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Key Points:

- Why we have a high correlation between the PDO and precipitation dipole
- PDO-storm track mechanism as an explanation to the precipitation dipole
- PDO-storm track relationship is robust regardless of ENSO teleconnection

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A physical mechanism of the precipitation dipole in the western United States based on PDO-storm track relationship

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Abstract It is known that the western United States (US) precipitation displays a north-south contrast, i.e., the so-called "precipitation dipole," during El Niño and La Niña winters. Furthermore, the Pacific Decadal Oscillation (PDO) has been known to modulate this precipitation dipole. However, the underlying physical mechanism regulating this modulation is not well understood. This study revisits previous studies and suggests a physical mechanism of precipitation dipole modulation based on the PDO-storm track relationship. We found that both jet stream and storm track tend to move northward (southward) over the North Pacific during negative (positive) PDO winters, contributing to the increase of precipitation over the northwestern (southwestern) US, respectively. This relationship is robust regardless of El Niño-Southern Oscillation (ENSO), possibly facilitating modulation of the precipitation dipole. Moreover, changes in oceanic baroclinicity associated with the PDO phase are suggested to be responsible for anchorage of storm tracks over the North Pacific.

1. Introduction

Previous studies identified widespread impacts of Pacific Decadal Oscillation (PDO), a leading mode of multi-decadal variability in sea surface temperature (SST) in the extratropical North Pacific, on socioeconomic systems such as fisheries and hydrological supplies [*Mantua and Hare*, 2002; *Mantua et al.*, 1997]. One of the foremost climatic impacts of the PDO is a modulation of the precipitation pattern in the western United States (US), which displays a north-south contrast, i.e., the so-called "precipitation dipole." Such anomalous dipolar precipitation patterns manifest during El Niño and La Niña years, and they can be enhanced or weakened according to the PDO phase [*Dettinger et al.*, 1998; *Wise*, 2010]. In addition to the modulating effect, it has been argued that the PDO itself exerts a notable influence on US drought even when the El Niño-Southern Oscillation (ENSO) signal is neutral [*Goodrich*, 2007]. Despite knowledge of distinct statistical relationships between the PDO and downstream precipitation in the western US, the underlying physical mechanisms are not yet well understood.

The relationship between the precipitation dipole and ENSO seems subject to pronounced decadal variability. *Gutzler et al*. [2002] showed that ENSO-based predictability of US precipitation before 1977 substantially differed from that after 1977. *Brown and Comrie* [2004] also argued that correlations between ENSO and US winter precipitation vary spatially, commensurate with decadal phase shifts of the PDO. Nonetheless, the physical understanding of the decadal modulation effect of the PDO is still problematic.

In this study, we attempted to understand how the PDO affects downstream climate and modulates ENSO teleconnections. As indicated by its name, the PDO refers to a leading mode of multi-decadal variability in the North Pacific. However, it also shows pronounced variability on an interannual time scale. This study focuses on interannual time scale variability of the PDO and the upper atmosphere, and further addresses implications on a decadal time scale.

As an intermediary between North Pacific oceanic variability and downstream precipitation, we focus particularly on the North Pacific storm track. Conventionally, the PDO has not been regarded as a single dynamical mode but as a superposition of responses to several physical processes, i.e., ENSO teleconnections, Aleutian low variability, and oceanic processes in the Kuroshio-Oyashio Extension (KOE) [*Park et al.*, 2013; *Schneider and Cornuelle*, 2005]. Recent studies have identified an anchoring effect of oceanic frontal zones, such as the KOE, on storm development [*Frankignoul et al.*, 2011; *Nakamura et al.*, 2004; *Sampe et al.*, 2010]. A linkage between the PDO and storm tracks may be attributable to this oceanic frontal influence, which will also be examined in this study.

2. Data

In order to examine the PDO and associated atmospheric variability over the North Pacific and nearby regions, we used daily atmosphere reanalysis data, sea surface temperature (SST) data, and precipitation data. Daily reanalysis data sets were obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) [*Kalnay et al*., 1996] and analyzed for a period from the winter (November to March) of 1948–1949 to the winter of 2011–2012. The sea surface temperature (SST) was also analyzed for the same period with the atmospheric reanalysis data. We obtained the monthly SST data from the Met Office Hadley Centre [*Wu et al*., 2011].

The PDO index was downloaded from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) website (http://jisao.washington.edu/pdo), which spans a period from 1900 to 2012. Since the atmospheric circulation pattern corresponding to the PDO is largely affected by ENSO through the atmospheric wave response [*Van Loon and Madden*, 1981], we checked the predominance of the results irrespective of ENSO. El Niño and La Niña years were selected using the Niño-3.4 index, which was defined as area-averaged SST over the region covered by 5°N–5°S latitude and 170°W–120°W longitude. If the Niño-3.4 index, averaged over the period from September to December (SOND) was above or below the threshold of half a standard deviation ($\pm 0.5\ \sigma$), the year was regarded as either an El Niño or a La Niña year. The PDO years were selected in a manner identical to the selection of ENSO years.

The downstream climatic impact of the PDO was analyzed using the United States Historical Climatology Network (USHCN) daily precipitation data set [*Menne et al*., 2013], obtained from the Carbon Dioxide Information Analysis Center (CDIAC) website (http://cdiac.ornl.gov). Daily precipitation data were accumulated for each winter period from 1948 to 2012. We considered station observations that began before the year 1948 and obtained 337 stations over the western US.

3. Results

A linkage between the PDO and storm track activity has been noticed previously by *Chang and Fu* [2002]. They examined a statistical relationship between the PDO and interannual variations of wintertime storm tracks over the North Pacific and found a significant correlation between the PDO and storm track intensity. Subsequently, another study also examined the relationship between these two phenomena [*Lee et al*., 2012]. While examining interdecadal variations of storm track activity, *Lee et al*. [2012] found that these correlation coefficients largely display decadal variation, becoming insignificant over longer periods of time; this contradicted the findings of the previous results.

These studies addressed the relationship between the PDO and storm track from the perspective of storm track intensity variation. However, the interannual storm track variability is very high over the North Pacific, in terms of both intensity and location. In this study, we revisit the relationship between the PDO and storm track, with a focus on spatial storm track variations. Following *Lau* [1988], we calculated the root mean square (RMS) of 2–8 days band-pass filtered geopotential height at 500 hPa (Z500) for each grid point and designated the particularly enhanced RMS area as the storm track. The shaded region in Figure 1a shows the climatological storm track distribution, centered over the western North Pacific, extending toward the northern part of the North American continent. Contours show the leading eigenvector (EOF1) of covariance matrix computed using the anomalous RMS fields of 2–8 days band-pass filtered Z500 for 64 individual winters over the North Pacific basin (20°N–70°N, 100°E–110°W). The leading eigenvector shows the most pronounced covariant pattern between grid point RMSs, which can be regarded as a dominant pattern of the storm track variability. The eigenvalue corresponding to the EOF1 indicated that the EOF1 pattern explains 21.9% of the interannual variability of the North Pacific storm track. Note that the EOF 1 was well separated from the second EOF (EOF2) which accounts for 13.5% of total variance [*North et al*., 1982]. The EOF1 pattern superimposed on the climatological storm track shows enhanced but southward shifted storm track activities. As the storm track moves southward, storm track activity near northwestern part of the North American continent weakens. Therefore, the EOF1 pattern indicates that the meridional storm track displacement is one of the prominent characteristics of interannual storm track variation.

Figure 1b shows the first principal component time series (PC1, orange colored line), and its scatterplot against the PDO index is presented in Figure 1c. Interestingly, a linear relationship is clearly observed in

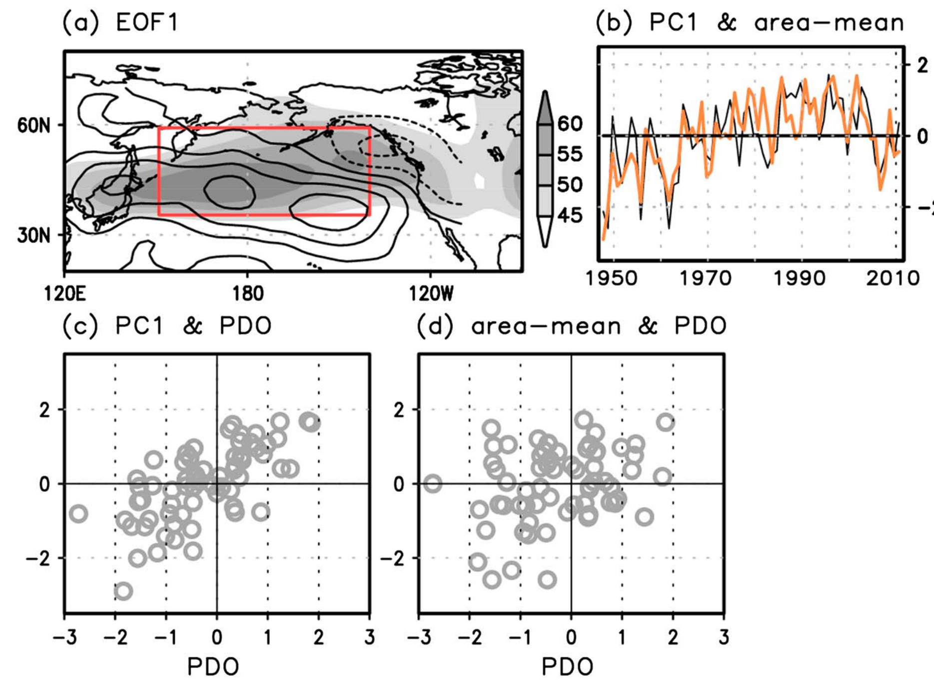

Figure 1. (a) Leading eigenvector of RMS of the 2–8 day band-pass filtered Z500 for the 20°N–70°N, 100°E–110°W region (contour) and its climatology (shading). (b) Temporal coefficients of the leading eigenvector (first principal component (PC1), orange colored line) and area-mean Pacific storm track activity (black line) over the climatological storm track region (20°N–70°N, 150°E–140°W, denoted by the red box in Figure 1a). (c) Scatterplot of PC1 against the corresponding Pacific Decadal Oscillation (PDO) index. (d) Same as Figure 1b but for the area-mean Pacific storm track activity.

Figure 1c (correlation coefficient, R = 0.68). This implies that the storm track tends to move southward (northward) during positive (negative) PDO years. As noted above, previous studies examined the relationship between the PDO and storm track from the perspective of storm track intensity variation. Therefore, we also checked whether storm track intensity variation and the PDO are related each other. Black line in Figure 1b shows the area-mean storm track intensity index in the climatological center region, and Figure 1d is the corresponding scatterplot against the PDO index. As shown in Figure 1d, the strength of this relationship is considerably weaker than that shown in Figure 1c (R = 0.30). This supports an intimate link between the meridional migration of the storm track and PDO and implies that the correlation between the PDO and storm track indices may depend on definitions made to identify storm track variability. Previously, *Chang and Fu* [2002] adopted EOF analysis for representation of storm track activity, while *Lee et al*. [2012] used the area-mean storm track intensity index; however, these studies paid little attention to spatial storm track variation. The interdecadal variation of correlation shown in *Lee et al*. [2012] may be due to the interdecadal phase shift of the PDO and the ensuing storm track meridional change.

The upper-level circulation field also shows a feature consistent with how storm track variability depends on the PDO phase. Figures 2a and 2b show the mean zonal wind distribution at 300 hPa, during positive and negative PDO years, respectively. Distributions of 10 and 20 m/s isotachs show clear differences for the jet downstream region near the western coast of North America: the jet exit tends to be located slightly northward of the climatology during negative PDO years, while it was shifted southward during positive PDO years. This difference can be understood through the nature of subpolar jets, driven by eddy [*Hartmann*, 2007]. Momentum transport by transient eddies acts to maintain midlatitude westerlies, which are often referred to as a subpolar jet or polar front jet. Therefore, the tendency of the storm track to move northward during negative PDO years provides a condition conducive to jet sustenance in the north of the climatology. Consistently, a southward shift of the storm track during positive PDO years is anticipated to accompany southward jet shift, which coincides with Figure 2a.

Here, we regarded the PDO as an extratropical variability which is distinct from equatorial phenomena such as ENSO. However, the intimate relation between the PDO and ENSO [*An et al*., 2007; *Park et al*., 2013; *Schneider and Cornuelle*, 2005] suggests that meridional movements of the storm track and jet stream may be due to remote

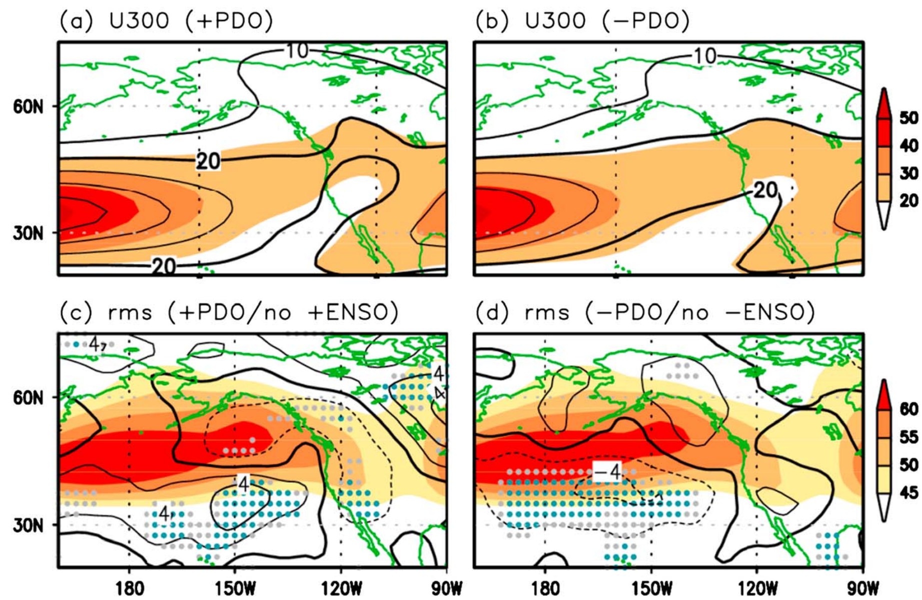

Figure 2. Zonal wind at 300 hPa during (a) +PDO years (n = 17) and (b) −PDO years (n = 31) (contour) superimposed on climatological zonal wind (shading, m/s). Anomalous storm track activity during (c) +PDO years with no ENSO event (n = 6) and (d) −PDO years with no ENSO event (n = 10) (units: m). Grey and blue dots denote areas that are significant at the 90 and 95% confidence levels, respectively.

impacts of ENSO [*Li and Lau*, 2012; *Park and An*, 2014; *Straus and Shukla*, 1997]. It is known that the storm track over the North Pacific tends to move toward the equator during El Niño [*Straus and Shukla*, 1997; *Zhang and Held*, 1999]. This meridional movement of the storm track is consistent with atmospheric behavior during positive PDO years. In order to exclude tropical interference by ENSO in the North Pacific atmosphere, storm track variability was checked for pure PDO years, i.e., years not accompanied by El Niño or La Niña (Figures 2c and 2d). Figure 2c shows a distribution of anomalous storm track activity almost identical to that shown in Figure 1a. In particular, the storm track activity is still enhanced over the south of the climatological storm track during positive PDO years with no El Niño, while it is weakened along the western coast of North America. During negative PDO years, the storm track also exhibits consistent features without the interference of La Niña, showing a distribution that is symmetric but of opposite sign to that of positive PDO years. Therefore, it is inferred that the relationship between the PDO and storm track is robust regardless of annual ENSO phase.

Meridional displacements of storm tracks have notable implications for downstream regional climates. As noted in the introduction, ENSO exerts a considerable climatic impact on the western US precipitation, known as a "precipitation dipole" [*Brown and Comrie*, 2004; *Dettinger et al.*, 1998; *Horel and Wallace*, 1981; *Kiladis and Diaz*, 1989]. Previous researchers have also revealed that the dipolar distribution of precipitation anomalies becomes stronger when ENSO and PDO are in a constructive phase (+ENSO/+PDO or −ENSO/−PDO) [*Gershunov and Barnett*, 1998; *Wise*, 2010]. Figures 3a and 3b show such modulation effects of the PDO on the precipitation dipole during El Niño winters. During El Niño winters accompanied by positive PDO phases, contrasting regions of decrease (grey dotted region) and increase (red dotted region) are found over the north and south of the western US, respectively. Compared to the prominent dipolar structure shown in Figure 3a, meridional contrast is much weaker in Figure 3b which depicts precipitation anomalies during El Niño winters accompanied by negative PDO phases. The preference of the precipitation dipole for PDO phases is also found in La Niña winters with reversed dipolar precipitation anomalies, i.e., increased (decreased) precipitation over the northwestern (southwestern) US when the PDO phase is negative (Figure 3d). However, precipitation anomalies do not show such characteristic features during La Niña winters accompanied by positive PDO phases (Figure 3c).

We suggest that the climatic impact of ENSO on the western US altered by the PDO condition arises from meridional movement of the storm track over the North Pacific. When ENSO and the PDO are in phase, the shifting tendency of storm tracks is expected to be more prominent. In fact, Figures 3a and 3d show

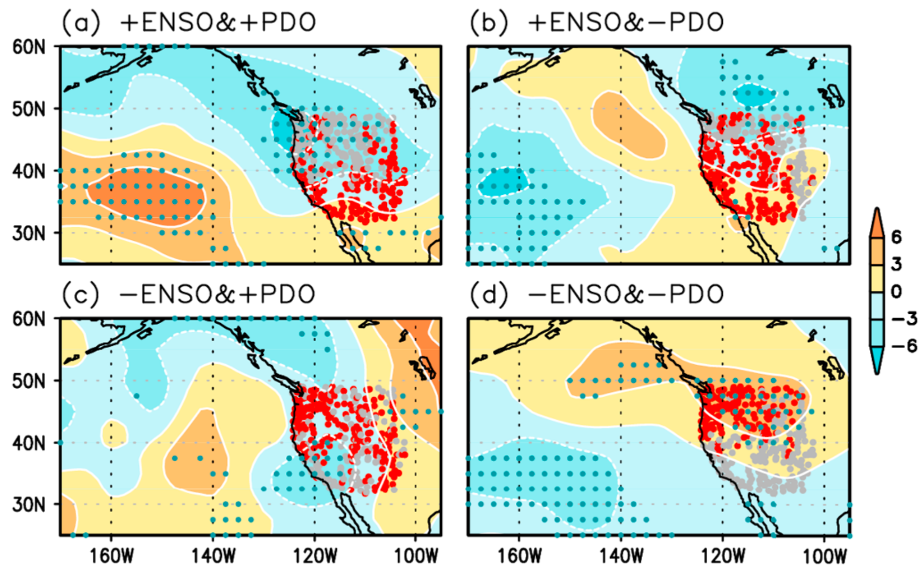

Figure 3. United States Historical Climatology Network (USHCN) accumulated precipitation anomaly composite of (a) El Niño/+PDO (n = 8), (b) El Niño/−PDO (n = 5), (c) La Niña/+PDO (n = 3), and (d) La Niña/−PDO years (n = 16), denoted by red and grey dots for positive and negative precipitation anomalies, respectively. Shading denotes anomalous storm track activity (units: m). Blue dots denote areas of storm track change that were significant at the 95% confidence level.

coinciding features, particularly regarding the weakened (intensified) storm track anomalies in regions of decreased (increased) precipitation depicted by blue (yellow) shading. The characteristic meridional storm track migration shown in Figure 1 is most pronounced in Figures 3a and 3d. Note that the storm track variation is significant over the precipitation dipole regions. For years during which ENSO was out of phase with the PDO, however, the characteristic migration feature of the storm track is unclear. The modulation effect of the PDO on the ENSO precipitation is unlikely to be dependent on the ENSO intensity. In order to check whether the precipitation dipole is more linked to stronger ENSO events, we repeated similar analyses but for weak ENSO years ($0.5\ \sigma <$ Niño3.4 $< \sigma$) and obtained similar results (figure not shown).

Meridional displacements of the North Pacific storm track that brings different climatic impacts on downstream regions can be regarded as a result of ocean-atmosphere interaction. Based on the intimate relationship between oceanic baroclinicity and synoptic activity in the atmosphere [*Nakamura and Shimpo*, 2004], we examined a meridional SST gradient over the North Pacific basin with respect to PDO phase. Figure 4a shows an anomalous SST distribution for negative PDO years. During negative PDO years, a warm SST anomaly is located over the central North Pacific, surrounded by a cold anomaly along the

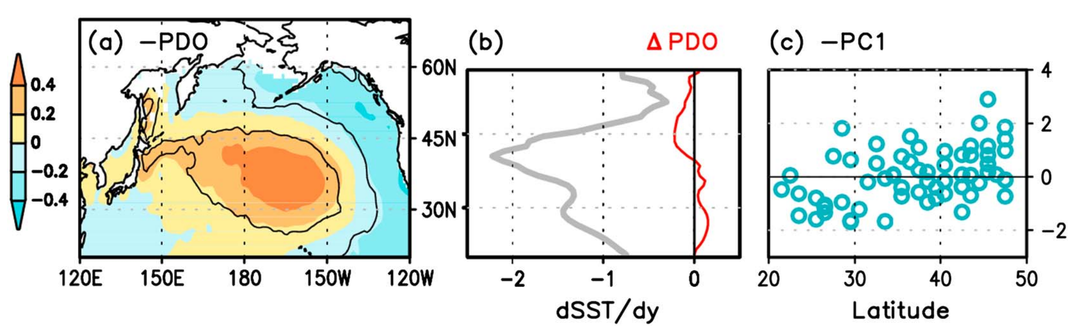

Figure 4. (a) Sea surface temperature (SST) anomaly (in °C) during −PDO years (denoted by shading), significant at the 95% confidence level (contour). (b) Climatological meridional SST gradient (SST_y) over the North Pacific (zonal average over 140°E–120°W), denoted by the grey line, and the difference of the SST gradient between negative and positive PDO years ($(SST_y)_{-PDO}$ minus $(SST_y)_{+PDO}$), denoted by the red line. (c) Scatterplot of inverted PC1 values against peak latitude of anomalous SST gradient.

westerncoast of North America. Figure 4b shows a climatological meridional SST gradient over the North Pacific (140°E–120°W), which peaks at about 40°N (grey line), and the difference of the SST gradient between negative and positive PDO years (red line). The distribution of SST anomalies shown in Figure 4a enhances the meridional gradient to the north of the climatological peak, and the changes in the SST gradient during negative PDO years are well reflected by the red line in Figure 4b. As the SST anomaly pattern during positive PDO years is almost opposite to that during negative PDO years, cold and warm anomalies appear in the central North Pacific and on the western coast of North America, respectively. This pattern strengthens the oceanic baroclinicity to the south of the climatological peak.

The distribution of climatological storm track shown in Figures 1 and 2 seems to be anchored along a strong oceanic baroclinic region. Note that the meridional movement of storm tracks according to PDO phase also coincides with the anomalous SST gradient, particularly the northward shifted storm track and the enhanced SST gradient to the north of the climatological peak. A general relationship between storm track movement and anomalous SST gradient may be inferred from Figure 4c. We multiplied PC1 by -1 in order to represent a northward shift of the storm track when the index indicates a positive value. Overall, the scatterplot in Figure 4c shows a linear relationship, implying that the storm track tends to move northward when the anomalous SST gradient peaks at higher latitudes.

The agreement between storm track displacement and the anomalous SST gradient region corresponds well with the arguments that heat and moisture fluxes that enter into the atmosphere from the ocean front help latitudes of storm tracks anchor to oceanic baroclinic regions [*Kwon et al*., 2010; *Nakamura et al*., 2004]. Recent high-resolution modeling experiments also indicate the importance of SST gradients in the generation of storm tracks and their variability [*Brayshaw et al*., 2008; *Graff and LaCasce*, 2012; *Sampe et al*., 2010]. Therefore, the observed modulation of downstream US precipitation may originate from PDO-based modulation of ocean-atmosphere interactions over the North Pacific. This physical process differs from that of ENSO by which the North Pacific storm track is modulated. The southward shift of the storm track during El Niño years is attributed to the increased vertical wind shear in the eastern Pacific and resultant shift of atmospheric baroclinic region, in response to the enhanced local Hadley circulation and tropical warming [*Straus and Shukla*, 1997]. Nonlinear interaction among the tropical heating, storm track eddies, and the midlatitude stationary wave was also suggested to be crucial to make correct attributions of the storm track structural changes during ENSO years [*Chang et al*., 2002].

4. Discussion

In the conventional view of ocean-atmosphere interactions in the extratropical North Pacific, atmospheric variables are thought to be primarily responsible for the generation of local SST variations by changing turbulent heat fluxes [*Davis*, 1976; *Frankignoul*, 1985; *Iwasaka et al*., 1987; *Kushnir et al*., 2002]. Subsequently, however, the role of the ocean has been suggested to promote individual cyclone development through heat and moisture supply [*Kuo et al*., 1991; *Neiman and Shapiro*, 1993]. *Kuo et al*. [1991] argued that the low-level heating and moistening from warm ocean surface significantly reduce atmospheric stability and provide an environment conducive to storm intensification.

More recent results emphasize the active role of meridional SST gradients, rather than that of SST itself, in determining overlying atmospheric response and storm track formation [*Brayshaw et al*., 2008; *Nakamura et al*., 2004]. Oceanic baroclinicity in the oceanic frontal zone acts to restore the atmospheric baroclinicity, which is relaxed rapidly through atmospheric heat transport by eddy. Therefore, major storm tracks are organized along or just downstream of main oceanic frontal zones such as western boundary currents and their extensions (WBCs) [*Frankignoul et al*., 2011; *Kwon et al*., 2010]. Due to the interaction between ocean and atmosphere over the North Pacific basin, the PDO can be a useful indicator reflecting responses to atmospheric and oceanic forcing, i.e., ENSO teleconnection, Aleutian low variability, and thermal advection associated with ocean Rossby waves in the Kuroshio-Oyashio Extension [*Park et al*., 2013; *Schneider and Cornuelle*, 2005].

Although this study addressed atmospheric variability associated with the PDO by focusing on an interannual time scale, the decadal variations of the PDO also provide important implications for the variation of the precipitation dipole over the western US. As previously noted, it has been identified that ENSO teleconnections and the associated precipitation dipole display decadal variability [*Brown and Comrie*, 2004;

Gutzler et al., 2002; *McCabe and Dettinger*, 1999]. *Gutzler et al*. [2002] noticed a pronounced difference in ENSO-based predictability of winter precipitation over the southwestern US before and after 1977, coinciding with a major shift in the PDO. It was realized that, before 1977, negative winter precipitation anomalies were strongly tied to La Niña, but warm ENSO years did not lead to positive precipitation anomalies. After 1977, however, this asymmetry was reversed, and positive precipitation anomalies predictably followed El Niño years, but La Niña years yielded no precipitation predictability. Although a clear understanding of such PDO-based decadal modification requires further study, our findings in the present study may be applicable to this decadal modification. As described in Figure 3, a negative PDO tends to neutralize and promote El Niño and La Niña remote impacts, respectively. Therefore, during negative PDO decades (i.e., before 1977), La Niña can be a more effective predictor of the western US precipitation. Conversely, during positive PDO decades (i.e., after 1977), El Niño can be more influential in the prediction of the western US precipitation. This implies that collaborative impact from ENSO and the PDO is crucial for a better prediction of precipitation over the western US.

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