COMPLEX EOF PATTERNS OF THE NORTHWEST PACIFIC SST ANOMALIES

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Introduction

Large-scale variations of sea surface temperature (SST) are conventionally recognized as standing oscillations with no significant signal propagation. This conception has recently been changing with emerging of the new paradigm for propagating SST anomalies. An evidence of a global El Nino – Southern Oscillation (ENSO) wave in surface temperature and pressure travelling in the tropical region along the equator is demonstrated in (White & Cayan, 2000). Enfield & Mestas-Nunez (2000) showed that moving signal in global SST anomalies is mostly associated with ENSO-related variability. The southwestward propagation of ENSO-scale SST anomalies was determined for the Northwest Pacific in winter, with Subtropics and Subarctics being 180° out of phase (Ponomarev *et al*., 2000, 2001); opposition of water temperature anomalies in the Northwest Pacific Subtropics and Subarctics was demonstrated earlier (White, 1977).

Dominant low-frequency timescales were earlier revealed in the Northwest Pacific. In the subtropical area warmer (cooler) wintertime SST occur during warm (cold) ENSO events, associated with weakening (strengthening) of the winter East Asian Monsoon and intensification (relaxation) Pacific jet stream (Hanawa *et al*., 1989). Hanawa (1995) also found that the Sverdrup transport and Far East Zonal Index fluctuate with the 6-7 yr. periodicity over the Northwest Pacific. Nakamura *et al*. (1997) showed that decadal North Pacific variability is centered in the subarctic frontal zone. Considering those facts and having the post-World War II rich observation history in the area, it is intriguing to resolve fine regional features of the low frequency Northwest Pacific SST variations. Based on higher resolution data sets, the present study is targeted on revealing standing and moving patterns and dominant timescales and relating them with atmospheric conditions over the North Pacific.

Data and Methods

Wintertime SST anomalies for 1945-1989 are obtained by averaging (from December through January) of 1°x1°-gridded monthly mean SST data retrieved from WMU/COADS World Atlas of Surface Marine Data (NOAA/NESDIS/NCDC CD-ROM, 1994). The area covers the Northwest Pacific and Far-Eastern marginal seas northward 20°N and westward 170°E, including more than 1500 grid locations.

To relate SST anomaly patterns to the atmospheric conditions over the North Pacific we use the following wintertime climatic indices. The Western Pacific Index (WPI; 1950-1989; Barnston & Livezey, 1987) represents a low-frequency temporal function of the "zonal dipole" sea level pressure spatial pattern with negative anomalies over Kamchatka Peninsula and positive anomalies over the southeastern Asia and far western tropical and subtropical North Pacific. In the positive phase the pattern corresponds to intensification of the Pacific – East Asian westerly jet stream. The East Asian Monsoon Index (MOI; 1935-1995; Hanawa *et al*., 1989) has its higher values pointing to the East Asian Monsoon strengthened and air temperature in the Japanese Islands lowered. To examine relationship to ENSO we use the Southern Oscillation Index (SOI; 1945-1989) and Nino3 Index (1949-1989). Lower negative (higher positive) values of SOI correspond to warm (cold) ENSO events (El Ninos or La Ninas), the opposite is true for Nino3.

To resolve standing/moving SST anomaly patterns we apply Complex Empirical Orthogonal Function (CEOF) analysis, the time-domain techniques (Horel, 1984). Spatial complex empirical orthogonal functions (CEOFs) and temporal principal components (PCs) are usually represented in amplitude/phase form, with phase confined in limits, for example, from -180° to 180°. Moving signal is characterized by steady phase propagation through amplitude maxima, while high phase gradient in low-amplitude areas only points to standing oscillation pattern. CEOF-related anomalies are reconstructed for core grid locations associated with CEOF amplitude maxima; lag correlation analysis is applied to reveal their relationship to atmospheric conditions.

Results

Spatial patterns of three principal wintertime CEOFs accounting for about 60% of total variance are represented in Fig. 1. The spatial phase patterns (Fig. 1b, d, e) suggest the presence of SST anomaly moving from the Subarctics to Subtropics, associated with CEOF1, while standing oscillations prevail in CEOF2 and CEOF3. In this paper we focus on propagating SST signal, so the main CEOF1 only is discussed hereafter.

The CEOF1 amplitude pattern has several cores which are located in the western subarctic gyre (45-52°N, 155-170°E), in the southern Japan Sea, northward Taiwan, along the Kuroshio Extension path, and inside the subtropical gyre centered around 160°E (Fig. 1a). The CEOF1-related core anomalies are denoted hereafter as CEOF1#1 – CEOF1#6. Spatial phase steadily increases south-southwestward, starting from -180° in the northern CEOF1#1 core and coming to zero in the subtropical CEOF1#5 and CEOF1#6 cores (Fig. 1b). So, the Northwest Pacific Subarctics are opposed to Subtropics in winter that corresponds to earlier findings (White, 1977).

Steady phase propagation trend between the cores and increase of temporal phase (Fig. 2b) demonstrate anomalies moving from the Subarctics to Subtropics, superimposed by standing oscillations revealed by conventional EOF techniques. This suggestion is confirmed by correlation between anomalies in CEOF1 cores (Fig. 3). Namely, zero-lag coefficient is equal to -0.997 for cores #1 and #6 180° phase lag, 0.99 for cores #5 and #6 (10° phase lag), 0.9 for cores #2 and #4 (22°), and just 0.39 for cores #4 and #6 (90° lag).

Any estimate of power spectrum based on 45 yr. winter time series would be unreliable, so we are left with indirect ways to determine characteristic timescales. The charts of temporal amplitude/phase (Fig. 2a, b) reveal interannual variability in PC1; ignoring marginal effects, one can estimate the dominating periodicity as 7 yrs according to PC1 phase. Lagged correlation patterns between the CEOF1-related SST anomalies lead to oscillation period estimate as 6-8 yr. (Fig. 3), with anomaly coming through from Subarctics to Subtropics in 3-4 yrs. Remarkably, White (1977) determined 3 yr. time shift between the Subarctics and Subtropics.

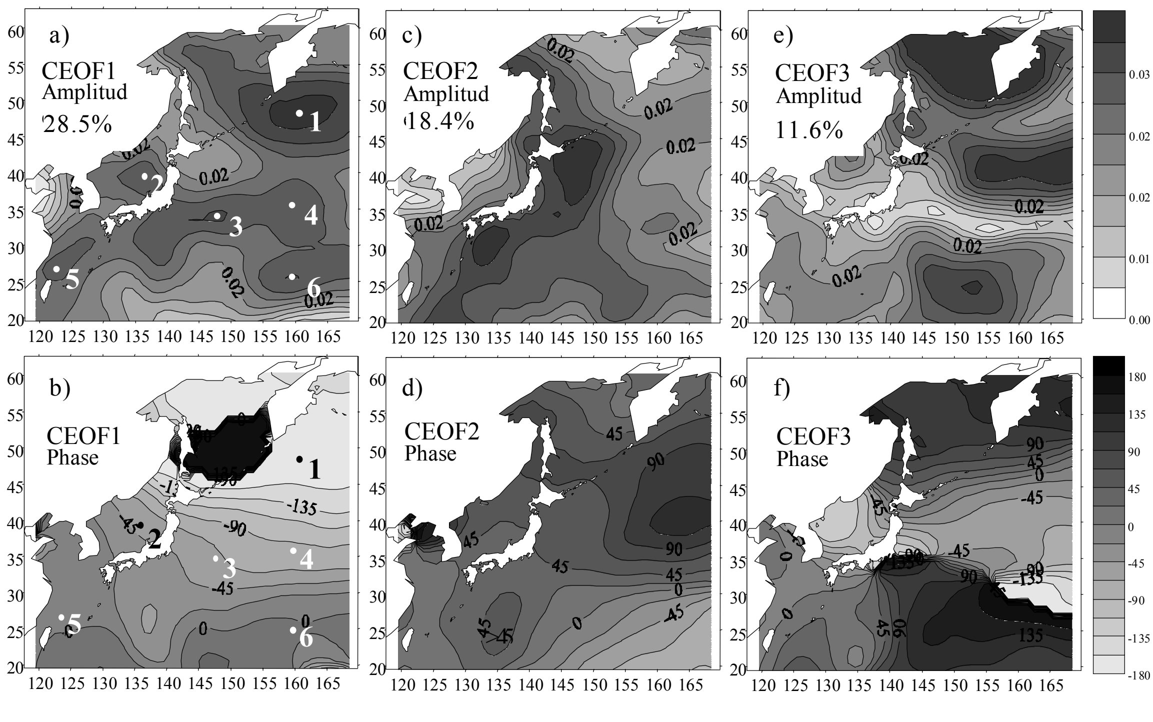

Fig. 1. The Northwest Pacific wintertime SST spatial amplitude (a) and phase (b) for CEOF1, amplitude (c) and phase (d) for CEOF2, amplitude (e) and phase (f) for CEOF3. Grid locations of "core" anomalies used for correlation analyses are also shown

As correlation between CEOF1 cores in the Subarctics and Subtropics is almost equal to -1 (Fig. 3), we can estimate relationship with atmospheric indices for the subarctic CEOF1#1 only and extend conclusions to the subtropical cores, taking into account 180 phase shift.

The ENSO signal can be clearly seen in the Northwest Pacific wintertime SST. Statistically significant negative correlation of CEOF1#1 with November Nino3 Index (Fig. 4a) implies the negative (positive) SST anomaly in the Northwest Pacific Subarctics during El Nino (La Nina) winters. In line with earlier findings (Hanawa, 1989), cooling during El-Nino winters in Subarctics (CEOF1#1) means warming in Subtropics (CEOF1#6), including the East China Sea (CEOF1#5) and, in less degree, the southern Japan Sea (CEOF1#2).

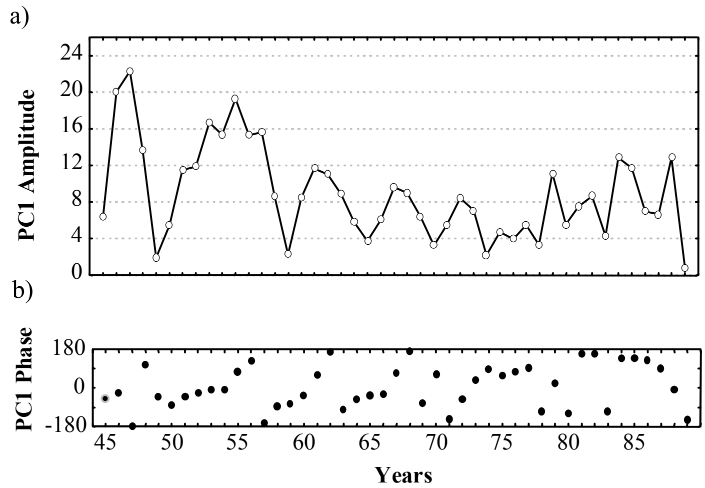

Fig. 2. PC1 temporal amplitude (a) and phase (b) for the Northwest Pacific wintertime SST

Positive synchronic correlation of CEOF1#1 anomaly with MOI (Fig. 4c) means warming (cooling) in subarctic SST and, correspondingly, cooling (warming) in subtropical SST, associated with strengthening (weakening) of the winter East Asian Monsoon. The Monsoon weakening matching the positive SST anomaly occurs in the Northwest Pacific Subtropics during warm ENSO events (El Nino) as earlier demonstrated in (Hanawa *et al.*, 1989). That is consistent with the mirrored correlation patterns of CEOF1#1 anomaly with Nino3 and MOI (Fig. 4a, c).

As illustrated by CEOF1#1/WPI correlation pattern, CEOF1-related SST anomalies are highly influenced by the Pacific westerly jet stream (Fig. 4d). Namely, negative synchronic correlation means cooling (warming) of subarctic Northwest Pacific SST associated with intensification (relaxation) of the Pacific jet stream. The relationship is of the opposite character for the subtropics in accordance with (Hanawa *et al.*, 1989).

Intensification (relaxation) of extratropical westerlies accompanying warm (cold) ENSO events (Yang, Webster, 1990) is demonstrated here by SOI/WPI unlagged correlation equal to -0.56. Similarly, weakening (strengthening) of the Asian Monsoon accompanied by intensification (relaxation) of the Pacific jet stream (Hanawa *et al.*, 1989) is illustrated by MOI/WPI synchronic correlation equal to -0.54 (Fig. 5).

For temporal lags within the interval from – 7 to 8 yrs, there is a coherence in correlation between CEOF1-related SST anomalies and November Nino3, wintertime SOI, MOI and WPI. Namely, correlation coefficients reach extreme negative (positive) values for Nino3 and WPI, and extreme positive (negative) values for SOI and MOI for temporal lags is of – 6, 0, and 6 yr. (2 and 4 yr.), respectively (Fig. 4). Even though some of extrema are not 95%-statistically significant, oscillating cycle with 6 yr. period is obvious. Cold (warm) SST anomaly in the Subarctics and warm (cold) SST anomaly in the Subtropics accompanies, trails, and leads to atmospheric interannual cycles, thus providing a feedback. Remarkably, this 6 yr. periodicity corresponds to that deduced from the PC1 temporal phase and correlation between anomalies in CEOF1 cores.

Discussion

Wintertime CEOF1 represents the ENSO signal in the Northwest Pacific SST affected by the atmospheric extratropical ENSO devices, particularly East Asian – Pacific westerly jet stream and the East Asian Monsoon. In the Subarctics cold (warm) wintertime SST anomalies accompany warm (cold) ENSO events, intensified (relaxed) westerly jet stream, and weakened (strengthened) Monsoon. The CEOF1 pattern represents a signal propagating from the Subarctics to Subtropics, providing 180° phase change in response to ENSO. In the Subtropics CEOF1-related pattern is of opposite character and is consistent with results earlier obtained from the SST composite (Hanawa *et al.*, 1989).

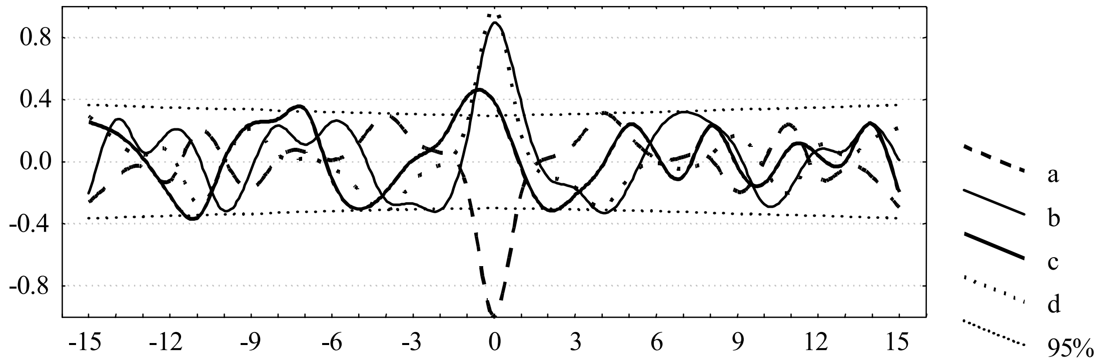

Fig. 3. Correlation between SST anomalies in CEOF1 cores: #1 and #6 (a), #2 and #4 (b), #4 and #6 (c), and #5 and #6 (d). Core numeration is from Fig. 1. Lag (yrs) is positive if the second time series of every couple leads; 95% confidence level is shown

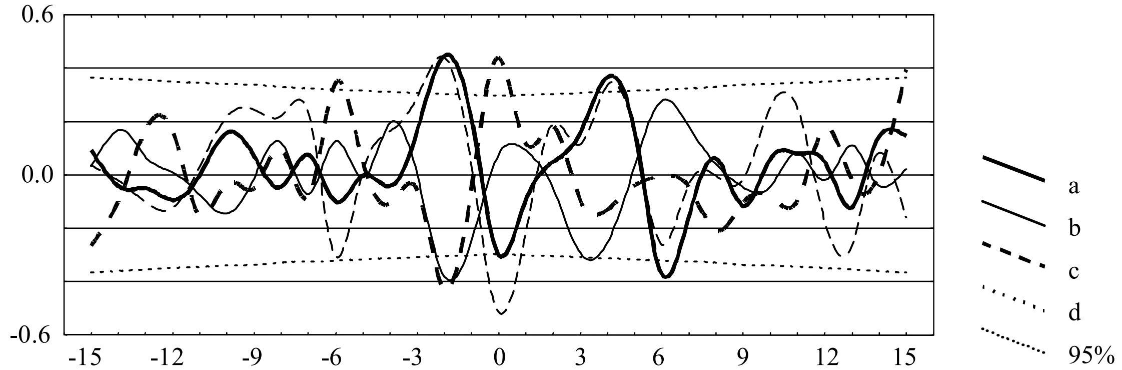

Fig. 4. Correlation between CEOF1#1 SST anomaly and climatic indices: Nino3 in November (a), wintertime SOI (b), wintertime MOI (c), wintertime WPI (d). Lag (yrs) is positive for the index leading; 95 % confidence level is shown

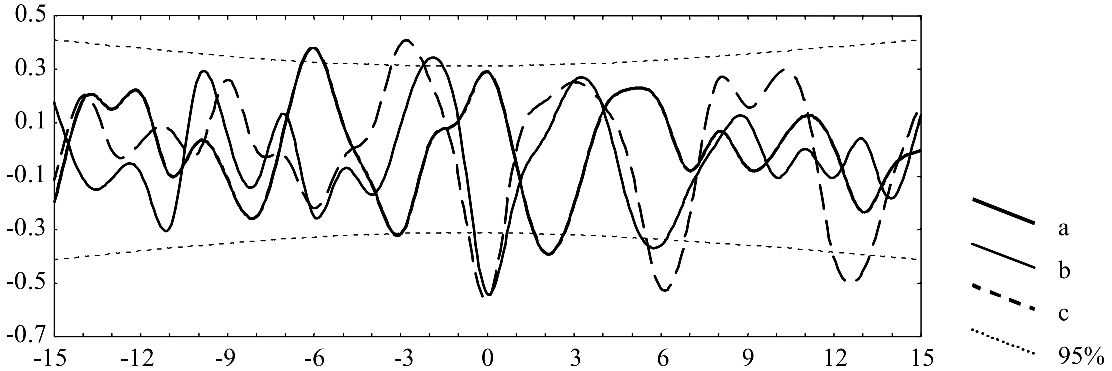

Fig. 5. Correlation between wintertime mean MOI and SOI (a); WOI and SOI (b) and WPI and MOI (c). Lag (in yrs) is positive if the second time series of every couple leads; 95% confidence level is shown

Similar changing pattern in response to ENSO was earlier found in wintertime surface air temperature over the Northwest Pacific – Northeast Asia marginal zone: the Subarctics is cooler (warmer) and the Subtropics is warmer (cooler) during warm (cold) ENSO events (Ponomarev *et al.*, 1999a, 1999b; 2001). Based on both COADS data analysis and coupled ocean – atmosphere modeling, cold (warm) SST and high (low) SLP anomalies were earlier found in the tropical western Pacific (southward 20°N), associated with El Nino (La Nina) by Wang *et al.* (1999).

Based on the mentioned findings, the following changing wintertime response to ENSO in the western Pacific can be suggested: cooling (warming) in the Tropics (Wang *et al.*, 1999), warming (cooling) in the Subtropics (Hanawa *et al.*, 1989; Ponomarev *et al.*, 2001; the present study), cooling (warming) in the Subarctics (Ponomarev *et al.*, 1999a, 1999b; 2001; the present study), and warming (cooling) in the Chukchi Peninsula area (Ponomarev *et al.*, 2001) associated with warm (cold) ENSO events. This pattern is quite opposite to that in the eastern Pacific region and North America where warming (cooling) is associated with warm (cold) ENSO events in the whole huge region from equator to Alaska (for example, Livezey *et al.*, 1997).

The 6-7 yr. periodicity attributed to CEOF1 is not "pure" ENSO timescale (2-7 yr.) but is shifted towards decadal oscillations. The same 6-7 yr. "borderline" timescale was earlier found in the Northwest Pacific area for the Sverdrup transport and Far East Zonal Index (Hanawa, 1995). Its presence in the regional atmospheric characteristics can also be demonstrated by lag correlation patterns between MOI, WPI and SOI (Fig. 5). The 6-7 yr. periodicity was determined as dominant in the principal CEOF mode of the whole North Pacific SST (Ponomarev *et al.*, 2001). It was also found in the equatorial region: although the first global ENSO wave in tropical surface temperature and pressure (White & Cayan, 2000) has the "typical" ENSO period of 4 yrs, the second global wave is of 6 yr periodicity. That implies that 6-7 yr. borderline timescale may be interconnected with global response to ENSO.

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