Multi-Decadal Modulations of the Low-Frequency Climate
Variability in the Wintertime North Pacific since 1950

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Abstract

The North Pacific decadal variability (PDV) is known to manifest itself as two distinct spatial patterns. Observations since 1950 reveal that the wintertime PDV underwent notable modulations of their dominance in sea-surface temperature (SST) variability and accompanying atmospheric variability. Until the 1980s, decadal SST variability was strongest along the subarctic frontal zone (SAFZ), the boundary between the warm Kuroshio and cool Oyashio waters. The SAFZ variability was highly correlated with decadal variability of the surface Aleutian Low but not simultaneously with tropical SST variability. Since the 1990s, however, this extratropical ocean-atmosphere variability has lost its predominance, taken over by SST variability in the subtropical frontal zone. It accompanies subtropical anticyclone variability, exhibiting significant anti-correlation with tropical SST variability. These long-term PDV modulations have remotely modulated temperature variability over Canada and Alaska. Similar PDV modulations are simulated in a centennial integration of a global climate model.

1. Introduction

El Niño/Southern Oscillation (ENSO), coupled ocean-atmosphere variability with periods of 2~6 years, is known as the dominant mode of natural climate variability with prominent sea-surface temperature (SST) anomalies (as departures from local climatology) in the equatorial Pacific. Its extensive impacts onto the extratropical North Pacific and
North America are through changing a westerly jetstream and large-scale semi-permanent maritime low-pressure system at the surface, Aleutian Low (AL) \cite{Trenberth et al., 1998; Ropelewski and Halpert, 1989}, especially in winter. Through this remote ENSO influence or “atmospheric bridge” \cite{Lau, 1997; Alexander et al., 2002}, the anomalous intensity and/or position of AL modify heat release from the ocean surface and water mixing underneath, generating large-scale SST anomalies in correlation simultaneously with the tropical SST anomalies.

Superimposed on the ENSO influence, more persistent climate anomalies associated with the Pacific decadal variability (PDV) are observed in the North Pacific \cite{Nitta and Yamada, 1989; Trenberth, 1990}, influencing climatic conditions and marine ecosystems \cite{Mantua et al., 1997}. In responding primarily to large-scale wind variability \cite{Deser et al., 1999; Seager et al., 2001}, PDV is known to manifest itself as two distinct spatial patterns. One is called the Pacific Decadal Oscillation (PDO) \cite{Mantua et al., 1997}, defined statistically as an anomaly pattern that explains the largest fraction of SST variance over the extratropical North Pacific through an empirical orthogonal function (EOF) analysis. The PDO is characterized by anti-correlated SST anomalies between the Tropics and midlatitudes with the anomalous AL. Defined through an EOF analysis of unfiltered SST data, the PDO may include several dynamically-independent modes of SST variability on interannual through multi-decadal scales \cite{Schneider and Cornuelle, 2005}. In fact, decadal
SST anomalies tend to be confined into oceanic frontal zones where meridional SST gradient is climatologically tight [Nakamura et al., 1997; Nakamura and Kazmin, 2003]. If applied to SST over the extratropical North Pacific from which its interannual variability has been filtered out, an EOF analysis could isolate SAFZ variability, which is in only weak simultaneous correlation with tropical SST, from variability in the subtropical frontal zone (STFZ) around 30°N, which is anti-correlated strongly with the tropical variability [Nakamura et al., 1997]. The STFZ variability resembles what is called Victoria mode [Bond et al., 2003], which is an SST manifestation of the North Pacific Gyre Oscillation (NPGO) [Di Lorenzo et al., 2008], recognized as another important mode of decadal variability with pronounced anomalies in sea-surface height (SSH).

Carried out with data sets for different periods, these statistical identifications of the different modes of PDV may reflect long-term modulations in their activity. In fact, decadal variability in the Tropics changed its characteristics. Recently ENSO “Modoki” [Ashok et al., 2007] (or called central Pacific [Kao and Yu, 2009], dateline [Larkin and Harrison, 2005] or warm-pool El Niño [Kug et al., 2009]) with more persistent SST anomalies in the central equatorial Pacific occurs more frequently than ENSO with SST anomalies confined to the eastern equatorial Pacific. Recent EOF analyses of midlatitude SST variability also suggest modulations in amplitude of the PDO and NPGO-like modes [Yeh et al., 2011; Park et al., 2012].
This study aims to provide a comprehensive picture of long-term PDV modulations occurring over the last six decades based on global reanalysis [Kalnay et al., 1996] and other observational data. Focuses are on boreal winter when persistence of SST anomalies is enhanced through their re-emergence mechanism [Alexander et al., 1999].

2. Data and methods

Monthly fields of SST and streamfunction at selected pressure levels are obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [Kalnay et al., 1996] for 65 recent winters (1948/49–2012/13). The SST data are available on a grid with resolution of 1.875° in latitude and longitude, which is sufficient for detecting variability along SAFZ and STFZ. Corresponding to sea-level pressure (SLP), 1000-hPa streamfunction can better depict anomalies in near-surface airflow in the Tropics, and airflow at the jetstream level is depicted by 250-hPa streamfunction. Before analyzed, SST and streamfunction have been averaged for the December-January (DJ) period. This seasonal period is chosen because atmospheric variability associated with SAFZ is coherent from December to January but not into February [Taguchi et al. 2012]. Station-based data of monthly surface air temperature (SAT) with 5° grid intervals available from the Climate Research Unit (CRU) [Jones et al., 2012] were also averaged for the DJ period.
To isolate low-frequency climate variability, more specifically (quasi-) decadal variability, from year-to-year variability, including the remote ENSO influence, the bi-monthly fields have been exposed to 3-winter running mean before being analyzed. Seasonality is thus retained, which is of particular importance especially for extracting the signal of the developing AL anomalies in the presence of SAFZ SST anomalies, as stressed by Taguchi et al. [2012]. Furthermore, STFZ and its associated SST variability also exhibit strong seasonality, diminishing in warm seasons. For a given 20-year epoch, decadal-scale anomalies are defined as departures of the 3-winter running means from the mean state entirely over the epoch, and statistics for the anomalies are then obtained, including the correlation and variance. These statistics are then compared among the nine partially-overlapping epochs (1950-1969, 1955-1974, ..., 1990-2009; Figure S1) to examine multi-decadal PDV modulations. We have confirmed that the results are qualitatively unchanged if based on data filtered with either 5-winter running mean or DJF-mean fields.

Remote influence of SST anomalies via large-scale atmospheric circulation can be illustrated by diagnosing energy propagation of stationary Rossby waves through the longitudinally-varying climatological westerlies with a wave-activity flux [Takaya and Nakamura, 2001] based on 250-hPa streamfunction anomalies.

The CGCM used in this study is a global coupled ocean-atmosphere model for the Earth Simulator (CFES) [Komori et al., 2008]. Its atmospheric component has 48 levels in the
troposphere and stratosphere with horizontal resolution equivalent to 100-km grid intervals. The ocean component of CFES has 54 vertical levels with horizontal resolution of 0.5° in both latitude and longitude. The resolution is not enough to resolve meso-scale eddies that are of vital importance for shaping oceanic jets. Nevertheless, CFES can simulate pronounced meridional SST contrast across SAFZ and decadal SST anomalies induced by its meridional displacement [Taguchi et al., 2012].

Dominant modes of the observed and CGCM-simulated decadal SST variability within the extratropical North Pacific have been extracted through an EOF analysis. The first and second EOFs (EOF1 and EOF2) are highlighted that can explain the largest fractions of the area-averaged SST variance. The corresponding principal component time series, PC1 and PC2, represent amplitude and polarity of the SST anomaly patterns extracted in EOF1 and EOF2, respectively. The EOF analysis was applied to the 3-winter running-mean SST anomalies within [150°E~140°W, 20°~50°N] to extract decadal variability, which tends to be strong around SAFZ and STFZ (see Figures 5a and 5e).

3. Observed modulations of Pacific decadal variability

Long-term modulations in (quasi-) decadal SST variability are highlighted in maps of local standard deviation of 3-winter running-mean SST for two non-overlapping bi-decadal epochs (Figure 1). The running mean was applied to highlight variability with periods
longer than ~5 years. In most of the nine partially-overlapping bi-decadal epochs (Figure S1), the decadal SST variability was particularly strong along SAFZ and STFZ [Nakamura and Kazmin, 2003], though showing distinctive modulations in magnitude. The SST variability has weakened recently along SAFZ especially in its western portion (solid rectangle in Figure 1d), whose statistical significance is not quite high, though (at the 77~83% confidence level depending on estimated numbers of degrees of freedom). In addition, the variability along STFZ (dashed rectangle in Figure 1d) has shifted southwestward with its center of action located around [35°N, 160°W] in 1970-1989 but now around [27°N, 175°W] (Figures 1a and 1d). It occurred concurrently with the westward shift of the center of action in tropical SST variability, reflecting more frequent occurrence of persistent “Modoki” events [Yeh et al., 2009].

The aforementioned modulations are illustrated in a latitude-time section of 3-winter running-mean SST anomalies (Figure 2). In the western Pacific [150~170°E], decadal SST variability was consistently strong along SAFZ (~40°N), peaking in the late-1970s through the early 1990s until diminished in the mid-1990s. Those SST anomalies are uncorrelated with those observed in the Tropics simultaneously and even two months earlier [Nakamura et al., 1997; Taguchi et al., 2012], suggesting that they are unlikely formed through the atmospheric bridge mechanism. In the latest bi-decadal epoch, strongest SST anomalies were observed along STFZ around 27°N, which are anti-correlated with those in the

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western/central tropical Pacific (Figure 2). As shown in Figure S2, wavelet analysis applied to area-averaged unfiltered SST confirms the aforementioned modulations in SST variability with 5~15-year period along SAFZ and STFZ.

Signatures of long-term PDV modulations are not limited to SST but also in the tropospheric circulation. Figure 3 compares maps of simultaneous correlation coefficients of atmospheric variables with area-averaged (quasi-) decadal SST anomalies between the same pair of bi-decadal epochs as in Figure 1. In the 1970s~1980s, when SAFZ variability was prominent and thus highlighted in literature [Nakamura et al., 1997; Taguchi et al., 2012], a warm anomaly in SAFZ tended to accompany surface anticyclonic and cyclonic anomalies over the subpolar and subtropical Pacific, respectively (red contours in Figure 3a). They correspond to the weakening of both the surface AL and subtropical high-pressure belt in addition to that of the midlatitude westerlies in between. The corresponding dipolar pressure anomalies in the upper troposphere (black contours in Figure 3a) resemble the Pacific/North American (PNA) pattern [Taguchi et al., 2012], a recurrent anomaly pattern dominant over the North Pacific with its eastward extension into North America [Wallace and Gutzler, 1981]. The polarities of all the anomalies are reversed in the presence of a cold anomaly in SAFZ. These atmospheric anomalies are similar to their counterpart associated with the PDO but uncorrelated with tropical SST anomalies simultaneously (Figure 3a) or two months earlier.
By the latest bi-decadal epoch, the weakened decadal-scale SST variability in SAFZ has dramatically reduced its correlation with atmospheric anomalies, including the PNA pattern (Figure 3b). Concomitantly, decadal-scale atmospheric variability over the central North Pacific has weakened substantially (grey hatches in Figures 1e-f), with marked variance reductions in streamfunction near the surface around the Aleutian Islands (Figures 1b and 1e) and at the jetstream level over western Canada, the Aleutian and subtropical North Pacific (Figures 1c and 1f). The latter three regions correspond to pressure anomaly centers of the PNA pattern.

The same correlation analysis reveals that both the correlation and its significance of decadal SST anomalies along STFZ with those in the central and western tropical Pacific have strengthened in the latest bi-decadal epoch (shaded in Figures 3c-d). The central Pacific SST anomalies are consistent with the recent enhancement of ENSO-Modoki. The domain of significant surface anticyclonic anomalies (red solid lines in Figures 3c-d) observed with anomalous warmth along STFZ (yellow shading) extended zonally across the subtropical basin in the earlier epoch, but in the later epoch the domain has shrunk and shifted into the Tropics. The corresponding upper-tropospheric signature of anticyclonic anomalies in the subtropics (solid black lines in Figures 3c-d) has substantially weakened recently. These atmospheric anomalies are cyclonic when observed with the abnormal coolness in the STFZ. The inter-decadal modulations in the STFZ-related atmospheric
variability are consistent with the significant variance reduction in the subtropics both at the
upper and lower levels and the enhanced variance in near-surface streamfunction in the
deep Tropics during the latest epoch (Figures 1b and 1e).

The aforementioned multi-decadal modulations in decadal-scale ocean-atmosphere
variability are manifested as the corresponding modulations in the dominant modes of
North Pacific SST variability, consistently with Yeh et al. [2011]. Within the extratropical
North Pacific (rectangular domain in Figure S3d), the SAFZ variability was identified as
the most dominant mode (EOF1) of (quasi-) decadal SST variability up to the 1980s
(Figure S3d), while the STFZ variability was identified as the second most dominant mode
(EOF2; Figure S3g) [Nakamura et al., 1997]. The prominent SAFZ variability
accompanied the anomalous surface AL and the PNA pattern aloft (Figures S3e-f). Since
the 1990s, however, the STFZ variability has become most dominant as extracted in EOF1
(Figure S4d). The SAFZ variability has lost its dominance, as extracted in EOF2 for
1985-2004 (not shown) and for 1990-2009 (Figure S4g), though SST anomalies displaced
northward.

The above findings have some implications for predictability of the North Pacific climate
variability, which is important for seasonal weather prediction for the surrounding areas.
Specifically, the corresponding multi-decadal modulations are found in SAT variability in
North America. Though not necessarily quite significant statistically, the modulations are
recognizable in bi-decadal standard deviation of 3-winter running-mean SAT [Jones et al., 2012] (Figure 4). In and around the 1970s, decadal-scale SAT variability over Alaska and the Canadian Rockies was particularly large, exhibiting strong negative correlation with the SAFZ SST variability (closed circles in Figure 4a) through the associated AL variability (Figure 3a). Specifically, persistent weakening of AL associated with anomalous warmth in SAFZ weakened the warm southerlies into Alaska to yield extreme coldness and vice versa. As the SAFZ variability has weakened afterward losing its correlation with AL, SAT variability has reduced substantially over Alaska and western Canada, losing its correlation with SAFZ variability (Figure 4b). In the latest epoch, the SAT variability only along the Arctic coast is correlated significantly with STFZ variability (black triangles in Figure 4b).

4. Implications from a CGCM simulation

One may wonder whether the observed modulations occurred with the changing background state under the global warming. In fact, SAFZ, STFZ and the tropical Pacific are undergoing persistent warming (Figure S2). Interestingly, such multi-decadal modulations in PDV as observed are simulated in a CGCM experiment without any external forcing (Figure 5). A 150-year CFES integration under fixed CO₂ concentration includes a bi-decadal epoch (55~74th year) where strong SAFZ variability, which is uncorrelated with tropical variability, is extracted in EOF1 of 3-winter running-mean SST
anomalies over the extratropical North Pacific (Figure 5b). In the following epoch (75~94\textsuperscript{th} year), however, the corresponding EOF1 represents STFZ variability in strong anti-correlation with tropical variability (Figure 5f). The STFZ variability represents the strengthening/weakening of the Kuroshio Extension jet associated with SSH variability (not shown), as observed with the NPGO [Di Lorenzo et al., 2008]. Between the two epochs CFES simulates a warming tendency in the western tropical Pacific (not shown). The CFES experiment suggests that the multi-decadal modulations observed in PDV may have occurred under the changing basic state.

5. Concluding remarks

The present study based on a reanalysis data set [Kalnay et al., 1996] has found that the wintertime decadal SST variability over the North Pacific has been modulated over the last six decades, with respect to positions of its centers of action and their magnitudes, accompanied by coherent modulations in atmospheric variability. Those modulations in SST variability are found robust, supported consistently through analyses of in-situ ship observations [Worley et al., 2005] and satellite measurements [Reynolds et al., 2002], as well as interpolated SST data sets, including COBE SST [Ishii et al., 2005] and HadISST [Rayner et al., 2003].

Further studies are required to clarify mechanisms for the multi-decadal modulations in
the North Pacific decadal SST variability and associated atmospheric variability. Possible
causes of the modulations may include i) internal modulations of the coupled
atmosphere-ocean variability in the extratropical North Pacific, ii) modulations in tropical
decadal variability and their remote influence onto the extratropics, iii) modulations of the
ocean variability induced by modulated internal atmospheric variability, and iv) random
collection of higher-frequency variability. For clarifying relative importance of these factors,
analysis of multi-model CGCM experiments and observed long proxy data will be
important as well as accumulation of continuous observations. Furthermore, it is of
scientific and social importance to assess how much uncertainty the presence of such the
multi-decadal modulations as observed in the Pacific can yield in the future climate
projection and how the global warming can further modulate the natural climate variability.

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References


Lau, N.-C. (1997), Interactions between global SST anomalies and the midlatitude


Trenberth, K. E., et al. (1998), Progress during TOGA in understanding and modeling


Figure 1. Maps of 20-yr standard deviation of 3-winter (DJ) running-mean anomalies in (a,d) SST, (b,e) 1000-hPa streamfunction, and (c,f) 250-hPa streamfunction for (a-c) 1969/70-1988/89 and (d-f) 1989/90-2008/09. Red (grey) hatch is applied where local variance is greater (less) than its counterpart in the other epoch at the 85% confidence level by the $F$-test with seven degrees of freedom if assumed for each of the epochs. Solid rectangles in (a,d) indicate the SAFZ domain for a wavelet analysis shown in Figure S2a. Dotted and dashed rectangles in (a) and (d) indicates the eastern and western STFZ domains used in Figures S2c and S2b, respectively. Green dashed and solid rectangles in (a) and (d) indicates the eastern and western tropical domains used in Figures S2e and S2d, respectively. Open circles in (b,c) and closed circles in (e,f) signify centers of streamfunction anomalies associated with the most dominant SST anomalies in the corresponding epochs shown in Figures S3 and S4, respectively.
Figure 2. Detrended DJ-mean SST and their 3-winter running-mean anomaly over the Pacific. (a) Time-latitude sections of the running mean SST (contoured for every 1.5°C) and the corresponding anomalies from the 60-year climatology (shaded for ±0.1, 0.3, 0.5, ... °C), (upper) between 10°N and 50°N averaged from 150°E to 170°E and (lower) between 10°S and 10°N averaged from 170°E to 170°W. Rectangles with dashed blue and orange lines indicate SAFZ and STFZ, respectively. Black dashed lines highlight anti-correlation in SST anomalies between STFZ and the Tropics. Climatological profile of meridional SST gradient (°C/100km) is attached to the right. Arrows below the section indicate the bi-decadal epochs for Figures 1, 3, 4, S3 and S4. (b) 21-year running standard deviation of the running-mean SST (°C) averaged in SAFZ and STFZ as indicated in (a).
Figure 3. Maps of 20-year correlation of 3-winter (DJ) running-mean anomalies with the corresponding SST averaged within (a-b) SAFZ (time series in Fig. S2a) or (c-d) western STFZ (time series in Fig. S2b), as indicated by green rectangles. Correlation coefficients of SST (yellow for positive; blue for negative), 1000-hPa streamfunction (red contours), and 250-hPa streamfunction (black contours) have been computed separately for (a,c) 1970-1989 and (b,d) 1990-2009. Color shading and contours indicate the correlation significant at the 90% confidence level. Negative correlation is indicated with dashed lines. Vectors represent a wave-activity flux by Takaya and Nakamura [2001] for 250-hPa streamfunction. Signs of the anomalies correspond to those observed when SAFZ or STFZ is warmer and otherwise reversed, but the flux is unchanged regardless the sign of SST anomalies.
Figure 4. 20-year standard deviation of 3-winter running-mean SAT (°C) based on station-based CRU data for (a) 1970-1989 and (b) 1990-2009. Closed circles (triangles) indicate grid boxes for which correlation of SAT anomalies with SST anomalies in SAFZ (STFZ) based on an EOF analysis exceeds the 95% confidence level (correlation coefficient of 0.67 or greater in magnitude, or more than ~45% of the SAT variance can be explained by the linear relation with the remote SST variability). The correlation is positive and negative if the closed circles (triangles) are colored in black and blue, respectively. According to the $F$-statistic with 7 degrees of freedom if assumed for each of the epochs, the reduction of the SAT variance is statistically significant at the 90% confidence level only in the coastal region along the Gulf of Alaska.
Figure 5. Standard deviation of 3-winter running-mean anomalies in (a,e) SST (°C, colored) and (c,g) 925-hPa streamfunction (10^6 m^2 s^-2, colored) simulated in CFES. Linear regression of those anomalies in (b,f) SST (contoured for ±0.2, 0.6, 1.0, ... °C) and (d,h) 925-hPa streamfunction (contoured for every 0.5 × 10^6 m^2 s^-2) onto the principal component (PC) for EOF1 of those SST anomalies within the rectangular domain indicated in (b,f). The local linear regression of a given variable onto PC represents its typical anomaly co-varying with EOF1, and the signs of the anomalies are reversed for negative PC values. The statistics are shown for the (a-d) 55-74th year and (e-h) 75-94th year of the CFES integration. (i) 21-year running standard deviation of the running mean SST anomalies (°C) averaged near centers of action of variability in SAFZ (black; 150°E-175°W, 35°N-45°N) and STFZ (red; 165°E-165°W, 20°N-30°N) variability. Arrows in (i) indicates the bi-decadal epochs for (a-d) and (e-h).
Introduction

To investigate modulations in strength and period of SST variability, a wavelet analysis (Figure S2) is applied to unfiltered SST time series averaged within the five Pacific regions where decadal SST variability is strong, as identified in maps of SST standard deviation (Figure S1). Multi-decadal modulations in the coupled ocean-atmosphere variability is highlighted in Figures S3 and S4, where observed patterns of SST anomalies and associated atmospheric circulation anomalies are compared between the two contrasting periods as discussed in the main text.
Figure S1. Standard deviation of 3-winter running averaged DJ-mean SST (°C; colored) in the NCEP/NCAR reanalysis for partially-overlapping 20-year epochs, as indicated. The blue and orange rectangles indicate the bi-decadal epochs used for Figures 1, 3, 4, S3 and S4.
Figure S2. Wavelets and time series of area-averaged SST anomalies in the reanalysis. Wavelets (shading) and time series (color bar) with their 3-winter running mean (black line plot) of area-averaged SST in (a) [150°E-175°W, 35°-45°N], (b) [175°E-160°W, 25°-35°N], (c) [170°-140°W, 30°-40°N], (d) [160°E-175°W, 5°S-5°N], and (e) [140°-110°W, 5°S-5°N]. Each of the time series indicated includes its linear trend and has been normalized by its standard deviations, while the wavelet analysis is based on the detrended and non-normalized time series. Coloring convention is shown to the right of (a). White dashed lines indicate 8- and 12-year period. Heavy black contour in each panel indicates the contour of 1.2 (K^2) duplicated from (a). Blue and orange arrows on each of the time series plots denote the bi-decadal epochs highlighted in Figures 1, 3, 4, S3 and S4.
Figure S3. Standard deviations of SST and atmospheric variability, the leading EOFs of decadal SST variability in the wintertime midlatitude Pacific and associated atmospheric anomalies in reanalysis for 1970-1989. (a-c) Standard deviation of the 3-winter running mean anomalies, linear regression onto (d-f) PC1 and (g-i) PC2 of (a,d,g) SST (contoured for every 0.2°C), (b,e,h) 1000-hPa streamfunction (every $5 \times 10^5$ m² s⁻², corresponding to 0.6-hPa SLP anomaly at 43°N) and (c,f,i) 250-hPa streamfunction (every $5 \times 10^5$ m² s⁻², corresponding to 5-m height anomaly at 43°N). EOF analysis is applied to the running-mean SST anomalies within the rectangular domain in (d,g). In (f,i) vectors show a wave-activity flux by Takaya and Nakamura [2001] for 250-hPa streamfunction. Lighter (heavier) shading in (d-i) denotes the anomalies at the 90% (99%) confidence level. Zero lines are omitted in (e,f,h,i).
Figure S4. Same as in Figure S3, but for 1990-2009.