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Aerosol optical depth over the Tibetan Plateau and its relation to aerosols over the Taklimakan Desert

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[1] The Multiangle Imaging SpectroRadiometer (MISR) aerosol optical depths (AODs) over the Tibetan Plateau (TP) are compared with ground-based remote sensing data. The result shows that 27 out of 32 MISR AODs fall within the expected uncertainty, i.e., 0.05 or 20% × AOD. The mean bias and the root mean square error between ground and satellite AODs are 0.01 and 0.03, respectively. The 7-year MISR AOD data are used to study seasonal and inter-annual variations of AOD over the TP. The results show distinct seasonal variation, with seasonal AOD being 0.27, 0.25, 0.13 and 0.11 from spring to winter. AOD over the TP is closely related to that over the Taklimakan desert in summer; however poor correlation is observed in spring. Higher AOD in spring and summer over the TP merits further study, including its causes and implications for climate and environment.

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1. Introduction

[2] The Tibetan Plateau (TP) is a vast and elevated plateau in East Asia that extends over the area of 27°–45° N, 70°–105° E and its mean elevation is higher than 4000 m above sea level. The influence of the TP upon atmospheric circulation and climate through its mechanical as well as thermal forcing is early recognized [*Yeh et al.*, 1957; *Wu et al.*, 2007]. The elevated heating of the TP to the atmosphere plays a fundamental role in the formation and maintenance of the Asian monsoon system [*Wu et al.*, 2007]. Much attention has been paid to atmospheric chemistry over the TP since discoveries of Tibetan ozone valley [*Zhou and Luo*, 1994; *Zou*, 1996] and an ozone mini-hole over the TP [*Bian et al.*, 2006]. Active upwelling motion over the TP is an important factor contributing to the ozone minimum. Large adiabatic expansion of air mass along with the upwelling motion is also favorable for particle formation [*Tobo et al.*, 2007]. The heterogeneous chemistry on aerosol surfaces is an important mechanism influencing ozone; more importantly, aerosol has widely been recognized as an important climate-forcing agent via its direct and indirect effects [*Wang et al.*, 2001].

[3] In-situ measurements and ground-based remote sensing of aerosol have been carried out over the TP. Elemental compositions of aerosol at sites such as, for example, in Udaoliang, Lasha, and Gongga, were measured [*Zhang et al.*, 2000]. The average dust concentration at these sites was 82 μg m^{-3}, which was about 30% and 48% of that over the Chinese deserts and over the Loess Plateau, respectively. The concentrations of S and Pb in Mount Qomolangma region (28.19° N, 86.83° E) are 91.64 ng m^{-3} and 2.93 ng m^{-3}, respectively, indicating this region is rarely influenced by human activities and long-range transportation [*Zhang et al.*, 2001]. Measurements of vertical profiles of aerosols concentration using a balloon-borne optical particle counter at Lasha showed number concentration of sub-micron size aerosols with radii of 0.15 $\sim$ 0.16 was 0.7–0.8 particles cm^{-3} near the tropopause region (130–70 hPa) [*Tobo et al.*, 2007]. Short-term ground-based remote sensing aerosol optical depth in Lasha, showed that the daily average aerosol optical depth (AOD) at 500 nm was less than 0.2 during summer of 1998 [*Bai et al.*, 2000]. AOD at 600 nm measured at Dangxiong (30.50° N, 91.10° E) during May and June 1998 ranged from 0.02 to 0.12, with mean values being about 0.08 [*Zhang et al.*, 2000]. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite data, such as column-averaged volume depolarization and total volume color ratios, suggested that in summer frequent dust events occurred over remote northwestern Tibet where surface observation was very limited due to high elevation and harsh climate [*Huang et al.*, 2007]. Surface observation showed the annual days of dust storms were about 20 over the west Tibet region [*Bai et al.*, 2006].

[4] Satellite remote sensing is able to observe large, inaccessible high plateau regions. The objective of this study is to present seasonal and inter-annual variations of aerosol optical depth (AOD) using the Multiangle Imaging SpectroRadiometer (MISR) aerosol retrievals from May 2000 to May 2007. While spatio-temporal characteristics of aerosol over the TP were derived from Stratospheric Aerosol and Gas Experiment II (SAGE II) data [*Li and Yu*, 2001] and the Moderate Resolution Imaging Spectroradiometer data [*Jin*, 2006], current study differs in several ways. First, ground-based remote sensing data over the TP are used to validate the MISR aerosol retrievals at the first time. Second, only satellite aerosol retrievals over the TP are analyzed (27°–39° N, 76°–105° E and elevation >3000 m). Third, the potential influence of dust storms

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Table 1. MISR Version Numbers to Time Periods

Begin	End	Version
2000/03	2000/11	F02_0014
2001/12	2001/11	F06_0017
2001/12	2002/11	F06_0021
2002/12	2003/05	F02_0012
2003/06	2003/11	F09_0025
2003/12	2004/05	F02_0012
2004/06	2004/11	F09_0025
2004/12	2005/11	F06_0017
2005/12	2006/06	F06_0021
2006/07	F007/05	F13_0029

originated in Taklimakan Desert on AOD over the TP is discussed.

2. Data

[5] Ground-based remote sensing aerosol data employed in this study were acquired by the LED (light-emitting diode) hazemeter at two Chinese Ecological Research Network (CERN) sites over the TP since August 2004. One is Lhasa (91.33° E, 29.67° N) and the other is Haibei (101.32° E, 37.45° N). The AODs at four wavelengths (405, 500, 650 and 880 nm) are derived from hazemeters measurements from 10:00 to 14:00 local time. The hazemeter results are generally in good agreement with the CIMEL results with discrepancies on the order of 2% to 6% [*Xin et al.*, 2007].

[6] MISR is a push-broom camera instrument measuring the same point on Earth at 9 different along-track view angles (with 4 forward, one nadir and 4 aft cameras), and at four spectral bands (446, 558, 672 and 866 nm). Over a period of 7 min, as the MISR flies overhead, a 400-km-wide swath of Earth is viewed by each of MISR's nine cameras. Global coverage is obtained about once per week. Co-registered multi-angle and multi-spectral MISR data at 1.1 km^2 are used for aerosol processing. Aerosol retrievals are performed over 16 × 16 arrays of these 1.1 km pixels, comprising 17.6 × 17.6 km regions. For aerosol retrievals over heterogeneous land, ground reflectance is represented by the sum of empirical orthogonal functions (EOFs) that is computed from the measurements. Regional mean radiances are compared to the ground (sum of EOFs) and path radiance information from the Simulated MISR Ancillary Radiative Transfer (SMART) data. Chi-square statistical tests are performed to assess the residuals from comparison and aerosol properties from all models that satisfy a given set of criteria are reported as successful retrievals. A detailed description on the construction of EOFs and MISR aerosol retrieval are given by *Martonchik et al.* [1998, 2002].

[7] Hazemeter AOD data are firstly used to validate MISR aerosol level-2 data (MIL2ASAE, version F09_0017, F09_0018 and F10_0020) that are available from http://eosweb.larc.nasa.gov/PRODOCS/misr/table_misr.html. As recommended by the MISR team, the MISR aerosol parameters evaluated in this study are regional mean AODs (MISR parameter name: RegMeanSpectralOptDepth), which are averages, with equal weight, of the AOD obtained for all successful retrievals based on different mixtures of aerosol models. The seasonal and inter-annual variations of AOD over the TP are discussed based on daily MISR level-3 data with 0.5° × 0.5° resolution. Table 1 shows the versions of MISR level-3 AOD.

3. Results

3.1. Validation of MISR AOD

[8] The ground AODs are matched with the MISR retrievals in time and space following the method of *Kahn et al.* [2005]. The ground-based AODs at 405, 500, 650 nm from hazemeters are interpolated to the MISR channels. As shown in Figure 1, most collocated data points show an excellent agreement. The correlation coefficient is 0.81 and 27 out of total 32 data points are within the expected MISR uncertainty (i.e., maximum of 0.05 or 20% of AOD [*Kahn et al.*, 2005]). The mean bias is about 0.014 and the root mean square error (RMSE) is 0.035, respectively. The MISR AOD accuracy over the TP is apparently better than MODIS AOD. MODIS AOD is poorly correlated to hazemeter AOD over the TP, with the square of the correlation coefficient of about 0.1 [*Wang et al.*, 2007; *Li et al.*, 2007]. A comparison study by *Abdou et al.* [2005] showed that that over land, the MISR AOD retrievals compare better with AERONET when compared with MODIS AOD retrievals.

3.2. Spatio-Temporal Distribution of MISR AOD Over the TP

[9] Annual mean MISR AOD at 550 nm over the TP is 0.19 (±0.03). Figure 2 presents the monthly spatial mean MISR AOD over the TP. Seasonal variation of AOD is distinct that is characterized by one peak. Monthly AOD increases gradually from January to May or June, and then decreases gradually in the following months (see Table 2). The monthly MISR AOD ranges from about 0.05 to 0.40, however it ranged from about 0.2 to 0.5 for MODIS AOD [*Jin*, 2006]. This is likely due to overestimation of AOD by MODIS over bright surface [*Wang et al.*, 2007]. Seasonal mean MISR AODs are 0.27 and 0.25 in spring and summer,

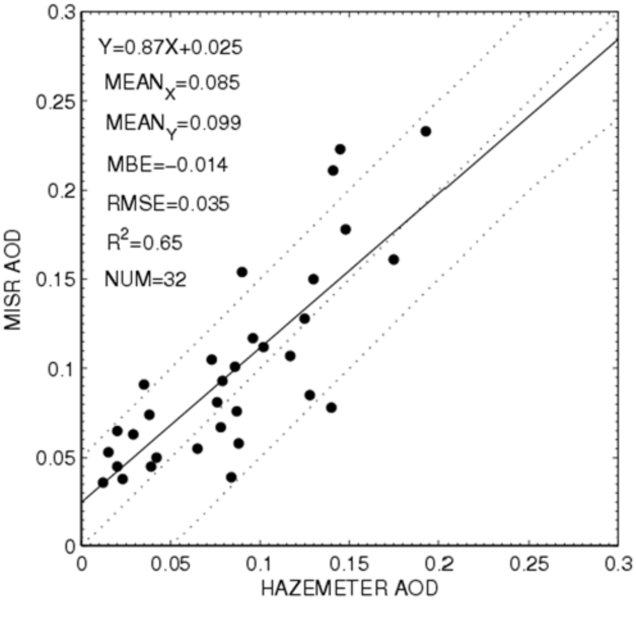

Figure 1. Comparison of MISR AOD with ground-based hazemeter measurements made at Lhasa and Haibei.

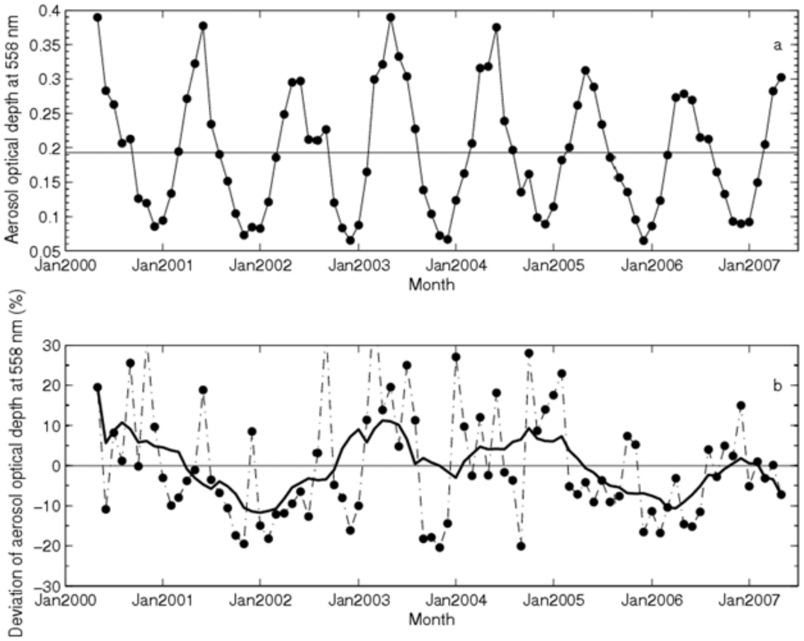

Figure 2. (a) Tibetan Plateau area-averaged MISR aerosol optical depth at 588 nm (averaged for aerosol retrievals available pixels over 76°–105° E and 35°–43° N and elevation higher than 3000 m). (b) Monthly percent departure of MISR aerosol optical depth at 588 nm from 7-year average (%).

respectively, which are more than twice that in autumn (0.13) and winter (0.11). Monthly MISR AOD percent departure from 7-year average from May 2000 to May 2007 is also shown in Figure 2. The solid line represents the 9-points smooth of the time series. The MISR AODs during 2000, 2003 and 2004 are generally larger than the multi-year averages, contrarily; most monthly MISR AODs during 2001 and 2005, 2006 and 2007 are not larger than the multi-year mean AODs. The monthly percent departure from 7-year mean AOD ranges from −20% to +30%. The MISR AOD shows a weak decreasing tendency during this period. Note that MISR AOD data have different version numbers (Table 1), therefore, the inter-annual variation of MISR AOD is likely influenced by the changes in the MISR retrieval algorithm.

[10] Figure 3 presents the spatial distribution of MISR AOD in four seasons. In spring, most MISR AODs exceed 0.35 in the eastern TP regions (east of 90° E), the area of the sources of the three great rivers, i.e., the Yangtze River, the Yellow River and the Lancang River. Surface observations in this region show that the annual days with dust events are more than 10 days [*Bai et al.*, 2006]. The situation has been getting worse for years due not only to the climate change but also to damage by human activities [*Duan and Wu*, 2006]. MISR AODs at the southwestern edge (at the north of Mount Qomolangma) are about 0.35 that is obviously higher than the northern adjacent regions. This is in accordance with the surface observations that show frequent dust storms, for example, the annual days of dust events are close 20 days at Shiquanhe (32.5° N, 80° E). Spring MISR AODs in northern TP (regions adjacent to the Taklimakan Desert and the Qaidam Desert are larger than 0.25.

[11] Summer MISR AODs in most regions of eastern TP is close to 0.10, indicating rare occurrence of dust storms in this season. In the north slope of the TP, summer MISR AODs are still very high and even exceed 0.4. The MISR AOD decreases generally from north to south.

[12] The MISR AODs over the TP are close to the background level in autumn and winter. AODs in the north slope of the TP are still larger than that in other regions of the TP.

3.3. Relation Between AOD at the Taklimakan Desert and that Over the TP

[13] *Huang et al.* [2007] pointed out that dust aerosols originated from the Taklimakan Desert in summer could accumulate over the northern slopes of the TP where MISR AODs show relatively higher values in spring and summer. Monthly MISR AOD percent departures over the Taklimakan Desert are compared with those over the TP or the northern slope of the TP (north of 35°N) in spring and summer, respectively. Spring MISR AODs over the TP and the

Table 2. Monthly Mean MISR AOD (μ) and One Standard Deviation (σ) Over the TP

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
μ	0.10	0.15	0.21	0.28	0.32	0.32	0.23	0.20	0.17	0.13	0.09	0.08
σ	0.02	0.02	0.04	0.03	0.05	0.05	0.03	0.01	0.04	0.02	0.02	0.01

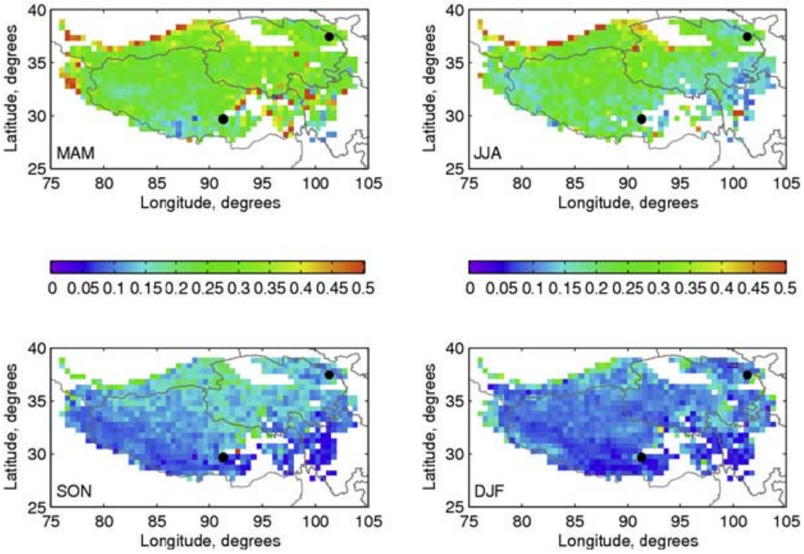

Figure 3. Spatial distribution of 7-year averaged MISR aerosol optical depth at 588 nm for four seasons. The filled black dots represent Lhasa and Haibei.

northern slope of the TP (north of 35°N) are poorly correlated to AOD over the Taklimakan Desert (Figure 4a). Given that local dust storms occur frequently over the TP in spring [*Bai et al.*, 2006], this is likely the dominant cause for the higher AOD in this season. Thus, it is expected that the inter-annual variations of MISR AOD in spring over the TP be dominantly determined by changes in local dust emission and the influence of Taklimakan dust storm plays a negligible role. On the contrary, good positive correlation between MISR AOD over the TP and in the Taklimakan Desert has been obtained in summer (Figure 4b). The inter-annual variations of summer MISR AOD in the Taklimakan Desert can explain 46% of that over the TP. Local dust storm over the TP is rarely observed in summer from surface observation [*Bai et al.*, 2006]. Higher AOD over the TP, especially over the northern TP region in summer, is thus mainly due to the transport of dust aerosols from the Taklimakan Desert. In that case, it is not surprising that the inter-annual variations of dust emission in the Taklimakan Desert partly determine the inter-annual changes in aerosol loading over the TP in summer.

4. Conclusions

[14] 7-year MISR AOD data over the TP are used to study seasonal and inter-annual variations of aerosol loading over this key region. The main conclusions are as following.

[15] Comparison of ground-based remote sensing and satellite AOD retrievals shows that MISR AOD product has good accuracy over the TP. The mean bias and the root mean square error of MISR AOD are 0.01 and 0.03, respectively.

[16] AOD over the TP shows distinct seasonal variation with one peak occurred in May or June. Seasonal mean AODs are 0.27 and 0.25 in spring and summer, respectively. The values are more than twice that in autumn (0.13) and winter (0.11). AOD over the TP shows significant inter-

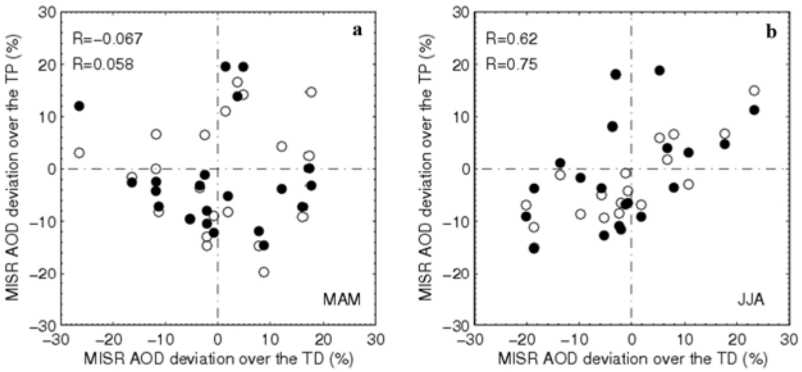

Figure 4. Relationships between area-averaged MISR aerosol optical depth at 588 nm over the Tibetan Plateau (filled) and the north of the Tibetan Plateau (unfilled) to that in Taklimakan Desert in (a) spring and (b) summer.

annual variation and the monthly percent departure ranges from −20% to +30%.

[17] Spring MISR AODs over the TP tend to be controlled by local dust storms; however, transportation of dust aerosols originated from the Taklimakan Desert is likely to be important factor determining inter-annual variation of AODs over the TP in summer.

[18] Relatively higher occurrences of dust storms in spring and transportation of dust aerosols from adjacent dust source regions to the TP suggest much attention should also be paid to aerosol in the TP. Further analysis is required to study effects of aerosols on radiative budget and atmospheric chemistry in this key region.

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