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Key Points:
- There is a slow (~10 year) precession of atmospheric pressures around the North Pacific
- This mode of atmospheric variability is termed the Pacific Decadal Precession (PDP)
- Many recent climate variations are consistent with the current phase of the PDP

Supporting Information:
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A decadal precession of atmospheric pressures over the North Pacific

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Abstract Sustained droughts over the Northwestern U.S. can alter water availability to the region's agricultural, hydroelectric, and ecosystem service sectors. Here we analyze decadal variations in precipitation across this region and reveal their relation to the slow (~10 year) progression of an atmospheric pressure pattern around the North Pacific, which we term the Pacific Decadal Precession (PDP). Observations corroborate that leading patterns of atmospheric pressure variability over the North Pacific evolve in a manner consistent with the PDP and manifest as different phases in its evolution. Further analysis of the data indicates that low-frequency fluctuations of the tropical Pacific Ocean state energize one phase of the PDP and possibly the other through coupling with the polar stratosphere. Evidence that many recent climate variations influencing the North Pacific/North American sector over the last few years are consistent with the current phase of the PDP confirms the need to enhance our predictive understanding of its behavior.

1. Introduction

Persistent, multiyear shifts in atmospheric pressure patterns over the North Pacific and their concomitant changes to regional climates impose significant stresses on physical, biological, and socioeconomic systems [*Mantua et al.*, 1997; *Pagano et al.*, 2004; *Schoennagel et al.*, 2005; *McCabe-Glynn et al.*, 2013]. Recent climate manifestations of such shifts include extended droughts across California [*Swain et al.*, 2014], exceptional warmth in the Gulf of Alaska [*Bond et al.*, 2015], and destabilization of marine ecosystems [*Kilduff et al.*, 2015]. However, it is unclear whether these manifestations represent a response to human-induced global warming, a natural deviation of the state of the atmosphere from its mean, or a combination of both [*Swain et al.*, 2014; *Funk et al.*, 2014; *Seager et al.*, 2015; *Baxter and Nigam*, 2015]. Here we use data from weather stations across the U.S., in combination with observations of the atmospheric state, to analyze one particular climate manifestation of multiyear shifts in atmospheric pressures over the North Pacific, namely, sustained drought conditions over the Northwestern U.S., with a specific focus on the precipitation deficiencies that facilitate these conditions. We chose this region because comparison of the observed precipitation variability with that induced by the inherently unpredictable behavior of typical meteorological events (i.e., noise) suggests a prominent decadal time scale signal to the variability (Figure 1; see also supporting information), which motivates our analysis. In the process, we uncover a mode of climate variability characterized by the decadal precession of an atmospheric pressure dipole around the North Pacific that explains these long-term droughts with potential links to other tropical Pacific and North Pacific climate variations.

2. Data

Observed station data are taken from the serially complete daily precipitation data compiled by the U.S. Historical Climate Network (USHCN) spanning 1 January 1900 through 31 December 2009 [*Williams et al.*, 2006]. The 774 stations analyzed here are the same as in *Gianotti et al.* [2014] and were selected based on the following criteria: (a) the data start from 1930 or earlier; (b) the data extend up to and include the end of 2009; and (c) the data have less than 5% missing values. For the current analysis, we also include the data from 2010 to 2014 for those stations in the Northwest U.S. region (as delineated in Figure 1). Monthly mean observed atmospheric fields—including near-surface temperatures, geopotential heights of standard pressure levels, and tropospheric and stratospheric air temperatures—are taken from both the NCEP/NCAR Reanalysis 1 (R-1) [*Kalnay et al.*, 1996] and the Twentieth Century Reanalysis V2 (20CRv2) [*Compo et al.*, 2011], which span the period 1948 to present and 1871–2012, respectively. Anomalous values at each grid

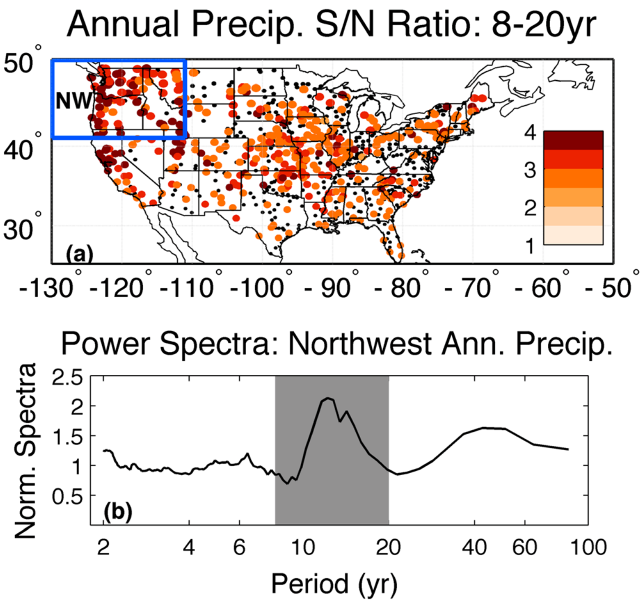

Figure 1. Decadal variability of annual precipitation accumulation over the Northwestern U.S. (a) Colored circles: Fraction of variance of observed station-based annual precipitation accumulation (mm/year) within the (8–20 year)$^{-1}$ frequency bin normalized by the stochastically generated variance within the same frequency bin as derived from the median of 1000 stochastically generated 80+ year records for that station (see supporting information). Black dots: Stations whose fraction of variance within the (8–20 year)$^{-1}$ frequency bin fails to meet the 90th percentile ($p < 0.10$) threshold value based upon the cumulative distribution of fraction of variance values returned by the 1000 stochastically generated, band-pass filtered records for that station (see supporting information). Blue rectangle represents Northwest (NW) area used for regional analysis. (b) Median fraction of annual precipitation accumulation variance across stations within the Northwest, plotted as a function of frequency. For presentation purposes, the fraction of variance is normalized by the median 90th percentile threshold value as determined from the stochastically generated variance estimates at the given frequency; values less than 1 indicate that the median variance within the given frequency bin does not exceed the $p < 0.10$ value. Gray shaded region represents the decadal timescale designated for further analysis.

point are derived by removing from the monthly values the long-term climatological mean for that month and then averaging over the respective seasons/years.

3. Results

To start we examine the conditions leading up to and following decadal-scale variations in annual mean precipitation in the Northwestern U.S., as represented by the leading mode of 7 year low-pass filtered annual precipitation variability over the region (Figure 1). We find that during periods of sustained drought over this region (Figures 2d–2g)—as well as across California and the Interior Plains—a broad expanse of higher-than-normal pressure is situated off the coast of western North America, a well-known pattern noted by others [*Dettinger et al.*, 1998] and termed the “ridiculously resilient ridge” in its latest incarnation [*Swain et al.*, 2014; *Swain*, 2015]. In turn, this ridge is part of a broader basin-scale pressure pattern that spans the mid-latitudes to high latitudes of the North Pacific, particularly at the onset of the drought period when an east-west pressure dipole is present (Figures 2d and 2e).

The evolution of this pressure dipole in turn displays a coherent spatial and temporal signature. In the years leading up to sustained drought conditions over the Northwestern U.S., the dipole has a pronounced north-south orientation with higher than normal pressures situated over the central subtropical Pacific and lower than normal pressures situated over Alaska (Figures 2a and 2b). As time evolves, the dipole rotates counterclockwise, assuming its east-west orientation during the drought period, then reassuming a north-south orientation of opposite sign in the years following the drought (Figures 2h and 2i), and eventually reverting to an east-west orientation of opposite sign concurrent with the onset of sustained pluvial conditions over the Northwestern U.S., California, and Interior Plains.

Importantly, the east-west and north-south orientations of the pressure dipole map onto two of the leading patterns of atmospheric pressure variability, here represented by low-frequency variations in lower tropospheric (i.e., 850 hPa) height fields over the North Pacific. The second leading mode of 850 hPa heights displays a distinct meridional dipole structure with centers of action over the Bering Sea and north of the Hawaiian Islands, while the third leading mode has a distinct zonal dipole structure with a primary center of action off Vancouver Island and a secondary center of action over the Aleutian Islands (supporting information (SI) Figure 3a). (The leading mode of 850 hPa heights is well known and represents variability in the Aleutian Low. Our study focuses on the importance of other low-frequency modes of variability in the 850 hPa height field.) Further, these two patterns have a joint power spectrum that contains a decadal signal similar to that found in Northwestern U.S. precipitation (SI Figure 3b). The physical evolution of these two leading patterns

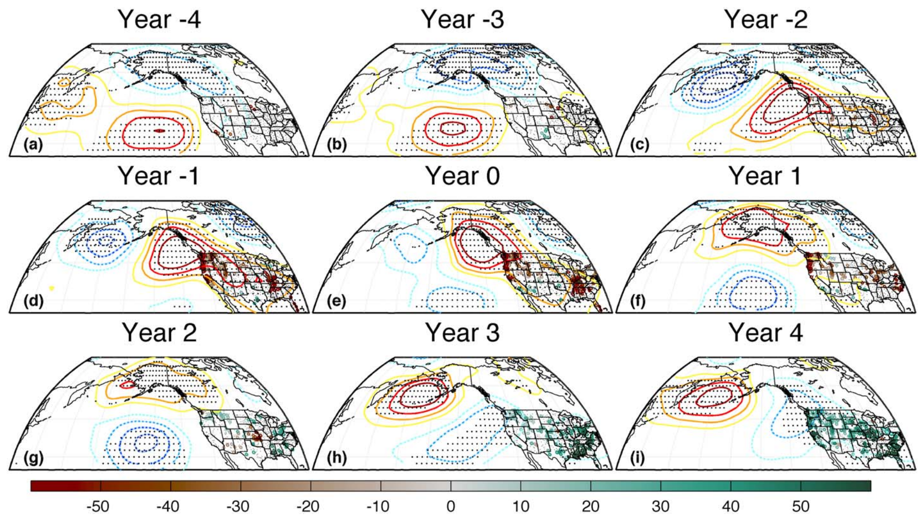

Figure 2. Precipitation and atmospheric pressure variations associated with decadal-scale variations in annual mean precipitation in the Northwestern U.S. Fields are shown separately in SI Figures 1 and 2. Colored circles: Lag regression of annual mean precipitation (mm) at the station locations onto the first empirical orthogonal function (EOF) time series of 7 year low-pass filtered annual precipitation variability over the Northwestern U.S. (see Figure 1 for location). Values shown by brown/green color bar at the bottom of the figure. Only stations where the regression coefficient meets or exceeds the $p < 0.10$ threshold based on 1000 stochastically generated records for that station are colored (see supporting information). Line contours: Lag regression of annual mean 850 hPa geopotential height anomalies (m) onto the first EOF time series of low-pass filtered annual precipitation variability over the Northwestern U.S. Warm (cool) colored-contours indicate positive (negative) geopotential height regression coefficients. Contour interval 1 m; zero contour is omitted. Stippling indicates regression coefficients exceeding the $p < 0.10$ significance level based on a two-tailed Student's *t* test. By construction, the first EOF time series of precipitation variability is keyed to concurrent (Year 0) drought conditions in the Northwestern U.S. Positive (negative) lags indicate that the field lags (leads) the leading mode of precipitation variability. Geopotential height fields are from the NCEP/NCAR Reanalysis 1.

of atmospheric pressure variability, as revealed in Figure 2, suggest that they may represent different phases of a single mode of variability, analogous to the leading patterns of (subseasonal) atmospheric variability over the tropical Indian and Pacific Oceans, which represent different phases of the Madden-Julian Oscillation (MJO) [*Zhang*, 2005]. Lead/lag correlations of the time series for these two patterns of atmospheric pressure variability, as well as their temporal evolution through phase space, confirm this phase relation (SI Figure 4).

As such, we follow the lead of MJO-based researchers and construct a single time series that captures the evolving nature of the pressure dipole revealed in Figure 2, with a focus on boreal winter conditions when the atmospheric variations are most apparent and the accompanying precipitation signal is largest relative to underlying noise [*Gianotti et al*., 2014]. Two methods of constructing such a time series are used in this study (see supporting information). Importantly, the resulting time series has the appropriate timing with drought and pluvial periods over the Northwestern U.S. (as well as elsewhere—cf. Figures 2 and 3). Further in its east-west orientation (Figures 3d and 3e), it is an apparent source for the well-known decadal land-surface temperature signature over Alaska [*Wiles et al*., 2014], while its transition to a north-south orientation coincides with a warming and cooling of waters over the eastern North Pacific that has been termed the "Blob" [*Bond et al*., 2015].

With regard to the evolution of the pressure variations themselves, the inherently noisier boreal winter pressure variations reduces the significance of the local anomaly values, particularly during transition years (e.g., Year −2 in Figure 3) and during years in which the pressure dipole overlays patterns of strong interannual variability (e.g., Year −3 and Year 3 in Figure 3, which align with the West Pacific Oscillation and concomitant shifts of the Pacific storm track [*Linkin and Nigam*, 2008]). Nevertheless, the time evolution from a north-south orientation (Years −4 and −3 in Figure 3) to east-west orientation (Years −1 and 0 in Figure 3) and back to north-south orientation (Years 2 and 3 in Figure 3) is evident and mirrors that derived independently from the pressure fields' relation with extended drought and pluvial periods over the Northwest. A Hovmöller diagram along an arc spanning the Northeast Pacific also captures the precessional behavior of the pressure variations as they propagate around the North Pacific (SI Figure 8). The precession of these pressure variations has been most prominent since 1970—in agreement with the concurrent enhancement of the dipole's

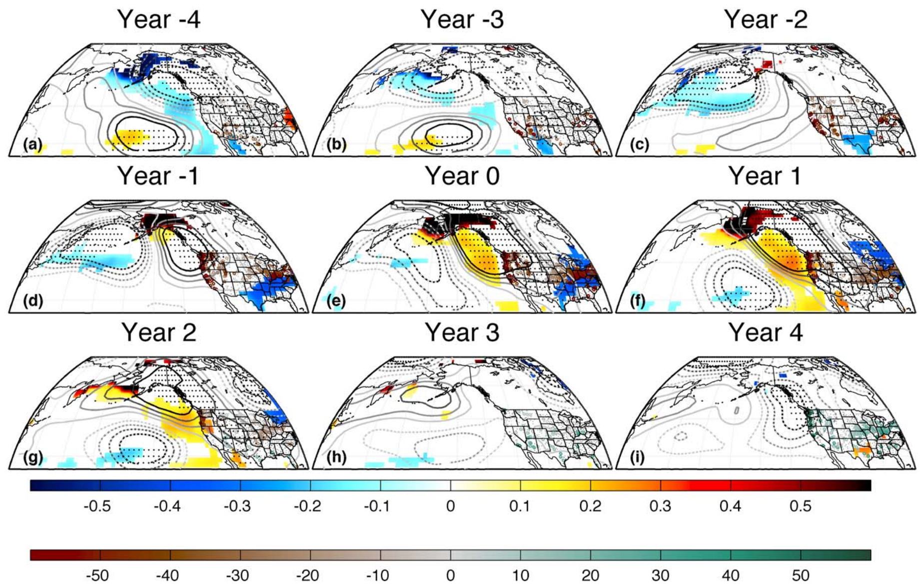

Figure 3. The evolution of climate variations associated with the Pacific Decadal Precession (PDP). Fields are shown separately in SI Figures 5–7. Colored circles: Lag regression of November–March precipitation anomalies (mm) onto the Pacific Decadal Precession (PDP) index. Values shown by brown/green color bar at the bottom of the figure. Only stations with regressions that meet or exceed the $p < 0.10$ threshold based on 1000 stochastically generated records for that station are colored (see supporting information). Line contours: Lag regression of November–March 850 hPa geopotential height anomalies (m) onto the PDP index. Solid (dashed) contours indicate positive (negative) regression coefficients. Contour interval 1 m; the zero contour is omitted. Stippling indicates regression coefficients exceeding the $p < 0.10$ significance level based on a two-tailed Student's *t* test. Shaded contours: Lag regression of November–March near-surface temperature anomalies (K) onto the PDP index. Values designated by red/blue color bar at the bottom of the figure. Only regression values exceeding the $p < 0.10$ significance level based on a two-tailed Student's *t* test are shown. Positive (negative) lags indicate that the field lags (leads) the PDP index. Data sources as in Figure 2.

power in the (8–20 year)$^{-1}$ band (SI Figure 9)—during which time there were two main events that circumnavigated the North Pacific, one spanning ~1970 to the late-1980s and a second spanning ~1990 to the present. Further, as revealed by the Hovmöller diagram the periodicity of these events, their initiation point, and their magnitude can differ over time.

Finally, we find that this mode of variability not only has expressions at the surface and in the lower troposphere but also in the upper troposphere extending into the stratosphere (SI Figure 10). During its north-south orientation, there is a thermodynamically consistent north-south pattern in the midtroposphere temperature structure (SI Figures 10a and 10b) along with a broad expanse of stratospheric temperature deviations centered over the Bering Strait (SI Figures 10e and 10f). During the following years, these stratospheric deviations persist and spread across the Arctic to the North Atlantic (SI Figures 10g and 10h). In the process a warm stratosphere/cold troposphere pattern develops over western North America (SI Figures 10d and 10h), which in turn is consistent with the east-west phase of the pressure dipole (cf. Figure 3d).

Overall, our multiple analyses indicate that this atmospheric pressure dipole and its time evolution is a robust mode of low-frequency atmospheric variability. Because of its location, dominant quasi-decadal frequency, and sense of progression, we term it the Pacific Decadal Precession (PDP). Importantly, these three characteristics also differentiate it from the longer-lived, quasi-stationary standing-wave like structure of variability in the Aleutian Low that accompanies the Pacific Decadal Oscillation [*Mantua et al.*, 1997].

4. Discussion

Having identified and characterized the spatial and temporal signatures of the PDP, we now ask from whence it originates. Here we propose a set of plausible hypotheses, recognizing that as with the initial identification of the MJO (circa early 1970s [*Madden and Julian*, 1971]), substantial research by the community will be required to fully elucidate the underlying physical mechanisms. To start, we analyze the PDP's relation to low-frequency

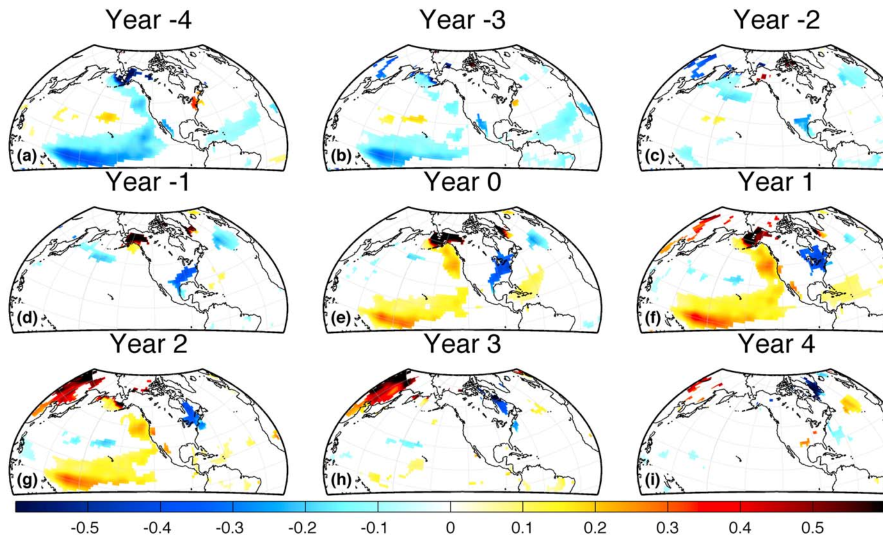

Figure 4. The evolution of Northern Hemisphere near-surface temperature variations associated with the Pacific Decadal Precession (PDP). Shading: Lag regression of November–March near-surface temperature anomalies (K) onto the PDP index. Values designated by red/blue color bar at the bottom of the figure. Only regression values that exceed the 90% significance level, based upon a two-tailed *t* test, are shown. Positive (negative) lags indicate that the field lags (leads) the PDP index. Data sources as in Figure 2.

fluctuations of the tropical Pacific Ocean state, which has been proposed as a driver of global-scale variations in atmospheric circulations that resemble those seen here [*Hartmann*, 2015]. Indeed, the north-south phase of the PDP—which maps onto the atmospheric pressure variations associated with the North Pacific Oscillation (NPO) [*Walker and Bliss*, 1932]—occurs concurrently with significant warming and cooling of the western and central tropical Pacific (cf. Years −4 and −3 and Years 1 and 2 in Figures 3 and 4), as has been shown previously [*Di Lorenzo et al.*, 2010; *Furtado et al.*, 2012]. As the warming and cooling in this region subsides (Years −2 and −1 in Figure 4) the PDP shifts into its east-west phase and maintains its magnitude (Years −2 and −1 in Figure 3) despite the lack of robust ocean state changes in the tropics. It then shifts back to its north-south phase as the low-frequency fluctuations of the tropical Pacific reemerge (cf. Years 0 and 1 in Figures 3 and 4). These results suggest that the PDP may in part be related to forcing by low-frequency fluctuations of the tropical Pacific Ocean; however, these do not explain the maintenance of the PDP through its full evolution.

While not investigated here, it is possible that the stratospheric temperature deviations—which are consistent with the slowly evolving tropical Pacific temperature deviations [*Iza and Calvo*, 2015] and which persist even after the tropical Pacific deviations subside—induce the east-west phase of the PDP through their influence on the underlying tropospheric circulations [e.g., *Baldwin and Dunkerton*, 1999]. Alternatively, solar variability could also be an important driver of the high latitude decadal-scale stratospheric temperature variations [*Gray et al.*, 2010]; however, such variability is out of phase with the PDP (SI Figure 11). Other potential mechanisms for inducing the slow evolution of the PDP include local oceanic forcing—either associated with the western boundary current structure [*McCabe-Glynn et al.*, 2013] or the extensive variations in the central and eastern North Pacific affiliated with the "Blob" [*Bond et al.*, 2015]—or extratropical atmospheric forcing [*Baxter and Nigam*, 2015] associated with the interaction of the mean state circulation with transient disturbances [*Baldwin et al.*, 2007]. Further, it remains to be determined whether the PDP circulations themselves are instrumental in establishing the quasi-decadal period of the PDP, for instance, by sustaining the temperature variations in the western and central tropical Pacific through the influence of the north-south phase on the North Pacific Meridional Mode [*Di Lorenzo et al.*, 2015]. Alternatively, the PDP may simply be a response to decadal-scale fluctuations of the tropical Pacific, which in turn may be determined by the frequency characteristics of the Pacific basin [*Solomon et al.*, 2008].

5. Summary

Here we analyze shifts in atmospheric pressure patterns over the North Pacific leading up to and following persistent, multiyear droughts and pluvials over the Northwestern US. In doing so, we reveal a mode of atmospheric variability—termed the Pacific Decadal Precession (PDP)—that spans the tropical and extratropical

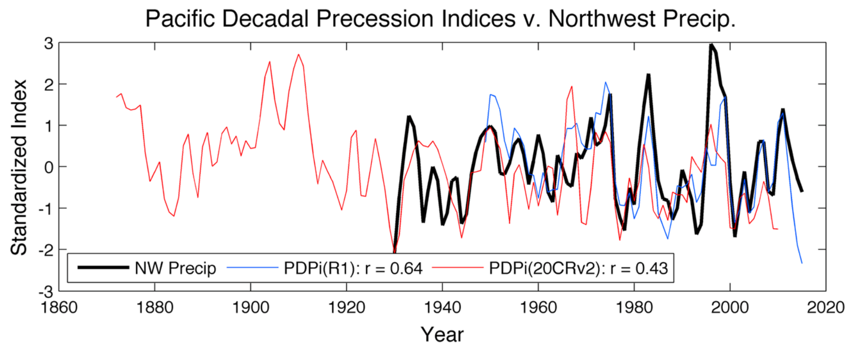

Figure 5. Time evolution of the Pacific Decadal Precession over the last 140 years. The PDP index from the NCEP/NCAR Reanalysis 1 (1948–2015—blue) and the NOAA Twentieth Century Reanalysis V2 (1871–2012—red) plotted along with the first empirical orthogonal function (EOF) time series of 7 year low-pass filtered annual precipitation variability over the Northwestern U.S. (see Figure 1 for location; 1930–2015—black). The PDP indices are inverted to represent the influence of the positive (negative) phase of the PDP on sustained drought (pluvial) conditions over the Northwestern U.S. Correlation of Northwest annual precipitation with the PDP in NCEP/NCAR R1 (r = 0.64) and the Twentieth Century Reanalysis V2 (r = 0.43) for the periods of overlap also included.

North Pacific and has signatures that extend from the ocean's surface through to the stratosphere. Its evolution consists of a slow (~10 year) progression of atmospheric pressure variations around the North Pacific basin, which produces accompanying changes to regional climates across the region. Emergence of warming and cooling of the western and central tropical Pacific on these timescales appears to energize one phase of the PDP, characterized by a north-south pressure dipole over the North Pacific reminiscent of the NPO. During the other phase of the PDP, characterized by an east-west pressure dipole over the North Pacific, no clear signatures are found in any of the tropical ocean basins, suggesting a separate mechanism may be maintaining the atmospheric pressure variations during this phase. Possible candidates include extratropical oceanic boundary forcings, the downward influence of PDP-induced anomalous stratospheric circulations on the troposphere, and/or transient eddy activity and its reinforcement of mean circulation anomalies.

Nevertheless, recognition of the underlying presence of the PDP and its evolution better contextualizes many of the recent climate variations that have influenced much of the North Pacific/North American sector over the last few years, including the ongoing, multiyear drought in California, the abnormally warm wintertime temperatures across the western U.S. and Alaska juxtaposed with the abnormally cold temperatures across much of eastern North America, and the formation and persistence of the "Blob" in the North Pacific (SI Figure 12). Indeed, an extended reconstruction of the PDP suggests that the winters of 2013–2015 represent a particularly large deviation of the PDP (Figure 5) equivalent to, e.g., the 1930s during which time much of the Northwestern U.S. experienced severe sustained droughts [*Knapp et al.*, 2004]. However, despite this recent deviation of the PDP, precipitation in the Northwest U.S. has remained near normal, suggesting that while the PDP is a substantial contributor to low-frequency variance in this region's precipitation (16–40%, depending on the dataset; Figure 5), it is not the only contributor to such variance. Thus, distinguishing the mechanisms underpinning the PDP's relation to precipitation in this region—both in isolation and conjunction with other drivers of variability [e.g., *Seager et al.*, 2005]—is still required to understand its influence (or lack thereof) during particular years.

Nevertheless, given the apparent relation of many recent climate variations to quasi-decadal-scale fluctuations in the PDP, our findings carry important implications for how such disturbances may evolve over the coming years, particularly if the PDP reverts to form and induces the onset of extended pluvial conditions in the coming years. Further, given the potential of these climate variations to impact various physical, biological, and socioeconomic systems, we argue that enhanced predictive understanding of the PDP's behavior leading to improved forecasts of its subsequent evolution could potentially benefit a wide range of scientific, practitioner, and user communities.

Acknowledgments
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