On the relationship between the interannual and decadal SST variability in the North Pacific and tropical Pacific Ocean

Sang-Wook Yeh and Ben P. Kirtman[1]

Center for Ocean-Land-Atmosphere Studies, Calverton, Maryland, USA

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[1] To address the relationship between the North Pacific and tropical SST anomalies on decadal and interannual timescales, we analyzed observed SST during the period 1950–2000. The SST variability in the North Pacific has two fairly well separated timescales: (1) decadal and (2) interannual, and each has a markedly different relationship with tropical variability. Both the decadal and interannual variability in the North Pacific is connected to the evolution of tropical SST variability with different lead-lag relationships. The decadal SST variability in the North Pacific is found to lead tropical decadal variability by approximately 5 $\sim$ 7 years; however, the interannual SST variability is in the North Pacific in equilibrium with the tropical interannual variability. It is also shown that the spatial structure of the decadal variability in the North Pacific is significantly different from the interannual variability. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4215 Oceanography: General: Climate and interannual variability (3309); *KEYWORDS:* decadal, interannual, SST variability, North and tropical Pacific

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1. Introduction

[2] A rich spectrum of interannual to decadal climate variability appears in the North Pacific [*Nitta and Yamada*, 1989; *Trenberth*, 1990; *Alexander*, 1992; *Graham*, 1994; *Miller et al.*, 1994; *Lau and Nath*, 1994; *Nakamura et al.*, 1997; *Giese and Carton*, 1999; *Barlow et al.*, 2001]. Interannual sea surface temperature (SST) variability in the North Pacific is often described as the result of teleconnections with the tropics. Significant interannual variations in the North Pacific associated with El Niño and Southern Oscillation (ENSO) events have been well-documented [*Wallace and Gutzler*, 1981; *Zhang et al.*, 1996; *Lau and Nath*, 1996]. Decadal SST variability in the North Pacific also has been extensively documented [*Trenberth and Hurrel*, 1994; *Graham*, 1994; *Latif and Barnett*, 1994; *Barnett et al.*, 1999; *Tourre et al.*, 1999; *Pierce et al.*, 2000; *Schneider et al.*, 2001]. The possible mechanisms for both the interannual and the decadal variability include midlatitude ocean-atmosphere coupled feedbacks, stochastic forcing and tropical remote forcing.

[3] Even though there have been numerous modeling and observational studies on North Pacific variability, the relationship between SST variability in the North Pacific and the tropical Pacific remains unclear. *Nakamura et al.* [1997] identified two SST modes which represent decadal and quasi-decadal wintertime variability over the North Pacific (20°N–50°N, 150°E–140°W), respectively. The first mode has strong variability in the North Pacific basin extending zonally at 42°N and the second mode nearly coincides with the subtropical front oriented in a northeast-southwest direction. They argued that since the first mode exhibits no significant simultaneous correlation with tropical and subtropical variability, it is largely independent from the tropical variability. The second mode was found to be is associated with tropical variability.

[4] There have also been studies regarding the spatial structure of SST variability in the tropical and midlatitude Pacific. Based on empirical orthogonal function (EOF) analysis of winter SSTA over the Pacific domain (60°N–20°S), *Deser and Blackmon* [1995] identified an interannual mode of variability in the North Pacific that is linked to ENSO, as well as an interdecadal mode, which is often called the 'North Pacific mode' that is independent of ENSO. *Barlow et al.* [2001] extracted three modes from monthly SST anomalies including all seasons via rotated principal component analysis over the Pacific domain. The first mode is the typical ENSO mode with a spatial pattern similar to a well-developed El Nino. The second mode, referred as the 'Pacific decadal oscillation' extends throughout the tropical and extratropical Pacific. The spatial patterns of these two modes in the North Pacific were significantly different from each other. The spatial structure was also different in the tropical Pacific. The third mode, often referred as the 'North Pacific mode' has a spatial structure that confined to the North Pacific. Conversely, *Giese and Carton* [1999] found that the interannual and decadal variability in the North Pacific had essentially the same structure.

[1]Also at School of Computational Sciences, George Mason University, Fairfax, Virginia, USA.

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[5] *Zhang et al.* [1997] separated the global SST into two components: one identified with the 'ENSO cycle' and the other a linearly independent 'residual' comprising all the longer-term variability. The structure of the 'ENSO cycle' in the tropical Pacific was quite similar to the first mode identified by *Barlow et al.* [2001]. However, the 'residual' variability was broadly similar to the Pacific decadal mode of *Barlow et al.* [2001] in the tropical Pacific, but not in the North Pacific. *Mestas-Nunez and Enfield* [1999] also decomposed rotated EOF modes of global SST of non-ENSO residuals. Even though they used data in which the ENSO signal had been removed, the second rotated EOF mode (see Figure 2 in their paper) is quite similar to the Pacific decadal mode of *Barlow et al.* [2001].

[6] As mentioned above, much of the previous work focused on the spatial structure in both the North Pacific and tropical Pacific SST variability on decadal and interannual timescales. Although there is evidence for a link between the North Pacific and tropical Pacific SST variability, the relationship on the SST evolution between the North Pacific and tropical Pacific on interannual and decadal timescales is weak. For example, *Lau et al.* [2002] argued that the first EOF mode of summer SST variability in the North Pacific may actually be influenced by ENSO events in the previous spring, but as the season progresses through the summer and fall, its evolution appears to decouple from the influence of tropical SST; on the other hand, the second mode does not have a significant relationship to ENSO.

[7] While these previous studies used different averaging periods, temporal filtering, spatial domains and analysis techniques, they fundamentally agree that there is well-separated decadal and interannual variability in the North Pacific. They also agree that the interannual variability is linked to tropical variability, although the details are somewhat in doubt. On the other hand, there is considerable disagreement as to whether the spatial structure of the variability is timescale-dependent, and whether the decadal variability is somehow connected to tropical variability.

[8] The purpose of this paper is to resolve some of this disagreement. In order to do this we reexamine the relationship between North Pacific and tropical SST anomalies (SSTA) by focusing the interannual and decadal evolutional relationships. We first analyze the decadal and interannual SST evolution in the North Pacific because we speculate that if the analysis domain includes the entire Pacific domain, the structure of SST variability in the North Pacific is contaminated by the ENSO-related variability. Then we addressed how distinct SST modes of variability (i.e., interannual and decadal) in the North Pacific are related to the tropical Pacific variability.

[9] Our results suggest that the SST variability in the North Pacific has two separated timescales: (1) decadal and (2) interannual; however, these two distinct timescales have markedly different lead-lag relationships to tropical interannual and decadal SST variability. The progression of the North Pacific SST variability on decadal timescales are closely connected to the evolution of the tropical decadal SST variability but lagged in time by 5–7 years. On interannual timescales, the dominant variability in the North Pacific and tropical Pacific seems to be simultaneously related. We also argued that the spatial structure of the decadal variability is fundamental different from the interannual variability.

2. Data and Methodology

[10] We used monthly mean SST data taken from January 1950 to December 2000 which were analyzed by the National Centers for Environmental Prediction (NCEP [*Reynolds and Smith*, 1994]). Note that the SST data used in this work is detrended. Although the midlatitude response to the tropical forcing is known to be strongest in the winter season, our analysis period includes the entire calendar year. *Barlow et al.* [2001] suggested that the SST variability on the North Pacific has vigorous activity in summer although most previous analyses have concentrated on the wintertime structure. *Zhang et al.* [1998] argued that the dominant mode of SSTA variability over the North Pacific exhibits a rather similar spatial structure year-round, with largest amplitude during summer. Monthly anomalies were defined by subtracting the mean annual cycle calculated over the entire record (1950–2000).

[11] To extract temporal evolution of a typical mode in a given time interval, an extended empirical orthogonal function (EEOF) analysis was performed [*Weare and Nasstrom*, 1982; *Robertson et al.*, 1995]. The EEOF technique has been frequently used in oceanographic and atmospheric problems to identify dominant patterns of space-time variability, specifically cyclical behavior in the field. It is essentially the same as multichannel singular spectrum analysis [*Vautard and Ghil*, 1989]. The covariance matrix is constructed with the original time series supplemented with time-lagged versions of the original time series. As the number of lags increases, the time series must be shortened [*von Storch and Frankignoul*, 1996].

3. Results

3.1. EOF Analysis in the North Pacific

[12] Figure 1 shows the first two empirical orthogonal function (EOF) modes of SST in the North Pacific and the associated time series of the principal components (PC). The first SST mode explains 23.8% of the total SST variance within the domain. The dominant mode of variability is zonally extended with a basin-scale positive SSTA centered near 40°N. The second SST mode, which accounts for 13.4% of the total variance within the domain, has a strong meridional SST gradient around 35°N with a change in the sign of the SST anomaly (SSTA). The negative SSTA in the second mode has a northeast to southwest orientation. The PC time series for each mode indicates that these first two EOFs are related with a lead-lag relationship in the North Pacific. The maximum lead-lag correlation between two PC time series is at 120 months.

[13] The spatial structure of the first EOF SST mode is very similar to SSTA generated via the atmospheric-bridge associated with the tropical ENSO variability [*Lau and Nath*, 1994, 1996; *Alexander et al.*, 2002]. However, these first two EOF SST modes also resemble the decadal SST variability in the North Pacific during the 1970s and 1980s as shown in *Miller et al.* [1994]. Based on the first and second EOF modes for the filtered wintertime SST (Period

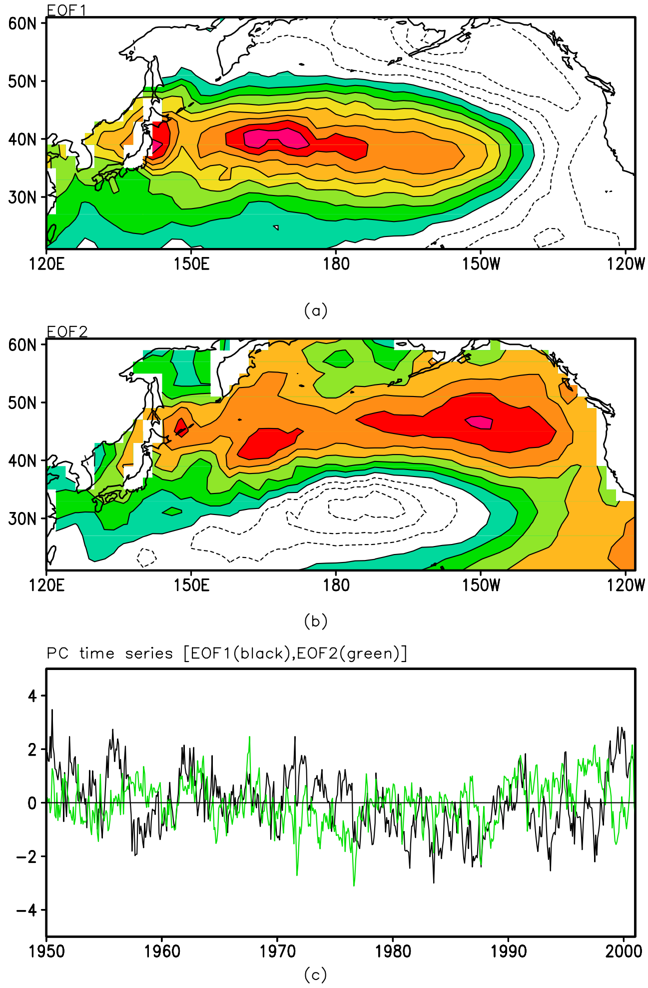

Figure 1. The first (a) and second (b) sea surface temperature EOF mode in the North Pacific (20°N–60°N, 120°E–240°E) during the period: 1950–2000. Dashed for negative and contour interval is 0.1°C. (c) Time series of the principal component of the first (black) and second (green) mode.

(P) > 7 yrs) in the North Pacific, *Nakamura et al.* [1997] argued that these two modes were concentrated near two major oceanic fronts. The first mode, which broadly resembles Figure 1a, represents the decadal SST variability associated with the northern subpolar gyre along the subarctic front. The second mode, which resembles Figure 1b, represents the SST fluctuations along the subtropical front. *Nakamura et al.* [1997] also pointed out that the second mode represents the decadal SST variability in the North Pacific subtropical gyre and associated variability in the tropics. Thus, suggesting that the basic structure of decadal and interannual variability in the North Pacific is similar.

[14] Figure 2 shows the spectral density calculated from the PC time series. The first EOF mode has significant spectral density at periods greater than 10 yrs but with no preferred periodicity. On the other hand, the dominant spectral density of second mode has a broad spectrum on both inteannual and decadal timescales (the red noise spectra is shown in the dashed line).

[15] In order to clarify how the spatial pattern of North Pacific SST variability depends on timescale, we separated the data by high/low-pass filtering into two frequency bands: decadal (P > 9yr) and interannual (P < 9yr). The cutoff period (9yr) is subjectively chosen based on the spectral analysis of the two SST EOF modes shown in Figure 2. The EOFs were recomputed separately for each filtered data set.

[16] The results of the first two SST modes for each frequency band are shown in Figure 3. The spatial pattern of the first two interannual SST modes (Figures 3c and 3d) is very similar to that of unfiltered SST shown in Figures 1a and 1b. This is expected since most of the power (i.e., area under the curve) in Figures 2a and 2b corresponds to periods less than 9 years. The decadal modes have less power than the interannual modes, but also have different spatial structures. This difference is most apparent with the second EOF where the decadal mode has two centers of

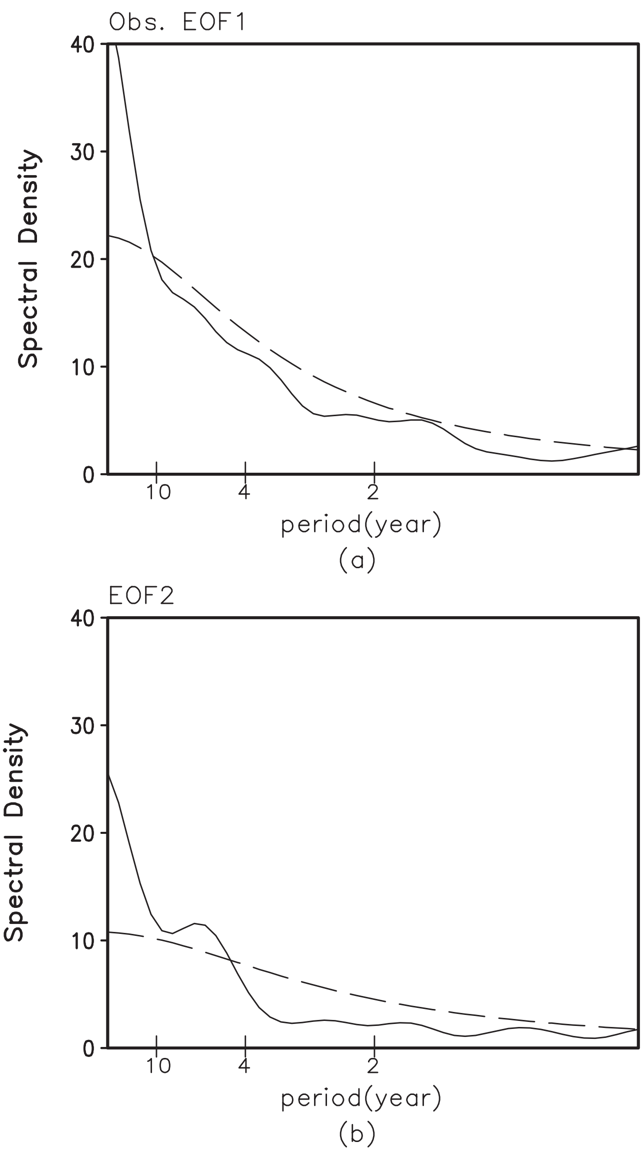

Figure 2. Power spectral density of the time series of PC of the first (a) and second (b) SST EOF mode. The red noise spectra are shown in the dashed line.

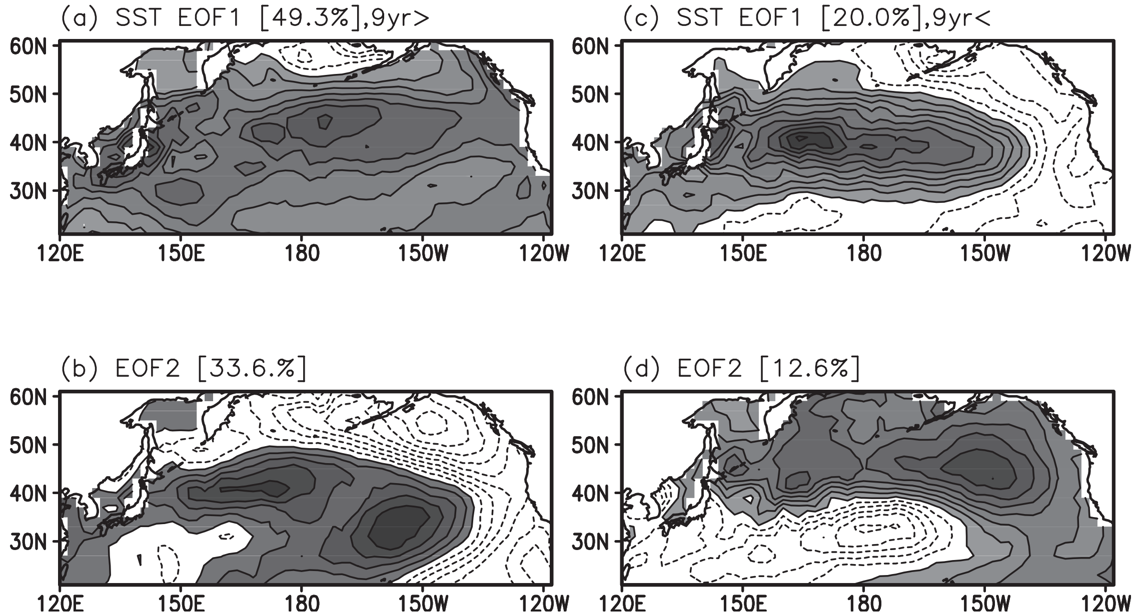

Figure 3. The first (a) and second (b) EOF mode of SST anomalies derived using the filtered data for decadal period (P > 9yr). (c) and (d) As in (a) and (b) except for the nterannual period (P < 9yr). Dashed for negative and contour interval is 0.1°C.

action to the south of 50°N, whereas the interannual mode has only one center of action. Put simply, we argue here that the decadal variability has a different spatial structure than the interannual variability. As further support for this assertion we examine the space-time evolution of the North Pacific variability in the next subsection. As shown below, the difference in the spatial structures noted here emerges without any explicit temporal filtering.

3.2. Evolution of SST Variability in the North Pacific

[17] The result of the PC time series shown in Figure 1c suggests that first two EOF modes of the unfiltered data describe a propagating mode in the North Pacific. This suggestion of a propagating mode has been proposed in the literature. For example, *Latif and Barnett* [1994] investigated the characteristic evolution of upper-ocean low pass filtered heat content anomalies in the North Pacific using a complex EOF (CEOF) analysis. Their leading CEOF mode, which was dominated by basin-scale positive SSTA centered near 35°N and negative anomalies in the southern part of North Pacific, broadly resembles the combined pattern of the first and second EOF SST mode noted here. The leading CEOF also has the characteristic of oscillatory nature showing a clockwise propagation reminiscent of the general gyre circulation round the Pacific with a period of about 20 years.

[18] Here we explore the characteristic evolution of unfiltered SSTA in the North Pacific based on an EEOF analysis with lags up to seven years. Figures 4a–4d and 4f–4i show the temporal-spatial evolution of the first (Figures 4a–4d) and third (Figures 4f–4i) EEOF modes of the SSTA in the North Pacific, respectively. Figure 4e shows the time series of the first (solid) and second (dashed) PC of the EEOF analysis. Figure 4j is the same as in Figure 4e except for the third (solid) and fourth (dashed) PC. The spatial patterns are displayed at interval of every four years with a sequence of twelve years (Figures 4a–4d) and every one year with a sequence of three years (Figures 4f–4i) for the two modes, respectively. The spatial structure of modes one and two are the same and the structure of modes three and four are the same.

[19] Although we used temporarily unfiltered SST data, the time series of PCs shown in Figures 4e and 4j indicates that the North Pacific SST variability has two well-separated timescales (i.e., decadal and interannual). Moreover, the spatial pattern of each EEOF mode shown in Figures 4a–4d and Figures 4f–4i is comprised of a combined pattern of EOF SST modes constructed by a low-pass (P > 9yr, Figures 3a and 3b) and high-pass (P < 9yr, Figures 3c and 3d) filtered SST data, respectively. Again, the differences in the spatial structures of the decadal and interannual modes are readily apparent.

[20] On decadal timescales, Figures 4a and 4d are similar to the first EOF SST mode (Figure 3a) with a basin-scale structure and Figure 4c resembles the pattern of the second EOF SST mode shown in Figure 3b. On interannual timescales, Figures 4f and 4i indicate a spatial structure that is zonally extended with a basin-scale, which is similar to the first EOF (Figure 3c). Figure 4h is similar to the second EOF with a northeast to southwest orientation in the southern part of the North Pacific shown in Figure 3d. It suggests that North Pacific SST variability has two fairly well separated timescales, i.e., decadal and interannual, and that both timescales are well described by the two dominant EOFs as shown in Figure 3.

[21] The first EEOF SST mode has two distinct structures in the North Pacific, i.e., one is zonally extended with a basin scale (Figures 4a and 4d) and the other is the northeast-southwest oriented positive center of action in the southern part of the North Pacific and the positive center of action in the Kuroshio extension (Figure 4c). With time, the basin-scale positive anomalies change into a westward-

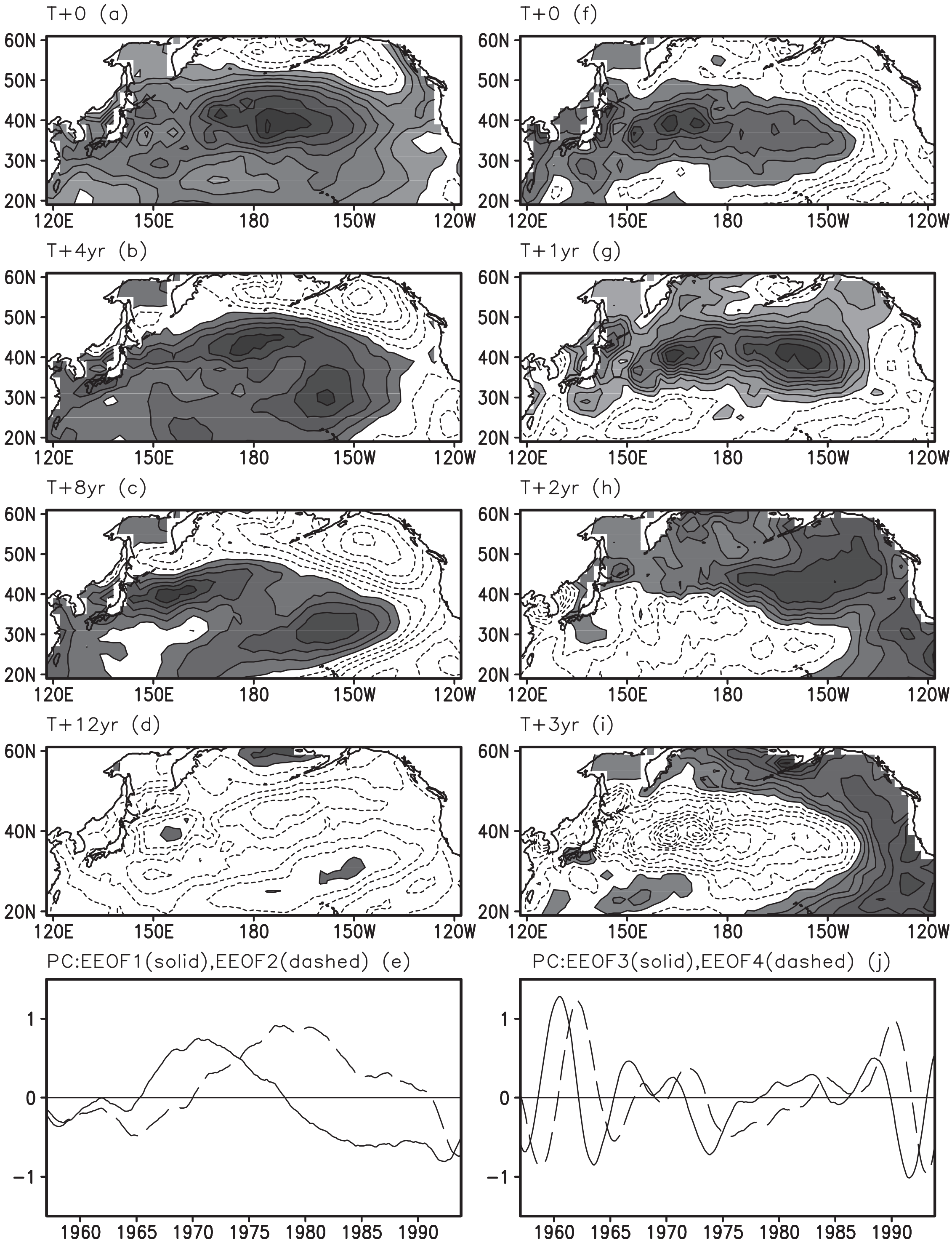

Figure 4. The temporal-spatial evolution of the first (panela a–d) and the third EEOF (panels f–i) mode of the SST anomalies in the North Pacific. The spatial patterns are displayed at an interval of every four years with a sequence of twelve years (a) for T + 0, (b) for T + 4year, (c) for T + 8year and (d) for T + 12year and at every year with a sequence of three years (f) for T + 0, (g) for T + 1year, (h) for T + 2year and (i) for T + 3year. Dashed for negative and contour interval is 0.1°C. (e) is the principal components of the 1st (solid) and 2nd (dashed). (j) as in (e) except for the 3rd (solid) and 4th (dashed) mode.

intensified pattern in the western and southern part of the North Pacific.

[22] The spatial-temporal pattern of the third EEOF SST mode is distinctive to that of the first EEOF. This mode shows a basin-scale propagating mode on interannual timescales. The positive SSTA covers the majority of the western and central North Pacific with a negative SSTA in the southern part of the North Pacific (Figure 4f). As time

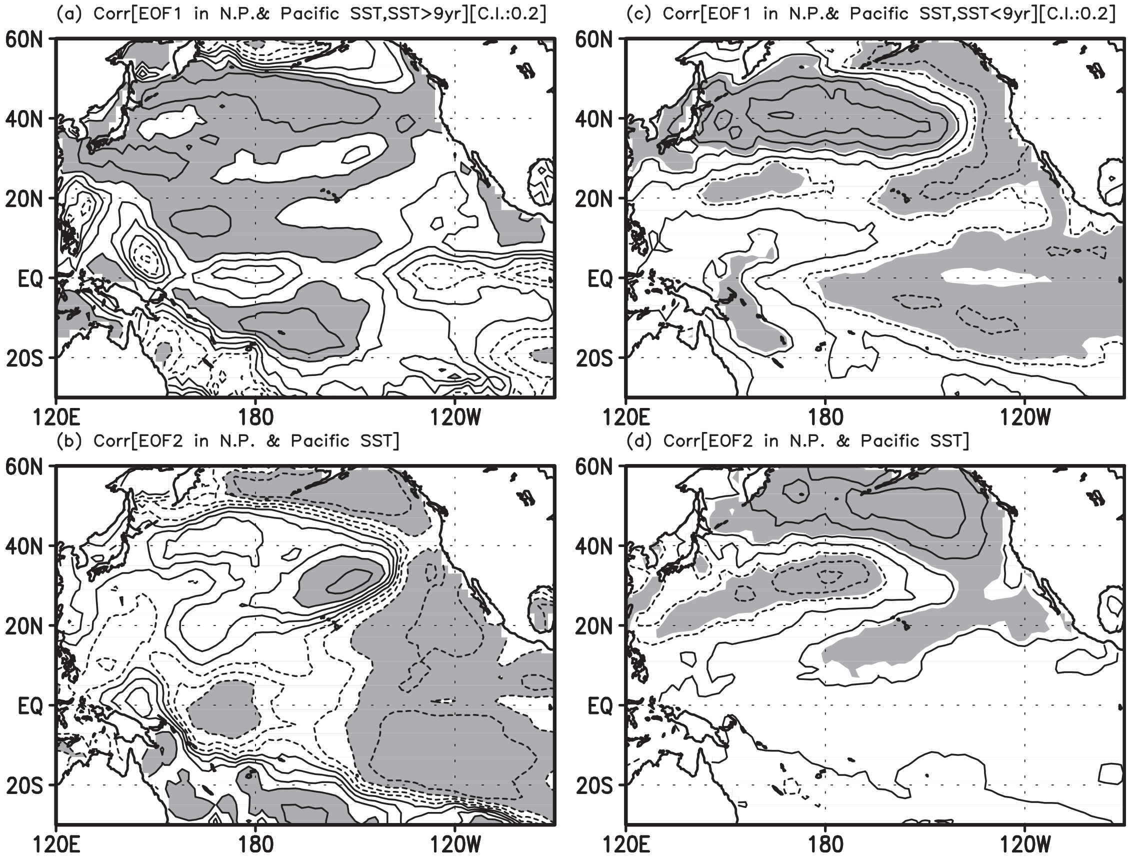

Figure 5. Simultaneous correlation coefficients plotted between Pacific SST and PC of the first (a) and second (b) SST EOF mode for decadal variability. (c) and (d) as in (a) and (b) except for the interannual period. Contour interval is 0.2. Areas ≤ -0.6 and ≥ 0.6 are shaded in (a),(b). (c),(d) corresponds to the areas ≤ -0.25 and ≥ 0.25. Shaded regions in which correlation between SST and a given PC exceeds 90% significance.

progresses, the positive SSTA propagates to the east (Figure 4g) and the negative SSTA increases in the western and central North Pacific (Figure 4h). At this point in the evolution, the negative maximum variability again covers the majority of the western and central North Pacific with a positive SSTA in the southern part of the North Pacific (Figure 4i). The result presented here suggests that there are two well separated two modes of variability in the North Pacific. Not surprisingly, the two modes also have different relationship to tropical variability. This later point is the subject of the next subsection.

3.3. Relationship Between the North Pacific and the Tropics

[23] The current literature basically agrees that the interannual variability in the North Pacific is associated with tropical variability. However, there is no consensus regarding how the decadal variability is related to the tropics. For example, *Nakamura et al.* [1997] showed that the first EOF SST mode in the North Pacific exhibits no significant simultaneous correlation with tropical and subtropical variability and the second mode is associated with the tropics on decadal timescales. ($P > 7$yr). *Tourre and White* [1995] discussed the sequencing between the first and second EOFs of inteannual variability and identified the second EOF as a precursor to the first EOF (representing the mature phase of ENSO) over the Pacific domain.

[24] In order to examine the relationship with tropical variability, we separately computed the simultaneous correlation between Pacific SSTA and the four PCs corresponding to the four EOFs shown in Figure 3. In other words, we are separately examining how the decadal and interannual modes of variability related to tropical variability. Figures 5a and 5b show the correlation between the SSTA and PC one and two for the low frequency filtered (i.e., decadal) data. The SSTA have been filtered for periods greater than nine years before the correlation is computed. Similarly, Figures 5c and 5d show the correlation between the SSTA and PC one and two for the interannual filtered data. Again, the SSTA has been filtered for periods less than nine years before computing the correlation. On decadal timescales (Figures 5a and 5b), the strongest tropical correlations are for EOF2. The spatial structure of this correlation is similar to the 'residual' variability identified by *Zhang et al.* [1997] and the Pacific decadal oscillation by *Barlow et al.* [2001]. In contrast, for the interannual modes, the largest tropical correlation corresponds to EOF1 and the spatial structure of the correlation is ENSO-like.

[25] These correlations suggest that the North Pacific decadal variability leads the tropical variability and that North Pacific interannual variability is simultaneously

related to tropical variability. In order to see this, recall that on both timescales EOF1 and EOF2 combine to form a propagating mode in which the peak phase is described by EOF1. Therefore, based on the EEOF analysis shown in Figure 4, we conclude that the peak phase of the decadal mode in the North Pacific leads the tropics and that the interannual mode is simultaneously related to the tropics.

[26] In order to clarify this lead-lag relationship we have repeated the EEOF analysis for the larger Pacific domain. In this case we have performed the EEOF analysis twice. First we used the unfiltered SSTA but attempted to remove the linearly and contemporaneously related ENSO variability. Second we performed the EEOF analysis on the SSTA that is linearly and contemporaneously related to ENSO. The motivation behind this second calculation is to examine the evolution of North Pacific SSTA that is directly connected to ENSO and compare this with the EEOF analysis shown in Figure 4.

[27] To remove ENSO variability over the Pacific domain, first, we calculated the regression field between the Pacific SSTA and the time series of SSTA averaged in the 5°N–5°S, 170°E–90°W which includes both the NINO3.4 (5°N–5°S, 170°E–120°W) and NINO3 (5°N–5°S, 150°W–90°W) region. Then we subtracted the regression field multiply by the above SSTA time series from the original SST data. The idea here is to remove SSTA variability that is linearly and contemporaneously related to ENSO. Note that because the tropical Pacific SSTs usually lead those in the North Pacific by a few months, it is likely that a contemporaneous single index is not sufficient to remove all of the ENSO signal in the North Pacific.

[28] Figures 6a–6d show the temporal-spatial evolution of the first EEOF mode over the Pacific domain. The spatial patterns are displayed at interval of every four years with a sequence of twelve years. Figure 6e shows the time series of the first (solid) and second (dashed) PC of the EEOF analysis. The second EEOF mode has similar temporal variability as the first EEOF mode except for the lag shown in Figure 6e.

[29] The time series of the first PC has a decadal timescale similar to that shown in Figure 4e. The spatial-temporal structure of SSTA variability in the North Pacific is also similar to that of the EEOF analysis restricted the North Pacific as shown in Figures 4a–4d. Moreover, the tropical SST variability shown in Figures 6a–6d is similar to a combined pattern of the tropical structure shown in Figures 5a and 5b. Note that the tropical structure shown in Figures 5a and 5b represents tropical decadal SST variability. The dominant structure of the tropical decadal SST variability is less equatorially confined in the eastern Pacific and extends along much of the North and South American coasts in the eastern part of the tropical basin with a triangular shape [*Knutson and Manabe*, 1998]. This spatial-temporal structure of tropical SST variability shown in Figure 6 seems to represent the evolution of decadal variability. This suggests that both North and tropical Pacific decadal SST variability are largely independent of the tropical Pacific interannual SST variability.

[30] The evolution of the first EEOF mode demonstrates the lead-lag relationship between the decadal North Pacific and tropical Pacific variability. For example, at 0-lag the North Pacific pattern is zonally extended with a basin-scale positive anomaly, which is the dominant mode variability in the North Pacific (Figure 6a). However, the tropical Pacific pattern does not show a distinct structure of decadal variability at this time. With time, the dominant SST variability in the North Pacific changes into two distinct structures (Figures 6b and 6c). One is the northeast-southwest oriented positive center of action in the southern part of the North Pacific and the other is the positive center of action in the western part of the basin. As this variability progresses in the North Pacific, the tropical SST variability goes to a mature state showing an extension along much of the North and South American coasts in the eastern part of the tropical basin with a triangular shape. Taken together, the simultaneous linear correlation shown in Figures 5a and 5b and the EEOF results restricted to the North Pacific (Figures 4a–4e), suggest that the dominant North Pacific decadal variability leads the dominant tropical decadal variability by approximately 5–7 years. Figure 6 suggests that the progression of the North Pacific SST variability on decadal timescales is closely connected to the evolution of the tropical decadal SST variability but lagged in time.

[31] These structures in the North Pacific are associated with the subtropical variability nearly coincidence with the subtropical front and the subpolar gyre including the Kuroshio-Oyashio Extension, respectively. Recently, *Miller et al.* [1998] examined an ocean model forced by observed wind stress and heat flux anomalies from 1970–1988. The model current fields indicate that the North Pacific subpolar and subtropical gyre are strengthened by roughly 10% from the 1970s to the 1980s and the decadal-scale thermocline change is forced by a basin-scale perturbation in the wind stress curl that concomitantly strengthens the subpolar and subtropical gyres. Within the main thermocline (400-m depth), *Deser et al.* [1999] argued that the variability is dominated by a westward-intensified pattern on decadal timescales, indicative of enhanced eastward geostrophic flow along the southern flank of the Kuroshio Current extension during the 1980s relative to the 1970s. Our results suggest that this progress is closely associated with the evolution of the tropical decadal SST variability.

[32] As mentioned above, we again performed the EEOF analysis on the SSTA that is linearly and contemporaneously related to ENSO. The SSTA was taken from the original SST data subtracted by the SSTA used in Figure 6. Figures 7a–7e show the temporal-spatial evolution of the first EEOF modes of the above SSTA over the Pacific domain. The spatial patterns are displayed at intervals of every six months with a sequence of two and half years. The time series corresponding to the first PC of the EEOF (not shown) has a dominant ENSO cycle on interannual timescales.

[33] The EOF structure of SST variability in the North Pacific is influenced by the ENSO signal when the entire larger Pacific domain is analyzed. The overall structure broadly resembles the peak phase of the interannual mode restricted to the North Pacific (Figures 4f and 4i). However, the spatial-temporal structure of SSTA variability does not show a basin-scale propagating mode, which is comprised of a combined pattern of EOF SST modes constructed by a high-pass ($P < 9$yr) filtered SST (Figures 3c and 3d). This is expected since only the peak phase of the interannual mode in the North Pacific, which is zonally extended with a

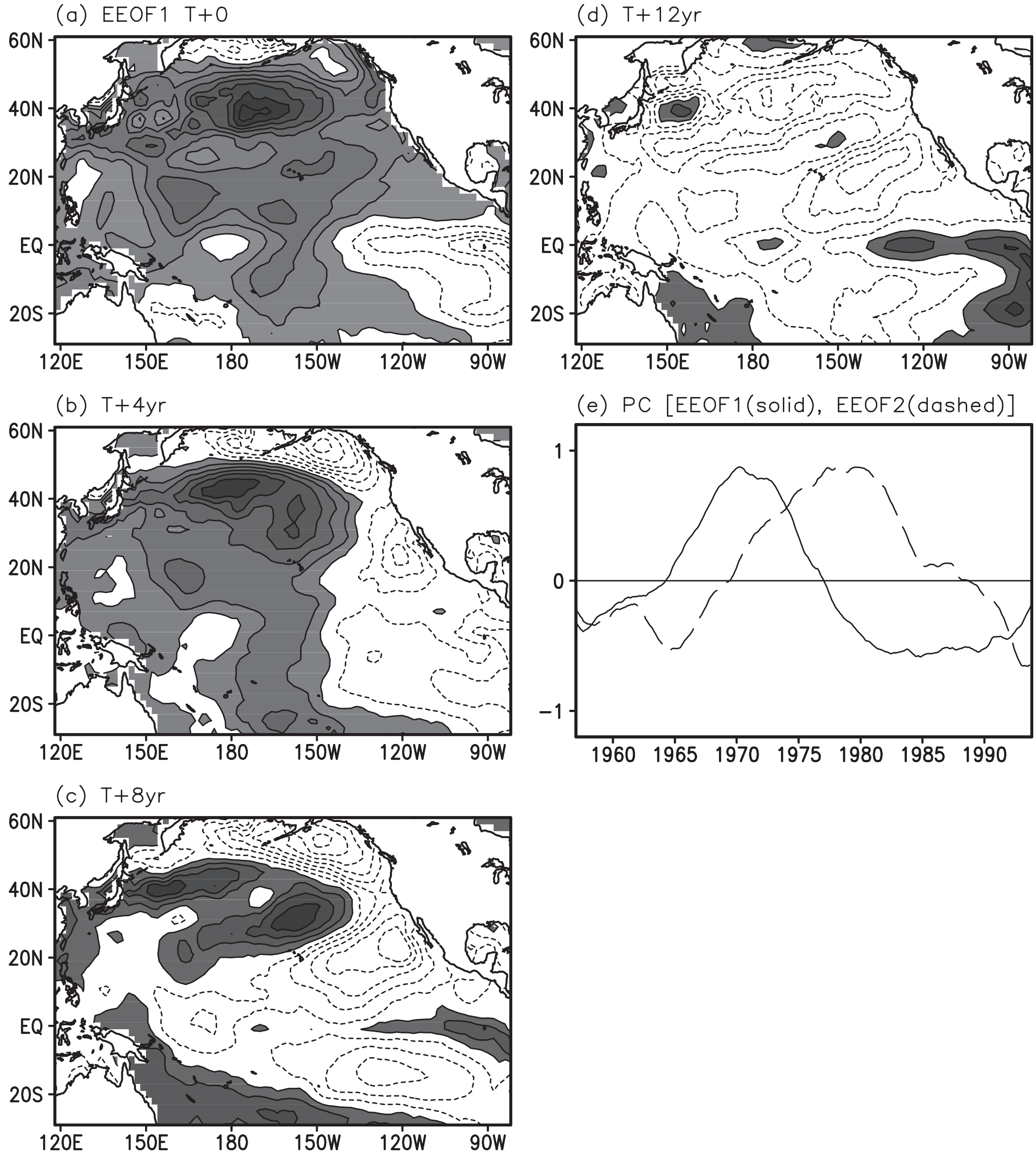

Figure 6. The temporal-spatial evolution of the first EEOF mode of the SST data has been filtered to remove the linearly related ENSO signal in the Pacific (panels a–d) and the 1st and 2nd principal components (panel e). The spatial patterns are displayed at an interval of every four years with a sequence of twelve years, with (a) for T + 0, (b) for T + 4year, (c) for T + 8year, (d) for T + 12year. Dashed for negative and contour interval is 0.1°C. The solid and dashed curves in (e) are the 1st and 2nd principal components, respectively.

basin-scale, has a strong simultaneous correlated to tropical variability (Figure 5c).

[34] In order to clarify the evolutional relationship between the interannual SST variability in the North Pacific and the tropics, we have performed a composite analysis. The composite years, i.e., 1951, '57, '63, '65, '69, '72, '76, '82, '86, '91, '94, '97 (12 years), are chosen based on NINO3 (210°E–270°E, 5°S–5°N) SST index being above +0.45°C during the northern winter. Figure 8 shows the seasonal change of composite SSTA in the North Pacific (Figures 8a–8g) and the tropical Pacific ocean basin (Figures 8h–8n) from the northern spring to the fall of the following year. The North Pacific SST variability, which is associated with the tropical variability on the interannual timescale, has comparable amplitude during the whole season based on a composite analysis although most previous analyses have concentrated on the wintertime.

[35] The distinctive feature to note is the change of SSTA in the North Pacific as the composite ENSO evolves. The time evolution of the SSTA in the North Pacific is similar to the result of an EEOF analysis shown in Figures 4f–4i. The SST structure during the northern spring (Figure 8a) has a

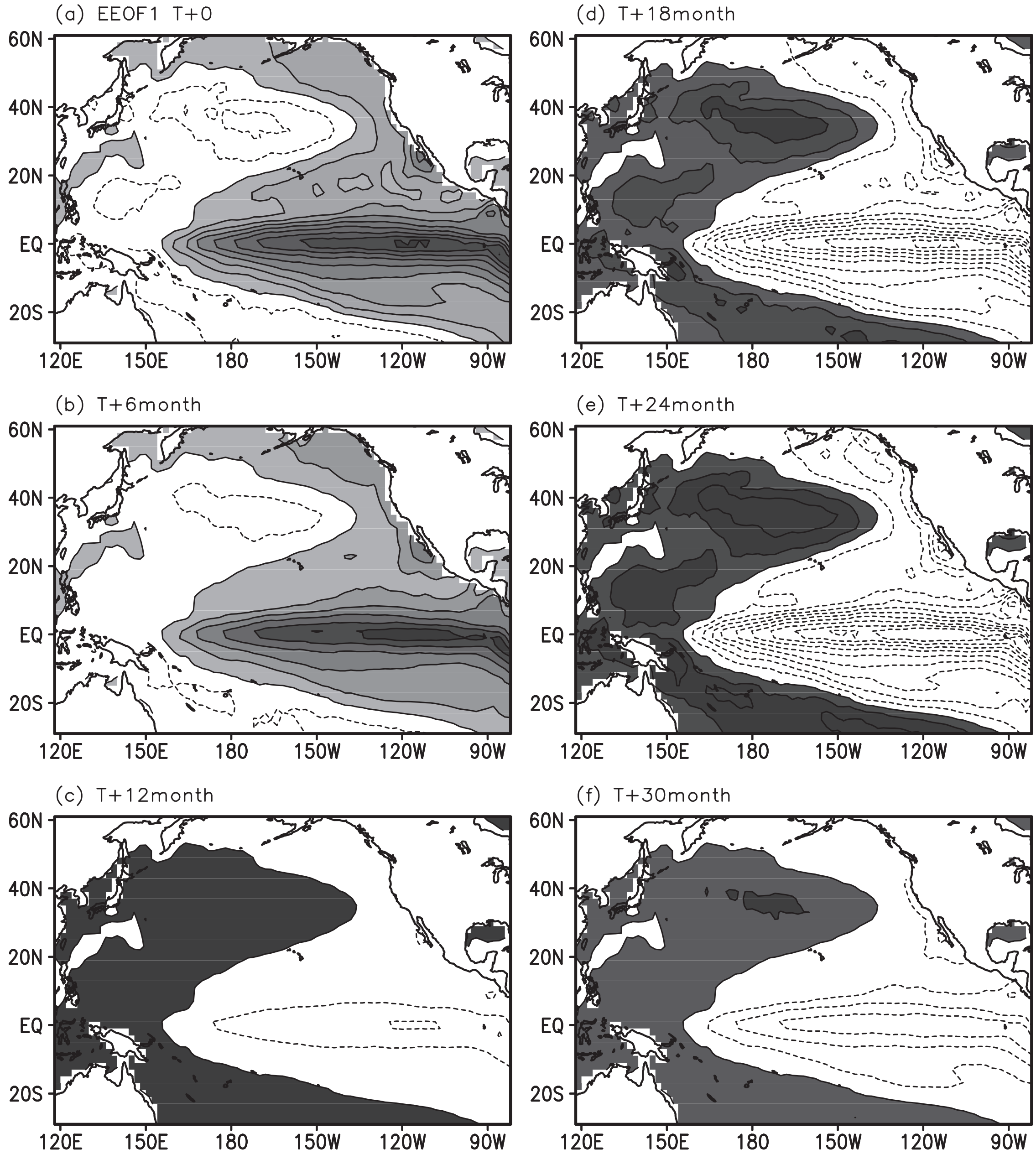

Figure 7. The temporal-spatial evolution of the first EEOF mode of the SST data in the Pacific (panels a–f). The spatial patterns are displayed at an interval of every six months with a sequence of two and half years, with (a) for T + 0, (b) for T + 6month, (c) for T + 12month, (d) for T + 18month (e) for T + 24month and (f) for T + 30month. Dashed for negative and contour interval is 0.1°C.

similar pattern shown in Figures 4g and 4h in the North Pacific. The negative SSTA in Figure 8a, which has a northeast-southwest orientation in the southern part of the North Pacific, propagates to the east and stretches across the North Pacific to the west coast of the North America (Figures 8d and 8e) as time progresses. This propagation is consistent with the evolution of interannual SST variability in the North Pacific shown in Figures 4f–4i.

4. Summary and Discussion

[36] It is well known that the North Pacific atmospheric-ocean climate system has prominent timescales that range from interannual to decadal. Understanding the natural variability in the climate system is important for both short-term climate prediction and credible long-term projection of global climate change. There is increasing evidence for a close relationship between the interannual and decadal-scale variability in the North Pacific and the tropics. Still, the causes and mechanisms for the low-frequency relationship between the North Pacific and the tropical Pacific are not fully understood.

[37] To reexamine the relationship between the North Pacific and tropical SSTA evolution on decadal and interannual timescales, the observed SST data during the period 1950–2000 were analyzed. An EOF analysis of North

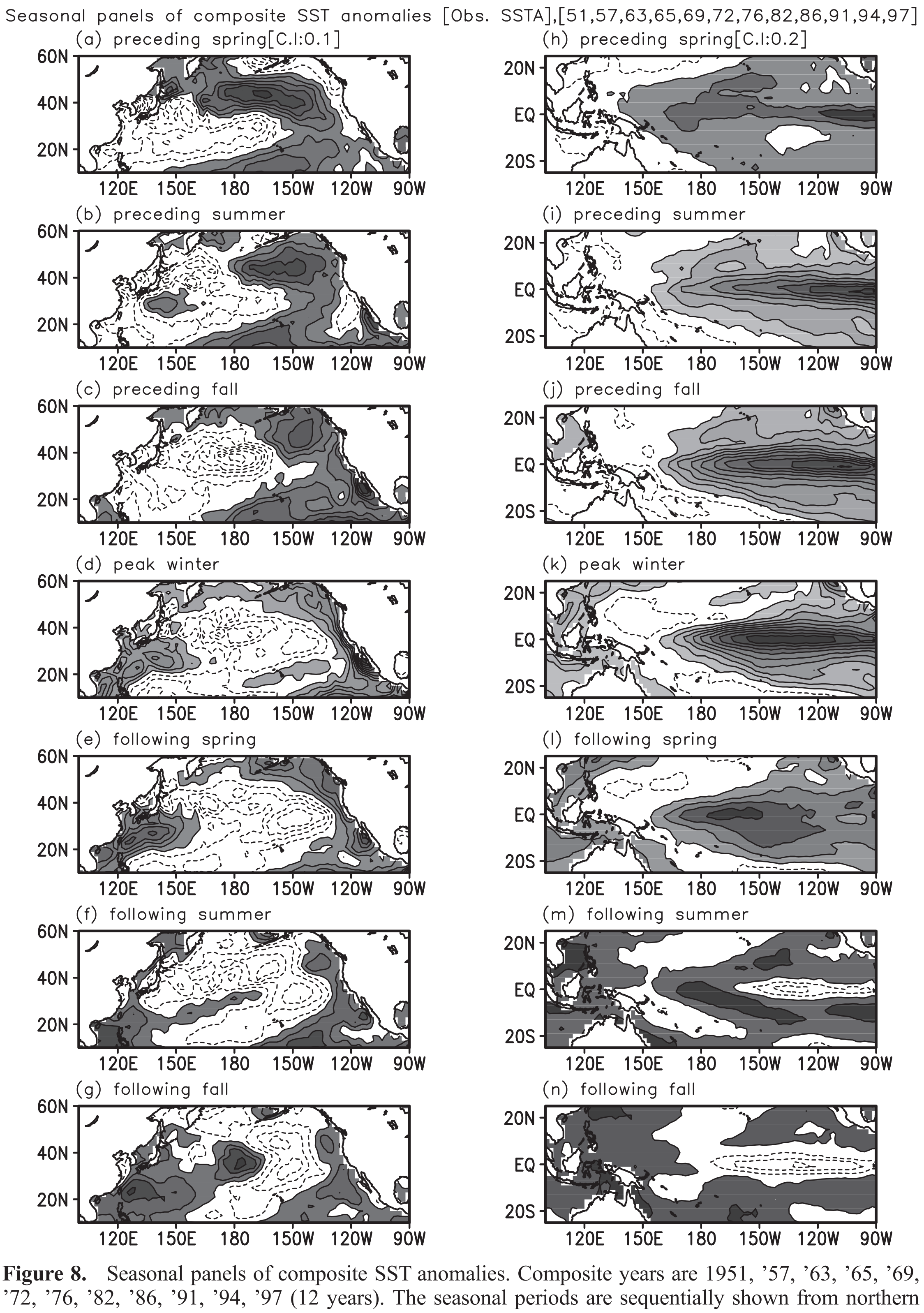

Figure 8. Seasonal panels of composite SST anomalies. Composite years are 1951, '57, '63, '65, '69, '72, '76, '82, '86, '91, '94, '97 (12 years). The seasonal periods are sequentially shown from northern spring (a) to the fall of the next year (g) in the North Pacific. (h)–(n) As in (a)–(g) except the tropical Pacific (100°E–270°E, 25°S–25°N). The contour interval is 0.1°C for (a)–(g) and 0.2°C for (h)–(n). The negative values are depicted by dashed line.

Pacific SSTA yields two modes on interannual and decadal timescales. The North Pacific SST variability on these two timescales has different spatial structures and it is most apparently in the second EOF mode. The interannual mode has only one center of action, whereas the decadal variability has two centers of action in the western and southern North Pacific.

[38] We explore the characteristic evolution of the North Pacific SST variability based on an EEOF analysis. This result suggests that the North Pacific SST variability has two fairly well separated timescales, i.e., decadal and interannual with different spatial structures. The evolutionary characteristics of these two structures are also different from each other. The basin-scale positive SSTA in the dominant decadal SST variability changes into a westward-intensified pattern in the western and southern part of the North Pacific. The spatial-temporal pattern of interannual SST variability shows a basin-scale propagating structure. As time progresses, the basin-scale positive SSTA propagates to the east and the negative SSTA, which is oriented to the northeast to the southwest, increase in the western and central North Pacific.

[39] Our results are different from that of *Latif and Barnett* [1994]. The spatial pattern of interannual SST variability is reminiscent of the leading CEOF identified by *Latif and Barnett* [1994]. The difference is that the *Latif and Barnett* [1994] mode has a decadal time, whereas the mode identified here is primarily interannual. The spatial pattern of North Pacific decadal SST variability described here also does not indicate a clockwise propagation as described by *Latif and Barnett* [1994].

[40] In order to examine the relationship between the North Pacific and the tropics, first, we separately computed the simultaneous correlation between Pacific SSTA and the first two PCs on both decadal and interannual timescales. These correlations suggest that the peak phase of the decadal mode in the North Pacific leads the tropics and the interannual mode is simultaneously related to the tropics.

[41] Based on the EEOF analysis for the larger Pacific domain, we clarified the lead-lag relationship between the North Pacific and the tropics. The EEOF analysis was applied to the SSTA in two different ways. First, the ENSO signal was removed from the data and then the EEOFs were calculated. Second, the EEOFs were calculated on only that part of the SSTA that is linearly and contemporaneously related ENSO.

[42] The first basin wide EEOF analysis clearly showed the decadal lead-lag relationship between the North Pacific and the tropical Pacific. The spatial-temporal structure of SSTA variability comprises a single developing mode in which the dominant North Pacific decadal variability leads the dominant tropical decadal variability by approximately 5 $\sim$ 7 years. As the decadal tropical SST variability progresses to a mature state, the dominant North Pacific decadal variability changes into two distinct structures. These structures seem to be closely associated with the strength of subpolar and subtropical gyre, respectively. Recent observations in the North Pacific shows that the subpolar gyre-scale structure, which is related to the main thermocline in the North Pacific, is intensified in the western part of the basin north of 30°N. This intensification can also be seen as an increase in the transport of the Kuroshio current from the early 1970s and the mid-1980s [*Deser et al.*, 1999; *Miller et al.*, 1998; *Kawabe*, 1995]. Our result suggests that this Kuroshio intensification is related to the evolution of the tropical decadal SST variability.

[43] These results suggest a possible midlatitude influence in the tropics. Moreover, despite the fact that the decadal lead-lag relationship between the tropics and extratropics has not been previously noted, there are several possible mechanisms for the midlatitudes to influence the tropics [*Gu and Philander*, 1997; *Xu et al.*, 1998; *Schneider et al.*, 2001; *Barnett et al.*, 1999; *Kleeman et al.*, 1999; *Pierce et al.*, 2000] (and many authors). Recently, *Zhang et al.* [1998] presented observational evidence that at middle latitudes a subsurface warm anomaly formed in the early 1970s from subducted surface-waters and penetrated through the subtropics and into the tropics.

[44] The second basin wide EEOF analysis, which is based on the SSTA that is linearly and contemporaneously related to ENSO, showed that the peak phase of the interannual mode in the North Pacific has a strong connection to ENSO variability. Note that the spatial structure of peak phase on interannual timescales is zonally extended with a basin-scale in the North Pacific. However, compared to the result of EEOF mode restricted to the North Pacific, the spatial-temporal structure did not show a basin-scale propagating pattern in the North Pacific on interannual timescales. These propagating structures in the North Pacific were identified in a composite analysis based on the NINO3 SST index. The negative SSTA during the northern spring, which has a northeast-southwest orientation in the southern part of the North Pacific, propagates to the east and stretches across the North Pacific to the west coast of the North America as time progresses. These results indicate that on interannual timescales, the tropics seems to be simultaneously related to this North Pacific SSTA variability in each peak phase structure. Also, the second EOF mode, which has a northeast to southwest orientation in the southern North Pacific, seems to be a precursor mode of ENSO variability. Understanding this result requires further analysis.

[45] Our result does not exclude the role of the southern Pacific. Figures 5a and 5b and Figures 6a–6d show a significant signal in the southern Pacific which may have important effects on the tropical decadal variability. *Luo and Yamagata* [2001] and *Giese et al.* [2002] suggested that the propagation of subsurface temperature anomalies off the equator in the Southern Hemisphere are closely related to the ENSO-like decadal variation between the tropical Pacific and the South Pacific.

[46] We briefly discussed the relationship between the North Pacific and the tropical SSTA on decadal and interannual timescales. Our result suggests that the temporal-spatial progress for both decadal and interannual variability in the North Pacific are connected to the evolution of tropical SST variability with different lead-lag relationships. Still, some important questions remain open. For example, the physical mechanism of how North Pacific variability impacts tropical decadal variability is entirely unexplained.

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B. P. Kirtman and S.-W. Yeh, Center for Ocean-Land-Atmosphere Studies, 4041 Powder Mill Road, Suite 302, Calverton, MD 20705, USA. (swyeh@cola.iges.org)