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Evaluation of dust activity and climate effects in North China

XIA Xiang-ao, LIANG Feng, WANG Ming-xing

(Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. E-mail: xiangaoxia@sina.com)

Abstract: *TOMS/AI* data with nearly 20 years are utilized in the paper to evaluate dust activities in North China. Combined with simultaneous *NCEP* reanalysis climate data, climate effects on dust activities are assessed. The results showed that the whole North China suffers impact by dust aerosols, with three centers standing out in *TOMS/AI* spring average map that are western three basins, which are characterized by lower annual precipitation and elevation. Gobi deserts in Mongolia Plateau do not attain higher *TOMS/AI* value due to cloud contamination and relative higher elevation. Spring is the season with the highest *TOMS* dust aerosol index; within the western three basins, high dust aerosol index appears in both spring and summer, especially in Tarim Basin. Wind speed in spring and precipitation in previous rainy season play important roles in controlling dust activities, higher wind speed and less precipitation than the normal are in favor of dust activities in spring. Temperature in spring and previous winter also affect dust activity to a certain extent, but with contrary spatial distribution. Temperature in winter exert effect principally in west part, contrarily, temperature effect in spring is mainly shown in east part. Both of them have negative correlation with dust activity.

Keywords: *TOMS/AI*; *NCEP* climate data; dust activity; correlation analysis

Introduction

At the turn of the century, unprecedented dust activities with higher frequencies stroke most part of North China, which caused more attention to the phenomenon(Ye, 2000). Uncertainties in dust aerosol direct and indirect radiative forcing also make it one of hot research fields (Sokolik, 2001). Surface observations, such as visibility observations and dusty weather records carried out in climate stations, play an important role in characterizing temporal variation of dusty weather occurrence owing to its long-term records(more than half century) (Zhou, 2000). Many significant results concerning dust activity variation characteristics and their relation with climate were obtained in North China based on these records(Quan, 2001). However, it should merit mention that surface observations have their inherent limitations including three points: (1) Surface observations are subject to influence of artificial factors, for example, different observers recording differently toward the same phenomenon; the alternation of observation standard making it hard to interpretation of the observations from the different period. (2) Long-term surface observations were accumulated until now, but the sparse spatial distribution of surface observations hampers their usage, especially for dust activity study since dust sources are always located in those unfrequented regions such as desert and Gobi. (3) Surface observations only represent dust information within the lower boundary layer; so the usually layered structure of dust aerosol causes these observations are not the optimal records of dust.

Satellite remote sensing of tropospheric aerosol is thought to be feasible and prospective method to quantify objectively aerosol content with high spatial and temporal resolution, although many scientific issues concerning satellite measurement remain unresolved, among which large contribution from land surface reflectivity and its high spatial and temporal variation are one of the major obstacles, additionally, uncertainties in aerosol properties such as size distribution and refractive index etc. may produce large errors on satellite inversion(King, 1999). It is the reason why operational satellite retrieval of aerosols is only available over open sea that is dark at visible wavelength. However, with regard to satellite remote sensing of dust aerosols, three advantages are in existence. The first is dust activities always have very large spatial distribution and lead to strong signal in satellite measurement, additionally, dust aerosol unique radiative properties such as strong absorption at UV and infrared spectrum provide other approaches that are different from that at visible spectrum, finally, the surface contribution to satellite measurements at UV is not dominant and does not attain large spatial and temporal variation in comparison with that at visible region. Two well-known examples of satellite remote sensing are *TOMS*/aerosol index data(*TOMS/AI* abbreviated herein), which rely on satellite measurement at UV spectrum, and *IDDI* data (Infra-red difference dust index), which are based on measurement at atmospheric window region. *TOMS* (total ozone mapping spectrometer) onboard Nimbus 7(from 1979 to 1993) and EP (Earth Probe, from 1997 to the present) satellite has accumulated data of nearly 20 years from 1979 with global coverage(Herman, 1997). However until now *IDDI* data are only for Sahara region(Legrand, 2001).

Since surface observations have inherent limitations and satellite monitor have accumulated nearly 20 years data, furthermore, since dust activities in North China showed high inter-annual variation in recent years, so it is of significance to evaluate dust activity in North China based on satellite data and to evaluate climate effects on dust activity with the aid of climate reanalysis data, which are the focus of this paper.

1 *TOMS* aerosol data description and methodology

1.1 Basic theory of *TOMS/AI*

Aerosol layer can cause two contrary effects on backscattering UV radiation to satellite, one is aerosol backscattering that increases satellite measurement, another is absorption of Rayleigh scattering radiation under the aerosol layer that decreases satellite measurement. On the average, strong absorptive aerosols such as dust and biomass burning aerosol may cause less backscattering radiance to satellite at UV spectrum owing to their absorption effect dominating over scattering, contrarily, the existence of non-absorption aerosols such as sulfate causes more satellite measurement than expected under the absence of aerosol due to the enhancement of backscattering effect of these aerosols. Based on the analysis, *NASA/TOMS* aerosol group developed a half-quantitative index to describe aerosol content.

$$N_\lambda = -100\left\{\log_{10}\left[\frac{I_{340}}{I_{380}}\right]_{meas} - \left\{\log_{10}\left[\frac{I_{340}}{I_{380}}\right]_{calc}\right\}, \quad (1)$$

where I_{meas} is the measured backscattering radiance at given wavelength, and I_{calc} is the calculated radiance at that wavelength using a modified Dave's LER model (Lambert Equivalent Radiation). Since surface reflectivity is determined by requiring I_{meas} equal to calculated I_{calc} in the ozone retrieval procedure, so aerosol index is equivalent to equation below.

$$N_\lambda = -100\ln\left(\frac{I_{meas}}{I_{calc}}\right)_{340}. \quad (2)$$

So aerosol index for strong absorptive aerosols is positive owing to decrease of backscattering radiance, on the contrary, index for scattering aerosols is negative; moreover, index corresponding to the presence of cloud is close to zero. Therefore, *TOMS/AI* produces good separation between the presence of absorbing aerosols, non-absorptive aerosols and cloud.

1.2 Methodology

The *TOMS/AI* utilized in the research are version 2 data, which have spatial resolution of 1.25° × 1° and daily global coverage. We work primarily on daily *TOMS/AI* to prepare monthly maps showing the average *AI* beyond some threshold, then obtain seasonal maps. The setting of threshold is to eliminate minor dust events and reduce the statistics "noise" introduced by low *AI*. Research results showed that 0.6 for pixel or 0.2 for spatial average are suitable for extract dust or biomass burning aerosol information. In the paper, 0.6 for pixel is used and *TOMS/AI* average is calculated by Equation (3). In reality, the consistent pattern may be yielded with threshold ranging from 0.2 to 1.0; so large differences are not anticipated due to diverse choices of threshold.

$$AI(\text{average})_{pixel} = \sum_i (AI_i > \text{Threshold} = 0.6)/N(\text{days}). \quad (3)$$

With regard to seasonal variation of dust activity, five typical regions are selected according to *TOMS/AI* distribution map in spring, which are signed from west to east (in order from ZONE 1 to ZONE 5). The exact range of each region is listed in Table 1. *NCEP* reanalysis climate data are utilized to evaluate climate effects on dust activities. Spring is emphasized in the analysis due to more than 50% dusty days occurring in this season. Mean fields with *TOMS/AI* in spring and climate factors composed of wind speed in spring, precipitation in summer and spring, temperature in winter and spring are created firstly for each of the pixels (1.25° × 1°) (the *NCEP* reanalysis data with 2.5° × 2.5° are interpolated into resolution of *TOMS/AI*). In order to get physically meaningful inter-annual deviation, the anomaly fields are calculated by subtracting the mean fields from the annual *TOMS/AI* and climate fields. Additionally, for the sake of diminishing the possible systematic deviation between *TOMS/AI* data from Nimbus and EP, the *TOMS/AI* and climate deviations are produced respectively for these two periods (1979 to 1991 for Nimbus and 1997 to 2000 for EP, the data of last two years for Nimbus are eliminated due to eruption of Pinatubo volcano). Correlation analyses are carried out based on deviation field of corresponding climate and *TOMS/AI* data.

Table 1 Five regions selected for seasonal variation analysis

Region	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Latitude, N	35°—42°	38°—42°	35°—40°	42°—45°	35°—40°
Longitude, E	80°—95°	95°—105°	107°—112°	110°—118°	114°—118°

2 Results

2.1 Evaluation of *TOMS/AI* ability

In order to evaluate *TOMS/AI* ability in representing dust aerosol content in China, *TOMS/AI* data in 2000 are compared with aerosol optical depth (AOD) at 400 nm obtained from sun/sky radiometer measurements in Dunhuang, which is similar with researches carried out by Hsu *et al*. in African and South America (Hsu, 1999). Long-term and continuous ground-based spectral sun/sky radiation observation in Dunhuang is part of SKYNET and supported by Chinese and Japanese institutes. The data processing procedures in detail are described in the literature, which are composed of calibration of radiometer field of view angle (FOV) and instrument responding constant at the top of atmosphere (TOA), then, strict cloud screening and quality controlling algorithm is carried out to eliminate cloud contamination to aerosol optical depth (Xia, 2002). The comparison results are shown in Fig.1. The vertical bars represent one standard deviation of AOD corresponding to one *TOMS/AI*, also included in Fig. 1 is linear relation formula.

The sound linear relation shows that *TOMS/AI* data are suitable for analysis of dust aerosol in China, although obvious disperse is present for small *TOMS/AI* values, which is mainly resulted from large spatial resolution of *TOMS/AI*.

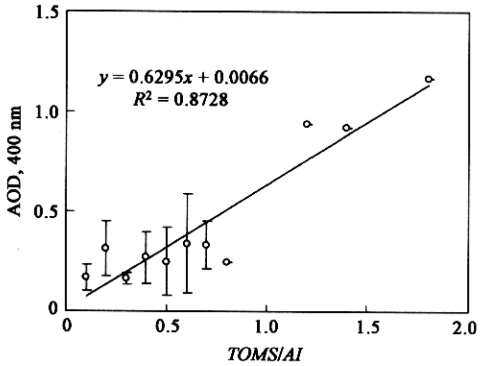

Fig.1 Comparison between *TOMS/AI* and ground-based optical depth observations in Dunhuang. Ground-based optical depth data are from sun/sky radiance measurements. Data processing procedure and precision are referred to the literature

2.2 Seasonal variation and spatial distribution of dust activity in North China

Spatial distribution map for *TOMS/AI* average in spring is shown in Fig.2. A majority of North China is impacted by dust aerosol. The western three basins (that are Tarimu, Qaidam and Junggar Basin) are standing out dust center due to less precipitation (with 50—100 mm precipitation annually) and uninterrupted supply of materials. The additional reason why these areas stand out prominently in *TOMS/AI* map is owing to their lower elevation. Gobi Desert located east of Tarimu Basin on the Mongolia Plateau such as Badain Jaran Desert, Tengger Desert, Ulan Buh Desert and Hexi Corridor are identified by previous studies of China dust transport to be a major dust source, but *TOMS/AI* for these regions are much less than that in basins. This is due in part to the fact that Gobi Desert dust storms usually occur in response to cold air broken-out that emerges from Siberia, so clouds may hamper *TOMS/AI* detection of dust aerosol, in addition, higher elevation in these regions than that in basins also contribute to lower *TOMS/AI*. The *TOMS/AI* average in spring for North China Plain is beyond 0.5 that manifest the region is disturbed by dust aerosol seriously in this season.

TOMS/AI seasonal variations for the five chosen regions are shown in Fig. 3. Distinctive seasonal variation is presented for all of regions with highest frequency in spring. Persistent dust activity starts in Mar., reaches its maximum in April-May and decreases rapidly for east regions. It merits attention that frequent dust activity also occurs in summer for west regions; all years except in winter are full of dust activity in Tarimu Basin in particular.

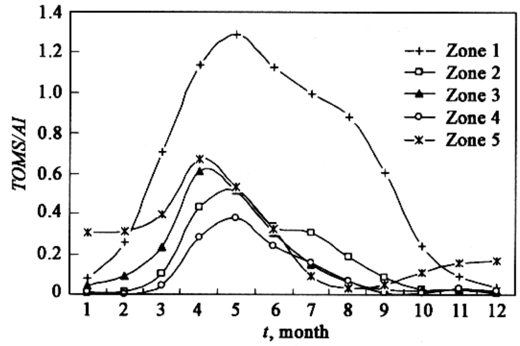

Fig.3 Seasonal variation in *TOMS/AI* in five selected regions

2.3 Climate effects on dust activity in North China

Correlation between *NCEP* reanalysis data and *TOMS/AI* are shown respectively in Fig. 4. A majority of areas shows positive correlation between *TOMS/AI* and *NCEP* wind speed in spring, which illuminates that energy needed for dust activity is the critical factor controlling dust aerosol amount in North China. Most regions with vegetation cover in the map show negative correlation between corresponding precipitation in previous rainy season and *TOMS/AI*, which implies more precipitation in previous rainy season may influence dust activity in the succeeding dusty season via its effects on vegetation growth and land cover. Analyses between *TOMS/AI* and temperature in spring and winter showed that temperature, in general, has negative correlation with dust activity in North China. In winter, the negative correlation appears mostly in the west part of the studied

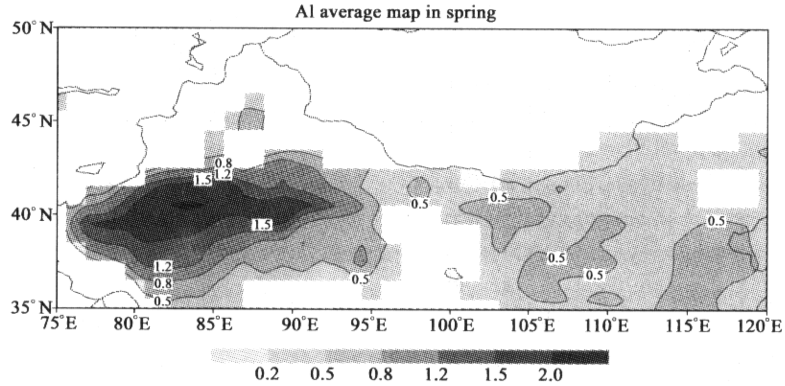

Fig.2 *TOMS/AI* spatial distribution in spring in North China (threshold of 0.6 for pixels is used to eliminate potential errors and pixels of *TOMS/AI* average beyond 0.2 are shown

region, contrarily, temperature effect in spring is manifested in the east part. Dust activity is always connected with cold air broken-out and dust aerosol may lead to temperature decline due to its radiative effects, which may be the potential mechanism for the negative correlation. Lower temperature in winter is favorable for soil frozen; accordingly, the rapid increase of temperature in spring will result in more materials for supporting dust activity, so temperature in winter has negative correlation with *TOMS/AI*. No significant correlation between *TOMS/AI* and precipitation in spring is present, which implies the dry deposition of dust aerosol dominates over the wet deposition in spring; the potential reason is that less precipitation events appear in spring in North China.

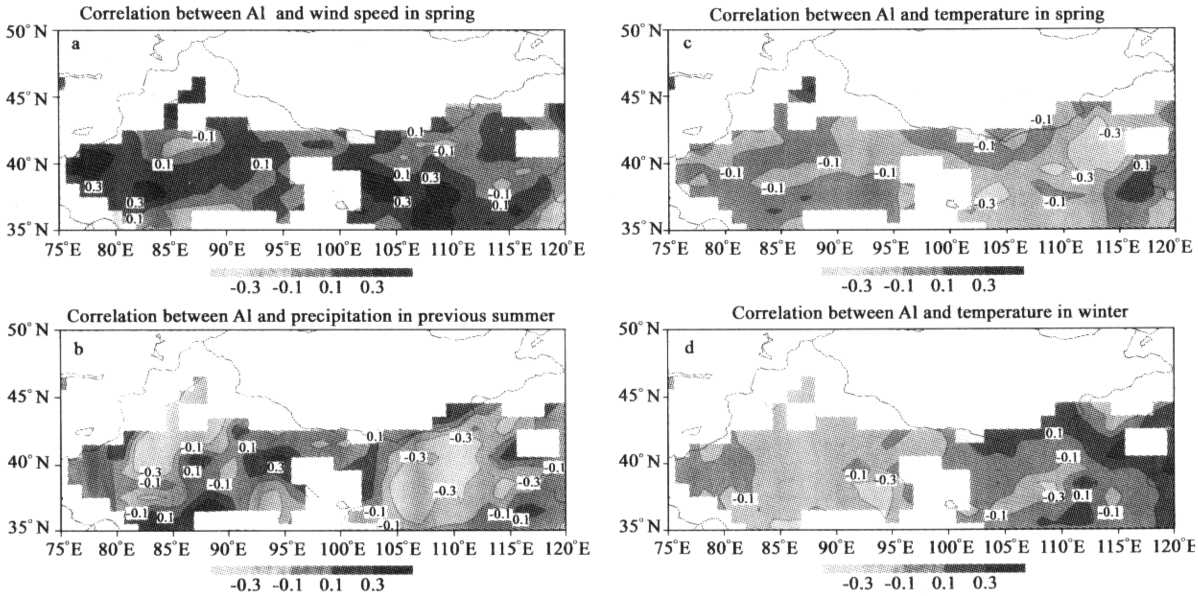

Fig.4 Spatial distribution map of correlation between *TOMS/AI* with wind speed, precipitation and temperature
a. Correlation between *AI* and wind speed in spring; b. correlation between *AI* and precipitation in previous summer; c. correlation between *AI* and temperature in spring; d. correlation between *AI* and temperature in winter

3 Discussion and conclusions

TOMS onboard the Nimbus 7 and EP satellite has accumulated valuable data for nearly 20 years that have played an important role in dust source identification and evaluation of chemical transportation models' competence etc. Combined the simultaneous climate data, *TOMS* aerosol data may uncover the potential mechanisms that control dust activities, just as we have carried out in the paper.

In our analysis based on *TOMS/AI* data, distinctive seasonal variation and spatial distribution of dust activity in North China have been shown. Climate factors such as wind speed, precipitation and temperature play a significant role in controlling dust activity, among which spatially consistent positive correlation between wind speed and *TOMS/AI* is distinct, but temperature and precipitation attain negative correlation with dust activity, although less consistent in space and significant than that of wind speed.

However, it is essential to keep firmly the disadvantages of *TOMS/AI* in mind, which mainly include *TOMS/AI* sensitivity to the height of aerosol layer above the ground, sub-pixel cloud contamination; in addition, relative short temporal coverage of *TOMS/AI* in comparison with nearly half century ground-based observations, undoubtedly, hampers analysis more quantitatively based on these data. So it is essential to extend the satellite monitoring data and improve monitoring quality. With the advent of new generation of space-borne radiometer for EOS (Earth Observing Science) such as MODIS and MISR and so on, more quantitative analyses are expected.

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