Spatio-temporal variation trends of satellite-based aerosol optical depth in China during 1980–2008

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1. Introduction

The aerosols have two effects on the climate by scattering and absorbing both solar and terrestrial radiation and as well as modifying the distribution of clouds and their radiative properties: one is direct effect by reflecting solar radiation back to the atmosphere, and another refers to the indirect effect, which, in principle, affects the Earth’s radiation budget through clouds. The latter receives the most attention recently in that the increase of cloud droplet concentration and a decrease in cloud droplet size for a cloud will increase the reflection of solar radiation (called first indirect aerosol effect, Twomey, 1977) by assuming a fixed liquid water content. At the same time, the reduction in droplet size reduces the precipitation efficiency, thereby increasing the cloud liquid water content, cloud lifetime (called second indirect aerosol effect, Albrecht, 1989) and cloud geometrical and optical thickness (Pincus and Baker, 1994). In addition, absorption by aerosols heats the atmosphere locally, which results in the evaporation of cloud droplets (Ackerman et al., 2000; Hansen et al., 1997; Koren et al., 2004), and changes in the atmospheric lapse rate and horizontal advection patterns, affecting cloud formation and precipitation efficiency on regional or global scale (Rosenfeld, 2000).

Due to the sparse surface network, increasing attention has been paid to satellite-based aerosols retrievals. As such, numerous global

**Abstract**

This paper analyzes TOMS AOD at 500 nm (1980–2001), along with MODIS data (2000–2008) at 550 nm to investigate variations at one-degree grid over eight typical regions in China and the trends in AODs, temporally and spatially. In contrast to recently reported global decrease in AOD over global ocean beginning around 1990, we find there virtually exists no apparent AOD transition in China for that: firstly no notable upward tendencies in AOD during 1980–1992 for the relative low value (+0.001/decade); then during 1996–2001 a discernible ascending tendency with larger magnitude at 0.01/decade, and finally, since 2000, a weak upward trend with +0.004/decade. The large increases during 1996–2001 are presumably consequences of large increases in industrial activities and bear a strong resemblance to the long-term decreasing observations of incident solar radiation and cloud cover in China. Specifically, in late 1990’s, only in Taklimakan Desert a negative trend with a maximum magnitude of −0.04/decade is detected. However, over regions such as Jingjinji and Pearl River Delta influenced by industrial activities, positive tendencies at +0.01/decade are observed.

Seasonal patterns in the AOD regional long-term trend are evident. AODs exhibit generally similar seasonality and the summer dominates higher AOD value than the autumn. In particular, during the period 1980–2001, all the eight regions except Taklimakan Desert witness the maximum aerosols in winter while there is not such seasonality during the period 2000–2008. Geographically, we also document spatial patterns of AOD variations over China. Results reveal that no apparent upward trends in AOD (about 15% per decade) are observed in 1980’s, while beginning 1990 till 2008, both data (TOMS and MODIS) are indicative of a significant AOD increase across China, especially in 1990’s it is indeed the case, roughly in accordance with the overall trends at regional scale.

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satellite aerosol products have been generated for both environmental monitoring and climate studies from the following satellite platforms: AVHRR, MODIS, MISR, TOMS/OMI, SeaWiFS, GOMS, AATSR, etc. spanning the period late 1970s to the present. There exists, however, the substantial discrepancies between them. Advantages of individual products are retained due in large part to the lack of integrated products generated which reconcile their differences (Kinne et al., 2006; Kinne, 2009). Several inter-comparison studies (King et al., 1999; Lee et al., 2009), fortunately, were conducted and some insights were gained on the causes of the discrepancies (Jeong and Li, 2005; Kahn et al., 2007; Kokhanovsky et al., 2007; Mishchenko et al., 2009). Despite that the discrepancies still present in the currently available aerosol products and its corresponding possible causes that are not the topic of this paper, long-term continuous aerosol observations have become indispensable for use in various assessments of climate and climate change. A host of researches concerning the long-term aerosol trend analysis have been performed mainly from space-borne aerosol products on account of the merits of wide coverage by satellite-based remote sensing.

Based on 14.5 years (1979–1993) of TOMS aerosol data, global observations of the 5 typical major sources of UV-absorbing aerosols from biomass burning and desert dust showed that late October–November dominated the minimum aerosol loading while the period June–July dominates the maximum (Herman et al., 1997). Using TOMS observations from 1979 to 2000, the research conducted by Massie et al. (2004) suggested that aerosol increased by 17% per decade during winter over the China coastal plain using TOMS observations from 1979 to 2000. Meanwhile, over the Indian sub-continent (land) upward trend in AOD was observed in TOMS observations as well.

The prevailing view is that it has been increasing over the sea (Ramanathan et al., 2005) as a consequence of the increasing anthropogenic emissions and that it also undergoes episodic changes due to volcanic eruptions or forest fires as well as due to weather anomalies of different scales. However recent works relevant to this problem indicate a possible reduction of AOD and an increase in solar radiation reaching the ground over large parts of the globe, noticeable from the beginning of 1990s (Mishchenko and Geogdzhayev, 2007; Mishchenko et al., 2007a,b; Stern, 2006; Wild et al., 2005; George et al., 2008).

Ramanathan et al. (2005) reported an extensive study of regional trends in India including decreasing trends in measured and predicted solar radiation. A general decrease in solar radiation in many Indian cities since 1990 has been found in a recent paper (Porch et al., 2007), which is in agreement with an increasing trend in AOD from total ozone mapping spectrometer (TOMS) measurements. As a result of residue trend analysis made by De Graaf et al. (2010), a small decreasing trend of −0.029 per year from 1995 to 2000 was found across Africa.

Using a method developed by Qiu (1998), 750 nm aerosol optical depths at 47 solar stations from 1961 to 1990 were retrieved. Furthermore, the results of AOD variation over China in recent 30 years indicated that AOD increased obviously over China from 1961 to 1990 (Lu et al., 2000, 2001). But it is based on in-situ ground-based measurements, which cannot be used to determine the aerosol variation on large spatial scale.

On global scale, both MODIS and MISR AODs seem to fully agree that there may have been a weak upward tendency over the land and no apparent long-term tendency over the oceans (Mishchenko et al., 2009). Without doubt, the newer instruments, taking MISR and MODIS as examples, can be expected to provide more accurate and robust aerosol retrievals, while the older instruments, especially the Advanced Very High Resolution Radiometer (AVHRR) and the Total Ozone Mapping Spectrometer (TOMS) can be used to assess potential long-term trends (Mishchenko et al., 2007a) due to its advantage of long duration.

The long-term trend of aerosol optical thickness over the global oceans has been studied by using a nearly 25-year aerosol product from the AVHRR PATMOS-x data (Zhao et al., 2008). This negative tendency is even more evident for globally and annually averaged AOD with the magnitude of −0.03/decade. The decreasing tendency in global AOD is consistent with that from the GACP data set (Geogdzhayev et al., 2005; Mishchenko and Geogdzhayev, 2007). Zhang and Reid (2010), however, studied both regional and global aerosol trends over oceans using the ten-year (2000–2009) MODIS and MISR aerosol products, found that on global scale, there exists a statistically negligible global trend of ±0.003/decade for the past 10 years, which does not agree with a decreasing trend (−0.014/decade) as reported by Mishchenko et al. (2007b) using the AVHRR data for the years of 1991–2005. While, AODs over the Indian Bay of Bengal, east coast of Asia, and Arabian Sea show ascending trends of 0.07, 0.06, and 0.06 per decade for MODIS, respectively. Negative AOD trends, low in confidence levels, are found off Central America, the east coast of North America, and the west coast of Africa.

Negative trends in AOD derived from MODIS, MISR, combined with AERONET over Europe and North America for the period 2000–2009 were observed, which appeared to be statistically significant, whereas over South and East Asia they are mostly positive (De Meij et al., 2010), in qualitative agreement with the results of previous studies by Zhang and Reid (2010), Lu et al. (2010), Remer et al. (2008) and Chylek et al. (2007).

By instituting the reform and opening-up policies since late 1970’s, China has made remarkable achievements in economic development. As a consequence, the emissions of greenhouse gases and aerosols have also been increased during past decades, thereby dramatically affecting regional climate in China (Menon et al., 2002). As a result, China has become one of the world’s most dense aerosol regions (Li et al., 2007; Duncan et al., 2003), wherein urban regions over eastern China contain large volumes of aerosols, owing to both human activities (construction, traffic, etc.) and remote biomass burning or dust storms transported to the urban regions (Jin and Shepherd, 2005; Zhao and Li, 2007).

Accounting for the fact that China is one of the heavily polluted areas with higher concentration of sulfate, dust and carbonaceous aerosols as well. In addition, the mineral aerosol, which is derived from Northwest China especially in spring season, can transfer along with wind to the downstream far away and impact the environment and climate of East China. In fact, the aerosol direct observations in China are much scarce except for a limited number of observation sites. Till now, an understanding about the spatial and temporal variation of aerosols over China is limited due to sparse network of observations. Hence, it is the primary problem to obtain the spatio-temporal distribution of aerosols over China.

Notwithstanding the considerable work devoting to the topic of AOD retrieval and long-term trend analysis, overall the current knowledge of the global distribution of the AOD and, especially, aerosol microphysical characteristics remain limited (Mishchenko et al., 2009). The level of scientific understanding of aerosol effects on climate system is medium-low and the uncertainty in estimates can be very large (IPCC, 2007). Understanding long-term changes and trend in AOD on the Earth, especially in the developing countries like China, becomes increasingly essential for accurately assessing the radiative forcing, as well as better constraining the climate models.

Considering the severe impacts on the climate and human health caused by aerosols, attention recently has been paid to aerosols whether there is or not a clear increasing/decreasing regional or global trend of aerosol loading through satellite observations. In
particular, based on long-term uninterrupted record of global AOD estimates from AVHRR, Mishchenko et al. (2007b) found a global averaged AOD discontinuity over the oceans beginning around 1991, which is in good agreement with the fact of a recovery from the previous decline known as global “dimming” (Wild et al., 2005), with the “brightening” beginning around 1990 (Pink et al., 2005). To our knowledge, no work has been reported about the discontinuity in the long-term changes in AOD across China during the period 1980–2008. In this study, we will present the long-term trend analysis of aerosol loading in eight typical regions of China and attempt to find out the discontinuity by combining TOMS and MODIS aerosol data, which will provide a detailed insight into spatio-temporal variation of aerosol load and the possible causes for it as well.

A short overview of the contents of this paper is given below. Introduced in Section 2 are the data and methods employed. Results concerning the relatively comprehensive aerosol variation in China are given in Section 3, and the discussion in relation to the results also is made here. Finally, conclusions are drawn in Section 4.

2. Data and methods

2.1. Study area

Normally it can be easier to identify possible regional long-term tendencies since they are likely to be stronger than those in the global AOD averages (Zhao et al., 2008; Mishchenko and Geogdzhayev, 2007; George et al., 2008). As such, eight typical regions (see Fig. 1) rather than the whole China are selected for long-term trend analysis, 1: Taklimakan Desert; 2 Gobi Desert; 3: Jingjinji; 4: Northeast china; 5: Daxinganling; 6: Sichuan Basin; 7: Yangtze River Delta; and 8: Pearl River Delta.

The eastern part of China is in general more affected by the anthropogenic activities while western China more influenced by natural sources such as dust storm. Jingjinji, Yangtze River delta, and Pearl River delta (indicated by rectangle 3, 7 and 8 in Fig. 1) are the most developed regions in China undergoing rapid industrial development in recent years, wherein increasing anthropogenic emissions originate, having raised interest in the outflow of chemically and radiatively important gases and aerosols. The atmospheric pollution in Northeast (denoted by rectangle 4 in Fig. 1, the traditional heavy industrial base of China) is dominated by the coal burning mixed with dust advected from west-northern China (Herman et al., 1997). There is presumably the least aerosol load in Daxinganling, which is mostly affected by the biomass burning in the autumn (Wang et al., 2010). Sichuan Basin is surrounded by the mountains, wherein the anthropogenic emission takes the lead contributing the atmospheric pollution. Taklimakan and Gobi desert are two major sources of dust aerosols injected into atmosphere during springs which just do not affect the surrounding regions, but also blanket areas far away from the source region by means of advection by atmospheric circulations and synoptic weather system.

Taklimakan and Gobi desert dominate the injection of many dust aerosols into the atmosphere every spring and always blanket areas far outside of their source regions from advection of dust by atmospheric circulation and synoptic weather system.

2.2. Data

One of the biggest challenges in observational long-term aerosol trend studies is obtaining the temporally and spatially consistent observations for aerosols. TOMS AOD only takes the UV-absorbing aerosols into account by exploiting spectral absorption in the near-UV region. In comparison to TOMS, MODIS retrievals are based on aerosol scattering and use visible and near-IR channel measurements over the global except bright land surface (Kaufman et al., 1997; Chu et al., 2002; Remer et al., 2005). In addition, the footprint of both sensors is quite different (ca. 50 km of TOMS at nadir versus 10 km of MODIS). Large magnitude of difference, therefore, exists between TOMS–MODIS AODs, which makes it difficult to contemplate a straightforward and unequivocal unification of the MODIS and TOMS datasets into combined aerosol climatology. To quantify and mitigate all specific effects of these differences is very difficult and likely impracticable, both scientifically and logistically. However, we attempt to identify the trends in AOD by performing an integrated analysis by combining the TOMS (1980–1999) and MODIS (2000–2008), which is the objective of this study.

The Nimbus-7 TOMS instrument operated from October 1978 to April 1993, Meteor 3 TOMS worked from August 1991 to November 1994, and Earth Probe TOMS data dated from mid-1996 to 2001 are selected as well for the study area shown in Fig. 1. Because MODIS is on board NASA’s Earth Observing System (EOS) Terra platform, launched in December 1999, we obtained the AOD products as of the year of 2000.

TOMS AOD data are available on a 1° × 1° grid, which are retrieved using the direct method at two near-ultraviolet wavelengths (Torres et al., 1998). This method is based on the interaction between aerosols and the strong molecular scattering in the near ultraviolet, which produces spectral variations of the backscattered radiances that can be used to separate aerosol absorption from scattering effect, thus making detection of absorbing aerosols possible over land and oceans. TOMS, therefore, provides retrievals of total column ozone and AOD from 1979 to the present over a 1° spatial scale, with a data gap from 1994 to mid-1996 (Torres et al., 2002). In most cases the TOMS-derived optical depths of UV-absorbing aerosols are within 30% of the AERONET observations, while non-absorbing optical depths agree to within 20% (Torres et al., 2002). Satellite observations from 1980 to 1999 from the TOMS satellite (Massie et al., 2004), therefore, help put these observations in a larger temporal and spatial context, compared with MODIS AOD (as of 2000).

Operational aerosol products of MODIS/Terra level 2 aerosol datasets (MOD04 L2, Version 5.1) are acquired from National Aeronautics and Space Administration (NASA) Level 1 and Atmosphere
Archive and Distribution System (LAADS) (http://ladsweb.nascom.nasa.gov/data/), which are retrieved using the dark target algorithm, which is originally developed by Kaufman et al. (1997) and then refined and parameterized by Levy et al. (2007). The MOD04 data has numerous aerosol physical and optical parameters at $10 \times 10$ km$^2$ spatial resolution. We choose to aggregate the 10 km pixels into $1^\circ$ spatial scale to accommodate both MODIS and TOMS AOD products.

The MODIS AOD ($\tau$) has been widely validated with ground-based sun photometer AOD around the world by a spatio-temporal approach (Ichoku et al., 2002). The accuracy has been claimed that the MODIS aerosol retrievals over land surface, except in coastal zones, are found within retrieval errors $\Delta \tau = \pm 0.05 \pm 0.15\tau$ (Chu et al., 2002; Remer et al., 2005).

2.3. Analysis methods

The accuracy and reliability of each $1^\circ \times 1^\circ$ average through aggregation of MOD04 (at 10 km pixel level) depends on the number of individual values contributing to the average. In addition, given the range of natural aerosol variability, the values for individual pixels can be easily affected by local events such as dust storms, fires and changes in local atmospheric circulation conditions. To examine the cause of the changes in a particular small area and to decide whether they are realistic or not would require a detailed case-by-case pixel-level analysis, it is tedious and time-consuming and far beyond the scope of this paper. We, therefore, just concentrate on regional changes on larger spatial scale.

In view of the fact that TOMS AOD is only sensitive to the absorbing and up lofted aerosols, whereas MODIS AOD is simply valid for land surface except high reflective lands such as deserts (Region 1 and 2 in Fig. 1), all the results in this paper are confined to such prerequisite.

The linear change of AOD can be basically described as the linear long-term trend (LLT) in the unit of absolute or percentage changes per decade (Zhao et al., 2008). The AOT LLT is the slope of the linear regression for the time series of monthly or annually averaged AOD. We adopt the commonly used decision rule that a real trend is detected at 95% confidence level with $\text{LLT} > 2\sigma$ (see Weatherhead et al., 1998; Porch et al., 2007), where $\sigma$ denotes standard deviation.

Fig. 2. Domain averaged AOD distribution in relation to Month and Year (filled color). The vertical blue bars at the top (on the right) denote mean AOD over the entire period 1980–2008 for each year (month), in the eight regions indicated in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
3. Results and discussion

3.1. Domain-averaged temporal AOD trend analysis

Illustrated in Fig. 2 are the detailed temporal variations of aerosol contents, both monthly and yearly, from January 1980 through December 2008. Owing to the two different sources of aerosol products using here, both the inter-monthly and inter-annual variation analysis of AOD in the entire eight regions shown in Fig. 1 will be conducted separately, i.e. pre-2000 (TOMS) and post-2000 (MODIS).

TOMS AOD contains little information of non-absorbing aerosols such as sulfate aerosols in the boundary layer. This limitation explains that the magnitude of TOMS AOD is comparable to the MODIS AOT in regions where dust particles dominate such as region 1, but much lower in regions where industrial particles prevail such as Region 7, as shown in Fig. 2.

During pre-2000, as for Regions 1 and 2, which are typical major sources of UV-absorbing aerosols from desert dust, the period July–November dominates the maximum aerosol loadings, indicating the frequent occurrence of dust in these areas in autumn. Normally most dust events in Regions 1 and 2, however, were thought occurring in spring. In Region 4, the period July–September dominates the maximum aerosol content, which agrees with the results by Herman et al. (1997). It should be noted that in Region 5, there are distinctly high aerosol loadings during June–August 1987,
indicative of large forest fires occurring prior to June 1987. Severe forest fire was actually the case occurring in Daxinganling Forest fire in May–June 1987. Meanwhile, during September–December, Region 6 is characteristic of high aerosol content possibly due to the biomass burning over there. In Regions 7 and 8, however, there are no apparent loadings of UV-absorbing aerosol. This is for the industrial emission in these areas dominates the sources, which cannot be easily detected by TOMS.

During post-2000, areas with intensive industrial activities and high population density (Regions 3, 6, 7 and 8) tended to be characterized with high aerosol loadings, especially during the period March–November, except for Region 1, in which the high AOD was caused by desert dust. The underlying land cover accounted for the low AOD spreading over in Region 5.

Further, regarding the whole period 1980–2008, it seems that there exists apparent discrepancy between two different sources of AOD products, notably in Regions 3, 5, 7 and 8. The MODIS values in these regions can be up to 1.0, while the TOMS AOD stays at very low values, which is indicative of the presence of non-absorbing aerosol types prior to the year 2000, in view of the incapability of TOMS for the retrieval of non-absorbing aerosol. Or presumably the absorbing aerosols were confined in the boundary layer during pre-2000, which generally are not readily seen by TOMS because the small amount of underlying Rayleigh scattering leads to a weak signal (Herman et al., 1997). Also, this can be used to explain why the majority of regions in Region 5, 7 and 8 studied in this paper (see Fig. 3) are covered by low AODs.

3.2. AOD tendency analysis

In this section, the monthly time series of regional averaged AODs at the eight regions depicted in Section 2.1 and its long-term tendency over the years of operation of the two sensors will be analyzed in detail.

As shown in Fig. 3, the frequent alternation between high monthly and low monthly AODs is conspicuously noticeable in what Jia et al. (2008) called a sawtooth cycle, suggesting a strong seasonality of AOD variation. AOD on hazy or dust months (peaks in the sawtooth cycle) showed 2–4 times higher than those on clear months (valleys in the sawtooth cycle), suggesting the presence of inter-monthly AOD variation as well. The seasonal change of AOD will be discussed in Section 3.3. As illustrated in Fig. 3, there is a weak upward trend during 1980–1992 in region 3, which appears to be generally plausible for the accordance with ground-based observational trend by Qiu (1998) and Che et al. (2006). In individual cases the peaks of the sawtooth are indicative for absorbing aerosol events such as haze or dust storm during the months studied.

The effects of the disastrous forest fire happened in May 1987 in Daxinganling of northeastern China can be clearly seen in the TOMS AOD records (c.f. Fig. 3). With respect to entire time series, AOD of as high as 1.44 stands out clearly in May 1987, followed by decay in the following months, which presumably is due to the injection into the stratosphere of ash as a result of biomass burning. In order to avoid the contamination of the extremely high AOD caused by fire on the long-term trend, linear trend regression was performed using the AODs after removing those in May 1987 and the following several months.

Over eight typical regions shown in Fig. 1, there are virtually no notable upward or downward tendencies (−0.0006/decade) in AOD during 1980–1992, as described in Table 1. However, it seems intriguing from Table 1 that during 1996–2001, positive tendency prevails in all regions except for Region 8 (Pearl River Delta) and oscillates between 0.01/decade and 0.04/decade, with maximal magnitude of +0.04/decade occurring in Jingjinji and Taklimakan Desert. Also from Table 1, the ascending tendency magnitude during 1996–2001 is on average at 0.0231/decade, roughly forty times high than that (−0.0006/decade) during 1980–1992, implying a distinct discontinuity existing. But it is totally contrary to the transition from dimming to brightening over global ocean beginning around 1990 (Mishchenko et al., 2007b; Wild et al., 2005; Pinker et al., 2005), indicating that trends in AOD between ocean and land surface (especially in China) exhibit quite different results. The large increases during period 1996–2001 likely are consequences of large increases in industrial activities and bear a strong resemblance to the long-term observations of incident solar radiation and cloud cover in China (Zhang et al., 2004; Che et al., 2006; Qian et al., 2006).

Compared with the trends in TOMS AOD during period 1996–2001, it exhibits much lower magnitude (average trend: −0.0017/decade) for trends in MODIS AOD (the period 2000–2008) characterized by the weak downward tendency in the eight typical regions in China. This may be due to the implementation of flue gas desulphurization, resulting in emission reductions across China, thereby relatively reducing the aerosol loading. On the other hand, both emissions decrease by 10% from 1996 to 2000 over the China coastal plain (Smith et al., 2003) and reduction in industrial coal use (Carmichael et al., 2002) can attribute to the decline. Although Taklimakan Desert is the main region that contributes to the decreasing monthly mean AOD (Table 1) at −0.04/decade, the decreasing trend is not statistically significant at 95% confident level. Among others, Regions 3 and 8 (Jingjinji and Pearl River Delta) are the most obvious areas with escalating trend (0.01/decade, see Table 1).

To reflect the overall trend in the whole country of China, we perform the long-term trend analysis of AOD as well in China. As shown in Table 1, no apparent AOD transition in China dominates the trend: firstly no notable upward tendencies in AOD during 1980–1992 for the relative low value (+0.001/decade), then during 1996–2001 a discernible ascending tendency with larger magnitude at 0.01/decade, and finally, since 2000, a weak upward trend with +0.004/decade. As clearly shown in Table 1, there is an upward trend in AOD from TOMS and MODIS in 1990’s and 2000’s respectively. Noted that the absolute difference between them is of secondary importance and can be attributed to distinct retrieval philosophy. As a result, a trend of +0.02/decade was observed in China during the period 1996–2008.

Technically speaking, only the magnitude (0.01/decade) of TOMS AOD during 1996–2001 shows some degree of similarity to that (0.015−0.03/decade) found by Wang et al. (2009) using 30 years of ground-based measurements (denoted by visibility

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All trends are denoted as AOD variation per decade, at significance level P < 0.05 with 95% confidence interval except for those indicated by *.

inverse), except for both TOMS AOD during 1980–1992 and MODIS AOD during 2000–2008. Offsets where the trends in AOD vary quite different (both magnitude and signal) in different periods can possibly be due to the differences in measurement system.

3.3. Seasonal characteristics of AOD

From the previous Section 3.2, the obtained time series shows inter-monthly AOD variation cycle like sawtooth in all the eight regions, suggesting strong aerosol seasonality in all regions is indeed the case. The spring (March–April–May), summer (June–July–August), autumn (September–October–November) and winter (December–January–February) mean AOD in eight regions during 1980–2008 are shown in Fig. 4. On account of the different source of AOD (i.e. TOMS and MODIS) applied in this research, we study the seasonality during 1980–2001 (TOMS) and 2000–2008 (MODIS) separately.

According to Fig. 4, the climatology of AOD does not show similar seasonality during both periods of 1980–2001 and 2000–2008 except in Region 4 (Northeast China), and Region 5 (Daxinganling). In Region 4, the minimum AOD (about 0.18) is observed in autumn while maximum (about 0.40) in winter for both periods. Likewise, similar seasonal pattern is apparent in Regions 5 for both periods, i.e. AOD in this region has seasonal variability with the minimum occurring during autumn and the maximum occurring during spring, obeying the precipitation patterns and weather system common to this region.

Noted that during the period 1980–2001, all the eight regions except Taklimakan Desert have the maximum aerosols in winter, possibly due to the emission increases caused by coal burning in that season. There is not such seasonality during the period 2000–2008, which can be explained by the high efficiency of TOMS in capturing the absorbing aerosols in winter. During the period 2000–2008, spring almost dominates the maximum AOD in Regions 3, 6, 7 and 8. Such seasonality is partly due to the stagnant meteorological conditions common in those regions.

Also, Fig. 4 reveals that AODs in the eight regions exhibit generally similar seasonality and the summer dominates the higher value than that in autumn, which is in harmony with the results found by Herman et al. (1997). During summer, photochemical interactions are more active owing to higher air temperatures, which increase aerosol concentrations in the atmosphere (Dickerson et al., 1997).

Fig. 4. Seasonal mean distribution of TOMS AOD during 1980–2001 (upper panel) and MODIS AOD during 2000–2008 (lower panel) in the eight regions given in Fig. 1.
3.4. Spatial variations in annual mean AOD

First of all, we divide the period 1980–2008 into three different time period, i.e. 1980–1989; 1990–1999 and 2000–2008. Then the spatial changes pattern of AOD has been examined in this section in percentage relative to the decadal mean AOD during the corresponding 10 years studied, which is calculated by least square fitting by minimizing the chi-square error statistic based on time series of annual mean AOD. It should be pointed out that all of the AOD spatial trend analyses during the period 1980–2001 are only limited to absorbing aerosols.

In general, the results in Fig. 5 reveal that positive AOD trends are observed from 1980 to 2008, i.e. both data (TOMS and MODIS) are indicative of a significant AOD increase across China, especially in 1990’s it is indeed the case, in accordance with the overall trends illustrated in Fig. 3. In particular, there are notable escalating tendency in AOD in eastern China after 1990 (middle and lower panel of Fig. 5), when both industrial and anthropogenic activities over there witnessed rapid increase, resulting in aerosols injecting into the atmosphere, which is similar to the results found by Porch et al. (2007) over the Ganges River Basin of India. Meanwhile, the increase by about 15% per decade over most coastal plain of eastern China is found in upper panel of Fig. 5 is roughly in harmony with 17% claimed by Massie et al. (2004).

Furthermore, the lowest panel (MODIS AOD) of Fig. 5 suggests that most of the Northwest China and the Tibet Plateau are blank (implying no significant upward trend or no data). While the upward tendency in the same area is more or less common to the upper and middle panels (TOMS AOD). This can be explained by the uniqueness of TOMS aerosol record in its ability to detect aerosol over high reflective land such as snow or sand. MODIS, however, has difficulty retrieving desert dust optical depths over such land surfaces as Tibetan Plateau.

In addition, the discernable increase of AOD can be found in areas of Sichuan Basin (Region 6) during 1990′s and 2000′s and a negative trend occurs in 1980′s, as notably illustrated in Fig. 5. This spatial variation in AOD in this region, therefore, is in good agreement with the findings revealed in Fig. 3. Concerning Region 5 (Daxinganling), the discernable AOD change can be only detected during 1980′s, which is presumably due to biomass burning in Daxinganling caused by the forest fire occurred in 1987.

In general, Fig. 5 does show an increase in aerosol load in most parts of China during 1980–2008, and its spatial shift towards more developed eastern China since late 1990′s. In particular, the aerosols shift towards Southeast China such as Guangdong and Fujian provinces as of 2000.

4. Conclusions

We conduct a long-term trend analysis of AOD in eight typical regions across China, both spatially and temporally, using TOMS AOD products (1980–2001), along with MODIS/Terra AOD data (2000–2008). Insights into the temporal variations, spatial pattern of changes in regional AOD and their corresponding causes have been yielded.

Results show that a continual upward tendency during 1980–1992 (0.001/decade), 1996–2001 (0.01/decade), 2000–2008 (0.004/decade), proving that no transition of aerosol loading is observed starting around 1990, which is totally contrary to the transition from dimming to brightening over global ocean beginning around 1990 (Mishchenko et al., 2007b; Wild et al., 2005; Pinker et al., 2005), indicating that trends in AOD between ocean and land surface (especially in China) exhibit quite different results. Also, the magnitude of 0.01/decade interpreted from TOMS AOD data during 1996–2001 shows some degree of similarity to that (0.015–0.03/decade) observed by ground-based measurements (denoted by visibility inverse, Wang et al., 2009), except for both TOMS AOD during 1980–1992 and MODIS AOD during 2000–2008. In addition, AODs in the eight regions exhibit generally similar seasonality, i.e. the summer dominates the higher value than that in autumn, which is in harmony with the results found by Herman et al. (1997).

The spatial pattern of the changes in AOD suggests that apparent upward trends in AOD are observed from 2000 to 2008, especially in 1990′s it is indeed the case, in accordance with the overall trends reduced from monthly time series. In particular, there is discernible escalating tendency in AOD in eastern China after 1990, presumably due to the increasing aerosol particles injecting into the atmosphere by the intensive industrial and anthropogenic activities over there.

In conclusion, TOMS AOD, in conjunction with MODIS AOD, has the potential to provide an integrated historical perspective of the global aerosol distribution, thereby leading to reduction in the uncertainty as to the quantitative role of aerosols in climate forcing in China. The results given in this paper, however, show that neither MODIS nor TOMS can be used to determine unambiguously whether the recent AOD trend is due to long-term global changes in natural or anthropogenic aerosols. There is a need to better delineate/quantify the contribution made by natural and anthropogenic activities in total aerosol loading.

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