Distinct effects of winter monsoon and westerly circulation on dust aerosol transport over East Asia

Liu Yang

Institute of Earth Environment, Chinese Academy of Sciences

Zhengguo Shi (✉ shizg@ieecas.cn)

Institute of Earth Environment, Chinese Academy of Sciences

Hui Sun

Institute of Earth Environment, Chinese Academy of Sciences

Xiaoning Xie

Institute of Earth Environment, Chinese Academy of Sciences

Xiaodong Liu

Institute of Earth Environment, Chinese Academy of Sciences

Zhisheng An

Institute of Earth Environment, Chinese Academy of Sciences

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Abstract

The transport of dust aerosol in East Asia is affected by the East Asian winter monsoon (EAWM) and westerly circulation both for modern and geological periods. There are obvious seasonal changes in the intensity and range of EAWM and westerly jet; however, their impacts and relative contributions to East Asian dust transmission are still unclear. In this study, we use Regional Climate Model 4 (RegCM4) to simulate the changes in the East Asian dust cycle under present conditions, assessing the effects of EAWM and westerly jet on dust transport. The results show that the dust at the upper level is mainly transported by the westerly circulation, while that of the lower layer is mainly transported by the EAWM. In March, the westerly jet is located on the south side of the Tibet Plateau and the high-level dust aerosol is transmitted eastward to the northern Pacific. Low-level dust is transmitted to the southeastern China with the influence of EAWM. With the northward shift of the westerly jet, the control range of the westerly winds increases in May and their correlations are weakened. In contrary, the impact of EAWM on the lower layer dust is enhanced. Due to the strengthened interaction between the westerly winds and the EAWM, they can both affect the middle-level dust transmission. The effect of EAWM is sensitive to the dust particle sizes. Under the action of EAWM, fine-grained dust is transmitted far away, while coarse-grained dust is limited to the vicinity of the source area. Once the dust is carried to the westerly layer, the influence of westerly winds on the transmission of different particle sizes dust is similar.

1 Introduction

Mineral dust, mainly from desert areas, is an important component of tropospheric aerosols (*Ridgwell, 2002*), and has a significant impact on air quality and human health. Dust aerosol changes the climate by scattering and absorbing solar radiation (*Song et al., 2014; Wang et al., 2014*), or by changing the number of cloud droplets and the lifetime of the cloud, influencing the short-wave radiation and the amount of precipitation (*Twomey, 1977; Albrecht, 1989; Li et al., 2011a; Liu et al., 2011; Ding et al., 2013; Yang et al., 2013; Ji et al., 2011*). Dust connects different earth spheres through emissions, translations, and depositions (*IPCC, 2013*). The long-distance transport of dust aerosol affects the deposition of terrestrial loess and oceanic chemical cycles and iron in dust has an essential impact on the exchange of ocean-atmospheric CO₂ (*Cassar et al., 2007*). Therefore, researches on dust aerosol become a global hotspot in past decades.

East Asia dust is an important component of global dust cycle, which accounts for about 11% of the total global emission and 6% of the total load in the atmosphere (*Tanaka et al., 2006; Taichu et al., 2006; Shao et al., 2011; Hu et al., 2019*). Investigations of East Asia dust deposition indicate that 30% of the dust in the atmosphere settles in the desert, 20% in the mainland China, and 50% transports to the Pacific and other places across long distances (*Zhang et al., 1997*). Observations, numerical simulations, and satellite imagery shows that dust in East Asia can be transmitted to the North Pacific Ocean and western coast of the United States (*Holzer et al., 2003; Tanaka et al., 2006*). The Taklimakan Desert and the Gobi Desert are two major dust source areas in East Asia (*Sun et al., 2001; Chen et al., 2014; Abulaiti et al., 2014; Lee et al., 2012; Li et al., 2012*), which account for 70% of total Asian emissions (*Zhang et al.,*

2003). The dust from Mongolia and China are the primary sources of dust deposits in the Loess Plateau and southeastern China (*Sun, 2002; Shao et al., 2003; Tan et al., 2012*). The dust of Taklimakan Desert can be carried to higher than 5,000 meters and then transported over long distances. They are an essential source of aeolian sediments in the North Pacific (*Shi and Liu, 2011*).

East Asian monsoon and westerly circulations have an impact on the eolian dust transmission, respectively. The low-level dust concentration can be affected by the EAWM and the strong winter monsoon transports dust away from the source area (*Lou et al., 2016; Zhang et al., 2010; Yan et al., 2011; Zhu et al., 2012; Wang et al., 2018; Li et al., 2016*). *Hao et al. (2006)* found there is always higher AOD over the South China Sea in winter with strong winter monsoon, which is conducive to transporting aerosols from the land. Both observations and numerical simulations suggest that the seasonal variation of aerosol concentrations over eastern China has a strong negative correlation with the summer monsoon (*Yumimoto et al., 2015; Niu et al., 2010; Qin et al., 1997*). While the monsoon circulation controls the regional scale transport of Asian dust, the global scale transport is mainly realized by the westerly circulation (*Guo et al., 2017; Uno et al., 2009*). The strength of the westerly winds and the position of large-scale meteorological features were related to the dust concentrations over eastern Asia (*Wu et al., 2017; Gao et al., 1992*). The mid-latitude westerly winds are considered as an essential factor in North American dust from northwestern China (*Yu et al., 2012*). By simulating the transmission path of dust during a dust storm, *Guo et al., (2017)* proved that the dust on the upper troposphere is mainly transmitted along with the westerly circulation.

Marine and loess deposits, as the vehicles of past climate, can reverse inference the changes in circulation strength during geological periods (*Yang et al., 2015; Wen et al., 2017; Sun et al., 2008; An et al., 2001; Poter and An, 1995; An et al., 1991; Dong et al., 2017; Hovan et al., 1989*). Meteorological observation on modern dust emissions and decomposition results of loess grain size data have suggested that two significant dynamics, including near-surface northwesterly winter monsoon and high-altitude westerly jet, are responsible for the dust transportation and deposition processes in East Asia (*Sun et al., 2004; Prins et al., 2007; Lin et al., 2016*). Asian monsoon velocity changes may affect the loess grain size. When the younger dryas event occurs, the East Asian winter monsoon strengthened, causing the coarse dust is carried and accumulated on the Loess Plateau (*Yang and Ding, 2014*). During glacial intervals, the surface winter speeds are accelerated, and the particle size of the loess becomes coarse (*Sun et al., 2008; Sun et al., 2011*). During the cold period, strong westerly circulation brings the dust sediments to the Japan Sea (*Dong et al., 2017*). The intensity of the westerly circulation can not only change the particle size of the sediment, but also change the dust transport path (*Nagashima et al., 2007*). Therefore, to fully understand the effects of winter monsoon and westerly circulation on dust aerosol transport can provide theoretical support for paleoclimate dynamics.

In this study, we use a regional climate model experiment to evaluate the effects of EAWM and westerly winds on dust transport over East Asia with a special focus on their seasonal changes. We compare the contribution of monsoon and westerly winds to dust transport in different months (March, May, and July) as an analogy of warm and cold periods. The model and experiments are introduced in Section 2. The

results, including the effects of winter monsoon and westerly circulation on dust aerosol transport over East Asia, are shown in Section 3. The discussion and conclusion are presented in Section 4 and 5, respectively.

2 Model And Experiments

The model used in this study is the Regional Climate Model version 4.1 (RegCM4.1), which is developed and supported by the National Center for Atmosphere Research (NCAR) and the International Center for Theoretical Physics. RegCM4.1 has primitive equation, hydrostatic, grid point limited area model, with σ -pressure vertical coordinate, and its dynamic framework is based on the hydrostatic core of the mesoscale model MM5. The Biosphere Atmosphere Transfer Scheme (BATS1e) is the land surface process schemes (Yang *et al.*, 1997; Oleson *et al.*, 2008), and the dust cycle diagnose can only use BATS1e (Sun *et al.*, 2017). The coupling of the dust module is based on the dust emission mode (Alfaro and Gomes, 2001).

The dust module of RegCM4.1 takes into account the dust emission, transmission, dry and wet deposition of different particle sizes, which divides the dust into four particle sizes, i.e., the fine (0.01-1.0 μm), accumulation (1.0-2.5 μm), coarse (2.5-5.0 μm) and the giant (5.0-20.0 μm) modes. The description of the sanding process in the dust module is critical, which is depend on the wind, soil properties and particle size of the dust. The estimation of dust emission is mainly divided into the following three steps (Zakey *et al.*, 2006). Firstly, it is determined whether the soil in the grid can be subject to wind erosion, which is depending on soil texture, soil type, particle size and composition. Secondly, the friction velocity threshold of the wind erosion is calculated. When the friction velocity exceeds the threshold, the dust will leave the ground and the dust emission can be regarded as a function of friction velocity (Marticorena and Bergametti, 1995). Finally, the horizontal and vertical emissions of dust are calculated. The horizontal mass flux can be considered as a function of the dust particle and the vertical mass flux depends on the kinetic energy during dust emission.

In the experiment, changes in the East Asian dust cycle during 1988-2009 are simulated. To eliminate the influence of other aerosols, only the dust aerosol is included. The initial and boundary conditions are derived from NCAR/NCEP reanalysis data. The NOAA sea surface temperature data is chosen. The spatial resolution is set to 40km and the center of the domain is 32°N, 105°E, with 160 grids in the north-south direction and 240 grids in the east-west direction. The model is based on the standard σ coordinate system, which simulates 18 layers with the model top at 10 hPa. The model was integrated from January 1, 1988 to December 31, 2009, with the first two years as the spin-up time. The results of the last 20 years are analyzed.

In order to evaluate the model performance, we compare the simulated results with the ERA-interim reanalysis from 1990 to 2009, which the spatial resolution is 2.5° $\times$ 2.5°. The westerly index over East Asia is defined by the averaged 200hPa westerly wind velocity for 35°N-50°N, 80°E-110°E. The EAWM index is the averaged 850hPa northerly wind speed for 35°N-45°N, 100°E-120°E and the East Asia

Summer Monsoon (EASM) index is the averaged 850hPa southerly wind speed for 25°N-35°N, 100°E-120°E. To consider the seasonal changes of westerly jet and East Asian monsoon, the modeling results for dust transport process in March, May and July are analyzed.

3 Results

The model performance of wind field is first validated by ERA-interim reanalysis data (Fig. 1). The high-level westerly winds in March, May, and July are gradually weakened, and the westerly jet moves northwards. In March, the location of the westerly jet is at 30°N, and the maximum value is over the east of the Tibet Plateau (Fig. 1d). In May, the jet moves northwards from the southern part of the Tibet Plateau (Fig. 1e). The velocity decreases and the position slightly moves to the north. In July, the jet moves to 45°N and the speed is significantly weakened (Fig. 1f). In the low-level atmosphere, China and Mongolia is controlled by the EAWM in March and the main wind direction is the northwesterly (Fig. 1j). In May, the northern China was still controlled by the winter monsoon, while the EASM develops over southern China (Fig. 1k). In July, the summer monsoon, prevailing by the southerly winds, controlled the whole East Asia (Fig. 1l). In the simulations, the seasonal changes in the westerly jet and monsoon is in agreement with the reanalysis data (Fig. 1a-1c, 1g-1i).

The validity of our simulation was examined by comparing the simulated aerosol optical depth (AOD) over East Asia with CALIPSO, as shown in Figure 2. From March to May (Fig. 2a and 2b), the AOD over the Taklimakan Desert, the Gobi Desert and the Loess Plateau gradually increased, while it decreased in July (Fig. 2c). In Central Asia, the AOD gradually increased from March to July, and AOD peaked in July, which is consistent with satellite data. In general, the model slightly overestimate the AOD over East Asia in May and July.

The spatial pattern of correlation coefficients between the westerly index and the 200hPa westerly winds velocity is shown (Fig. 3). In March, positive correlation coefficients are higher than 0.5 in the north of Tibetan Plateau and northern China, which indicates that the westerly jet controls the wind speeds over this region (Fig. 3a). The range of the positive correlation area decreases in May and moves slightly to the north (Fig. 3b). In July, the positive correlation area is weakened and constrained to a shallow belt (Fig. 3c). For the low-level winds, the correlations between the EAWM index and 850hPa meridional winds show that the East Asia is mainly affected by the winter monsoon in March and the correlation coefficients exceed 0.7 (Fig. 3d). The positive correlation coefficient in May is higher than 0.4, and the range becomes smaller than March (Fig. 3e). In July, the southern East Asia is mainly affected by the summer monsoon (Fig. 3f).

The winds are correlated with the dust AOD to examine the relationship between dust transport and westerly wind intensity. Figure 4 shows that in different months, the correlation coefficient distributions are different. In March (Fig. 4a), the positive correlation center is located over the Tibetan Plateau and east of source areas. It shows a band-like distribution from northern China to northwestern Pacific, which indicates that the intensity of westerly jet facilitates the westward and long-distance transport of dust. In

May when the westerly jet moves southwards, the positive correlation areas expand but the correlation coefficients are smaller than March (Fig. 6b). In July (Fig. 4c), the jet retreats to the north side of the Tibetan Plateau and the dust AOD does not significantly correlate with the westerly index. Since the prevailing wind direction of EAWM is northerly and northwesterly, the correlations between winter monsoon index and dust AOD are found over eastern China (Fig. 4d, 4e), which is distinctly different from those for westerly index. In May, the correlations are most significant with largest areas over eastern China when the summer monsoon starts to develop. When the summer monsoon matures in July, the southerly winds suppress the southward transmission of dust and thus they mainly show negative correlations (Fig. 4f).

The correlation coefficient maps of the westerly index and monsoon index with the dust deposition fluxes are also shown (Fig. 5). Similar with the dust AOD, the correlations with deposition fluxes present that the westerlies dominate the westward transport and deposition of dust and the winter monsoon controls the northwestward ones. In May, the controlling areas of westerly index and monsoon index on dust transport are both larger than March although their intensity and correlations with wind speeds are smaller.

We express the interannual variation of the 1990-2009 index by a line chart and select the strong and weak years of the westerly and winter monsoon. Through composite analyses, the influence of westerly and monsoon on dust transmission is shown in Fig. 6. The AOD and dust concentration difference between the strong and weak westerly wind years in March shows (Fig. 6e, 6i) that there is a high-value area in the range of 30°N-45°N. And it presents a band pattern and extends from the source area to the Japan Sea, similar with Fig. 4a. In May, the area with a large difference in dust AOD and concentration (Fig. 6f, 6j) between strong and weak years is also consistent with the relevant high area in figure 4b. The EAWM mainly transports dust to the southeastern part of China. In March (Fig. 6g, 6k), the impact of the EAWM on dust is mainly confined to the East Asian continent; In May, the AOD and dust concentration difference between the strong and weak monsoon years shows that the dust can be carried to farther areas, such as the Japan Sea and the North Pacific (Fig. 6h, 6l).

To examine the relationships of dust deposition over specific regions, we select four representative regions: Japan Sea, Tibetan Plateau, Southern China, and Loess Plateau. The interannual variations of deposition fluxes and circulation index are calculated, as shown in Fig. 7. Over the Japan Sea which is located in the downwind region of the westerlies, the dust depositions are mainly controlled by the westerlies in March and May, no matter where the westerly jet is (Fig. 7a, 7b). The transport of dust over Tibetan Plateau is also obviously affected by the westerlies although the winter monsoon index might correlate to the westerly jet (Fig. 7c, 7d). The Tibetan Plateau is a dust source area and a channel for uplifting dust to upper troposphere, thus, the strong westerly winds will lead to increasing dust emission and settlement, especially in March (Liu et al., 2020; Xu et al., 2018). In contrast, the dust depositions over southern China and Loess Plateau have larger correlations with the winter monsoon intensity in March and the contributions of westerlies increase in May when the jet shifts northwards (Fig. 7e, 7f, 7g, 7h).

The correlations of the circulation index and dry depositions of different dust bins are calculated to examine the sensitivity of dust sizes to the winds (Fig. 8). The positive correlation patterns of four particle sizes with the westerly index are similar (Fig. 8a-8d), we believe that after the dust is lifted to the westerly layer, the strong westerly wind can carry the different sizes dust to the east. The positive correlation maxima for all the bins are located over Tibetan Plateau and northwestern Pacific. When the dust is carried into the westerlies, the particles in all sizes are transported eastward to northwestern Pacific. However, the correlation coefficients of EAWM show that the sizes are sensitive to the winter monsoon. When the size of dust particle is less than $1\mu\text{m}$ (Fig. 8e), the EAWM can transport it to southern Japan and the South China Sea. As the particle size increases, the range of dust deposition gradually decreases, and most of the $5\text{-}20\mu\text{m}$ dust settles in the Loess Plateau (Fig.8h). Such patterns qualitatively indicate that the smaller the dust particle is, the larger areas the winter monsoon controls.

To examine the vertical distribution of eastward and southward transport of dust under the impact of westerlies and winter monsoon, respectively. Fig. 9 presents the correlation coefficient distributions of dust mixing ratio and circulation index in different months. In March (Fig. 9a), the dust of $80^{\circ}\text{E}\text{-}90^{\circ}\text{E}$ is quickly raised to 300hPa and transmitted eastwards under the action of the westerlies wind. The controlling areas of westerlies occupy nearly the whole mid-to-high troposphere, from approximately 700hPa to 200hPa. However, the correlation between the westerlies and the dust concentration is small and not significant over the near surface. In May (Fig. 9b), the dust transport associated with the westerly is suppressed due to the weakening of the westerly winds. The controlling areas is shifted downwards, which indicates that the westerlies affect the near surface transport at this time. For the southward transport by the winter monsoon, in March (Fig. 9c), the positive correlations between dust and westerly index are mainly concentrated below 850hPa, showing that the winter monsoon merely controls the low-troposphere since it is a shallow system. There are two related high-value areas at $38^{\circ}\text{N}\text{-}41^{\circ}\text{N}$ and $42^{\circ}\text{N}\text{-}44^{\circ}\text{N}$, which correspond to the Taklimakan Desert and the Northern Desert (Gobi Desert and Deserts in northern China). The winter monsoon weakened in May, and the summer monsoon gradually increased (Fig. 9d). The dust is still affected by the winter monsoon and can continue to be transmitted upwards to 700hPa. Thus, the influence of the westerly winds extends downwards, and winter monsoon rises to the upper level in May compared to a colder time of March.

Spatially, the westerly winds at 300hPa and 550hPa facilitate a strip of eastward dust transmission (Fig. 10a, 10b), consistent with the vertical distribution (Fig 9a). At the lower levels (Fig. 10c), the strip shapes become not significant and disappear, which indicates that the influence of westerly winds is weakened. Unlike March, the correlation coefficient distribution in May show strip patterns in the mid to low troposphere (Fig 10e, 10f). For the monsoon, the EAWM can not affect the dust transport above the mid-level in March and May (Fig. 10g, 10h, 10j, 10k). On the 850hPa level (Fig. 10i), the positive correlation coefficient between EAWM and dust concentration is significant over eastern China. In May, the correlation coefficients decrease compared to March (Fig. 10l).

We selected two regions, the Japan Sea and South China, to calculate the percentages of dust content of different levels. The Japan Sea is located in the downwind region of the westerly winds while South

China is mainly affected by the EAWM. In Fig. 11, the dust contents in Japan are largest in the mid-troposphere, which reach approximately 18% of the whole layer. The ratios are reduced obviously to both the low and high troposphere. The peak of vertical distribution of dust over South China is located at low troposphere, lower than that over Japan Sea, which supports that the dust transport levels by the westerlies are relatively higher than those by the winter monsoon.

4 Discussion

Our analysis based on modeling data show that the dust is raised to the upper layer and effected by the westerly jet for long distance transportation. In March, the westerly winds are strong and the dust tends to be lifted to mid-to-high troposphere under the influence of westerly jet and delivered eastwards to the Pacific Ocean in a strip. Once the dust is lifted to the mid-upper levels and carried into the strong westerly jet, it would be easy to be carried by a long distance. *Uno et al. (2009)* used the lidar data analysis to show that, the dust was lofted to the upper troposphere around 8–10 km above the Earth's surface and transported around the globe. Further researches showed that dust aerosols originated from the Taklimakan and Gobi Desert, they were mainly located in the latitudes range from 1-7km over the source region, then ascended to 2-9km over the Pacific Ocean (*Guo et al., 2017; Chen et al., 2017*), and finally reached North America (*Yu et al., 2012; Holzer et al., 2003*). The East Asian monsoon has an impact on the local transmission of dust over this region (*Gong et al., 2006; Guo et al., 2014; Li et al., 2015; Zhao et al., 2013*). The transmission of dust by the winter monsoon is mostly over the tropospheric bottom layer, which is in agreement with a previous study (*Lou et al., 2016*).

The movement of the westerly jet has a significant relationship with the dust transport path and sediment area in East Asia. *Dong et al. (2017)* proposed that the influence scope of westerly wind is broad when the westerly jet is located on the southern side of the Tibetan Plateau. Comparatively, our results indicate the influent area is narrower when the westerly jet stay in the south of the Tibetan Plateau; and at this period, the deposition of the Japan Sea is mainly carried by the westerly winds, which could be supported by numerous observations (*Wan et al., 2012; Shen et al., 2017; Dong et al., 2017; Hovan et al., 1989*).

Geological sediments show that strong westerly winds are closely related to higher dust flux distribution and accumulation rate, dust deposits in some cold periods could prove this conclusion, such as Last Glacial Maximum, Heinrich Event and the Younger Dryas Event. Since dust is transported to the Japan Sea mainly via the westerly jet, the gradual increases of dust grain size during interstadials were mainly reflected by the increasing wind speed of the westerly jet. The estimated mass accumulation of aerosol dust exhibited two distinct peaks at 17.6ka BP and 11.4ka BP, which are coincident with Heinrich Event 1 and the Younger Dryas, respectively. (*Lu et al., 2013; Sun et al., 2004; Irino and Tada, 2003; Schiemann et al., 2009; Mahowald et al., 1999; Yokoyama et al., 2006*). Our simulation results show that the dry deposition in the Loess Plateau has high correlation coefficient with the winter monsoon index.

Paleoclimate studies use the dust particle size as a proxy of the winter monsoon intensity, they believe that the strong winter monsoon can transmit more dust to East Asian continent (*An et al., 2012; Xu et al., 2012; Sun et al., 2011; Sun et al., 2010; Jiang et al., 2010; Sun et al., 2004*). Further analysis show that the strong EAWM can transport more dust with larger particle sizes to the southeast of source area. When the

winter monsoon intensity increases, the particle size of the dust deposition become larger (Sun et al., 2010; Zhang et al., 2002), the dust flux and accumulation rates become higher (Kang et al., 2015; An et al., 1997), which was also identified by a modeling study (Shi et al., 2011).

5 Conclusions

East Asia is typically affected by the combined westerly circulation and East Asia monsoon. From colder to warmer seasons, the westerly jet gradually moves northwards, which induces different patterns of atmospheric circulation and dust transport in the troposphere. In this study, a remarkable seasonal feature of dust transport is highlighted by the westerly winds and winter monsoon, respectively. In March, the westerly winds transport dust eastward until it reaches to the Pacific Ocean. The winter monsoon mainly transmits dust to the southeast. Westerly circulation controls the high-level dust transmission, and the monsoon controls the low-level transmission. The influence of westerly winds on the transmission of different particle sizes dust is similar, while the monsoon can transport fine-grained dust to a distant area, and the coarse-grained dust can only be settled in the near-source area. The relationship between the dust transmission and the atmospheric circulation is very complicated, which is worthy of further researches.

Declarations

I write on behalf of myself and all co-authors to confirm that the results reported in the manuscript are original and neither the entire work, nor any of its parts have been previously published. The authors confirm that the article has not been submitted to peer review, nor has been accepted for publishing in another journal. The authors confirm that the research in their work is original, and that all the data given in the article are real and authentic. This work was jointly supported by the Strategic Priority Research Program of Chinese Academy of Sciences, National Key Research and Development Program of China and National Natural Science Foundation of China. No conflict of interest and no third-party copyrighted material exist in the submission of this manuscript, and there are no online supplementary materials.

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References

Abulaiti A, Kimura R, Shinoda M, Kurosaki Y, Mikami M, Ishizuka M, Yamada Y, Nishihara E, Gantsetseg B (2014) An observational study of saltation and dust emission in a hotspot of Mongolia. *Aeolian Res* 15: 169-176

- Albrecht BA (1989). Aerosols, Cloud Microphysics, and Fractional Cloudiness. *Science* 245: 1227-1230
- Alfaro S, and Gomes L (2001) Modeling mineral aerosol production by wind erosion: Emission intensities and aerosol size distributions in source areas. *Journal of Geophysical Research-Atmospheres* 106: 18075-18084
- An ZS, Kukla G, Porter SC, Xiao JL (1991) Late Quaternary Dust Flow On The Chinese Loess Plateau. *Catena* 18: 125-132
- An ZS, Kutzbach JE, Prell WL, Porter SC (2001) Evolution of Asian monsoons and phased uplift of the Himalayan Tibetan plateau since Late Miocene times, *Nature*, 411, 62-66
- An ZS, Colman SM, Zhou WJ (2012) Interplay between the Westerlies and Asian monsoon recorded in Lake Qinghai sediments since 32 ka. *Scientific Reports*: 2
- Cassar N, Bender ML, Barnett BA, Fan SM, Moxim WJ, Levy H, Tilbrook B (2008) Response to comment on the Southern Ocean biological response to aeolian iron deposition. *Science* 319: 2
- Chen SY, Huang JP, Kang L, Wang H, Ma X, He Y, Yuan T, Yang B, Huang Z, Zhang G (2017) Emission, transport, and radiative effects of mineral dust from the Taklimakan and Gobi deserts: comparison of measurements and model results. *Atmospheric Chemistry and Physics* 17: 2401-2421
- Chen SY, Zhao C, Qian Y, Leung LR, Huang JP, Huang ZW (2014) Regional modeling of dust mass balance and radiative forcing over East Asia using WRF-Chem. *Aeolian Res* 15: 15-30
- Ding AJ, Fu CB, Yang XQ, Sun JN, Petaja T, Kerminen VM (2013) Intense atmospheric pollution modifies weather: a case of mixed biomass burning with fossil fuel combustion pollution in eastern China. *Atmospheric Chemistry and Physics* 13: 10545-10554
- Dong Z, Shi X, Ge C, Zou J, Yao Z, Gorbarenko S, Wang C, Zong X (2017) Evolution of westerly jet during the last 60 ka: Evidence from core deposits in the central Japan (East) Sea. *Chinese Science Bulletin* 62: 1172-1184
- Gao Y, Arimoto R, Zhou MY, Merrill JT, Duce RA (1992) Relationships between the dust concentrations over Eastern Asia and the remote North Pacific. *Journal of Geophysical Research-Atmospheres* 97: D9
- Gong S, Zhang XT, Zhao X, Zhang L, Barrie I, McKendry M, Zhao C (2006) A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part II: Interannual variability and climate connections. *Journal of Climate* 19:1
- Guo J, Lou MY, Miao YC, Wang Y, Zeng ZL, Liu H, He J (2017) Trans-Pacific transport of dust aerosol from East Asia: Insights gained from multiple observations and modeling. *Environ Pollution* 230:1030-1039

- Guo S, Hu M, Zamora ML, Peng JF, Shang DJ, Zheng J, Du ZF (2014) Elucidating severe urban haze formation in China. *Proceedings of the National Academy of Sciences of the United States of America* 111: 17373-17378
- Holzer M, McKendry IG, Jaffe DA (2003) Springtime trans-Pacific atmospheric transport from east Asia: A transit-time probability density function approach. *Journal of Geophysical Research-Atmospheres* 108: D22
- Hovan SA, Rea DK, Pisias NG, Shackleton NJ (1989) A direct link between the china loess and marine delta-O-18 records-aeolian flux to the north pacific. *Nature* 340: 296-298
- Hao Z, Pan D, Sun Z, Fang G (2006) Retrieval of the columnar aerosol grain density from SeaWiFS over the China seas. *Acta Oceanologica Sinica* 28:32-38
- Hu Z, Huang J, Zhao C, Bi J, Jin Q, Qian Y, Leung LR, Feng T, Chen S, Ma J (2019) Modeling the contributions of Northern Hemisphere dust sources to dust outflow from East Asia. *Atmospheric Environment* 202:234-243
- IPCC (Intergovernmental Panel on Climate Change): *Climate change-the physical science basis*, Cambridge University Press, New York, 252–271, 2013
- Irino T, Tada R (2003) High-resolution reconstruction of variation in aeolian dust (Kosa) deposition at ODP site 797, the Japan Sea, during the last 200 ka. *Global and Planetary Change* 35: 143-156
- Ji Z, Kang S, Zhang D, Zhu C, Wu J, Xu Y (2011) Simulation of the anthropogenic aerosols over South Asia and their effects on Indian summer monsoon. *Climate Dynamics* 36: 1633-1647
- Jiang H, Ding ZL (2010) Eolian grain-size signature of the Sikouzi lacustrine sediments (Chinese Loess Plateau): Implications for Neogene evolution of the East Asian winter monsoon. *Geological Society of America Bulletin* 122: 843-854
- Kang S, Roberts HM, Wang X, An ZS, Wang M (2015) Mass accumulation rate changes in Chinese loess during MIS 2, and asynchrony with records from Greenland ice cores and North Pacific Ocean sediments during the Last Glacial Maximum. *Aeolian Research* 19: 251-258
- Lee JJ, Kim CH (2012) Roles of surface wind, NDVI and snow cover in the recent changes in Asian dust storm occurrence frequency. *Atmospheric Environment* 59: 366-375
- Li Q, Zhang R, Wang Y (2016) Interannual variation of the wintertime fog-haze days across central and eastern China and its relation with East Asian winter monsoon. *International Journal of Climatology* 36: 346-354
- Li X, Zhang H (2012) Seasonal variations in dust concentration and dust emission observed over Horqin Sandy Land area in China from December 2010 to November 2011. *Atmospheric Environment* 61: 56-65

- Li ZQ, Lau WKM, Ramanathan V, Wu G, Ding Y, Manoj MG, Liu J (2016) Aerosol and monsoon climate interactions over Asia. *Reviews of Geophysics* 54:866-929
- Lin Y, Mu G, Xu L, Zhao X (2016) The origin of bimodal grain-size distribution for aeolian deposits. *Aeolian Research* 20: 80-88
- Liu XD, Xie XN, Yin ZY, Liu C, Gettelman A (2011) A modeling study of the effects of aerosols on clouds and precipitation over East Asia. *Theoretical and Applied Climatology* 106: 343-354
- Liu YZ, Li YH, Huang JP, Zhu QZ, Wang SS (2020) Attribution of the Tibetan Plateau to northern drought. *National Science Review* 7(3): 489.
- Lou S, Russell LM, Yang Y, Xu L, Lamjiri MA, DeFlorio MJ, Miller AJ, Ghan SJ, Liu Y, Singh B (2016) Impacts of the East Asian Monsoon on springtime dust concentrations over China. *Journal of Geophysical Research: Atmospheres* 121: 8137-8152
- Lu HY, Yi SW, Liu ZY, Mason JA, Jiang DB, Cheng J, Stevens T (2013) Variation of East Asian monsoon precipitation during the past 21 k.y. and potential CO₂ forcing. *Geology* 41: 9
- Mahowald N, Kohfeld K, Hansson M, Balkanski Y, Harrison SP, Prentice IC, Schulz M, Rodhe H (1999) Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments. *Journal of Geophysical Research-Atmospheres* 104:15895-15916
- Marticorena B, Bergametti G (1995) Modeling the Atmospheric Dust Cycle .1. Design of a Soil-Derived Dust Emission Scheme. *Journal of Geophysical Research-Atmospheres* 100: 16415-16430
- Nagashima K, Tada R, Matsui H, Irino T, Tani A, Toyoda S (2007) Orbital- and millennial-scale variations in Asian dust transport path to the Japan Sea. *Palaeogeography Palaeoclimatology Palaeoecology* 247: 144-161
- Niu F, Li Z, Li C, Lee KH, Wang M (2010) Increase of wintertime fog in China: Potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading. *Journal of Geophysical Research-Atmospheres* 115
- Oleson KW, Niu GY, Yang ZL, Lawrence DM, Thornton PE, Lawrence PJ, Stockli R (2008) Improvements to the Community Land Model and their impact on the hydrological cycle. *Journal of Geophysical Research-Biogeosciences* 113
- Qian Y, Giorgi F, Huang Y, Chameides W, Luo C (2001) Regional simulation of anthropogenic sulfur over East Asia and its sensitivity to model parameters. *Tellus B* 53(2): 171-191.
- Qian Y, Leung LR, Ghan SJ, Giorgi F (2003) Regional climate effects of aerosols over China: Modeling and observation. *Tellus B* 55:914–934

- Porter SC, An ZS (1995) Correlation Between Climate Events In The North-Atlantic And China During Last Glaciation. *Nature* 375: 305-308
- Prins MA, Vriend M, Nugteren G, Vandenberghe J, Lu H, Zheng H, Weltje GJ (2007) Late Quaternary aeolian dust input variability on the Chinese Loess Plateau: inferences from unmixing of loess grain-size records. *Quaternary Science Reviews* 26: 230-242
- Qin Y, Chan CK, Chan LY (1997) Characteristics of chemical compositions of atmospheric aerosols in Hong Kong: spatial and seasonal distributions. *Science of the Total Environment* 206: 25-37
- Ridgwell AJ (2002) Dust in the Earth system: the biogeochemical linking of land, air and sea. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* 360: 2905-2924
- Schiemann R, Luethi D, Schaer C (2009) Seasonality and Interannual Variability of the Westerly Jet in the Tibetan Plateau Region. *Journal of Climate* 22: 2940-2957
- Shao YP, Yang Y, Wang JJ, Song ZX, Leslie LM, Dong CH, Zhang ZH (2003) Northeast Asian dust storms: Real-time numerical prediction and validation. *Journal of Geophysical Research-Atmospheres* 108: 18
- Shao Y, Wyrwoll KH, Chappell A, Huang J, Lin Z, McTainsh GH, Mikami M, Tanaka TY, Wang X, Yoon S (2011) Dust cycle: An emerging core theme in Earth system science. *Aeolian Research* 2: 181-204
- Shen XY, Wan SM, France LC, Clift PD, Tada R, Revillon S, Shi XF (2017) History of Asian eolian input to the Sea of Japan since 15 Ma: Links to Tibetan uplift or global cooling. *Earth and Planetary Science Letters* 474: 296-308
- Shi ZG, Liu XD (2011) Distinguishing the provenance of fine-grained eolian dust over the Chinese Loess Plateau from a modelling perspective. *Tellus B* 63: 959-970
- Song F, Zhou T, Qian Y (2014) Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophysical Research Letters* 41: 596-603
- Sun D (2004) Monsoon and westerly circulation changes recorded in the late Cenozoic aeolian sequences of Northern China. *Global and Planetary Change* 41: 63-80
- Sun H, Liu X, Pan Z (2017) Direct radiative effects of dust aerosol emitted from the Tibetan Plateau on the East Asian summer monsoon - a regional climate model simulation. *Atmospheric Chemistry and Physics* 17: 13731-13745
- Sun J, Zhang M, Liu T (2001) Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960-1999: Relations to source area and climate. *Journal of Geophysical Research* 106: 10325-10333

- Sun JM (2002) Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. *Earth and Planetary Science Letters* 203: 845-859
- Sun Y, An ZS, Clemens SC, Bloemendal J, Vandenberghe J (2010) Seven million years of wind and precipitation variability on the Chinese Loess Plateau. *Earth and Planetary Science Letters* 297: 525-535
- Sun YB, Clemens SC, Morrill C, Lin X, Wang X, An ZS (2012) Influence of Atlantic meridional overturning circulation on the East Asian winter monsoon. *Nature Geoscience* 5: 46-49
- Sun YB, Tada RJ, Chen JC, Liu QS, Toyoda S, Tani A, Ji JF, Isozaki Y (2008) Tracing the provenance of fine-grained dust deposited on the central Chinese Loess Plateau. *Geophysical Research Letters* 35: 5
- Tan SC, Shi GY, Wang H (2012) Long-range transport of spring dust storms in Inner Mongolia and impact on the China seas. *Atmospheric Environment* 46: 299-308
- Tanaka TY, Chiba M (2006) A numerical study of the contributions of dust source regions to the global dust budget. *Global and Planetary Change* 52: 88-104
- Twomey S (1977) Influence of pollution on shortwave albedo of clouds. *Journal of the Atmospheric Sciences* 34: 1149-1152
- Uno I, Eguchi K, Yumimoto K, Takemura T, Shimizu A, Uematsu M, Liu Z, Wang Z, Hara Y, Sugimoto N (2009) Asian dust transported one full circuit around the globe. *Nature Geoscience* 2: 557-560
- Wan S, Yu Z, Clift PD, Sun H, Li A, Li T (2012) History of Asian eolian input to the West Philippine Sea over the last one million years. *Palaeogeography Palaeoclimatology Palaeoecology* 326: 152-159
- Wang H, Xie X, Yan L, Liu X (2018) Impact of East Asian summer monsoon circulation on the regional aerosol distribution in observations and models. *Theoretical and Applied Climatology* 133: 377-384
- Wang Y, Zhang R, Saravanan R (2014) Asian pollution climatically modulates mid-latitude cyclones following hierarchical modelling and observational analysis. *Nature Communications* 5
- Wen R, Xiao J, Fan J, Zhang S, Yamagata H (2017) Pollen evidence for a mid-Holocene East Asian summer monsoon maximum in northern China. *Quaternary Science Reviews* 176: 29-35.
- Wu P, Ding Y, Liu Y (2017) Atmospheric circulation and dynamic mechanism for persistent haze events in the Beijing-Tianjin-Hebei region. *Advances in Atmospheric Sciences* 34: 429-440
- Xu C, Ma YM, Yang K, You C (2018), Tibetan Plateau Impacts on Global Dust Transport in the Upper Troposphere. *Journal of Climate* 31(12): 4745-4756.
- Xu Y, Yue L, Li J, Sun L, Sun B, Zhang J, Ma J, Wang J (2012) Red clay deposits on the Chinese Loess Plateau during 11.0-2.6 Ma and its implications for long-term evolution of East Asian monsoon. *Environmental Earth Sciences* 66: 2021-2030

- Yan L, Liu X, Yang P, Yin ZY, North GR (2011) Study of the Impact of Summer Monsoon Circulation on Spatial Distribution of Aerosols in East Asia Based on Numerical Simulations. *Journal of Applied Meteorology and Climatology* 50: 2270-2282
- Yang S, Ding Z (2014) A 249 kyr stack of eight loess grain size records from northern China documenting millennial-scale climate variability. *Geochemistry Geophysics Geosystems* 15: 798-814
- Yang S, Ding Z, Li Y, Wang X, Jiang W, Huang X (2015) Warming-induced northwestward migration of the East Asian monsoon rain belt from the Last Glacial Maximum to the mid-Holocene. *Proceedings of the National Academy of Sciences of the United States of America* 112: 13178-13183
- Yang X, Ferrat M, Li Z (2013) New evidence of orographic precipitation suppression by aerosols in central China. *Meteorology and Atmospheric Physics* 119: 17-29
- Yang Z, Dickinson R, Robock A, Vinnikov K (1997) Validation of the snow submodel of the biosphere-atmosphere transfer scheme with Russian snow cover and meteorological observational data. *Journal of Climate* 10: 353-373
- Yokoyama Y, Naruse T, Ogawa NO, Tada R, Kitazato H, Ohkouchi N (2006) Dust influx reconstruction during the last 26,000 years inferred from a sedimentary leaf wax record from the Japan Sea. *Global and Planetary Change* 54: 239-250
- Yu H, Remer LA, Chin M, Bian H, Tan Q, Yuan T, Zhang Y (2012) Aerosols from Overseas Rival Domestic Emissions over North America. *Science* 337: 566-569
- Yumimoto K, Takemura T (2015) Long-term inverse modeling of Asian dust: Interannual variations of its emission, transport, deposition, and radiative forcing. *Journal of Geophysical Research-Atmospheres* 120: 1582-1607
- Zakey AS, Solmon F, Giorgi F (2006) Implementation and testing of a desert dust module in a regional climate model. *Atmospheric Chemistry and Physics* 6: 4687-4704.
- Zhang DF, Zakey AS, Gao XJ, Giorgi F, Solmon F (2009) Simulation of dust aerosol and its regional feedbacks over East Asia using a regional climate model. *Atmospheric Chemistry and Physics* 9: 1095-1110
- Zhang L, Liao H, Li J (2010) Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China. *Journal of Geophysical Research-Atmospheres* 115
- Zhang X, Arimoto R, An ZS (1997) Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *Journal of Geophysical Research-Atmospheres* 102: 28041-28047
- Zhang XY, Lu HY, Arimoto R, Gong SL (2002) Atmospheric dust loadings and their relationship to rapid oscillations of the Asian winter monsoon climate: two 250-kyr loess records. *Earth and Planetary Science*

Zhang X, Gong S, Zhao T, Arimoto R, Wang Y, Zhou ZJ (2003) Sources of Asian dust and role of climate change versus desertification in Asian dust emission. *Geophysical Research Letters* 30: 2272

Zhao XJ, Zhao PS, Xu J, Meng W, Pu WW, Dong F, He D, Shi QF (2013) Analysis of a winter regional haze event and its formation mechanism in the North China Plain. *Atmospheric Chemistry and Physics* 13: 5685-5696

Zhu J, Liao H, Li J (2012) Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon. *Geophysical Research Letters* 39

Figures

Figure 1

Mean 200 hPa (a-f) and 850 hPa wind vectors (g-l, m/s) in March (left column), May (middle column), and July (right column) from RegCM4 simulation and ERA-Interim reanalysis. The blue line represents the location of westerly jet axis. Note: The designations employed and the presentation of the material on

this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Annual mean AOD (dust only) simulated with RegCM4 (a, b, c) and that from the CALIPSO (d, e, f) over East Asia. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Distributions of correlation coefficients between westerly index and mean 200hPa westerly winds speeds, and between monsoon index and 850hPa northerly wind speeds in March (a, d), May (b, e), and July (c, f). The dotted areas indicate statistical significance with 95% (P value < 0.05) from a two-tailed Student's t -test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any

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Figure 4

Distributions of correlation coefficients between westerly index and dust AOD, and between monsoon index and dust AOD in March (a, d), May (b, e), and July (c, f). The dotted areas indicate statistical significance with 95% (P value < 0.05) from a two-tailed Student's t -test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Distributions of correlation coefficients between westerly index and dust deposition, and between monsoon index and dust deposition in March (a, d), May (b, e), and July (c, f). The dotted areas indicate statistical significance with 95% (P value < 0.05) from a two-tailed Student's t -test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or

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Figure 6

The interannual variation of the westerly index and EAWM index in March (a, b) and May (c, d), the dotted line represents the standard deviation, the red and blue dot represents the weak and strong year of westerly or monsoon. Horizontal distributions of differences dust AOD (d-h) and tracers mixing ratios (i-l) between most energetic and weak westerly or monsoon years (strongest-weakest) in March and May. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Dry deposition and monsoon index, westerly index annual correlation coefficient chart in the Japan Sea (35°N-45°N,130°E-135°E), Tibet Plateau (30°N-35°N,80°E-100°E), Southern China (25°N-30°N,110°E-120°E) and Loess Plateau (34°N-41°N,101°E-114°E) in March (left column), May (right column).

Figure 8

Distributions of correlation coefficients between westerly index and dust deposition of four particle sizes (a-d), and between monsoon index and dust deposition of four particle sizes (e-h) in March. The dotted areas indicate statistical significance with 95% (P value< 0.05) from a two-tailed Student's t-test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 9

Pressure-longitude cross sections over 35°N for the correlation coefficient distributions between westerly index and tracers mixing ratios (left column), and averaged over 100°E-120°E for the correlation coefficient distributions between WAWM index and tracers mixing ratios (right column). The dotted areas indicate statistical significance with 95% (P value < 0.05) from a two-tailed Student's t -test.

Figure 10

Distributions of correlation coefficients between westerly index and tracers mixing ratios (a-f), and between monsoon index and tracers mixing ratios (g-l) in March (first and third row) and May (second and fourth row). The dotted areas indicate statistical significance with 95% (P value < 0.05) from a two-tailed Student's t-test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 11

Percentage of vertical dust content. The solid line is the dust content over the 35°N-45°N, 135°E-140°E area, and the dotted line is the dust content over the 25°N-30°N, 110°E-120°E area.