Correlation between east Asian dust storm frequency and PNA

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[1] Large-scale climate teleconnections play evident roles in spring dust storm variability over east Asia through influencing regional weather and climates. In the present study authors found that dust storm frequency in northern China is significantly correlated to the Pacific/North American (PNA) pattern with a Pearson's correlation coefficient of +0.60 on interannual time scale during the period 1962–2002. The atmospheric circulation changes (including weather disturbances at 850hPa, monthly mean wind and height at 500 hPa and 200 hPa levels) in association with dust storm and PNA bear remarkable similarity, confirming the robustness of their connections. East Asian jet stream is, at least partly, responsible for generating the evident co-variations between dust storm frequency and PNA. This teleconnection and the corresponding circulation changes exist in non-El Niño/Southern Oscillation (ENSO), likely independent of ENSO phases. The results are helpful for better understanding how East Asian dust storm responds to the global change.
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1. Introduction

[2] Dust storm is one kind of the severe natural disasters in East Asia occurring most frequently in spring. During the last decades its activities have decreased in both station-based dust storm days and dust weather events [*Zhou*, 2001; *Zhou and Zhang*, 2003]. For example, the number of dust storm days in north China experienced a significant trend of −26.0%/10yr from 1962–2002 [*Gong et al.*, 2006a], also see Figure 1. Compared to land cover changes, the weather-climate factors play more important roles in influencing East Asian dust storm variability [*Zhang et al.*, 2003]. Higher land surface air temperature, less precipitation, and strong wind are favorable regional climate conditions for dust storm occurrence and intensity [e.g., *Qian et al.*, 2002; *Gao et al.*, 2003; *Kurosaki and Mikami*, 2003; *Liu et al.*, 2004; *Ding et al.*, 2005]. The teleconnections of dust storm frequency to the large-scale climate signals are of interests [*Gong et al.*, 2006b], particularly in conjunction with the global change since these climate connections could exert influence on dust storm through impacting regional weather and climate. For example, declining trends in dust storm frequency is found to be linked to the northern polar vortex and Siberian High via their impacts on the cold air activities in East Asia [*Zhao et al.*, 2004; *Gong et al.*, 2006a]. Arctic Oscillation is significantly correlated with the dust storm frequency in a out-of-phase manner through influencing weather disturbances at lower troposphere in northern China [*Gong et al.*, 2006a]. Some authors supposed that ENSO might be related to the dust storm changes by influencing East Asian winter monsoon [e.g., *Gao et al.*, 2003]. *Fan and Wang* [2004] even identified a southern annular mode signal in northern China's dust frequency. So far, these climate teleconnections are investigated to explain the long-term changes in the dust storm activities. Whereas, how and why East Asian dust storm activities are connected to these large-scale climate factors are still not well understood.

[3] In the present study, by analyzing inter-annual changes, we report that there is a significant correlation between PNA and dust storm frequency in northern China.

2. Data and Method

[4] The regional mean number of the dust storm days in March–May for 26 stations in about 100°–120°E and 39°–46°N are used as the dust frequency (F_D). These stations are located in/near the central and eastern part of the Chinese deserts (Figure 1), which are also high frequency centers of the dust storms [*Zhou*, 2001]. To avoid the possible data discontinuity, our analysis period is limited to the period 1962–2002, same as *Gong et al.* [2006a].

[5] Following *Wallace and Gutzler* [1981] the PNA index is defined as the linear combination of the normalized ERA40 500 hPa height anomalies (Z^*) at four centers: $PNA = \frac{1}{4}\,[Z^*_{(20^\circ N,160^\circ W)} - Z^*_{(45^\circ N,165^\circ W)} + Z^*_{(55^\circ N,115^\circ W)} - Z^*_{(30^\circ N,85^\circ W)}]$.

[6] Another frequently used PNA index is defined as the time coefficient of the rotated principal component analysis of 700/500 hPa heights. For simplicity we used only *Wallace and Gutzler* [1981] index. To use a different PNA index is most likely incapable of changing the conclusion of our analysis since these two PNA indices are highly correlated ($r = 0.91$) for spring during the period 1958–2002.

[7] A puzzling fact arising from previous studies is that the relationship between dust storm and climate signals as established based on the low-frequency changes often diminish or disappear on the interannual time scale, making the physical explanation very questionable, particularly in explaining the long-term trends in dust storm frequency. Low-frequencies exist in many climate indices, that is easy to misleadingly result in a spurious correlation even two indices have no physical connection. Therefore, in the present study we focus on interannual time scale. Prior to analysis all variables are filtered using a Butterworth filter and only high frequency components with time period shorter than 10 years are remained. For F_D, the remaining

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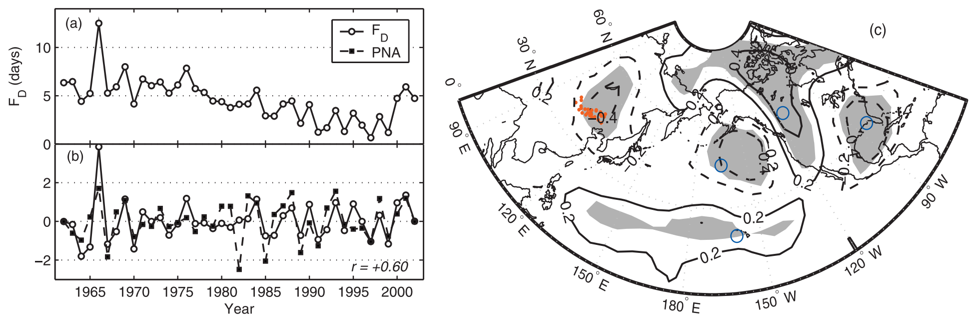

Figure 1. Time series of East Asian dust storm frequency(F_D) and PNA index. (a) Unfiltered F_D. (b) Interannual variations in F_D and PNA. Units in Figure 1b are arbitrary. (c) Correlations between the ERA40 spring 500 hPa heights and filtered F_D. Zero contours are omitted for clarity. Shading areas are significant at the 95% level. Dots in northern China denote dust stations. Four PNA grids are shown as open circles.

inter-annual variability accounts for about 58.3% of the total variance.

3. Results

3.1. Correlation

[8] Figure 1 displays the time series of F_D and PNA. The in-phase relation between two curves on the inter-annual time scale are impressive. Two timeseries are correlated at a high value of +0.60, significant at the 99% level (Table 1). It is of interest to check whether there exist any time-lags between F_D and PNA indices. It is found that the F_D correlates with PNA of the preceding winter and following summer at only −0.06 and −0.11, respectively. Therefore, their strong correlation exists nearly simultaneously.

[9] To delineate the robustness of their statistical correlation, we checked the geopotential height anomalies at 500 hPa level in association with F_D. The outstanding feature of the correlation map (Figure 1) is the trains of correlation centers in north Pacific-North America sector. This well-defined structure clearly manifests the PNA pattern with regard to the locations of the anomaly centers. In addition, the negative contours in 40°–60°N extending from western coast of North America to east Asia, with another significant center appearing in 100°–120°E. Evidently, the consistent changes in 500hPa heights is suggestive of physical-relationship between the high co-variance of F_D and PNA.

3.2. Associated Synoptic Activities

[10] The direct forcing factor of dust storm is the high-frequency weather activities in lower troposphere [e.g., *Sun et al.*, 2001; *Qian et al.*, 2002; *Gong et al.*, 2006a]. To confirm the robustness of the high correlation between F_D and PNA as shown above, we analyzed the synoptic variance of ERA40 geopotential heights at 850hPa level($Z850$), which is defined in the form of $\overline{Z'^2}^{1/2}$, where the prime denotes the departure from the band pass (1–7 days) filter and an overbar denotes the time average over March 1–May 31.

[11] As can be seen in Figure 2a, the well-defined pattern of synoptic variance in association with F_D is evident. Significant variance elongates from northwest to the south-east in about 20°–60°N and 90°–120°E in East Asia with an anomalous center locating in around northern China to Mongolia, suggesting the importance of the East Asian weather disturbances in influencing the frequency of dust storms. In addition, it is interesting to note that high variance appears also in a broad region in north Pacific along about 40°N, implying the changes in synoptic scale variance are of large-scale in geography over north Pacific.

[12] It is generally accepted that the synoptic disturbances own mainly to the baroclinic instability of the basic state. The increasing instability is well accompanied by a greater synoptic variance in lower troposphere over East Asia [*Gong et al.*, 2006a]. We compared the Eady index of clinic instability in association with F_D and PNA indices, found that there are larger instability in high F_D and PNA years over East Asia with center in 30–55°N, 90–120° (figure not shown). Previous studies indicated that in East Asia the synoptic disturbances tend to propagate along distinct, northwest-southeast oriented 'waveguides' [*Wallace et al.*, 1988]. In Figure 2 the changes of seasonal mean horizontal wind at 500 hPa level in association with F_D are also plotted. In East Asia stronger northwestern wind are notable. The anomalous winds could not only change the vertical wind shear and heat advection and thus baroclinic instability, but also steer the weather disturbances, resulting in the principal northwest-southeast tracks. Impressively, the regression maps for PNA display very similar patterns in height variance as well as the horizontal wind anomalies (Figure 2b). In high PNA conditions, there are significantly stronger synoptic variance in East Asia with high centers near north China and west North Pacific. It can be seen that even the negative variance anomalies in high latitudes between 160°E–150°W are almost identical in Figures 2a and 2b. One exception is that the PNA-related positive anomalies in

Table 1. Correlation Coefficients for Inter-Annual Variations Over the Period 1962–2002 in March–May[a]

	F_D	PNA	U200	Niño3.4 SST
F_D	-	+0.60[b]	+0.28[c]	+0.21
PNA	(+0.57)[b]	-	+0.31[d]	+0.40[b]
U200	(+0.35)[d]	(+0.47)[b]	-	−0.27[c]
Niño3.4 SST	(0.0)	(0.0)	(0.0)	-

[a]Shown in parentheses are results after ENSO signals have been excluded by linear fitting to Niño3.4 SST index. U200 denotes the mean zonal wind over jet core region of 30°–35°N and 110°–170°E.
[b]Significant at the 99% level.
[c]Significant at the 90% level.
[d]Significant at the 95% level.

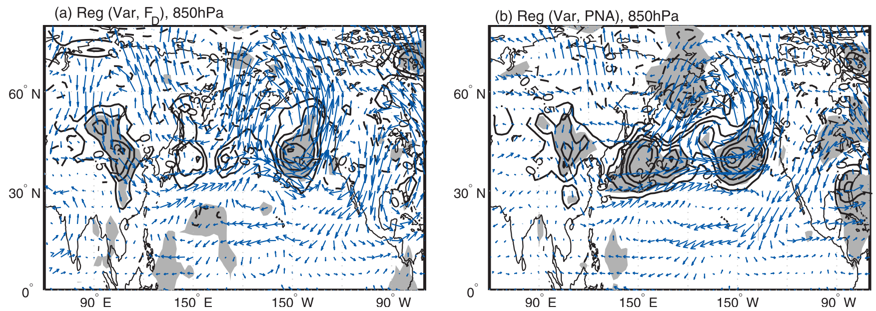

Figure 2. Contour lines are regression of the synoptic variance of daily 850hPa heights upon (a) F_D and (b) PNA. Contour intervals: 0.5m. Zero contours are omitted for clarity. Shading areas are significant at the 95% level. Horizontal wind changes at 500 hPa level corresponding respectively to the F_D and PNA are plotted together. Linear component of Niño3.4 SST in 500hPa wind have been removed. Maximum wind vectors in Figure 2a are 1.8m/s and in Figure 2b are 2.8 m/s.

140°E–180° is much stronger than F_D-related variance. Generally speaking, the high correlation between PNA and F_D is well consistent in the view of weather disturbances in East Asia-North Pacific sector.

[13] Although there are evident co-variations in the East Asian monsoon regions, the synoptic changes in the western deserts such as Taklimakan desert are not significant. This likely suggests that there is regionality in the dust storm teleconnections [*Gong et al.*, 2006b].

3.3. Changes in the East Asian Jet Stream

[14] The elongated maxima in the synoptic variance of geopotential height is often referred to as storm tracks, which mainly related to and follows the East Asian jet stream over East Asian-North America sector. The synoptic variance maxima in association with F_D and PNA resemble the principal storm tracks (Figure 2) and the zonally oriented variance belts are more evident in upper levels (figures not shown), implying that the jet stream likely plays an important role in producing the co-variance between F_D and PNA.

[15] Thus we investigated the ERA40 zonal wind of 200 hPa level (U200) in March–May. Although the PNA pattern itself is a inherent mode of atmosphere variability, external forcings such as Niño sea surface temperature (SST) can generate quasi-stationary wave trains [e.g., *Horel and Wallace*, 1981; *Trenberth et al.*, 1998]. The seasonal zonal-mean response to ENSO is basically linear in middle latitude upper troposphere [*Hoerling et al.*, 1995], therefore we identified ENSO signals by linearly fitting U200 to the Niño3.4 SST time series. After excluding the ENSO signals, we yielded the U200 changes corresponding to F_D and PNA, respectively (Figure 3). It is evident that the increase in F_D and PNA are accompanied by an intensification of the jet stream with strengthening zonal winds upstream and downstream and southward shift. Impressively, the westerly in jet core region tends to be enhanced by 1–1.5 m/s while its position shifts southward from climate position when F_D gets one-standard-deviation stronger. In East Asian sector between 100°–120°E, the center of zonal wind anomaly appears in 30°N, about 5–10 degrees south of the anomalous center of 850 hPa weather disturbances. In addition, there is a reduction of westerly over the northern extratopics from high latitude East Asia to the Alaska and over the tropical north Pacific. The PNA-related U200 anomaly pattern is almost identical, except that the maximum of wind anomaly is about 1 m/s stronger.

[16] These elongated patterns with alternative signs of anomaly in the zonal wind is a large-scale phenomenon accompanying the variation of East Asian jet stream [see *Yang et al.*, 2002, Figure 3]. The active synoptic eddies in lower troposphere along with the jet cores is most likely suggestive of the active jet stream. To confirm this we constructed the jet intensity by averaging U200 in jet core region over 110°–170°E by 30°–35°N where wind speed larger than 40m/s in March–May. The U200 intensity is significantly correlated with F_D (r = +0.35) and PNA (r = +0.47). A question is how the jet stream and PNA are connected. One possibility is that the synoptic-scale eddy forcing in relating to the jet stream strongly contributes to

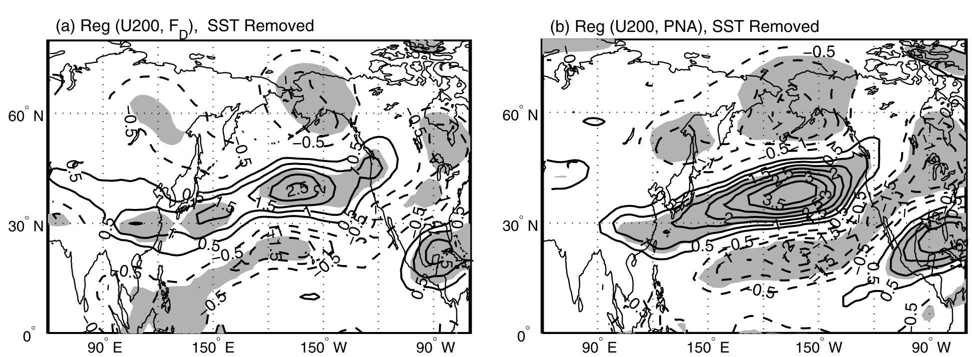

Figure 3. Regression of seasonal mean zonal wind at 200hPa level upon (a) F_D and (b) PNA. Zero contours are omitted for clarity. Shading areas are significant at the 95% level. ENSO components as estimated by linear fitting to Niño3.4 SST have been removed.

the seasonal circulations anomalies [*Lau and Holopanien*, 1984; *Lau*, 1988], including PNA-like anomalies. *Lau* [1988] indicated that the south-north migration of the jet stream and synoptic transient eddies in north Pacific is accompanied by a PNA-like pattern in month mean 300 hPa height anomalies. These low-frequency waves were tightly connected to the vorticity transport by transient eddies (see his Figures 4 and 11). In North Pacific sector, the zonally elongated above-normal synoptic-scale activities are accompanied by the positive height tendencies immediately to the south, negative height tendencies to the north of the extrema, and eastward accelerations at the sites of the extrema. *Yang et al.* [2002] also displayed that during the strong East Asian jet stream years, the active low-frequency waves as defined in the form of Plumb flux in 300hPa level appear in the PNA region, originating from east North Pacific (center locates about 150°W, 45°N) and propagating northeastward North America and then turning to the southeast (see their Figure 7). As shown in Figure 2, in the south side of the active synoptic-scale eddies (along about 35°–40°N), an anticyclonic circulation in 500hPa level is located in about 20°–30°N, while a strong cyclonic circulation appears in the north side with center at 45°–55°N in north Pacific. These might imply the importance of the transient eddy forcing. It must be pointed out that possible roles by many other processes such as the interaction between transient eddies and quasi-stationary waves and basic air-flow, lower troposphere transient heat transport and so on have not been ruled out, these complex questions are beyond the scope of the present study.

3.4. ENSO Influence

[17] The variability of extratropical atmospheric circulation over North Pacific, including PNA, jet stream, and storm tracks, are related to ENSO [e.g., *Trenberth et al.*, 1998; *Yang et al.*, 2002; *Chang and Fu*, 2002]. But we found that from the preceding autumn and winter to spring, the Niño 3.4 SST has only moderate correlation with spring F_D, and the simultaneous correlation of +0.21 is the maximum. This is different from the strong PNA-SST relationship(their simultaneous correlation is +0.40). However, when ENSO signals were excluded by linearly fitting to Niño 3.4 SST, more significant association among PNA, U200, and F_D are observed. As shown in Table 1 the correlation between F_D and PNA is $r = +0.57$. The significant correlations of U200 with F_D and PNA are +0.35 and +0.47, respectively. In addition we also rechecked the circulation changes (i.e., 500hPa heights and wind, and 200 hPa zonal wind) using original data and found that no matter the ENSO signals removed or not the circulation patterns in association with F_D and PNA are essentially similar. Although the ENSO-related climate changes would influence East Asian dust storm activities, the co-variance between F_D and PNA and the relating circulation changes under the frame of East Asian jet stream are most likely robust and independent of ENSO.

4. Concluding Remarks

[18] Above analysis reveals that there is a significant correlation between East Asian dust storm frequency and PNA ($r = +0.60$) on inter-annual time scale. Changes in synoptic-scale transient eddies, monthly mean atmospheric circulation in middle and upper troposphere in association with F_D and PNA bear remarkable similarity, confirming the robustness of their co-variations. The East Asian jet stream very likely plays an important role in generating these connections.

[19] Although ENSO can significantly modulate PNA and hemispheric inter-annual climates, the teleconnection between F_D and PNA and the corresponding changes in atmospheric circulation likely exist in non-ENSO years too. These results are helpful for better understanding how East Asian dust storm responds to the global change.

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