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Global aerosol change in the last decade: An analysis based on MODIS data

K.B. Mao [a,b,*], Y. Ma [a], L. Xia [a], Wendy Y. Chen [b], X.Y. Shen [c], T.J. He [d], T.R. Xu [e]

[a] National Hulunber Grassland Ecosystem Observation and Research Station, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, 12 Zhongguancun South Avenue, Beijing 100081, China
[b] Department of Geography, The University of Hong Kong, Pokfulam, Hong Kong
[c] Hydrometeorology and Remote Sensing Laboratory, University of Oklahoma, Norman 73072, USA
[d] Department of Geography, University of Toronto, Toronto M5S 3G3, Canada
[e] State Key Laboratory of Remote Sensing Science, School of Geography, Beijing Normal University, Beijing 100875, China

HIGHLIGHTS

- Global aerosol change in different regions in the last decade.
- Which year is the highest or lowest of aerosols in different regions.
- Where are the aerosols decreasing or increasing.
- The aerosol changes with seasons in northern and southern hemisphere.

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ABSTRACT

Abstract: Our understanding of the global aerosol change is rather limited, although it is well known that aerosol forcing could affect the global radiative budget, hydrological processes, carbon, nitrogen and sulfur cycles, as well as climate change. To understand the wide range effects of aerosols, it is key to obtain aerosol characteristics at high spatio-temporal resolutions. In this study, we try to map the global variations of the aerosol optical depth (AOD) using two aerosol products retrieved from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite instrument. It is found that the global average AOD is 0.126 over the last decade (2003–2012). The highest and the lowest AOD occurred in 2007 and 2010, respectively. AOD variations between land and ocean, north and south hemispheres, among seven continents and four oceans were also explored. It is interesting to find that high concentrations of aerosols are mainly distributed in regions where developing countries are located (Asia and Africa), and an increasing trend could also be observed. Seasonal variations of AOD (air quality) can also be noted, which is decreasing in the north hemisphere from spring, summer to autumn and winter, but increasing in the south hemisphere.

1. Introduction

In recent years, especially in developing country, air pollution is getting worse. Aerosols are an important component of haze. The diameters of aerosol particles in Earth's atmosphere range from 0.1 to 1.0 micron, which are coincident with the sunlight wavelength. The atmospheric aerosols could thus disturb solar radiation income and global climate through influencing the transfer of energy in the atmosphere in two ways (Hansen et al., 1997; Carslaw et al., 2013). On the one hand, the atmospheric aerosols can directly reflect and absorb the solar radiation in both the troposphere and stratosphere. On the other hand, the atmospheric aerosols could modify the optical properties of clouds through cloud condensation nuclei which lead to increase cloud droplet number concentrations, and thus affect the incoming radiation indirectly (Gao et al., 2000; Wang et al., 2009). The atmospheric aerosols play a dominant role in the global energy balance by contributing to a net reduction

* Corresponding author. National Hulunber Grassland Ecosystem Observation and Research Station, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, 12 Zhongguancun South Avenue, Beijing 100081, China.
E-mail addresses: kebiaomao2004@hotmail.com, maokebiao@126.com (K.B. Mao).

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of 5–10% in solar energy received at the Earth's surface, therefore the dynamics of the atmospheric aerosol load is of vital importance for the science and policy of environmental pollution and global climate change (Charlson et al., 1992; Fuzzi et al., 2006).

However, our understanding of the global aerosol change is rather limited, because it is difficult to assess the profile of atmospheric aerosols at a global scale (Hess et al., 1998). Traditionally, ground-based observation stations have been established to measure the concentration of aerosols, which are mainly located in densely populated areas. In addition, the lifetimes of most aerosols are short and therefore their geographical distribution is highly variable and strongly related to their sources. Thus the observations tend to be biased by local/regional industrial activities, vehicle transport, land surface cover and soil type, and climatological condition. In recent years, satellite instruments have been used to estimate indirectly the spatial distribution of aerosol optical depth. AVHRR (Advanced Very High Resolution Radiometer) is the first satellite instrument used to estimate the global-mean AOD (Husar et al., 1997; Kaufman et al., 2002; Zhao et al., 2008). However, the accuracy of aerosol estimates over land area assessed by AVHRR data need to be improved, because the limited band number cannot fully capture the radiative properties of land surface which are highly variable (Robert et al., 2009; Hsu et al., 2012). MODIS (Moderate Resolution Imaging Spectrometer) is a 36-band Earth Observing System (EOS) instrument onboard the National Aeronautics and Space Administration's (NASA) satellites. It could provide accurate daily insight into the global distribution of aerosols because of its global coverage, radiometric resolution and dynamic ranges, and accurate calibration in the visible and infrared regions of the spectrum bands designed for retrievals of atmospheric properties (King et al., 1996). Moreover, MODIS aerosol products can provide consistent evaluation over land and ocean surfaces because we use the same instrument MODIS, and there is relatively better comparability because the measurement error is similar for different time and place (Ichoku et al., 2004). These observations have been widely used in the research of climate change (Yu et al., 2006; Pauli et al., 2013; Remer et al., 2008) and to monitor atmosphere environment (Chu et al., 2003; Al-Saadi et al., 2005; Wang et al., 2010; de Meij et al., 2012; Kim et al., 2014).

In recent year, pollution (haze) is very serious, especially in developing country. Spatio-temporal variation and trends in atmospheric aerosols as well as their impact on solar radiation and clouds are crucial for regional and global environment (air quality) assessment. The purpose of this paper is to use MODIS aerosol

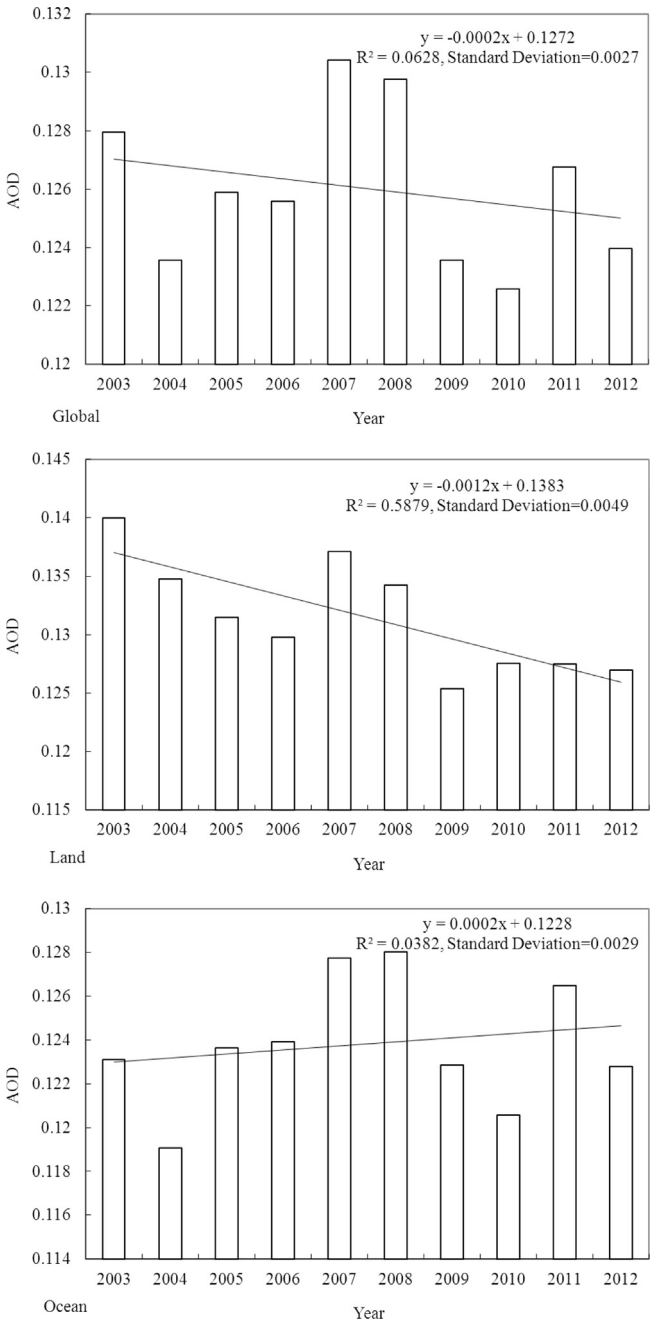

Fig. 1. The average AOD over land, ocean, and the whole globe from 2003 to 2012.

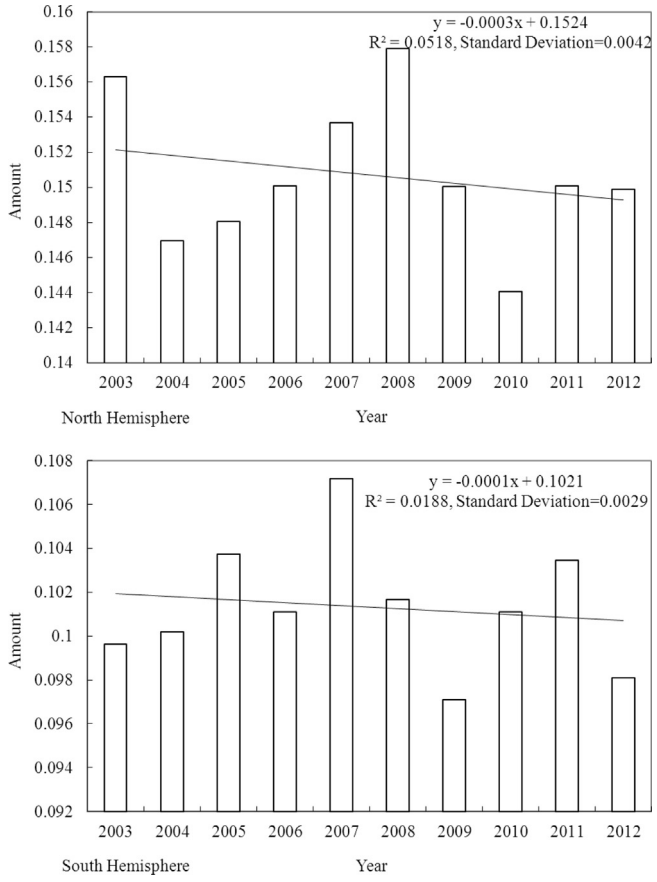

Fig. 2. The mean AOD over the north and south hemispheres from 2003 to 2012.

product to analysis the spatio-temporal characteristics of aerosol at global and regional scale, which help people know our environment (the distribution of pollution) in recent years. So People and government take appropriate measures to protect our environment.

2. Data and method

NASA has two polar-orbiting EOS satellites, Terra (launched in 1999) and Aqua (launched in 2002). Terra crosses the equator in the early morning (10:30) and early evening (22:30) and Aqua in the afternoon (13:30) and late evening (01:30). MODIS instruments are onboard these two satellites to provide two-daily global aerosol observations for the same place (10:30, 13:30 local solar time). MODIS data level 2 aerosol products are geophysical parameters derived directly at 10-km pixel spatial resolution from MODIS radiance data (Level 1B), which are operationally aggregated to generate global daily, eight day (weekly), and monthly products at 1° spatial resolution. They are suitable for large regional or global studies (Ichoku et al., 2004). MODIS aerosol products are validated by using data obtained from AErosol RObotic NETwork (AERONET) ground-based sun-photometers, which are located in approximately 200 continental or island sites around the world (Holben et al., 1998, 2001). In order to assess and ensure the product quality at global and regional scale, many validation programs and analysis for MODIS aerosol products have been made by many people (Chu et al., 2002; Ichoku et al., 2002, 2004; Remer et al., 2002, 2005; Levy et al., 2009; Zhang and Reid, 2010; Kanniah et al., 2014). All the analysis indicates that monthly global mean AOD values can be used to study the global aerosol change. The MODIS aerosol monthly products at 1° spatial resolution (MOD 04/MYD 04) and Eq. (1) are used to estimate the global aerosol characteristics.

$$AOD_{mk} = \frac{1}{pq}\sum_{i=1}^{i=p}\sum_{j=1}^{j=q} S(j)\left(AOD_{ij}^{10:30} + AOD_{ij}^{13:30}\right)\Big/2 \quad (1)$$

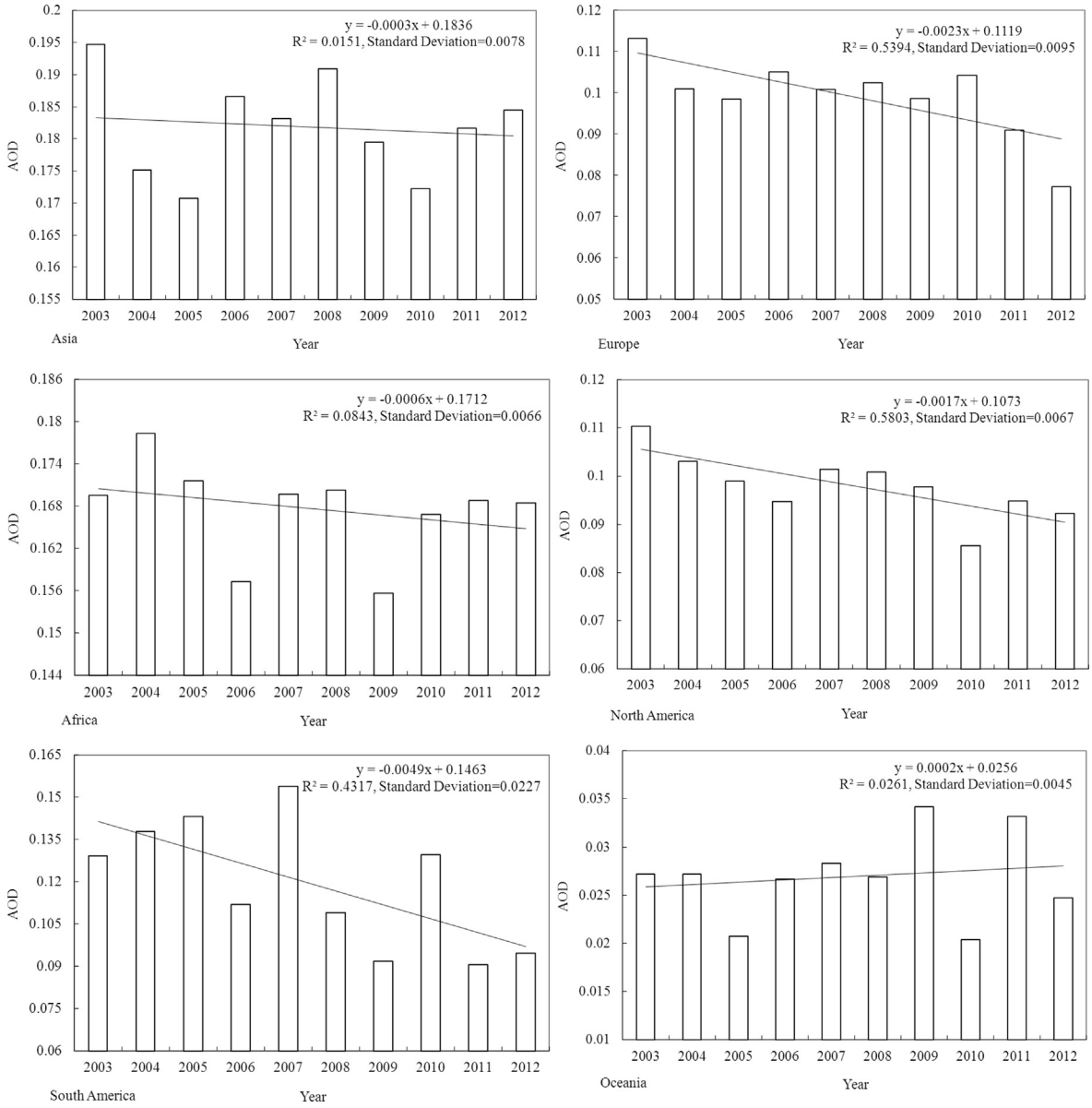

Fig. 3. The mean AOD over continental regions (2003–2012).

where AOD_{mk} is mean aerosol optical depth in kth year, i is the number of month of every year, p is the total number of month, j is the number of pixel, q is the total number of pixel, $S(j)$ is the area weighting function of the pixel$j$, AOD_{ij} is the aerosol optical depth in time (10:30, 13:30) of day for the same location. Eq. (2) is used to estimate the changing rate of AOD from 2003 to 2012.

$$Slope\_Rate = \frac{n\sum_{k=1}^{n}(k \times AOD_{mk}) - \sum_{k=1}^{n} k \sum_{k=1}^{n} AOD_{mk}}{n \times \sum_{k=1}^{n} k^2 - \left(\sum_{k=1}^{n} k^2\right)} \quad (2)$$

Slope_Rate denotes the change rate, k is the number of year, AOD_{mk} is the mean AOD of kth year, and n is the total number of year.

3. Results

AOD can be used to indicate the quality of the air, and we made an analysis for different region in different year. The annual average AOD over ocean, land surface, and the whole globe from 2003 to 2012 is shown in Fig. 1. The global mean AOD is 0.126 during the period from 2003 to 2012. And the highest and lowest values occur in 2007 and 2010, respectively. Biomass burning in the Amazon basin along the so-called arc of deforestation dominated the aerosol signal in South America in 2007 (Levinson and Lawrimore, 2009). Over land surface, the mean AOD is 0.131, and the highest and lowest values can be observed in 2003 and 2009. In 2003, it has been observed that the severity and extent of the damage in the fire season made it one of Canada's worst. It is about 6863 km^2 of forests, rangeland, and residential areas across British Columbia, which is 11 times the annual average area burned in the province over the past 10 yr. The other serious wildfires happened in other regions in 2003, like New Mexico and Arizona in May–July, the northern Rockies in July–September and southern California in October (Levinson and Waple, 2004). The mean AOD over ocean is 0.124, lower than that over land surface. And the years with highest value (2008) and lowest value (2004) over ocean surface are inconsistent with AOD over land surface. Fig. 1 shows that the decreasing trend of the mean AOD over land surface is distinct, while it is not possible to find explicit changing trend with regard to the AOD over ocean or at the global scale.

The annual mean AOD over the north and south hemispheres are given in Fig. 2. The mean AOD over the north hemisphere is 0.151 in the last decade, and the highest and lowest values occurred in 2008 and 2010. The mean AOD over the southern hemisphere is much lower, only at 0.101, and the highest value is 0.107 in 2007 and lowest value is 0.097 in 2009.

The variations of the mean AOD over six continents are shown in Fig. 3. The mean AOD over Asia in recent ten years is 0.182, which is the highest amongst all continents. The mean AOD over Africa is ranked the second, at 0.168, followed by South America at 0.119. The mean AOD over North America and that over Europe are consistently low, at 0.098 and 0.099 respectively. Except for the Antarctic where the mean AOD over is very low and it is very difficult to estimate due to the existence of many invalid values, the lowest mean AOD can be found over the Oceania at only 0.027. The occurrence of highest and lowest AOD values varies across different continents. Nevertheless, a general decreasing trend of the AOD can be found over North America, South America and Europe. These findings suggest that the AOD values are comparatively high and increasing over regions where developing countries are located.

The aerosols over oceans show different pattern in comparison with that over continental regions (Fig. 4). The mean AOD over the Atlantic Ocean is the highest at 0.148, followed by Indian Ocean (0.133), the Pacific Ocean (0.113), and Arctic Ocean (0.061). Analysis

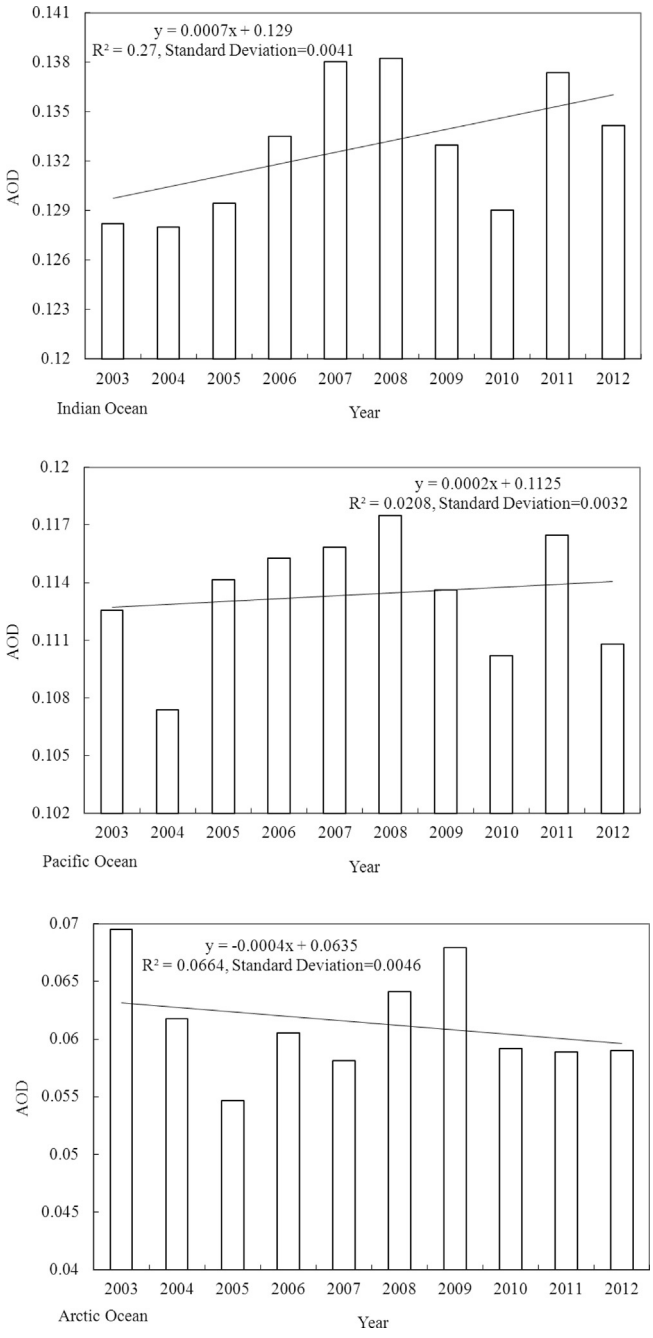

Fig. 4. The mean AOD over ocean regions (2003–2012).

indicates the AOD over the Pacific and Indian Ocean is increasing slightly in the last ten years.

The overall global mean AOD of aerosol from 2003 to 2012 is shown in Fig. 5a. It can be found that high concentrations of aerosols are mainly distributed in the western Africa, Indian Peninsula, and east of China. The linear regression has been made for every pixel from 2003 to 2012 using Eq. (2) to calculate the change rate, and the result is given in Fig. 5b. It indicates that the concentrations of aerosols are decreasing in recent ten years in eastern of America, middle of South America, Europe, and north-east of Oceania, while the concentrations of aerosols are increased in the most parts of the rest of regions, especially in the north of Indian Ocean, and north-east Asia.

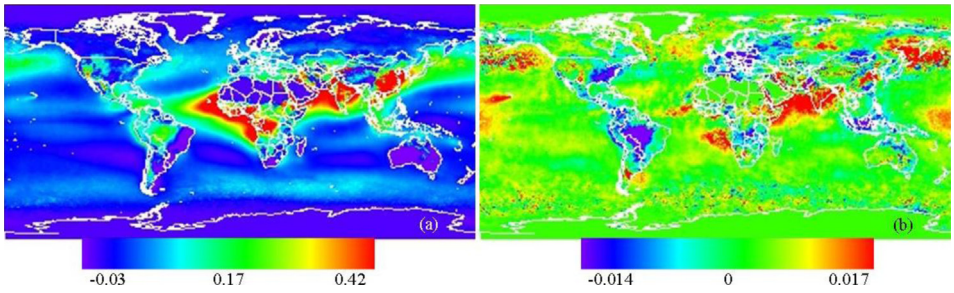

Fig. 5. (a)The mean AOD from 2003 to 2012; (b) The change rate of AOD from 2003 to 2012.

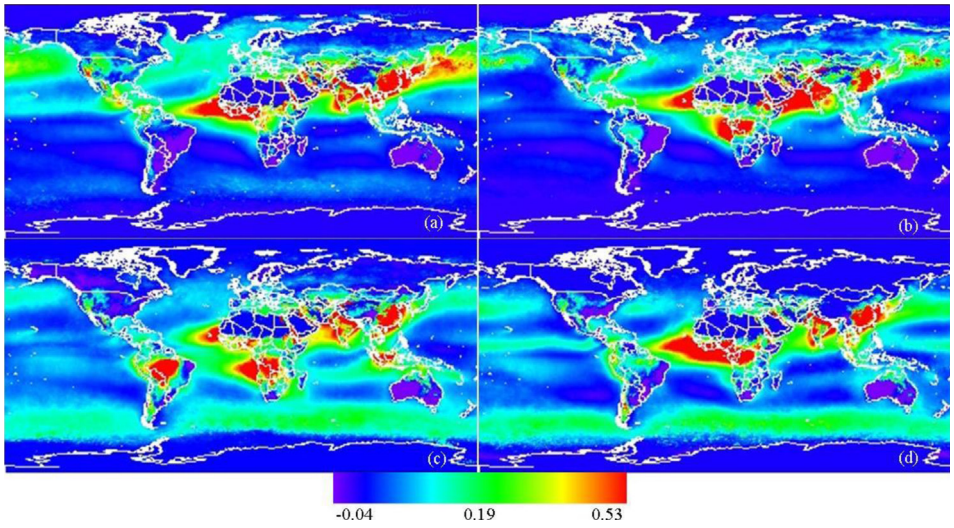

Fig. 6. (a) The mean AOD during March to May; (b) The mean AOD during June to August; (c) The mean AOD during September to November; (d) The mean AOD during December to February in the last ten years.

We further analysed the seasonal variations of the AOD from 2003 to 2012, and the results are given in Fig. 6. It is interesting to find that the AOD is decreasing from the spring season (March to May) to the winter season (December to January) in the northern hemisphere, but increasing during the same period in the southern hemisphere. In the spring season, the highest concentrations of aerosols are observed in the north-east Asia (especially in the east of China). In summer, the concentrations of aerosols are very high in the Indian Peninsula. In autumn, the concentrations of aerosols are very high in the middle of South America. And in winter the concentrations of aerosols are very high in the middle-western of Africa. Moreover; the concentrations of aerosols are fairly high (AOD is about 0.2) in during September to January between 40° and 55° in the south hemisphere, but it is low between 40° and 55° in

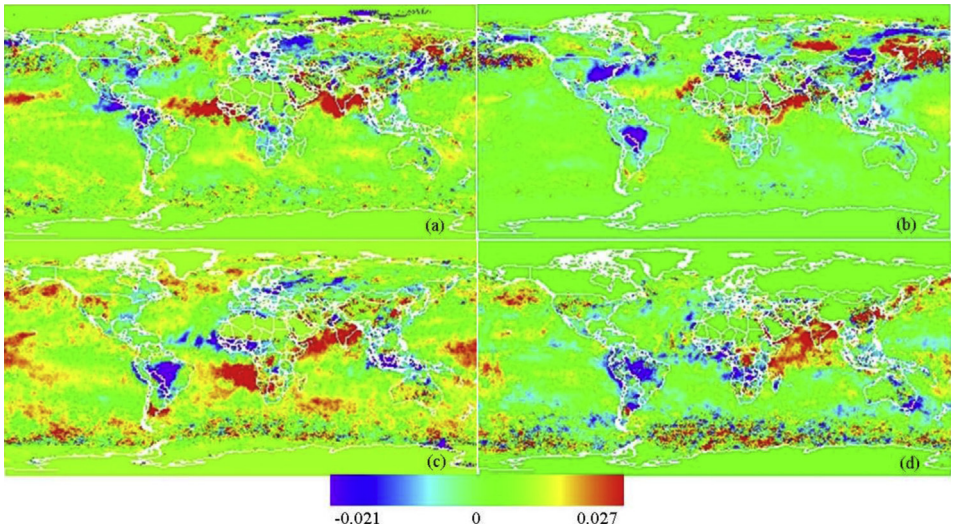

Fig. 7. The overall change rate of the AOD by seasons from 2003 to 2012: (a) March to May; (b) June to August; (c) September to November; (d) December to February.

the north hemisphere. In the rest of the time of the year, the AOD value is high in the region of N 40°–55°, but low in S 40°–55°. The temperature changes with the season, so these findings suggest that temperature might be a key factor influencing the distribution of aerosols, especially over the ocean regions.

The change trends of the global AOD (air quality) by seasons in the last decades are given in Fig. 7. A year- round increasing trend would be found in the Indian Peninsula and the north of Indian Ocean. There is a clear decreasing trend in the east of American in the spring and summer seasons (from March to August). And a similar decreasing trend can be found in the middle of the South America in throughout the year excluding the autumn season (from September to November). Although a consistent increasing trend is found over ocean surface, it is more rapid during March to May and September to November.

4. Discussion and conclusions

It is very important to make the uncertainty analysis for the data set. The sampling bias and perturbations in sensor calibration could introduce biases to the ten-year trend. The analysis indicated that the sampling bias due to the difference in Terra and Aqua equatorial crossing time is on the order of 0.18% (Remer et al., 2006; Zhang and Reid, 2010). Recently studies suggested that sampling bias could introduce large bias to regional aerosol climatologies, while the biases in the seasonal means are insignificant, which are less than 5% for the monthly means if all MODIS data over global oceans are included (Zhang and Reid, 2009, 2010). Many other validation programs and analysis for MODIS aerosol products have been made by many people to ensure the product quality at global and regional scale (Chu et al., 2002; Ichoku et al., 2002, 2004; Remer et al., 2002, 2005; Levy et al., 2009; Zhang and Reid, 2010). We made a computation for the standard deviation of yearly mean based data provided by aerosol products, and the average difference of standard deviation error in different years is under 0.001. All the analysis indicates that monthly global mean AOD values can be used to study the global aerosol change.

The concentrations of the atmospheric aerosols affect not only air quality but also global solar energy forcing. The studies focusing on aerosols have drawn much attention from scientists, governments and international organizations. During the last ten years, the high concentrations of aerosols are mainly found in the northeast Asia, middle-east Asia, and the central regions of Africa, where developing countries are distributed. The concentrations of aerosols are decreasing in the eastern America, middle of the South America, Europe, and the north-east of Oceania, while the concentrations of aerosols are increasing in the most parts of the rest of regions, especially in the north of Indian Ocean, and the north-east Asia. The concentration of aerosols in Atlantic Ocean is higher than in Pacific due to the influence of Africa. The concentrations of aerosols decrease obviously in the east of North America, Europe and the middle of South America. The seasonal variations analysis indicates that the AOD is decreasing from March to February in the northern hemisphere, but increasing in the southern hemisphere. Compared with previous studies, we made more detail spatial statistical and seasonal analysis for different regions in global scale. This comprehensive examination of aerosol promises a holistic understanding of the global climate change and potential underlying mechanisms.

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