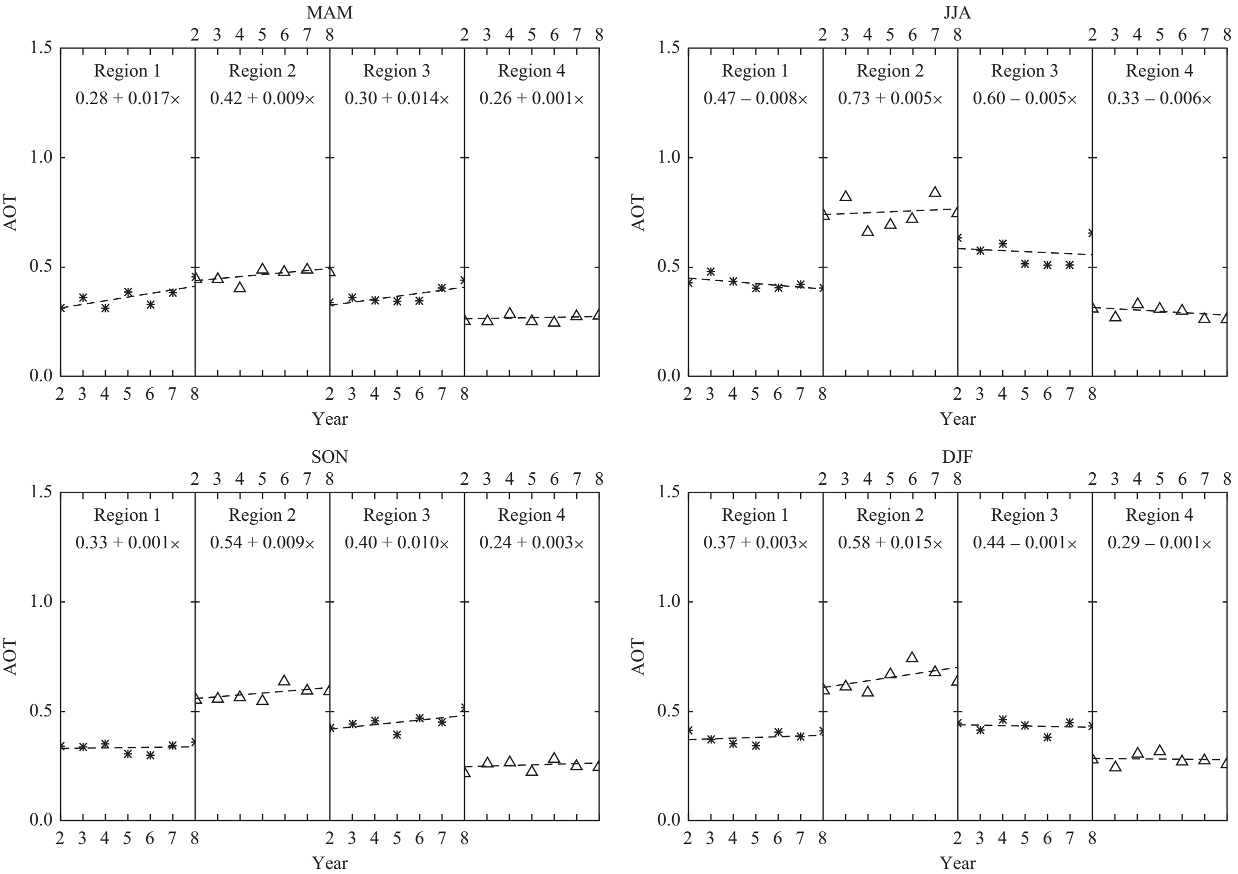

Fig. 6. Average AOT variation within ±5° latitude/longitude grid centered over the permanent source regions during 2002-2008.

trend in region 3 does not reveal any significant change during 2002-2008, but it can be seen that the AOT in spring registers an increase of about 45% during 2006-2008, about 30% increase in the same years in summer, and about 25% increase during 2005-2008 in autumn. There is a slight decreasing trend in winter. Region 4 shows least year-to-year variation of AOT where, except in winter, the AOT seems to have an overall decrease.

In Fig. 5, the inter-annual AOT variation within a small location over the source regions are given. In order to verify if similar trend exists over the entire source region, the average of all AOT data points within a latitude-longitude grid of ±5° centered over each of the four regions (Fig. 3) are plotted in Fig. 6. Comparing with Fig. 5, it can be seen that the overall trends more-or-less remain the same over a larger area. The increasing trends in spring over region 1 and region 2 persist even in the average values in Fig. 6. It can be noted from Figs. 5 and 6 that largest AOT values are seen over region 2 in all the seasons, and followed by region 3. Another important aspect to note is a periodic variation of AOT values during 2002-2008 over all the regions. Though the data length is not sufficient to quantify a periodicity, the variation seems to suggest the signature of quasi-biannual oscillation of AOT over the regions.

In addition to examining the AOT variation over the permanent source regions, the influence of the regions in the aerosol loading over nearby areas is also analyzed. The yearly variation of AOT and AE over six selected stations over the study area in different seasons is shown in Fig. 7. The stations selected are Mukdahan, Bac-Giang, Beijing, Taipei, Osaka and Gosan, the locations of which are marked in Fig. 8. Note that Fig. 8 also gives the seasonal wind pattern over the entire area, averaged during the years 2002-2008. The linear fit of the data points in Fig. 7 indicates the average annual trend, though there is significant inter-annual variation in some cases. Over Mukdahan the AOT is largest in spring with an average value of about 0.5, and remains smaller in all other seasons. There is an overall decrease of about 30% during 2002-2008 in summer and an increase of about 54% in autumn. The AOT levels in spring and winter do not show any consistent trend with an overall increase (decrease) of about 7% in winter (spring). The AE values suggest that there is a decreasing trend during 2002-2008 in all seasons, and is significant in summer and autumn. Over the neighboring Bac-Giang the annual variation is different with a net increase of about 22-23% in spring and winter, and about 16% in autumn. Note that this is the only station with average AOT greater than 0.5 in winter. There is no significant change in AOT in summer with a slight decrease of about 8% over the years. In contrast to Mukdahan, the AE values over Bac-Giang shows increasing trend in all the seasons.

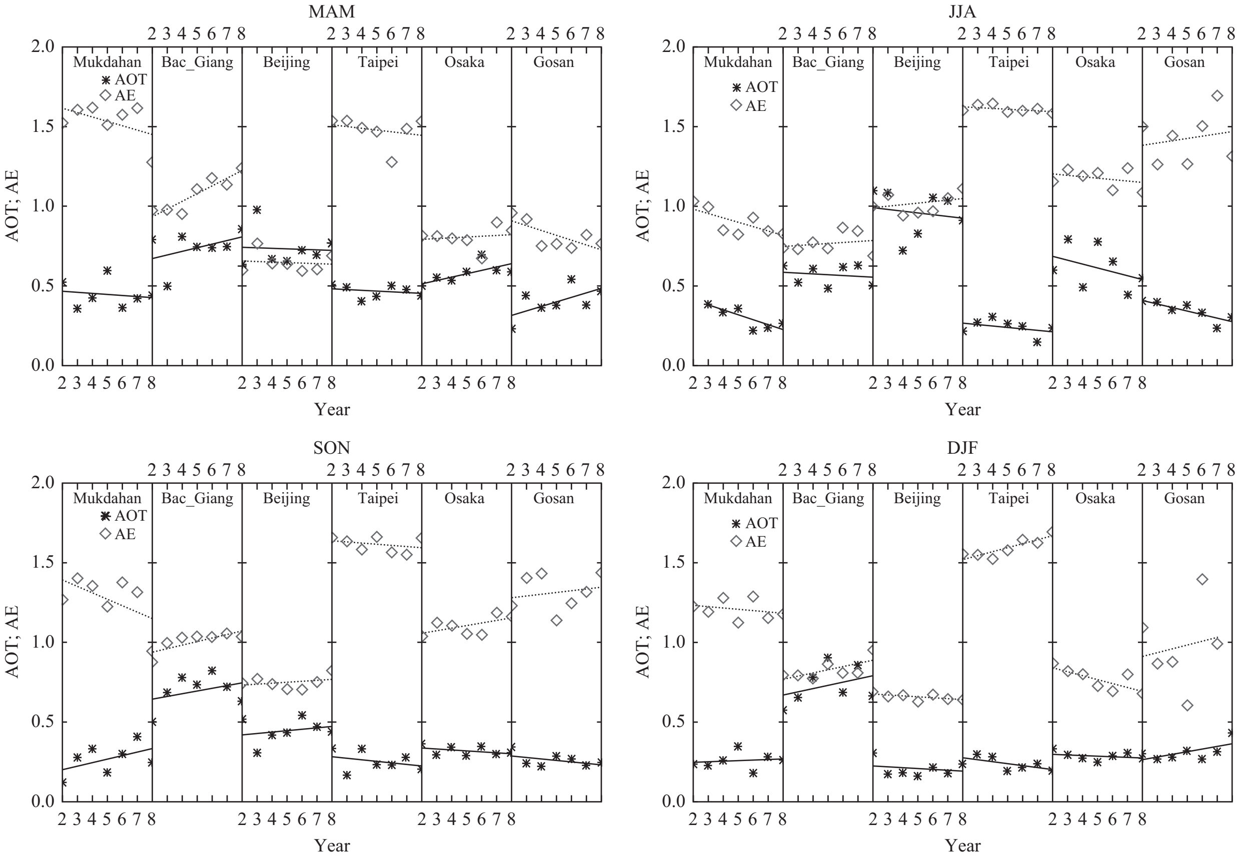

Fig. 7. Trends of MODIS AOT and AE over selected stations within the region during 2002-2008.

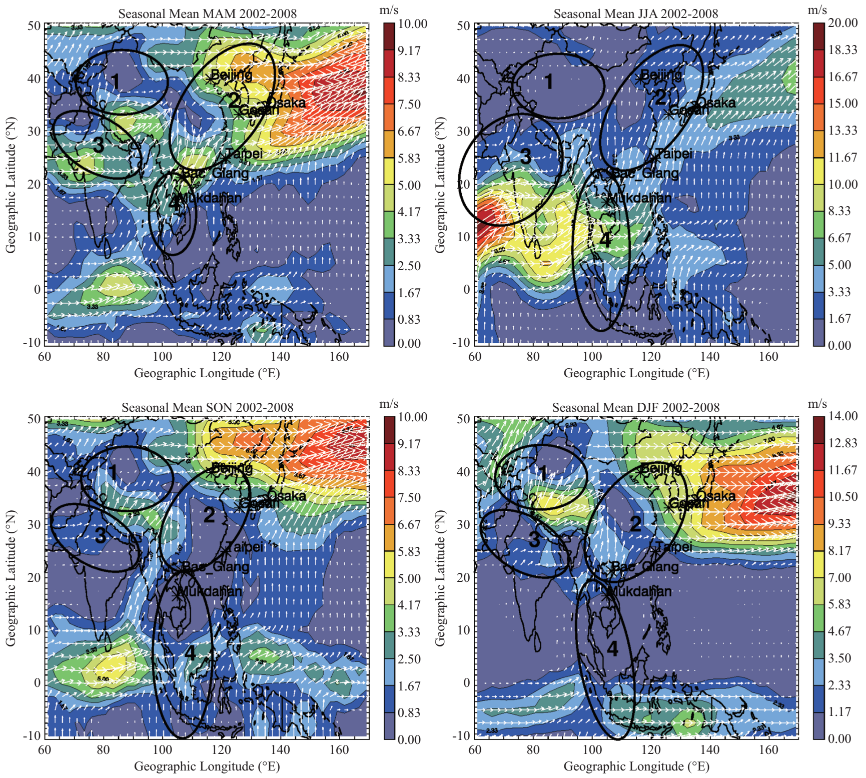

Fig. 8. Seasonal mean NCEP/NCAR wind pattern at 850 hPa during 2002-2008.

Though the trend line over Beijing indicates more-or-less consistent AOT in spring during 2002-2008, mainly because of the large AOT in 2003, the yearly values suggest a steady increase after 2004. Similarly, the trend in summer is also biased by the large inter-annual variation, with the overall trend indicating falling levels of AOT. In autumn, there is an increase of about 28% during 2002-2008. The AOT in winter over Beijing is mostly consistent, with the overall change suggesting a slight increase of approximately 5%. Note that there is no significant inter-annual variation of AE in any of the seasons. The AOT over Taipei is less than 0.5 in all the years, and shows least inter-annual variation. There is a decreasing trend in all the seasons, with a change of about 5% in spring, and about 27% in other seasons. In winter, the AE values indicate a consistent increasing tendency, while there is no noticeable variation in other seasons.

The trends over Osaka and Gosan are similar to each other in all seasons except winter. In spring, there is an increase of about 25% over Osaka, while it is about 50% over Gosan. In summer, the AOT shows a net decrease of about 15% over Osaka, and about 40% over Gosan. The decreasing trend continues in autumn also, with about 13% over Osaka and about 28% over Gosan. In winter there is about 25% decrease over Osaka, while there is an increase of about 37% over Gosan. The spring AE tends to decrease over Gosan, but there is no significant change over Osaka. Note that there is large inter-annual variation of AE over Gosan in other seasons, especially in winter. However, over Osaka, there is a consistent decrease of AE in winter.

III. AEROSOL CHARACTERISTICS OVER THE SOURCE REGIONS

The results reported above shows that space based retrieval of AOT serves as an effective tool to identify and monitor regions that continuously load aerosol particles into the atmosphere. The four permanent regions that are revealed in the 7-year average, which exist in all seasons, are known to contribute to the aerosol loading over Asia and other continents. The smaller AE values in region 1 indicate the dominance of larger size particles over the region. Region 1 includes north-west of China and south of Mongolia, which are dry areas and desert regions (Qian et al., 2002; 2004; Wang et al., 2008; Wang et al., 2011). This region also includes the Tarim basin, which is a major location where several dust storms are reported to occur. Note that the AE values remain mostly the same in all the seasons over this region, suggesting that the type of particles do not change with season. This indicates that transport of other kind of particles from different areas is not significant and dust particles dominate the average aerosol values. The average wind pattern shown in Fig. 8 also do not reveal any possibility of wind driven transport from other source regions to region 1, except probably in spring from region 3, when the difference in the particle type over the two regions is least.

The eastern parts of China included in region 2, are known for smoke and pollution owing to rapid industrialization and developmental activities over the area (Eck et al., 2005; Kim et al., 2005; Kim et al., 2007). Dust storms are also recorded over north eastern parts within this region, and regional soil emissions also occur (Qian et al., 2004; Wang et al., 2011). Unlike region 1, the AE values over region 2 vary with season. For example, in spring, the smaller AE values indicate presence larger type of particles. The wind pattern confirms the possibility of transport form the desert areas of region 1. However, the southern parts of region 2 receives airmass blowing over region 4, which are dominated by smaller particles, and results in slightly larger AE values over that area. In summer region 2 is mostly dominated by smaller type particles. It can be seen that the AOT values in region 2 is of slightly larger magnitude in spring than in summer, especially over the area surrounding the central parts. In summer, the AOT over this area seems to be lesser, where the decrease is more visible at the north-east parts. This shows that the aerosols in spring could include contribution from local sources as well as those transported from nearby source regions, and dust particles might dominate the total aerosols, whereas in summer probably pollution and smoke from industrial sources and fossil fuel burning, forest fires, etc. could be the major cause (Kim et al., 2005; He et al, 2012). The possible wind driven transport to this region in summer is from region 4, which again is dominated by smaller particles (Fig. 8). In autumn and winter, the southern part of the region is dominated by smaller particles, while the northern part indicates a mixture of small and large particles. The results suggest possibility of dust outbursts in cold weather conditions (Qian et al., 2002; 2004), though the measurements at northern parts in winter could be affected by snow cover. Thus, there could be transport from the dust sources in region 1 to the northern parts of region 2 in autumn and winter.

Region 3 shows the pollution rich areas over northern and north-east parts of India (Habib et al., 2006; Suresh Babu et al., 2008). The large increase in AOT in summer months when compared to mostly similar values in other seasons could be due to the transport of additional aerosol particles with the south westerly winds associated with Indian monsoon (Habib et al., 2006; Gautam et al., 2011; Sharma et al., 2014). The AE values over the north-western parts of Indian continent mostly remain smaller in all seasons, indicating presence of larger particles. This region includes the Thar desert and other arid and semi-arid areas, which could contribute to dust particles that might dominate the aerosols over the region (Léon et al., 2003; Dey et al., 2004; Kim et al., 2005). Further, the particles transported with the monsoon winds are also associated with smaller AE values. The effect of transport from these desert regions seems less effective in autumn and winter seasons over the central and north-eastern parts of the region, where mixing with local pollution and smoke results in the moderate AE values (Fig. 8).

The aerosol loading over region 4 is the smallest in magnitude compared to other regions, and appears to be significant mostly in spring and autumn. Bio-mass and fossil fuel burning, forest fires, and pollution over Thailand, Vietnam, Indonesia, and Philippines contributes to the aerosols in region 4 (Lelieveld et al., 2001; Reid et al., 2013). The AE value, which is the largest among all the regions, confirms the presence of smaller size particles in all the seasons. The presence of larger particles such as dust appears to be not significant in the multi-year average. The wind pattern also does not reveal any possibility of transport from source regions dominated by dust particles.

In the case of the selected stations within the study area (Fig. 7), the AOT values indicate how the permanent source regions affect the environment and air quality of these stations and also the significance of any possible local emission over these locations. Mukdahan, Taipei, Osaka and Gosan have AOT of almost similar magnitude, however the AE values are different depending on season. Both Taipei and Mukdhahan have AE > 1.0 in all seasons, indicating that smaller size particles dominate the aerosol loading. Thus, there is less influence from dust source regions over these locations, while smaller size particles resulting from pollution or smoke dominates, indicating that local emissions play important role. On the other hand, over Osaka and Gosan AE < 1.0 in spring, suggesting that transport from region 1 affects theses stations significantly. Similarly, transport of pollutants from region 2 could be possibly responsible for the larger AE in summer and autumn. It is worth to note that Beijing and Bac-Giang are two stations showing largest AOT values. While Beijing could be significantly influenced by region 1, over Bac-Giang mostly local emissions could be contributing with possible transport from region 3. A detailed description of the aerosol characteristics over these stations is given by Gerelmaa et al. (2015).

IV. TRENDS DURING 2002-2008

Though the aerosol properties over the permanent source regions have been investigated by several ground-based as well as satellite measurements, this is probably the first attempt to isolate such regions using multi-year averaging from space based observations and to characterize the variation of aerosol particles in different seasons over the regions during a 7 year period. From a climatological point-of-view, the long-term changes in the amount and distribution of aerosols are of great importance. Such studies are also useful to understand the inter-annual variation of AOT and relate the trends with the corresponding variations in meteorological parameters. It is also important topic for further investigation to understand how, if any, the changes in AOT and that in meteorological parameters are inter-related and if there are any feedback processes.

The increasing trend of AOT over region 1 in spring suggests potential increase in dust storm frequency in the recent years. In fact, there has been a continuous decreasing trend of dust storms in the past few decades (Qian et al., 2002; 2004 Zhou et al., 2003; Wang et al., 2008; Zhu et al., 2008). Though there was sudden increase during 2001-2003 (Gao et al., 2003; Kurosaki and Mikami, 2003), it could well have been part of the inter-annual fluctuations of larger magnitude (Wang et al., 2008; Zhu et al., 2008). However, the increasing AOT trend reported here suggests significant increase, especially during 2006-2008, indicating the possibility of such enhanced occurrence again. Similarly, previous studies of NOx emissions over China by Richter et al. (2005) and Zhang et al. (2007), using Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) data, had shown an increase by a factor 1.5 to 2 from 1996 to 2004. The trend over region 2 shown in this study reveals that similar increase continues during 2003-2008. This further indicates that the anthropogenic emission rate in China still remains large in recent years. In the case of region 3, the previous analysis by Habib et al. (2006) showed a steady increase in the aerosols resulting from smoke, pollution etc. The current results suggests that the increasing trend is still continuing and more measures are required to control the pollution levels.

In order to examine how the rapid increase of AOT in region 1 and region 2 in spring are associated with the changes in meteorological parameters, the trends of NCEP/NCAR temperature, precipitation and humidity are plotted in Figs. 9-11, respectively. Note that the precipitation (Fig. 10) is more random, making the trend less reliable, and hence it may appear as not well correlated with AOT. Over region 1, the increase in AOT during 2002-2008 in spring seems to be related with a similar increase of temperature as well as a decrease of relative humidity. The precipitation also shows a decreasing trend. This indicates more dry and hot weather over region 1 and could potentially result in increase of dust outbreaks, which could also affect nearby regions as well as even remote continents, and is a matter of concern. The year-to-year fluctuations in AOT match with the corresponding fluctuations in meteorological parameters. Though the long term studies of dust storm frequency reveals a decreasing trend, which is explained by the changes in large scale circulation related to global warming, resulting in an increase of surface air temperature over Mongolian plateau and cooling over Northern China, causing a subsequent decrease of cyclonic activity (Wang et al., 2008; Zhu et al., 2008), the results in this study indicates that changes in local meteorological parameters could be important in deciding the strength and magnitude of inter-annual fluctuations in the dust storm occurrence (Qian et al., 2002; Liu et al., 2004).

The AOT increase in spring in region 2 is also associated with slight increase in temperature and decrease in humidity, suggesting hotter and drier conditions to prevail. Rainfall over region 2 in spring also decreases during 2002-2005, but shows increase in later years. The increase in AOT could also indicate increase in local emissions such as smoke, pollution, etc., and also possible transport from region 1. Increasing trend of AOT over region 2 and region 3 in autumn are also associated

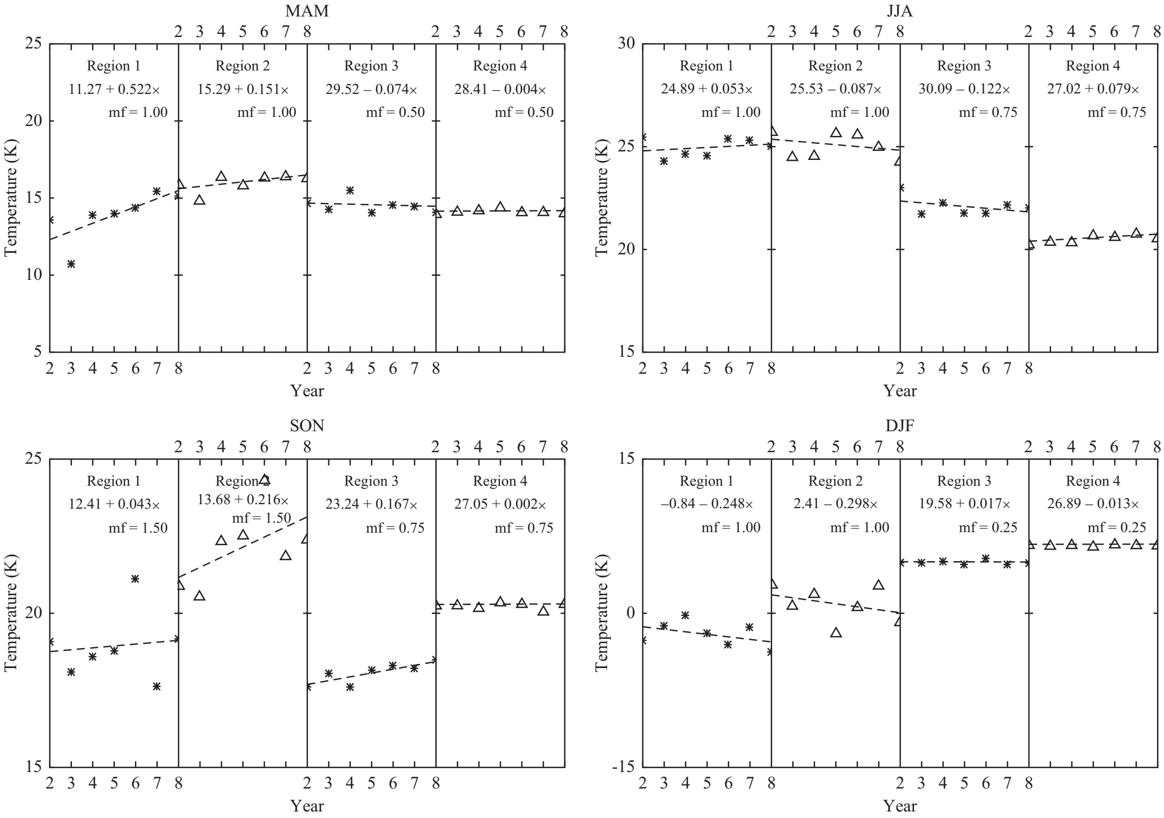

Fig. 9. Mean NCEP/NCAR temperature over the study area in different seasons during 2002-2008.

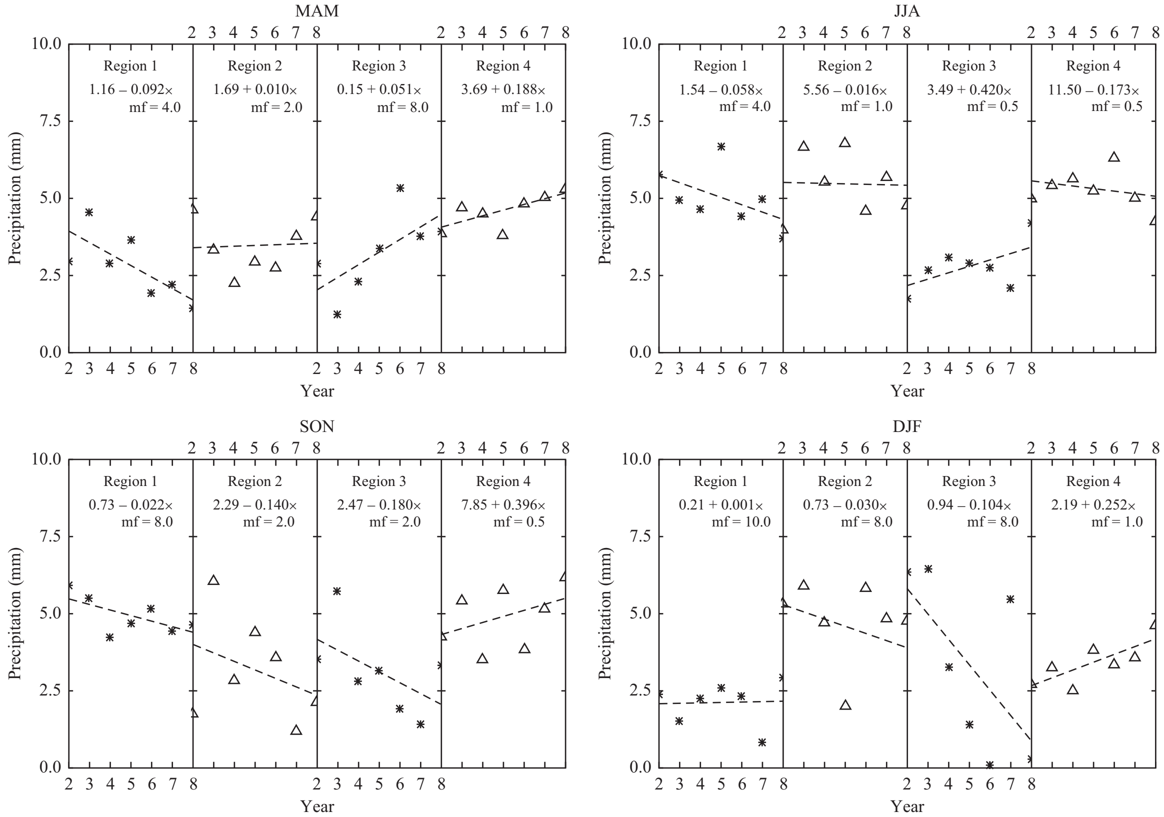

Fig. 10. Mean NCEP/NCAR precipitation over study area in different seasons during 2002-2008.

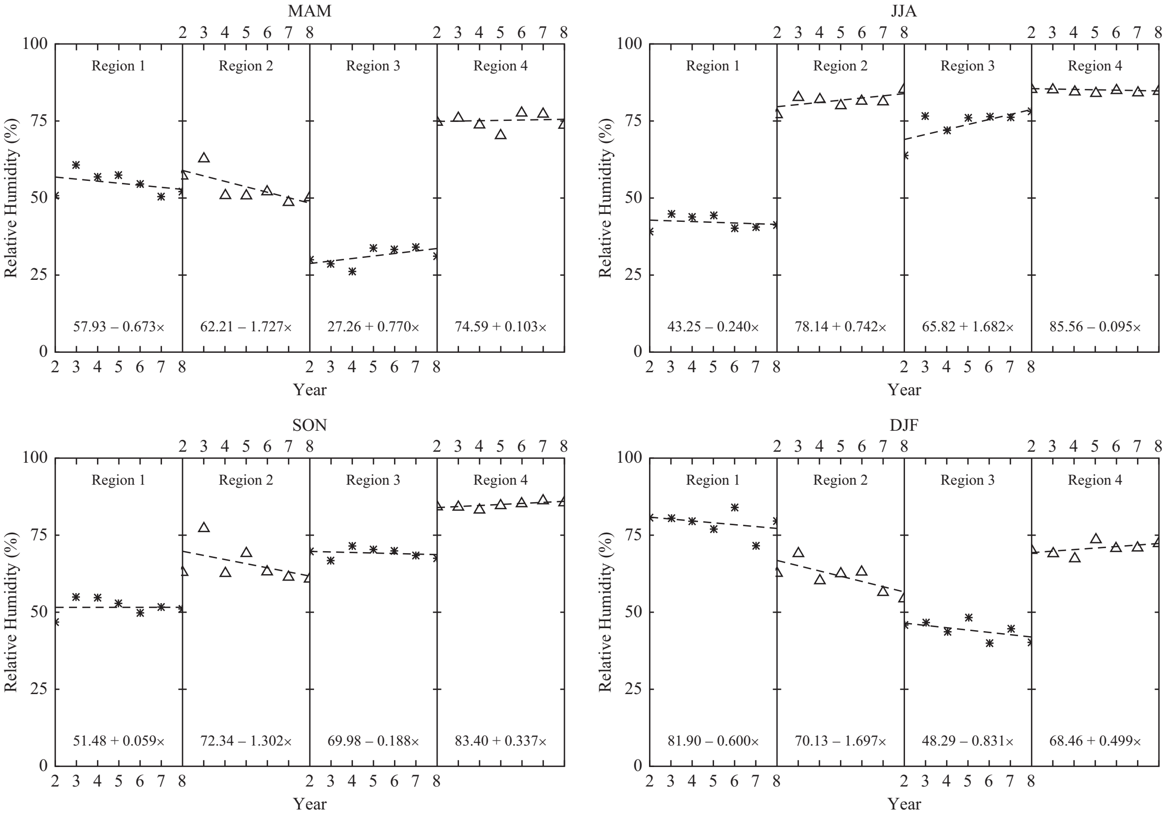

Fig. 11. Mean NCEP/NCAR relative humidity over study area in different seasons during 2002-2008.

with small increase in temperature, and decrease in humidity and rainfall. The AOT increase in this region suggests possible increase of dust emissions in the western parts and smoke, pollution etc. in the eastern parts. Similar variations also exist over region 1 in autumn where the AOT increase is seen during 2005-2008. Note that over region 1 and region 2, AOT increases in winter also. This AOT increase in winter however is associated with a decrease in temperature, together with decrease in precipitation and humidity suggesting colder and drier conditions. Such similarities that could be found with the AOT variation and meteorological parameters in different regions suggests that even if there is no one-to-one relationship with the yearly variation, a persisting change in meteorological parameters reflect as a corresponding change in AOT or vice versa.

As in the case of the permanent source regions, some of the selected stations in the nearby areas also reveal consistent AOT changes during 2002-2008. There is a slight increase of AOT over Mukdahan in autumn and an increase over Bac-Giang in spring as well as in autumn. The aerosol loading over these stations could result from forest fire, bio-mass burning activities and/or more transport from surrounding regions (Kaufman et al., 1997; Reid et al., 2013; Gerelmaa et al., 2015). Bac-Giang in spring could receive air mass from region 3, and Mukdahan in autumn might be influenced by region 4 (Kim et al., 2005; Gerelmaa et al., 2015). Note that except in summer, there is an increasing trend of AOT over Bac-Giang, which needs to be further monitored. The increasing AOT trend in the spring over Beijing, Osaka and Gosan indicates the impact of increasing dust transport to these areas, mostly from region 1 (Chun et al., 2001; Eck et al., 2005; Kim et al., 2005; Kim et al., 2007). This is significant, especially considering that the AOT in other seasons over Gosan and Osaka do not vary much from the average and in some cases tend to be decreasing. Thus the influence of spring dust transport on the air quality of these regions and its climatological implications calls for serious and urgent attention.

V. CONCLUSION

The space-based analysis of multi-year averaging of aerosol products reveals four main permanent aerosol source regions over Asia: (1) the region at North and North-West of China and South of Mongolia, (2) Eastern part of China, (3) North-East of Indian continent, and (4) Parts of Thailand, Vietnam and Indonesia. The trends during 2002-2008 indicate increase of AOT, possibly associated with the increase in dust outbreaks, and also emissions from industrial pollution, bio-mass burning, fossil fuel burning, forest fires etc., over different regions. The increase in AOT in some of the regions seems to be associated with increase in temperature, decrease in humidity and rainfall. The AOT change in the permanent source regions appears to influence the aerosol characteristics in the surrounding areas. The increasing AOT trend over Osaka and Gosan, and also over Beijing since 2004 is probably related to the increasing dust outbreaks in region 1. Local meteorological conditions might play a role in such inter-annual variations in dust storm occurrence. The study suggests that identifying such permanent aerosol source regions and continuous monitoring of the AOT variation over the regions are very essential to assess the air quality of the surrounding areas as well as the regions in the downwind side, and also to take necessary counter measures to diminish the emissions. Finally, the results demonstrate that a similar approach using satellite measurements could be applied to other locations for identifying and monitoring aerosol sources.

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REFERENCES

Alam, K., M. J. Iqbal, T. Blaschke, S. Qureshi and G. Khan (2010). Monitoring the spatio-temporal variations in aerosols and aerosol-cloud interactions over Pakistan using MODIS data. Advances in Space Research 46, 1162-1176.

Alam, K., S. Qureshi and T. Blaschke (2011). Monitoring spatio-temporal aerosol patterns over Pakistan based on MODIS, TOMS and MISR satellite data and a HYSPLIT model. Atmos. Environ. 45, 4641-4651.

Anderson, J., J. Wang, J. Zeng, G. Leptoukh, M. Petrenko, C. Ichoku and C. Hu (2013). Long-term statistical assessment of Aqua - MODIS aerosol optical depth over coastal regions: bias characteristics and uncertainty sources. Tellus B, 65, 20805.

Babu, S. S., S. K. Satheesh, K. K. Moorthy, C. B. S. Dutt, V. S. Nair, D. P. Alappattu and P. K. Kunhikrishnan (2008). Aircraft measurements of aerosol black carbon from a coastal location in the north-east part of peninsular India during ICARB. J. of Earth System Science 117, 263-271.

Chin, M., T. Diehl, P. Ginoux and W. Malm (2007). Intercontinental transport of pollution and dust aerosols: implications for regional air quality. Atmos. Chem. Phys. 7, 5501-5517.

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanre and B. N. Holben (2002). Validation of the MODIS aerosol retrieval over land. Geophys. Res. Lett. 29(12), 1617.

Chu, D. A., Y. J. Kaufman, G. Zibordi, J. D. Chern, J. Mao, C. Li and B. N. Holben (2003). Global monitoring air pollution over land from the earth observing system-terra moderate resolution imaging spectroradiometer (MODIS). J. of Geophys. Res. 108, D21.

Chun, Y., K.-O. Boo, J. Kim, S.-U. Park and M. Lee (2001). Synopsis, transport, and physical characteristics of Asian dust in Korea. J. Geophys. Res. 106(D16), 18461-18469.

Dey, S., S. N. Tripathi, R. P. Singh and B. N. Holben (2004). Influence of dust storms on the aerosol optical properties over the Indo-Gangetic basin. J. Geophys. Res. 109, D20211.

Eck, T. F., B. N. Holben, O. Dubovik, A. Smirnov, P. Goloub, H. B. Chen, B. Chatenet, X.-Y. Zhang, S.-C. Tsay, Q. Ji, D. Giles and I. Slutsker (2005). Columnar aerosol optical properties at AERONET sites in central eastern Asia and aerosol transport to the tropical mid-Pacific. Geophys. Res. Lett. 110, D06202.

Gao, T., L. J. Su, Q. X. Ma, H. Y. Li, X. C. Li and X. Yu (2003). Climatic analyses on increasing dust storm frequency in the spring of 2000 and 2001 in Inner Mongolia. Int. J. Climatol. 23, 1743-1755.

Gautam, R., N. C. Hsu, S. C. Tsay, K. M. Lau, B. Holben, S. Bell, A. Smirnov, C. Li, R. Hansell, Q. Ji, S. Payra, D. Aryal, R. Kayastha and K. M. Kim (2011). Accumulation of aerosols over the Indo-Gangetic plains and southern slopes of the Himalayas: Distribution, properties and radiative effects during the 2009 pre-monsoon season. Atmos. Chem. Phys. 11, 12841-12863.

Gerelmaa, D., G. R. Liu, T. H. Kuo and T. H. Lin (2015). Analysis of aerosol properties coupled with meteorological parameters over East Asia, Terr. Atmos. Ocean Sci. 26, 301-318.

Habib, G., C. Venkataraman, I. Chiapello, S. Ramachandran, O. Boucher and M. Shekar Reddy (2006). Seasonal and interannual variability in absorbing aerosols over India derived from TOMS: Relationship to regional meteorology and emissions. Atmos. Environ. 40(11), 1909-1921.

He, Q., C. Li, F. Geng, Y. Lei and Y. Li (2012). Study on long-term aerosol distribution over the land of East China using MODIS data. Aerosol Air Qual. Res. 12, 300-315.

Heald, C. L., D. J. Jacob, R. J. Park, B. Alexander, T. D. Fairlie, R. M. Yantosca and D. A. Chu (2006). Transpacific transport of Asian anthropogenic aerosols and its impact on surface air quality in the United States. J. Geophys. Res. 111, D14310.

Husar, R. B., D. M. Tratt, B. A. Schichtel, S. R. Falke, F. Li, D. Jaffe, S. Gasso, T. Gill, N. S. Laulainen, F. Lu, M. C. Reheis, Y. Chun, D. Westphal, B. N. Holben, C. Gueymard, I. McKendry, N. Kuring, G. C. Feldman, C. McClain, R. J. Frouin, J. Merrill, D. DuBois, F. Vignola, T. Murayama, S. Nickovic, W. E. Wilson, K. Sassen, N. Sugimoto and W. C. Malm (2001). Asian dust events of April 1998. J. Geophys. Res. 106(D16), 18317-18330.

Ichoku, C., D. A. Chu, S. Chu, Y. J. Kaufman, L. A. Remer, D. Tanré, I.Slutsker and B. N. Holben (2002). A spatio-temporal approach for global validation and analysis of MODIS aerosol products. Geophys. Res. Lett. 29(12), 8006.

Jaffe, D., T. Anderson, D. Covert, R. Kotchenruther, B. Trost, J. Danielson, W. Simpson, T. Berntsen, S. Karlsdottir, D. Blake, J. Harris, G. Carmichael and I. Uno (1999).Transport of Asian air pollution to North America. Geophys. Res. Lett. 26(6), 711-714.

Jones, T. A. and S. A. Christopher (2007). MODIS derived fine mode fraction characteristics of marine, dust, and anthropogenic aerosols over the ocean, constrained by GOCART, MOPITT, and TOMS. J. Geophys. Res. 112, D22204.

Kaufman,Y. J., D. Tanre, L. A. Remer, E. F. Vermote, D. A. Chu and B. N. Holben (1997). Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradio-meter. J. of Geophys. Res. 102(D14), 17051-17067.

Kim, D. H., B. J. Sohn, T. Nakajima and T. Takamura (2005). Aerosol radiative forcing over East Asia determined from ground-based solar radiation measurements. J. Geophys. Res. 110, D10S22.

Kim, S. W., S. C. Yoon, J. Kim and S. Y. Kim (2007). Seasonal and monthly variations of columnar aerosol optical properties over East Asia determined from multi-year MODIS, LIDAR and AERONET Sun/sky radiometer measurements. Atmos. Environ. 41, 1634-1651.

Kurosaki, Y. and M. Mikami (2003). Recent frequent dust events and their relation to surface wind in East Asia. Geophys. Res. Lett. 30(14), 1736.

Lelieveld, J., P. J. Crutzen, V. Ramanathan, M. O. Andreae, C. A. M. Brenninkmeijer, T. Campos, G. R. Cass, R. R. Dickerson, H. Fischer, J. A. de Gouw, A. Hansel, A. Jefferson, D. Kley, A. T. J. de Laat, S. Lal, M. G. Lawrence, J. M. Lobert, O. L. Mayol-Bracero, A. P. Mitra, T. Novakov, S. J. Oltmans, K. A. Prather, T. Reiner, H. Rodhe, H. A. Scheeren, D. Sikka and J. Williams (2001). The Indian ocean experiment: Widespread air pollution from South and Southeast Asia. Science 291 (5506), 1031-1036.

Léon, J. F. and M. Legrand (2003). Mineral dust sources in the surroundings of the north Indian Ocean. Geophys. Res. Lett. 30, 1309.

Lesins, G. and U. Lohmann (2006). Using MODIS and AERONET to determine GCM aerosol size. J. Atmos. Sci. 33, 1338-1347.

Liang, Q., L. Jaeglé, D. A. Jaffe, P. Weiss-Penzias, A. Heckman and J. A. Snow (2004). Long-range transport of Asian pollution to the Northeast Pacific: Seasonal variations and transport pathways of carbon monoxide. J. Geophys. Res. 109, D23S07.

Liu, X., Z.-Y. Yin, X. Zhang and X. Yang (2004). Analyses of the spring dust storm frequency of northern China in relation to antecedent and concurrent wind, precipitation, vegetation, and soil moisture conditions. J. Geophys. Res. 109, D16210.

Qian, W. H., L. S. Qian and S. Y. Shi (2002). Variations of the dust storm in China and its climatic control. J. Climate 15, 1216-1229.

Qian, W. H., T. Xu and L. S. Qian (2004). Regional characteristics of dust storms in China. Atmos. Environ. 38, 4895-4907.

Ramachandran, S and S. Kedia (2013). Aerosol optical properties over South Asia from ground-based observations and remote sensing: A review. Climate 1, 84-119.

Reid, J. S., E. J. Hyer, R. S. Johnson, B. N. Holben, R. J. Yokelson, J. Zhang, J. R. Campbell, S. A. Christophere, L. Di Girolamo, L. Giglio, R. E. Holz, C. Kearney, J. Miettinen, E. A. Reid, F. J. Turkk, J. Wang, P. Xian, G. Zhao, R. Balasubramanian, B. N. Chew, S. Janjai, N. Lagrosas, P. Lestari, N.-H. Lin, M. Mahmud, A. X. Nguyen, B. Norris, N. T. K. Oanh, M. O., S. V. Salinas, E. J. Welton and S. C. Liew (2013). Observing and understanding the Southeast Asian aerosol system by remote sensing: An initial review and analysis for the seven Southeast Asian studies (7SEAS) program. Atmospheric Research 122, 403-468.

Remer, L. A., R. G. Kleidman, R. C. Levy, Y. J. Kaufman, D. Tanré, S. Mattoo, J. V. Martins, C. Ichoku, I. Koren, H. Yu and B. N. Holben (2008). Global aerosol climatology from the MODIS satellite sensors. J. Geophys. Res. 113, D14S07.

Richter, A., J. P. Burrows, H. Nüß, C. Granier and U. Niemeier (2005). Increase in tropospheric nitrogen dioxide over China observed from space. Nature 437, 129-132.

Sharma, M., D. G. Kaskaoutis, R. P. Singh and S. Singh (2014). Seasonal variability of atmospheric aerosol parameters over greater Noida Using ground sunphotometer observations. Aerosol Air Qual. Res. 14, 608-622.

Shaw, G. E. (1980). Transport of Asian desert aerosol to the Hawaiian islands. J. Appl. Meteor. 19, 1254-1259.

Tanr, D., Y. J. Kaufman, M. Herman and S. Mattoo (1997). Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. J. of Geophys. Res. 102(D14), 16971-16988.

Uematsu, M., R. A. Duce, J. M. Prospero, L. Chen, J. T. Merrill and R. L. McDonald (1983). Transport of mineral aerosol from Asia over the North Pacific ocean. J. Geophys. Res. 88(C9), 5343-5352.

Wang, X., J. Huang, M. Ji and K. Higuchi (2008). Variability of East Asia dust events and their long-term trend. Atmos. Environ. 42, 3156-3165.

Wang, X. M., Z. B. Dong, J. W. Zhang and L. C. Liu (2004). Modern dust storms in China: an Overview. J. Arid Environ. 58, 559-574.

Wang, Y., J. Xin, Z. Li, S. Wang, P. Wang, W. M. Hao, B. L. Nordgren, H. Chen, L. Wang and Y. Sun (2011). Seasonal variations in aerosol optical properties over China. J. Geophys. Res. 116, D18209.

Zhang, Q., D. G. Streets, K. He, Y. Wang, A. Richter, J. P. Burrows, I. Uno, C. J. Jang, D. Chen, Z. Yao and Y. Lei (2007). NOx emission trends for China, 1995-2004: the View from the ground and the view from space. J. Geophys. Res. 112, D22306.

Zheng, J., W. Che, Z. Zheng, L. Chen and L. Zhong (2013). Analysis of spatial and temporal variability of PM concentrations using MODIS aerosol optical thickness in the pearl river delta region, China. Aerosol Air Qual. Res. 13, 862-876.

Zhou, Z and G. Zhang (2003). Typical severe dust storms in northern China during 1954-2002. Chinese Science Bulletin 48(21), 2366-2370.

Zhu, C., B. Wang and W. Qian (2008). Why do dust storms decrease in Northern China concurrently with the recent global warming?. Geophys. Res. Lett. 35, L18702.