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Pacific Decadal Oscillation Modulation on the Relationship between Moderate El Niño-Southern Oscillation and East Asian Winter Temperature

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Abstract: Based on observation data from 1958 to 2020, the current study explores the interdecadal modulation effects on moderate El Niño-Southern Oscillation (ENSO) episodes and East Asian (EA) winter surface air temperature (SAT) through the Pacific Decadal Oscillation (PDO). Strong and moderate ENSO episodes are classified by their amplitudes. The current work investigates the influence of moderate ENSO episodes on the EA winter SAT, especially moderate La Niña episodes, which show a close relationship with the EA winter SAT. To explore the PDO modulation effect on the influence of ENSO episodes, these ENSO episodes are further divided into two categories in terms of warm or cold PDO phases. The composite results show that in the warm phase of the PDO, the moderate La Niña signal is relatively strong and stable, with a profound impact on the EA winter SAT variability, whereas in the cold PDO phase, the relationship between the EA winter SAT and moderate La Niña episodes becomes ambiguous. Further studies show that the PDO modulates the moderate La Niña impacts on EA winter SAT primarily through varying the East Asian winter monsoon (EAWM). While moderate La Niña episodes take place in a warm PDO phase, positive and negative anomalies of sea level pressure (SLP) are observed in the Eurasian continent and mid–high-latitude North Pacific, respectively, favoring anomalous northerlies along the eastern coast of East Asia and therefore a colder-than-normal EA winter. In contrast, in a moderate La Niña winter during the cold PDO phase, the mid–high-latitude North Pacific is controlled by an anomalous high-pressure system with southerly anomalies along its western flank, and therefore, a weak warm pattern is observed for the EA winter SAT.

Keywords: East Asian SAT; PDO; moderate ENSO; winter; EAWM

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1. Introduction

The East Asian (EA) winter climate is broadly governed by the East Asian winter monsoon (EAWM). The EAWM mainly originates from the large maritime–continental thermal gradient between the Pacific Ocean and Eurasian continent, and usually displays climatological northerly wind and works as the background of cold-wave activities. As one of the most important and active systems during boreal winter, the EAWM can have not only climatic but also socio-economic influences on the EA countries [1–5]. Due to these large socio-economic impacts, understanding and predicting EAWM variability have received a lot of attention. The EAWM has a complicated vertical structure; i.e., at the surface, the typical construction of the EAWM inhibits a cold Siberia High (SH), a warm Aleutian Low (AL), and strong northwesterly winds between them, and these winds can pass through the whole of East Asia and neighboring oceans, all the way down to the subtropical western Pacific (WP) and the Indochina Peninsula, directly affecting the underlying-area climate; in the middle troposphere, a broad trough (usually called the East Asian trough) is observed along the longitude of Japan; and in the upper layer (200 hPa), the most remarkable characteristic of the EAWM is the East Asian jet stream with its center near the southeastern Japan [1,3,6–9].

As the most prominently interannual air–ocean coupled mode, the El Niño-Southern Oscillation (ENSO) has enormous impacts on the EA winter climate [8,10–16], which can be used as an indicator for practical seasonal prediction [10,13,17]. The mechanisms for ENSO impacts on the EA climate have been analyzed by many previous studies [8,18,19]. During the mature phase of El Niño, the positive sea surface temperature anomalies (SSTAs) over the tropical central-eastern Pacific can trigger more precipitation and form an atmospheric heat source through enhancing the latent heat release, which further intensifies the northeast trade wind to the west in the Northern Hemisphere and gives rise to an anomalous divergence and descending motion in the Northwest Pacific with the propagation of a Rossby wave, favoring the development of an anomalous surface anticyclonic system around the Philippines. Moreover, local negative SSTAs over the warm pool region are also critical in the formation and development of this anomalous anticyclone through modulating the intensity of local convection. As a result, the anomalous low-level anticyclonic system enhances the surface southerlies along its northwest flank, resulting in a wetter- and warmer-than-normal winter over East Asia [8,18]. An almost-opposite process occurs during La Niña episodes. However, some studies have found that the ENSO effect on the EA winter climate is not stationary [10,11,13]. Jia et al. [13] pointed out that the correlation between the ENSO and the second mode of empirical orthogonal function of the EA winter surface air temperature (SAT) obviously intensifies after the mid-1980s, as a result of the enhanced sea surface temperature (SST) and precipitation anomalies related to the ENSO over the tropical WP during this period.

Several scholars have pointed out that the Pacific Decadal Oscillation (PDO) can modulate the ENSO influence on global climate via direct and indirect pathways [20–32], which is the dominant SST mode in the North Pacific [27,33]. Recently, Jia and Ge [24] investigated the interdecadal effect of the PDO in modulating the influences of moderate ENSO episodes on the North American winter climate. They emphasized that the signal of moderate El Niño episodes is relatively strong and steady in the cold PDO phase, which can exert robust impacts on the North American winter climate variability, whereas in the warm PDO phase, the relationship becomes ambiguous. In addition, it was demonstrated in an earlier study that in the warm phase of the PDO, there is no robust correlation between the EAWM and ENSO; however, in the cold PDO phase, ENSO episodes have evident influence on the EAWM, with anomalous cold temperature dominant over East Asia [30]. In a later study, Kim et al. reported that while the PDO and ENSO are in phase (that is, El Niño–warm PDO phase and La Niña–cold PDO phase), the ENSO impact on the EAWM significantly enhances, with a robust anomalous warm (cold) SAT occurring over East Asia during El Niño–warm PDO (La Niña–cold PDO) winters; by contrast, there are no obvious climate anomalies over East Asia in the case of La Niña–warm PDO and El Niño–cold PDO episodes [25]. Wu and Mao also proposed that when La Niña (El Niño) episodes take place in the cold (warm) PDO phase, below-normal (above-normal) rainfall is observed in South China in the following spring, but the rainfall variability in spring over South China is weak and not notable when the PDO and ENSO are out of phase (that is, El Niño–cold PDO phase and La Niña–warm PDO phase) [32].

Although there are plenty of studies analyzing the impact of ENSO episodes on the East Asian winter climate, most of them did not take the intensity of the ENSO into account or mainly focused on strong ENSO events. In contrast, moderate ENSO events have received considerably less attention. In recent work of Jia et al., the impacts of not only strong but also moderate ENSO episodes on the Maritime Continent (MC) winter rainfall have been explored. They imply that in moderate La Niña winters, precipitation anomalies in the MC exhibit a similar pattern to those in strong La Niña winters [34]. Jia et al. indicated that the climatic effect of ENSO episodes is closely related to its intensity, and such a linkage seems nonlinear; i.e., a moderate ENSO is able to exert strong impacts on the regional climate. It is not clear, however, whether the moderate

La Niña episode could also impact the winter climate variability over East Asia, and if it could, whether its influences on the EA winter climate would be modulated by the PDO. In the present study, we illustrated that moderate La Niña events exhibit a more pronounced influence on EA winter SAT compared to strong ENSO events. Our findings may contribute additional information for seasonal forecasting, representing one of the innovative aspects of our research.

The structure of this article is arranged as follows: The datasets and analytic methods used are depicted in Section 2. The impacts of moderate La Niña episodes on the EA winter SAT are investigated in Section 3. The interdecadal PDO modulation of the moderate La Niña impacts on the EA winter SAT is illustrated in Section 4. In Section 5, the possible mechanisms for the role of the PDO in modulating the relationship between the EA winter SAT and moderate La Niña episodes are explored. Section 6 presents the conclusion, and Section 7 provides a concise associated discussion.

2. Datasets and Methodologies

The data applied in this paper are described as follows. The main atmospheric data are derived from the Japanese 55-year Reanalysis (JRA) dataset released by the Japan Meteorological Agency, with a 1.25° latitude–longitude grid [35–37]. The air temperature at 2 m (i.e., SAT in this study), monthly mean SLP, geopotential height at 500 hPa (Z500), and wind at 850 hPa and 200 hPa are the main variables. The SST data from the Met Office Hadley Centre adopted in this study are a special association of monthly globally complete fields of sea ice and SST, with a resolution of 1.0° × 1.0° [38]. In addition, precipitation data use the PRECipitation REConstruction Dataset of National Oceanic and Atmospheric Administration, with a horizontal resolution of 2.5° × 2.5° [39]. All the data used in the current work cover the period from 1958 to 2020, and the winter in 1958 refers to the seasonal average from December 1958 to February 1959. Additionally, monthly mean SAT data (Version TS4.07) from the Climatic Research Unit (CRU) of the University of East Anglia [40], with a spatial resolution of 0.5° × 0.5°, for the period of 1901–2020 are employed to verify the results obtained from the reanalysis data.

The Niño3.4 index, the winter mean SSTA in the Niño-3.4 region (5° S–5° N, 170°–120° W), is selected to represent the ENSO variability. The PDO index is the leading principal component of SSTAs in the North Pacific, poleward of 20° N. Composite analysis is performed to obtain the ENSO-induced and PDO-forced circulation anomalies. The significance of the composite differences is evaluated through a two-tailed Student's *t* test.

3. Impacts of Moderate La Niña Episodes on the EA Winter SAT

The bars in Figure 1 depict the normalized Niño3.4 index during 1958–2020. In the current work, ENSO episodes are chosen while the absolute value of Niño3.4 index passes 0.5. According to these standards, twenty-one El Niño and twenty La Niña episodes are chosen (Table 1). According to previous studies, strong and moderate ENSO episodes might exert various influences on climate variations [34,41–43]. Therefore, these selected ENSO episodes are further classified into four sub-types, namely strong La Niña episodes with a Niño3.4 index <-1.0, strong El Niño episodes with a Niño3.4 index >1.0, moderate La Niña episodes with a Niño3.4 index ≥ -1.0 and <-0.5, and moderate El Niño episodes with a Niño3.4 index >0.5 and ≤ 1.0. Based on this definition, nine strong La Niña episodes, eight strong El Niño episodes, eleven moderate La Niña episodes, and thirteen moderate El Niño episodes are obtained, as shown Figure 1.

3.1. ENSO-Related SAT Anomalies

The composite SAT anomalies associated with strong and moderate ENSO episodes are depicted in Figure 2. Obvious positive SAT anomalies are observed over the subtropical northwestern Pacific in strong El Niño winters (Figure 2a), consistent with previous studies [44], while negative SAT anomalies appear in East Asia westward of 120° E related to strong La Niña episodes, with limited significant areas almost invisible (Figure 2c).

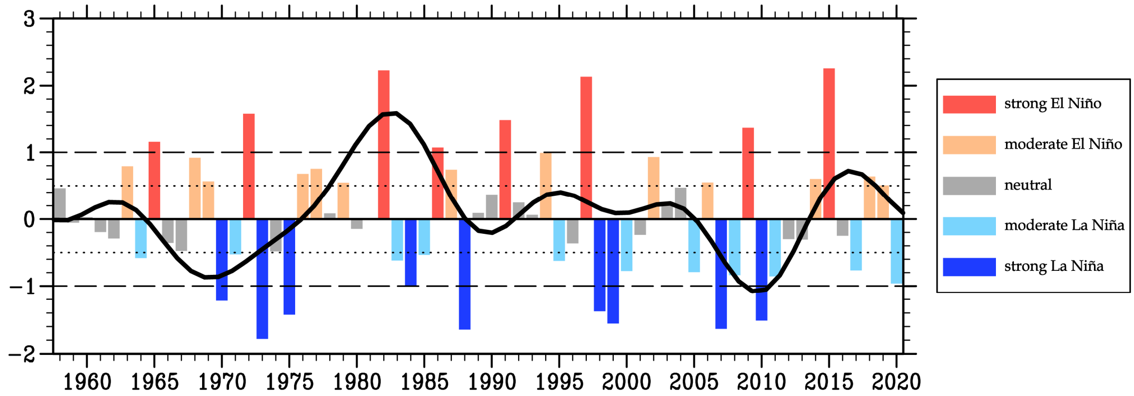

Figure 1. The normalized winter-mean Niño3.4 index (bars) with the decadal component (longer than 10 years) of PDO index overlaid by thick black curve. Dark (light) bars represent strong (moderate) ENSO episodes and blue (red) bars denote La Niña (El Niño) episodes. Gray bars refer to neutral years without evident ENSO signal occurring in the tropical central-eastern Pacific Ocean. Dotted and dashed lines denote the criteria of moderate and strong ENSO episodes, respectively.

Table 1. El Niño and La Niña episodes.

	El Niño		**La Niña**		**Neutral**	
	Strong	**Moderate**	**Strong**	**Moderate**		
PDO warm	1982 1986 1991 1997 2015	1963 1976 1977 1979 1987 1994 2002 2014 2018 2019	1984 1988 1998 1999	1983 1985 1995 2000 2005 2017 2020	1958 1960 1962 1980 1989 1992 1996 2003 2016	1959 1961 1978 1981 1990 1993 2001 2004
PDO cold	1965 1972 2009	1968 1969 2006	1970 1973 1975 2007 2010	1964 1971 2008 2011	1966 1974 2013	1967 2012

Obvious differences can be noticed from the associated climate anomalies over East Asia between moderate and strong ENSO episodes. Significant negative SAT anomalies are observed over a large area of the EA continent northward of 40 °N in moderate La Niña winters (Figure 2d), with the significant anomalous area even larger than its strong La Niña counterpart. Conversely, the SAT anomalies related to moderate El Niño episodes over East Asia are relatively weak and almost not significant (Figure 2b).

Most previous research emphasizes the influences of strong ENSO episodes on the EA climate variation [30,45,46], as usually strong ENSO episodes exert a more remarkable impact on the climate variation than moderate ENSO episodes. However, Figure 2 indicates that this is not valid for the influences of ENSO episodes on the EA winter climate, which show a stronger influence on the climate anomalies over East Asia during moderate La Niña episodes. As proposed by Jia et al. [34], the robust impact of moderate La Niña episodes on the winter climate might provide additional seasonal forecast information for some regions. Inspired by Figure 2, in the following, focus is given to investigating the impact of moderate La Niña episodes on the EA climate variation.

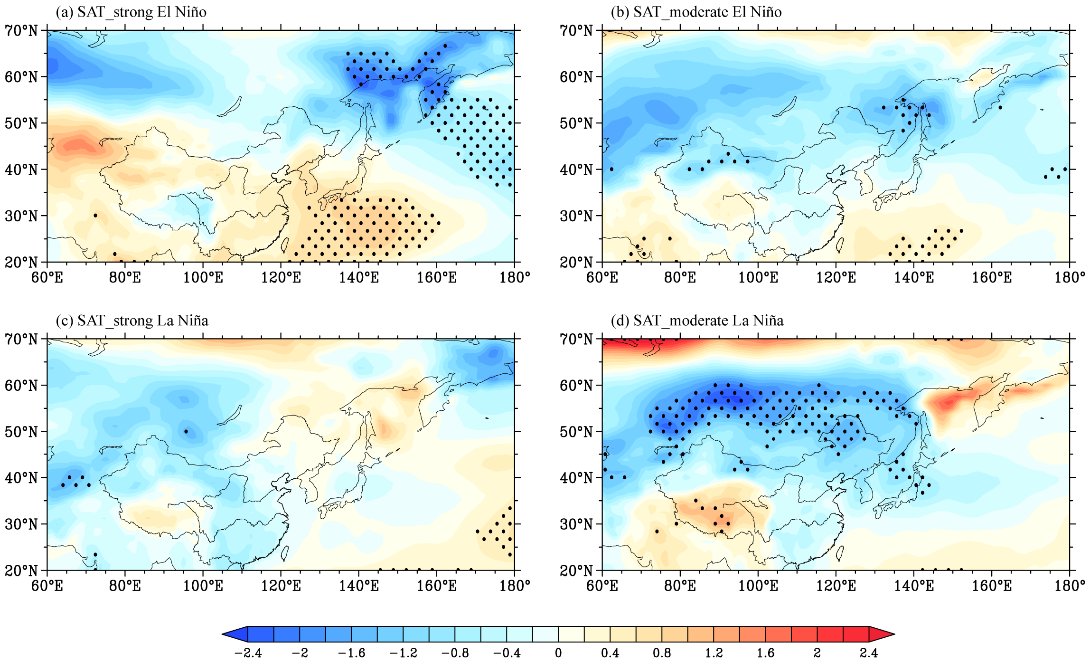

Figure 2. Composite SAT anomalies during (**a**) strong El Niño, (**b**) moderate El Niño, (**c**) strong La Niña, and (**d**) moderate La Niña winters. Anomalies significant at the 95% confidence level are dotted.

3.2. Circulation Anomalies Related to Moderate La Niña

The composite SST (Figure 3a) and precipitation (Figure 3b) anomalies during moderate La Niña winters are depicted to demonstrate the tropical Pacific anomalies associated with moderate La Niña episodes. Corresponding to moderate La Niña episodes, a narrow band of significant negative SSTAs is detected over the tropical central-eastern Pacific, while significant positive SSTAs are observed over the tropical WP and the subtropical central Pacific in both Hemispheres (Figure 3a). The anomalous precipitation is manifested as a zonal dipole structure along the equator, with dry anomalies near the dateline and wet anomalies centered around the Philippines (Figure 3b). The composite divergent wind at 850 hPa (vector) together with the velocity potential (contour) related to moderate La Niña episodes are presented in Figure 3c, which could reveal the Walker circulation anomalies and also the large-scale convergent/divergent as well as vertical movements [8,18,20,46]. When a moderate La Niña episode occurs, the anomalous Walker circulation at the lower level displays a pattern of east–west dipolar distribution, with prominent convergence (divergence) and upward (downward) movement around the MC (tropical central Pacific). The above moderate La Niña-related Pacific forcing is analogous in structure with that of Jia et al. [34] (Figure 2d, Figure 6d, and Figure 7d in Jia et al., respectively).

To depict the common circulation anomaly characteristics related to moderate La Niña episodes, Figure 3d–f give the composite maps of SLP, Z500, and 850 hPa wind anomalies during moderate La Niña winters. At the surface, corresponding to a moderate La Niña event, significant positive SLP anomalies occupy the high-latitude Asian continent (Figure 3d), implying an enhancement in the SH. Accordingly, a low-level anomalous northeasterly wind prevails along the southeastern flank of these positive SLP anomalies (Figure 3f), which brings cold air from the high-latitude inland regions southward to the subtropical area, leading to significant negative SAT anomalies over East Asia, consistent with those shown in Figure 2d. The Z500 anomalies (Figure 3e) display a pattern similar to the SLP anomalies, showing a quasi-barotropic vertical structure. Compared to the climatology, the obvious negative height anomalies in Northeast China and the surrounding regions at this level reflect a deeper-than-normal EA trough and a stronger-than-normal EAWM, in line with the northwesterly anomalies depicted in Figure 3f. The above results are generally in accordance with previous research [8,13,25], which reported that a La Niña episode can intensify the EAWM and lead to a colder-than-normal winter over East Asia, although only moderate La Nina episodes are considered here.

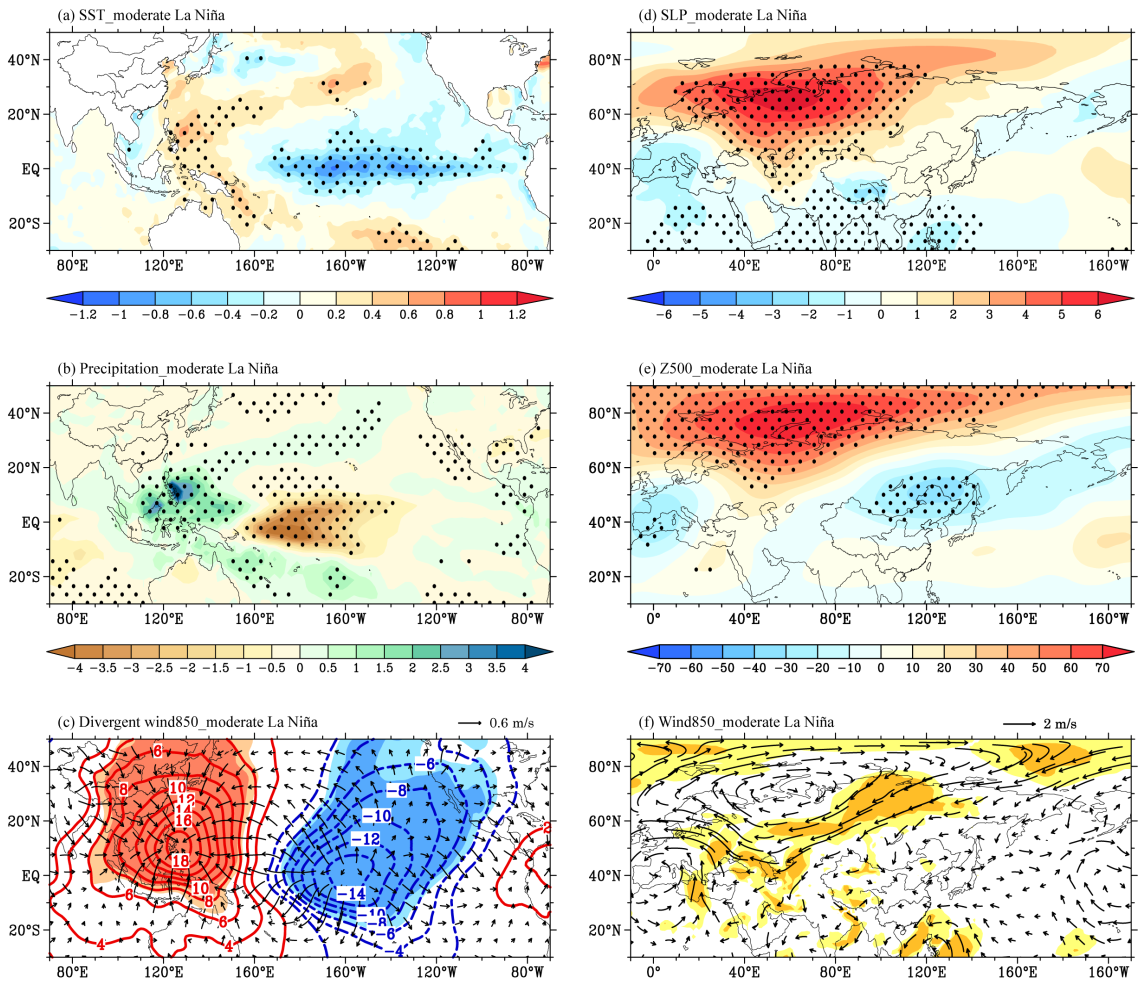

Figure 3. Composite (**a**) SST, (**b**) precipitation, (**c**) divergent wind at 850 hPa (vector) together with velocity potential (contour), (**d**) SLP, (**e**) Z500, and (**f**) 850 hPa wind anomalies during moderate La Niña winters. Anomalies significant at the 95% confidence level are dotted in (**a**,**b**,**d**,**e**). Dashed (solid) lines in (**e**) represent negative (positive) values, with zero lines omitted, and the contour interval is 2×10^5 m^{2}s^{-1}. Light and dark shading areas in (**c**,**f**) indicate the anomalies passing the 95% and 99% confidence levels, respectively.

4. The PDO Modulation of the Moderate La Niña-Related SAT

The significant climate anomalies related to moderate La Niña episodes, as shown in the last section, indicate that moderate La Niña episodes have a profound influence on the EA winter SAT. Previous studies indicated that the PDO can modulate the ENSO impacts [20,22–27,29,30,32]. We also speculate that the EA SAT anomalies during moderate La Niña winters may also arise from the composite influences induced by a special moderate La Niña–PDO combination, which is therefore discussed in this section.

4.1. The Circulation Anomalies Related to Different PDO Phases

A low-pass time filtering with a period of over a decade is carried out on the normalized PDO index (thick black curve in Figure 1) to see the PDO interdecadal variability. Three positive epochs (i.e., 1958–1963, 1976–2005, and 2014–2020) and two negative epochs (i.e., 1964–1975 and 2006–2013) are observed. According to previous research [21,25,27,33], the PDO may act like a long-lived weak ENSO-like pattern in the SST field with the most pronounced anomalies over the North Pacific, which can be confirmed by Figure 4a. During the warm PDO phase, significant cold SSTAs appear over the mid-Pacific in the Northern Hemisphere, while significant warm SSTAs exist over the tropical Pacific, western coast of North America, high-latitude Pacific, and the margin sea of East Asia.

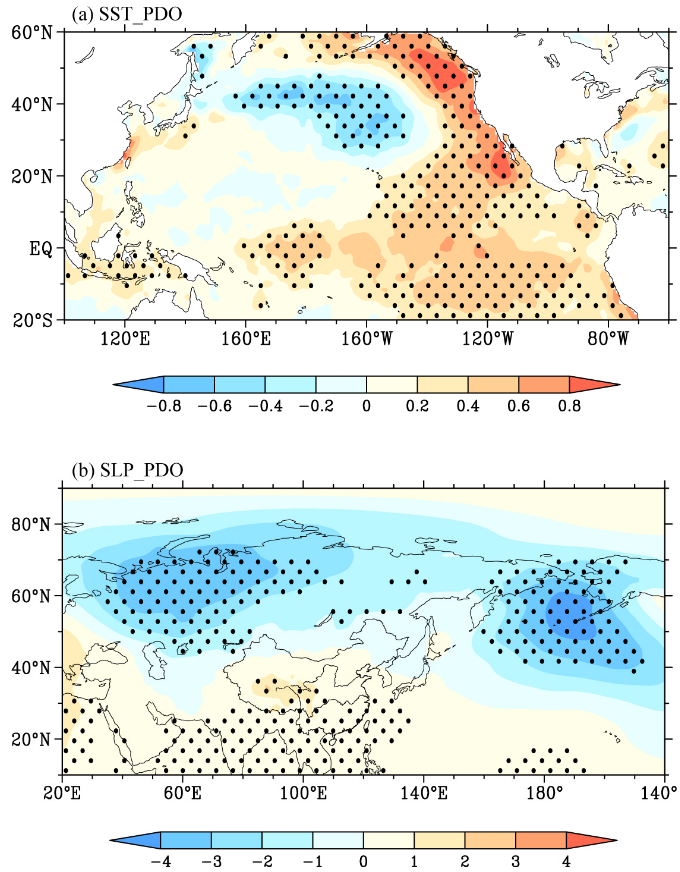

Figure 4. Composite differences of the winter average (**a**) SST and (**b**) SLP anomalies between the warm and cold phases of PDO. Anomalies significant at the 95% confidence level are dotted.

Since the memory of the atmosphere is shorter than that of the ocean, continuous SSTA distributions in the North Pacific are commonly linked to continuous atmospheric teleconnection patterns [32,47]. Therefore, different patterns of SSTA between the two PDO phases may force various atmospheric teleconnection patterns. Figure 4b displays the composite differences of SLP anomalies between the two phases of the PDO. During the warm phase, a significant anomalous low covers the central North Pacific (Figure 4b), indicating an intensified AL [27], which is a typical characteristic of the PDO.

4.2. The Modulated PDO Effect on Characteristics of Moderate La Niña Episodes

According to the PDO phases, the ENSO episodes defined in Section 2 are further separated into two categories, namely the strong and moderate ENSO episodes under a warm PDO background (upper row in Table 1) and the strong and moderate ENSO episodes under a cold PDO background (lower row in Table 1). It should be noted that the PDO is a long-lived pattern and can persist in one phase for 20 to 30 years. However, the PDO also experiences some fluctuations on shorter time scales. The method of separating warm and cold phases of the PDO based on the low-pass-filtered index does not guarantee that the selected ENSO event in a specific year consistently aligns with the year in which the PDO phase and sign are the same.

As shown in Table 1, eleven moderate La Niña episodes occur during the period from 1958 to 2020, comprising four moderate La Niña–cold PDO episodes and seven moderate La Niña–warm PDO episodes. Sub-composite analysis is therefore carried out on the wintertime SST to illustrate the basic characteristics of moderate La Niña episodes during the warm (Figure 5a) and cold phase of the PDO (Figure 5b), respectively. Substantial SSTA differences appear in the tropical Pacific Ocean between Figure 5a,b. When a moderate La Niña episode takes place in a warm PDO phase, a narrow band of significant negative SSTAs is observed in the tropical central-eastern Pacific, which is restricted to the equatorial region. Significant positive horseshoe-like shaped SSTAs also appear in the western subtropical-tropical Pacific (Figure 5a). On the contrary, the negative SSTAs related to moderate La Niña episodes in a cold PDO phase feature a relatively disorganized pattern covering the central tropical Pacific, with a comparatively weak and insignificant amplitude. In addition, compared with their counterparts in the warm PDO phase, the negative SSTAs (Figure 5b) extend farther in the meridional direction. The distinguishing moderate La Niña-related tropical Pacific forcing under different PDO backgrounds is even clearly seen from the precipitation fields (not shown), with a zonal dipole structure appearing in the tropical Pacific in a warm PDO phase, whereas no significant precipitation anomalies are noticed in a cold PDO phase. The above results imply a possibly different impact on climate anomalies of the moderate La Niña episodes between the two PDO phases.

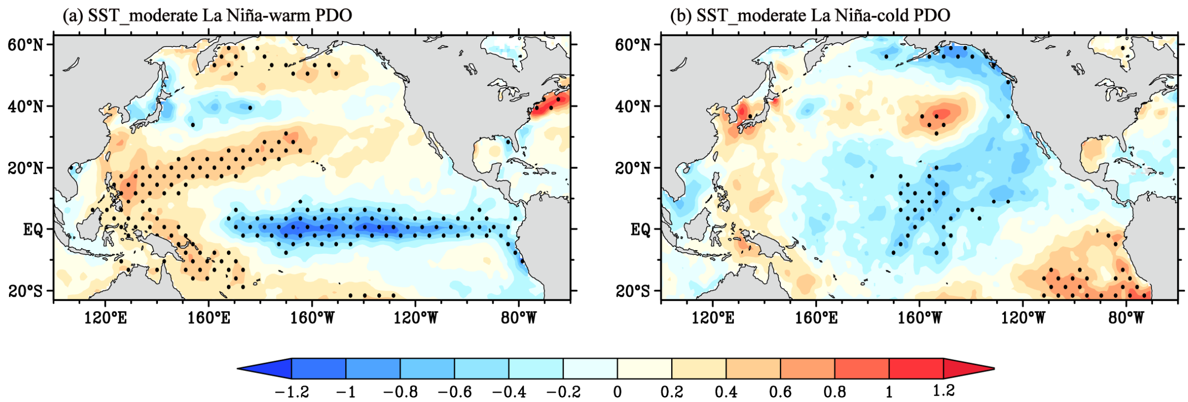

Figure 5. Composite SSTAs during moderate La Niña winters in (**a**) warm and (**b**) cold PDO phases. Anomalies significant at the 95% confidence level are dotted.

4.3. Moderate La Niña-Related SAT Anomalies in Different PDO Phases

Figure 6a,b depict the SAT anomalies related to moderate La Niña episodes in the two PDO phases, respectively, where pronounced differences over East Asia between them are observed. Significant moderate La Niña-related negative SAT anomalies dominate most of the area of the East Asian continent and surrounding Northwest Pacific during warm PDO winters (Figure 6a), with a stronger magnitude and a larger significant area compared to those shown in Figure 2d, whereas in the cold PDO phase, the moderate La Niña-related SAT anomalies in East Asia are quite weak and barely pass the significance test (Figure 6b). The different SAT anomalies shown in Figure 6a,b confirm that the PDO really plays a crucial part in modulating the relationship between the EA winter SAT and moderate La Niña episodes.

To better understand the PDO modulation effect on the impact of moderate La Niña episodes, Figure 6c,d examine the 850 hPa wind anomalies during moderate La Niña winters in warm and cold phases of the PDO. The northerly anomalies in a warm PDO phase include three branches of anomalous winds: that is, one northeasterly along the latitude of approximately 55 °N, transporting robust cold air from high latitude to the Lake Baikal region, one northeasterly related to a cyclonic circulation system over the middle-latitude North Pacific, bringing cold air from the inland area into the Northwest Pacific, and another one northerly along the eastern coast of the Asian continent, which penetrates all the way down to the subtropics and then turns easterly at the Yangtze River region. The above three branches of anomalous northerlies suggest an enhancement of the EAWM, favoring cold air from the high-latitude inland areas transported to lower latitude, leading to obvious negative SAT anomalies in East Asia and the adjacent seas (Figure 6a). Conversely, compared to Figure 6c, the anomalous winds over the EA eastern coasts in Figure 6d turn into southerlies along the western flank over an anticyclonic system centered at approximately 45° N, 170° E. As a consequence, positive SAT anomalies over East Asia are observed despite the limited significant areas (Figure 6d).

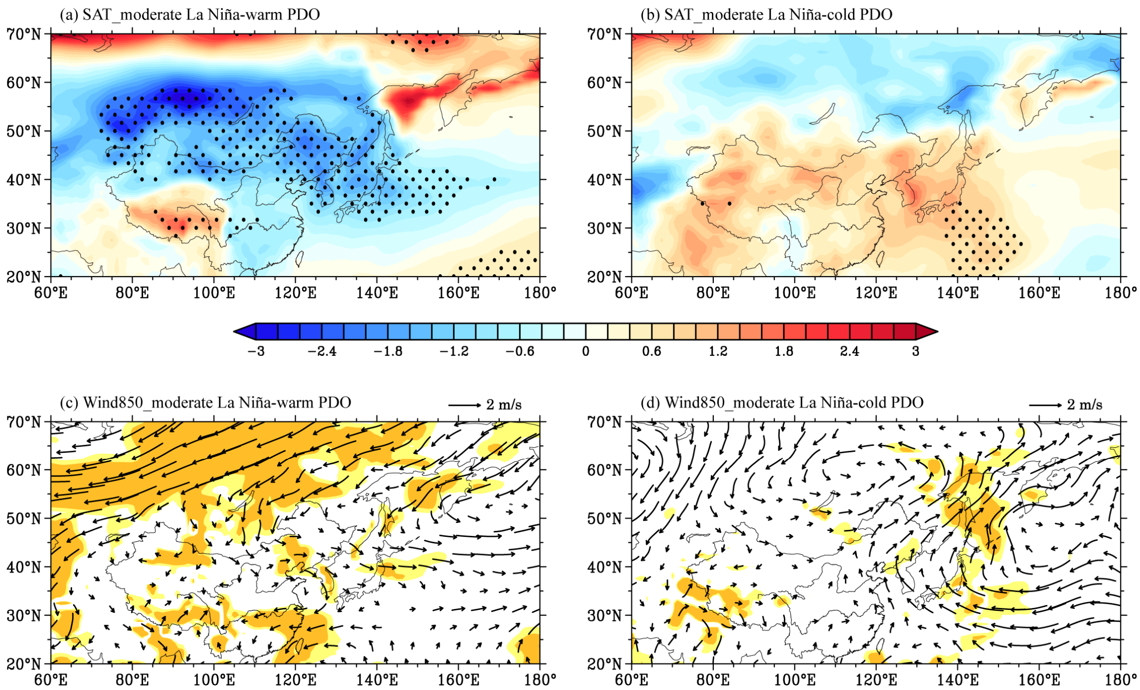

Figure 6. Composite (**a**,**b**) SAT and (**c**,**d**) 850 hPa wind anomalies during moderate La Niña winters in (**a**,**c**) warm and (**b**,**d**) cold PDO phases. Anomalies significant at the 95% confidence level are dotted in (**a**,**b**), while light and dark shading areas in (**c**,**d**) indicate the anomalies passing the confidence levels of 90% and 95%, respectively.

To test whether the results presented in the current study are sensitive to the thresholds that have been used to define ENSO events, further analyses are performed (not shown). For example, some ambiguous events during moderate La Niña years near the boundary lines (e.g., 1971, 1985, and 2020) are excluded from the composite analysis. The revised analysis still reveals significant negative SAT anomalies over a substantial area of the EA continent northward of 35 °N during moderate La Niña winters. Furthermore, considering the co-occurrence of moderate La Niña events in 2005 and 2020 close to the zero line of the low band-pass-filtered PDO index, we have reassigned these events from moderate La Niña–warm PDO events to moderate La Niña–cold PDO events. Despite a reduction in amplitude and significance, the results show that the basic characteristics presented in Figure 6a,b remain unchanged. These findings affirm the reliability of our classification method.

5. Possible Mechanisms

In the last section, we demonstrated that the PDO can modulate the influences of moderate La Niña episodes on the EA winter SAT. To better understand the modulation effect of the PDO, the anomalous circulation related to moderate La Niña episodes is examined under a warm PDO background (Figure 7a,c,e) and cold PDO background (Figure 7b,d,f), respectively. Substantial differences are observed between the two PDO phases over the North Pacific.

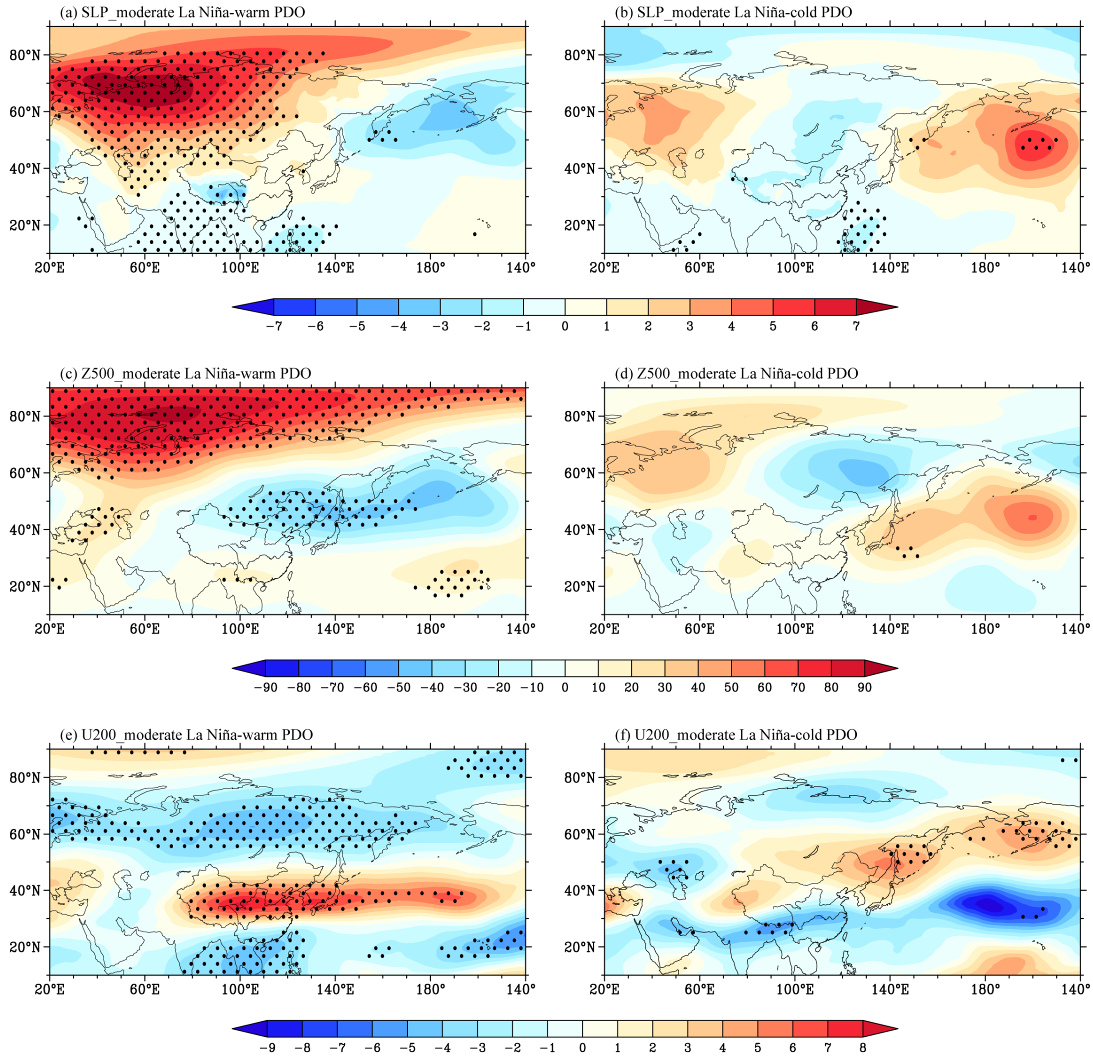

Figure 7. Composite (**a**,**b**) SLP, (**c**,**d**) Z500, and (**e**,**f**) U200 anomalies during moderate La Niña winters in (**a**,**c**,**e**) warm and (**b**,**d**,**f**) cold PDO phases. Anomalies significant at the 95% confidence level are dotted.

During a warm PDO phase, the most prominent surface circulation anomalies associated with moderate La Niña episodes (Figure 7a) feature obvious positive SLP anomalies in the entire middle–high-latitudinal Eurasian continent, indicating a stronger-than-normal SH. Meanwhile, evident negative SLP anomalies appear in the North Pacific, reflecting an enhanced AL. The increased pressure contrast between the anomalous high-pressure system in the Eurasian continent and low-pressure system in the North Pacific leads to northerly anomalies along the eastern coastline of East Asia (Figure 6c), which corresponds to a stronger-than-normal EAWM. The moderate La Niña-related North Pacific low anomalies are even clearer in the Z500 (Figure 7c), which extend southwestward into the EA continent, implying a deeper-than-normal EA trough. However, when moderate La Niña episodes combine with a cold PDO phase, the negative SLP anomalies over the Aleutian Basin are replaced by positive SLP anomalies (Figure 7b). A comparison between Figure 3d, Figure 4b, and Figure 7a,b suggests that the change in the AL probably results from the PDO-related anomalies in the North Pacific. Meanwhile, there is a weak negative SLP anomalies over the EA continent. As a result, the low-level wind anomalies related to moderate La Niña–cold PDO episodes display anomalous southerlies along the coast of East Asia between the anomalous negative-SLP system in the EA continent and the positive-SLP system in the North Pacific (Figure 7b). At the upper jet level, associated with moderate La Niña episodes, a zonally oriented positive 200 hPa zonal wind (U200) anomaly over the East Asia–WP sector at approximately 38 °N is noticed during a warm PDO phase (Figure 7e), indicating a strengthened East Asian westerly jet, which is also one of the signs of an enhanced EAWM. On the contrary, the U200 anomalies related to moderate La Niña episodes in the cold PDO phase display a meridional dipole structure, with negative and positive anomalies in the south and north, respectively, favoring a weaker-than-normal EAWM (Figure 7f). The above results imply that the PDO can modulate the influences of moderate La Niña episodes on the EA winter SAT through changing the circulation anomalies over the East Asia–Pacific region from the surface to tropopause level, sequentially changing the EAWM system. Among them, the anomalies related to moderate La Niña episodes in the Aleutian Basin are the key system.

6. Conclusions

Based on observational data for the period from 1958 to 2020, this study investigates the interdecadal modulation effect of the PDO on the impact of moderate La Niña episodes on the EA winter SAT. On the basis of amplitudes, ENSO episodes are split into strong and moderate episodes. In terms of the cold and warm phases of the PDO, these ENSO episodes are further divided into two categories. This study concentrates on the moderate La Niña impact on the EA winter climate which is much less studied. The SAT is chosen as the critical factor for examining the ENSO influence on the EA winter climate variability.

Substantial differences in moderate La Niña influences on the EA winter SAT emerge between cold and warm phases of the PDO. Obvious negative SAT anomalies related to moderate La Niña episodes dominate East Asia during the warm PDO phase, whereas in the cold PDO phase, the SAT anomalies related to moderate La Niña episodes over East Asia are weak and not evident. Possible causes of the PDO modulation effect on the relationship between the EA wintertime SAT and moderate La Niña episodes are explored. The PDO modulates the influence through changing the circulation anomalies from the surface to the jet level over the East Asia–Pacific sector associated with the EAWM system. While moderate La Niña episodes take place in a warm PDO phase, an anomalous high and an anomalous low are observed over the Eurasian continent and mid–high-latitudinal North Pacific, respectively, reflecting enhancements in both SH and AL. The increased pressure contrast between the anomalous high in the Eurasian continent and low in the North Pacific results in northerly anomalies along the EA eastern coastline and therefore leads to a colder-than-normal winter over East Asia. On the contrary, while a moderate La Niña winter combines with a cold phase of the PDO, the negative SLP anomalies in the mid–high-latitude North Pacific are replaced by positive ones, leading to an anomalous southerly wind along the eastern EA coast. Consequently, weak warm SAT anomalies appear over East Asia. Additionally, the EA trough and upper-level westerly jet are both intensified during moderate La Niña winters in the warm PDO phase. This also implies an anomalously strong EAWM. However, in a cold PDO phase, these moderate La Niña-related circulation anomalies are invisible.

7. Discussions

Most previous studies paid attention to investigating the effects of strong ENSO episodes, especially strong El Niño episodes, on global climate anomalies. Our resultssuggest that moderate La Niña episodes can also play a key role in the EA winter climate anomalies, and their impacts are even more enhanced under a warm PDO phase, indicating that moderate La Niña episodes may also serve as a potential predictor for seasonal prediction over East Asia.

However, seven moderate La Niña–warm PDO episodes and four moderate La Niña–cold PDO episodes seem a bit insufficient, although significance testing has been carried out in the current work. Therefore, a longer-term SAT dataset from the CRU, covering the period of 1901–2020, is used to validate the above results. Thirty-one strong El Niño episodes, twelve strong La Niña episodes, sixteen moderate El Niño episodes, and sixteen moderate La Niña episodes are chosen according to their amplitudes. The composite CRU

SAT anomalies during the four types of ENSO episodes are shown in Figure 8. In moderate El Niño winters, almost the entire EA continent is occupied by warm SAT anomalies, with significant areas observed over coastal areas and high-latitude inland regions (Figure 8b). Strong negative SAT anomalies, significant at the 90% confidence level, are seen over a large area of the EA continent northward of 40° N during moderate La Niña winters (Figure 8d). However, the EA winter SAT anomalies associated with strong El Niño and strong La Niña episodes are relatively weak and barely significant (Figure 8a,c). When the PDO phases are taken into account, twelve moderate La Niña–warm PDO episodes and six moderate La Niña–cold PDO episodes are obtained. It shows that moderate La Niña-related cold SAT anomalies cover most of the EA continent in a warm PDO phase (Figure 9a), whereas those in the cold PDO phase are quite weak (Figure 9b). The results obtained from CRU data are basically in agreement with those from JRA, suggesting the credibility of the previous results in this paper.

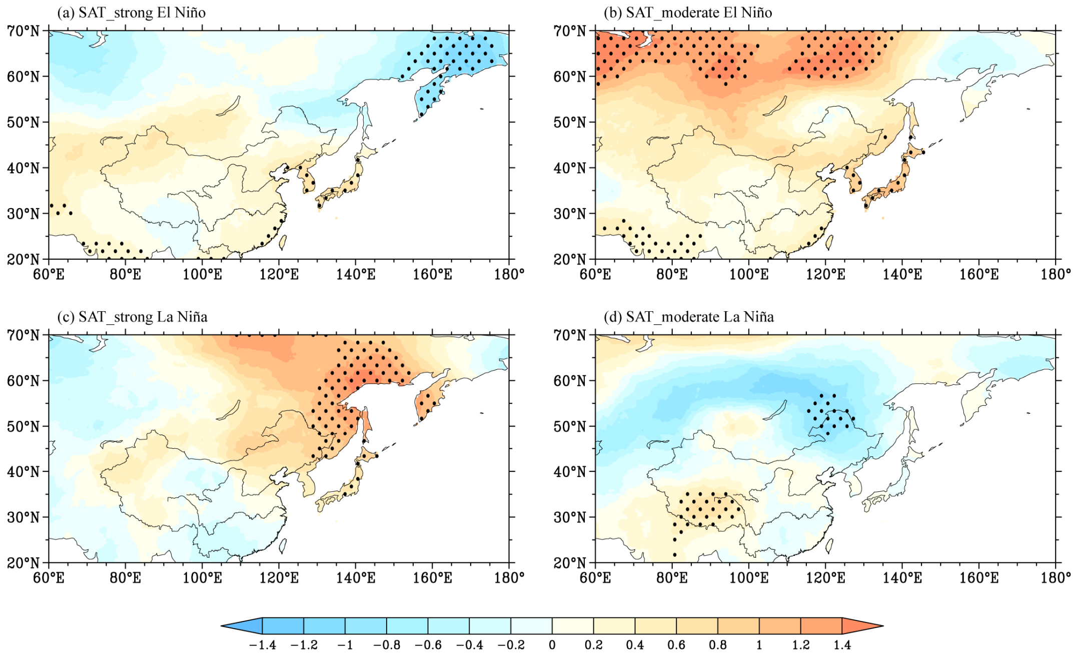

Figure 8. Composite CRU SAT anomalies during (**a**) strong El Niño, (**b**) moderate El Niño, (**c**) strong La Niña, and (**d**) moderate La Niña winters. Anomalies significant at the 90% confidence level are dotted.

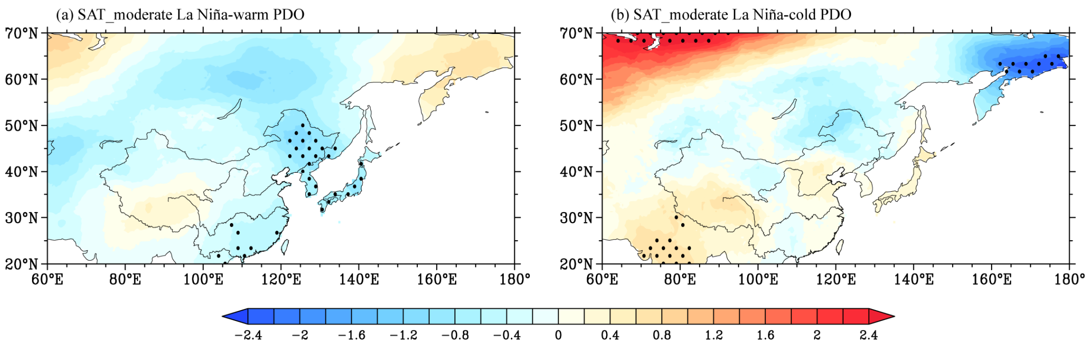

Figure 9. Composite CRU SAT anomalies during moderate La Niña winters in (**a**) warm and (**b**) cold PDO phases. Anomalies significant at the 90% confidence level are dotted.

Furthermore, some previous research documented that when the PDO and ENSO are in phase, i.e., an El Niño is in phase with a warm PDO, or vice versa, the ENSO influences on the climate variability may be obviously intensified, whereas the ENSO influences are relatively weak and not significant when they are out of phase [21,25,33]. However, results in this work show that this is not valid for the influences of moderate ENSO episodes on the EA winter SAT, which indicates that compared with the cold phase, moderate La Niña episodes have more profound impacts on the EA winter SAT in the warm phase of the PDO. An earlier work reported that in the warm phase of the PDO, no robust correlation is observed between the ENSO and the EAWM; however, the ENSO has obvious influence on the EAWM in the cold PDO phase, with anomalous cold temperature dominant over East Asia [30]. However, our results validate that this is only suitable for strong ENSO episodes. The current work also indicates the necessity of classifying the strong and moderate ENSO episodes as well as the cold and warm PDO phases while analyzing the relation between the EA climate variability and ENSO episodes.

In spite of the evident combined effect of moderate La Niña episodes and PDO phases on the variability in EA winter SAT through diagnostic analysis, questions remain about why moderate La Niña episodes have a more profound influence on EA winter SAT than strong ENSO events and whether the atmospheric response to a La Niña forcing is dependent on the PDO phases. In the future, numerical experiments might be performed to explore the dynamic process by which the PDO modulates the effects of moderate La Niña episodes on the EA winter climate, which may supply valuable insights for this work. We also acknowledge that the number of selected ENSO cases is limited in the current work due to the restricted length of the observational data. To address this limitation, significance tests were conducted in the current study. In the future, consideration may be given to utilizing outputs from numerical models, such as those from Coupled Model Intercomparison Project Phase 6 models, for further investigation.

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