Weakened dust activity over China and Mongolia from 2001 to 2020 associated with climate change and land-use management

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Abstract
Dust cycle is actively involved in the Earth’s climate and environmental systems. However, the spatiotemporal pattern and recent trend of dust emission from the drylands in East Asia remain unclear. By calculating dust aerosol optical depth (DOD) from the newly released moderate resolution imaging spectrometer aerosol products, we obtain a relatively long satellite-based time series of dust activity from 2001 to 2020 over China and Mongolia. We identify pronounced interannual variability of dust activity that is consistent with ground-based meteorological observations in the study area. A substantial reduction in spring dust activity in northern China is also found, which seems in accordance with the long-term weakening trend since the 1970s that has been attributed to the wind speed decline by previous studies. However, the spatial pattern of the trends in both annual mean and seasonal dust activity during the last 20 years is divergent, and the most significant dust diminishing is found over north-central China where large-scale vegetation restoration projects have been implemented. It indicates that in addition to the potential contribution of wind speed change, land-use change also plays an important role in the recent inhibition of dust emission. The current results show that dust activity occurs most intensively in spring, followed by summer and relatively weaker in autumn and winter. However, dust activity in autumn and winter has increased significantly in NW China despite the overall decreasing trend in other two seasons, probably associated with different seasonal atmospheric and land surface conditions. Finally, the DOD distribution reveals that the Tarim Basin, Gobi and Qaidam Basin Deserts are three major dust sources in East Asia. Compared to ground observations which are spatially limited and distributed unevenly, remote sensing provides an important complement, and it can serve as reference for identification of dust sources using other methods such as geochemical fingerprint and modeling.

1. Introduction
About 2000 Mt of mineral dust is released from the degraded land into the atmosphere each year (Shao et al 2011). Dust can alter the radiative energy balance and influence the climate by absorbing solar radiation and modifying cloud properties (Kaufman et al 2002), and can travel a long distance of thousands of kilometers and thus have even broader impacts by affecting the land and ocean biogeochemical cycles (Uno et al 2009, Mahowald 2011) and interacting with the monsoon systems (Jin et al 2021).

Our understanding about the dust cycle has been largely improved in recent years, especially due to the increasing application of remote sensing (RS) on dust monitoring. For example, the moderate resolution imaging spectrometer (MODIS) aerosol products have been used for extracting the occurrence of dust
storms, thereby identifying dust emission hotspots (Ginoux et al. 2012, Baddock et al. 2016). In particular, the drylands in North Africa and Middle East have been a hotspot in dust study in recent years (Ridley et al. 2012, Yu et al. 2013, 2016, 2018, 2019a, Prospero et al. 2021, Pu and Jin 2021). By contrast, fewer studies have applied these products to investigate dust activity in East Asia until recently (Yu et al 2012, 2019b, Ginoux and Deroubaix 2017, Tan et al 2017). Yu et al (2020) recently examined a 15-year record of global dust flux using the MODIS retrievals from 2003 to 2017, and noticed a decreasing trend in dust activity over East Asia. A more recent study by Liu et al (2021) retrieved dust aerosols to identify dust sources in Xinjiang, one arid region of NW China. Nevertheless, there is still an urgent need for more satellite-based evidence to study the trend and causes of dust aerosols emitted from East Asia, which has been regarded as the second largest dust source in the world (Shao et al 2011, Wu et al 2020, Yin et al 2021).

More importantly, by analyzing the meteorological record of dust storms in China from 1960 to 2007, previous studies have found a long-term reduction in dust storm frequency (DSF), and attributed this trend to a large-scale wind speed decline (Qian et al 2002, Guan et al 2017). However, whether the weakening trends (including annual and seasonal trends) continued in the last 20 years is doubtful (An et al 2018, Guo et al 2019, Song et al 2021, Wang et al 2021). This question is even more challenging considering the fact that the wind speed over the global land has recovered after 2010 and this reversal could occur earlier in Asia (Zeng et al 2019). Moreover, the interannual variability of Asian dust is still poorly understood (Shao and Dong 2006), though it is of importance to project its future dynamics (Liu et al 2020).

Furthermore, dust emissions are sensitive to vegetation disturbance caused by climate, CO2 fertilization and anthropogenic land-use (Li et al 2021). A recent study shows a prominent vegetation greening pattern in most part of China since 2000 largely due to land-use change (Chen et al 2019). A modeling study suggests that ecological restoration programs may lead to vegetation increase and thus potentially impact dust activity (Long et al 2018), though more empirical evidence is still needed (Fan et al 2014, Tan and Li 2015). Moreover, because there might be a contrasted picture of restoration success in the dust source regions of northern China and Mongolia (Eckert et al 2015, Xu et al 2018, Wang et al 2020, 2022), the combined effects of recent climate change and land-use management on East Asian dust activity largely remain elusive especially for the last 20 years.

An accurate description of the temporal and spatial pattern of dust aerosols is the basis for accurately parameterizing the dust emission in modeling studies (Zhang et al 2019), and for better understanding the dynamics of dust cycle (Shao et al 2013, Du et al 2018). In this study, we calculated the dust aerosol optical depth (DOD) to characterize the relative abundance of atmospheric dust from 2001 to 2020 over China and Mongolia using the most recently developed algorithm (e.g. Ginoux et al 2012, Pu et al 2019, 2020, Yu and Ginoux 2021). This 20-year RS record of dust aerosols was then integrated with ground-based observations of dust storms and climate reanalysis data, to investigate the trend, interannual variability and possible causes of dust activity in the study area. The results would improve our understanding about the processes of dust activity in East Asia.

2. Study area and method

2.1. Study area

Deserts and dune fields occupy a vast area in the arid and semi-arid region of northern China and southern Mongolia (figure 1). The annual precipitation in northern China ranges from more than 450 mm to less than 50 mm, decreasing from the southeast/east to the northwest/west. Mongolia has a typical continental climate with annual precipitation less than 50 to 400 mm, increasing from the south to the north. Accordingly, vegetation type in the study area is generally desert vegetation and steppe, and the coverage is relatively low. Gobi Desert occupies a large area across southern Mongolia and northern China, while other deserts are mostly located in northern China. The study area is generally dominated by northerly and northwesterly winds, which are largely determined by the winter monsoon circulation and the local topography.

2.2. Remote sensing (RS) data and DOD calculation

The MODIS aboard the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) satellites acquires data in 36 spectral channels ranging from 0.42 to 14.24 μm (King et al 1992). It has a viewing swath width of 2330 km and views the Earth surface every one to two days. In this study, the MODIS aerosol products are used to characterize the aerosol concentration (Kaufman et al 2002). The Deep Blue (DB) retrievals are applied, because the DB algorithm is the most adequate for bright surfaces such as the desert regions (Hsu et al 2004, Levy et al 2013), though the retrieved aerosol optical depth (AOD) may exhibit underestimation over the deserts in East Asia (Tao et al 2017). The method to retrieve DOD has been proposed by Ginoux et al (2012), and further developed with some modifications in following studies (Pu and Ginoux 2016, 2018, Pu et al 2019, 2020). In this study, the latest criteria described by Pu et al (2020) are applied to retrieve daily DOD from the newly released collection 6.1, level 2 MODIS DB aerosol products (Hsu et al 2013, Sayer et al 2013), including AOD, single-scattering albedo (ω), and the Ångström exponent (α). To account for dust’s absorption of solar radiation and separate dust from scattering.
Figure 1. (a) Spatial distribution of annual mean DOD for 2001–2020 over China and Mongolia. (b) Spatial distribution of trends in annual mean DOD from 2001 to 2020 based on Mann–Kendal test. The trends were calculated for dust-active regions with annual mean DOD exceeding 0.1. Green or yellow color indicates regions where the trends are statistically significant ($p < 0.05$). Note that the pre-whitening procedure according to Yue et al. (2002) was applied to eliminate the effect of autocorrelation on trend analysis. The linear trends were shown in figure S3, and the results were similar to the Mann–Kendal test. (c) Annual DSF from 2001 to 2020 based on 138 meteorological stations in northern China. The red dash line in (b) outlines the approximate location of the Chinese Loess Plateau, where one of the most extensive ecological projects, i.e. ‘Grain for Green’ project, has been implemented. The light gray shade in (c) indicates the spatial coverage of northern China. a): Taklamakan Desert in the Tarim Basin. b): Gurbantunggut Desert. c): Kumtagh Desert. d): Qaidam Basin Desert. e): Badain Jaran Desert. f): Tengger Desert. g): Ulan Buh Desert. h): Hobq Desert. i): Mu Us dune field. j): Otindag dune field. k): Horqin dune field. The Alxa region includes Badain Jaran, Tengger and Ulan Buh Deserts, while the Ordos region includes Mu Us and Hobq Deserts. The temperate dry steppe near the border between China and Mongolia is located to the west of Otindag dune field and to the east of the Gobi Desert.
aerosols, such as sea salt, we require the \( \omega \) at 412 and 470 nm to be less than 0.95 and 0.99, respectively, for the retrieval of DOD, and a positive difference of \( \omega \) between 412 and 670 nm (\( \omega_{670} - \omega_{412} \)). Based on the size distribution of dust towards the coarse range and to separate it from fine particles, DOD is retrieved as a continuous function of AOD and Ångström exponent:

\[
DOD = AOD \times (0.98 - 0.5089\alpha + 0.0512\alpha^2).
\]

This retrieval of DOD is on the basis of Ångström exponent’s sensitivity to particle size, with smaller values of Ångström exponent indicating larger particles (Eck et al. 1999), and the previously established relationship between Ångström exponent and fine-mode AOD (Anderson et al. 2005). The calculated DOD only represents the coarse mode of the dust, while it has been estimated that the fine mode of the dust is less than 10% when discharged (Kok et al. 2017). Details about the retrieval process and estimated errors are summarized by Pu and Ginoux (2018). Here, both MODIS aerosol products from the Terra and Aqua platforms are used. Note that the Terra time series cover from 2001 to 2020 while the Aqua time series cover from 2003 to 2020. We compare the DODs derived separately from the two sensors, and they show similar spatial patterns (figure S1 (available online at stacks.iop.org/ERL/16/124056/mmedia)) and interannual variability (figure S2) from 2003 to 2020. Finally, these two time series are averaged, and the obtained DOD datasets cover from 2001 to 2020, with spatial resolution of \( 0.1^\circ \times 0.1^\circ \). The annual average and seasonal mean of DOD is calculated for northern China and Mongolia.

### 2.3. Ground-based dust observations

The meteorological record of dust storms from 2001 to 2020 obtained from China Meteorological Administration is analyzed. This dataset is constituted by continuous records of daily dust storm observations at 138 stations in northern China during the last 20 years. According to the standard of dust storm classification formulated by the China National Standard GB/T 20480-2017, the day when one station recorded at least one dust storm is recorded as one dusty day. It includes floating dust, blowing dust, dust storm, severe and super-severe dust storm. The dust conditions are defined by near-surface wind speed and horizontal visibility (Shao and Dong 2006, Guan et al. 2017, An et al. 2018). In this study, the DSF in one station is calculated by the number of dusty days in either each year or each season.

### 2.4. Climate data and vegetation cover

To examine the possible climatic effects on dust activity in the study area, different climatic variables such as precipitation, temperature and wind speed are analyzed. The climate data are derived from the fifth generation Europe Center for Medium-range Weather Forecasts reanalysis dataset for global climate monitoring (the ERA5 reanalysis). The dataset has a spatial resolution of \( \sim 31 \) km (Herbach et al. 2020). Furthermore, the normalized difference vegetation index (NDVI), which has been widely used to indicate vegetation change, is analyzed to investigate the possible impact of vegetation growth on dust activity. The growing season NDVI time series are derived from the MODIS images (MOD09A1 V6 products), which have been corrected for atmospheric conditions such as gases, aerosols and Rayleigh scattering (Vermote 2015). The MODIS NDVI time series cover from 2001 to 2020 and have a resolution of 500 m.

### 3. Results

#### 3.1. Spatial pattern of dust activity over China and Mongolia

Spatial pattern of dust activity over China and Mongolia is clearly indicated by the distribution of annual DOD averaged for 2001–2020 (figure 1(a)). The regions with annual DOD exceeding 0.1 are mostly located in the deserts and dune fields in northern China and southern Mongolia, including Taklamakan Desert and Lop Nor in the Tarim Basin, Gurbantunggut Desert, Turpan Depression, Kumtagh Desert, Qaidam Basin Desert, Gobi Desert, Alxa region (including Badain Jaran, Tengger and Ulan Buh Deserts), Ordos region (including Hobq Desert and Mu Us dune field), Otindag dune field and Horqin dune field. The regions with DOD exceeding 0.1 also include the areas located in the downwind direction of the deserts, such as Hexi Corridor, and the western Chinese Loess Plateau that locates to the southeast of the Alxa region. Among them, the Tarim Basin and the Qaidam Basin Desert show highest annual mean DODs that often exceed 0.2. The eastern Gobi Desert in the southern Mongolia and the temperate dry steppe, which is located west to the Otindag dune field, also have high DOD. Meteorological record (figure 1(c)) reveals that the stations with annual DSF exceeding 10 d are all located in the areas with DOD higher than 0.1. The annual mean DOD in the east part of the Mu Us and Otindag dune fields, as well as the Hulun Buir dune field, is lower than 0.1, indicating relatively weaker dust activity in these regions compared to the other deserts and dune fields.

#### 3.2. Seasonal variability of dust activity

The seasonal DOD distribution over China and Mongolia reveals a strong seasonality in dust activity (figure 2(a)). The spatial distribution of seasonal DOD resembles the annual mean DOD pattern, while over most pixels, DOD reaches its maximum in spring, followed by summer. The Taklamakan and Qaidam Basin Deserts show strong dust activity almost all year round. Except for these two regions, other parts of northern China and Mongolia have relatively low DOD in autumn and winter. The summer
dust activity is less pronounced in previous studies, but the summertime DOD is substantially high, for many regions as extensive as in spring, including the Tarim Basin, Qaidam Basin and Gobi Deserts, as well as the temperate dry steppe located near the border between China and Mongolia.

3.3. Long-term trend and interannual variability of dust activity from 2001 to 2020
The past two decades witnessed significant decrease in annual mean DOD over some parts of the study area, including the Alxa region, the Ordos region, Hexi Corridor, western Chinese Loess Plateau and the temperate dry steppe (figure 1(b)). However, significantly increasing trends in annual mean DOD also appear in the western Gobi Desert and some regions in the Tarim Basin, Gurhantunggut and Qaidam Basin Deserts of NW China. Their seasonal trends show a divergent pattern as well. In autumn and winter, significantly increasing trends in seasonal DOD are identified in the Tarim Basin, Qaidam Basin and western Gobi Deserts (figure 2(b)), despite that the DODs of these two seasons are relatively low in comparison to spring and summer (figures 2(a) and S4). In contrast, both springtime and summertime DOD show significantly declining trends in most part of the study area, including the deserts in NW China.

Moreover, the springtime DOD of northern China as a whole has decreased significantly from 2001 to 2020 (figure 3(b)), while the annual mean DOD displays an insignificant trend with substantial
4. Discussion

4.1. Consistent changes between RS and ground observations

The trend of MODIS DOD in northern China shows an excellent consistency with the observational record of the annual and springtime DSF (figure 3). Seasonal mean DOD and DSF in northern China are positively correlated, with the highest correlation exceeding 0.8 in spring (figure S4). Both records reveal significantly decreasing trend in spring dust activity and have similar interannual variations. The relatively high DOD and DSF values in 2001–2002 and 2006 accord with the frequent and strong dust storms observed in these years (Yang et al. 2008, Song et al. 2016). All these lines of evidence suggest that the...
RS-retrieved DOD time series are a reliable record to represent the general pattern and interannual variability of dust activity in the study area. Considering that the ground stations are mostly located outside or near the margin of the deserts, and have uneven spatial distribution (figure 1(c)), the RS monitoring of dust activity provides an important complement to the ground-based observations.

4.2. Possible causes for the changes in dust activity in northern China

Based on the meteorological record, previous studies have reported a long-term weakening in dust activity in northern China from the 1970s to 2007 (e.g. Qian et al 2002, Guan et al 2017). Our analysis suggests that this dramatic reduction in spring dust activity may have continued during the last two decades (figure 3(b)). Moreover, the significantly decreasing trends in either annual mean DOD (figure 1(b)) or springtime DOD (figure 2(b)) are mostly found in north-central China. However, the overall trend in either annual mean DOD or DSF in northern China as a whole is insignificant from 2001 to 2020 (figure 3(a)). Instead, a divergent pattern of the DOD trends is clearly identified (figures 1(b) and 2(b)). In contrast to the long-term decreasing trend, the seasonal DODs in autumn and winter from 2001 to 2020 have increased significantly in large part of the deserts in NW China.

Changes in dust activity are influenced by surface conditions in the dust source regions and wind speed. The surface conditions, such as soil texture, soil moisture, and vegetation cover, etc., influence the availability of dust particles and surface erodibility. Both climate change and land-use management affect these factors, and could result in the divergent pattern of DOD trends. The current analysis of climate reanalysis data from 2001 to 2020 reveals that the decreasing springtime DOD was accompanied by statistically significant warming (figure 4(a)) and statistically insignificant wetting (figure 4(b)) over the entire northern China. Previous studies have attributed the long-term weakening in dust activity over northern China to the wind speed decline since the 1970s (e.g. Lee and Sohn 2009, Guan et al 2017, Liu et al 2020). However, the near-surface wind speed from 2001 to 2020 in northern China is relatively low and has no significant trend (figure 4(c)), probably as a result of the reversal in global terrestrial stilling after 2010 (Zeng et al 2019). Spatial distribution of the trends in these climatic variables from 2001 to 2020 is shown in figure S5. While a large part of northern China has insignificant climate trends in the last 20 years, some areas of Loess Plateau show spatial coherence between significant wind speed trends and DOD trends. Nevertheless, changes in climatic variables (i.e. wind speed decline and drought) should still have impacts on dust emission at both decadal and interannual time scales. For example, the remarkable dust outbreaks occurred in 2001–2002 and 2006 are believed to be associated with severe droughts and more wind gusts in these years (Kurosaki and Mikami 2003, Uno et al 2009).

More importantly, the regional NDVI shows a dramatic increasing trend since 2001, and is negatively correlated with the DOD change (figures 4(d) and S6). Vegetation increase indicated by NDVI in northern China during the last two decades has been largely attributed to anthropogenic land-use change (Wang et al 2018, Chen et al 2019), though it could also be partially related to the recent climate shift toward wetter, warmer and possibly less windy conditions in some regions (Shi et al 2007, Xu et al 2018, Wang et al 2022). In particular, the policy-driven, large-scale ecological restoration projects have been recently implemented in north-central China, and increased vegetation and stabilized sand dunes effectively in some arid regions (Xu et al 2018, Wang et al 2020, 2022). The widespread vegetation recovery in the dust source regions can exert strong feedbacks through increased surface roughness and inhibited near-surface wind speed, thereby reducing erodibility of the top soils (Zender and Kwon 2003, Yu et al 2017). Indeed, the areas with the most significant decrease in dust activity are exactly in accordance with the regions where extensive restoration projects have been implemented (figure 1(b)). For example, the ‘Grain for Green project’ has largely increased vegetation coverage on the Chinese Loess Plateau during the last two decades, which has a profound effect by reducing soil and sediment erosion (Wang et al 2015). Accordingly, dust activity has been greatly diminished in the western and northern Loess Plateau, especially in the spring and summer growing seasons (figure 2(b)).

Furthermore, it is clear from figure 5(a) that NDVI and DOD are statistically correlated ($p < 0.001$). As the NDVI increases, the maximal DOD decreases dramatically. The NDVI in dust-active regions with DOD $> 0.1$ is mostly less than 0.4. The areas with DOD $> 0.4$ that may indicate more frequent or stronger dust events, are almost restricted in the regions with NDVI $< 0.1$. Note that the areas with very low NDVI can also have low DOD. It indicates that although the low vegetation cover is one of the prerequisites of strong dust emissions, the bare lands with sparse vegetation cover are not necessarily major dust sources (also see figure 1(a)). Moreover, the areas with significant decrease in DOD usually have a decadal increase in NDVI larger than 0.01 (figure 5(b)). In comparison, the areas with significant increase in DOD mostly have minor increase or decrease in NDVI within 0.01 per decade. Thus, we argue that the decadal-long reduction in dust emission in north-central China can be viewed as a response to vegetation increase as a result of both climate change and land-use management in the dust source regions.
4.3. Implications for dust source and dust emission processes
It has been suggested that high DOD usually correspond to the regions with high DSF or with great intensity of dust storms (Ginoux and Torres 2003, Ginoux et al 2012). In this study, the regions with DOD exceeding 0.1 are defined as dust-active regions, and they are largely restricted near the previously
recognized dust sources such as the Gobi and Taklamakan Deserts (Zhang et al. 2003, Shao and Dong 2006, Chen et al. 2017), and their downwind regions such as the Chinese Loess Plateau southeast of the Alxa region, and the dry steppe east of the Gobi Desert.

Based on meteorological observations (Sun et al. 2001, Wang et al. 2003, Xuan et al. 2004) and modelings (Eguchi et al. 2009, Uno et al. 2009), previous studies suggest that the Tarim Basin and the Gobi Desert (and surrounding regions such as Alxa and Ordos) are the two main East Asian dust sources. While these results are generally consistent with the dust-active regions identified in this study, the DOD distribution uncovers an additional, year-round dust source in the Qaidam Basin Desert. Recent geochemical fingerprint analysis of the loess deposits points out that the Qaidam Basin Desert may contribute significant amount of dust to the Loess Plateau during the past glacial periods (Pullen et al. 2011). Wang et al. (2017) estimate that although more than 3 Tg of PM50 dust aerosol is available from riverbeds alone in the Qadaim Basin, the Qadaim Basin contributes less than 15% to modern day dust availability from three potential dust sources including the Tarim Basin, the Qaidam Basin, and the Alxa region. This study supports the viewpoint that the Qaidam Basin Desert, together with the Tarim Basin, the Gobi Desert and surrounding regions, are the three most important dust sources. The DOD distribution can provide a direct reference for identification of dust source using other methods such as geochemical fingerprint and modeling (e.g. Li et al. 2009, Liang et al. 2021).

The dust frequency and intensity vary between these three major dust sources, probably due to their different atmospheric and land surface conditions. The Tarim Basin is surrounded by high mountains and has higher DOD than others, probably because the dust is often difficult to be transmitted out of the basin unless it is lifted high into the westerly jets (Chen et al. 2017). The Gobi Desert and surrounding regions have a large area but relatively lower DOD. The relatively flat terrain in these regions and high wind speed at upper levels may result in a relatively unstable atmospheric stratification and are conducive to the vertical lifting and dispersal of dust (Guan et al. 2017, Yu et al. 2019b). The high DOD in the Qaidam Basin are more likely related to a large coverage of playa and sand sheets in the basin, as well as the exposure of thick paleo-fluvial deposits, which provide rich materials for dust emission (Prospero et al. 2002).

The strong seasonality in dust activity in the study area may also relate to various atmospheric and land surface conditions (Proestakis et al. 2018). In winter, the snow or ice cover and frozen soils suppress dust release from these regions. Meanwhile, the dominance of Siberian High in large parts of the study area and the southward movement of the westerly jets to the southern edge of Tibetan Plateau (Schiemann et al. 2009) may create a relatively stable air mass and contribute to the dearth of wintertime dust storms. In spring, the exposure of sparsely vegetated, dry ground due to rising temperature provides sufficient loose materials for dust emission. The increased atmospheric instability due to the weakening of Siberian High, and an enhanced meridional temperature gradient over the Gobi Desert lead to more frequent cold front passages and wind gusts (Roe 2009). The movement of westerly jets to the northern part of the Tibetan Plateau, where major dust sources locate, is also conducive to dust transmission (Serno et al. 2017). The summertime DOD is high in most dust source regions. The warming in the ground surface and lower atmospheric layer in summer may weaken the boundary layer stability and encourage more local convection, both of which favor dust

Figure 5. Relationship between growing season NDVI and DOD in northern China. (a) Density plots between the two variables. (b) Histograms showing that the percentage of different NDVI trends per decade relative to the total number of pixels with significantly increasing or decreasing DOD, respectively.
activity (Guan et al 2017). In autumn, the inversion layer is often established, and makes the atmospheric stratification stable and unfavorable to dust emission (Li et al 2012). Therefore, we speculate that the increasing DOD in autumn and winter in NW China is likely due to more occurrence of unstable atmospheric boundary layer under recent global warming conditions.

5. Conclusion

This study generates a continuous DOD time series for East Asia from 2001 to 2020, which reveals a clear spatiotemporal pattern of dust activity mainly in northern China and southern Mongolia. The dust-active regions with annual DOD exceeding 0.1 have NDVI < 0.4, and correspond well to the previously recognized, year-round dust sources including the Tarim Basin, Gobi, and Qaidam Basin Deserts. Moreover, a divergent spatial pattern of the trends in both annual and seasonal DOD during the last 20 years is remarkably different from the long-term weakening in dust activity as previously reported. Spring dust activity has been substantially reduced from 2001 to 2020, and the most significant dust diminishing is found over north-central China where large-scale vegetation restoration projects have been implemented. It indicates the potential contribution of land-use change to the recent inhibition of dust emission, in addition to the effect of low wind energy environment. Finally, this study reports strong seasonality in dust activity and different seasonal trends, both of which could be explained by various atmospheric and land surface conditions that affect dust emission. Our study indicates that the recent changes in dust activity in East Asia can be attributed to a combined effect from both climate change and anthropogenic land-use management.

Data availability statements

The MODIS level-2 aerosol products (new Collection 6.1) were obtained from website of the Level-1 and Atmosphere Archive and Distribution System (LAADS) Distributed Active Archive Center (DAAC) (https://ladsweb.modaps.eosdis.nasa.gov). The ECMWF ERA5 climate reanalysis data were downloaded from the Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-mean?). MOD09A1 data were available from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/products/mod09a1v006/).

All data that support the findings of this study are included within the article (and any supplementary files).

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