

# Geophysical Research Letters

## RESEARCH LETTER

10.1029/2019GL083508

### Key Points:

- There is a distinct relationship of dust aerosol in Gobi and Taklimakan deserts with the dust aerosols in western North America
- The difference of terrain and background wind account for the different remote influences of dust aerosol in Gobi and Taklimakan deserts
- The influences of dust aerosol in Gobi desert on the western North America experienced an obvious regime shift around 1999

### Supporting Information:

- Supporting Information S1

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### Citation:

Liu, L., Guo, J., Gong, H., Li, Z., Chen, W., Wu, R., et al. (2019). Contrasting influence of Gobi and Taklimakan deserts on the dust aerosols in western North America. *Geophysical Research Letters*, 46, 9064–9071. <https://doi.org/10.1029/2019GL083508>

Received 29 APR 2019

Accepted 27 JUL 2019

Accepted article online 1 AUG 2019

Published online 8 AUG 2019

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## Contrasting Influence of Gobi and Taklimakan Deserts on the Dust Aerosols in Western North America

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**Abstract** The dust generated in East Asia influences the western North America (WNA) through its trans-Pacific transport. This study investigates the distinct contribution between two main dust sources in East Asia on this remote influence based on Modern-Era Retrospective analysis for Research and Applications version 2 data set. Results show that the dust generated in Gobi desert (GD) exerts a larger influence on the WNA compared to those in Taklimakan desert (TD). This difference is attributed to the different terrain and background winds in GD and TD. The GD is relatively flat and dominated by westerlies throughout the troposphere, which facilitates the trans-Pacific transport of dust to WNA. However, the TD is located in the Tarim Basin and dominated by easterly wind in the lower troposphere. The uplifted dust is largely redeposited in TD. Moreover, the influence of GD on dust in WNA experiences decadal change around 1999, which is related to intrinsic change of dust loading in GD.

### 1. Introduction

Dust aerosol is an important component of atmospheric aerosols. Dust aerosol arises mainly from arid desert regions and exerts a significant influence on global climate and energy budgets (e.g., Chen et al., 2017; Ge et al., 2010; Hu et al., 2017; Huang et al., 2006). The emission of dust aerosol can not only change the radiative budget of the Earth system through absorbing and scattering solar radiation directly but also influence the cloud microphysical processes indirectly, and even the ecosystems at regional and global scales (Chen et al., 2014; Degobbi et al., 2011; DeMott et al., 2003; Jickells et al., 2005; Mahowald et al., 2007; Miller et al., 2004; Rosenfeld & Nirel, 1996). East Asia is a major source of dust aerosol as there are several deserts located in north-western China and Mongolia that contribute a large amount of dust particles to the global dust mass loading (e.g., Chen et al., 2017; Guan et al., 2017; Hara et al., 2006; Huang et al., 2011, 2014). The long-range transport of dust aerosols from source regions to the downstream regions and their regional climate impacts have been widely documented (e.g., Duce et al., 1980; Guo et al., 2013, 2017; VanCuren & Cahill, 2002; Uno et al., 2011).

The Taklimakan desert (TD) and Gobi desert (GD) are two of the most important dust sources in East Asia (e.g., Chen et al., 2017; Ding et al., 2005). The TD is located in the center of the Tarim Basin and is the second largest drifting desert in the world. The GD covers a relatively larger domain than TD and spans from the southern Mongolia to northwestern and northern China. Although some previous studies have found that the dust aerosol generated in some of the strong dust storm events in East Asia can be transported to the North Pacific Ocean and reach the western North America (WNA) after a week (e.g., Guo et al., 2017; Hu et al., 2016), they did not separate the roles of TD and GD in the contributions to the dust aerosol observed in WNA. Based on numerical simulations, Chen et al. (2017) found that the dust aerosol from GD may be more likely transported to the downstream region than that from TD. However, the relationship has yet to be resolved between the long-term variation of dust mass loading over TD and GD and that over the western parts of North America from the observational perspective. Besides, the relative role of the dust that originated from TD and GD needs to be elucidated in the changes of dust aerosols in the downstream regions from East Asia to WNA. To this end, this study investigates the long-term relationship of the dust aerosol concentration in these two dominant dust sources in East Asia and that in WNA. Meanwhile, the possible causes for the different influence of TD and GD on the remote region dust aerosol are further discussed.

## 2. Data and Methods

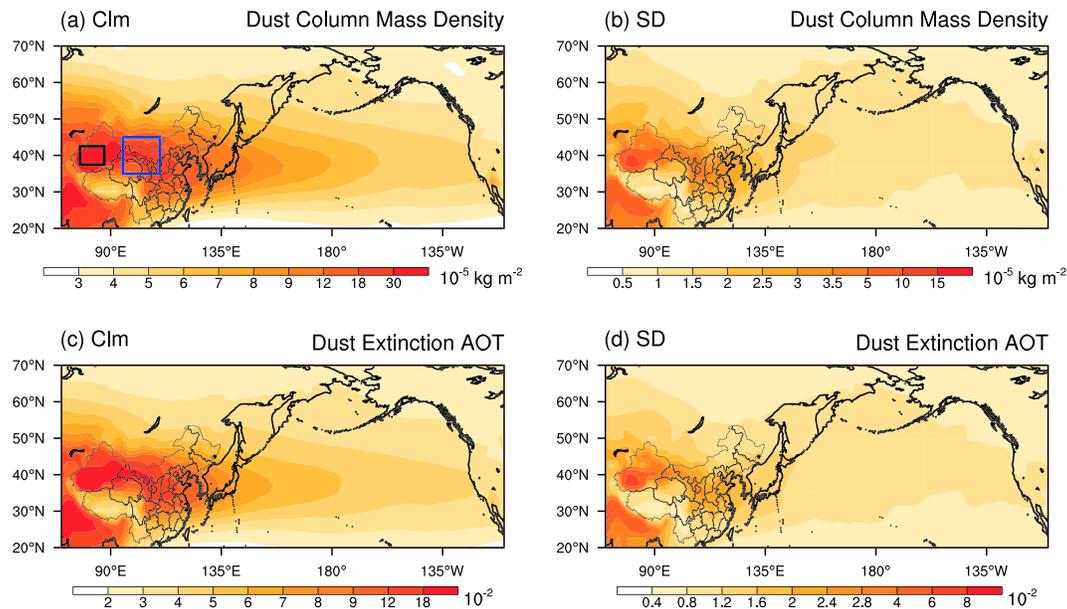
In this study, the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) Aerosol Reanalysis data from the National Aeronautics and Space Administration Global Modeling and Assimilation Office (Gelaro et al., 2017) are employed, which has a horizontal resolution of  $0.5^\circ \times 0.625^\circ$  and covers the period from January 1980 to present. MERRA-2 assimilates bias-corrected aerosol optical thickness (AOT) from the Moderate Resolution Imaging Spectroradiometer and Advanced Very High Resolution Radiometer, AOT retrievals from the Multiangle Imaging Spectrometer, as well as ground-based AOT from the Aerosol Robotic Network. The MERRA-2 system also incorporates new observations and reduces spurious trends and jumps related to changes in the meteorological observing system (Randles et al., 2017). It shows a high accuracy based on the validations against the aerosol index and absorption AOT from Ozone Monitoring Instrument over dusty regions (Buchard et al., 2015). Recently, Sun et al. (2019) indicated that the MERRA-2 data have a good agreement with ground-based or satellite observations in China during the period when both are available. In view of the lack of long-term ground-based observations for dust loading in China (e.g., Ge et al., 2014), thus the MERRA-2 data with the large spatial coverage and relatively high reproducibility are employed to investigate the long-term changes of dust aerosol. In this study, the dust column mass density (DCMD) and dust extinction AOT (DEA) data from MERRA-2 are used to represent the dust aerosol. We also use the independent satellite observed Multi-Sensor Absorbing Aerosol Index data that combine TOMS, GOME-1, SCIAMACHY, Ozone Monitoring Instrument, GOME-2A, and GOME-2B to further verify the reliability of MERRA-2 dust data. The results are basically consistent between two data sets, especially for the long-term changes of dust loading (Figure S1 in the supporting information). To illustrate the physical mechanism for the transport of dust aerosol in GD and TD to WNA, the independent atmospheric circulation field will be analyzed using the ERA-interim reanalysis data (Dee et al., 2011). The ERA-interim products cover the period from January 1979 to the present with a horizontal resolution of  $2.5^\circ \times 2.5^\circ$ . For the sake of better comparison, the MERRA-2 data are bilinearly interpolated to a resolution of  $2.5^\circ \times 2.5^\circ$  grid prior to further analysis.

The present analysis covers the period from 1980 to 2017 in view of the data availability. The loading of dust aerosol over East Asia is the largest during boreal spring when the synoptic-scale cyclonic activity is frequent in Mongolia and northwestern China (Qian et al., 2002). This synoptic cyclone facilitates the uplifting of dust into the free troposphere, leading to more dust particles residing in the upper troposphere. Therefore, the present study focuses on spring when dust storms frequently swept through the Asian continent toward the Pacific Rim. Spring means are constructed by averaging monthly mean data of March, April, and May. Linear correlation and regression analyses are used to investigate the linkage of dust aerosols over source region and downstream regions. A two-tailed Student's *t* test is used to evaluate the confidence level of correlation and regression.

## 3. Results

Figures 1a and 1b show the geographical distributions of climatological and interannual standard deviation of spring DCMD, respectively, during 1980–2017. In a broad climatic sense, high dust loading can be seen in the desert regions over almost the whole northwestern and northern China with a magnitude exceeding  $3 \times 10^{-4} \text{ kg/m}^2$ . Spatially, the dust concentration exhibits a pronounced west-east gradient, gradually decreasing from central China to Korea and Japan, all the way to the North Pacific Ocean and the WNA. The DCMD maxima are located in TD and GD, indicative of frequent occurrence and strong intensity of dust events in these regions. The pattern of interannual standard deviation of DCMD (Figure 1b) displays a similar feature with relatively larger amplitudes in the northwestern China. These spatial distributions of the climatology and standard deviation of spring DCMD are consistent with those based on the DEA presented in Figures 1c and 1d. This suggests that the spatial distribution patterns of dust aerosol should be reliable. In view of the consistency of results based on DCMD and DEA, hereafter, the DCMD data are employed for further analysis in the following sections. The results based on DEA data are also shown in the supporting information for reference.

To separate the roles of dust aerosol from TD and GD in the loading of dust aerosol in the downstream regions, we compare the temporal evolution of the DCMD indices in TD and GD and associated spatial distribution of dust aerosol variations. Here, the DCMD indices are defined as the area-averaged DCMD in the

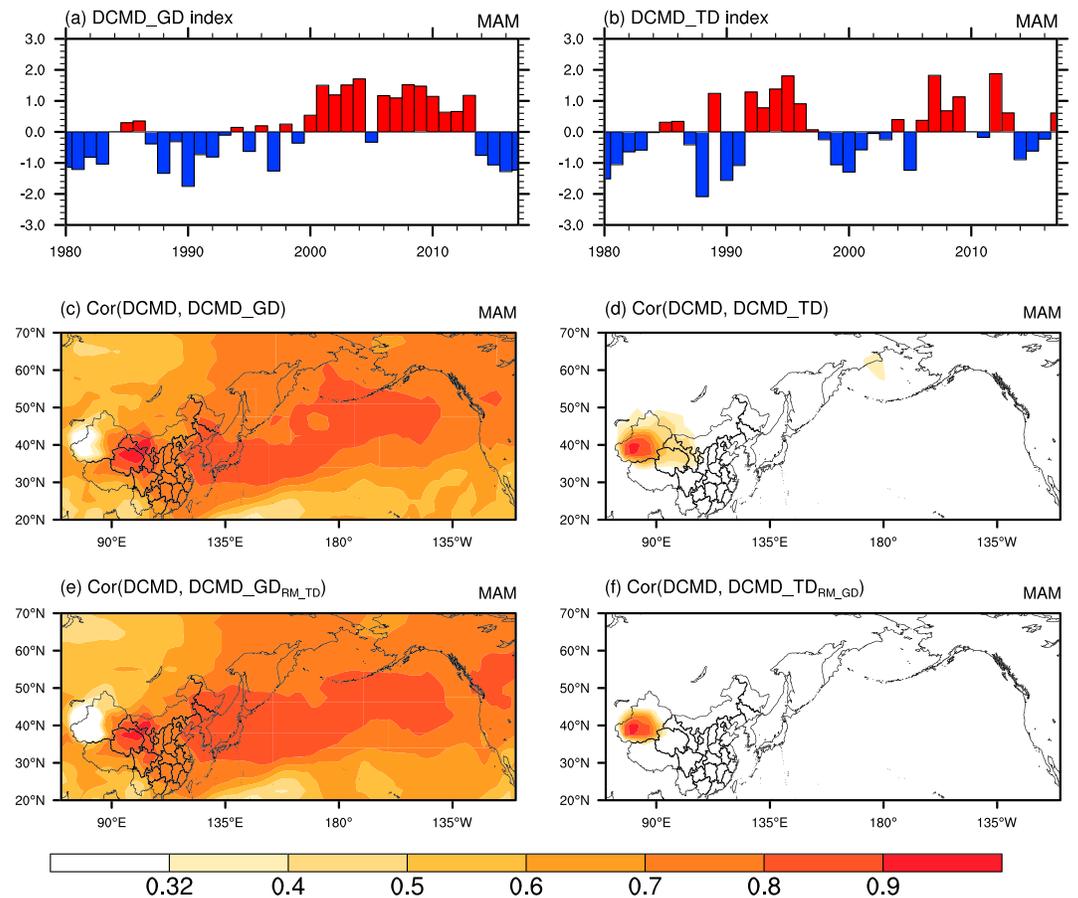


**Figure 1.** (a) The climatological mean and (b) the interannual standard deviation of dust column mass density during spring (March–April–May) based on the Modern-Era Retrospective analysis for Research and Applications version 2 data set from 1980–2017. (c and d) As in (a) and (b), respectively, but for the dust extinction AOT. The black and blue boxes in (a) indicate the regions of Taklimakan desert and Gobi desert, respectively. AOT = aerosol optical thickness.

GD region (35–45°N and 95–110°E) and TD region (37.5–42.5°N and 77.5–87.5°E), respectively. Figures 2a and 2b illustrate the normalized time series of the spring dust index in GD (DCMD\_GD) and TD (DCMD\_TD), respectively. The normalized time series are convenient for intercomparison among different variables. The DCMD\_GD index and DCMD\_TD index display quite different temporal evolutions. The dust aerosol in GD experience a significant decadal change around 1999 with a higher dust loading during 2000–2013 compared to that during 1980–1999. The dust aerosol in TD exhibits more prominent interannual variations.

To clarify which dust source regions is more important to the trans-Pacific transported dust aerosols, the correlation maps of the dust aerosol index in GD and TD with the DCMD are shown in Figures 2c and 2d, respectively. In terms of GD dust aerosol index, there are high correlations not only in the source region but also in its downstream regions including Korea and Japan, North Pacific Ocean, and WNA. The correlation coefficients are great than 0.8 over the majority of these regions, exceeding the 95% confidence level (Figure 2c). This indicates that the aerosol source in the Gobi region has an important contribution to aerosol variations in the above-mentioned downstream regions. In contrast, the Taklimakan dust index has notably high correlation only in the local region (Figure 2d). This suggests that the Taklimakan source plays little role in dust aerosol variations in other regions. Note that the correlation between Gobi dust index and Taklimakan dust index is insignificant, implying little connection of aerosol variations between these two regions.

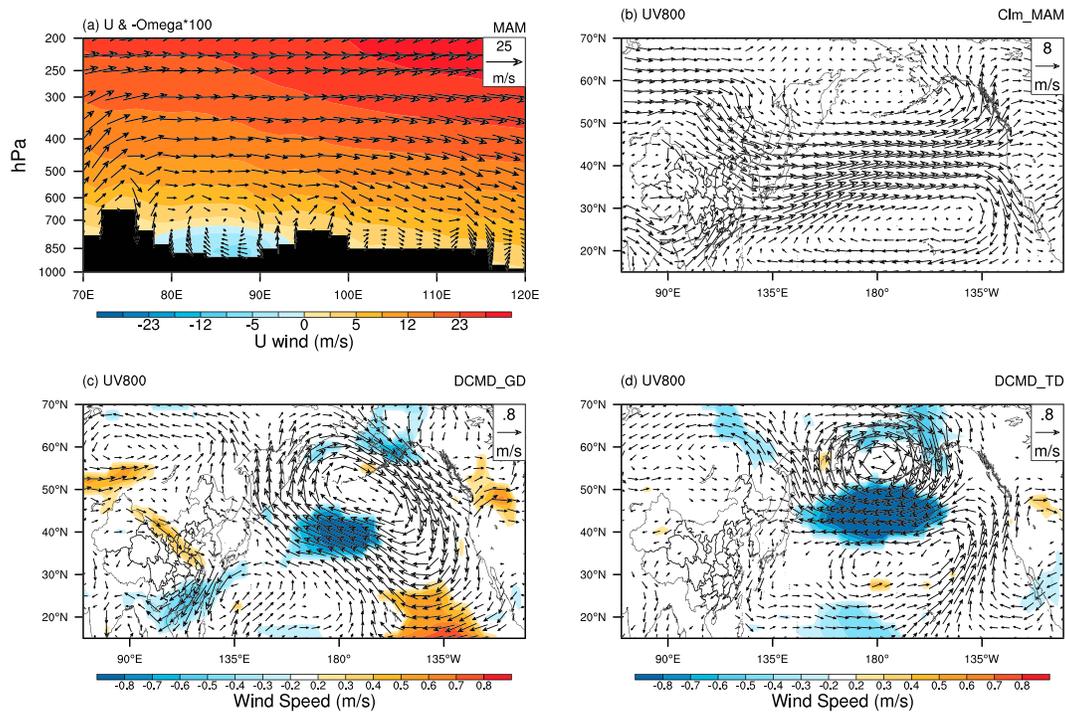
To interpret the respective influence of GD dust aerosol and TD dust aerosol more clearly, the TD dust aerosol variability is linearly removed from GD dust aerosol index using a linear regression method (Gong et al., 2017; Liu et al., 2018, 2019). The residual GD dust aerosol can be represented as a TD-independent GD dust aerosol index (DCMD\_GD<sub>RM\_TD</sub>). Similarly, we can obtain the GD-independent TD dust index (DCMD\_TD<sub>RM\_GD</sub>). The distributions of correlations between DCMD\_GD<sub>RM\_TD</sub> index and DCMD in East Asia to western North America are consistent with the original DCMD\_GD index, with high correlation in most regions of East Asia, the North Pacific, and the WNA regions (Figure 2e). The high correlations between DCMD\_TD<sub>RM\_GD</sub> index and DCMD are mostly confined in the TD regions compared to that using original DCMD\_TD index (Figure 2f). The large-scale high and significant correlation between GD dust aerosol index and dust aerosol in the large domain indicates that the dust loadings over downstream regions even in WNA are largely originated from GD, whereas the dust particles from TD may mostly redeposits



**Figure 2.** (a) Normalized time series of spring DCMD\_GD index. (b) As in (a), but for DCMD\_TD index. (c) Correlation maps between DCMD\_GD index and DCMD spanning from East Asia to western North America. (d) As in (c), but for the DCMD\_TD index. (e and f) As in (c) and (d), but for the results based on TD-independent DCMD\_GD index (DCMD\_GD<sub>RM\_TD</sub>) and GD-independent DCMD\_TD index (DCMD\_TD<sub>RM\_GD</sub>), respectively. The 95% significant level is 0.32 in 38-year correlation coefficient between two time series. DCMD = dust column mass density; GD = Gobi desert; TD = Taklimakan desert; MAM = March-April-May.

after uplifting and show little influences on the downstream regions. The similar results are also presented by using the DEA data (Figure S2 in supplemental materials).

The emission and uplifting of dust aerosol in the dust sources mainly depend on the near-surface wind speeds (e.g., Qian et al., 2002). The transport of dust aerosol depends not only on the wind speed in the source region, but also on the wind direction in the source and downstream regions. To reveal the possible mechanism responsible for the distinct influences of GD and TD on the downstream regions, the atmospheric circulation data are employed. To avoid the dependence of results to the same data set, the atmospheric circulation data in ERA-interim are used for the following analysis. Figure 3a shows the cross sections of the spring wind field over the longitude 70–120°E along 40°N for the period 1980–2017. The TD is located in the Tarim Basin surrounded by mountains with approximate longitudes from 80°E to 90°E. The mountains block the transport of dust aerosol to other regions. In contrast, GD is situated in a relatively flat terrain with longitudes approximately from 100°E to 110°E. The near-surface wind directions are opposite in these two regions. In TD, easterly winds dominate in the lower troposphere. The uplifted dust aerosol is difficult to be transported eastward. Meanwhile, there is a zonal vertical circulation cell in the Tarim basin around 80–90°E with sinking motion in the east side of the TD. The sinking motion may redeposit uplifted dust particles in the TD region. Therefore, although TD is the largest dust source region over East Asia, it is not likely to exert substantial influences on the trans-Pacific regions via transport due to the adverse terrain and background winds. On the contrary, in the GD region, the westerlies dominate in the whole

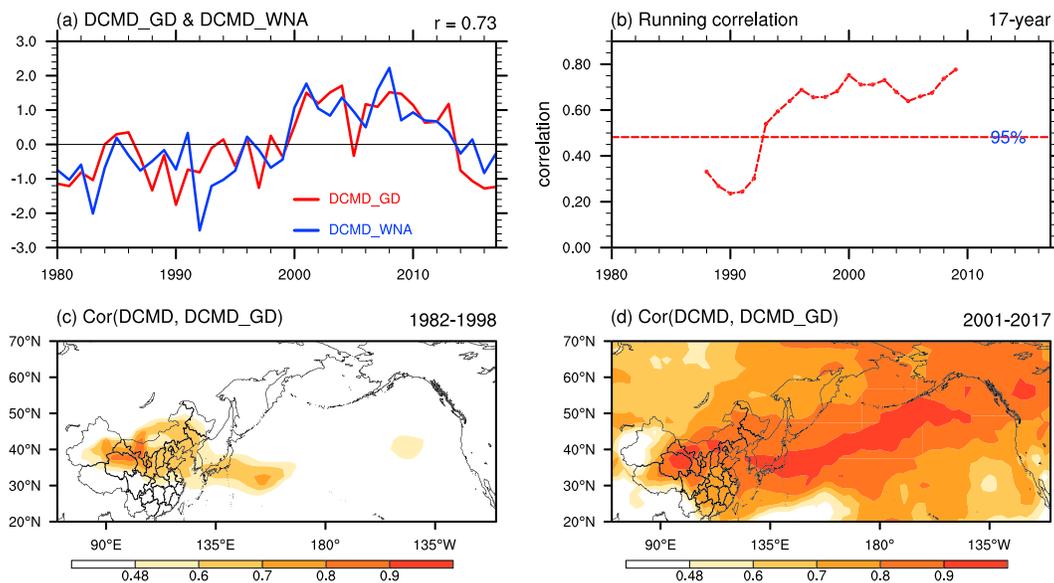


**Figure 3.** (a) Cross sections of the wind vectors consisting of zonal wind (m/s) and vertical velocity (0.01 Pa/s) with longitude (70–120°E) along 40°N during spring (March–April–May, MAM) for the period 1980 to 2017. The black shading regions represent the terrain. (b) The climatological 800-hPa winds (vector) over the East Asia to western North America for the period 1980–2017. (c) The regression maps of 800-hPa winds (vector) and wind speed (shading) anomalies against the normalized DCMD\_GD index for the period 1980–2017. (d) As in (c), but for the DCMD\_TD index. The wind anomalies less than 0.1 m/s are masked in (c) and (d). DCMD = dust column mass density; GD = Gobi desert; TD = Taklimakan desert.

troposphere. Moreover, the dust particulars can be ejected into higher altitudes than those in TD (Chen et al., 2017). Thus, the uplifted dust aerosols can be transported to remote downstream regions through strong background westerly winds.

To further clarify the mechanisms behind the dust transport across the Pacific Ocean, the climatology of 800-hPa wind in spring is displayed in Figure 3b. In general, the midlatitude regions are dominated by westerlies, which is favorable to eastward dust transport from GD to WNA. The spatial distribution of the 800-hPa westerlies is quite consistent with the high correlation coefficient pattern of the dust aerosol with the DCMD\_GD index (Figures 2c and 2e). In contrast, TD is dominated by easterly winds. As a result, the dust particles are blocked by the mountain to the west side and redeposited in the Tarim Basin. Figure 3c reveals the regressed 800-hPa wind anomalies on the normalized time series of DCMD\_GD index. Here, the regression coefficients of the winds with respect to the DCMD\_GD index are used to represent the wind anomalies (or changes) linearly related to the changes of DCMD\_GD index. During the positive phases of the DCMD\_GD index, there are northwesterly anomalies over the GD region, which strengthen the background northwesterlies and induce more dust particular ejected into the atmosphere. Therefore, more dust aerosol can be transported eastward from GD to the North Pacific and WNA. Figure 3d shows the regression map of wind anomalies relative to normalized TD index. During the positive phases of the TD index, there are easterly anomalies over TD, leading to westward transport of dust particles. Due to the blocking effect of the surrounding mountains, the dust particles are redeposited in the Tarim Basin. The similar results are also displayed by using the DEA data (Figure S3 in the supporting information), which further confirms the above-mentioned findings.

The following analysis indicates that the trans-Pacific transport of dust aerosol originated from GD exhibits large decadal variability during 1980–2017. Figure 4a shows the time series of the dust aerosol index in GD and WNA. The dust aerosol index in WNA is defined as the area-averaged DCMD in the region (30–50°N, 110–125°W). The correlation coefficient between GD and WNA reaches as high as 0.73 in the whole period of 1980–2017 (Figure 4a). However, the relationship between dust aerosol in GD and WNA experiences a



**Figure 4.** (a) Time series of normalized spring DCMD\_GD index and DCMD\_WNA index. (b) Sliding correlation between the spring DCMD\_GD index and DCMD\_WNA index displayed at the central year of a 17-year window. Panels (c) and (d) are the correlation maps between DCMD\_GD index and DCMD spanning from East Asia to western North America (EA&WNA) during 1982–1998 and 2001–2017, respectively. The 95% significant level is 0.48 in 17-year correlation coefficient between two time series. DCMD = dust column mass density; GD = Gobi desert; TD = Taklimakan desert.

pronounced decadal change. For example, the correlation was weak and insignificant before mid-1990s, and afterward became stronger and statistically significant (Figure 4b). We further compare the correlation maps between the dust aerosol index in GD and the dust aerosol in the whole East Asia to western North America regions in the periods with lowest (corresponding to 1982–1998) and highest (corresponding to 2001–2017) correlations. Apparently, the high correlation is confined in East Asia in the earlier period of 1982–1998, whereas high correlation shrouded the Pacific Ocean all the way to the WNA in the latter period (2001–2017). The composite analyses based on background wind fields between the two time periods reveal that there are no obvious differences in background westerlies in the North Pacific and WNA (not shown). The loading of dust aerosol in GD is much less before the end of 1990s than that after early 2000s. The relatively low loading of dust aerosol in GD before the early 2000s may limit the transport of dust to a short distance due to the deposit effect of dust aerosol. The relatively large loading of dust aerosol in the GD source in the latter period may lead to more far transport of aerosol and exert a more pronounced influence on the dust aerosol in WNA. These results are also consistent with those based on the DEA data (Figure S4 in the supporting information).

#### 4. Discussion and Conclusion

In the present study, we analyzed the influences of TD and GD on the trans-Pacific transport of dust aerosol during 1980–2017 using DCMD and DEA data from MERRA-2 aerosol reanalysis data set, combined with atmospheric circulation data from ERA-interim reanalysis.

Compared with in TD, the dust aerosol generated in GD is found to be the most important source for eastward transport to the downstream regions, including Korea, Japan, the Pacific Ocean, and even WNA. The dust aerosol ejected from TD was confined in the Tarim Basin and showed little influence on the dust loading in the surrounding regions. This result thus provides us a solid observational evidence for the fact that GD is a main source region of East Asian dust aerosols, which has been found to be able to significantly influence the loading of dust aerosol in WNA through its trans-Pacific transport. The difference in terrain and background winds in GD and TD to a certain extent could explain the contrasting influences of dust aerosol in TD and GD. Particularly, the relatively flat terrain and prevailing westerly winds in GD are in favor of the dispersion and trans-Pacific transport of dust aerosol to reach the WNP, exerting a pronounced influence on the loading of dust aerosol in WNA. In contrast, although TD is the largest dust source region over East Asia,

it is hard to transport eastward and exert a substantial influence on surrounding regions due to the unfavorable basin terrain and background easterly winds. Our results also show that the transport of dust aerosol from GD to the WNA with the westerly is not stationary and experiences the obvious decadal changes around 1999, which is related to intrinsic change of dust loading in GD. Nevertheless, the underlying mechanism for the decadal change of dust aerosol loading in GD around 1999 is unclear. A preliminary inspection suggests that it may be related to the phase of the Pacific decadal oscillation (not shown), and this will merit further investigation in the future by combining model simulation with explicit observations. Note that the results reported in this study are based on the statistics of spring mean data. The daily or shorter scales data could provide more insightful results, which merits further analyses in the future.

Some previous studies indicated that the frequency of dust events in some stations in the western China experiences a decrease trend during recent decades (e.g., Wang et al., 2008), which seems to be inconsistent with our results based on MERRA-2 data. In fact, it should be pointed out that this inconsistency may result from different variables used. The changes of DCMD actually depend not only on the frequency but also on the intensity of dust events. Therefore, the variability of dust frequency cannot be fully equal to the variability of dust loading. Previous studies have demonstrated that the dust emission is closely tied to the intensity of the near-surface wind speeds in the dust sources both in observations and models (e.g., Allen et al., 2013; Cheng et al., 2008; Peng et al., 2012). Given that there are no long-term ground-based records of dust loading yet in the dust sources in East Asia, we utilize near-surface wind speed to verify the reliability of long-term changes of dust loading indirectly. Figure S5 shows the temporal evolution of spring DCMD index and 800hPa wind speed obtained from ERA-interim data in the dust sources over East Asia (35–45°N, 75–110°E). The long-term change of wind speed is basically consistent with the DCMD in the dust sources, with an increasing trend after early 1990s. This result indirectly verifies the reliability of MERRA-2 data in representing the long-term changes of dust loading in East Asia. In view of the lack of long-term ground-based observations for the dust loading, the MERRA2 data (observation based) may be useful as the observational proxies in some regions, although its uncertainty still need to be further verified.

#### Acknowledgments

This work was supported by the Ministry of Science and Technology of China under Grants 2017YFC1501401 and 2016YFA0600604, the National Natural Science Foundation of China under Grants 41805126, 41771399, 41605060, and 41661144016, and the Chinese Academy of Meteorological Sciences under Grant 2017Z005. MERRA-2 data were available at MDISC (<https://disc.gsfc.nasa.gov/>), managed by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). ERA-Interim data were made available through the ECMWF (<https://apps.ecmwf.int/datasets/>). The MS-AAI data were available at TEMIS (<http://www.temis.nl/airpollution/absaai>).

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