The Trend Reversal of Dust Aerosol Over East Asia and the North Pacific Ocean Attributed to Large-Scale Meteorology, Deposition, and Soil Moisture

Jianping Guo1, Hui Xu1, Lin Liu1, Dandan Chen1, Yiran Peng2, Steve Hung-Lam Yim1,4, Yuanjian Yang4, Jian Li1, Chun Zhao5, and Panmao Zhai1

1State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China, 2Department of Earth System Science, Tsinghua University, Beijing, China, 3Department of Geography and Resource Management, The Chinese University of Hong Kong, Sha Tin, Hong Kong, 4Institute of Environment, Energy, and Sustainability, The Chinese University of Hong Kong, Sha Tin, Hong Kong, 5School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China

Abstract The long-term trend in dust loading over East Asia remains under debate and is dependent on the study period chosen. In this study, the long-term trends in springtime dust over East Asia and the North Pacific Ocean (NPO) during 1980–2017 were examined based on the Modern-Era Retrospective Analysis for Research and Applications version 2 reanalysis. Results showed that there was a spatial gradient in dust aerosol loadings, with decreases from western China eastward toward the NPO. This pattern was corroborated by Cloud-Aerosol Lidar with Orthogonal Polarization observations. Furthermore, the empirical orthogonal function method was used to reveal the leading modes of springtime dust aerosol optical depth (AOD) over East Asia and the NPO. An abrupt shift occurred in the dust AOD trend in 2010 for the empirical orthogonal function 1 mode. The dust AOD increased at a rate of approximately 2 × 10⁻⁴/year during 1999–2009 and then decreased more sharply (around 5 × 10⁻⁴/year) afterward. This trend reversal of dust AOD was closely associated with a decrease in 10-m wind velocity, which induces reduced dust emission. Compared with 10-m wind, the soil moisture is less correlated with the trend reversal in dust AOD. Additionally, the trends of dry (wet) deposition were closely associated with the trends of the dust AOD, especially for the period 2010–2016. Overall, our findings add new insights to the long-term nonlinear variability of dust.

Plain Language Summary Dust aerosols originating from East Asia (EA) play an important role in the Earth’s climate system, due to their strong radiative effects. The long-term trend in dust loading in this region and surrounding areas remains unclear and is dependent on the study period chosen. Here, we investigated the long-term trends in springtime dust aerosols over EA and the North Pacific Ocean (NPO) for the period 1980 to 2017, using the Cloud-Aerosol Lidar with Orthogonal Polarization observations, along with the Modern-Era Retrospective Analysis for Research and Applications version 2 reanalysis. Time series analyses from Rodionov sequential algorithm indicated that the springtime dust aerosol optical depth (AOD) over EA&NPO experienced an abrupt shift in 2010. The dust AOD increased (2 × 10⁻⁴/year) during 1999–2009, followed by a decreasing trend (5 × 10⁻⁴/year) afterward. Besides, the roles of atmospheric circulation, deposition, and soil moisture in the shift in springtime dust aerosol trends were further analyzed. The decrease in 10-m wind velocity and reduced dry deposition partly account for this decreasing trend in dust AOD for the period 2010–2016. Our findings provide an insightful look into the drivers for the trend reversals observed in EA&NPO.

1. Introduction

The deserts in the arid and semiarid regions of northwestern China, including the Taklamakan Desert and the Gobi Desert, are some of the largest dust sources in the Eurasian continent (Ding et al., 2005). Dust aerosols not only scatter solar radiation directly but also modify the microphysical properties of clouds and precipitation through indirect radiative effects (Ge et al., 2011; Z. Liu, Yim, et al., 2018; Su et al., 2008; Wang et al., 2013; Zhao et al., 2010, 2011), thereby influencing global weather and the climate system (Guo et al., 2018; Huang et al., 2006; Li et al., 2016; R. Li, Dong, et al., 2017; Z. Li, Guo, et al., 2017; Zhao et al., 2012). In addition, dust aerosols may degrade air quality (Chin et al., 2007) and thus have adverse effects on human health (Cohen et al., 2017; Hou et al., 2010; Pope et al., 2002).
Many efforts have been made to understand the multiscale variations of the dust loading from its sources to downstream regions (Kang et al., 2016; Kurosaki & Mikami, 2003; Tian et al., 2007; Zhao et al., 2017). For instance, the dust occurrences in Mongolia and northern Inner Mongolia were shown to increase during 1998–2007, based on dust reports from synoptic observation stations, which could be caused by degraded vegetation and reduced soil moisture (Lee & Sohn, 2011). Nevertheless, a recent investigation by An et al. (2018) indicated that the number and intensity of dust events for East Asian dust source regions were declining significantly during 2007–2016, which was likely due to the improvement in vegetation coverage and the decrease in the intensity of the polar vortex. Also, a similar declining aerosol optical depth (AOD) trend observed from 2001 to 2010 over the Sahara Desert and the Middle East region was attributed to the changes in meteorology (Pozzer et al., 2015). Overall, the trend differs greatly by the regions of interest (ROIs) and the time periods chosen (e.g., Yoshino, 2002; Hara et al., 2006; Song et al., 2016; Zhao et al., 2006).

During spring, dust aerosols derived from the Taklamakan Desert and the Gobi Desert spread throughout the eastern coast of China, to Japan (Ma et al., 2005) and Korea (Kim et al., 2004; Mori et al., 2003), and then cross the Pacific Ocean to North America in the prevailing westerly winds (Guo et al., 2017; Hu et al., 2016; Huang et al., 2010, 2015; Yu et al., 2008). Therefore, the variations in dust aerosols could be strongly influenced by the meteorological fields, such as the wind speed (Yang et al., 2017) and vertical wind shear (Yang et al., 2019). The changes in tropospheric winds can affect the emission, uplift, and even long-range transport of dust aerosols (Kaskaoutis et al., 2018; Kim et al., 2005; Luan & Jaegle, 2013; Songa et al., 2008). Meanwhile, the atmospheric circulation variations are also largely impacted by some climate physical modes, including the El Niño-Southern Oscillation (Hara et al., 2006), North Atlantic Oscillation (Shao et al., 2013; Zhao et al., 2013), and Pacific Decadal Oscillation (Gong et al., 2006) and their combined effects. This may result in the nonlinear trends in dust aerosol loadings. Moreover, it is also noted that during the process of dust transport, dry- and wet depositions are nonnegligible factors influencing the dust loading in the downstream regions (Dai et al., 2018; Guo et al., 2017; Yim et al., 2019). Interestingly, soil moisture in China has shown to be experiencing significant increasing trend in recent decade (Guo et al., 2019), which could be due to the fast greening speed through land use management in this region (C. Chen, Park, et al., 2019). Therefore, the changes in soil moisture should also be taken into account when analyzing the long-term trend of dust over East Asia and the North Pacific Ocean (EA&NPO).

Although many studies surrounding the variations in dust AOD have been conducted, to date, few previous studies have comprehensively analyzed the trend of dust aerosol using a combination of observations (especially vertical-resolved ones) in association with the changes in large-scale atmospheric circulation, dust deposition, and soil moisture. It is therefore imperative to revisit the trend in dust aerosols over the past several decades in EA&NPO, and especially its possible causes.

This paper intends to make a comprehensive study of spatial-temporal variation and vertical distribution in dust aerosol over the whole EA&NPO regions by using Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) reanalysis data sets, combined with Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) observation data. More importantly, the empirical orthogonal function (EOF) method will be utilized in attempt to deepen our understanding of the long-term trend of dust over EA&NPO from 1980 to 2017, apart from analyzing the roles of meteorology, soil moisture, and deposition, respectively. The rest of paper is organized as follows. The data and methods used in this study are described in section 2. Section 3 assesses the horizontal and vertical distribution of MERRA-2 dust AOD over the study area. The analysis of the spatial and temporal variations in dust AOD and the shift in dust AOD trends are described in section 4. Section 5 discusses the roles of meteorology, deposition, and soil moisture in the shift of dust AOD trends. Finally, overall conclusions are provided in section 6.

2. Data and Methods

2.1. Data

The dust aerosol data are obtained from MERRA-2, which provides a relatively long time series of global dust AOD reanalysis data from 1980 to the present (Adhikary et al., 2008). MERRA-2 is the first long-term global reanalysis data set to assimilate space-based observations of aerosols that represent their interactions with other physical processes in the climate system (https://gmao.gsfc.nasa.gov/GMAO_products/reanalysis_
products.php). The data set provides accurate estimates of dust emissions, loadings, and deposition (Buchard et al., 2017; Randles et al., 2017) by assimilating AOD products from the spaceborne instruments such as Moderate Resolution Imaging Spectroradiometer (Remer et al., 2005), the Advanced Very High Resolution Radiometer (Heidinger et al., 2014), and the Multiangle Imaging SpectroRadiometer (Kahn et al., 2005), as well as ground-based instruments from the Aerosol Robotic Network (Holben et al., 1998).

In this study, 38 years (1980–2017) of springtime (March, April, and May) dust AOD, 10-m wind and deposition (including wet and dry depositions) data from MERRA-2 reanalysis data set are used to investigate the shift in dust aerosol trends.

To further characterize the spatial distribution of dust aerosols, we use the vertical profiles of dust particle counts at 2° × 5° grid resolution, which are derived from the CALIOP Level 3 aerosol profile products (version 3) of “CAL_LID_L3_APro” (https://subset.larc.nasa.gov/calipso/login.php). The CALIOP is a payload onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, providing high-resolution vertical profiles of aerosols (Winker et al., 2007). The CALIOP Level 3 aerosol profile product, which is simply derived from quality-screened Level 2 aerosol extinction profiles at 532 nm, offers monthly mean globally gridded aerosol profiles below 12 km with a vertical resolution of 60 m. The detailed quality filtering methods proposed by Tackett et al. (2018) have been employed. The detected aerosol profiles are further classified into six subtypes: polluted continental, biomass burning, desert dust, polluted dust, clean continental, and marine (Omar et al., 2009). Since other types of aerosols are not directly relevant to dust, here we consider only the desert dust and polluted dust aerosols in this work. Notably, there exist large certainties caused by daytime solar illumination, the signal to noise of CALIOP during daytime is not good enough (Guo et al., 2016; Liu et al., 2009), especially in the case of dust episode. Therefore, only the nighttime CALIOP products are used here. The counts of dust below a 12-km altitude can be derived from the following equation:

\[
N = \sum_{i=0}^{n} N_i,
\]

where \(N_i\) is the number of times that dust detected by CALIPSO fell in the \(i\)th 30-m (60-m) vertical bin and \(n\) is the total number of vertical bins.

To investigate the role of land surface condition in the shift in dust AOD trend, the present study uses the soil moisture from ERA-Interim reanalysis (Dee et al., 2011), which is provided on the monthly basis, and at a spatial resolution of 0.75° × 0.75°.

### 2.2. Methods

This study uses the EOF method to examine the spatial characteristics of the dominant modes of dust AOD data and the associated temporal variations in the study region. The EOF analysis can uniquely decompose the temporally and spatially varying dust AOD observations into a set of orthogonal signals that represent the maximum variance of the underlying data set (Cohen, 2014). As a statistical method, the EOF technique has been widely used in climate research since it was first introduced to the field of meteorology (e.g., Hannachi et al., 2007; Lorenz, 1956; L. Liu, Guo et al., 2018; Monahan et al., 2009; von Storch & Zwiers, 1999).

Trends are calculated using the robust Theil-Sen estimator (Sen, 1968; Theil, 1992), in which the linear trend represents the median slope between all paired values. The Theil-Sen estimator is designed to reduce the effects of outliers and end points in linear trend analyses. Confidence intervals in the median slopes are calculated as proposed by Sen (1968). Change points in the climatological time series of dust AOD are evaluated using the sequential algorithm proposed by Rodionov (2006), with a cutoff length set to 10 years. This algorithm is applied to both 3-year-running means and 3-year-running trends, where the latter are calculated using the Theil-Sen estimator. Confidence intervals in the mean value were approximately twice the standard error of the mean, after adjustment using a factor based on the degrees of freedom. Spiegelhalter’s (1977) test has been used to confirm the suitability of the mean and standard error for describing climate shifts in dust AOD over the EA&NPO region. Only climate shifts that are statistically significant at 95% confidence level are reported. Besides, the spatial relationships are utilized between the trend of dust AOD and the corresponding trends of meteorology, soil moisture, and dust deposition, which has been widely used to elucidate the mechanism underlying the long-term trends in geophysical variables (e.g., Shen et al., 2015; Xue et al., 2019).
3. Spatial Distribution of Dust Aerosols

3.1. Horizontal Distribution

In order to better understand the spatial and temporal variability of dust aerosols over EA&NPO and their mechanisms, six ROIs have been selected (Figure 1), including two ROIs at source regions (ROI-S1 and ROI-S2) and four ROIs at receptor regions (ROI-R1 to ROI-4). Based on the MERRA-2 reanalysis data set, the geographical distribution of climatological dust AOD and its variability during the period 1980–2017 is shown in Figures 1a and 1b, respectively.

High dust AOD values are mainly found over the desert regions of northwestern and northern China, including the Taklamakan Desert (ROI-S1) and Gobi Desert (ROI-S2). As the two major dust source regions in EA, the regional mean dust AOD values are higher than 0.4 and 0.2 over ROI-S1 and ROI-S2, respectively. The regional mean dust AOD value gradually decreases to 0.13 over northeast China (ROI-R1) all the way to the western coast of North America (ROI-R4) with AOD of 0.07, due to the increase in distance from source regions. This distribution pattern features a large dust gradient belt (25–45°N) extending from the desert regions of Taklamakan and Gobi via the NPO to North America, which is consistent with previous satellite observations (e.g., Huang et al., 2008; Proestakis et al., 2018; Uno et al., 2009). Furthermore, a larger variability in dust AOD is observed in the Taklamakan Desert and the Gobi Desert compared with other regions (Figure 1b). This may result from the quite different magnitudes of the climatic dust AOD state in source domains and downstream regions. Besides, the large interannual variability of springtime EA dust could in part account for this phenomenon (Chen et al., 2019).

3.2. Vertical Distribution

To further characterize the spatial distribution of dust particles, the vertical profiles of dust loadings derived from CALIOP over six ROIs are illustrated in Figure 2. Due to the large potential retrieval uncertainties in CALIOP-observed aerosol profiles near the surface (Guo et al., 2016), dust layers below 1.5 km were not analyzed in this study. Results show that the largest dust loadings are over the Gobi Desert in western China (ROI-S2; N = 111,162; Figure 2b). This result suggests that the Gobi Desert is the largest source of the dust aerosols emission. Meanwhile, the dust loading gradually decreased from the dust source regions to the NPO (Figure 2), which could be likely due to the decreases in dust deposition with the increasing distance (Colarco et al., 2003).

The vertical profiles also illustrate that dust counts are increasing from the near surface to approximately 2–4 km height and then decline with the increasing altitudes in all six ROIs. The peak of dust counts is around 3 km height in Taklamakan and Gobi Deserts (Figures 2a and 2b), and it declines to around 1.2 km height in the Northeastern China (Figure 2c). It implies that vertical distribution of the dust counts from the dust sources to the downstream region is influenced by the deposition effect to some extent. This is consistent with previous studies (Huang et al., 2008; Sun et al., 2001), which concludes that dust layers have low-altitude peaks (around 1–3 km) over their source regions, although dust could also be present at higher altitudes (8–10 km) due to entrainment. Moving from the desert source regions toward the east coast of China, most of the observed dust is at altitudes below 2 km over northeast China. Depending on the dust source region, dust aerosols over the NPO generally reach higher altitudes (usually around 4–6 km but can be up to 10 km; shown in Figures 2d and 2e), likely due to the interactions of synoptic-scale, mesoscale and local-scale circulations (Guo et al., 2010; Yang et al., 2018). This tends to lift the aerosols that have originated from distant sources and are subsequently transported to the downwind regions by westerly winds in the middle and high troposphere (Guo et al., 2017).

4. The Dominant Mode and Shift in Springtime Dust Trends Over EA&NPO

As described in above section, the variations in springtime dust AOD are much more evident over EA, with the most pronounced variability located over dust source regions (Figure 1b). To elucidate further the characteristics of dust AOD variations over the EA&NPO region, EOF analysis is performed using MERRA-2 dust AOD reanalysis data. In the following discussion, the first two leading modes will be analyzed, which are significantly separated from other modes according to North et al. (1982).

The spatial pattern of the EOF1 of dust AOD is characterized by the loading of same sign over the whole study area (Figure 3). EOF1 explains 59.1% of the total variance in dust AOD over the EA&NPO region.
Besides, it is noteworthy that the temporal evolution of the corresponding principal component (PC1) experiences an abrupt change around 1999, with the negative phase dominating before, whereas the positive phase dominating afterward (Figure 3c). The power spectrum of PC1 shows that it was dominated by low-frequency variations with a spectral peak larger than 10 years (Figure 3e). During the positive (negative) phase of PC1, dust AOD exhibits positive (negative) anomalies over most areas of EA&NPO. Therefore, the EOF1 mode is determined to represent the phase variations in dust AOD over the EA&NPO region.

To characterize the abrupt change in PC1, a moving average method was carried out on PC1 with a 3-year time window (Figure 4). Visually check indicates that a decadal temporal shift took place around 1999 that
involved PC1 changing from the predominant negative phase to a positive phase. Further application of the climate change point detection algorithm developed by Rodionov (2006) reveals that dust aerosol does not exhibit monotonic linear trend but contains two tipping points. One turning point is in 1999, with a change in PC1 from \(-0.71 \pm 0.25\) during 1980–1998 to 1.06 ± 0.53 during 1999–2009. Another point is detected in 2010, when the mean PC1 state changed from 1.06 ± 0.53 during 1999–2009 to 0.34 ± 0.62 during 2010–2016. Compared with the increasing trend from 1999 to 2009, the decreasing trend from 2010 to 2016 is more significant, with a negative slope as large as \(-0.27\). This first tipping point could be related to the fact that the AOD products began to be assimilated to MERRA-2 from Moderate Resolution Imaging Spectroradiometer onboard Terra satellite since December of 1999 (Remer et al., 2005). However, our focus is on the second tipping point that occurred in 2010. Therefore, the trend reversal observed around 2010 could not be due to the abrupt changes in data sources being assimilated into MERRA-2 products.

Correspondingly, the spatial distribution of the trends in springtime dust AOD during the periods 1999 to 2009 and 2010 to 2016 are displayed in Figure 5 in attempt to verify further the shift in PC1 trends. It can be clearly seen that dust AOD exhibited an increasing trend over most areas of EA&NPO between 1999 and 2009 (Figure 5a). Nevertheless, it is worth noting here that this trend is not obvious, since there were only a few areas in which dust AOD trends passed the significance test at the 95% confidence level (Figure 3a). This result is in general agreement with several previous studies (e.g., Chin et al., 2014; Kurosaki et al., 2011; Wang et al., 2017). For example, dust loadings over Mongolia, Inner Mongolia, and Northeast China were found to be enhanced by up to 5% between 1990–1999 and 2000–2009. On average, linear trend analysis over EA&NPO implies that dust AOD increased at a rate of approximately \(2 \times 10^{-3}\)/year over these areas for the period 1999 to 2009. Consistent with our results, Chin et al. (2014) showed similar increasing trends in dust related AOD over EA during 2000–2009 by combining model-simulated dust AOD

Figure 3. Empirical orthogonal function (EOF) analyses performed on the Modern-Era Retrospective Analysis for Research and Applications Version 2 dust aerosol optical depth reanalysis over East Asia and trans-Pacific Ocean in spring from 1980 to 2017. The spatial patterns of EOF1 (a) and EOF2 (b), the time series of corresponding principle component (PC) of EOF1 (c) and EOF2 (d), and the spectrum of PC1 (e) and PC2 (f).
and dust observations from multiple satellite sensors and ground-based networks. Similarly, Wang et al. (2017) demonstrated that the frequency of large-scale and longer-lived dust storms over northern China increased from 1997 to 2007. More importantly, the EOF1 pattern shown in Figure 3a agrees well with the spatial distribution in springtime dust AOD trends by Wang et al. (2017). This further confirms that the trend is the dominant feature of dust AOD variability over the EA&NPO region.

The shift in the trend of PC1 after 2010 is evidenced by the opposite tendency in dust AOD, which shows a significant negative trend (about $-5 \times 10^{-4}$/year) during the time period 2010 to 2016 (Figure 5b). This decreasing tendency in springtime dust AOD during the last decade over EA has been noticed in recent studies (e.g., Kang et al., 2016), which should be interpreted carefully when compared to the previous studies. However, they did not perform the change point detection for the year-to-year records of dust, and their study periods generally included the active dust emission period during 2007–2010. In addition to the first EOF mode, the spatial pattern of the second mode (EOF2) and the corresponding time series (PC2) are also

**Figure 4.** Time series of normalized Principle Component 1 of dust aerosol optical depth (blue bars). The black curves indicate the 3-year moving average based on the annual Principle Component 1 of dust aerosol optical depth, and the red lines show the linear trends, which are calculated based on the robust Theil-Sen estimator. The red-shading areas enveloped by dotted lines indicate 95% confidence intervals on the trends in this normalized time series. The vertical dash black lines mark the years experiencing significant trend reversals.

**Figure 5.** Spatial distributions of the linear trends in springtime dust aerosol optical depth (AOD) from Modern-Era Retrospective Analysis for Research and Applications Version 2 reanalysis over the East Asia and the North Pacific Ocean for the period from 1999 to 2009 (a) and that from 2010 to 2016 (b), respectively. The stippling areas indicate that the trend is statistically significant at the 95% confidence level.
The EOF2 displays a positive loading in the source region of dust and transport pathway approximately to the south of 30°N, even though it simply accounts for 12.1% of the total variance in dust AOD in the whole domain of EA&NPO. The corresponding time series of PC2 (Figure 3d) presents both decadal variations and interannual fluctuations. Notably, during the positive phases of PC2, dust AOD has significant positive anomaly in the source region of dust and along the transport route as well, and vice versa. Given the small variation explained by the EOF2 component, our analysis focus will be on the variations of EOF1 mode in the following sections.

5. Roles of Meteorology, Soil Moisture, and Dust Deposition in the Shift of Dust AOD Trends

Apart from dust deposition, the soil moisture, local-, regional-, and synoptic-scale meteorological factors are also key to the dust emissions and long-range transport (Beegum et al., 2018; Guo et al., 2013; Hermida et al., 2018). As such, in this section we will discuss the relative roles by meteorology, soil condition, and dust deposition, in an attempt to better understand the mechanisms underlying the trend reversal in dust variations observed over EA&NPO.

5.1. Role of Meteorology in the Shift of Dust AOD Trends

Dust AOD is known to be significantly associated with surface wind speed. Strong winds can cause large amounts of dust to be emitted into the atmosphere. Previous studies demonstrated that the cube of the wind speed is highly correlated with AOD. The correlation coefficient between AOD and the cube of wind speed is given in Figure 6 for the period from 1999 to 2009 (a) and from 2010 to 2016 (b), respectively.

![Figure 6](Image)

**Figure 6.** Correlation maps between normalized Principle Component (PC) 1 of dust aerosol optical depth and the cube of the 10-m wind speed ($V_{10m}^3$) over the East Asia and the North Pacific Ocean for the period from 1999 to 2009 (a) and the period from 2010 to 2016 (b), respectively.

The spatial relationships between the trend of dust aerosol optical depth (AOD) and the corresponding trend of $V_{10m}^3$ over six regions of interest (ROIs) over the East Asia and the North Pacific Ocean for the periods (a) from 1999 to 2009 and (b) from 2010 to 2016, respectively. The correlation coefficients are given for six ROIs in each panel as well. Note that each sample represents one grid over a given ROI, which is colored according to the six ROIs.

![Figure 7](Image)

**Figure 7.** Spatial relationships between the trend of dust aerosol optical depth (AOD) and the corresponding trend of $V_{10m}^3$ over six regions of interest (ROIs) over the East Asia and the North Pacific Ocean for the periods (a) from 1999 to 2009 and (b) from 2010 to 2016, respectively. The correlation coefficients are given for six ROIs in each panel as well.
speed has a much stronger correlation with dust emission than wind speed (e.g., Allen et al., 2013; Marticorena & Bergametti, 1995). Particularly, the dust uplifting is directly proportional to the cube of the wind speed at 10 m above surface ($V_{10 \text{ m}}^3$; Gillette & Passi, 1988). As such, even a small increase in surface wind speed could lead to substantial increases in dust emissions. In spring, there is high frequency of strong winds over EA. The strong winds not only generate dust storms but also lift dust into the westerly jet in the free atmosphere. To explore the possible relationship between surface wind speeds and the shift in dust AOD trends, we first examine the correlation coefficients ($R$) between $V_{10 \text{ m}}^3$ and PC1 for the periods 1999–2009 (Figure 6a) and 2010–2016 (Figure 6b), respectively. The correlation maps are obtained from the temporal $R$ value between PC1 and $V_{10 \text{ m}}^3$ at each grid point. The correlations between PC1 and $V_{10 \text{ m}}^3$ are positive over northern China and Mongolia. The spatial pattern of the correlations over the Gobi Desert, one of large dust source regions in EA, is similar to that of EOF1 (Figures 3b and 6b), suggesting that the temporal variations in dust AOD over the dust source regions are associated with changes in $V_{10 \text{ m}}^3$. In order to further explore the possible links between the shift in dust AOD trends and the changes in $V_{10 \text{ m}}^3$, a correlation analysis has been performed between the dust AOD trend and $V_{10 \text{ m}}^3$ trend at each grid points for six ROIs during the periods 1999–2009 (Figure 7a) and 2010–2016 (Figure 7b), respectively. During the period 1999–2009, $R$ value in ROI-S1 is as high as 0.56, indicating that the increase in dust AOD is accompanied by the increase in $V_{10 \text{ m}}^3$ in the Taklamakan Desert (Figure 7a). During the period of 2010–2016, $V_{10 \text{ m}}^3$ in the Gobi Desert exhibits a significant declining trend, which is closely associated with the decreasing dust AOD (Figure 7b). These findings have been well confirmed by previous observational efforts. For instance, Tan et al. (2012) used observations from meteorological stations to show that the interannual variation in spring dust storms over Inner Mongolia is positively correlated ($R = 0.75$) with wind speed during 2000–2007. Besides, long-term model simulation studies (e.g., Gong et al., 2006) demonstrate that the emission of springtime Asian dust aerosols is strongly correlated with the surface wind speed in source regions.

Figure 8. The same as Figure 5, but for $V_{10 \text{ m}}^3$ over the East Asia and the North Pacific Ocean.
is similar to that of the linear trend in dust AOD over the Taklamakan Desert and Gobi Desert (Figures 5a and 8a), indicating that the increasing trend in dust AOD is somehow linked to the increase in $V_{10 \text{ m}}^3$ over dust source regions. In contrast, $V_{10 \text{ m}}^3$ shows a negative trend over the Gobi Desert during 2010–2016 (Figure 8b). Over the Gobi Desert, the spatial pattern of the linear trends in $V_{10 \text{ m}}^3$ is similar to that of the linear trends in dust AOD (Figures 5b and 8b), suggesting that the decreasing trend in dust AOD is associated with the decreases in $V_{10 \text{ m}}^3$ over the dust source regions. Overall, the shift in trend in dust AOD, from increasing to decreasing, is likely attributed to the decrease in $V_{10 \text{ m}}^3$.

To better illustrate the effect of large-scale atmospheric circulation on the shift in dust aerosol trends over EA, the trends in the cube of the 10-m wind vectors for the periods of 1999–2009 and 2010–2016 are shown in Figure 9. From the perspective of climatology, the easterly winds prevail in the Taklimakan Desert, and the westerly winds prevail in the Gobi Desert, which accounts for most parts of the dust emissions in the EA (Figure 9a). During the former time period, there are easterly anomalies in the Taklimakan Desert that tend to strengthen the background easterly and intensify the wind speed in the Taklimakan Desert (Figure 9b). This is consistent with the linear trends in 10-m wind speed as revealed in Figure 8a. The enhanced wind velocity facilitates the uplifting of the dust aerosols and thus results in the increase in AOD trend in the Taklimakan Desert (Figure 5a). During the latter time period, there are easterly anomalies in the Gobi Desert during 2010–2016, which tend to weaken the background wind speed and reduce the uplifting of dust aerosols in the Gobi Desert. Thus, the dust aerosols reverse to decreasing tendency during the period 2010–2016 compared with the period 1999–2009.

5.2. Role of Soil Moisture in the Shift of Dust AOD Trends

The soil moisture, among others, is another primary factor that controls interannual variation in the frequency and intensity of dust emissions (e.g., Ishizuka et al., 2005). Soil moisture favors the improvement in vegetation coverage, thereby suppressing the dust emission and thus reducing the intensity and frequency of dust emissions. To explore the possible role of soil moisture in the trend reversal of dust AOD, we first examine the correlation coefficients ($R$) between soil moisture and PC1 for the periods 1999–2009 (Figure 10a) and 2010–2016 (Figure 10b), respectively. The correlation maps are obtained from the temporal $R$ value between PC1 and soil moisture at each grid point. For the period from 1999 to 2009, the correlations between PC1 and soil moisture are negative over the Taklimakan Desert and Gobi Desert. The spatial pattern of this correlation over the dust source regions is opposite to that of EOF1 (Figures 3a and 10a), suggesting that the temporal variations in dust AOD over the dust source regions are negatively associated with changes in soil moisture. In contrast, during the period from 2010 to 2016, positive correlations are observed between PC1 and soil moisture over the dust source regions. More importantly, the $R$ values between the dust AOD trend and soil moisture trend at each grid points for six ROIs (Figure 11) are much lower than those between the dust AOD trend and soil moisture trend at each grid points for six ROIs (Figure 11).
V_{10\text{ m}}^3 trend. This further indicates that the impact of soil moisture is much less than that caused by V_{10\text{ m}}^3.

Figure 12a shows that soil moisture V_{10\text{ m}}^3 exhibits a negative trend in the Taklamakan Desert and Gobi Desert during 1999–2009. This spatial pattern of soil moisture trend V_{10\text{ m}}^3 is opposite to that of dust AOD trend over the Taklamakan Desert and Gobi Desert (Figures 5a and 12a), indicating that the increasing trend in dust AOD is somehow linked to decreases in soil moisture V_{10\text{ m}}^3 over dust source regions. Nevertheless, soil moisture also V_{10\text{ m}}^3 exhibits a decreasing trend over the Gobi Desert and the Taklamakan Desert during 2010–2016 (Figure 12b). Overall, the shift in trend in dust AOD, from increasing to decreasing, is not depended on the soil moisture very much. Therefore, we argue that the impact of soil moisture on the temporal disparity of dust AOD trends could not be of paramount significance but be much less than the impacts caused by 10-m wind speed and wind direction.

5.3. Role of Deposition in the Shift of Dust AOD Trends

The dust in the atmosphere can be removed via deposition processes, including wet scavenging and dry deposition (Chen et al., 2014). Figure 13 illustrates the spatial relationships between the dust AOD trend and the trend of various deposition components for six ROIs during the periods 1999–2009 and 2010–2016, respectively. During the former period, the R values are almost uniformly positive in most ROIs, indicating that the increase in dust AOD is generally accompanied by more dry deposition (Figure 13a). In contrast, dust AOD exhibits a significant decreasing trend during the latter period, resulting in a dramatic reduction in dry deposition. Given the relative large R values (greater than 0.5, Figure 13b), the dust AOD is most likely to be highly correlated with and dry deposition. This finding agrees well with previous studies.

Figure 12. Spatial distributions of the linear trends of soil moisture (SM) over the East Asia and the North Pacific Ocean for the period from 1999 to 2009 (a) and from 2010 to 2016 (b), respectively. The stippling areas indicate that the trend is statistically significant at the 95% confidence level.
which concluded that the deposition intensity is highly associated with dust AOD in recent decade. On average, the $R$ values are higher over dust source regions (ROIs 1–3) than the receptor regions (ROIs 4–6) during the period 1999–2009. A similar result is also found for the period of 2010–2016. As illustrated in Figures 13c and 13d, the trend of dust AOD for the period 1999–2009 is negatively correlated with the trend of wet deposition, due to the negative $R$ values observed in most ROIs. This result is consistent with previous studies arguing that dust emissions are negatively correlated with precipitation (e.g., Gong et al., 2006). However, a close-up look at Figure 13d indicates that the $R$ values are nearly zero in dust source regions, which demonstrates that the changes in wet deposition may not be the main reason for shifts of dust AOD trends. For the period of 2010–2016, the $R$ values become much larger. In particularly, much higher $R$

Figure 13. Same as in Figure 7, but for the spatial relationships between the trends of dust aerosol optical depth (AOD) versus the corresponding trends of dry deposition (a and b), wet deposition (c and d), and total deposition (e and f) during the period 1999–2009 (left column) and 2010–2016 (right column) over six regions of interest.

(e.g., Shao et al., 2013), which concluded that the deposition intensity is highly associated with dust AOD in recent decade. On average, the $R$ values are higher over dust source regions (ROIs 1–3) than the receptor regions (ROIs 4–6) during the period 1999–2009. A similar result is also found for the period of 2010–2016. As illustrated in Figures 13c and 13d, the trend of dust AOD for the period 1999–2009 is negatively correlated with the trend of wet deposition, due to the negative $R$ values observed in most ROIs. This result is consistent with previous studies arguing that dust emissions are negatively correlated with precipitation (e.g., Gong et al., 2006). However, a close-up look at Figure 13d indicates that the $R$ values are nearly zero in dust source regions, which demonstrates that the changes in wet deposition may not be the main reason for shifts of dust AOD trends. For the period of 2010–2016, the $R$ values become much larger. In particularly, much higher $R$
values are observed in ROI-R1 to ROI-R3 than those in ROI-S1 and ROI-S2, indicating a much more significant dominant role of dust wet deposition in dust receptor regions compared with dust source regions. This could be due to wet deposition being the dominant removal process along the trans-Pacific transport pathway, which is closely associated with the frequent precipitation episodes over the NPO (Guo et al., 2017; Park et al., 2010; Zhao et al., 2003).

Figures 13e and 13f illustrate the spatial relationships between dust AOD trend and dust deposition (wet + dry) trend during the periods of 1999–2009 and 2010–2016. For the period 1999–2009, the $R$ values observed in dust receptor regions (ROI-R1 to ROI-R4) are obviously negative, while the $R$ values in dust source regions (ROI-S1 and ROI-S2) are nearly zero. This is most likely due to wet deposition being the dominant removal process both in the desert regions and along the trans-Pacific transport pathway. For the period of 2010–2016, the $R$ values are positive both in the dust source and receptor regions (ROI-S1, ROI-S2, and ROI-R1 to ROI-R4), indicating the decreases in dust deposition is correlated with the decreasing trend of dust AOD. Therefore, at this point, we can argue that the role of dust deposition, no matter if it is dry, wet, or dry-and-wet deposition, varies with time in governing the temporal disparity in long-term dust trend over EA&NPO.

6. Concluding Remarks

Based on 38-year (1980–2017) record of dust AOD, atmospheric circulation and dust deposition data from MERRA-2 reanalysis, and soil moisture data from ERA-Interim reanalysis, the spatial and temporal variations of springtime dust AOD have been analyzed over EA&NPO. Furthermore, the EOF method is applied to elucidate the long-term trend, and a reverse trend has been revealed in dust AOD over the last several decades. The possible physical mechanisms have also been laid out responsible for its possible temporal disparity of dust AOD.

In a climatological mean sense, the geographic distribution of dust AOD features a zonal belt with a significant dust gradient extending from the desert source regions such as Taklimakan Desert and Gobi Desert, via East China, all the way to North America. This agrees well with the well-known trans-Pacific transport pathway revealed by previous multiple satellite observations. Besides, CALIPSO measurements show that the vertical profiles of dust exhibit similar pattern: Dust particles can be lifted to approximately 2–4 km height in the source region, then decline sharply over downwind regions, which is approximately proportional to the distance to the source region of dust.

Moreover, the EOF method is employed to reveal the dominant variation characteristics of the spring dust aerosols. The spatial pattern of the EOF1 in dust AOD is characterized by a same sign loading over the whole study area and declines from the dust sources to the downstream regions. The principal component (PC1) of dust experienced an abrupt change around the 2010, with the positive phase dominating during the period 1999 to 2009, followed by the negative phase afterward. During the period of 1999–2009, the dust AOD on average increased at a rate of approximately $2 \times 10^{-5}$/year over EA&NPO. In contrast, the dust AOD decreases significantly from 2010 to 2016 with a rate of $-5 \times 10^{-4}$/year. Coincidently, there existed anomalies in easterly winds over the Taklimakan Desert, which tended to strengthen the background easterly and to facilitate the uplifting of the dust aerosols, thereby increasing the AOD. In contrast, there are easterly anomalies in the Gobi Desert during 2010–2016 that weakened the background wind velocity and thereby reducing the uplifting of dust aerosols. Furthermore, the possible effects of soil moisture on this temporal disparity (1999–2009 vs. 2010–2016) over EA&NPO are further analyzed. Results show that the correlation coefficient ($R$) values between the dust AOD trend and soil moisture trend at the dust source and receptor regions are lower than that between the dust AOD trend and $V_{10 m}$ trend. As such, the impact of 10-m surface wind on the shift in dust AOD trends could be larger than the impacts of soil moisture.

In the end, the possible impacts of dust depositions on this temporal disparity (1999–2009 vs. 2010–2016) over EA&NPO are analyzed. The intensities of dry, wet, and dry-and-wet deposition are found to be positively linked to the loading of dust aerosols, to varying degrees. Compared to the high association in the period 2010 to 2016, the deposition of dust is far less correlated with the shift of dust long-term trend for the period 1999 to 2009. This indicates that the impact of dust deposition could be much less than those exerted by 10-m wind speed and wind direction before 2010. Further, the pronounced reduction in dust deposition during the period of 2010–2016 may be caused by the significant declining trend in dust AOD. Overall,
10-m wind is a paramount factor influencing the shift of the dust AOD trends over EA&NPO. Our findings provide an insightful look into the long-term variability of dust, even though more explicit model simulation work is merited in order to better elucidate the mechanism behind temporal disparity of dust observed over EA&NPO.

Acknowledgments
This work was supported by the National Key R&D Program of China (2017YFC1501403); National Natural Science Foundation of China under Grants 41771399, 91544217, 41775137, and 41805126; and the Chinese Academy of Meteorological Sciences (2018Y014 and 2017Z005). Chun Zhao is supported by the National Natural Science Foundation of China (Grant 41775146). Also, we would like to sincerely acknowledge the NASA for granting access to the aerosol vertical data from CALIPSO and the meteorological data from MERRA-2 Reanalysis, which are publicly available at https://subset.larc.nasa.gov/calipso/login.php and https://gmao.gsfc.nasa.gov/GMAO_products/reanalysis_products.php, respectively.

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