Orthogonal PDO and ENSO Indices

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ABSTRACT

A framework for interpreting the Pacific decadal oscillation (PDO) and ENSO indices is presented. The two leading principal components (PCs) of sea surface temperature [SST; strictly speaking, the departure from globally averaged SST (SST*)] over the entire Pacific basin comprise a two-dimensional phase space. A linear combination of these pan-Pacific PCs corresponding to a $+45^\circ$ rotation (designated by P) is nearly identical to the PDO, the leading PC of Pacific SST* poleward of 20°N . Both P and the PDO index exhibit apparent “regime shifts” on the interdecadal time scale. The orthogonal axis (rotated by -45° and designated by T') is highly correlated with conventional ENSO indices, but its spatial regression pattern is more equatorially focused. SST variability along these two rotated axes exhibits sharply contrasting power spectra, the former (i.e., P) suggestive of “red noise” on time scales longer than a decade and the latter (i.e., T') exhibiting a prominent spectral peak around 3–5 years. Hence, orthogonal indices representative of the ENSO cycle and ENSO-like decadal variability can be generated without resorting to filtering in the time domain. The methodology used here is the same as that used by Takahashi et al. to quantify the diversity of equatorial SST patterns in ENSO; they rotated the two leading EOFs of tropical Pacific SST, whereas the two leading EOFs of pan-Pacific SST* are rotated here.

1. Introduction

The structure of ENSO-like variability in the sea surface temperature (SST) field is frequency dependent (Zhang et al. 1997, hereafter ZWB; Chen and Wallace 2015, hereafter CW). On the interannual time scale the anomalies are narrowly focused in the equatorial Pacific, whereas on the interdecadal time scale the band of equatorial SST anomalies widens toward the east and extends poleward along the coast of the Americas,

with anomalies of opposing sign over temperate latitudes farther to the west. The extratropical signature in the interdecadal variability exhibits a high degree of equatorial symmetry (ZWB; Garreaud and Battisti 1999), but it is more pronounced in the Northern Hemisphere.

As an index of the ENSO-like variability on the interdecadal time scale, Mantua et al. (1997) defined the Pacific decadal oscillation (PDO), the leading principal component (PC) of the monthly mean SST departure from the globally averaged SST (SST*) field over the Pacific sector in the domain poleward of 20°N . The PDO has been widely used in studies of El Niño impacts, often in combination with ENSO indices based on SST anomalies in the equatorial Pacific cold tongue region (Miles et al. 2000; Papineau 2001; Hidalgo and Dracup 2003; Hamlet et al. 2005; Chan and Zhou 2005; Schoennagel et al. 2005; Pavia et al. 2006; Roy 2006; Yu et al. 2007). Though it is based entirely upon the extratropical Northern Hemisphere SST field, the PDO index has proven to be a useful indicator of ENSO-like interdecadal variability throughout the Pacific basin. That the spatial SST signature of the PDO strongly resembles

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that of the 12-yr low-pass-filtered leading principal component (PC1) of global or pan-Pacific SST (Deser et al. 2012; CW, their Fig. 13) raises the question of whether it is useful to treat ENSO and the PDO as separate entities in studies of interdecadal variability. A related question is whether PDO variability on the interannual time scale is an oxymoron or whether it could be of use in real-time diagnosis and prediction of ENSO. These practical questions are rooted in the deeper question, does the PDO exist independently of the ENSO cycle?

In the recent review of Newman et al. (2016), the PDO is envisioned as representing not a single phenomenon but rather a combination of processes through which the “ENSO cycle” on the interannual time scale interacts with extratropical variability to produce a “red noise” spectrum of ENSO-like variability. In the ENSO cycle the SST anomalies are the surface signature of transient, wind-driven, equatorial oceanic planetary waves. The planetary-scale atmospheric response to the equatorial SST anomalies extends into the extratropics, where it forces a distinctive pattern of SST anomalies by modulating the fluxes of sensible heat, moisture, and radiative fluxes at the air–sea interface. The extratropical response to the ENSO cycle is reddened and rendered “PDO like” by the “thermal inertia” of the oceanic mixed layer as in the stochastic model of Frankignoul and Hasselmann (1977), and conversely, extratropical variability can influence the ENSO cycle [e.g., through the seasonal footprinting mechanism proposed by Vimont et al. (2001, 2002, 2003)]. Extratropical oceanic Rossby wave dynamics is also envisioned as playing a role in the dynamics of the PDO.

PDO-like variability on the interdecadal time scale has been observed in numerical experiments in which a global atmosphere is coupled to a slab ocean with realistic land–sea geometry (Kitoh et al. 1999; Dommenges and Latif 2008; Dommenges 2010; Alexander 2010; Clement et al. 2011; Okumura 2013; Dommenges et al. 2014). For example, Dommenges and Latif (2008) performed an 800-yr integration of the ECHAM5 model coupled to a slab ocean and examined global SST patterns as inferred from one-point correlation maps for a grid point in the extratropical central North Pacific. On time scales of 1–5 years their simulated correlation pattern was largely restricted to the extratropical North Pacific. However when the data were low-pass filtered to emphasize the interdecadal variability, the pattern that emerged became basinwide and PDO like. To emphasize this distinction, the authors referred to the interdecadal SST pattern as a “hypermode.” Clement et al. (2011) and Okumura (2013) show that the dominant mode of ENSO-like variability in coupled models’ slab oceans and oceans with full ocean dynamics are qualitatively similar and

explain roughly comparable fractions of the variance of Pacific SST. These experiments have established that ENSO-like interdecadal variability can exist in the absence of equatorial ocean dynamics.

In CW, we examined the frequency dependence of ENSO-like variability in time-filtered data. An important finding was that on the interdecadal time scale the PDO, defined on the basis of extratropical Northern Hemisphere data, closely resembles the leading mode of ENSO-like interdecadal variability, as defined by the regression map based on the 12-yr low-pass-filtered PC1 of SST* in the pan-Pacific domain. In this short contribution we explore the relationship between the PDO and ENSO based on the analysis of spatial patterns in 5-month running mean filtered monthly mean data using, as reference time series, not just the first but the first two leading PCs of the SST* field in the pan-Pacific domain. A simple rotation of these PCs in their own two-dimensional phase space enables us to decompose the ENSO-like variability into pairs of patterns and their associated time-varying indices. The linear combination of PC1 and PC2 of pan-Pacific SST* that corresponds to a 45° rotation turns out to be almost identical to the PDO index of Mantua et al. (1997), and the corresponding spatial pattern resembles the leading mode of variability in coupled models with slab oceans, such as the hypermode in Dommenges and Latif (2008) and the mode obtained by Okumura (2013). Variations in the index that is orthogonal to the *P* (or PDO) index in this two-dimensional phase space are marked by episodic positive excursions that correspond to El Niño events. The corresponding regression pattern is dominated by SST perturbations in the equatorial cold tongue to an even greater degree than conventional ENSO indices.

The analysis protocol is the same as that used by Takahashi et al. (2011) in their study of the structure of ENSO-like variability. The distinction between the two studies is that theirs is focused on the tropical Pacific, whereas ours is pan-Pacific in scope. Some interesting parallels between our results will be pointed out in the discussion. However, the two studies address different questions: theirs addresses whether canonical and Modoki El Niño events are fundamentally different, and ours addresses whether the PDO and the ENSO cycle are fundamentally different.

We will relate our PC-based indices to the ENSO indices that have been used in prior studies with acronyms and symbols listed in Table 1. In our study, values of most of these indices are based on SST anomalies from the Extended Reconstructed SST, version 3b (ERSST.v3b), analysis from the NOAA Climate Prediction Center. Further details concerning these indices and the other datasets used in this paper are provided in section 2 of

TABLE 1. Acronyms or symbols and full names of the indices referred to in this study together with brief definitions and references where applicable.

Acronym or symbol	Full name
P	$(PC1 + PC2)/\sqrt{2}$
T'	$(PC1 - PC2)/\sqrt{2}$
T	The axis coinciding with the axes of the CTI and Niño-3.4
P'	The axis that is orthogonal to the axis T (i.e., CTI and Niño-3.4)
EI	ENSO index; PC1 of global SST* (ZWB; CW)
DEI	Decadal ENSO index; 12-yr low-pass-filtered EI (CW)
CTI	Cold tongue SST* index (Deser and Wallace 1990)
Niño-3.4	Cold tongue SST index (Rasmusson and Carpenter 1982; Trenberth and Hoar 1997)
PDO	Pacific decadal oscillation; PC1 of Pacific SST* poleward of 20°N (Mantua et al. 1997)
PNA	Pacific–North American pattern (Wallace and Gutzler 1981)

CW. As in ZWB, Mantua et al. (1997), and CW, the analysis is based on the SST departure field (i.e., SST*), the difference between the SST at each grid point each month, and the global-mean SST for the same month.

2. Results

a. SST patterns

The two leading EOFs of the pan-Pacific SST* field, which account for 44% and 12% of the variance of SST*, respectively, and their PC time series are shown in

Figs. 1a–d. The leading mode is virtually identical to its counterpart for global SST*, which forms the basis for much of the analysis in ZWB and CW. The second mode exhibits the same extratropical and tropical features as the leading mode, but they are juxtaposed with opposing polarity such that adding a small increment of the second mode reinforces the extratropical features in the leading mode and subtracting a small increment of the second mode reinforces the tropical features in the leading mode. Deser and Blackmon (1995) and Hartmann (2015) obtained similar patterns for the second mode.

FIG. 1. (a),(b) The two standardized leading PCs of SST* in the Pacific basin. (c),(d) The corresponding EOFs as represented by regression maps of global SST onto the PCs. Percentages refer to explained variances. (e),(f) Standardized linear combinations of PC1 and PC2: (e) the sum and (f) the difference, labeled in accordance with the terminology introduced in the text. (g),(h) The corresponding regression maps.

Figure 2a shows a scatterplot of monthly mean (5-month running mean) PC1 versus PC2 of pan-Pacific SST* in the 1900–2014 historical record. The points are arrayed in a pear-shaped cloud in PC1–PC2 space, with El Niño events to the right of its centroid. The ENSO index (EI) in CW is, by definition, oriented along the x axis. The orientations of the axes of other indices are given by $\arctan(r_2/r_1)$, where r_1 and r_2 are the respective correlation coefficients between the index and PC1 and PC2. Axes for all the SST indices listed in Table 1 are indicated in Fig. 2a, and the corresponding values of r_1 , r_2 , $\sqrt{r_1^2 + r_2^2}$, and $\arctan(r_2/r_1)$ are listed in Table 2.

The cold tongue SST* index (CTI) axis is oriented at an angle of -16° (i.e., 16° clockwise relative to the x axis). The Niño-3.4 axis (not shown) has the same orientation. In the associated regression patterns for CTI and Niño-3.4, shown in Fig. S1 of the supplemental material, the small EOF2 contribution cancels out some but not all of the extratropical signal in EOF1, yielding a slightly purer tropical pattern.

CW's decadal ENSO index (DEI), defined as the 12-yr low-pass-filtered EI, is oriented at an angle of about $+45^\circ$. For this orientation in PC1–PC2 phase space, the extratropical signals in EOF1 and EOF2 interfere constructively to produce a strong pattern, while the tropical components partially cancel, leaving a weaker but still significant equatorial signal. It is notable that the PDO axis indicated by the labeling in Fig. 2a is also oriented at an angle close to $+45^\circ$. The 12-yr low-pass filtering of the PDO index causes its projection on PC1–PC2 phase space to rotate counterclockwise but only by 13° , as opposed to 55° in the case of PC1 (i.e., compare EI and DEI in Fig. 2a).

Although the regression patterns for CTI and the PDO are based on mutually exclusive data—the former tropical and the latter extratropical—they are not linearly independent. The redundancy between them derives from the tropical–extratropical coupling inherent in ENSO-like variability: both patterns span the entire Pacific basin and exhibit both tropical and extratropical features in common. The angle between them is $45^\circ - (-16^\circ) = 61^\circ$.

The cloud of data points in Fig. 2a exhibits symmetry with respect to an orthogonal pair of axes $P = (PC1 + PC2)/\sqrt{2}$ and $T' = (PC1 - PC2)/\sqrt{2}$, rotated 45° relative to the PC1 and PC2 axes. In the remainder of this section, we reexamine the spatiotemporal structure of ENSO-like variability from the perspective of this rotated coordinate system. The P axis, where P denotes pan-Pacific, lies very close to the PDO axis irrespective of whether the PDO index is derived from raw data or 12-yr low-pass-filtered data, and it also lies close to the DEI axis. The correlation coefficient between the

FIG. 2. Scatterplots of SST as represented in a two-dimensional phase space defined by PC1 and PC2. The gray axes represent the P and T' axes, rotated by 45° relative to PC1 and PC2 as indicated. (a) Based on unfiltered monthly mean (5-month running mean) filtered data. Labeled arrows indicate the directions of selected indices of ENSO-like variability, as represented in this phase space. (b) As in (a), but for data that are smoothed by performing EMD and retaining IMF5–IMF9. (c) As in (a), but for data that are high-pass filtered by performing EMD and retaining IMF1–IMF4.

TABLE 2. Statistics for selected indices during the period 1900–2014 based on 5-month running mean data for all calendar months. SOI* is the same as that in ZWB.

	r_1	r_2	$\sqrt{r_1^2 + r_2^2}$	$\arctan(r_2/r_1)$
CTI	0.96	−0.19	0.98	−11°
Niño-3.4	0.89	−0.18	0.91	−12°
PDO	0.72	0.65	0.97	42°
SOI*	−0.90	0.05	0.90	−3°

P index [i.e., $(PC1 + PC2)/\sqrt{2}$] and the PDO based on 5-month running mean data is 0.97 (see also Fig. S2 of the supplemental material). It is less than 1 because the PDO index lies slightly outside of PC1–PC2 phase space. That it is very close to 1 shows that to a close approximation, the variability of the P index can be inferred from extratropical SST data alone.

The regression pattern for the P index, shown in Fig. 1g, embodies all of the features of the low-frequency pattern shown in Fig. 13 of CW. It is made up mainly of two elements, which appear to be spliced together: the leading EOF of North Pacific SST within its own domain (poleward of 20°N) and an equatorial and Southern Hemisphere pattern reminiscent of EOF1 in Fig. 1c. The corresponding P index time series, shown in Fig. 1e, accounts for much of the extended 1940–42 El Niño event (Brönnimann et al. 2004) and it reflects the abrupt shift toward the warm polarity of the ENSO cycle in 1976/77 (Nitta and Yamada 1989; Trenberth and Hurrell 1994; ZWB; Deser et al. 2004) and the equally prominent shift back toward the cold polarity in 1998.

There are two axes in Fig. 2a bearing the label T , which denotes tropical. The T axis, (without the prime) is defined as coinciding with the axes of CTI and Niño-3.4, both of which are based on SST anomalies in the equatorial cold tongue region. The T' axis is defined as being orthogonal to the P axis. The T' index time series, shown in Fig. 1d, is positively skewed; positive excursions correspond to El Niño events. The seven events included in the Rasmusson and Carpenter (1982) composite (1951, 1953, 1957, 1963, 1965, 1969, and 1972, labeled in terms of the year of their “onset,” “peak,” and “transition” phases) are all clearly evident, as well as the more recent 1982, 1987, and 1997 events. In agreement with results of Okumura and Deser (2010), these El Niño events tend to be short lived compared to the intervening cold (La Niña) events. However, which years are classified as La Niña as well as which as neutral appears to be more sensitive to the choice of index. For example, in Fig. S1 CTI and T' exhibit quite different chronologies immediately before and after the very strong 1997 El Niño event. It is notable that most of the

prominent El Niño and La Niña events are not clearly discernible in the P index.

Regression patterns based on the equatorial ENSO T indices (i.e., Niño-3.4 and CTI) exhibit a weak but statistically significant extratropical signature by virtue of the “atmospheric bridge” as elucidated by Lau and Nath (1996), Alexander et al. (2002), and numerous other studies. In contrast, the regression pattern for T' is almost devoid of extratropical structure. The clockwise rotation of T in PC1–PC2 phase space to make it perpendicular to P subtracts out the extratropical structure, leaving a more tropically focused pattern.

Figures 2b and 2c show scatterplots for 5-month running mean data that have been time-filtered using empirical mode decomposition (EMD) and retaining the intrinsic mode functions 1–4 (IMF1–IMF4) as the high pass and IMF5–IMF9 as the low pass. The effective cutoff of the filters is around a period of 6 years. The cloud of points representing the high-pass-filtered data is elongated along the T' axis, and the skewness associated with El Niño events is clearly evident. In contrast, the cloud of points representing the low-pass-filtered data is elongated along the P axis. That the points trace out a trajectory in phase space reflects the strong month-to-month autocorrelation inherent in the low-pass-filtered indices.

Power spectra for the P and T' indices shown in Fig. 3a and the corresponding autocorrelation functions shown in Fig. 3b provide further evidence of the contrasting time scales of the ENSO-like variability along the P and T' axes. The negative autocorrelation in the T' index at a lag of one year reflects the tendency for strong El Niño events to be followed, a year later, by strong La Niña events with below-normal SST in the equatorial Pacific cold tongue region (Okumura and Deser 2010). The 3–5-yr spectral peak in the T' index is slightly more prominent in our T' index than in the CTI. The power spectra for the P and PDO indices are nearly identical, except that the P index exhibits slightly larger power at low frequency but smaller at higher frequency than the PDO index. Deser et al. [2012, their Fig. 20b (right)] obtained spectra similar to those shown in Fig. 3 in a 500-yr run of Community Climate System Model, version 4 (CCSM4), with full ocean dynamics.

Also indicated in the labeling of Fig. 2a is the P' index, which is defined as the direction orthogonal to the T index (i.e., the CTI and Niño-3.4 indices) and lies at an angle of +74° relative to the x (i.e., PC1) axis. Its regression pattern and time series are shown in Fig. S3 of the supplemental material. By construction, it is almost a pure extratropical pattern.

FIG. 3. (a) Power spectra and (b) autocorrelation functions for P , T' , PDO, and CTI. The power spectra are normalized such that the area below each line is the same in each.

To summarize and interrelate the SST indices derived by rotating PC1 and PC2:

- The P and T are obtained from data in their own respective (extratropical and tropical) domains.
- The P' and T' are defined as being orthogonal to the T and P axes, respectively.
- The P and T axes are not orthogonal to one another, nor are the P' and T' axes.
- Despite their different definitions, our P index and the PDO index are nearly identical (correlation $r = 0.97$).
- Our T' index provides a definition of individual El Niño events as clear as or even slightly clearer than CTI (Fig. S1).

b. SLP patterns

As noted in Trenberth and Hurrell (1994), ZWB, and CW, the sea level pressure (SLP) signature of ENSO-like variability in the extratropics tends to be strongest during the boreal winter. Accordingly, in this subsection we will focus on November–March means.

Global November–March SLP regression patterns and correlation patterns based on the standardized P and T' indices, shown in Figs. 4a–d, exhibit the familiar tropical Southern Oscillation (SO) signature, which is more clearly expressed in the correlation maps, as well as distinctive extratropical signatures, which are more clearly expressed in the regression maps and particularly the one based on the P index. The most striking Northern

Hemisphere feature is the strong center of action over the extratropical North Pacific, which corresponds to the SLP signature of the Pacific–North American (PNA) pattern (Wallace and Gutzler 1981; Quadrelli and Wallace 2004). Its structure is expressed more clearly in the polar stereographic projection of the 500-hPa height (Z500) field shown in Figs. 4e and 4f. In Figs. 4e and 4f, the analysis is based on the period of record from 1920 onward. The SLP and Z500 patterns based on the 5-month running mean filtered P index in Figs. 4c and 4e bear a very strong resemblance to their counterparts based on the 12-yr low-pass-filtered fields shown in Figs. 5 and 15 of CW.

Okumura (2013) computed analogous regression patterns based on a 500-yr run of CCSM4 with full ocean dynamics. The patterns that she obtained for both SST and SLP are similar in many respects to those shown in Fig. 4. However, in the simulated patterns the Southern Hemisphere exhibits the stronger coupling to the tropical Southern Oscillation signature, whereas in the observations it is the Northern Hemisphere that exhibits the stronger coupling.

c. Statistical significance

To evaluate the statistical significance of the results in the two previous subsections, we will employ the strategy of subdividing the historical record into segments and comparing selected statistics for the respective segments.

Counterparts of Table 2 for the first and second halves of the record, shown in Table S1 of the supplemental material, attest to the robustness of the correlations and the associated angles in PC1–PC2 space.

Figure S4 of the supplemental material shows four different versions of the P and T' indices based on ~30-yr segments of the observational record as indicated. The high degree of agreement indicates that a sampling interval on the order of 30 years long is sufficient to obtain indices that are consistent with those derived from the full 115-yr long record. The robustness of the reference time series ensures that the power spectra and autocorrelation functions shown in Fig. 3 are robust as well. Pan-Pacific SST* PCs based on the Hadley Centre Sea Ice and SST dataset (HadISST; Rayner et al. 2003) yield P and T' time series that are correlated with those derived from ERSST at a level of $r = 0.93$ for both indices, based on the 1900–2014 record.

We have also considered the robustness of the correlation and regression patterns derived from these same SST* PCs—and for this purpose we include PC3 (Fig. S5 of the supplemental material) as well. Correlation maps for SLP and Z500 based on the 1948–78 and 1979–2014 periods of record are shown in Fig. S6 of the supplemental material. The reference time series are the same 1900–2014 SST* PCs, and the SLP and Z500 fields are

FIG. 4. (a),(b) Regression coefficients and (c),(d) correlation coefficients for the global SLP field based on (a),(c) the P and (b),(d) T' indices. The contour interval is 0.1. Regression coefficients for the SLP field (shaded) and the Z500 field (contoured), based on the (e) P and (f) T' indices. (a)–(d) are based on year-round data; (e) and (f) are based on November–March data.

based on the NCEP–NCAR reanalyses. It is evident that the SLP and Z500 correlation patterns based on PC1 are highly reproducible in the 1948–78 and 1979–2014 periods of record, but those based on PC2 and PC3 are less so. The patterns based on PC1 are more robust not only because the SST* anomalies are larger but also because they possess more statistical degrees of freedom by virtue of the faster drop off of PC1's autocorrelation function, as shown in Fig. S7 of the supplemental material.

The regression and correlation patterns based on the P and T' indices, which are linear combinations of PC1 and PC2, appear to be quite robust, as evidenced by the similarity of the patterns derived from the 1920–60 and 1960–2014 segments of the record, shown in Figs. S8 and S9 of the supplemental material. That the patterns were stronger during the period from 1960

onward, especially in the Southern Hemisphere, probably reflects the improvements in the global observing system.

3. Discussion

We have shown that rotating the two leading PCs of the monthly SST departure field over the Pacific Ocean by 45° yields an informative pair of orthogonal indices of ENSO-like variability, here labeled P and T' . The P index is almost identical to the PDO index of Mantua et al. (1997) and exhibits the same apparent “regime shifts” on the interdecadal time scale. Positive excursions in T' are closely associated with El Niño events in the ENSO cycle. The power spectrum for P resembles red noise, transitioning to white noise on the interdecadal time scale, whereas the power spectrum for T' is

FIG. 5. (a) The two standardized PCs of SST* in the tropical Pacific (30°N–30°S) and (b),(c) their corresponding EOFs. Percentages refer to explained variances. (d) As in Fig. 2a, but for the tropical PCs shown in (a).

dominated by a 3–5-yr spectral peak associated with the ENSO cycle.

In the patterns of SLP and 500-hPa height regressed on the P index, the familiar SO signature appears in linear combination with the PNA pattern, a prominent mode of internal variability of the Northern Hemisphere wintertime circulation that is capable of extracting kinetic energy from the climatological-mean flow and therefore exists independently of ENSO (Simmons et al. 1983; Nakamura et al. 1987). In the patterns based on the T' index the SO is the dominant feature in the SLP field and the extratropical Northern Hemisphere 500-hPa height signature resembles the tropical Northern Hemisphere (TNH) pattern in Barnston and Livezey (1987) (see also Barnston and Van den Dool 1993).

The attributes of variability along the T' axis—the narrow equatorial focus and the spectral peak around a period of 3–5 years—are consistent with the traditional interpretation of the ENSO cycle in which the atmosphere–ocean coupling involves the mechanical forcing of the ocean by the equatorial surface wind anomalies. In contrast, the attributes of the variability oriented along the P axis—the red noise spectrum, the close association with the PNA pattern, and the absence of well-defined, equatorial El Niño events—are reminiscent of the dominant mode of ENSO-like variability in coupled models with slab oceans [e.g., Fig. 2 of Dommenget and Latif (2008); Fig. 1b of Okumura (2013)].

It is informative to compare our results with those of Takahashi et al. (2011), who performed a similar analysis but with emphasis on the tropical SST patterns associated with ENSO-like variability. Our

study involves a 45° rotation of the two leading PCs of pan-Pacific SST*; theirs involves a 45° rotation of the two leading PCs of tropical SST as shown in Fig. 5. It is evident from comparing Figs. 1 and 5 that their EOF2 exhibits a node near 130°W, whereas ours does not. Hence, while the PC1s for the pan-Pacific and tropical Pacific domains are virtually identical ($r = 0.99$), the PC2s are substantially different ($r = 0.69$) and thus emphasize different aspects of ENSO-like variability. In the scatterplots based on the tropical PCs [Figs. 1, 2, and 4 of Takahashi et al. (2011); Fig. 5d of this paper], the 45°-rotated axes C and E relate to the longitudinal structure of the SST anomalies in the equatorial Pacific; the C axis relates to the amplitude and polarity of SST anomalies in the central Pacific and the E axis to those in the eastern Pacific. Yet despite these differences in the interpretation of the axes, the orientations and shapes of the clouds of points in these phase spaces are remarkably similar.

Our results do not settle the question posed in the introduction: does the PDO exist independently of the ENSO cycle? It clearly exists independently of the ENSO cycle in coupled modes with slab oceans, but in the real world and in coupled models with equatorial ocean dynamics they are difficult to separate. It is evident from our results that the PC1 of pan-Pacific (or global) SST* is, in equal parts, an index of the ENSO cycle and an index of the PDO and that even the CTI and Niño-3.4 are not linearly independent of the PDO. On the other hand, we readily acknowledge that representing the ENSO cycle by T' masks two-way connections between tropics and extratropics that are known to be operative on the same time scale as the ENSO cycle.

4. Concluding remarks

Because the P and T' indices are linearly independent, in combination they provide more information on the current status of ENSO-like variability than any single index such as Niño-3.4 or the CTI. Such a bivariate representation of ENSO could conceivably be of use in seasonal to annual climate prediction. Variability in T' lends itself to prediction using statistical and dynamical methods that are already in use. Additional (albeit limited) information can be obtained by predicting P based on damped persistence, exploiting its 0.48 lag correlation between November–March means for successive years. Whether the variability in P exhibits additional predictability remains to be seen.

It is also conceivable that the availability of two linearly independent ENSO indices could be of use in quantifying the impacts of ENSO-related climate variability. However, results of a recent study by X. Guan (Lanzhou University, 2015, personal communication) suggest that the gains, relative to the use of a single predictor—PC1 of pan-Pacific SST* for unfiltered, seasonal mean data and the PDO or P index for the interdecadal variability—are likely to be modest.

It is unlikely that the P and T' indices defined in this study will replace any of the existing ones. The former is largely redundant with the PDO, and the latter is quite similar to the CTI and Niño-3.4, as documented in Figs. S1 and S2. CTI and Niño-3.4 are simpler to derive, and the subtle differences between T' and those indices are difficult to interpret. For example, it is not obvious why the CTI and Niño-3.4 exhibit a more pronounced multiyear La Niña event following the 1997 El Niño than T' does. The intent of this study is not to propose a new set of indices of ENSO-like variability but to validate the existing ones (in particular, the PDO index) by showing that they can be recovered as linear combinations of the two leading EOFs of unfiltered, pan-Pacific SST*.

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