Impact of the El Niño type and PDO on the Winter Sub-seasonal North American Zonal Temperature Dipole via the Variability of Positive PNA Events

Yao Ge
Institute of Atmospheric Physics Chinese Academy of Sciences

Dehai Luo (ldh@mail.iap.ac.cn)
RCE-TEA, Institute of Atmospheric Physics, Chinese Academy of Science

Research Article

Keywords: Winter Sub-seasonal, Zonal Temperature, PNA Events

Posted Date: November 2nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1018314/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Abstract

In recent years, the winter (from December to February, DJF) North American surface air temperature (SAT) anomaly in midlatitudes shows a “warm west/cold east” (WWCE) dipole pattern. To some extent, the winter WWCE dipole can be considered as being a result of the winter mean of sub-seasonal WWCE events. In this paper, the Pacific SST condition linked to the WWCE SAT dipole is investigated. It is found that while the sub-seasonal WWCE dipole is related to the positive Pacific North American (PNA+) pattern, the impact of the PNA+ on the WWCE dipole depends on the El Niño SST type and the phase of Pacific decadal Oscillation (PDO). For a central-Pacific (CP) type El Niño, the positive (negative) height anomaly center of PNA+ is located in the western (eastern) North America to result in an intensified WWCE dipole, though the positive PDO favors the WWCE dipole. In contrast, the WWCE dipole is suppressed under an Eastern-Pacific (EP) type El Niño because the PNA+ anticyclonic anomaly dominates the whole North America.

Moreover, the physical cause of why the El Niño type influences PNA+ is further examined. It is found that the type of El Niño can significantly influence the location of PNA+ through changing North Pacific midlatitude westerly winds associated with the Pacific Hadley cell change. For the CP-type El Niño, the eastward migration of PNA+ is suppressed to favor its anticyclonic (cyclonic) anomaly appearing in the west (east) region of North American owing to reduced midlatitude westerly winds. But for the EP-type El Niño, midlatitude westerly wind is intensified to cause the appearance of PNA+ anticyclonic anomaly over the whole North America due to enhanced Hadley cell.

1. Introduction

In the recent decades, North American east experienced frequent severe cold extreme weathers. For example, 2013/14 and 2014/15 winters are characterized by warm and drought in California with a strong cold anomaly in the east of North America, whose temperature anomalies show a North American “warm west/cold east” (WWCE) dipole in midlatitudes (Wang et al. 2014; Lee et al. 2015; Hartmann 2015; Singh et al. 2016). Such a temperature dipole pattern was expected to frequently occur in the future (Wang et al. 2017; Chien et al. 2019). Thus, the physical cause of the North American WWCE dipole has attracted a great interest of scientists and has been an important research topic in recent years (Wang et al. 2014, 2015; Seager et al. 2016; Lee et al. 2015; Yu and Zhang 2015; Hartmann, 2015; Yu et al. 2016, 17, 2018; Singh et al. 2016; Xie and Zhang 2017; Schulte and Lee 2017; B. Luo et al. 2020).

Many previous studies have mentioned the role of sea surface temperature (SST) in the winter WWCE dipole of 2013/14 and 2014/15. For example, Wang et al. (2014, 2015) indicated that the presence of the WWCE dipole in the North America in 2013/14 winter might be associated with the developing phase of El Niño. Seager and Henderson (2016) found that the SST anomaly pattern in the tropical Pacific and the south Indian Ocean might have contributed to California’s drought during the 2013/14 winter. Hartmann (2015) suggested that the North American cold anomaly in the 2013/14 winter was related to the North
Pacific mode of the SST anomaly. Peng et al (2019) further found that the abnormal atmospheric circulation related to the extreme climate on the North America for the 2013/14 winter was also influenced by the tropical Madden-Julian Oscillation. However, Xie and Zhang (2017) pointed out that the cold winter in 2014/2015 is likely related to internal atmospheric variability, even though Peng et al. (2018) connected it to the effect of El Niño or North Pacific mode. Furthermore, some studies have suggested that the low sea ice concentration might modify the frequency of North American WWCE dipole in the future (Lee et al. 2015). Chen and Luo (2017, 2019) found that the westward shift of Greenland blocking due to the sea ice concentration decline in the west of Greenland could lead to such a WWCE dipole. More recently, B. Luo et al. (2020) noted that the WWCE dipole not only depends on the North Pacific blocking, but also on the phase of the North Atlantic Oscillation. Of course, such a midlatitude temperature dipole has been shown to be related to North Pacific Oscillation/West Pacific pattern (Baxter and Nigam 2015).

The PNA pattern is an internal mode with 10-20 days timescale, characterized by a quadrupole structure from North Pacific to North America (Feldstein. 2002, Franzke et al. 2011). The PNA has been shown to have an important impact on the weather and climate over North America (Yu et al. 2016; Harnik et al. 2016). Some studies have indicated that the PNA as an atmospheric internal mode is modulated by the air-sea interaction (Straus and Shukla 2002, Peng 2014). Luo et al. (2020) found that the North Pacific winds could influence the period, spatial shape, movement and amplitude of the PNA events with a timescale of 10-20 days, whereas the structure and strength of midlatitude westerly winds over North Pacific are related to the SST anomaly patterns on interannual/decadal timescales. Thus, it is inferred that the PNA events can be influenced by the Pacific SST anomaly through the background wind condition change. While some studies have noted the effect of the PNA on the air temperature anomaly over North America (Harnik et al. 2016), what type of Pacific SST condition favors or suppresses PNA+ leading to a strong North American WWCE SAT dipole is not clear so far. Thus, examining under what SST condition the PNA+ can lead to a North American WWCE dipole has an important implication in understanding and predicting extreme weather over the North America, which is the main purpose of our present paper.

This paper is arranged as follows. The data and method are described in Section 2. In Section 3, atmospheric circulation patterns during the 2013/14 and 2014/15 winters are presented to establish the relationship of North American SAT anomaly with the phase of PNA. The different weather regimes of PNA+ events and their connection to the type of El Niño are investigated in Section 4. In this section, we also explore why the type of El Niño can cause a large change in the PNA+. In Section 5, we examine a connection of the WWCE dipole to the combined effect of the CP-type El Niño and PDO. The conclusions and discussion are given in the final section.

2. Data And Method

The reanalysis data in winter (from December to February, DJF) used in this study is taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research (Kalnay et al.
(1996) from December 1950/February 1951 to December 2018/February 2019 (1950-2018, hereafter). This dataset includes the daily mean 500-hPa geopotential height (Z500) and surface air temperature (SAT) as well as the monthly horizontal (zonal and meridional components U and V) field and vertical velocity with 2.5°×2.5° grids. For the winter SST anomaly, we used the monthly-mean sea surface temperature (SST) dataset with 1°×1° grids resolution taken from the Hadley Centre (Rayner et al. 2003) from 1950-2018. All the anomalies at each grid were obtained by removing the seasonal cycle and linear trend.

Furthermore, we used the daily PNA index provided by the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/), which is obtained based on the Rotated Empirical Orthogonal Function (REOF or rotated EOF) of 500-mb height anomalies. Here, a PNA⁺ (PNA⁻) event is defined if the daily PNA index is above 1.25 (below -1.25) standard deviations (STDs) for at least three consecutive days. During the life cycle of PNA, lag 0 denotes the peak day of the PNA event. In the following discussions, we calculate the time-mean composite daily Z500 and SAT anomalies averaged from lag -5 to 5 days of individual PNA events to reflect the contribution of the mature PNA to the SAT anomaly over the North America. But the temporal variations of the composite daily SAT anomalies averaged over the east and west parts of the North America and the composite daily warm west/cold east SAT dipole of PNA events are presented for the entire PNA event lifetime (from lag -10 to 10 days) because the PNA event is of two weeks (10-20 days) (Feldstein 2002).

Here, we also used a combined regression-EOF procedure as in Kao and Yu (2009) to classify the El Niño-Southern Oscillation (ENSO) into CP and EP types. We subtracted the SST anomalies regressed with the Niño1+2 index in the eastern equatorial Pacific (10°S-0°, 80°-90°W) from the original SST anomalies and then used the EOF analysis to obtain the CP-ENSO structure of the subtracted SST anomalies. Similarly, the EOF analysis of the SST anomalies regressed onto the Niño 4 index in the central Pacific region (5°S-5°N, 160°E°-150°W) and subtracted from the original SST anomalies is performed to obtain the EP-type ENSO structure. In this case, the principal component (PC1) time series of the first empirical orthogonal function (EOF1) of the DJF-mean SST anomaly for a CP-type (EP-type) El Niño is defined as the CP-type (EP-type) El Niño index. The SST anomaly averaged over the region (10°S-0° and 80°-90°W) or the region (5°S-5°N and 160°E°-150°W) is defined as the Niño1+2 or Niño 4 index respectively. Moreover, the winter Pacific Decadal Oscillation (PDO) index was defined as the PC1 time series of the EOF1 mode of DJF-mean SST anomalies over the North Pacific (120°E-120°W, 20°-70°N) as in Ding et al. (2015).

In this paper, we used the k-means clustering method as used in Michelangeli et al., (1995), Ferranti et al., (2015) and Champagne et al., (2019) to classify the different regimes of SAT and Z500 anomalies over North America (25°N-70°N, 140°W-60°W) for PNA⁺ events during the 1950-2018. Using such a method can help us to identify what types of PNA⁺ patterns favor the WWCE dipole over North America. The k-means clustering algorithm was constructed by minimizing the sum of the squares of distances between each sample and the corresponding cluster centroid based on an iterative process, in which the Euclidean distance was used. The detail of this clustering method can be found in Michelangeli et al. (1995).
3. Winter North American Warm West/cold East Dipole And Its Link To The Phase Of PNA

a) Case analysis of 2013/14 and 2014/15 winters

The winters of 2013/14 and 2014/15 are two typical examples of the warm west/cold east SAT anomaly over the North America widely analyzed in previous studies (Wang et al. 2014, Lee et al. 2015; Hartmann 2015; Yu and Zhang 2015; Peng et al. 2018; B. Luo et al. 2020). We first analyzed the two winters to motivate our present study. Figures 1a-b show the DJF-mean Z500 and SAT anomalies during 2013/14 and 2014/15. It is noted that the winter-mean SAT anomaly shows an intense WWCE dipole along the zonal direction of North American mid-latitudes during 2013/14 (Fig. 1a) and 2014/15 (Fig. 1b) winters. Clearly, the warm anomaly associated with the anticyclonic anomaly in the west part of North America are located in higher latitudes than the cold anomaly in its east part. Thus, the domain-averaged SAT anomalies over the northwest ($T_W$: 35°N-65°N, 125°W-100°W, red box) and east ($T_E$: 25–55°N, 100°W–65°W, blue box) parts of North America, as denoted by $T_W$ and $T_E$ respectively, can be used to characterize the zonal SAT dipole. The difference $T_{WE}=T_W-T_E$ between $T_W$ and $T_E$ is defined as the SAT dipole index. Such an index definition is slightly different from that of Singh et al. (2016). To guarantee that the $T_{WE}$ index is continuous in winter, we do not require that $T_W$ is positive and $T_E$ is negative in two winters. But we require $T_W$ being positive and $T_E$ being negative to select individual WWCE events.

For 2013/14 and 2014/15 winters, the daily variations of the zonal SAT dipole index $T_{WE}$ and the PNA index from December to February are shown in Fig.1c-f. It is seen that the $T_{WE}$ index shows a notable sub-seasonal variability. When PNA is positive, the $T_{WE}$ index is mostly positive. But when PNA is negative, the $T_{WE}$ index is negative or shows a change from negative (positive) to positive (negative) (Figs. 1c-e). This indicates that the SAT WWCE dipole is mainly related to PNA$^+$. It is also found from the wavelet power spectrum analysis that the timescale of the $T_{WE}$ variation is about 20 days (Figure S1 in the supplementary file), crudely consistent with the lifetime of the PNA events (Feldstein 2002). Here, we used

$$p = \frac{T_{WE}(PNA)}{T_{WE}(DJF)} \times 100\%$$

to calculate the contribution of the PNA to the winter WWCE SAT dipole, where $T_{WE}(PNA)$ represents the total sum of $T_{WE}$ indices for $T_W >0$ and $T_E <0$ from lag-10 to 10 for PNA events and $T_{WE}(DJF)$ denotes the total sum of $T_{WE}$ indices in winter for the same condition. It is found that the contribution of PNA to the winter WWCE dipole is about 64.7% during 2013/14 or 51.8% during 2014/15, in which the contribution of PNA$^+$ is 50.5% during 2013/14 or 51.8% during 2014/15. Thus, the PNA$^+$ can significantly influence the two winter WWCE dipoles via the generation of sub-seasonal WWCE dipoles.

It is useful to show the time-mean fields of daily Z500 and SAT anomalies averaged from lag -5 to 5 days of PNA$^-$ and PNA$^+$ events in Figs. 2a-d during the two winters, where lag 0 denotes the peak day of PNA. It is found that during the 2013/14 winter PNA$^-$ corresponds to an intense cold anomaly over the whole North American mid-high latitude region (Fig. 2a). But its combination with the PNA$^+$ (Fig. 2b) can
produce an intense WWCE dipole over North America (Fig. 2c). While the PNA$^+$ during the 2013/14 winter does not correspond to a strong cold anomaly in the east part of North America (Fig. 2b), it can correspond to an intense WWCE dipole during the 2014/15 winter (Fig. 2d). This suggests that the effect of the PNA$^+$ on the North American SAT anomaly exhibits a significant interannual variability.

We can see from the DJF-mean SST anomaly fields in the 2013/14 and 2014/15 winters as shown in Figs. 2e-f that there is a cold SST anomaly in the tropical region (Fig. 2e). Thus, the weak role of the PNA$^+$ in the WWCE dipole during the 2013/14 winter is likely related to the tropical cold SST anomaly (Fig. 2e) and a negative PDO (PDO$^-$) phase with a value of -0.5 STDs as noted below. However, there is a central Pacific (CP) El Niño during the 2014/15 winter. Thus, it is likely that a strong WWCE dipole in the presence of a PNA$^+$ (Fig. 2d) is associated with CP El Niño (Fig. 2f) and a positive PDO (PDO$^+$) positive with a value of 1.7 STDs as noted below. Thus, the role of the PNA$^+$ in the North American WWCE dipole might depend on the different SST anomaly patterns. Although the PNA$^+$ is is an internal atmospheric mode and driven by synoptic-scale eddy forcing (Luo et al. 2020), it does not imply that the PNA is not influenced by the Pacific SST anomalies. Moreover, because the PNA$^-$ event does not correspond to a typical WWCE SAT dipole over North America, our emphasis in the following discussion is mainly placed on examining the effect of the varying PNA$^+$ associated with Pacific SST anomalies on the North American WWCE dipole.

**b) Composite result of PNA$^+$ events**

As noted above, an individual PNA$^+$ event can produce a sub-seasonal WWCE dipole pattern with the timescale of 10-20 days. To establish the linkage of the seasonal SAT pattern to sub-seasonal SAT anomalies, we should examine whether the frequency of sub-seasonal WWCE dipoles influence the seasonal SAT pattern. First, the WWCE dipole for each day is defined as an instantaneous daily WWCE dipole event if the value of $T_{WE}$ is above 1.0 STDs. Additionally, we require a limitation that $T_W > 0$ in the west and $T_E < 0$ in the east domains of North America must be satisfied. Figures 3a-b show the time series of the winter frequency (total number of days) of daily WWCE events and the composite SAT and Z500 anomaly fields for all days of daily WWCE events during the winters from 1950 to 2018. It is seen that the Z500 anomaly mainly shows a zonally oriented wave train structure from the North Pacific to the Atlantic (Fig. 3b). As noted below, the zonal wave train looks like the PNA$^+$ during the CP-type El Niño winter. The composite DJF-mean SAT and Z500 anomaly during winters with high WWCE days shows a winter WWCE pattern (Fig. 3c). In contrast, the winter WWCE dipole cannot be seen during winters with low WWCE days (Fig. 3d). Thus, the winter WWCE pattern is mainly related to the frequency of the sub-seasonal WWCE dipole. In Figs. 3c-d, the winter with high (low) WWCE days is defined as the normalized time series of the winter frequency of daily WWCE events being above 1.0 STDs (below -1.0 STDs).

It is found that there are 835 days of daily WWCE dipole events during 1950-2018. However, there are 549 days of daily WWCE dipole events associated with PNA$^+$, if the daily WWCE dipole event is defined to be associated with PNA$^+$ when the PNA$^+$ index is above 0.5STDs. Thus, nearly 66% of daily WWCE dipole
events are related to PNA\(^+\). We also note that nearly 77\% of daily WWCE dipole events are linked to PNA\(^+\) if the PNA\(^+\) index is above 0.25 STDs.

To indicate whether the PNA\(^+\) leads to a typical WWCE dipole over North America, we show the time series of the event number of individual PNA\(^+\) events during 1950-2018 in Fig.4a. Statistical calculation shows that there are 79 PNA\(^+\) events during 1950-2018. Figure 4b shows the corresponding time-mean fields of composite daily Z500 and SAT anomalies averaged from lag -5 to 5 days for the PNA\(^+\) events. It is seen that there is a warm anomaly in the northwest side of North America for the PNA\(^+\) (Fig. 4b) followed by an anticyclonic anomaly there. Correspondingly, a weak cold anomaly can be seen over the southeast side of North America. The variation of the composite daily T\(_{WE}\) index from lag-10 to 10 days of PNA events is shown in Fig. 4c. It is found that the daily T\(_{WE}\) index is positive during the period from lag -4 to 6 days, indicating that the PNA\(^+\) can lead to a relatively weak WWCE SAT dipole over North America. This also suggests that these PNA\(^+\) events may include some cases related to a more or less typical sub-seasonal WWCE dipoles. As we will find below, the PNA\(^+\) event can lead to a more typical WWCE dipole under the CP-type El Niño SST anomaly condition than the EP-type El Niño SST condition.

4. North American WWCE Dipole And Its Link To The Different Regime Patterns Of The Positive PNA And The Pacific SST Anomaly

a) Preferred regime patterns of the positive PNA associated with the WWCE dipole

To examine under what SST anomaly condition the PNA\(^+\) events lead to a strong North American WWCE dipole, it is useful to use a k-means clustering method as widely used in previous studies (e. g., Michelangeli et al., 1995; Champagne et al. 2019) to classify time-mean SAT anomalies averaged from lag-5 to 5 days over the North America (25°N-70°N\(\oplus\)140°W-60°W) associated with the PNA\(^+\) events. For 79 PNA\(^+\) events during the 1950-2018 winters, the time-mean SAT anomalies associated with the PNA\(^+\) events can be classified into six clustering regimes: C1, C2, C3, C4, C5 and C6. By compositing daily Z500 and SAT anomalies associated with the six clustering regimes, one can find the preferred regime of the PNA\(^+\) associated with the typical WWCE dipole.

Figure 5 shows time-mean fields of composite daily Z500 and SAT anomalies averaged from lag -5 to 5 days of the PNA\(^+\) events related to six clustering regimes (C1, C2, C3, C4, C5 and C6). It is found that C3 with a zonal wave train structure with an anticyclonic (cycloonic) anomaly in the west (east) part of the North America corresponds to a typical WWCE dipole (Fig. 5c) which resembles the large-scale circulation pattern associated with the WWCE dipole (Fig.3b), whereas C6 corresponds to a PNA\(^+\) concurrent with a negative Arctic Oscillation (AO\(^-\)) and a strong cold anomaly in the eastern North America (Fig. 5f). C4 corresponds to a weak WWCE dipole (Fig. 5d). Although C1 (Fig. 5a), C2 (Fig. 5b) and C5 (Fig. 5e) are the PNA\(^+\) patterns, they do not produce typical WWCE dipoles over North American midlatitudes (Fig. 5e). However, C2 can have a cold anomaly over the whole North America midlatitudes (Fig. 5b). The above
results lead us to infer that some of PNA$^+$ events can produce a typical WWCE dipole over North America, but some cannot. Through a comparison with Figs. 2a-d, we can find that C3 (Fig. 5c) looks like the PNA$^+$ event in the 2014/15 winter (Fig. 2d) in that they have a pattern correlation coefficient of 0.73 in the region (150°E-30°W, 20°-80°N). In the six clustering regimes, the C4 regime is most frequent (Fig. 5d) and resembles the composite pattern of all the PNA$^+$ events (Fig. 4b) because its pattern correlation coefficient with Fig. 4b is nearly 0.95.

Figure 6 shows the time series of the event number of PNA$^+$ events in winter for each one of the six clustering regimes during 1950-2018. It is interesting to see that C3, C4 and C5 regimes show notable interannual and decadal variability (Figs. 6c, d, e), whereas the C6 (C1) regime takes place mainly during the 1950-1981 (1994-2018) winters (Figs. 6a, f). We can also see from Fig. 6 that the PNA$^+$ event in the 2014/15 (2013/14) winter belongs to the C3 (C4) type. Thus, the variability of the PNA$^+$ events can produce the different spatial pattern of the North American SAT anomaly.

To further quantify which of the six clustering regimes is responsible for the North American WWCE dipole, the temporal variation of $T_{WE}$ during the life cycle of the PNA$^+$ (from lag-10 to 10 days) is shown in Figure 7 for the six clustering regimes of the PNA$^+$. It is found that in the six clustering regimes, the WWCE dipole is strongest during the PNA$^+$ life cycle for C3 (Fig. 7c). Thus, C3 is an optimal PNA$^+$ pattern that promotes a typical WWCE dipole. Although C4 and C6 favor North American WWCE dipoles (Figs. 7d, f), C6 mainly appears before 1981 (Fig. 6f). Furthermore, we show the correlation coefficients between the WWCE dipole index (Fig. 3b) and the event number of each regime in the six clustering regimes (Fig. 6) in Table 1. It is noted that C3 (C4) shows a significant positive correlation of 0.34 (0.39) (p<0.05) with the WWCE dipole index. Thus, the North American WWCE dipole is associated with the C3- and C4-type PNA$^+$ events. Below, we will examine the SST anomalies associated with the six clustering regimes to understand what types of SST anomalies cause the PNA$^+$ events to have different North Atlantic SAT anomaly patterns.

b) Pacific SST anomaly patterns linked to different clustering regimes

While the PNA$^+$ is an internal mode, its variability depends on the type of ENSO as an external forcing (Straus and Shukla 2002; Yu et al. 2012a, b). In other words, the PNA$^+$ event in strength and location may become different as the ENSO-type SST anomalies are different. To establish the linkage of the six clustering regimes with different Pacific SST anomaly patterns, we show the composite DJF-mean SST anomalies of the six clustering regimes in Figure 8. It is seen that C3 (C5) corresponds to a typical CP-type (EP-type) El Niño in addition to C3 having a PDO$^+$-like SST signal (Figs. 8c, e), whereas C4 corresponds to a rather weak CP-type El Niño (Fig. 8d). This indicates that the C4-type PNA$^+$ is influenced by a weak CP-type El Niño. Although C6 corresponds to a CP-type El Niño (Fig. 8f), the El Niño signal is relatively weak compared to that of C3 (Fig. 8c). Our calculation of the correlation coefficients (Table 2) with the CP and EP El Niño indices (Fig. 9 below) shows that C3 (C4) has modest significant positive correlations of 0.22 and 0.29 (0.22 and 0.22) (p<0.1 for 0.22 and P<0.05 for 0.29) with the CP El Niño and
PDO indices. But C1 (C5) not associated with the WWCE dipole has a significant positive correlation of 0.29 (0.37) (p<0.05) with the EP El Niño index. Thus, the WWCE dipole associated with C3 is related to a CP-type El Niño (Fig. 8c), whereas C5 without a WWCE dipole is linked to a strong EP-type El Niño (Fig. 8e). This result leads us to infer that the different types of El Niño might be an important factor influencing the WWCE dipole through the change of the PNA$^+$. To examine the possible role of CP- and EP-type El Niños in the WWCE dipole, we show the winter SST EOF1 anomaly for the CP-type (EP-type) El Niño based on the combined EOF-regression method in Fig.9a (Fig. 9b) and the corresponding PC1 time series in Figs. 9c-d. Here, a CP- (EP-) type El Niño winter is defined if the CP (EP) El Niño index is above 0.5 STDs. It is easy to see that there are 12 CP-type El Niño winters (0.3/year) during 1950-1989, but 11 winters (0.38/year) during 1990-2018. Thus, the CP-type El Niño has slightly increased since 1990, consistent with the previous results (Kao and Yu 2009; Kug et al. 2009; Lee and McPhaden 2010; Yu et al. 2012a). Of course, the different spatial pattern of the North American SAT anomaly in the CP- or EP-type El Niño winter might be associated with the wave trains in response to tropical convection anomalies (Peng et al. 2018), the presence of PNA$^+$ does not necessarily require the appearance of tropical convection (Franzke et al. 2011).

Moreover, it is useful to show the time-mean composite daily Z500 and SAT anomalies averaged from lag -5 to 5 days associated with PNA$^+$ events in the CP- and EP-type El Niño winters in Figs.9e-f. It is noted that in the CP-type El Niño winter the PNA$^+$ events become a zonal midlatitude wave train like C3, which can produce an intense WWCE dipole over North America (Fig. 9e). But such a WWCE dipole is hardly seen for the EP-type El Niño winter (Fig.9f) because the anticyclonic anomaly of the PNA$^+$ almost occupies the whole North America and resembles the C5 regime. Thus, it is suggested that the PNA$^+$ events in the CP-type and EP-type El Niño winters played different roles in the North American WWCE dipole because of their spatial patterns being different.

c). Physical mechanism of the CP- and EP-type El Niño SSTs influencing the PNA$^+$

Here, we further examine why the CP- and EP-type El Niño SSTs have different influences on the PNA$^+$ events. Because the variation of PNA events depends on the change of the North Pacific midlatitude westerly wind field (Luo et al. 2020), it is not difficult to infer that the type of El Niño can influence the PNA$^+$ events probably through changing midlatitude westerly wind due to the change of the winter meridional circulation such as Hadley cell. In fact, because the PNA$^+$ is sub-seasonal timescales (10-20 days), the interannual Hadley cell and midlatitude westerly winds associated with the type of El Niño can be considered as the background conditions influencing the sub-seasonal PNA$^+$. In this paper, the climatological plus the interannual circulation associated with the type of El Niño is considered as the background condition of sub-seasonal PNA$^+$ even though CP- and EP-type El Niño SSTs may require the same climatological condition. Such a consideration is reasonable because CP- and EP-type El Niño SSTs can correspond to different interannual Hadley cells. Below, we further calculate the winter Hadley cell and midlatitude westerly winds related to CP- and EP-type El Niño SSTs. According to Wang (2004) and
Feng and Li (2013), the winter Hadley cell can be well characterized by the divergent component of the winter wind and vertical velocity.

We show the height-latitude profiles of the DJF-mean anomalous Hadley cell averaged over 150°E - 120°W and the horizontal fields of DJF-mean U500 anomalies in Fig. 10 for the CP- and EP-type El Niño winters. It is found that the sinking movement of the Hadley cell is relative weak in the subtropical Pacific (10°-30°N) for the CP-type El Niño (Fig. 10a), but strong for the EP-type El Niño (Fig. 10b). Their difference is significant (Fig. 10c). Clearly, on interannual timescales the Hadley cell is significantly modulated by the type of El Niño, though it is influenced by enhanced convection in the central-east tropical Pacific associated with enhanced upward motions and enhanced poleward divergent wind anomalies in the subtropical Pacific (Fig.S2), as noted in Feng et al. (2017). Moreover, while the PNA+ is also influenced by high-frequency convectively tropical disturbances during the CP- and EP-type El Niño winters (Wang et al. 2013), some studies have indicated that the PNA+ events are driven by synoptic-scale eddies in the Pacific storm track (Feldstein 2002; Franzke et al. 2011). As noted above, because the type of El Niño can influence the interannual Hadley cell and midlatitude westerly winds, the PNA+ is inevitably changed by the background wind condition (Luo et al. 2020) associated with the type of El Niño, no matter how the PNA+ is generated.

To examine the linkage between the type of El Niño and the spatial distribution of winter midlatitude westerly winds and why the EP-type El Niño is favorable for the North American WWCE dipole, we show the composite winter 500-hPa zonal wind anomalies in Figs. 10d-f for the CP- and EP-type El Niño winters. It is seen that the winter midlatitude westerly winds are stronger and extend more east for an EP-type El Niño (Fig.10e) than for a CP-type El Niño (Fig.10d). Because the descending branch of the strong Hadley cell mainly appears in the latitudes 10°-30°N for the EP-type El Niño and favors an intensified subtropical high (not shown), the midlatitude westerly winds are enhanced in the north of 30°N according to the geostrophic adjutsment. As seen from Fig. 10f, the winter midlatitude westerly winds are stronger in the latitudes 30°-50°N for the EP-type El Niño than for the CP-type El Niño. For this reason, the anticyclonic anomaly of the PNA+ shifts more east so that it occupies the larger region of the North America for an EP-type El Niño (Fig. 10f) than for a CP-type El Niño (Fig. 10e). Thus, in the EP-type El Niño winter the eastward shift of the PNA+ is related to enhanced Hadley Cell, which is also consistent with the modeling result of Yu et al. (2012b). These results explain why the PNA+ events associated with the EP-type El Niño cannot produce the North American WWCE dipole. The physical mechanism of the type of El Niño influencing the North American WWCE dipole can be simply described by the pathway: the type of El Niño different interannual Hadley cells different interannual Pacific midlatitude zonal wind changes in sub-seasonal PNA+ in spatial shape and location changes in the North American WWCE dipoles.

5. Combined Effect Of The Enso And Pdo Types On The Pna And North American Air Temperatures
While the CP-type El Niño favors the North American WWCE dipole via changing the zonal location of the PNA* and its spatial shape, the PDO as a decadal signal of the North Pacific SST likely modulates the effect of the CP-type El Niño. Here, we further explore whether the phase of PDO modulates the North American WWCE dipole associated with the CP-type El Niño. A CP-type El Niño and PDO* (PDO+) combination is defined if the CP index has a value $\geq 0.5$ STDs and the PDO index (Figure 11a) is positive above (negative below) zero. To examine the impact of the CP-type El Niño combined with the different phase of PDO on the North American WWCE dipole related to the PNA+, we first show the DJF-mean SST anomalies in Figs. 11b-d for the CP-type El Niño and PDO* combination and the CP-type El Niño and PDO- combination as well as their difference. It is found that the phase of PDO can modulate the intensity and region of the positive Pacific SST anomaly associated with the CP-type El Niño (Figs. 11b-c). Thus, it likely influences the PNA+ and associated North American SAT anomaly.

Figures 11e-g show the time-mean composite daily Z500 and SAT anomalies averaged from lag -5 to 5 days of PNA+ events for the two combinations and their difference. It is seen that the PNA+ events can produce a typical North American WWCE dipole (Fig. 11e) if the Pacific SST anomaly corresponds to the combination of a CP-type El Niño and a PDO+ (Fig. 11b). But the North American WWCE dipole is relatively weak (Fig. 11f) under the Pacific SST anomaly with the combination of a CP-type El Niño and a PDO- (Fig. 11c). Their difference can be seen from the daily variations of $T_W$, $T_E$, and $T_{WE}=T_W-T_E$ (Fig. 11h-j), even though the strong warm anomaly are located in the Northwest North America relative to the cold anomaly over the east part of North America. Thus, the PDO+ (PDO-) tends to enhance (suppress) the role of the CP-type El Niño in the North American interannual WWCE dipole by strengthening (suppressing) cold and warm anomalies over the east and west parts of North America.

6. Conclusion And Discussions

A notable warm west/cold east (WWCE) zonal temperature dipole occurred over North America during 2013/14 and 2014/15 winters, which is characterized by an anticyclonic anomaly over the northwest part of North America and a negative height anomaly over the east part of North America. It is found that the PNA events with a timescale of 10-20 days contribute to the sub-seasonal WWCE SAT dipole in the two winters. By inspecting the composite results of PNA events in 2013/14 and 2014/15 winters, it is found that although the positive PNA (PNA+) events occurred in the two winters, the effect of the PNA+ is different between the two winters. Such a difference is likely related to the different SST anomalies conditions. The most notable difference between the 2013/14 and 2014/15 winters is that the two winters correspond to different SST anomalies over Pacific. Thus, it is speculated that the PNA+ could be significantly influenced by the winter SST anomalies in Pacific, even though it is an internal sub-seasonal mode. This motivates us to examine under what oceanic condition the PNA+ events can lead to a typical WWCE dipole.

In order to establish the link of the PNA+ events with the oceanic condition, it is useful to classify the North American SAT anomaly associated with the PNA+ events using the K-means clustering method. By
compositing daily Z500 anomalies associated with the six clustering regimes, one can know what types of PNA$^+$ correspond to what types of North American SAT patterns and Pacific SST anomalies. It is noted that C3 corresponds to a typical North American WWCE dipole with a strong cold (warm) anomaly over the east (northwest) part of North America. While C4 corresponds to a WWCE dipole, the cold anomaly over the eastern North America is relatively weak. It is also found that while C3 and C4 have a significant correlation with the CP-type El Niño and PDO$^+$. The PNA$^+$ events associated with C5, which does not produce a WWCE dipole, is strongly related to the EP-type El Niño. This suggests that the type of the El Niño can influence the PNA$^+$ events and associated sub-seasonal North American SAT anomaly to result in a notable interannual variability of the winter WWCE dipole as a winter-averaged result of sub-seasonal WWCE dipoles.

In addition, we further examine why the CP-type or EP-type El Niño can influence the PNA$^+$ events by calculating the interannual winter-mean zonal winds and Hadley cell associated with the type of El Niño. It is revealed that the type of El Niño can influence the position of the anticyclonic anomaly of the PNA$^+$ through changing interannual Hadley cell and associated midlatitude westerly winds over North Pacific. For the EP-type El Niño, the interannual zonal winds over North Pacific midlatitudes are intensified due to intensified Hadley cell, which cause the eastward shift of the sub-seasonal PNA$^+$ event and make its anticyclonic anomaly appear in the whole North America. Such a PNA$^+$ event does not produce a North American WWCE dipole. The reversed is seen for a CP-type El Niño. Under a CP-type El Niño condition the interannual Hadley cell is weakened, which leads to reduced interannual midlatitude zonal winds over North Pacific favoring the westward shift of the sub-seasonal PNA$^+$ and the appearance of the anticyclonic (cycloonic) anomaly of the sub-seasonal PNA$^+$ in the west (east) part of North America. Such a sub-seasonal PNA$^+$ shift can generate an intense North American sub-seasonal WWCE dipole. Because the presence of a strong winter WWCE dipole is mainly related to intense or frequent sub-seasonal WWCE dipoles, the type of El Niño can modulate the winter WWCE dipole over North America through changes in the sub-seasonal WWCE dipoles. As a result, the winter North American WWCE dipole can show a notable interannual variability. Furthermore, it is shown that while the CP- (EP-) type El Niño favors (suppresses) the North American sub-seasonal WWCE dipole associated with the PNA$^+$ events, the phase of PDO as a decadal signal can modulate the role of CP-type El Niño in the variability of the North American WWCE dipole. In particular, the negative phase of PDO tends to suppress the WWCE dipole of the PNA$^+$ event under the CP-type El Niño.

However, it must be pointed out that in this paper we do not examine the role of other circulation in the WWCE SAT dipole, such as the North Atlantic Oscillation and North Pacific Oscillation/West Pacific pattern. Also, the role of tropical convection activity associated El Niño and its combined effect with other processes were not discussed. These problems deserve a further study.

**Declarations**

**Acknowledgements**
This research was supported by the National Natural Science Foundation of China (Grant numbers: 41790473), Chinese Academy of Sciences Strategic Priority Research Program (Grant XDA19070403) and the National key research and development program of China (2016YFA0601802).

References

Baxter, S., S. Nigam (2015), Key Role of the North Pacific Oscillation-West Pacific Pattern in Generating the Extreme 2013/14 North American Winter, Journal of Climate, 28(20), http://dx.doi.org/10.1175/jcli-d-14-00726.1.

Champagne, O., B. Pohl, S. McKenzie, J. F. Buoncristiani, E. Bernard, D. Joly, F. Tolle (2019), Atmospheric circulation modulates the spatial variability of temperature in the Atlantic-Arctic region, International Journal of Climatology, 39(8), 3619-3638, http://dx.doi.org/10.1002/joc.6044.

Chen, X., D. Luo (2017), Arctic sea ice decline and continental cold anomalies: Upstream and downstream effects of Greenland blocking, Geophysical Research Letters, 44(7), 3411-3419, http://dx.doi.org/10.1002/2016gl072387.

Chen, X., D. Luo (2019), Winter Midlatitude Cold Anomalies Linked to North Atlantic Sea Ice and SST Anomalies: The Pivotal Role of the Potential Vorticity Gradient, Journal of Climate, 32(13), 3957-3981, http://dx.doi.org/10.1175/jcli-d-18-0504.1.

Chien, Y. T., S. Y. S. Wang, Y. Chikamoto, S. L. Voelker, J. D. D. Meyer, and J. H. Yoon (2019), North American Winter Dipole: Observed and Simulated Changes in Circulations, Atmosphere, 10(12), 15, http://dx.doi.org/10.3390/atmos10120793.

Ding, R., J. Li, Y.-h. Tseng, C. Sun, and Y. Guo (2015), The Victoria mode in the North Pacific linking extratropical sea level pressure variations to ENSO, Journal of Geophysical Research: Atmospheres, 120(1), 27-45, https://doi.org/10.1002/2014JD022221.

Feldstein, S. B. (2002), Fundamental mechanisms of the growth and decay of the PNA teleconnection pattern, Quarterly Journal of the Royal Meteorological Society, 128(581), 775-796, https://doi.org/10.1256/0035900021643683.

Feng, J., Chen, W., Li, Y. (2017). Asymmetry of the winter extra-tropical teleconnections in the Northern Hemisphere associated with two types of ENSO. Climate Dynamics, 48(7), 2135-2151. https://doi.org/10.1007/s00382-016-3196-2

Feng, J., J. Li (2013), Contrasting Impacts of Two Types of ENSO on the Boreal Spring Hadley Circulation, Journal of Climate, 26(13), 4773-4789, http://dx.doi.org/10.1175/jcli-d-12-00298.1.

Ferranti, L., S. Corti, M. Janousek (2015), Flow-dependent verification of the ECMWF ensemble over the Euro-Atlantic sector, Quarterly Journal of the Royal Meteorological Society, 141(688), 916-
Franzke, C., S. B. Feldstein, and S. Lee (2011), Synoptic analysis of the Pacific–North American teleconnection pattern, Quarterly Journal of the Royal Meteorological Society, 137(655), 329-346, https://doi.org/10.1002/qj.768.

Harnik, N., G. Messori, R. Caballero, S. B. Feldstein (2016), The CircumglobalNorth American wave pattern and its relation to cold events in eastern North America, Geophysical Research Letters, 43(20), 11015-11023, http://dx.doi.org/10.1002/2016gl070760.

Hartmann, D. L. (2015), Pacific sea surface temperature and the winter of 2014, Geophysical Research Letters, 42(6), 1894-1902, http://dx.doi.org/10.1002/2015gl063083.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, Bulletin of the American Meteorological Society, 77(3), 437-471, http://dx.doi.org/10.1175/1520-0477(1996)077<0437:Tnyrp>2.0.Co;2.

Kao, H.-Y., J.-Y. Yu (2009), Contrasting Eastern-Pacific and Central-Pacific Types of ENSO, Journal of Climate, 22(3), 615-632, http://dx.doi.org/10.1175/2008jcli2309.1.

Kug, J.-S., F.-F. Jin, S.-I. An (2009), Two Types of El Niño Events: Cold Tongue El Niño and Warm Pool El Niño, Journal of Climate, 22(6), 1499-1515, http://dx.doi.org/10.1175/2008jcli2624.1.

Lee, M.-Y., C.-C. Hong, H.-H. Hsu (2015), Compounding effects of warm sea surface temperature and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013-2014 boreal winter, Geophysical Research Letters, 42(5), 1612-1618, http://dx.doi.org/10.1002/2014gl062956.

Lee, T., M. J. McPhaden (2010), Increasing intensity of El Niño in the central-equatorial Pacific, Geophysical Research Letters, 37, http://dx.doi.org/10.1029/2010gl044007.

Luo, B., D. Luo, A. Dai, I. Simmonds, L. Wu (2020), Combined Influences on North American Winter Air Temperature Variability from North Pacific Blocking and the North Atlantic Oscillation: Subseasonal and Interannual Time Scales, Journal of Climate, 33(16), 7101-7123, http://dx.doi.org/10.1175/jcli-d-19-0327.1.

Luo, D., Y. Ge, W. Zhang, A. Dai (2020), A Unified Nonlinear Multiscale Interaction Model of Pacific-North American Teleconnection Patterns, Journal of the Atmospheric Sciences, 77(4), 1387-1414, http://dx.doi.org/10.1175/jas-d-19-0312.1.

Michelangeli, P. A., R. Vautard, and B. Legras (1995), Weather regimes - recurrence and quasi stationarity, Journal of the Atmospheric Sciences, 52(8), 1237-1256, http://dx.doi.org/10.1175/1520-0469(1995)052<1237:Wraqs>2.0.Co;2.
Peng, P., A. Kumar, M. Chen, Z.-Z. Hu, B. Jha (2019), Was the North American extreme climate in winter 2013/14 a SST forced response?, Climate Dynamics, 52(5-6), 3099-3110, http://dx.doi.org/10.1007/s00382-018-4314-0.

Peng, P., A. Kumar, Z.-Z. Hu (2018), What drove the Pacific and North America climate anomalies in winter 2014/15?, Climate Dynamics, 51(7-8), 2667-2679, http://dx.doi.org/10.1007/s00382-017-4035-9.

Peng, P., A. Kumar, B. Jha (2014), Climate mean, variability and dominant patterns of the Northern Hemisphere wintertime mean atmospheric circulation in the NCEP CFSv2, Climate Dynamics, 42(9-10), 2783-2799, http://dx.doi.org/10.1007/s00382-014-2116-6.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, Journal of Geophysical Research-Atmospheres, 108(D14), http://dx.doi.org/10.1029/2002jd002670.

Schulte, J. A., S. Lee (2017), Strengthening North Pacific Influences on United States Temperature Variability, Scientific Reports, 7, http://dx.doi.org/10.1038/s41598-017-00175-y.

Seager, R., N. Henderson (2016), On the Role of Tropical Ocean Forcing of the Persistent North American West Coast Ridge of Winter 2013/14, Journal of Climate, 29(22), 8027-8049, http://dx.doi.org/10.1175/jcli-d-16-0145.1.

Singh, D., D. L. Swain, J. S. Mankin, D. E. Horton, L. N. Thomas, B. Rajaratnam, N. S. Diffenbaugh (2016), Recent amplification of the North American winter temperature dipole, Journal of Geophysical Research-Atmospheres, 121(17), 9911-9928, http://dx.doi.org/10.1002/2016jd025116.

Straus, D. M., J. Shukla (2002), Does ENSO force the PNA? Journal of Climate, 15(17), 2340-2358, http://dx.doi.org/10.1175/1520-0442(2002)015<2340:Deftp>2.0.Co;2.

Wang C. (2004), ENSO, Atlantic Climate Variability, and the Walker and Hadley Circulations. Advances in Global Change Research, vol 21. https://doi.org/10.1007/978-1-4020-2944-87

Wang, H., Y. Pan, A. Kumar and W. Wang (2013), Modulation of convectively coupled Kelvin wave activity in the tropical Pacific by ENSO. Acta Meteor. Sinica, 27(3), 295–307, doi:10.1007/s13351-013-0306-5.

Wang, H., Pan, Y., Kumar, A., & Wang, W. (2013). Modulation of convectively coupled Kelvin wave activity in the tropical Pacific by ENSO. Acta Meteorologica Sinica, 27(3), 295-307. https://doi.org/10.1007/s13351-013-0306-5

Wang, S.-Y. S., W.-R. Huang, J.-H. Yoon (2015), The North American winter ‘dipole’ and extremes activity: a CMIP5 assessment, Atmospheric Science Letters, 16(3), 338-345, http://dx.doi.org/10.1002/asl.565.
Wang, S.-Y. S., L. Hipps, R. R. Gillies, J.-H. Yoon (2014), Probable causes of the abnormal ridge accompanying the 2013-2014 California drought: ENSO precursor and anthropogenic warming footprint, Geophysical Research Letters, 41(9), 3220-3226, http://dx.doi.org/10.1002/2014gl059748.

Wang, S.-Y. S., J.-H. Yoon, E. Becker, R. Gillies (2017), California from drought to deluge, Nature Climate Change, 7(7), 465-468, http://dx.doi.org/10.1038/nclimate3330.

Xie, J., M. Zhang (2017), Role of internal atmospheric variability in the 2015 extreme winter climate over the North American continent, Geophysical Research Letters, 44(5), 2464-2471, http://dx.doi.org/10.1002/2017gl072772.

Yu, B., H. Lin (2018), Modification of the wintertime Pacific-North American pattern related North American climate anomalies by the Asian-Bering-North American teleconnection, Climate Dynamics, 53(1-2), 313-328, http://dx.doi.org/10.1007/s00382-018-4586-4.

Yu, B., H. Lin, Z. W. Wu, W. J. Merryfield (2016), Relationship between North American winter temperature and large-scale atmospheric circulation anomalies and its decadal variation, Environmental Research Letters, 11(7), http://dx.doi.org/10.1088/1748-9326/11/7/074001.

Yu, B., H. Lin, Z. W. Wu, W. J. Merryfield (2017), The Asian-Bering-North American teleconnection: seasonality, maintenance, and climate impact on North America, Climate Dynamics, 50(5-6), 2023-2038, http://dx.doi.org/10.1007/s00382-017-3734-6.

Yu, B., X. Zhang (2015), A physical analysis of the severe 2013/2014 cold winter in North America, Journal of Geophysical Research-Atmospheres, 120(19), 10149-10165, http://dx.doi.org/10.1002/2015jd023116.

Yu, J.-Y., M.-M. Lu, S. T. Kim (2012a), A change in the relationship between tropical central Pacific SST variability and the extratropical atmosphere around 1990, Environmental Research Letters, 7(3), http://dx.doi.org/10.1088/1748-9326/7/3/034025.

Yu, J.-Y., Y. Zou, S. T. Kim, T. Lee (2012b), The changing impact of El Niño on US winter temperatures, Geophysical Research Letters, 39, http://dx.doi.org/10.1029/2012gl052483.

### Tables

**Table 1.** Correlation coefficients between the WWCE index (Fig 3b) and the six clustering regimes: C1, C2, C3, C4, C5, C6 (Fig. 6). The two asterisks represents the coefficient with a 95% confidence level.

|       | C1   | C2  | C3   | C4   | C5   | C6   |
|-------|------|-----|------|------|------|------|
| WWCE  | -0.21| 0.06| **0.34** | **0.39** | -0.05| **0.25** |
Table 2. Correlation coefficients of PNA+, PNA-, C1, C2, C3, C4, C5 and C6 regime events with the Niño1+2, Niño4, CP-type El Niño, EP-type El Niño and PDO indices. The one asterik (two asteriks) represents the coefficient with the 90% (95%) confidence level.

|          | Niño1+2 | Niño4 | CP index | EP index | PDO   |
|----------|---------|-------|----------|----------|-------|
| PNA+     | 0.34**  | 0.26**| 0.11     | 0.29**   | 0.31**|
| PNA−     | -0.26** | -0.23*| -0.16    | -0.23*   | -0.43**|
| C1       | 0.17    | -0.06 | -0.18    | 0.29**   | -0.11 |
| C2       | -0.06   | -0.15 | -0.16    | 0.06     | -0.16 |
| C3       | 0.14    | 0.28**| 0.22*    | -0.13    | 0.29**|
| C4       | -0.02   | 0.16  | 0.22*    | -0.11    | 0.22* |
| C5       | 0.39**  | 0.22* | 0.03     | 0.37**   | 0.21* |
| C6       | 0.02    | 0.11  | 0.17     | 0.01     | 0.25* |
| C3+C4    | 0.06    | 0.30**| 0.31**   | -0.16    | 0.35**|

Figures
Figure 1

DJF-mean fields of Z500 (contours, contour interval is 20gpm) and SAT (color shading with the unit of K) anomalies in the (a) 2013/14 and (b) 2014/15 winters. (c-f) Temporal evolution of daily TWE=TW - TE and the PNA index for the (c, e) 2013/14 and (d, f) 2014/15 winters, where TW and TE represent domain-averaged SAT anomalies over the northwest (35°N-65°N and 125°W-100°W, red box) and east (25°N-55°N, 100°W-65°W, blue box) regions of North America, respectively. In panels c-f, the red (blue) shading area
represents the time interval of PNA+ (PNA-) events from lag -10 to 10 days. The dash line represents the 1.25 (-1.25) STDs of PNA index.

**Figure 2**

Time-mean fields of composite daily Z500 (contours, contour interval is 30gpm) and SAT (color shading) anomalies averaged from lag -5 to 5 days (lag 0 denotes the peak day of the PNA) for (a) PNA-, (b) PNA+ and (c) combined PNA- and PNA+ events in the 2013/14 winter and (d) PNA+ events in the 2014/15
winter. (e, f) DJF-mean SST anomalies for the (e) 2013/14 and (f) 2014/15 winters. In panels a-d, the region of the SAT anomaly (color shading) deviated from the DJF-mean field during 1950-2018 winters with the 95% confidence level based on a two-sided Student's t-test is only plotted.

Figure 3

(a) Time series of the winter frequency (the number of total days) of daily WWCE events and (b) composite daily Z500 (contours, contour interval is 20gpm) and SAT (color shading and unit: K) anomaly fields for all days of North American WWCE dipole events during 1950-2018 winters. The composite DJF mean Z500 (contours, contour interval is 10gpm) and SAT anomaly for the winters of with (c) high WWCE days and (d) low WWCE days. The winter with high (low) WWCE days is defined that the normalized time series of the winter frequency of daily WWCE events is above (low) 1.0STDs. The region of the SAT anomaly (color shading) with the 95% confidence level based on a two-sided Student’s t-test is plotted.
Figure 4

(a) Time series of the event number of PNA+ - events in winter during 1950-2018. (b) Time-mean fields of composite daily Z500 (contours, contour interval is 20gpm) and SAT (color shading in the unit of K) anomalies averaged from lag-5 to 5 days of PNA+ events, where the region of the SAT anomaly (color shading) with the 95% confidence level based on a two-sided Student's t-test is plotted. (c) Temporal variations of composite daily TWE index during the PNA life cycle (from lag-10 to 10 days).
Figure 5

Time-mean fields of composite daily Z500 (contours, contour interval is 20gpm) and SAT (color shading in the unit of K) anomalies averaged from lag-5 to 5 days of PNA+ events related to six clustering regimes: (a) C1 (13 events), (b) C2 (15 events), (c) C3 (9 events), (d) C4 (19 events), (e) C5 (16 events) and (f) C6 (7 events), where the region of the SAT anomaly (color shading) with the 95% confidence level based on a two-sided Student's t-test is plotted.
Figure 6

Time series of the event number of PNA+ events for six clustering regimes: (a) C1, (b) C2, (c) C3, (d) C4, (e) C5 and (f) C6 during 1950–2018 as shown in Fig. 5.
Figure 7

Temporal variations of composite daily TWE=TW-TE of the PNA+ events during the PNA life cycle (from lag-10 to 10 days) for the six clustering regimes: (a) C1, (b) C2, (c) C3, (d) C4, (e) C5 and (f) C6.
Figure 8

Composite DJF-mean SST anomalies (color shading and unit: K) for six clustering regimes: (a) C1, (b) C2, (c) C3, (d) C4, (e) C5 and (f) C6 during 1950–2018 in Fig. 5. The dot represents the SST anomaly region above the 95% confidence level based on a two-sided Student’s t-test.
Figure 9

The first EOF (EOF1) mode of the Pacific SST anomaly based on the combined EOF-regression method for (a) CP- and (b) EP-type El Niño winters during 1950-2018. Normalized time series of the first principal component (PC1) of the Pacific SST EOF1 mode for (c) CP- and (d) EP-type El Niño winters. (e, f) Time-mean fields of composite daily Z500 (contours, contour interval is 20gpm) and SAT (color shading and unit: K) anomalies averaged from lag-5 to 5 days of PNA+ events during (e) CP- and (f) EP-type El Niño
winters whose indices exceed 0.5 STDs, and the region of the SAT anomaly (color shading) with the 95% confidence level based on a two-sided Student’s t-test is plotted.

Figure 10

(a, b, c) Height-latitude profiles of composite DJF-mean Hadley cell by averaging divergent wind and vertical velocity anomalies over 150°E-120°W. (d, e, f) Horizontal fields of composite DJF-mean U500 (m s-1) during (a, d) CP- and (b, e) EP-type El Niño winters and (c, f) the CP-type minus EP-type El Niño difference. The dot represents the region being the 95% confidence level based on a two-sided Student’s t-test.
Figure 11

(a) Time series of normalized PDO index. (b, c, d) Composite DJF-mean SST (color shading and unit: K) anomalies and (e, f, g) time-mean fields of composite daily Z500 (contours, contour interval is 20 gpm) and SAT (color shading and unit: K) anomalies averaged from lag -5 to 5 days of PNA+ events and the variations of composite daily (h) TWE, (i) TW and (j) TE with a 5-days smoothing of the PNA+ events from lag-10 to 10 days for the (b, e, h) PDO+ and CP-type El Niño combination, (c, f, i) PDO- and CP-type El Niño combination.
Niño combination and (d, g, j) their difference. The CP-type El Niño and PDO+ combination is defined as being a winter with the CP index above 0.5 STDs (Fig. 9c) and PDO index above 0. Similarly, the CP-type El Niño and PDO- winter is defined as being a winter with the CP index above 0.5 STDs (Fig. 9c) and PDO index below 0. The gray shading denotes the difference between the two curves being significant above the 90% confidence level based on 5000 Monte Carlo simulations.

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- ResponsetoReviewer2scomments.docx
- ResponsetoReviewer3scomments.docx
- supplementaryfile.docx