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A possible way to extract a stationary relationship between ENSO and the East Asian winter monsoon

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\section*{ABSTRACT}
Previous studies have revealed that the relationship between the El Niño–Southern Oscillation (ENSO) and the East Asian winter monsoon (EAWM) is not statistically significant when the Pacific Decadal Oscillation (PDO) is in its positive phase. This study explores a possible way to obtain a robust ENSO–EAWM relationship from a dynamical point of view. Here, the authors show that the East Asian winter temperature is significantly and continuously correlated with ENSO when the linear impact of the PDO has been linearly removed from ENSO. Such a conclusion is confirmed by different reanalysis datasets. The dynamical process intensifying the ENSO–EAWM is further investigated from the perspective of whether or not the atmospheric teleconnection between the Pacific and East Asia has established. Compared to the situation associated with the original ENSO in the positive phase of the PDO, the Walker circulation associated with the processed ENSO, from which the effect of North Pacific climate systems has been removed, tends to exert a more pronounced influence on the atmospheric circulation over the western North Pacific. Consequently, an anomalous anticyclone emerges in the Kuroshio extension. In this sense, the Pacific–East Asian teleconnection is also well established during the positive phase of the PDO, which favors the impact of ENSO on East Asian winter temperature.

\section{1. Introduction}
The East Asian winter monsoon (EAWM) is an important atmospheric climate system of the global climate system. An anomalous EAWM can lead to excessive damage and large economic losses in both China and adjacent countries (Wu and Wang 2002; Wang, Yu, and Yang 2011; Li and Wang 2012, 2013). In boreal winter, the northwesterly wind along the eastern flank of the Siberian high is dry and cold, and stronger-than-normal northwesterly wind often brings extreme cold surges and severe snowfall events to East Asia (Boyle and Chen 1987; Chang, Wang, and Hendon 2006; Liu et al. 2012). Besides the winter climate, the EAWM also has a potential relationship with the summer climate over East Asia. For example, statistical analyses have revealed that a stronger-than-normal EAWM in boreal winter implies a generally stronger-than-normal East Asian summer monsoon in the following boreal summer (Chen, Yang, and Huang 2005; Yan et al. 2011). Therefore, it is important to improve our understanding of, and ability to predict, EAWM anomalies.

The impact of El Niño–Southern Oscillation (ENSO) on the EAWM has been well studied. The EAWM generally becomes weak (strong) when a warm (cool) ENSO event occurs, with a warmer (cooler) winter therefore emerging in East Asia (Li 1990; Zhang, Sumi, and Kimoto 1996; Zhang, Sperber, and Boyle 1997; Gollan, Greatbatch, and Jung 2012). The impact of ENSO is transmitted to East Asia mainly by the Pacific–East Asian teleconnection (PEAT), as
revealed by Wang, Wu, and Fu (2000). In addition to PEAT, more and more recent studies have reported that the sea surface temperature (SST) anomalies in the North Atlantic Ocean could also play an important role in relaying the impact of ENSO on the East Asian climate (Chen, Wu, and Chen 2018; Zuo et al. 2019; Zhao et al. 2019a, 2019b).

However, previous studies have revealed that the ENSO–EAWM relationship is not stationary (Wang, Chen, and Huang 2008; Wang and He 2012; He, Wang, and Liu 2013). Specifically, the relationship between ENSO and the EAWM on interdecadal time scales shows low-frequency oscillation (Zhou et al. 2007), and the ENSO–EAWM relationship on interannual time scales also has low-frequency oscillation (He and Wang 2013; Wang, He, and Liu 2013).

In the climate system, a well-known predictable climatic signal comes from ENSO (Kirtman and Schopf 1998; Cheng, Tang, and Chen 2011; Sun and Wang 2012), and therefore the prediction of winter climate over East Asia could be more challenging when the ENSO–EAWM relationship is statistically non-significant. Wang, Chen, and Huang (2008) found that the weakening of the ENSO–EAWM relationship after the mid-1970s might be attributable to the interdecadal change of the Pacific Decadal Oscillation (PDO), which turns to a positive phase around the mid-1970s. Therefore, in this study, we attempt to obtain a stationary ENSO–EAWM relationship by removing the linear influence of the PDO on ENSO. The purpose of this work is to present a possible way to refine the impact of ENSO on the EAWM when the statistical relationship between ENSO and the EAWM is weak.

2. Data and methods

The description of the dataset parallels that of Wang, Chen, and Huang (2008) and He and Wang (2013). The datasets used in this study include: (1) monthly mean SST obtained from the Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadisst/) (Rayner et al. 2003); (2) monthly mean sea level pressure (SLP), surface air temperature (SAT), winds at 850 hPa, and 500-hPa geopotential height derived from the NCEP1 reanalysis dataset (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) (Kalnay et al. 1996). To support the results derived from NCEP1, we also use the SAT from ERA-Interim (Dee et al. 2011) (https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim). The Niño3.4 index (INiño34) and PDO index are obtained from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml and http://research.jisao.washington.edu/data_sets/pdo/, respectively.

Based on the study by Wang, Chen, and Huang (2008), this study focuses mainly on the positive phases of PDO during 1979–2017. The winter mean of 1979, for example, is constructed by averaging the monthly means of December in 1979 and January and February in 1980. Before analysis, the linear trend is removed from all data to emphasize the interannual variability. To remove the potential influence of the PDO on the ENSO–EAWM relationship, we calculate a linearly fitted INiño34 using the PDO index, which is then subtracted from the INiño34. Therefore, a processed INiño34 (INiño34-noPDO), from which the linear influence of the PDO has been removed, is used to extract a stationary ENSO–EAWM relationship.

3. Results

3.1. Different ENSO–EAWM relationship with/ without the PDO’s effect

To investigate the potential mechanisms involved in how the PDO modulates the ENSO–EAWM relationship, we first compare the SAT anomalies regressed onto the original INiño34 (INiño34-orig; the signal of the PDO has not been removed) and the SAT anomalies regressed onto INiño34-noPDO. It is noteworthy that the ENSO signal pattern in the eastern tropical North Pacific is hardly changed (not shown). However, ENSO’s signal over East Asia is strengthened dramatically after the linear impact of the PDO on ENSO has been removed. Originally, ENSO’s impact could only reach oceans adjacent to East Asia during positive phases of the PDO (Figure 1(a)). When the signal of the PDO has been removed from ENSO, ENSO’s impact can extend westwards to impact more parts of East Asia. Statistically significant correlations of INiño34-noPDO with SAT emerge over East Asia (Figure 1(b)). This implies that, in addition to being an important system that plays a key role in bridging ENSO and the North American climate (Bjerknes 1969; Overland, Adams, and Bond 1999), the atmospheric circulation anomalies associated with the PDO over the North Pacific might act as a barrier to the influence of ENSO on the EAWM. It is noteworthy that (1) such a feature also emerges in the middle troposphere (500 hPa) (Figure 1(c,d)) and (2) results derived from different reanalysis datasets are consistent (Figure 1(e,f)), indicating a robust effect of the PDO on the ENSO–EAWM relationship.

To support the above hypothesis, we further illustrate the regression map of 500-hPa geopotential height (Figure 2) onto INiño34-orig and INiño34-noPDO, respectively. Corresponding to the original ENSO during positive phases of the PDO, there are no statistically
significant anomalies in the 500-hPa geopotential field over East Asia (Figure 2(a)), indicating a weak ENSO–EAWM relationship when the PDO is in its positive phase. Such results are highly consistent with the conclusions revealed by previous studies (Wang, Chen, and Huang 2008). Interestingly, when the linear influence of the PDO has been removed from ENSO, the 500-hPa geopotential height field shows statistically significant anomalies over East Asia (Figure 2(b)), suggesting a significant weakening of the East Asian trough and a
stronger-than-normal EAWM for warm ENSO events if there is no effect of the PDO.

3.2. Role of the PDO in the establishment of PEAT

It has been suggested that the positive phase of the PDO might suppress the establishment of PEAT (Wang, Chen, and Huang 2008), which is an important system linking the EAWM to ENSO (Wang, Wu, and Fu 2000). We therefore examine the ENSO-related SLP anomaly and near-surface (850-hPa) wind anomaly considering the effect of the PDO. As illustrated in Figure 3(a), the SLP field shows significant positive anomalies over large sections of the western North Pacific; its center is located over the Philippine Sea (Figure 3(a); contours). Associated with the significant change in SLP, an anomalous anticyclone emerges over the western North Pacific (Figure 3(a); vectors). Even though significantly anomalous southerly winds appear in the west flank of the anomalous anticyclone over the western North Pacific, they are mainly confined to coastal East Asia. Therefore, there is a weak impact of ENSO on the EAWM. Consequently, only a few significant SAT anomalies are observed over continental East Asia (Figure 1; left-hand panel).

After the linear signal of the PDO has been removed from ENSO, the impact of ENSO on the EAWM-related atmospheric circulation is intensified dramatically (Figure 3(b)). The anomalous anticyclone shifts northwards to Japan and a more significant southerly anomaly emerges over East Asia. The anomalous anticyclone over the western North Pacific, which connects the EAWM and the warming of SST in the equatorial central-eastern Pacific, becomes stronger. It is characterized by the dominant anticyclone center located around the Kuroshio extension. To further show the difference in atmospheric circulation before and after the removal of the PDO signals, we examine the differences between Figure 3(a,b). The anomalous southerly winds over East Asia related to INiño34-noPDO are stronger than those related to INiño34-orig (Figure 3(c)). The above analyses indicate that PEAT is well established, which could favor the impact of ENSO on the EAWM. However, what are the dynamical processes behind this?

As shown above, the most dramatic change is the anticyclonic anomaly located in the Kuroshio extension, which has been suggested to be related to dynamical instability of the westerly jet (Wang, Wu, and Fu 2000). Given the potential modulation of the PDO (Wang, Chen, and Huang 2008), in Figure 4 we display SST anomalies regressed onto the PDO index (Figure 4(a)), the normalized INiño34-orig (Figure 4(b)), and the INiño34-noPDO (Figure 4(c)). The SST anomalies related to the PDO are mainly located over the mid-latitude North Pacific and are relatively weaker over the eastern tropical Pacific (Figure 4(a)). Interestingly, the ENSO pattern in the eastern tropical Pacific does not show many differences between the situation with and without the influence of the PDO (Figure 4(b,c)). The dramatic difference is mainly observed over the western North Pacific. A dipole pattern in the SST anomalies emerges over the western North Pacific (see box in Figure 4(c)) when the linear influence of the PDO has been removed (Figure 4(c)). It has been revealed by a previous study that such a dipole pattern could promote the emergence of the anticyclonic anomaly over

![Figure 3](image-url)

(a) Regression maps of winter SLP (shaded; units: hPa) and 850-hPa wind (vectors; units: m s⁻¹) anomalies for the positive PDO phase during 1979–2017 with respect to simultaneous INiño34-orig. Shaded regions denote SLP anomalies significant at the 90% confidence level from a two-tailed Student’s t-test. (b) As in (a) but with regard to INiño34-noPDO. (c) Difference of vectors between (b) and (a).
the western North Pacific, which is a necessary system for the ENSO–EAWM relationship (Kim, Yeh, and Chang 2014).

We therefore assume that PEAT could be better established if there is no effect from the PDO, because in this case the anomalous anticyclone located over the Kuroshio extension, which is an important factor to connect ENSO with the EAWM (He and Wang 2013; He, Wang, and Liu 2013), exists stably and continuously. This can be confirmed by the 25-year sliding correlation between INiño34-orig/INiño34-noPDO and the temperature area-averaged over (30°–45°N, 120°–150°E; T_EA), which is based on the definition by Kim, Yeh, and Chang (2014). As shown in Figure 5(b), the relationship between INiño34-orig and T_EA breaks down after the mid-1970s (solid curve in Figure 5(b)), which is consistent with the results documented by the study of He and Wang (2013). By contrast, the relationship between INiño34-noPDO and T_EA is consistently and significantly correlated (dashed curve in Figure 5(b)).

4. Conclusions and discussion

Previous studies have indicated that the ENSO–EAWM relationship undergoes low-frequency oscillation, which implies that periods with a statistically significant ENSO–EAWM relationship alternate with periods when the ENSO–EAWM relationship is very weak and non-significant (Zhou et al. 2007; He and Wang 2013). By removing the potential modulation of the PDO from ENSO (see section 2 for details on the method), this study explores the important role played by the North Pacific systems along the pathway of how ENSO impacts the EAWM.

Our analyses reveal that the SAT, surface wind, and 500-hPa geopotential height anomalies over East Asian–Pacific sectors are statistically significantly correlated with INiño34-noPDO for the positive phase of the PDO during 1979–2017, while they are statistically non-significantly correlated with INiño34-orig. This confirms the conclusion that positive phases of the PDO have suppressed the influence of ENSO on the EAWM after the mid-1970s, and implies a possible stationary ENSO–EAWM relationship is obtainable. Consequently, we suggest that the impact of ENSO on the EAWM would be...
more significant and stable when the signal of the PDO has been removed from ENSO, which might be helpful for the prediction of East Asian winter climate.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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