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DECADAL SCALE CHANGES IN THE ANNUAL CYCLE OF THE NORTH PACIFIC SEA-SURFACE TEMPERATURE

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ABSTRACT

Climatic variability of the annual cycle of the sea-surface temperature (SST) is studied in terms of long-term and pentadal (5 years) anomalies of amplitudes of annual cycle as well as of anomalies of annual, winter, and summer means. Anomalies of annual and seasonal means clearly indicate North Pacific climate shifts.

During the 1950s and 1960s, anomalies of annual amplitudes tended to result in anomalies of annual means of the same sign, later (in the 1970s) in anomalies of opposite sign. It was found out that these changes are due principally to different roles of seasonal anomalies in the formation of the annual cycle of SST. Before the North Pacific climate shift of the mid-1970s, anomalies in amplitudes of annual cycle were generally determined by summer anomalies. In the 1970s, winter anomalies played the leading role in the formation of annual cycle of SST. This switch from the governing role of summer anomalies to that of winter anomalies took place prior to the North Pacific climate shift. In the 1980s summer SST anomalies in the central North Pacific became stronger again.

Analysis of time series of spatially averaged and low-pass filtered summer and winter SST anomalies has revealed that in the southeastern North Pacific (near Baja California), winter and summer anomalies have approximately the same magnitude, though during the 1970s and 1980s winter anomalies were a bit stronger than summer ones. On the contrary, in the central North Pacific, during certain climatic periods (1950s, 1960s and 1980s), summer anomalies were essentially stronger than winter anomalies. Wavelet analysis demonstrated that interdecadal variations in the central North Pacific are much more pronounced in summer SSTs, while in the southeastern North Pacific interdecadal variations are slightly stronger during wintertime. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: North Pacific ocean; sea-surface temperature; decadal–interdecadal variability; seasonal anomalies; harmonic analysis; low-pass filtering; wavelet analysis

1. INTRODUCTION

The North Pacific climate shift of the mid-1970s has been noted and described by a number of investigators (Nitta and Yamada, 1989; Tanimoto *et al*., 1993, 1997; Graham, 1994; Trenberth and Hurrell, 1994; Nakamura *et al*., 1997) as the most striking manifestation of interdecadal variability in the ocean–atmosphere system. Briefly, this climate shift can be described as a sharp change in polarity of winter sea-surface temperature (SST) anomalies in the central and the southeastern North Pacific that occurred in 1976. As a result, positive anomalies of SSTs in the central North Pacific were replaced by negative anomalies. Opposite changes occurred in the southeastern North Pacific. At the same time, a strengthening of the Aleutian low and a related shift of the North Pacific storm track (Nitta and Yamada, 1989; Trenberth and Hurrell, 1994) are considered as atmospheric manifestations of the North Pacific climate shift. An opposite shift in the North Pacific climate in the late 1980s has been documented in many papers (Kachi and Nitta, 1997; Nakamura *et al*., 1997; Watanabe and Nitta, 1999), but it was not as strong as the climate shift of the mid-1970s.

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During the last few years several mechanisms have been suggested to explain decadal-scale variations in the North Pacific. Results of Nitta and Yamada (1989), Trenberth (1990) and Graham *et al*. (1994) suggest that decadal-scale changes in the tropical Pacific SST and convection could force the changes in the mid-latitude atmospheric circulation over the North Pacific during the mid-1970s. In the mid-latitudes local air–sea interaction may amplify the decadal-scale signal over the North Pacific (Trenberth, 1990; Trenberth and Hurrell, 1994; Yukimoto *et al*., 1996). Latif and Barnett (1994), Robertson (1996) and Jin (1997) debate that coupled extratropical air–sea interaction involving dynamics of the ocean gyre may result in self-sustained decadal-scale oscillations of the North Pacific climate system.

Because of the stronger persistence of the SST anomalies and the more intense coupling between ocean and atmosphere, most of the studies of large-scale ocean–atmosphere interaction in extratropics are focused on analysis of winter SST variability. Only a few papers (Namias and Born, 1970; Alexander and Deser, 1995; Zhang *et al*., 1998) consider summer SST anomalies. Results of Namias and Born (1970) and Alexander and Deser (1995) suggest that SST anomalies at fixed locations exhibit little memory from summer to the next winter and that the memory of the coupled system from one winter to the next resides in the subsurface temperature anomalies. On the other hand, more recent results of Zhang *et al*. (1998) indicate that the dominant mode of SST anomalies, defined by empirical orthogonal function (EOF) and singular-value decomposition (SVD) analyses, exhibits much more persistence from summer to the next winter than the local SST anomalies, which had been analysed in the earlier studies (Namias and Born, 1970; Alexander and Deser, 1995). Zhang *et al*. (1998) have also shown that this pattern is more persistent from one summer to the next than from one winter to the next, reflecting the relatively greater prominence of the interdecadal variability in the summertime SST anomalies. In an attempt to explain their results Zhang *et al*. (1998) speculate that some kind of positive feedback process can be effective at the air–sea interface during the summertime. In a companion paper, Norris *et al*. (1998) have shown that marine stratiform cloudiness plays an important role in atmosphere–ocean coupling over the North Pacific during the summer season when latent and sensible heat fluxes are not as dominant and the coupling between atmospheric circulation and SST is not as strong as in winter.

Most climatic studies, including those mentioned above, are based on analysis of climatic means, i.e. monthly, seasonal and annual means. At the same time it is quite obvious that different amplitudes of annual cycle can characterize 2 years having equal annual means, i.e. intensities of seasonal processes during these 2 years can be quite different. Thus, positive (negative) trends or anomalies of amplitudes of annual cycle do not necessarily result in positive (negative) trends and anomalies of annual means. Therefore, it appears that investigation of long-term changes of intensities of different scale processes and their relationships to variations of climatic means is very reasonable and can improve the understanding of climate variations.

In the present study climatic changes are analysed by focusing on amplitudes of annual cycle of SSTs and their relationships with changes of annual and seasonal means with respect to observed North Pacific climate shifts. Special emphasis is on the seasonality of decadal scale SST variations in the central and the southeastern North Pacific.

2. DATA AND METHODS

In the present study data from the Reconstructed Reynolds SST data (provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, CO, from their Web site at http://www.cdc.noaa.gov/) were used.

To produce this data set, the dominant EOFs modes were used as basis functions and were fitted to the *in situ* data to determine the time dependence of each mode. Global fields of SSTs were then reconstructed from these spatial and temporal modes (Reynolds and Smith, 1994; Smith *et al*., 1996). In this study monthly means are analysed from January 1950 to December 1997 on the 2° latitude × 2° longitude grid. The domain of analysis is limited within latitudes 0°–65°N, and longitudes 100°E–80°W.

The analysis scheme used in this study has been suggested by Lappo *et al*. (1986). According to this scheme, time series were decomposed into deterministic and random components that were represented in turn as a sum of fast and slowly varying terms. The deterministic component was represented by the seasonal cycle ($\tilde{X}(t)$). The random component comprised interannual variability ($\bar{X}(t)$), non-regular intraseasonal oscillations ($\hat{X}(t)$), and noise ($\zeta(t)$) associated with high frequency processes and data errors. $\zeta(t)$ was considered as non-correlated additive noise. Thus, the statistical model of time series has the form:

$$X(t) = \tilde{X}(t) + \bar{X}(t) + \hat{X}(t) + \zeta(t) \tag{1}$$

and polyharmonic seasonal cycle:

$$\tilde{X}(t) = \sum A_i \cos(\omega_i t + \varphi_i) + \bar{X}, \tag{2}$$

where n is the number of harmonics, ω_i, A_i and φ_i are, respectively, the frequencies, amplitudes and phases, and $\bar{X}$ denotes the climatic mean.

Making use of the above model, amplitudes and phases of annual cycle have been estimated for three climatic periods (i.e. 1951–1976, 1977–1988, and 1989–1997) and for each pentad (5-year period) beginning from 1951 (i.e. for 1951–1955, 1956–1960, ..., 1991–1995). Subsequently, anomalies of the above characteristics have been calculated by subtracting 'climatic' amplitudes and phases, which were estimated for the whole time period (1951–1997). Analogously, anomalies of annual and seasonal (winter and summer) means have been calculated for each climatic period and for each pentad. Because any essential changes of phases of annual cycle have not been found, they are not under consideration in the present paper.

To analyse time evolution of seasonal anomalies, wavelet analysis was applied to time series of regionally (for the central and the southeastern North Pacific) averaged winter and summer SST anomalies. In this analysis discrete wavelet transform (Strang and Nguyen, 1996) was used based on the so-called compactly-supported orthonormal wavelets of the Daubechies family (Daubechies, 1992).

3. LONG-TERM ANOMALIES OF ANNUAL CYCLE AMPLITUDES

Anomalies of annual amplitudes and of annual means of SSTs are presented in Figure 1. The anomalies are estimated for climatic periods defined due to the recent climate shifts in the North Pacific region. For the period 1951–1976 amplitudes of annual cycle of SST are close to their mean climatic values, and anomalies of amplitudes are close to zero over the most of the North Pacific (Figure 1(a)). Anomalies of annual mean SSTs during this period are well pronounced and reveal two maxima (Figure 1(d)). The first one is characterized by the highest (up to +0.3°C) positive anomalies along 40°N and is attributed to the Kuroshio Current extension. The second maxima is located near Baja California, where values of negative anomalies reach −0.3°C.

During 1977–1988, in agreement with other studies (Nitta and Yamada, 1989; Tanimoto *et al*., 1993; Graham, 1994; Trenberth and Hurrell, 1994; Nakamura *et al*., 1997), the polarity of anomalies of annual mean SSTs is reversed (Figure 1(e)). The central North Pacific is dominated by strong negative anomalies (up to −0.7°C), while maximum positive anomalies are observed near Baja California. Anomalies of amplitudes of annual cycle (Figure 1(b)) are, in general, of opposite sign to anomalies of annual means. They are positive in the central North Pacific and negative near Baja California.

Though not as strong as during 1977–1988, anomalies of annual mean SSTs in 1989–1997 have the same polarity (Figure 1(g)), demonstrating that the climate shift of 1988 was not as sharp as that of 1976. On the contrary, polarity of anomalies of annual amplitudes has changed (Figure 1(d)). During this period, in general, anomalies of annual amplitudes are attributed to anomalies of annual means of the same sign. The exception is the region in the central North Pacific between 150°W and the date line. Therefore, each of these three climatic periods demonstrates quite a different relationship between anomalies of amplitudes of annual cycle and anomalies of annual mean SSTs in the North Pacific.

Obtained relationships can be explained by the different roles of winter and summer SSTs in the formation of annual cycle during the considered climatic periods. Winter (December–January–February) and summer (June–July–August) anomalies estimated for the same periods are presented in Figure 2. To make the further considerations more understandable, it is noted that signs of winter and summer SST anomalies coincide over most of the North Pacific. In the case of positive anomalies, stronger winter (summer) anomalies will result in negative (positive) anomalies of amplitudes of annual cycle. In the case of negative SST anomalies, the relationship between seasonal anomalies and anomalies of amplitudes is opposite. Therefore, the relative strength of winter (summer) anomalies defines the sign of anomalies of annual cycle amplitudes. As is seen in Figure 2, not only winter, as it was noted in earlier studies (Nitta and Yamada, 1989; Tanimoto *et al.*, 1993; Graham, 1994; Trenberth and Hurrell, 1994; Nakamura *et al.*, 1997), but summer SST anomalies reflect recent North Pacific climate shifts pretty well. During 1951–1976, winter and summer SST anomalies, in general, are of the same magnitude over the most of the North Pacific (Figure 2(a), (d)), and their values are practically the same as those of anomalies of

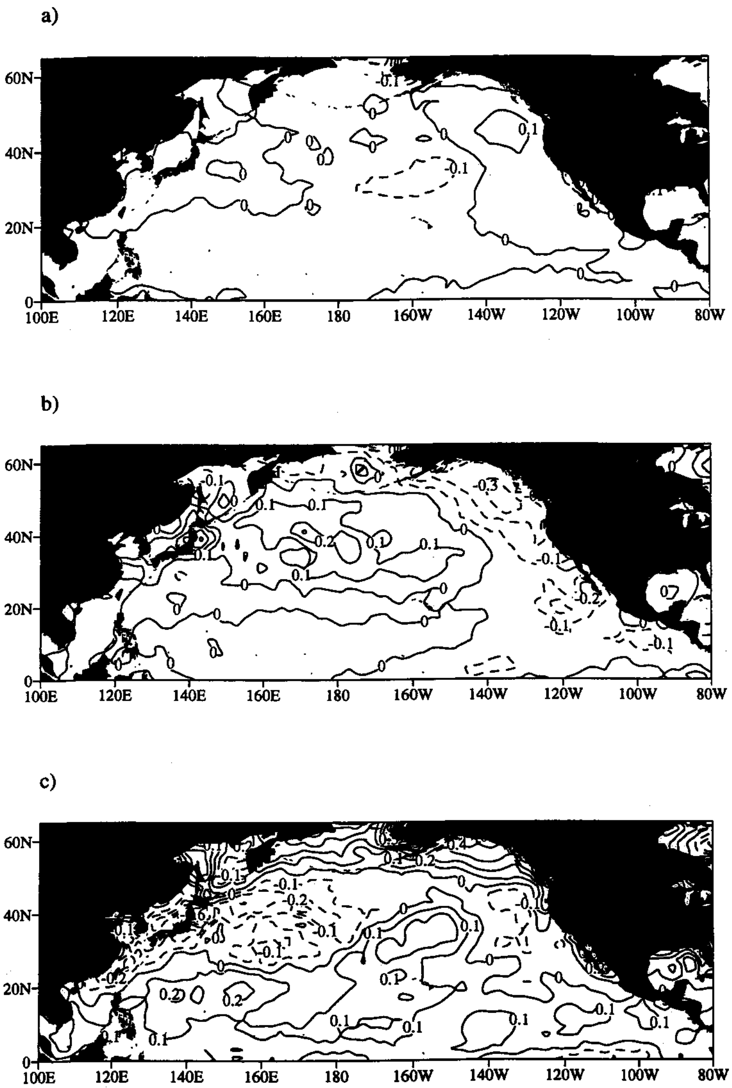

Figure 1. Anomalies (°C) of amplitudes of annual cycle (a, b, c) and of annual mean of SSTs (d, e, f), averaged for 1951–1976 (a, d), 1977–1988 (b, e), and 1989–1997 (c, f). Solid (dashed) lines represent positive (negative) values

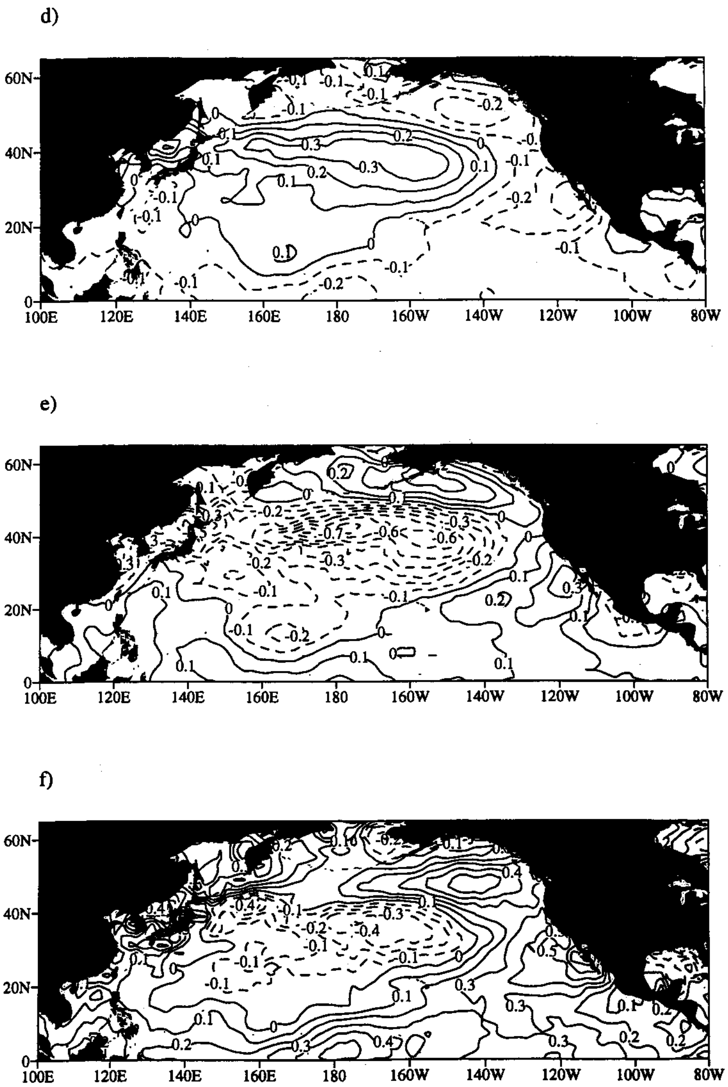

Figure 1 (*Continued*)

annual mean SSTs (Figure 1(d)). This results in zero anomalies of amplitudes of annual cycle (Figure 1(a)).

In 1977–1988, winter SST anomalies (both positive and negative) were, in general, stronger than summer anomalies (Figure 2(b), (e)). As a result, anomalies of annual amplitudes have the opposite sign to that of anomalies of annual mean SSTs (Figure 1(b), (e)). During 1989–1997, positive SST anomalies near Baja California were stronger in summertime (Figure 2(c), (f)), resulting in positive anomalies of amplitudes of annual cycle (Figure 1(c)). The maximum of negative summer SST anomalies in the central North Pacific was shifted to the west (Figure 2(f)), and anomalies of annual amplitudes in this region are negative too.

The considered anomalies and their relationships represent general characteristics of the climatic periods. It is apparent, however, that the strength of anomalies and their relationships can vary essentially during a particular climatic period. To look at such variations, pentadal (i.e. for a 5-year period) SST anomalies were estimated beginning from 1951. It appears that anomalies estimated for pentades after the North Pacific climate shift of 1976 (not shown) represent, in general, the same features as those defined for the above considered climatic periods 1977–1988 and 1989–1997. During 1951–1976, however, the strength of the seasonal anomalies essentially varied. The role of winter and summer SST anomalies in the formation of the annual cycle changed as well. During the first three pentades (1951–1955, 1956–1960, 1961–1965) summer SST anomalies were stronger than winter ones. In particular, a notable difference in the strength of seasonal anomalies is clearly seen in 1961–1965 (Figure 3). In the central North Pacific along 40°N, summer SST anomalies (1.4°C) are twice as high as winter anomalies (0.6°C). Negative SST anomalies near Baja California are also stronger during the summertime (Figure 3).

During pentad 1966–1970, winter and summer SST anomalies in the North Pacific were approximately of the same magnitude (not shown). In the next pentad (1971–1975), preceding the North Pacific climate shift, winter SST anomalies became stronger than summer anomalies (Figure 4). In the central North Pacific, values of winter anomalies reach 0.6°C, and near Baja California they are up to − 1.0°C (Figure 4(a)). Maximum summer SST anomalies in the respective regions are 0.4 and − 0.6°C. Therefore, since that time (1971–1975), winter SST anomalies have played a leading role in the annual cycle formation. As a result, the previously described relationship between anomalies of annual amplitudes and anomalies

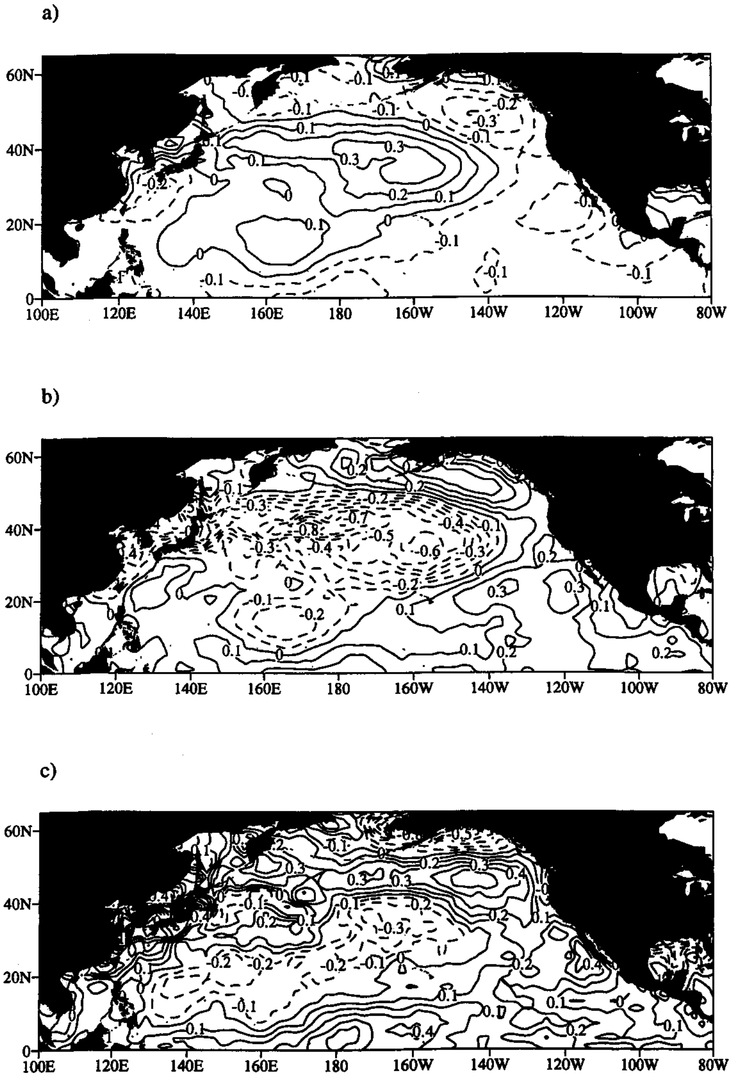

Figure 2. Same as Figure 1, but for winter (a, b, c) and summer (d, e, f) SST anomalies

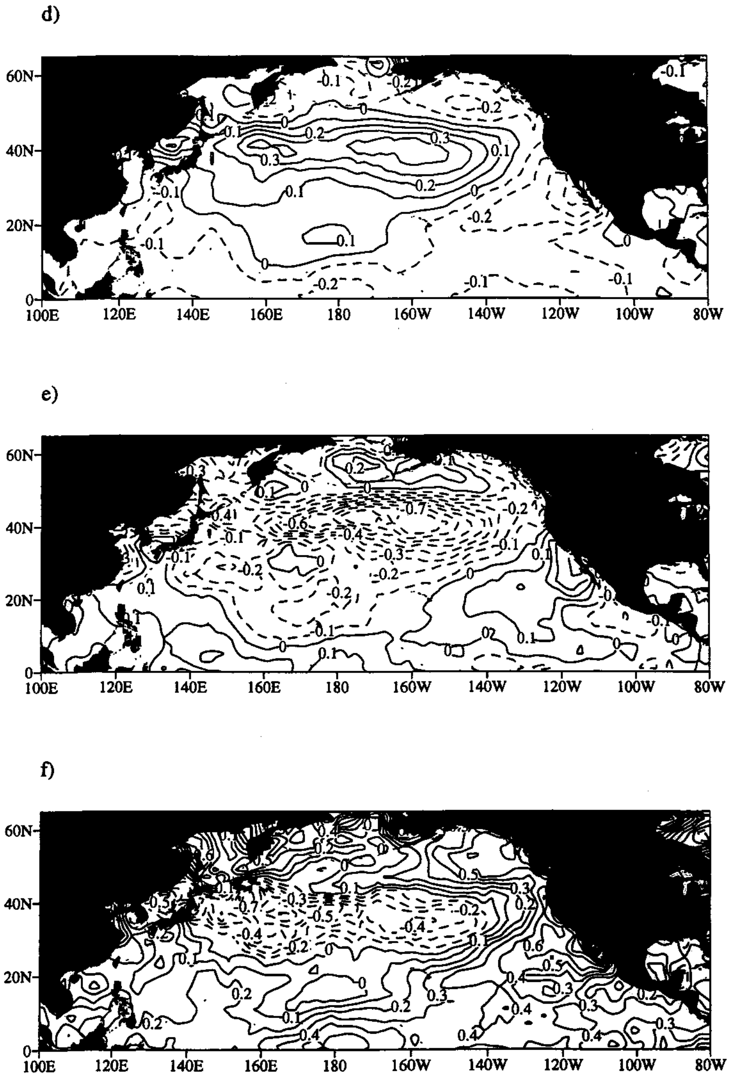

Figure 2 (*Continued*)

of annual mean SSTs has changed. However, in pentad 1981–1985 (not shown), the dominant role in the annual cycle formation reverted back to summer SST anomalies.

It would be very tempting to find anomalies of phases of the SST annual cycle related to changes defined in amplitudes and annual and seasonal means, but the analysis has not revealed such anomalies of phases. Over most of the North Pacific during the considered period (1951–1995) anomalies of phases are equal to zero. There are some small and statistically insignificant anomalies in the near equatorial region only. Therefore, it appears that phase is a more stable characteristic of the annual cycle of SST than its amplitude.

4. SEASONALITY OF DECADAL SCALE CHANGES

To analyse long-term evolution of sesasonal SST anomalies, time series of spatially averaged anomalies are considered in this section. To obtain these time series, summer and winter SST anomalies were

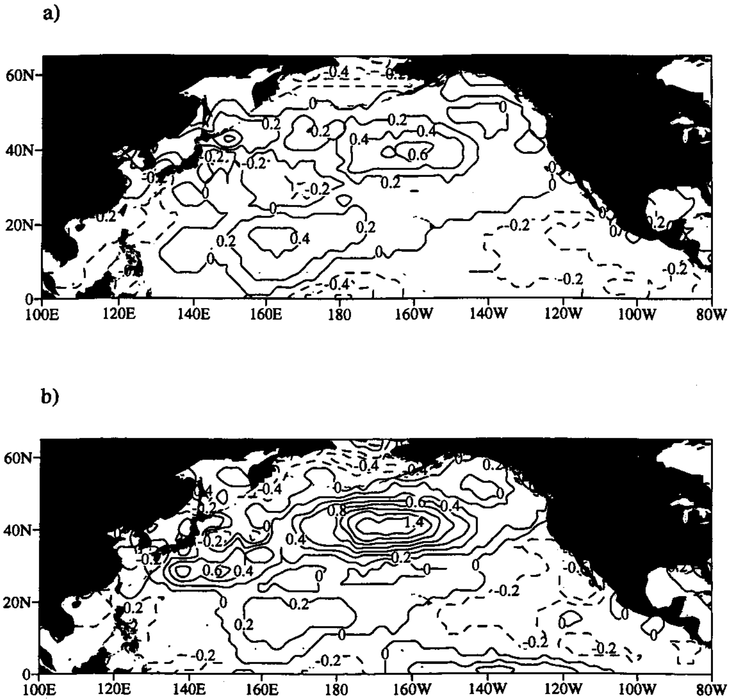

Figure 3. Winter (a) and summer (b) SST anomalies (°C) for 1961–1965. Solid (dashed) lines represent positive (negative) values

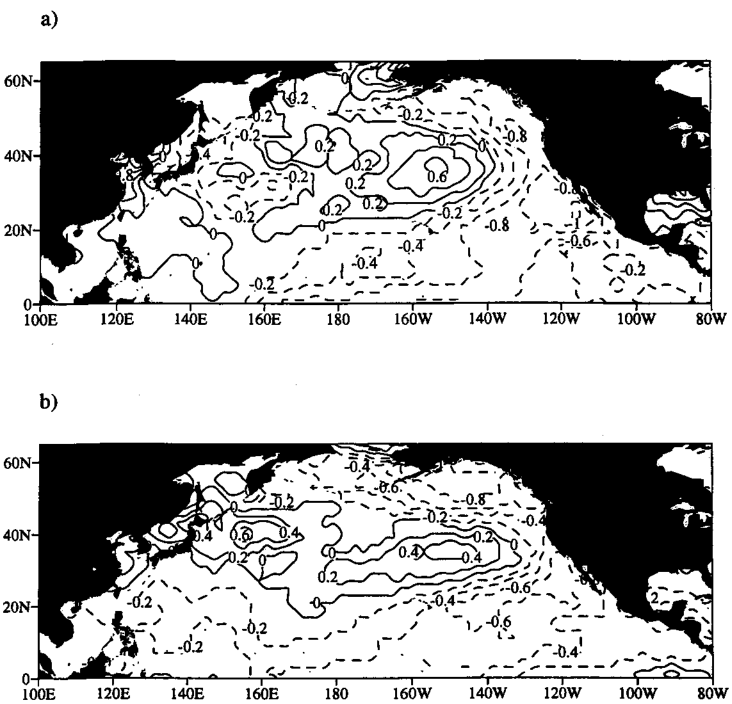

Figure 4. Same as Figure 3, but for 1971–1975

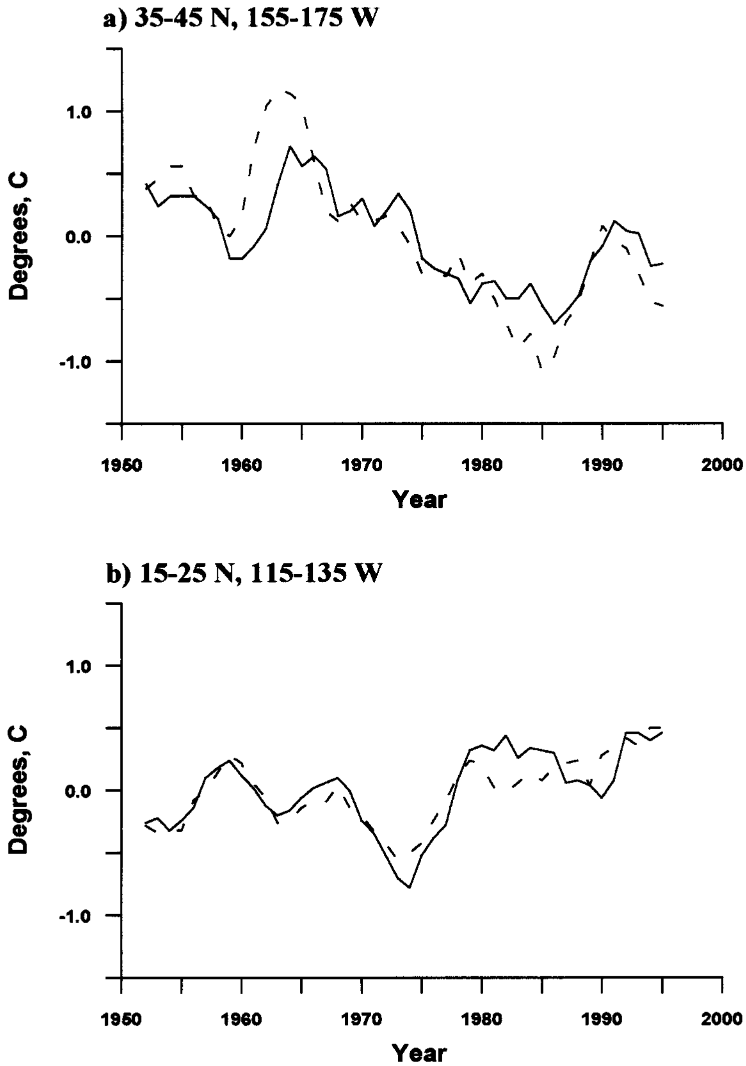

Figure 5. Time series of spatially averaged SST anomalies for the central (a) and the southeastern (b) North Pacific. Five-year running mean filtering is applied. Winter (summer) SST anomalies are presented by solid (dashed) lines

averaged for the two key regions of the North Pacific SST variability—the central North Pacific along 40°N, and the southeastern North Pacific near Baja California. Domains of spatial averaging were bounded by 35°–45°N and 155°–175°W for the central North Pacific, and by 15°–25°N and 115°–135°W for the southeastern North Pacific. To highlight decadal scale variability, a 5-year running mean filtering was applied. Time series of low-passed summer and winter SST anomalies are presented in Figure 5. Although opposite changes in the SST anomalies in the central and southeastern North Pacific have been documented during North Pacific climate shifts, it is seen that SST variations in these two regions cannot be treated as out-of-phase oscillations. Though statistically significant at the 95% confidence level according to the t-test (Bendat and Piersol, 1966), estimated correlation coefficients are not very high (-0.45 for the summer time series, and -0.49 for the winter time series). Previously defined periods of dominance of summer (winter) SST anomalies are also clearly seen in Figure 5. It is obvious that interdecadal variability is more pronounced in the central North Pacific, and summer SST anomalies demonstrate higher magnitudes on this time scale.

Though changes in winter and summer SST anomalies in the central and the southeastern North Pacific are evident, the presented time series of SST anomalies demonstrate that the North Pacific climate shift of the late 1980s was not as strong as that of the mid-1970s.

To investigate the structure of SST variability in the central and the southeastern North Pacific, the wavelet transform was applied to the time series of unfiltered winter and summer SST anomalies. The discrete wavelet transform (Strang and Nguyen, 1996) was performed, using the db4 wavelet of the compactly-supported orthonormal wavelets of the Daubechies family (Daubechies, 1992). Results of the wavelet decomposition of signals are shown in Figures 6 and 7. In terms of wavelet analysis the upper panels present approximations, i.e. low-frequency content of signals. Three other panels present details, i.e. higher-frequency components of signals. In this analysis, approximations represent interdecadal variations of SST, and details represent interannual and decadal scale variabilty.

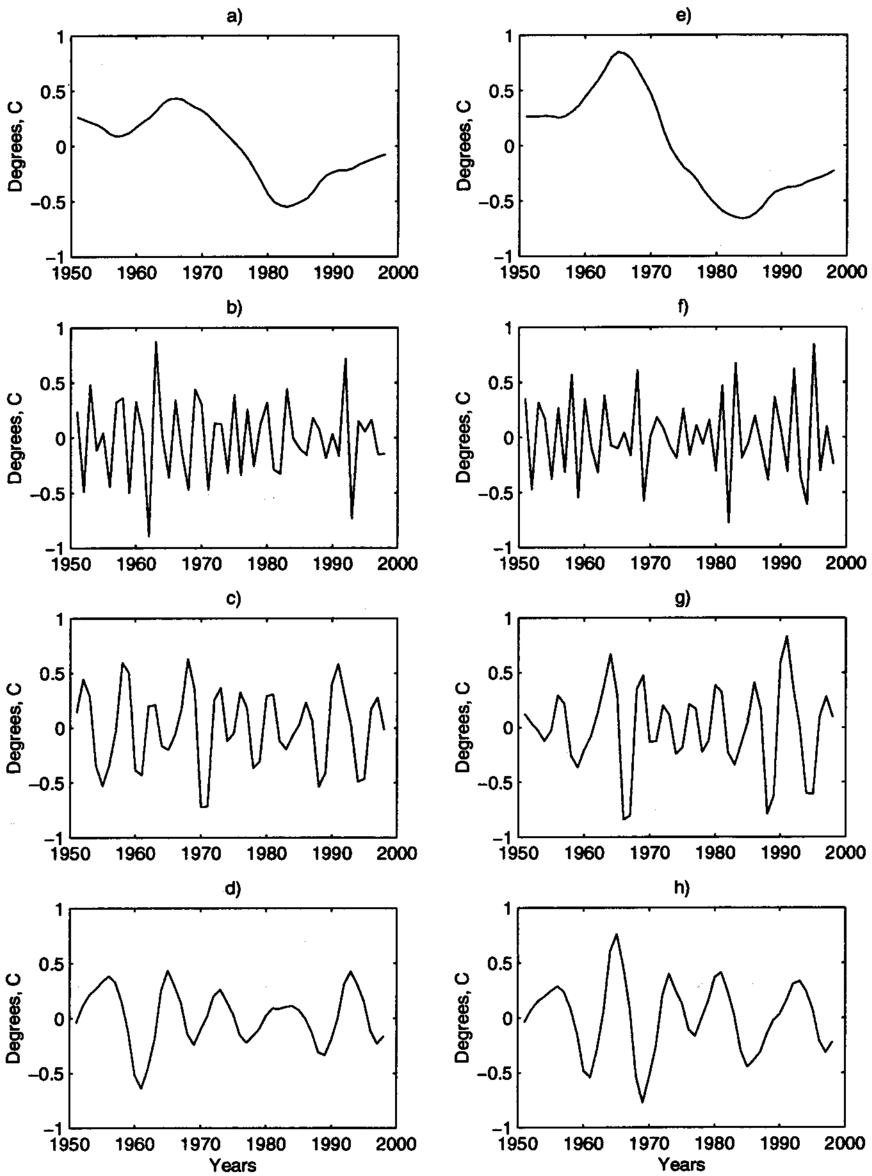

Figure 6. Wavelet transform of time series of winter (a, b, c, d) and summer (e, f, g, h) SST anomalies in the central North Pacific

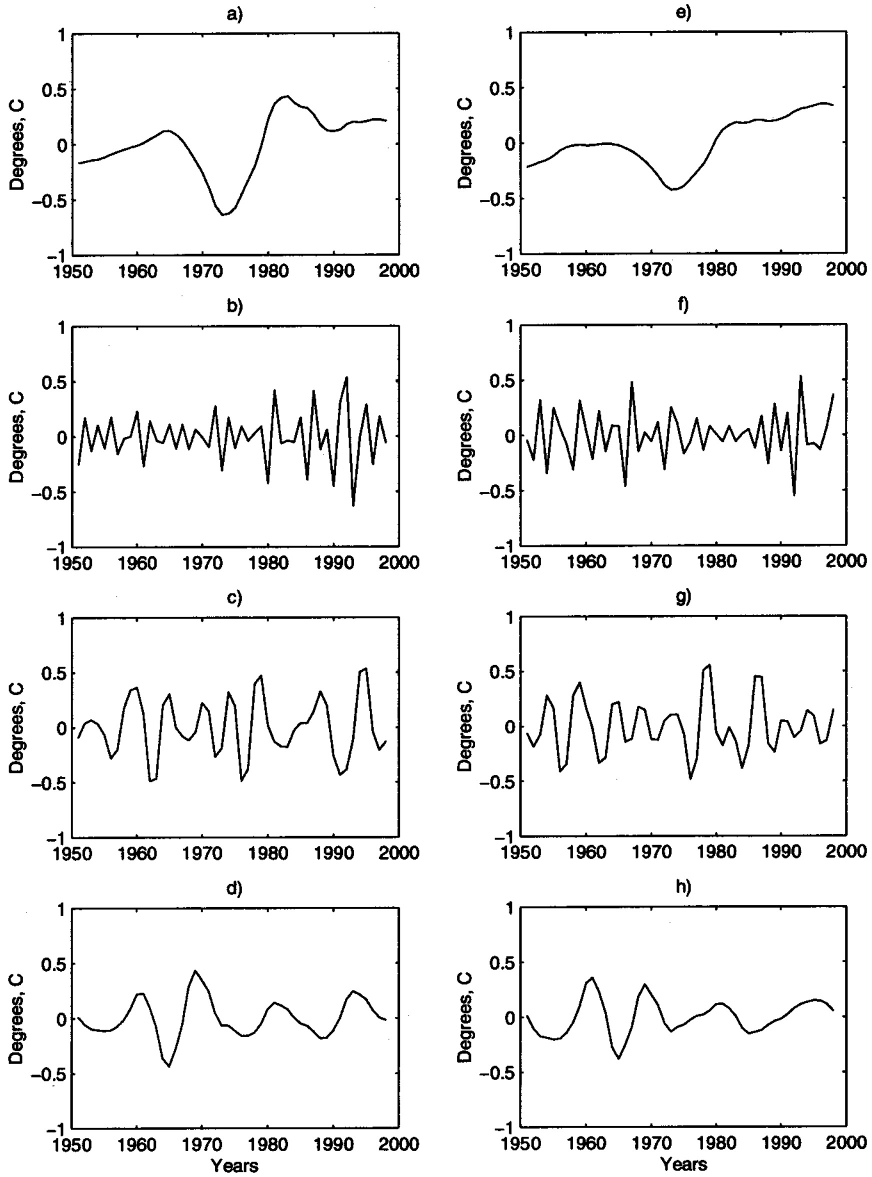

Figure 7. Same as Figure 6, but for the southeastern North Pacific

In the central North Pacific, interannual variations of the winter and summer SSTs are of the same magnitude (Figure 6(b), (c), (f), (g)). On the contrary, on decadal (Figure 6(d), (h)) and especially interdecadal time scales (Figure 6(a), (e)), summer SSTs demonstrate much stronger variability with higher magnitudes. Therefore, results of wavelet transform confirm the above defined greater prominence of the interdecadal variability in the summertime SST anomalies in the central North Pacific.

Interdecadal variations in the southeastern North Pacific summer SSTs are essentially weaker than those in the central North Pacific (Figures 6(e) and 7(e)). They are also slightly weaker than interdecadal variations in winter SSTs in the southeastern North Pacific (Figure 7(a)). In general, decadal–interdecadal variability is more pronounced in winter SST anomalies in this region. The remarkable intensification of the winter interannual variability near Baja California during the 1980s and 1990s is noteworthy (Figure 7(b)). This enchancement of magnitudes of interannual variability can be interpreted as a reflection of the intensification of El Nino–Southern Oscillation during the last two decades. At the same time, magnitudes of decadal scale variability are decreased during this period (Figure 7(d)).

5. CONCLUDING REMARKS

The present study has demonstrated that the recent North Pacific climate shifts were pronounced not only in winter mean SSTs as it was described in earlier studies (Nitta and Yamada, 1989; Tanimoto *et al*., 1993, 1997; Graham, 1994; Trenberth and Hurrell, 1994; Nakamura *et al*., 1997) but in annual and summer means as well. Related changes in amplitudes of annual cycle are documented, revealing different roles of winter and summer SST anomalies in the annual cycle formation. It appears that during the 1950s, 1960s and 1980s summer anomalies, especially in the central North Pacific, were in general stronger than winter ones. As a result, during these periods, anomalies of amplitudes of annual cycle of SSTs were attributed to anomalies of annual means of the same sign. From the early 1970s until the early 1980s, winter anomalies were in general stronger than summer ones, resulting in the reversed relationship between anomalies of amplitudes of annual cycle and anomalies of annual means. The changes of roles of seasonal anomalies in SST annual cycle formation occurred before North Pacific climate shifts is noteworthy.

Time series and wavelet analyses of spatially averaged (for the central and the southeastern North Pacific) seasonal SST anomalies have shown that summer SSTs in the central North Pacific have essentially higher magnitudes of variability on decadal–interdecadal time scales. Therefore, decadal and especially interdecadal variability are much more prominent in the summertime SST anomalies. In the southeastern North Pacific decadal and interdecadal SST variations are slightly stronger during wintertime.

Results of this study support, in general, results obtained by Zhang *et al*. (1998) from analysis of SSTs from the Comprehensive Ocean–Atmosphere Data Set (Fletcher *et al*., 1983). There is, however, an important difference. Zhang *et al*. (1998) explain the contradiction of their results with results of Namias and Born (1970) by the fact that in the latter study, the SST anomalies at fixed grid points were examined, while Zhang *et al*. (1998) analysed SST patterns defined by means of EOFs and SVD analyses. In fact, SST anomalies at fixed grid points were analysed in this study, but results obtained were close to those of Zhang *et al*. (1998). The principal difference between the present results and the ones of Namias and Born (1970) can be explained by a discrepancy in the quality of data used in these studies. It seems that a more reliable explanation is that in the present analysis SSTs from the Reconstructed Reynolds SST data set were used. As was mentioned in Section 2 EOF analysis has been used to reconstruct SST fields of this data set. Therefore, resulting SSTs are influenced by this procedure and carry the features of the dominant SST patterns.

While it is known (Kawamura, 1984; Cayan, 1992a,b; Iwasaka and Wallace, 1995) that winter SST anomalies are generated primarily through the latent and sensible heat fluxes at the air–sea interface driven by fluctuations in the atmospheric circulation (Frankignoul, 1985), mechanisms of summer SST anomalies formation are not as obvious. Norris *et al*. (1998) demonstrated a significant role of low cloudiness in summertime ocean–atmosphere interaction in the North Pacific. More recently, Norris (2000) has shown that variations in the storm track exhibit significant coupling to variations in summertime cloudiness and SST across the North Pacific. Nevertheless, further comprehensive studies are needed in order to understand mechanisms of generation of summer SST anomalies and formation of their decadal–interdecadal variability.

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