



APCC
APEC CLIMATE CENTER

TECHNICAL REPORT

PREFACE

It is our pleasure to present to you the APEC Climate Center (APCC)'s Technical Report 2011, which reports the core outcomes of our research activities from the past year.

Since 2005, APCC, as a hub of climate information in the Asia-Pacific region, has strived to share our analysis and prediction of abnormal climate and to apply this information to regional development. The center has established the largest Multi-Model Ensemble (MME) system for seasonal prediction through its international science network and has provided value-added products to various stakeholders. Recently, APCC has expanded its mandate to include enhancement of the capacity of APEC member economies information to respond effectively to climate change and variability through better application of climate.

To achieve its research and social objectives, in 2011, APCC made efforts to research improvements in its climate prediction performance from various angles and towards better understanding of climate variability and the reproducibility of the climate models for the relevant application of climate information to society. The following technical report provides more information about our research outcomes from 2011.

APCC will continue to improve the quality and accuracy of climate information, recognizing that the utility of this information is only as good as its quality. We would like to make the best use of our research results for the benefit of society and academia. We also welcome any feedback on this report or on our services.

My best and warmest regards to all of you.

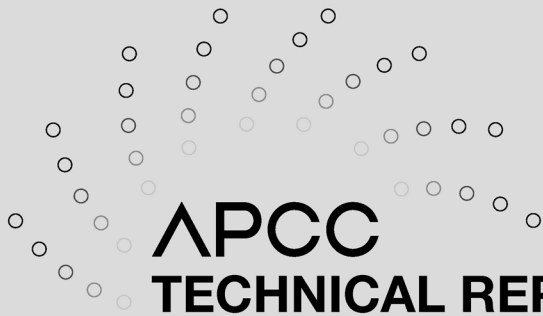
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TECHNICAL REPORT 2011-03

Changes in East Asian Winter Monsoon Due to the Effect of the ENSO and PDO Interaction

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ABSTRACT

The changes in the East Asian winter monsoon (EAWM) due to the effect of the interaction between the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are investigated using long-term surface air temperature (SAT) data and various reanalysis datasets. It is found that when the ENSO and PDO are in-phase (i.e., El Niño/high PDO phase or La Niña/low PDO phase), the EAWM tends to be significantly stronger or weaker. However, when the ENSO and PDO are out-of-phase (i.e., El Niño/low PDO phase or La Niña/high PDO phase), the EAWM does not exhibit distinct features. Hence, the relationship between the EAWM and ENSO on the interannual timescale is not only modulated by interdecadal variations of the PDO but also by the slowly-evolving PDO variations that become a synergistic or dissipative force on the ENSO-related interannual variability according to the phase interferences of ENSO and PDO. The dynamical process through which the EAWM is weakened or strengthened is closely linked to the northerly wind anomalies induced by the strength of Aleutian low variability during the winter season.

Wintertime variations in the magnitude of the western North Pacific subtropical high (WNPSH) and Siberian high are also examined to describe the strength of the EAWM. During the in-phase conditions, the magnitudes of both highs are significantly changed to effect an anomalously warmer and colder East Asian winter climate, but consistent with the above results, no changes are evident during the out-of-phase conditions. Consequently, the results suggest that ENSO-based long-range seasonal climate forecasts for East Asia should be considered with the interdecadal variations of the PDO to obtain more skillful prediction from an operational point of view.

1. INTRODUCTION

The East Asian winter monsoon (EAWM) is not only a great influencing factor on the local weather and climate in the East Asian region, but also one of the most active components in the global climate system during the boreal winter season. Hence, there have been many efforts to understand and predict the variations of the East Asian winter climate and monsoon circulations (Chang et al. 1979; Chang and Lau 1982; Lau and Li 1984; Ding 1994; Huang et al. 2003, 2007; Chan and Li 2004; Chang et al. 2006). Basic features of the EAWM, which is characterized by strong northwesterly winds and cold temperatures, are generally induced by the Siberian high, East Asian Jet and East Asian Trough. The source of the cold air outflow is the Siberian cold dome, which is maintained by strong radiative cooling and

subsidence by the Siberian high as well as the topological effect of the Tibetan Plateau (Ding and Krishnamurti 1987).

Meanwhile, the link between tropical atmospheric and oceanic phenomena and the winter monsoon system also have been examined in many studies. For example, Lau and Chang (1987) suggested that interannual variations of the winter monsoon and cold surges might be related to tropical intraseasonal and interannual oscillations. Ding and Krishnamurti (1987) noted an eastward shift of the tropical planetary-scale divergent circulation in association with the cold surges that is very similar to the shift of the divergent circulation seen between El Niño and La Niña years. Moreover, Zhang et al. (1997) summarized that the key driving force for the EAWM is the available potential energy generated by differential heating between the land and ocean areas of the region, and offered that the main heating source is located near the equatorial western Pacific Ocean based on the Southern Oscillation Index (SOI) (cf. SOI is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin located in the equatorial Pacific). Therefore, it is strikingly apparent that the winter monsoon and cold surges over East Asia have a dynamical link with climatological phenomena in the tropical Pacific Ocean.

The El Niño and Southern Oscillation (ENSO), characterized by feedback processes (e.g., 'Bjerkness feedback') of tropical ocean-atmosphere interaction, is the strongest internal climate mode operating on the interannual timescale (Bjerkness 1966, 1969 and many other studies). The ENSO exerts the greatest influence on the interannual variability of the global climate, although it is originated in the equatorial Pacific. Thus, in practical operation, it can be used as a potential predictor of climatological phenomena (Webster et al. 1998). Accordingly, there have been many studies regarding how ENSO affects the East Asian climate on the interannual timescale. As a result, the mature phase of El Niño (La Niña) is normally accompanied by a weaker (stronger) than normal winter monsoon along the East Asian coast (Zhang et al. 1996; Tomita and Yasunari 1996; Ji et al. 1997), and the climate in southeastern China and Korea is warmer (colder) and wetter (drier) than normal during the El Niño (La Niña) winter and the ensuing spring (Li 1990; Kang and Jeong 1996; Tao and Zhang 1998; Chen et al. 2000). Wang et al. (2000) reported that a key system

that bridges the ENSO and East Asian climate is an anomalous lower-tropospheric anticyclone (cyclone) located in the western North Pacific, causing anomalously warm (cold) and wet (dry) conditions over the East Asian continent. This relationship is referred to as the Pacific-East Asian teleconnection (PEAT).

Yet, the interannual relationship between ENSO and the global climate is not stationary, thus interdecadal variations in sea surface temperature (SST) associated with longer-term oscillations can have a significant impact on the strength and character of the ENSO (Tsonis et al. 2007; Swanson and Tsonis 2009). Hence, the Pacific Decadal Oscillation (PDO), a well-known decadal-scale SST oscillation mode which shifts every 20 to 30 years over the Pacific Ocean, has been proposed as an important modulation force on the ENSO-related interannual variability because the spatial patterns of SST, sea level pressure (SLP) and surface wind stress are quite similar to those associated with ENSO variability (Zhang et al. 1997; Mantua et al. 1997). For instance, Gershunov and Barnett (1998) argued that the typical influences of El Niño on the North American climate are strong and consistent only during the high phase of North Pacific Oscillation (NPO) and the generally reversed patterns during the La Niña winters are consistent only during the low NPO phase (cf. their NPO index is equal to the PDO index proposed by Mantua et al. 1997). Extending the work of Kung and Chern (1995), Lupo et al. (2007) suggested that the Pacific region SST associated with the ENSO tends to have different structures during the different phases of the PDO on the climate of the mid-Mississippi valley region. Similarly, dry and wet conditions in the Great Plains of the United States are strongly affected by the ENSO and PDO interferences (Hu and Huang 2009) and the variability of summer precipitation over South America is also linked to the ENSO (Paegle and Mo 2002) and PDO (Kayano and Andreoli 2007).

Naturally, the relationships between the East Asian monsoon system and ENSO, as modulated by the different PDO phases, have also been investigated. Chan and Zhou (2005) examined interdecadal variations in the early summer (May-June) monsoon rainfall over South China using phase combinations of the ENSO and PDO. The output indicated that when the ENSO and PDO are in-phase (i.e., El Niño/high PDO phase or La Niña/low PDO phase), rainfall tends to be below or above normal,

respectively. But when the ENSO and PDO are out-of-phase (i.e., El Niño/low PDO phase or La Niña/high PDO phase), the rainfall has no tendency toward wetness or dryness. Similarly, Yoon and Yeh (2010) argued the influence of the PDO on the relationship between El Niño and the northeast Asian summer monsoon (NEASM) using the method suggested by Lee et al. (2005). They separated summer rainfall into two components; the tropics-related and the extratropics-related components. The extratropics-related rainfall is enhanced by the Eurasian-like atmospheric circulation during the El Niño winters with a high phase of the PDO, resulting in the strengthening of the NEASM. However, when El Niño winters with a low phase of the PDO occur, the extratropics-related rainfall is reduced and the NEASM is also weakened.

In connection with the winter climate in East Asia, Wang et al. (2008) investigated the interdecadal modulation of the PDO on the impact of ENSO on the EAWM. They determined that ENSO exerts a strong impact on the EAWM only during the low PDO phase using significance tests on the composite differences between El Niño and La Niña winters with high or low PDO phases. Although this study provided insight into the interdecadal modulation effect of the PDO, the above composite analysis did not consider the interaction between ENSO and PDO phase because they considered the PDO only as an independent force. Also, the exact mechanism for the modulation effect of the PDO on the background condition has not been verified. To address these issues, the relationships between the EAWM and ENSO, as modulated by the different phases of the PDO, are reinvestigated with consideration for their interactive effect to determine if changes in PDO occurrence on the interdecadal timescale have significantly affected the robustness of the EAWM.

This paper is organized as follows. The data and methodology utilized in this study are described in section 2. Section 3 has three sub-sections that 1) analyze the changes in surface air temperature over East Asia for the period of 1900-2008 in the different ENSO and PDO phase combinations, 2) determine the robustness of the EAWM using various atmospheric variables and statistical significance tests and 3) illustrate wintertime variations of the subtropical high pressure over the western North Pacific (WNPSH, abbreviating western North Pacific subtropical high)

and Siberian high in order to describe the changes of the EAWM in the in-phase and out-of-phase conditions of the ENSO and PDO. Concluding remarks are presented in section 4.

2. DATA and METHODOLOGY

The three types of observed monthly mean datasets utilized in this study and detailed descriptions are listed in Table 1.

2.1 Datasets

The global surface air temperature data developed at the University of Delaware, which covers the entire span of the period from January 1900 to December 2008, was utilized (http://jisao.washington.edu/data_sets/ud). The dataset is provided in both its native 0.5-degree latitude-longitude resolution. Sources for the data are Global Historical Climatology Network (GHCN version 2) and Legates and Willmott's (1990a and b) station records of monthly and annual mean air temperature. The total number of GHCN stations used was 7,780. However, the actual number of GHCN stations available for each year varies from about 1,600 to 5,400 for air temperature. The monthly-mean meteorological datasets were obtained from 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA40) (http://data-portal.ecmwf.int/data/d/era40_moda/; Uppala et al. 2005) covering the period from September 1957 to August 2002. A horizontal resolution of the data is approximately $2.5^{\circ} \times 2.5^{\circ}$ in both latitude and longitude with extending from 1,000 to 1 hPa with 23 vertical pressure levels. In addition, the SST analysis data was taken from the monthly-mean $2.0^{\circ} \times 2.0^{\circ}$ gridded Extended Reconstruction SST (ERSST) version 3 (ERSSTv3; Smith et al. 2008; <http://www.esrl.noaa.gov/psd/data/gridded/>), which is the most recent version of the ERSST analysis. Although the temporal period of the ERSSTv3 covers the period from January 1854 to December 2010, the period used in this study is the same as that of ERA40 for comparison.

2.2 Definitions

There are two essential indices used in this study. One is the ENSO index which follows the definition provided by the Japan Meteorological Agency (JMA) (<http://coaps.fsu.edu/jma.shtml>). This is a widely accepted definition of ENSO which has been utilized in many climatic studies (O'Brien et al. 1996; Bove et al. 1998; Lupo and Jonhston 2000; Smith and O'Brien 2001; Berger et al. 2002; Wiedenmann et al. 2002; Akyuz et al 2004). This index is categorized into three phases of ENSO based on observed SST anomalies: El Niño, La Niña, and neutral. According to the specific definition, a particular phase of ENSO is determined by a 5-month running mean of spatially averaged SST anomalies contained within an area between 4°S-4°N, 150°W-90°W in the tropical Pacific basin. In order for a particular year to be classified as an El Niño (La Niña) year the SST anomaly must be 0.5°C (-0.5°C) or greater (less) for 6 consecutive months including October, November and December. Alternatively, the neutral years are determined when the values are between 0.5°C and -0.5°C. The other one is the PDO index, defined as the leading EOF mode of mean November through March SST anomalies for the Pacific Ocean to the north of 20°N latitude (http://jisao.washington.edu/data_sets/pdo/). The global mean SST anomaly was first removed for each month in order to reduce the influence of the long-term trends in the data. Also, an 11-year low pass filtering method was applied to separate the interdecadal variability because the PDO has both interannual and interdecadal variations by itself (Mantua et al. 1997). High and low phases PDO correspond to a case in which the PDO index is above and below zero. Table 2 shows the classification of winters according to the phases of ENSO and PDO for the period of 1900-2008. 24 El Niño, 27 La Niña and 58 neutral winters occurred along with 59 high and 50 low PDO phases during the period. For convenience, El Niño, La Niña, and Neutral winters will be referred to as EN, LN, and Neu and the El Niño winters with a high (low) PDO phase will be also referred to as EN+Hi_PDO (EN+Low_PDO). Similarly, La Niña and neutral winters with a high (low) PDO phase will be referred to as LN+Hi_PDO (LN+Low_PDO) and Neu+Hi_PDO (Neu+Low_PDO), respectively. Note that winter season defined in this study comprises December, January and February (DJF) and the DJF period for 1900 in Table 2, for example, means December 1900 to February 1901.

2.3 Statistical analyses

Regression, correlation and composite analyses are applied to examine the relationship between two variables. The statistical significance is assessed using Student's t test at the 90%, 95% and 99% confidence levels unless otherwise stated.

Table 1 Datasets utilized in this study

	Resolution	Range of Years	Source
Surface air temperature	0.5° × 0.5°	1900-2008	http://jisao.washington.edu/data_sets/ud
ERA40	2.5° × 2.5°	1957-2002	Uppala et al.(2005)
ERSSTv3	2.0° × 2.0°	1854-2010	Smith et al.(2008)
ENSO index		1868-2010	http://coaps.fsu.edu/jma.shtml
PDO index		1900-2010	http://jisao.washington.edu/data_sets/pdo/

Table 2 Classification of winters based on phases of ENSO and PDO for the period of 1900-2008

	High PDO	Low PDO
El Niño	1902, 1904, 1905, 1925, 1929, 1930, 1940, 1982, 1986, 1987, 1991, 1997, 2002, 2006	1911, 1913, 1918, 1951, 1957, 1963, 1965, 1969, 1972, 1976
Neutral	1900, 1901, 1907, 1921, 1923, 1926-1928, 1931-1937, 1939, 1941, 1943, 1978-1981, 1983, 1985, 1989, 1990, 1992, 1996, 2000, 2001, 2004, 2005	1912, 1914, 1915, 1917, 1919, 1920, 1945-1948, 1950, 1952, 1953, 1958-1962, 1966, 1968, 1977, 1993-1995, 2003, 2008
La Niña	1903, 1906, 1908-1910, 1922, 1924, 1938, 1942, 1984, 1988, 1998, 1999	1916, 1944, 1949, 1954-1956, 1964, 1967, 1970, 1971, 1973-1975, 2007

3. RESULTS

3.1 Changes in surface air temperature over East Asian continent

The spatial structure of the East Asian winter variability is revealed by regressing winter-averaged long-term surface air temperature (SAT) onto ENSO and PDO indices (Fig. 1). In figure 1a, significant positive and negative anomalies mainly appear along the coast of the East Asian continent as well as in some interior regions of China.

As expected, the spatial structure corresponds to the general characteristics of El Niño winters, meaning that an anomalously warmer climate exists over East Asia. In other words, the mature phase of El Niño exhibits relatively weaker than normal EAWM on the interannual timescale. However, the region located north of around 60°N, including far eastern China and southern Russia, clearly shows the opposite (negative) signs compared to the southern region. This dipole-like structure in the meridional direction indicates that the East Asian winter climate influenced by ENSO likely has a regional limitation. In this regard, the impact of Arctic Oscillation (AO), which displays a seesaw pattern in atmospheric pressure at northern polar and middle latitudes during cold seasons (Thompson and Wallace, 1998), on the EAWM has been widely discussed in previous researches. Wu and Huang (1999) first noted that the EAWM tends to be weak during the positive phase of the AO. Gong et al. (2001) pointed out the AO exerts its influence on the EAWM through the Siberian high whereas Wu and Wang (2002) argued that the influence of the AO on the EAWM is independent of the Siberian high. Since variability of the AO can significantly modulate the propagation of quasi-stationary planetary waves between the troposphere and the stratosphere (Chen et al. 2000, 2003; Chen and Huang 2005), Chen et al. (2005) examined the interannual AO-EAWM relationship from the perspective of the quasi-stationary planetary wave activity. They found that during the positive phase of the AO, more quasi-stationary planetary waves propagate from high latitudes to lower latitudes in the troposphere instead of propagating vertically to the stratosphere, accompanying a smaller perturbation in the polar vortex which tends to be cold and strong. To conclude, the impact of the AO on the EAWM is as important as that of the ENSO on the EAWM, but an in-depth investigation of the AO effect is outside the scope of this study.

Figure 1b presents the same regression map as figure 1a, but for the 11-year low pass filtered PDO index. The SAT field was also applied to the 11-year low pass filtering in order to focus on the interdecadal timescale. Interestingly, the result broadly shows significant positive anomalies over Eurasia, southern China and the inland portion of India; only a few significant negative anomalies appear over the Himalayan Mountains. Some areas in China and the coastal regions of East Asia show negative anomalies but statistically insignificant. A possible reason for positive signs

over East Asia is that many of the climate anomalies associated with the PDO are quite similar to those connected with ENSO variations (Latif and Barnett 1996). Nevertheless, the positive signs tend to extend over the Eurasian continent and the areas showing statistical significance are quite different compared to the ENSO regression map, especially along the coastal regions. These opposite responses are most likely related to the anomalously colder (warmer) SST occurred at the central and western north Pacific around the same latitude as Japan during the high (low) PDO phase.

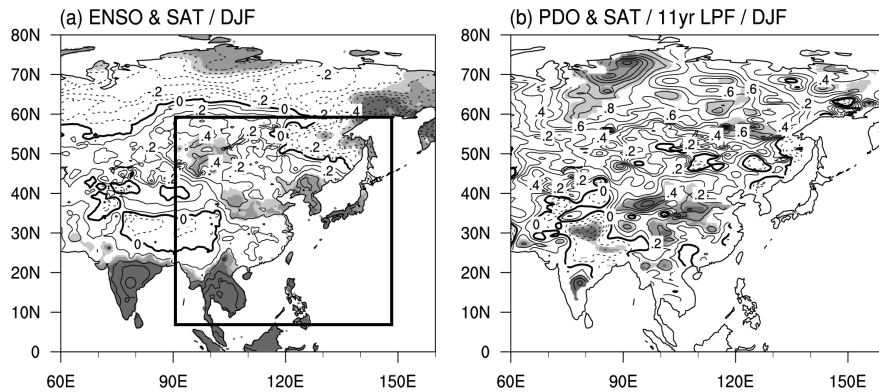


Figure 1 Regression maps of the winter mean (DJF) surface air temperature (SAT) onto (a) ENSO index and (b) 11-year low pass filtered PDO index for the period of 1900-2008. Contour intervals are 0.1°C, zero contour lines are thickened and negative lines are dashed. Light, medium and dark shadings indicate significant values at the 90%, 95% and 99% confidence levels, respectively. Significance based on a Student's *t* test. Rectangle indicates the East Asian region analyzed in this study.

To depict the wintertime temperature variations of East Asia, the area-averaged SAT within selected region (i.e., the area within the rectangle in figure 1a: 5-60°N, 90-150°E) was computed for the period of 1900-2008 (Fig. 2). For preprocessing, the 11-year low pass filtering method, normalization using the standard deviation of its own anomalies, and removing the linear trend to alleviate overall global warming signal for the last 100 years were applied. For brevity, this time series will be referred to as EAWSAT, abbreviating East Asian winter surface air temperature. Concurrently, 11-year low pass filtered ENSO (interdecadal-ENSO) and PDO indices are seen in Figure 2. The correlation coefficient of EAWSAT with interdecadal-ENSO shows quite

weak positive value, 0.27, because the ENSO-related features are associated with the dominant year-to-year global climate signals (McPhaden et al. 2006). However, the correlation coefficient between EAWSAT and PDO is a relatively strong value, 0.42, that is statistically significant at the 95% confidence level, suggesting that the high phase (low phase) of PDO is related to the warmer (colder) East Asian winter climate on the interdecadal timescale. Besides, the correlation coefficient between interdecadal-ENSO and PDO is 0.48 with significance at the 99% confidence level. It implies that there is a dynamical linkage between the tropical and extratropical decadal oscillations in the Pacific basin. Actually, extratropical PDO signals are considered to be transported into the tropics (Gu and Philander 1997; Kleeman et al. 1999; Nonaka et al. 2002; Vimont et al. 2003). Inversely, tropical Pacific variability due to ENSO also communicates into the extratropics and generates the extratropical PDO through teleconnection (Cane and Evans 2000; Newman et al. 2003; An et al. 2007; Holland et al. 2007). Therefore, it is fairly reasonable to hypothesize that the PDO has a significant impact on the East Asian winter climate due to interactions with ENSO-related interannual variability.

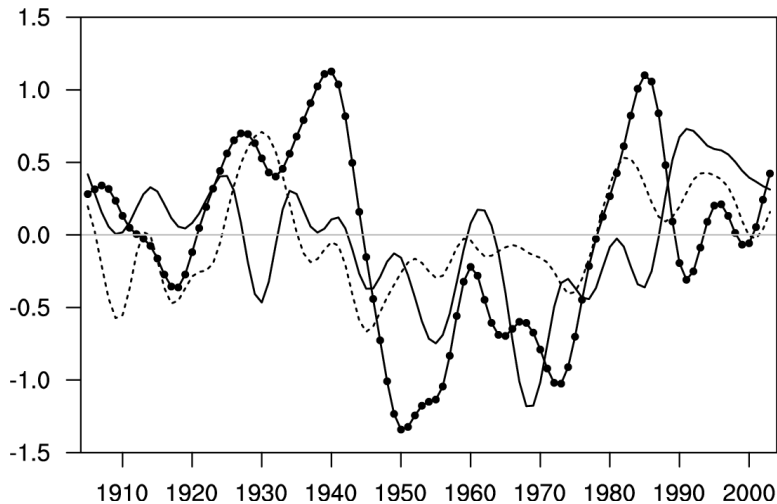


Figure 2 Normalized time series of winter mean (DJF) surface air temperature (SAT) anomalies over East Asia (solid), PDO (solid with circles) and ENSO (short dashed). The 11-year low pass filtering method is applied to all the plots and their linear trends are also removed.

In order to investigate the interactive effect of the ENSO and PDO on the East Asian climate, the winter SAT anomaly composites based on the different phases of ENSO and PDO were calculated for the period of 1900-2008 (Fig. 3). Figure 3a and 3b show the composites for the EN and LN winters; Figure 3c and 3d show the sub-composites for the EN+Hi_PDO and LN+Hi_PDO winters, whereas Figure 3e and 3f show the EN+Low_PDO and LN+Low_PDO winters, respectively (cf. see section 2 for the detailed explanations). Since the impacts of El Niño and La Niña are generally reversed, warm (cold) anomalies are dominant in the EN (LN) composites and their spatial structures are obviously opposite with the exception of the Tibetan Plateau area showing cold anomalies in both cases. Not surprisingly, these two structures are remarkably similar to the ENSO regression map as in figure 1a, implying that the impact of ENSO on the East Asian winter climate is very clear as seen in many previous literatures. Further sub-composites for the EN+Hi_PDO and LN+Low_PDO cases clearly exhibit the intensified SAT anomalies and their spatial structures are almost identical with those of EN and LN cases. A pattern correlation coefficient between EN (LN) and EN+Hi_PDO (LN+Low PDO) is significantly high at 0.82 (0.92). In contrast, cases for the EN+Low_PDO and LN+Hi_PDO show mostly incoherent structures compared to the EN+Hi_PDO and LN+Low_PDO cases. Gershunov and Barnett (1998) explained these incoherent patterns in terms of a destructive match of ENSO and PDO. However, the anomaly signals on the coastal regions of East Asia generally show the coherent patterns regardless of changes in PDO phase, indicating warm (cold) anomalies during El Niño (La Niña) winters. This is because the teleconnection between ENSO and the East Asian climate, demonstrated by PEAT, is stronger than that between the East Asian climate and PDO.

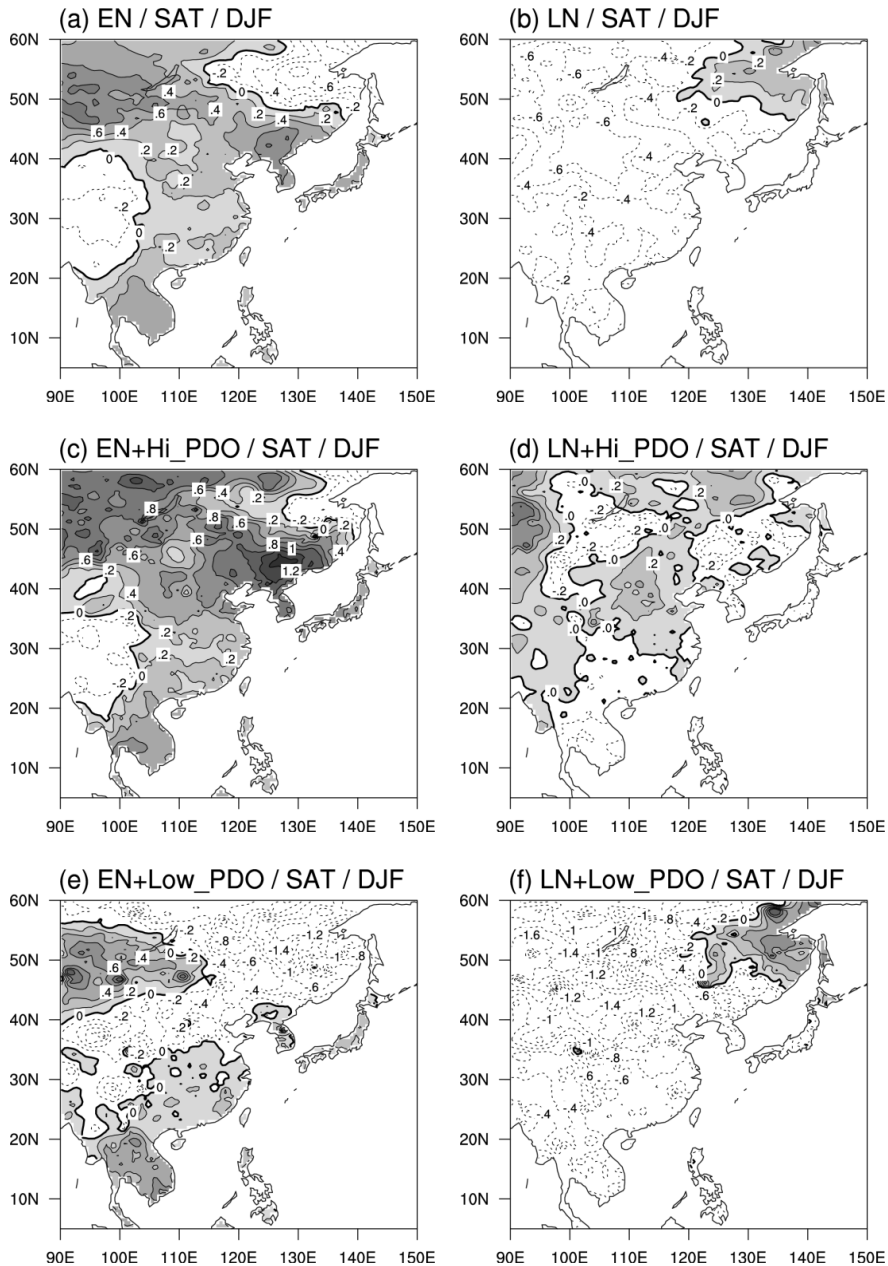


Figure 3 Winter mean (DJF) surface air temperature (SAT) anomaly composites based on (a) EN and (b) LN for the period of 1900-2008. (c), (d) are the same as in (a), (b) but for the EN+Hi_PDO and LN+Hi_PDO. (e), (f) are the same as but for the EN+Low_PDO and LN+ Low_PDO. Shadings indicate positive values and dashed lines indicate negative values. Contour intervals are 0.2°C and zero contour lines are thickened.

Because the specific effect of the PDO on the East Asian climate is still unclear, the winter SAT anomaly composites for the different PDO phases including or excluding ENSO winters are also examined in order to elucidate the pure PDO effect (Fig. 4). The spatial structure of Hi_PDO is essentially out-of-phase with that of the Low_PDO, showing warm (cold) anomalies in Hi_PDO (Low_PDO) except for relatively smaller magnitudes than those of the ENSO composite structures. Note that the pattern correlation coefficient between Hi_PDO and Low_PDO is -0.96, and the anomaly signals for the Hi_PDO and Low_PDO are similar to the EN and LN cases (cf. Figs. 3a, b). Therefore, it is possible that PDO not only has an opposite tendency with high and low phases, but also that it becomes a synergistic or dissipative force on the ENSO-related interannual variability, respectively, when they have in-phase or out-of-phase conditions with ENSO (cf. see section 1 for the explanation of in-phase and out-of-phase). However, the spatial structures of PDO excluding ENSO winters (i.e., Neu+Hi_PDO and Neu+Low_PDO) are quite different, suggesting that the PDO effect without ENSO variability on the East Asian winter climate is no longer associated with the coherent patterns of ENSO and PDO interaction. Surely, rigorous analysis will be required in future studies.

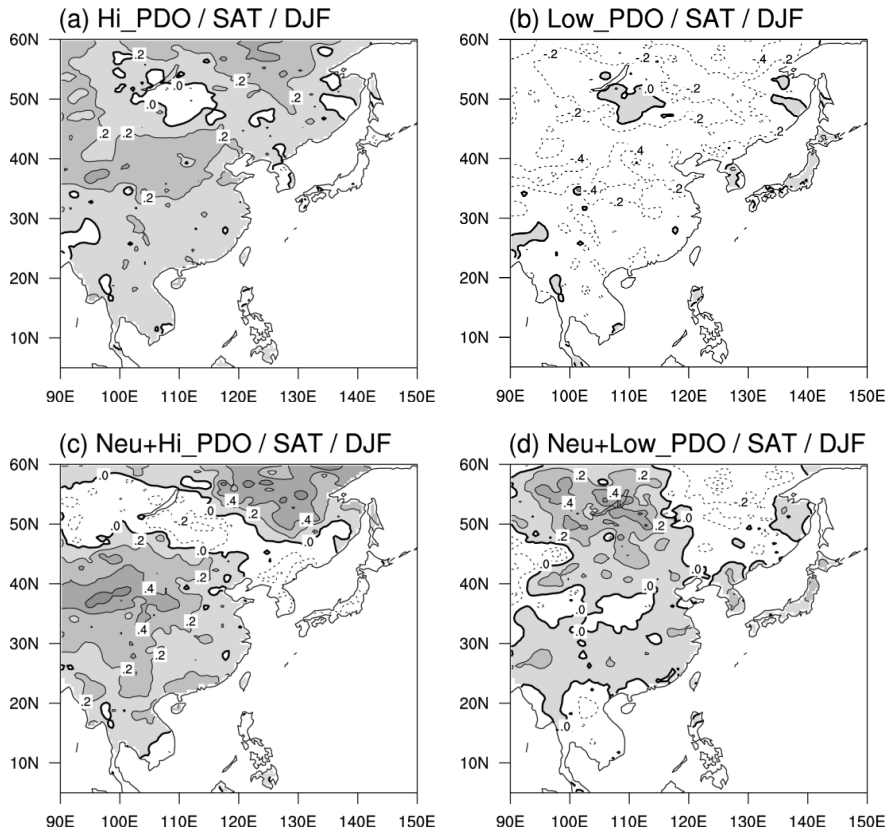


Figure 4 The same as in Figure 3 but for the (a) Hi_PDO and (b) Low_PDO. (c), (d) are the same as (a), (b) but with ENSO years excluded (Neu+Hi_PDO / Neu+Low_PDO).

3.2 Robustness of the East Asian Winter Monsoon

In this section, various atmospheric variables in the ERA40 datasets are utilized to compare with previous results and explain the physical mechanisms associated with the effect of ENSO and PDO interaction on the EAWM. The datasets, however, cover a period from September 1957 to August 2002, which is relatively shorter than that of SAT data. Thus, composite analysis completed for SAT was reconstructed using 1000-hPa air temperature from the ERA40 datasets (figures not shown). The results were almost exactly the same as for SAT, thus the ERA40 datasets can be used to complete the following analyses.

As in the method proposed by Wang et al. (2008), the 850-hPa air temperature composite differences of the winter mean during the in-phase and out-of-phase conditions of ENSO and PDO were calculated in order to determine the robustness of the EAWM (Fig. 5). Figure 5a shows the composite difference between EN+Hi_PDO and LN+Low_PDO (in-phase difference) cases, while figure 5b shows the difference between EN+Low_PDO and LN+Hi_PDO (out-of-phase difference) cases. The shaded areas in the figures represent statistically significant regions at 90% (light), 95% (medium) and 99% (dark) confidence levels as determined by a Student's t test. The in-phase difference exhibits significant warming signals over East Asia except for the Tibetan Plateau and the southern area of Russia. This indicates a weakening of the EAWM, which is consistent with previous studies (e.g., Chen et al. 2005). Note that if the order of computation for the composite difference is changed from EN+Hi_PDO minus LN+Low_PDO to LN+Low_PDO minus EN+Hi_PDO, the aforementioned anomalies are generally reversed. On the other hand, the out-of-phase difference does not show any significant signals despite showing plain cold anomalies over East Asia, indicating that there is no tendency toward a strengthened or weakened EAWM. This is very apparent evidence that the PDO is an important modulation force on the relationship between the EAWM and ENSO.

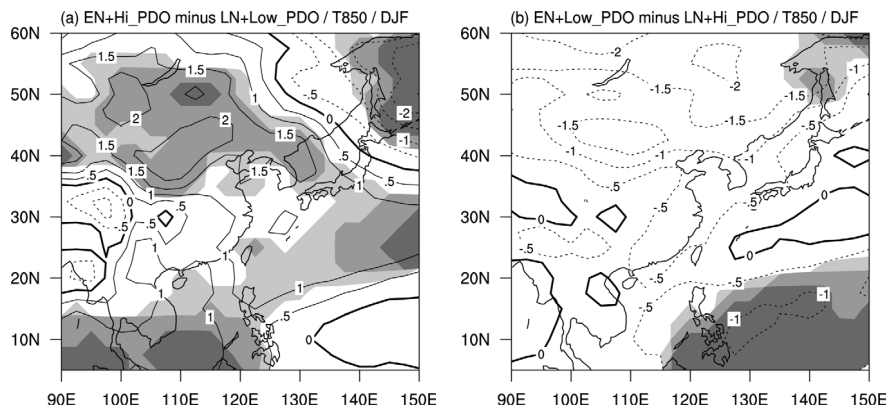


Figure 5 850-hPa air temperature composite differences of the winter mean (DJF) between (a) EN+Hi_PDO and LN+Low_PDO, and (b) EN+Low_PDO and LN+Hi_PDO for the period of 1957-2002. Contour intervals are 0.5°C and zero contour lines are thickened. Light, medium and dark shadings indicate 90%, 95% and 99% confidence levels, respectively. Significance based on a Student's t test. See table 2 for the composite.

Next we question how variations of PDO can have an effect its relationship with the EAWM in terms of atmospheric circulations. As discussed, the southerly wind anomalies along the margin of the East Asian continent critically influence the East Asian winter climate by serving as an atmospheric bridge via the PEAT pattern (Zhang et al. 1996; Wang et al. 2000). Accordingly, the 850-hPa wind field composite differences are illustrated using the same as in figure 5 (Fig. 6). The in-phase difference shows that the southerly wind anomalies are significantly well-established and penetrate to nearly 50°N, indicating that the EAWM is weakened by the movement of warm and moist air into the East Asian continent. Moreover, two massive cyclonic and anti-cyclonic wind circulations are also shown in the Pacific basin. The center of the cyclonic flow is situated over the northeastern Pacific near the Aleutian Islands and the anticyclone flow is widely located over the central to western Pacific and centered around 25°N and 165°E. They seem to be tightly connected, possibly as a result of an enhanced Rossby wave response to the anomalous equatorial central Pacific heating involved in the ENSO warming (Matsuno 1966; Gill 1980) and the deepened Aleutian low variability over the North Pacific. Since the PDO-related SST anomalies are closely linked to the strength of the Aleutian low (Wallace et al. 1992) and the ENSO variability also affects the Aleutian low through the PNA (Pacific-North American) teleconnection (Horel and Wallace 1981), it is reasonable to expect the atmospheric circulations to become stronger when the ENSO and PDO are in an in-phase condition.

On the contrary, the southerly wind anomalies are even weaker and insignificant during the out-of-phase condition, mainly limited to the south of 30°N over the Philippine Sea (Fig. 6b). The condition implies that the southerly wind anomalies hardly exert any impact on the EAWM and the atmospheric connection between two circulations is also weaker than that of the in-phase conditions.

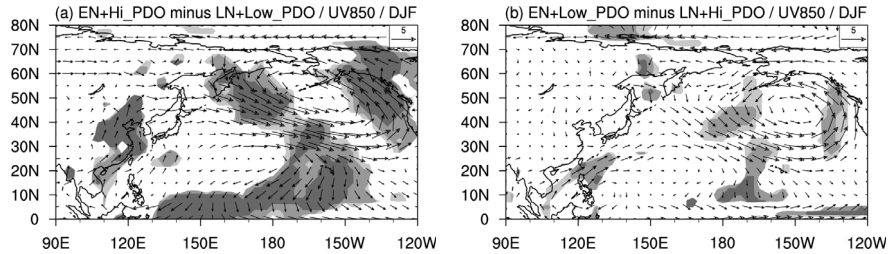


Figure 6 The same as in Figure 5 but for the 850-hPa wind field. Light, medium and dark shadings indicate 90%, 95% and 99% confidence levels of meridional wind, respectively.

The composite differences in SLP under in-phase and out-of-phase conditions were also computed in order to identify the air pressure anomaly distributions (Fig. 7). The in-phase difference reflects the deepened Aleutian low and intensified high pressure over the central to western Pacific, which are similar to the pattern previously seen in the wind composite difference in the in-phase conditions (cf. Fig. 6a). Meanwhile, the pressure gradient along the margin of the East Asian continent is significantly decreased due to the weakened Siberian high and strengthened high pressure anomalies over the Pacific. The decreased pressure gradient between cold Eurasian continent and the warm Pacific Ocean commonly causes a weakened winter monsoon circulation over East Asia, meaning a weakened EAWM. In contrast, the out-of-phase difference shows that the Siberian high is slightly strengthened despite its correlation having low significance. Further, the high pressure anomalies over the Pacific are strictly confined to the tropics and the Aleutian low is largely shifted southeastward. As a result, the Siberian high is likely to be isolated from the influence area of the atmospheric circulations generated in the Pacific basin and thereby it will be the only one dominant force on the East Asian winter climate regardless of the ENSO and PDO interactive effect.

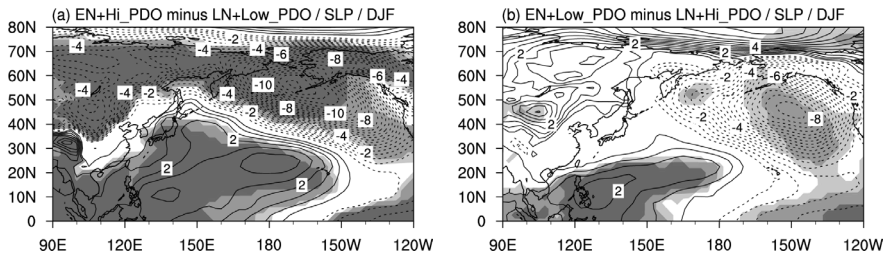


Figure 7 The same as in Figure 5 but for the Sea Level Pressure [SLP] field. Contour intervals are 0.5 hPa and zero contour lines are suppressed.

3.3 Wintertime variations of western North Pacific subtropical high and Siberian high

The WNPSH plays a prominent role in determining the strength of the EAWM supplying warm and moist air fluxes from the equatorial Pacific Ocean via PEAT (Wang et al. 2000). Therefore, it was illustrated that the wintertime variations of the WNPSH during the phase combinations of the ENSO and PDO with an examination of the 500-hPa geopotential height distributions (Fig. 8). The magnitude of the WNPSH, designated by the 5860-gpm contour, generally covers most of the tropical western North Pacific during the EN+Hi_PDO, while the magnitude is much weaker and even disappears in February during the LN+Low_PDO (Fig. 8a). On the other hand, the cases for the out-of-phase combinations show no apparent difference, although the EN+Low_PDO appears to show a slightly larger magnitude of the WNPSH than does the LN+Hi_PDO. Consequently, it would be difficult to determine the strength of the EAWM in the out-of-phase combinations.

Similarly, variations in the magnitude of the Siberian high were also demonstrated using the 1030-hPa contour over the East Asian continent (Fig. 9). Figure 9a shows that the Siberian high shrinks during the EN+Hi_PDO, but widely expands during the LN+Low_PDO, particularly in February. However, during the out-of-phase conditions, the magnitudes of Siberian high are somewhat similar except during February when some limited difference is notable (Fig. 9b). Thus, it is possible to conclude that the EAWM is weakened (strengthened) under the EN+Hi_PDO (LN+Low_PDO) condition, but there are no clear tendencies in determining the strength of the EAWM in other ENSO and PDO conditions.

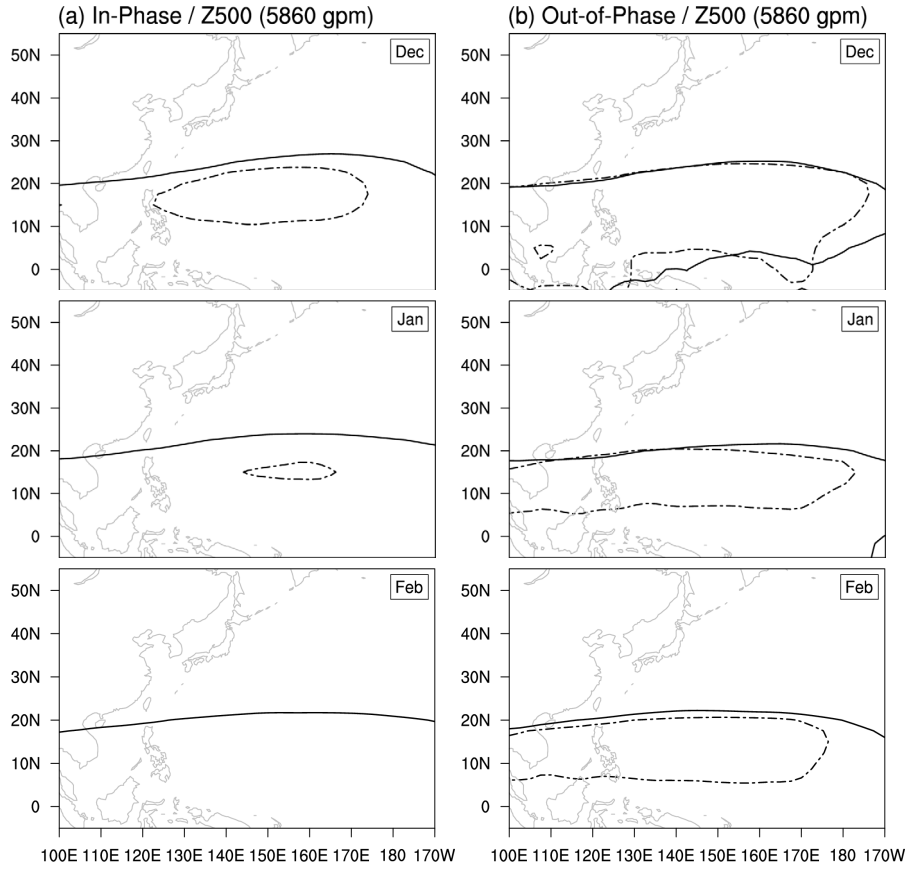


Figure 8 500-hPa geopotential height composites, designated by the 5860-gpm contour, from December to February based on (a) EN+Hi_PDO (solid) and LN+Low_PDO (long-short dashed), and (b) EN+Low_PDO (solid) and LN+Hi_PDO (long-short dashed) for the period of 1957-2002.

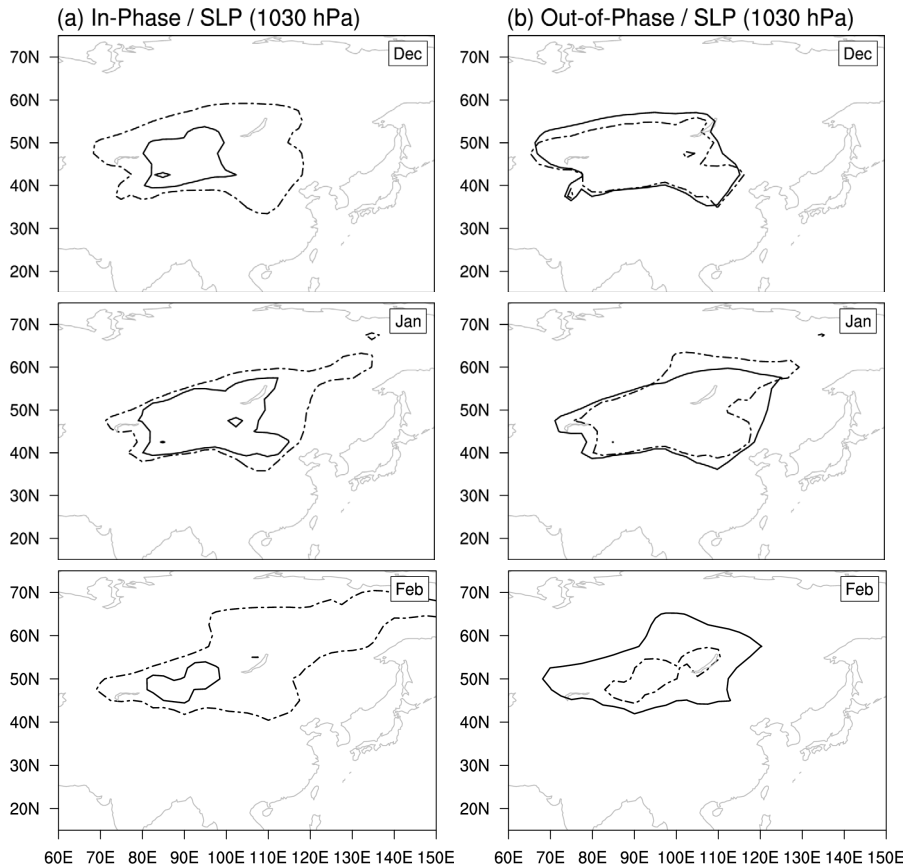


Figure 9 The same as in Figure 8 but for the SLP, designated by the 1030 hPa contour.

4. CONCLUDING REMARKS

By analyzing long-term SAT data and atmospheric reanalysis datasets, changes in the EAWM have been investigated using the ENSO and PDO phase combinations. First, interdecadal modulation of the PDO impact on the East Asian winter SAT was examined in order to clarify whether the PDO can have an effect on the relationship between the EAWM and ENSO by using regression, correlation and composite analyses. The PDO is positively correlated with EAWSAT ($r = 0.42$), and the SAT anomaly signals over East Asia are strong and spatially coherent when the ENSO and PDO

are in in-phase conditions. On the other hand, signals tend to be weak, spatially incoherent and unstable when they are in out-of-phase conditions. Considering this, there is a strong possibility that the PDO becomes a synergistic or dissipative force on the ENSO-related interannual variability due to the phase interferences of the ENSO and PDO. Furthermore, the robustness of the EAWM was determined using the composite differences of the winter mean atmospheric variables during the in-phase and out-of-phase conditions. The results indicated that interdecadal variations of the PDO are sufficiently able to modulate the robustness of the EAWM when the PDO has preferred phase of the ENSO.

We consider how the PDO modulates the EAWM across the Pacific basin. Basically, the strongest atmospheric manifestation of the PDO is the change in strength of the Aleutian low, which is also intimately affected by ENSO (e.g., PNA teleconnection). For example, when El Niño occurs with a high PDO phase during winter, the Aleutian low-related cyclonic flow is significantly enhanced by the interactive effect from ENSO and PDO (Fig. 10a). As a result, the SST in the central North Pacific is decreased by advection of cool and dry air from the north that is induced by increased westerly winds, ocean-to-atmosphere turbulent heat fluxes and strengthened equatorward advection of temperature by Ekman currents (Schneider and Cornuelle, 2005). Moreover, the anomalous anti-cyclonic flow located over the western Pacific is reinforced as the central Pacific warms. The passage that connects between the cyclonic and anti-cyclonic flows is the northerly wind anomalies coming from middle latitudes in the central Pacific. These wind anomalies generate cooling SST in the central-western Pacific due to the increased evaporative cooling and westward equatorial upwelling Rossby waves. In turn, a large-scale sinking motion arises and causes a strengthening of the WNPSH over the Philippine Sea. In contrast, when El Niño occurs with a low PDO phase, the Aleutian low-related cyclonic flow is markedly attenuated and thus the northerly wind anomalies are also significantly weakened (Fig. 10b).

Lastly, wintertime variations in the magnitude of the WNPSH and Siberian high during the different combinations of the two oscillations were depicted by designating specific contours from geopotential height and sea level pressure fields. During the

in-phase conditions, the magnitudes of the WNPSH and Siberian high appear to change, while there are no evident changes during the out-of-phase conditions. Overall, it is enough to conclude that the EAWM is clearly altered due to the effect of the ENSO and PDO interaction, especially on the in-phase combinations. Fundamentally, this conclusion supports the precedent results of Gershunov and Barnett (1998), who demonstrated that the typical ENSO signals tend to be stronger and more stable during preferred phases of the PDO and seriously distorted and unstable during opposite phases.

Although this study has represented the changes in the EAWM based on the co-variations of the ENSO and PDO only in an empirical sense, its findings may enhance our understanding of the uncertainties in ENSO-based seasonal climate forecasts. Indeed, Gutzler et al. (2002) argued that the ENSO-based seasonal predictability is modified only modestly by multivariate consideration of the PDO accounting for the PDO regime shift in 1977. During the pre-1977 period, when the PDO was largely negative, predictive skill was higher for cold Niño-3 temperatures leading dry winters in the Southwestern U.S. than for warm Niño-3 leading wet winters. After the regime shift in 1977, however, the asymmetry in predictability was reversed. More, Birk et al. (2010) emphasized that the seasonal climates experienced during a particular ENSO event may not necessarily mimic those of a similar ENSO event in the future. Instead, because the occurrence and amplitude of the ENSO can change over an extended period of time, the ENSO response may be modulated on the interdecadal timescale. Therefore, from an operational point of view, the ENSO-based long-range seasonal climate forecasts of the East Asian winter climate should be considered with the interdecadal variations of the PDO in order to achieve more skillful prediction.

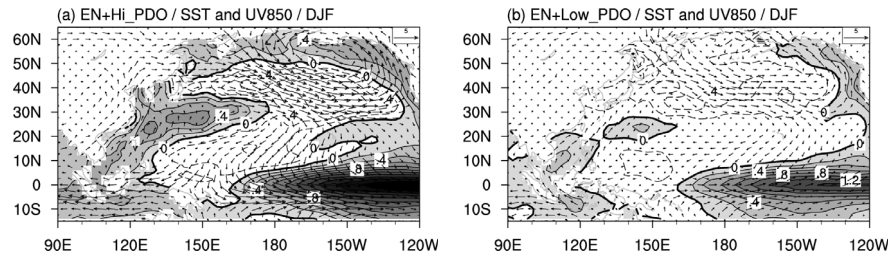


Figure 10 Winter mean (DJF) sea surface temperature (SST) and 850-hPa wind field anomaly composites based on (a) EN+Hi_PDO and (b) EN+Low_PDO for the period of 1957-2002. Shadings indicate positive values and dashed lines indicate negative values, respectively. Contour intervals are 0.2°C and zero contour lines are thickened.

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