AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061992

Key Points:
- Large uncertainty is found among real-time PDO indices
- SST data and EOF vector are important sources of uncertainty in PDO indices
- Systematic difference between ERSST 3b and HadISST is identified

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Citation:
Wen, C., A. Kumar, and Y. Xue (2014), Factors contributing to uncertainty in Pacific Decadal Oscillation index, *Geophys. Res. Lett.*, *41*, 7980–7986, doi:10.1002/2014GL061992.

Received 24 SEP 2014
Accepted 3 NOV 2014
Accepted article online 7 NOV 2014
Published online 28 NOV 2014

Factors contributing to uncertainty in Pacific Decadal Oscillation index

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Abstract Pacific Decadal Oscillation (PDO) index is an important indicator of climate variability. However, large discrepancies are found among real-time PDO monitoring indices maintained by several operational centers, with larger uncertainty exhibiting prior to 1950s and after late 1990s on seasonal to decadal time scales. Two historical sea surface temperature (SST) data sets are used to investigate causes for the uncertainty: the Extended Reconstructed Sea Surface Temperature version 3b (ERSST 3b) and the Hadley Center Sea Ice and SST data set (HadISST) version 1. It is found that choices of spatial structure of Empirical Orthogonal Function (EOF) vector and SST data set are important sources of uncertainty on seasonal to decadal time scales, while choice of climatological base period only contributes to uncertainty on seasonal time scale. Decadal variation of differences in PDO indices from ERSST and HadISST is associated with systematic differences between the two data sets in the central and the north-eastern Pacific.

1. Introduction

The Pacific Decadal Oscillation (PDO) index is a well-known climate index that captures sea surface temperature (SST) variations in North Pacific, which is characterized by a horseshoe pattern with one sign in the central North Pacific surrounded by anomalies of opposite sign. The PDO correlates well with many other historical records of North Pacific and North American climate and ecological variability on seasonal to decadal time scales, including productivity of marine ecosystems, precipitation, stream flow, etc. [*Mantua et al.*, 1997; *Ting and Wang*, 1997; *Neal et al.*, 2002; *Hu and Huang*, 2009]. Thus, the PDO is regarded as an important oceanic climate indicator in agriculture, fishery and water resource management.

Several operational centers provide real-time PDO monitoring indices for users. However, little attention is drawn to the uncertainty in PDO indices provided by different centers. Figure 1 shows winter PDO indices (November–March) since 1901 from four centers. Visually, large discrepancies are found before 1950s and in the last decade. At times, phases of PDO are uncertain. For example, in winter 2013–2014, the PDO index from Joint Institute for the Study of the Atmosphere and Ocean (JISAO) indicated that the PDO transited to a positive phase, while PDO indices from other three centers remained in a negative phase. Since phases of winter season PDO index are an important climate indicator, such large differences create confusion about the observed phase of the PDO, and inferences about its societal and climatic consequences.

Uncertainty associated with the real-time monitoring PDO monitoring indices has not been discussed in the literature. Traditionally, the PDO index is defined as the projection of North Pacific monthly SST anomalies (poleward of 20°N) onto their first empirical orthogonal function (EOF) pattern for the 1900–1993 period [*Mantua et al.*, 1997]. Global monthly mean SST anomalies are also removed in order to eliminate the effects of upward trends in SSTs [*Zhang et al.*, 1997]. However, procedures used to derived PDO index are different among operational centers. Table 1 summarizes methods and data sets used at four operational centers.

Three differences could contribute to uncertainties in PDO shown in Figure 1. The first is related to differences in climatology base period that is used to define SST anomalies. JISAO and National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) use 1900–1993 period to define climatology, while NOAA National Climatic Data Center (NCDC) and Japan Meteorological Agency (JMA) use the 1971–2000 and 1901–2000 periods, respectively. Since SSTs exhibit interdedadal variations [*Xue et al.*, 2003], SST anomalies with reference to different base periods might be quite different. The second possibility is related to choice of the EOF pattern onto which SST anomalies are projected to obtain in PDO index. As shown in Table 1, EOF vector is different among the four centers. A third possibility is related to SST data sources. JISAO uses three SST data sets to construct historical PDO index: U.K.

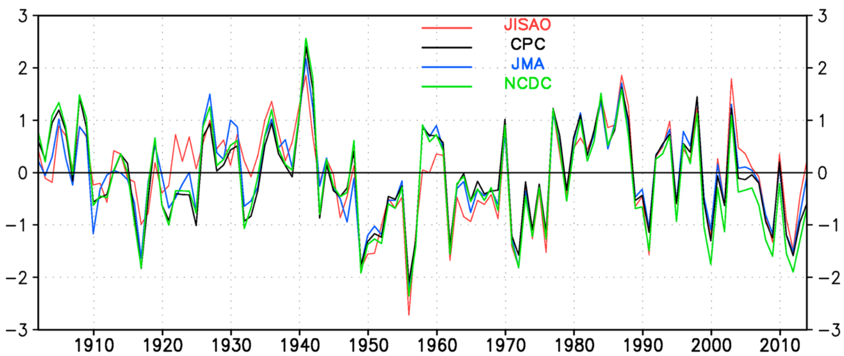

Figure 1. Time series of Climate Prediction Center (CPC) (black line), Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (red line), Japan Meteorological Agency (JMA) (blue line), and National Climatic Data Center (NCDC) Pacific Decadal Oscillation (PDO) indices (green line) from 1901 to 2014. Values are averaged over the months through November through March.

Meteorological Office Historical SST Data Set [*Folland and Parker*, 1990, 1995] from 1900 to 1981, Optimum Interpolation Sea Surface Temperature version 1 (OISST v1 [*Reynolds et al*., 2007]) for 1982–2001 and OISST v2 after 2002. Both NCDC and CPC use the NOAA Extended Reconstructed SST version 3b (ERSST 3b; [*Smith et al*., 2008]), and JMA uses the Centennial in situ Observation-based Estimate of SSTs (CORE-SST; [*Ishii et al*., 2005]). It is known that significant differences exist among different SST analyses resulting from differences in observational data sources, choice of methods, and bias adjustments that are used in SST analyses [*Yasunaka and Hanawa*, 2011; *Huang et al*., 2013; *Kennedy*, 2014]. Uncertainties in SST products therefore could also contribute to discrepancies in PDO indices.

This study examines the relative importance of three factors contributing to uncertainties in PDO index. In this analysis our goal is not to argue which PDO index shown in Figure 1 is more correct. Instead, we aim to highlight possible causes for the uncertainty in PDO indices available from various centers. We choose two historical gridded SST data sets which are widely used in the community to demonstrate uncertainty due to SST data sets. Details of the two SST sets and methods are described in section 2. The results of comparisons are presented in section 3.

2. Data and Methods

Two monthly averaged SST data sets with coverage in north Pacific are used to investigate sources of uncertainty in the PDO index. ERSST 3vb includes in situ data only (ships and buoys). It is available since 1854 on a 2° × 2° horizontal grid. The gridded 1° × 1° Met Office Hadley Center Sea Ice and SST data set

Table 1. Summary of Methods and Data Sets Used to Derived Pacific Decadal Oscillation (PDO) Index in Operational Centers

Institutes	Cover Periods	Data Sources	Climatology Base Period	Projected Empirical Orthogonal Function (EOF) Vector
Joint Institute for the Study of the Atmosphere and Ocean (JISAO)	1900–present	UKMO historical sea surface temperature (SST) set for 1900–1981; Optimum Interpolation Sea Surface Temperature version 1 (OISST V1) for 1982–2001; OISST V2 since 2002	UKMO Historical SST set from 1900 to 1993	First EOF of UKMO Historical SST from 1900 to 1993
Climate Prediction Center (CPC)	1854–present	Extended Reconstructed Sea Surface Temperature version 3b (ERSST v3b)	ERSST v3b from 1900 to 1993	First EOF of ERSST v3b from 1900 to 1993
National Climatic Data Center (NCDC)	1854–present	ERSST v3b	ERSST v3b from 1971 to 2000	Regression of ERSST anomalies against the JISAO PDO index from 1900 to 2001
Japan Meteorological Agency (JMA)	1901–present	Centennial in situ Observation-based Estimate of sea surface temperature (CORE-SST)	COBE SST 1901–2000	First EOF of COBE SST from 1901 to 2000

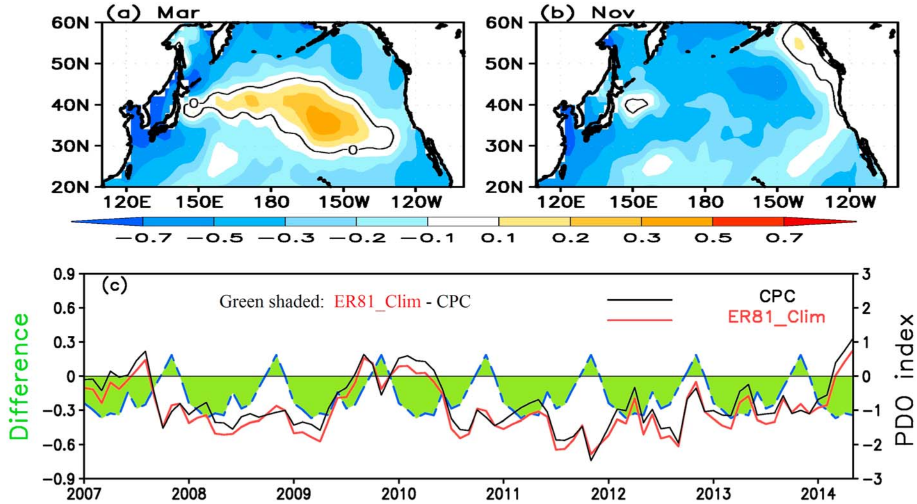

Figure 2. Sea surface temperature (SST) climatology difference (1900–1993 minus 1981–2010) in (a) March and (b) November of Extended Reconstructed Sea Surface Temperature version 3b (ERSST v3b). (c) Time series of CPC PDO and ER81_Clim PDO indices, and their difference (shaded, left axis). Blue dashed line in Figure 2c shows projection of climatology difference (1981–2010 minus 1900–1993) on the same first Empirical Orthogonal Function (EOF) vector as the CPC PDO.

(HadISST1; *Rayner et al.* [2003]) includes both in situ and satellite data, and is available since 1870 to present. Readers are referred to *Yasunaka and Hanawa* [2011] for more details about differences in these two data sets.

We first define a reference PDO index. Similar to that of *Mantua et al.* [1997], we compute SST anomalies from ERSST.v3b relative to the base period 1900–1993 and then apply a weighting by a square root of cosine of the corresponding latitude to each grid point. After removing the global mean temperature anomalies at each grid point, we calculate the leading EOF of North Pacific (20°N–60°N) SST anomalies. The PDO index is then computed over the entire data record by projecting the SST anomalies onto the leading EOF pattern. The procedure is identical to that used at the NOAA CPC. For brevity, we will refer this PDO index as CPC PDO.

Different choices of climatology, EOF pattern, SST data sets, or a combination of these might give rise to uncertainties in PDO indices. To examine the relative influences of each separately, we first compare differences in PDO indices due to choice of climatology and EOF pattern using one single data set. For this purpose, two new PDO indices are constructed. One is derived by projecting ERSSTv3b SST anomalies with respect to the 1981–2010 base period climatology onto the same EOF pattern as the CPC PDO (hereafter, this PDO index is named ER81_Clim). The 1981–2010 base period is chosen because it is used by most operational centers to define anomalies for real-time climate monitoring and predictions. Comparing this PDO with the CPC PDO will show influences of climatology base period on the uncertainty of PDO index. The other PDO index is derived by projecting SST anomalies relative to the 1900–1993 climatology onto its own first EOF pattern calculated in the 1981–2010 period (hereafter, this PDO index is named ER81_EOF). Contrasting this PDO with the CPC PDO will show influences of EOF pattern on the uncertainty of PDO index. Hereafter, the former and the latter cases are named case A and case B, respectively. Finally, we compare PDO index derived from ERSST and HadISST data sets. Before constructing the PDO index, HadISST is interpolated onto the same 2×2 grid as that of ERSST.

3. Results

We first examine the impact of climatology base period (case A). Difference in climatology between the 1900–1993 and 1981–2010 periods have spatial and seasonal variations (Figures 2a and b). Compared with the 1981–2010 base period, SST climatology during the 1900–1993 base period is generally cooler in high-latitude North Pacific and along the western boundary of North Pacific. There are also seasonal variations: the central Pacific is warmer in March and cooler in November.

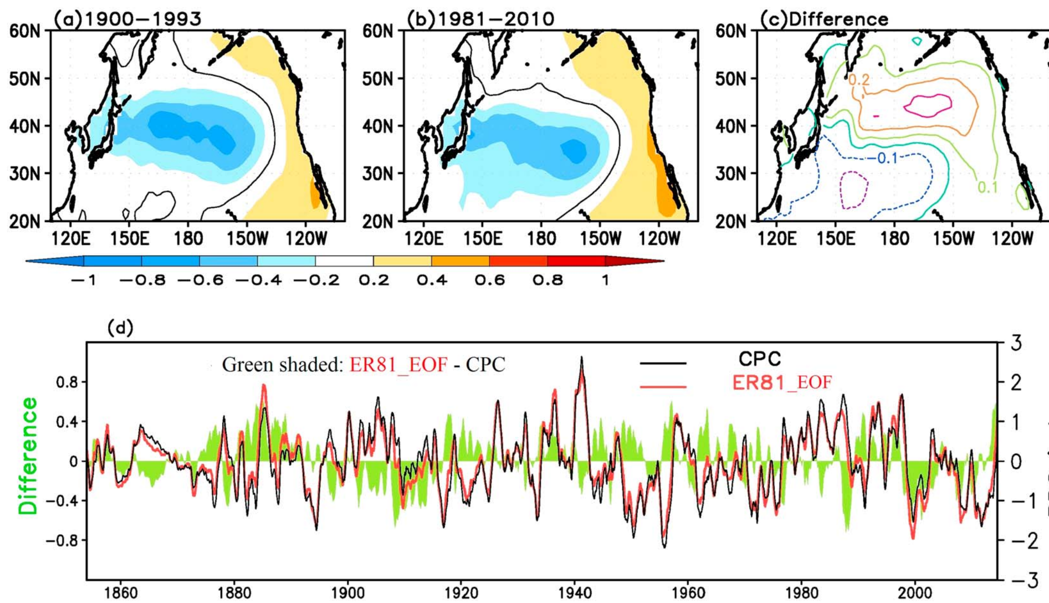

Figure 3. Spatial patterns of first EOF of SST anomaly over (a) 1900–1993, (b) 1981–2010 periods, and (c) their difference. (d) Time series of CPC PDO and ER81_EOF PDO indices and their difference (shaded, left axis). Time series have been smoothed with a 9 month running mean filter.

The projections of climatology difference onto the same first EOF as the CPC PDO index display a negative peak (−0.3) during spring and a positive peak (0.2) in November (Figure 2c, blue dashed line). The difference between the ER81_clim PDO index (Figure 2c, green shading) displays a systematic seasonal variation, which is identical to the differences in the EOF projections of two climatologies. This suggests that the choice for climatological base period can give rise to substantial difference in PDO indices on seasonal time scale. To compare PDO index of individual SST data sets, it is therefore better to define SST anomalies using the same base period or to make climatology adjustment to bring to the same base period. It is noteworthy that choice of climatology only gives rise to a constant seasonal difference. Thus, it plays a minor role in determining decadal variation of uncertainty shown in Figure 1.

The computation of EOF vector is also dependent on the coverage period and the region [*Hannachi et al*., 2007]. We next examine the influence of EOF pattern calculated for different periods but with the same climatology (case B). Figures 3a and 3b show the spatial patterns of first EOF over 1900–1993 and 1981–2010 periods, respectively. Relative to the 1900–1993 period, the negative anomaly center of the first EOF is shifted southward in 1981–2010 (Figure 3c), resembling the second EOF of North Pacific SST, often referred to as North Pacific Gyre Oscillation (NPGO) [*Di Lorenzo et al*., 2008]. This is consistent with the fact that NPGO variance increased in recent decades [*Di Lorenzo et al*., 2008]. Owing to the non-stationary pattern in the leading modes of climate variability, difference between the CPC PDO and ER81_EOF PDO indices exhibits variations on seasonal to decadal time scales (Figure 3d). It suggests that uncertainty in PDO indices can be at least partially attributed to choice of first EOF pattern. Comparison is also performed using the SST anomalies calculated relative to the respective climatology. The results remained unchanged (not shown).

Last, we examine the impact of SST data sets on the uncertainty in PDO. In order to exclude the impact of climatology and EOF pattern, HadISST PDO index is constructed as projection of SST anomalies onto the same EOF as that for the CPC PDO index. The HadISST SST anomalies are departures from the HadISST climatology for the 1900–1993 period.

The CPC PDO and HadISST PDO show similar interannual and decadal variations (Figure 4a). However, systematic differences are also found between the two indices. The CPC PDO and HadISST PDO indices show larger difference prior to 1950s and then agree well with each other during 1960–late 1990s. However, the CPC PDO index is consistently lower than the HadISST PDO index after late 1990s (Figure 4b). Consistent with temporal variations in the difference, the correlation coefficient over running a 30 year window is near 0.6 before 1920 and increases gradually to above 0.9 after 1950s (Figure 4c). The decadal variation in

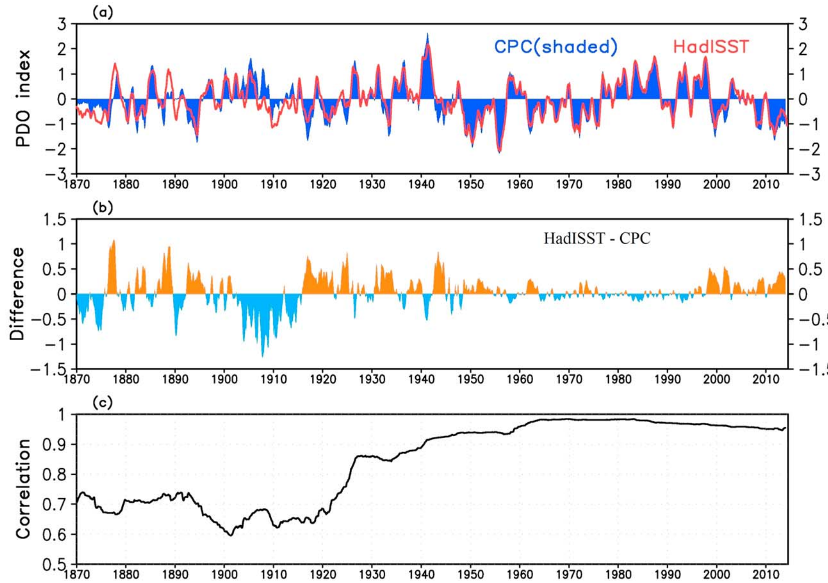

Figure 4. Time series of (a) CPC PDO and HadISST PDO indices and (b) difference. Time series have been smoothed with a 9 month running mean filter. (c) Thirty-year sliding window correlation between CPC and HadISST PDO indices.

difference between the CPC PDO and HadISST PDO is consistent with temporal discrepancies shown in Figure 1. It suggests that difference in SST data set is another important factor causing uncertainty in the PDO index.

The systematic difference between the CPC PDO and HadISST PDO indicates that there is a systematic difference between the ERSST v3b and HadISST data sets. In order to identify key locations where differences in SST products contribute to differences in PDO indices, SST anomaly difference between the HadISST and ERSST data sets is regressed onto the CPC PDO index for 1999–2013 and 1890–1920 periods corresponding to epochs with larger PDO differences shown in Figure 4b. Figures 5a and 5b display the regression patterns for the two periods. After the late 1990s, regions with large discrepancy between

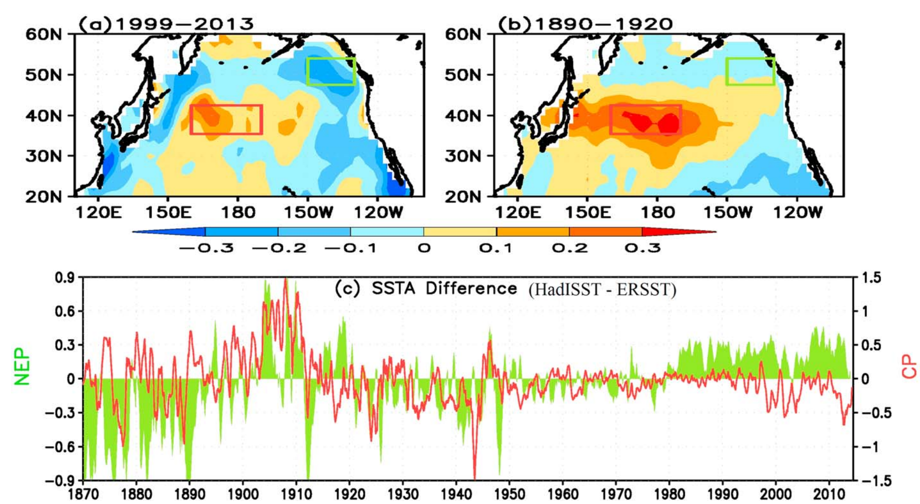

Figure 5. Regression of SST anomaly difference (HadISST minus ERSST) on CPC PDO over (a) 1999–2013 and (b) 1890–1920 periods. (c) Monthly differences of SST anomaly averaged over central Pacific (CP, red line, right axis) and over north-western Pacific (NEP, shaded, left axis). Red and green boxes shown in Figures 5a and 5b denote the CP and NEP regions, respectively. In Figure 5c, a 9 month running filter is applied.

the two data sets are found in the central Pacific and near the coast lines. During 1890–1920, areas with notable SST difference are located in the central Pacific near 40°N.

To further illustrate time variations between the two data sets, raw SST anomaly difference are averaged over the central Pacific (red box in Figure 5) and the north-eastern Pacific (green box in Figure 5). Large difference between the ERSST and HadISST is found over both regions before 1950s (Figure 5c), owing to the limited observational data [*Yasunaka and Hanawa*, 2011]. Over the north-eastern Pacific, HadISST is systematically warmer than ERSST since the satellite period (1981 onward). The systematic difference might result from the bias adjustment of Advanced Very High Resolution Radiometer SST in HadISST [*Rayner et al*., 2003] and different bucket bias corrections used in these two data sets [*Yasunaka and Hanawa*, 2011]. Over the central Pacific, HadISST is systematically colder than ERSST since the late 1990s, and as noted by [*Yasunaka and Hanawa*, 2011] might stem from the preliminary quality control of the Global Telecommunications System reports used in the two data since late 1990s. The results suggest that decadal variation of differences in PDO indices from ERSST and HadISST (Figure 4b) is associated with systematic differences between the two data sets in the central Pacific and the north-eastern Pacific because these regions are located at the maximum centers of first EOF vector on which SST anomalies are projected.

4. Conclusions

PDO is regarded as an important oceanic climate indicator in agriculture, fishery, and water source management. It is currently monitored in real time by various operational centers. However, at times, large discrepancies are found among those PDO indices from different centers giving rise to an uncertainty in the assessment of the current state of the PDO. Such large differences create confusion about the observed phase of the PDO, and inferences about its societal and climatic consequences. In this analysis we attempted to understand sources that may contribute to the uncertainty.

Unlike other area-averaged SST indices such as NINO SST indices, PDO is defined as a projection of SST anomalies onto the leading mode of SST variability in North Pacific that is generally inferred via EOF analysis. As part of the procedure, there are several factors that could contribute to the uncertainty in the PDO index. In this study we examined sources of uncertainty resulting from the choice of climatology, definition of EOF vectors on which SST anomalies are projected, and the choice of SST data sets. It is found that the choice of climatological base period is an important source of discrepancy in PDO indices on monthly to seasonal time scale, while choices of first EOF vector patterns and SST data set are important sources of uncertainty on seasonal to decadal time scales.

Decadal variation of differences in PDO indices from ERSST and HadISST is associated with systematic differences between the two data sets in the central and north-eastern Pacific: HadISST is persistently colder than the ERSST since the late 1990s in the central Pacific by 0.5°C between 30°N and 40°N; HadISST is persistently warmer than ERSST since 1981 in the north-eastern Pacific. Both regions display larger discrepancy prior to 1950s owing to limited in situ observations. Because these regions are located at the centers of first EOF vector on which SST anomalies are projected, SST differences in those regions contribute to large differences in PDO indices.

To our knowledge, uncertainty in real-time PDO monitoring indices has not been discussed in the literature. It is important for users to understand uncertainty in real-time PDO monitoring and forecasting related with PDO index on different time scales. To compare PDO indices from different data sets, it is better to use the same climatology base period and the same EOF vector. We also recommend that assessment of the state of the PDO be based on longer time averages to remove high-frequency variations that amplify uncertainties. To infer the current state of the PDO, another possibility may be to develop a PDO index that is based on temperature variations averaged over a depth of the ocean, e.g., a PDO index based on heat content over the upper 300 m [*Xue et al*., 2012].

Acknowledgments
We would like to thank Dr. Nathan J. Mantua, Dr. Boyin Huang, and Dr. Thomas M. Smith for helpful comments on the initial version of the manuscript. The JISAO PDO index was downloaded from http://jisao.washington.edu/pdo/PDO.latest. JMA PDO index was downloaded from http://www.data.jma.go.jp/gmd/kaiyou/data/db/climate/pdo/pdo.txt. NCDC PDO index was downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/cmb/ersst/v3b/pdo.pdo.dat.

Lisa Beal thanks Sayaka Yasunaka and Nathan Mantua for their assistance in evaluating this manuscript.

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