Spatiotemporal Variation Characteristics of Aerosol Optical Depth in Xinjiang from 2003-2019: Postprint

Authors: Yu Zhixiang, Li Xia

Date: 2022-04-12T00:00:00+00:00

Abstract

Based on Xinjiang atmospheric aerosol optical depth (Aerosol opt ical depth, AOD) products retrieved from MODIS Aqua Aerosol L2 data during 2003–2019, CE-318 sunphotometer observations from the Urumqi ground-based station of the Chinese aerosol optical property network (Chinese aerosol optical property network, CAOPNET) operated by the China Meteorological Administration were selected for comparative validation against MODIS AOD data. Employing Spearman rank correlation test, we investigated the annual mean variation of AOD in Xinjiang over the past 17 years, extracted 14 AOD high-value zones to analyze their interannual linear trends, and ultimately characterized the spatiotemporal variation patterns of AOD in Xinjiang over this period. The results demonstrate that: (1) MO DIS AOD and CAOPNET AOD exhibit strong correlation, with a correlation coefficient (r) of 0.6381, and 65% of data points fall within the expected error (Expect ed error, EE). Comparison between MODIS AOD products and CAOPNET AOD data indicates that MODIS AOD products achieve relatively high retrieval accuracy in Xinjiang. (2) During 2003–2019, AOD distribution in Xinjiang shows pronounced regional disparities, with mean values in southern Xinjiang significantly exceeding those in northern Xinjiang. The primary high-value zone is located in the Tarim Basin of southern Xinjiang, where annual mean values at the basin margins surpass 0.6, while the secondary high-value zone lies in the economic belt along the northern Tianshan slopes, with annual mean values exceeding 0.3. Throughout 2003–2019, except for significant AOD increases in Shihezi and the Urumqi-Changji region, most areas of Xinjiang show no evident AOD trend. (3) Seasonal AOD differences in Xinjiang during 2003–2019 are highly significant, generally following the pattern spring > summer > winter > autumn. Southern Xinjiang exhibits greater seasonal mean AOD variation than northern Xinjiang. (4) The monthly mean AOD range in Xinjiang is 0.11~0.51, displaying an overall unimodal variation pattern with monthly increases from January to April followed by monthly decreases from May to December. Monthly mean AOD peaks in April and reaches its minimum in December. These findings can provide scientific support for atmospheric environmental management and future pollution prevention and control efforts in Xinjiang.

Full Text

Spatiotemporal Variation Characteristics of Aerosol Optical Depth in Xinjiang from 2003 to 2019

YU Zhixiang[1,2], LI Xia[1], YU Xiaojing[3,4], ZHENG Yu[5], Manlen AYITKEN[1], LI Shuting[1], WANG Nan[1]

[1] Institute of Desert Meteorology, Chinese Meteorological Administration, Urumqi 830002, Xinjiang, China

[2] Urumqi Meteorological Satellite Ground Station, Urumqi 830011, Xinjiang, China

[3] LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

[4] University of the Chinese Academy of Sciences, Beijing 100049, China

[5] Institute of Atmospheric Composition and Environmental Meteorology, Chinese Academy of Meteorological Sciences, Beijing 100081, China

Abstract: Aerosol optical depth (AOD) represents the vertical integration of the aerosol extinction coefficient and serves as a crucial indicator of air pollution levels. This study investigates the spatiotemporal variation characteristics of AOD in Xinjiang, China from 2003 to 2019 using MODIS Aqua Aerosol L2 products. The MODIS AOD data were first validated against ground-based observations from the Chinese Aerosol Optical Property Network (CAOPNET) at the Urumqi station, yielding a correlation coefficient of 0.6381 and meeting the expected error criteria. The Spearman rank correlation test was then employed to analyze annual linear trends, and fourteen key AOD regions were extracted for detailed trend analysis. The results reveal pronounced regional disparities in AOD climatology across Xinjiang, with substantially higher values in southern Xinjiang compared to northern Xinjiang. The primary high-value center is located in the Tarim Basin of southern Xinjiang, where annual mean AOD exceeds 0.6, primarily attributable to frequent dust events. A secondary high-value zone occurs along the economic belt on the northern slope of the Tianshan Mountains, with mean values around 0.3, reflecting the combined influence of anthropogenic activities and natural sources. Seasonally, AOD peaks in spring (0.45) and reaches its minimum in autumn (0.15). The seasonal amplitude is more pronounced in southern Xinjiang due to dust activity. Monthly mean AOD exhibits a unimodal pattern, increasing from January to April and decreasing from May to December, with values ranging from 0.11 to 0.51. Long-term trend analysis indicates increasing AOD over the economic belt along the northern Tianshan slope, particularly in the Shihezi and Urumqi-Changji regions, while desert areas show decreasing trends. These findings provide a scientific basis for

atmospheric environmental management and future pollution prevention strategies in Xinjiang.

Keywords: MODIS; aerosol optical depth (AOD); sun photometer; distribution characteristics; variation trend

---

1 Introduction

Aerosols refer to liquid or solid particles suspended in the atmosphere with diameters ranging from 0.001 to 100 m. They can be categorized by source into natural and anthropogenic origins, with influencing factors similarly divided into natural and social components. Natural factors primarily include natural emissions (dust, sea salt, mineral particles, volcanic ash) and meteorological conditions (temperature, precipitation, humidity), while social factors encompass population density, economic development, vehicle emissions, fossil fuel combustion, and biomass burning. As a vital atmospheric constituent, aerosols alter solar radiation reaching the surface through multiple scattering and absorption processes. Additionally, serving as cloud condensation nuclei, they modify cloud radiative properties and lifecycles, thereby indirectly affecting regional climate. Investigating aerosol distribution characteristics at global and regional scales is essential for understanding their roles in ecological environments, climate change, air quality, human health, and the relationship between fine particulate matter and energy balance.

Aerosol optical depth (AOD) represents a fundamental optical parameter of aerosols, defined as the vertical integration of the aerosol extinction coefficient. It enables calculation of aerosol content, determination of aerosol size, and assessment of aerosol climate effects, thereby reflecting regional atmospheric pollution levels and types to a certain extent. Among various aerosol data sources, satellite remote sensing provides the most extensive spatial coverage and relatively accurate measurements. Current AOD datasets include ground-based observations and satellite retrievals. While ground-based measurements offer high accuracy, they suffer from poor temporal and spatial continuity. In contrast, satellite remote sensing provides continuous observations with broad coverage, offering significant advantages for regional-scale studies.

In recent years, numerous studies have examined AOD spatiotemporal distribution across China. At the national scale, AOD exhibits distinct regional variations, generally decreasing from east to west and from north to south. The maximum and minimum values vary by location. Between 2000 and 2015, increasing AOD trends were observed over the Tibetan Plateau, western Sichuan Basin, northern Guizhou, the middle and lower Yangtze River regions, Shandong Peninsula, and western Tarim Basin. Conversely, decreasing trends occurred across most of Northeast China, Northwest China, the Yunnan-Guizhou Plateau, western Guangxi, and the East China coast. The 2018 China Eco-Environmental Status Bulletin reported that, without excluding dust impacts, only 33.7% of 338 prefecture-level cities met national ambient air quality standards, with average $PM_{2\cdot5}$ and PM_{10} concentrations of 41 g·m^{-3} and 78 g·m^{-3}, respectively. In Xinjiang, only 9 out of 19 cities achieved air quality compliance, representing 21.1% with average $PM_{2\cdot5}$ and PM_{10} concentrations of 147 g·m^{-3} and 54 g·m^{-3}—substantially higher than national averages. With only 19 national-level air quality monitoring stations, Xinjiang' s current observation network is insufficient to fully characterize atmospheric pollutant distribution patterns, creating bottlenecks for implementing the "Three Lines and Single Permit" ecological environmental zoning control scheme.

Xinjiang' s arid and semi-arid climate, complex terrain, and underlying surface conditions make it particularly vulnerable to particulate pollution. The Taklamakan and Gurbantünggüt Deserts, located north and south of the Tianshan Mountains respectively, serve as natural dust emission sources. The "three mountains 夹 two basins" topography facilitates temperature inversion formation in winter, hindering exchange between upper and lower atmospheric layers and impeding pollutant dispersion, particularly in northern Xinjiang cities. Previous studies have validated MODIS AOD fusion products using AERONET ground-based data in Northwest China, demonstrating good coverage and high accuracy for regional aerosol optical property research. The latest MODIS Collection 6.1 AOD product shows improved performance globally compared to Collection 6, with strong correlations between AOD and ground-level $PM_{2\cdot5}$ concentrations or air quality indices in arid and semi-arid regions. Therefore, this study employs MODIS Collection 6.1 AOD data to investigate long-term spatiotemporal distribution characteristics in Xinjiang, providing scientific support for atmospheric environmental management and pollution prevention strategies.

---

2 Data and Methods

2.1 Study Area

Xinjiang is located in central Eurasia, in the northwestern border region of China, covering 1.66$\times10^{6}$ km^2 and representing the largest provincial administrative area in the country. The terrain can be summarized as "three mountains 夹 two basins" (Fig. 1). The Altay Mountains form the northern boundary, the Kunlun Mountains the southern boundary, and the Tianshan Mountains traverse the center, dividing Xinjiang into southern and northern regions. The Junggar Basin in northern Xinjiang (38$\times10^{4}$ km^2) contains the Gurbantünggüt Desert, while the Tarim Basin in southern Xinjiang (52.34$\times10^{4}$ km^2) holds the Taklamakan Desert—the largest desert in China and the second-largest shifting sand desert globally. Dust aerosols thus dominate southern Xinjiang' s atmospheric composition, significantly impacting regional climate and human activities. Xinjiang' s oases are primarily distributed along basin margins and dry river valleys, covering 14.3$\times10^{4}$ km^2 (8.6% of the total area). Precipitation is scarce and unevenly distributed, with annual averages of

150–200 mm in northern Xinjiang and <100 mm in southern Xinjiang, characterizing a temperate continental arid climate.

Administratively, Xinjiang comprises 14 prefecture-level units: 5 autonomous prefectures (Ili Kazakh, Bortala Mongol, Changji Hui, Bayingolin Mongol, and Kizilsu Kirgiz), 5 prefectures (Altay, Tacheng, Aksu, Kashgar, and Hotan), and 4 prefecture-level cities (Urumqi, Karamay, Turpan, and Hami). The Urumqi-Changji-Shihezi (U-Chang-Shi) urban agglomeration, a key regional city cluster developed by the national government, is located on the northern slope of the Tianshan Mountains and the southern margin of the Junggar Basin. This region covers only 6.38$\times10^{4}$ km^2 (3.8% of Xinjiang' s area) but concentrates over 50% of the urban population and generates approximately 70% of the regional GDP. High population density and intensive human activities create complex aerosol distribution patterns in this area.

2.2 Data Sources

The MODIS Aqua Aerosol 5-Min L2 Swath product (MOD04_{L2}) from NASA provides high-accuracy AOD retrievals widely used in scientific research. Zhao et al. validated MODIS AOD fusion products against AERONET sun photometer data in Northwest China, confirming their applicability. Wu et al. demonstrated that MODIS AOD retrievals achieve highest accuracy in China' s desert regions. The MODIS AOD product is a daily aerosol dataset providing retrievals from three algorithms: Deep Blue (DB), Dark Target (DT), and Combined (C6.1). The DT algorithm, based on the relationship between visible and infrared reflectance over dark vegetated surfaces, works well for low-albedo areas but cannot retrieve AOD over bright surfaces like deserts. The DB algorithm assumes blue-band surface reflectance is much lower than other bands over bright targets, enabling AOD retrieval over high-albedo surfaces. The C6.1 fusion algorithm integrates both approaches using Normalized Difference Vegetation Index (NDVI) thresholds: DT for NDVI > 0.3, DB for NDVI < 0.2, and the average of both for $0.2 \leq$ NDVI ≤ 0.3, maximizing coverage and accuracy over complex surfaces.

This study uses MODIS Collection 6.1 AOD data at 550 nm wavelength from March 2003 to December 2019, with a spatial resolution of 0.1°$\times$0.1°. Data preprocessing included geometric correction, mosaicking, and subsetting to generate daily gridded datasets. Seasons are defined as: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

2.3 Methods

2.3.1 Spearman Rank Correlation Test The Spearman rank correlation test was employed for time series trend analysis and significance testing. For a time series x_1, x_2, ⋯, x , values are ranked in descending order and assigned ranks R . The rank correlation coefficient (r) is calculated as:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)}$$

where n is sample size and d is the difference between ranks. According to critical value tables, when n = 17 and significance level $\alpha = 0.05$, the threshold is r $_{0 \cdot 05}$ = 0.485. Trends are considered significant when |r | > 0.485, with r > 0 indicating increasing trends and r < 0 indicating decreasing trends.

2.3.2 AOD Product Validation To confirm MODIS AOD applicability in Xinjiang, we compared it with ground-based CE-318 sun photometer data from the CAOPNET Urumqi station. The sun photometer measures at 380, 440, 500, 670, 870, and 1020 nm. AOD at 550 nm was obtained through Ångström exponent interpolation:

$$\tau_{550} = \tau_{500} \times \left(\frac{550}{500}\right)^{-\alpha_{500-670}}$$

where $\alpha_{500\ 670}$ is the Ångström exponent between 500-670 nm, calculated as:

$$\alpha_{500-670} = -\frac{\ln(\tau_{500}/\tau_{670})}{\ln(500/670)}$$

Validation used a temporal window of $±$30 minutes and spatial window of 50 km × 50 km around the station. From 2013-2017, 65 valid matchups were obtained (Fig. 2). The correlation coefficient (r) of 0.6381 and expected error (EE) envelope of $\pm(0.05 + 0.15\tau)$ show that 65% of data fall within EE, confirming good accuracy and applicability of MODIS AOD in Xinjiang.

---

3 Results and Analysis

3.1 Spatial Distribution of Annual Mean AOD

The annual mean AOD shows significant regional disparities (Fig. 3), strongly influenced by underlying surface conditions. Northern Xinjiang exhibits lower values overall, with high-value areas from west to east including Yining (0.28), Bole (0.27), and the Urumqi-Changji-Shihezi (U-Chang-Shi) region (0.31). The southern Tianshan slope economic belt shows elevated AOD due to dense population, concentrated heavy industry (70% of Xinjiang’ s total), and high urbanization levels, which significantly impact aerosol distribution. Previous studies demonstrate positive correlations between AOD and $PM_{2 \cdot 5}$ concentrations in this region. The Turpan Basin also shows high AOD due to terrain-trapped pollutants.

Southern Xinjiang displays markedly higher AOD than northern Xinjiang, with an arc-shaped high-value zone (>0.6) around the Tarim Basin margin. Clockwise from the eastern basin, this includes Ruoqiang (0.62), Minfeng (0.61), Hotan (0.60), Yarkant River basin (0.58), Kashgar (0.56), Kuqa-Shaya-Xinhe area (0.55), and Yanqi Basin (0.54). These regions experience frequent dust events with low vegetation coverage and minimal precipitation, resulting in weak aerosol removal. The Taklamakan Desert' s southern and northern boundaries are blocked by the Kunlun and Tianshan Mountains, while the western side connects to the Pamir Plateau. Northern and northwestern airflow enters the Tarim Basin through eastern Tianshan passes, generating dust storms under thermal and topographic forcing, creating persistently high AOD values.

3.2 Seasonal Distribution Characteristics

Seasonal AOD variations are highly significant (Fig. 4), with spring (0.45) > summer (0.29) > winter (0.21) > autumn (0.15). Southern Xinjiang shows greater seasonal amplitude than northern Xinjiang due to dust event frequency.

Spring is the dust season in Xinjiang. Under dust source influences, the Taklamakan and Kumtag Deserts exhibit widespread high AOD. Northern Xinjiang also shows elevated AOD along the Tianshan northern slope due to strong winds, low precipitation, and ongoing heating periods that limit atmospheric diffusion. High-value centers appear in Yining, the Dushanzi-Kuitun-Urumqi (DKU) area, Shihezi, and the U-Chang-Shi region. Central Junggar and Turpan Basins show high AOD due to topographic trapping.

Summer AOD decreases significantly from spring levels. The extensive high-AOD area over central Tarim Basin disappears, leaving only an arc-shaped zone along the eastern-southeastern margin. Northern Xinjiang AOD also declines substantially, though the DKU area, Shihezi, U-Chang-Shi region, and Turpan Basin maintain relatively high values (0.29–0.31). Despite increased summer precipitation and vegetation, arid and semi-arid surfaces remain natural particle sources.

Autumn AOD reaches its annual minimum with uniform spatial distribution. The Tarim Basin's arc-shaped high-value zone largely disappears, and differences between southern and northern Xinjiang diminish, coinciding with reduced dust frequency.

Winter AOD increases from autumn levels, with significant north-south differences. Most of Xinjiang shows AOD between 0.18–0.29. The DKU area, Shihezi, and Urumqi exhibit notably high values due to heating emissions. Snow cover in northern Xinjiang increases surface albedo, affecting AOD retrieval and limiting data availability. Southern Xinjiang shows increased AOD from November to December due to dust events, forming a Tarim Basin-centered high-value zone that diminishes as dust frequency decreases in January–February.

3.3 Monthly Distribution Characteristics

Monthly mean AOD shows a unimodal pattern (Fig. 5), increasing from January to April and decreasing from May to December, with values ranging 0.11–0.51. Peak AOD occurs in April (0.51), while the minimum occurs in December (0.11). North-south differences are most pronounced in April. From January to April, AOD increases across the Tianshan northern slope from west to east, with the DKU area, Shihezi, and Urumqi showing values >0.4. Southern Xinjiang' s Ruoqiang area exhibits AOD >0.6. From May to August, AOD decreases significantly, with the Tarim Basin' s high-value zone shrinking to its southeastern margin. September–October AOD remains at annual minima with uniform distribution. November–December AOD increases again, particularly in the DKU area and U-Chang-Shi region, where heating emissions contribute substantially to atmospheric pollution.

3.4 Temporal Variation Trends

3.4.1 Annual Mean Variation Monitoring Annual mean AOD distributions from 2003–2019 (Fig. 6) show values ranging 0.19–0.31. The maximum occurred in 2008 (0.31) and the minimum in 2019 (0.19). High-value centers were concentrated along the Tianshan northern slope economic belt and the southeastern Tarim Desert. From 2003–2008, AOD showed an increasing trend, with high-value zones expanding. During 2009–2014, AOD exhibited alternating decreasing and increasing patterns with no clear overall trend. From 2015–2019, AOD decreased significantly, with high-value zones markedly reduced.

3.4.2 Annual Mean Trend Analysis To quantitatively assess AOD trends, Spearman rank correlation tests were applied to each pixel (Fig. 7). The correlation coefficient map was density-sliced into five categories: significant decrease ($-1.000 < r < -0.485$), insignificant decrease ($-0.485 \leq r < 0.000$), insignificant increase ($0.000 < r \leq 0.485$), and significant increase ($0.485 < r < 1.000$). Significant decreasing trends occur primarily in northern Altay and southwestern Kashgar, while most of southern Xinjiang shows insignificant decreasing trends. Significant increasing trends concentrate in the Tianshan northern slope economic belt.

Fourteen key regions were selected for detailed trend analysis (Fig. 8, Table 2). Results show increasing trends in Yining, Bole, DKU area, Shihezi, U-Chang-Shi region, and Yanqi Basin, while decreasing trends occur in Turpan Basin, Kuqa-Shaya-Xinhe area, Aksu, Kashgar, Yarkant River basin, and Ruoqiang. Only Shihezi and U-Chang-Shi regions show statistically significant increases ($|r| > 0.485$), emerging as new high-value centers alongside traditional Tarim Basin dust sources.

4 Conclusions

This study analyzed spatiotemporal variation characteristics of AOD in Xinjiang from 2003–2019 using MODIS Collection 6.1 data. Key findings include:

1. **Data Validation:** MODIS AOD shows good correlation (r = 0.6381) with CAOPNET sun photometer data in Urumqi, with 65% of retrievals falling within expected error, confirming high accuracy and applicability in Xinjiang.

2. **Spatial Distribution:** AOD exhibits significant regional differences, with southern Xinjiang values substantially higher than northern Xinjiang. The primary high-value center in the Tarim Basin (mean AOD > 0.6) results from frequent dust events. A secondary high-value zone along the Tianshan northern slope economic belt (mean AOD 0.3) reflects combined natural and anthropogenic influences.

3. **Seasonal Variation:** Seasonal differences are pronounced, following spring (0.45) > summer (0.29) > winter (0.21) > autumn (0.15). Southern Xinjiang shows greater seasonal amplitude than northern Xinjiang due to dust activity.

4. **Monthly Variation:** Monthly mean AOD displays a unimodal pattern, increasing from January to April and decreasing from May to December (range: 0.11-0.51), peaking in April and reaching minimum in December.

5. **Long-term Trends:** AOD shows increasing trends in the Tianshan northern slope economic belt, with statistically significant increases in Shihezi and U-Chang-Shi regions, while desert areas exhibit decreasing trends.

These results enhance understanding of Xinjiang' s atmospheric environment and provide scientific guidance for environmental governance and pollution prevention.

References

[1] Li Chengcai, Mao Jietai, Liu Qihan, et al. Application of MODIS AOD products in the study of air pollution in Beijing[J]. Science in China (Series D), 2005, 35(Suppl. 1): 177-186.

[2] Wu Bangcan, Fei Long. Modern environmental monitoring technology[M]. Beijing: China Environmental Science Press, 2014.

[3] Kaiser D P, Qian Y. Decreasing trends in sunshine duration over China for 1954–1998: Indication of increased haze pollution?[J]. Geophysical Research Letters, 2002, 29(21): 381-384.

[4] Rosenfeld D, Dai J, Yu X, et al. Inverse relations between amounts of air pollution and orographic precipitation[J]. Science, 2007, 315(5817): 1396-1398.

[5] Cao J J, Chow J C. Recent advances for aerosol and environment study in Asia[J]. Particuology, 2013, 11(1): 3-4.

[6] Zhang Hua, Huang Jianping. An interpretation of man-made and natural radiative forcing in IPCC Fifth Assessment Report[J]. Climate Change Research, 2014, 10(1): 40-44.

[7] Van Zelm R V, Huijbregts M A J, Hollander H A Den, et al. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment[J]. Atmospheric Environment, 2008, 42: 441-453.

[8] He Q, Huang B. Satellite-based mapping of daily high-resolution ground PM2.5 in China via space-time regression modeling[J]. Remote Sensing of Environment, 2018, 206: 72-83.

[9] Huang Guan, Liu Wei, Liu Zhihong, et al. Spatio-temporal characteristics of aerosol optical depth in north Xinjiang[J]. Journal of Ecology and Rural Environment, 2015, 31(3): 286-292.

[10] Xia X, Chen H, Li Z, et al. Significant reduction of surface solar irradiance induced by aerosol in a suburban region in northeastern China[J]. Journal of Geophysical Research, 2007, 112(D22): 928-938.

[11] Li S, Chen L, Xiong X, et al. Retrieval of the haze optical thickness in North China Plain using MODIS data[J]. IEEE Transactions on Geoscience & Remote Sensing, 2013, 51(5): 2528-2540.

[12] Luo Yunfeng, Li Weiliang, Zhou Xiuji. Analysis of the 1980s atmospheric aerosol optical depth over China[J]. Acta Meteorologica Sinica, 2001, 59(1): 77-87.

[13] Luo Yunfeng, Lü Daren, Zhou Xiuji, et al. Analyses on the spatial distribution of aerosol optical depth over China in recent 30 years[J]. Chinese Journal of Atmospheric Sciences, 2002, 26(6): 721-730.

[14] Xie Yunxing, Tang Xiao, Guo Yuhong, et al. Spatial and temporal distribution of atmospheric particulate matter in Xinjiang[J]. Environmental Monitoring in China, 2019, 35(1): 26-36.

[15] Zhao Keming, Li Na, Li Xia, et al. Characteristic analysis of atmospheric diffusion conditions of winter foehn weather process in Urumqi City[J]. Arid Land Geography, 2021, 44(6): 1534-1544.

[16] Li X, Xia X, Wang L, et al. The role of foehn in the formation of heavy air pollution events in Urumqi, China[J]. Journal of Geophysical Research, 2015, 120: 5371-5384.

[17] Li X, Xia X, Zhong S, et al. Shallow foehn on the northern leeside of Tianshan Mountains and its influence on atmospheric boundary layer over Urumqi, China: A climatological study[J]. Atmospheric Research, 2020, 240: 104940.

[18] Ministry of Ecology and Environment of the People' s Republic of China. China eco-environmental quality report 2018[EB/OL]. [2019-05-29]. http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/201912/t20191231_{754139}.html.

[19] Department of Ecological Environment of Xinjiang. Xinjiang environmental quality report 2018[EB/OL]. [2019-06-11]. http://sthjt.xinjiang.gov.cn/xjepd/hjzkgb/202001/ad13302dfddb40f

[20] Zhang Xiya, Hu Haibao. Spatio-temporal characteristics of aerosol optical depth and their relationship with urbanization over Beijing-Tianjin-Hebei region[J]. Chinese Journal of Atmospheric Sciences, 2017, 41(4): 797-810.

[21] Wang Chenying, He Muquan, Chen Junhui, et al. Temporal and spatial variation characteristics of MODIS aerosol optical depth in Sichuan Basin from 2006 to 2017[J]. Research of Environmental Sciences, 2020, 33(1): 54-62.

[22] Wang Jiechun, Deng Yujiao. Spatial-temporal characteristics of aerosol optical depth in Guangdong based on MODIS C6 data[J]. Meteorological Science and Technology, 2018, 46(4): 809-813.

[23] Zhao Hui, Zheng Youfei, Xu Jingxin, et al. Variation characteristics of air pollutant concentrations in Urumqi[J]. Environmental Chemistry, 2016, 34(11): 2118-2126.

[24] Hu Jun, Zhong Ke, Kang Yanming, et al. Variation in aerosol optical depth over the typical cities in the Xinjiang region[J]. China Environmental Science, 2019, 39(10): 4074-4081.

[25] Huang Guan, Liu Wei, Liu Zhihong, et al. Relationship between MODIS aerosol optical depth and PM10 ground concentration in Urumqi[J]. Acta Scientiae Circumstantiae, 2016, 36(2): 649-657.

[26] Fu Hongchen, Sun Yanling, Chen Li, et al. Temporal and spatial distribution characteristics of PM2.5 and PM10 in Xinjiang region in 2016 based on AOD data and GWR model[J]. Acta Scientiae Circumstantiae, 2020, 40(1): 27-35.

[27] Sun Xiaoyun, Fang Yanjie, Zhao Jingfeng, et al. Spatial and temporal distribution characteristics of sand drift potential in Taklimakan Desert[J]. Arid Land Geography, 2020, 43(1): 38-47.

[28] Yue Hui, Liu Ying, Zhang Yuanmin. Study on temporal and spatial variability of aerosol optical depth in China region based on MODIS data[J]. Environmental Pollution & Control, 2020, 42(1): 89-93.

[29] Liu Zunchi. The occurrence and development of sand dust weather in the typical area of southern Xinjiang, China[D]. Shihezi: Shihezi University, 2016.

[30] Jia Rui, Li Jun, Zhu Qingzhe, et al. Three-dimensional distribution and causes of aerosols over northwest China[J]. Journal of Desert Research, 2021, 41(3): 34-43.

[31] Tan Ting, Wang Tianzhu. Analysis on spatial and temporal characteristics and circulation background of dust weather in Tarim Basin in summer from

1961 to 2015[J]. Journal of Institute of Disaster Prevention, 2020, 22(3): 69-76.

[32] Li Zhongbin, Wang Nan, Zhang Zili, et al. Validation and analyzation of MODIS aerosol optical depth product over China[J]. China Environmental Science, 2020, 40(10): 4190-4204.

[33] Imani Maryam. Particulate matter (PM2.5 and PM10) generation map using MODIS Level-1 satellite images and deep neural network[J]. Journal of Environmental Management, 2021, 281: 111888.

[34] Wei J, Li Z Q, Sun L, et al. An improved merge schemes for MODIS Collection 6.1 Dark Target and Deep Blue combined aerosol products[J]. Atmospheric Environment, 2019, 202: 315-327.

[35] Levy R, Mattoo S, Munchak L, et al. The Collection 6 MODIS aerosol products over land and ocean[J]. Atmospheric Measurement Techniques, 2013, 6(11): 159-259.

[36] Chen Peng, Zhang Qing, Li Yue. Analysis on correlation between MODIS aerosol optical depth values and air quality indices in Urumqi[J]. Desert and Oasis Meteorology, 2018, 12(2): 71-77.

[37] Zhao Shiwei, Gao Xiaoqing. Analysis of spatio-temporal distribution and variation characteristics of aerosol optical depth over the northwest of China by MODIS C6 product[J]. Environmental Science, 2017, 38(7): 2637-2646.

[38] Kaufman Y J, Wald A E, Remer L A, et al. The MODIS 2.1 channel correlation with visible reflectance for use in remote sensing of aerosol[J]. IEEE Transactions on Geoscience and Remote Sensing, 1997, 35(5): 1286-1298.

[39] Wei J, Li Z, Peng Y, et al. MODIS Collection 6.1 aerosol optical depth products over land and ocean: Validation and comparison[J]. Atmospheric Environment, 2018, 201: 428-440.

[40] Wang Y, Yuan Q, Li T, et al. Evaluation and comparison of MODIS Collection 6.1 aerosol optical depth against AERONET over regions in China with multifarious underlying surfaces[J]. Atmospheric Environment, 2019, 200: 280-301.

[41] Liu Xinchun, Chen Hongna, Zhao Kelei, et al. Analysis the effect and source on water soluble ions of fine particulate matter (PM2.5) in Urumqi[J]. Ecology and Environmental Sciences, 2015, 24(12): 2002-2008.

[42] Zheng Xiaobo, Zhou Chengxia, Luo Yuxiang, et al. Chinese province-level variations and trends in aerosol optical depth from recent 10 years of remote sensing data[J]. Ecology and Environmental Sciences, 2011, 20(4): 595-599.

[43] Zhang Lianglin, Pan Jinghu, Zhang Dahong. Spatio-temporal distribution characteristics of aerosol optical depths in China based on MODIS data[J]. Acta Scientiae Circumstantiae, 2018, 38(11): 4431-4439.

[44] Li Chengcai, Mao Jietai, Liu Qihan, et al. Analysis of distribution and seasonal variation characteristics of aerosol optical depth over the east of China by MODIS[J]. Chinese Science Bulletin, 2003, 48(19): 2094-2100.

Note: Figure translations are in progress. See original paper for figures.