6.7 A DETECTION OF INTERANNUAL AIR-SEA COUPLED SIGNAL ALONG THE SUBTROPICAL FRONT IN THE NORTH PACIFIC

Shoshiro Minobe*[1,2] and Takanobu Tokuno[1]
1: Graduate School of Science, Hokkaido University, Japan
2: Frontier Research System for Global Change/International Arctic Research Center, Alaska

1. Introduction

The propagating signals observed in both the atmosphere and the ocean have attracted large attentions in the last two decades. Such propagating signals were first observed in the annual cycle of the atmosphere and ocean in the equatorial Pacific (Horrel 1982), and in a development stage of El Ninos (Rassmusson and Carpenter 1982).

In mid-latitudes of the North Pacific, northeastward SST propagation on interannual timescale was reported forty years before (Namias, 1959) and were touched repeatedly by several papers. A recent extensive study by using a multi-channel singular spectrum analysis (MSSA) was documented by Zhang et al., (1998), who suggested the SST variations are caused by an atmospheric bridge proposed by Lau and Nath (1994). However, the relation between the atmosphere and ocean with respect to the northeastward SST propagation has not yet fully studied. The purpose of the present paper is, therefore, to clarify the interactions between the atmosphere and ocean in association with the propagating SST signal in the mid-latitude North Pacific.

2. Data and Method

In order to understand the ocean and atmosphere variability associated with the extratropical SST propagation, we analyze SSTs, wind speeds in the troposphere, surface heat fluxes on monthly NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) for the period from 1949–1999. Also we analyze subsurface temperatures from 1955–1999 produced by White (1995). Although these dataset are global one, the subsets over the North Pacific including the tropical Pacific (20°S–60°N, 120°E–80°W) are analyzed in the present paper. All data are applied a high-pass filter (half power point at 8 year period), since we are interested in interannual variations.

In order to identify the propagating signal in the atmosphere and the ocean, we used a Periodically Extended Complex Empirical Orthogonal Function (PXCEOF). PXCEOF is a natural extension of the Periodically Extended EOF (PXEOF) into the Complex Empirical Orthogonal Function (CEOF). Recently, Kim and Wu (1999) examined the nature and ability of PXEOF.

For a PXCEOF analysis, we compute CEOFs from a correlation matrix constructed from the yearly time series for each month at each grid point with the size given by the product of the number of months in a year (12) and the number of spatial grids. The resultant CEOF pattern for one mode can vary from a month to another, while principal components provide information on the year-to-year variability of the seasonally varying spatial structure.

3. Results

The PXCEOF was calculated for monthly SSTs after normalizing them with the standard deviation at each grid and each month. Figure 1a shows the spatial pattern of the first PXCEOF mode, which is calculated based on the SSTs north of 10°N, but correlation coefficients in the equatorial Pacific is also shown in order to know relations between the mid-latitudes and equatorial region. The spatial pattern exhibits a predominant equatorial signal associated with El Ninos in all of four seasons, with approximately uniform equatorial phases indicating a standing oscillation as widely known. Interesting large correlations in mid-latitudes are found mainly in the winter and spring seasons from the Philippine coast to the central North Pacific, with phase increasing to the northeastward until around 35°N, 170°W, where the phase is 180° out-of-phase to the phases in the equatorial eastern Pacific. The phase increase indicates the northeastward propagation. Further from the central North Pacific, the phases increase into three directions; northeastward, northward and northwestward, indicating simultaneous expansion of the signal in these directions. In the summer season, the propagating feature from the Philippine coast to the central North Pacific is still detectable, with weaker amplitudes than the amplitudes in the winter and spring seasons, while propagation feature is no longer observed in the fall.

The first principal component (PC) for the PXCEOF shows that the dominant timescale is about five years (Fig. 1b). The propagating signature in the mid-latitudes accompanied by the standing equatorial oscillation with the five year periodicity is consistent with the result of a MSSA analysis using data of all months by Zhang et al. (1998). In the present result, however, the seasonality of the propagating signal has been revealed.

*Corresponding author address: Shoshiro. Minobe, Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Sapporo 060-0810, Japan; e-mail: minobe@ep.sci.hokudai.ac.jp

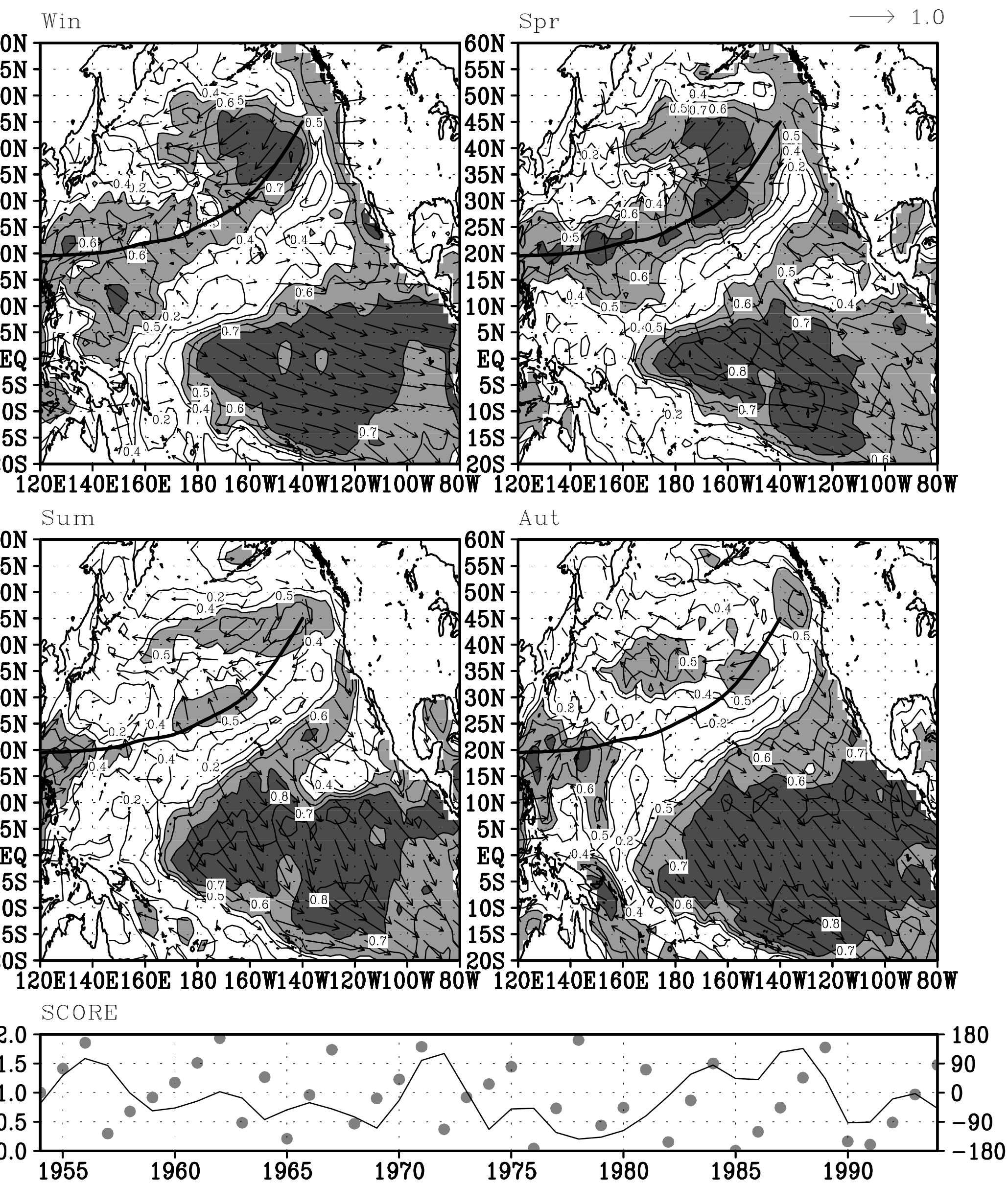

Figure 1. (a) The first PXCEOF of interannual variability in North Pacific SST (10°–60°N, 120°E–80°W) for 1954–1994. Complex correlation coefficients between seasonal SSTs north of 20°S and PC-1 are expressed by amplitudes (contour and shade) and phase (arrow directions). Thin and dense shades indicates 0.5 and 0.7 correlation coefficients, respectively. Counter clockwise rotation of the arrow in a direction indicate the phase propagation in that direction. The curve from the Philippine coast to the central North Pacific is propagation path subjectively chosen for the convenience of the latter discussion. (b) Amplitudes (curve) and phase (circles) of the time series of the PC-1.

The fact that the SST anomalies in one winter season re-emerge in the next year suggests that the SST anomalies survive at depth below the seasonal thermocline, which develops in summer. This interpretation is consistent with the reemergence mechanism studied by Alexander and Deser (1995) and Alexander et al (1999). This idea is confirmed by the evidence of the propagating signal through the year found in a mixed layer temperature shallower 120 m (not shown).

In order to obtain some idea for the atmospheric variations accompanied by the SST propagation, we examine atmospheric parameters and air-sea heat fluxes. Clear propagating signatures are observed in meridional wind speed and latent, sensible and net heat fluxes in winter with a similar phase speed to the phase speed of the SST propagation (Fig. 2). The phase of the downward net flux is in-phase with the phase of the meridional wind speed, and slightly leads the phase of the SST. The similar propagating signatures in the atmosphere and ocean strongly suggest that the atmosphere and ocean interact to each other. The propagating signatures in the meridional wind fields are observed below 700 hPa, but at higher geopotential levels the meridional wind variations tend to be standing oscillations, suggesting that the atmospheric surface boundary layer plays an important role. The zonal wind speeds exhibit propagating feature only in the central North Pacific and not in the western North Pacific.

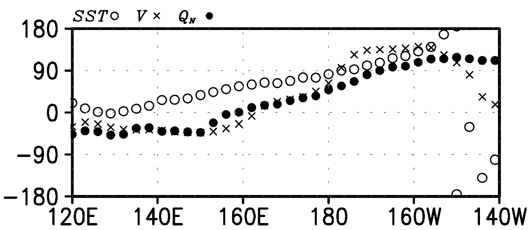

Figure 2. Phases of the correlation coefficients on the propagation path, which is shown in Fig. 1. Open circle denotes the springtime SST, close circle denotes the wintertime downward net heat flux, and crosses denote the wintertime meridional

4. Simple Heat Budget Model

Because the phase of the downward net heat flux leads the SST phase as shown in Fig. 2, the heat flux is expected to play a significant role in the SST variations. Also, partial propagation of zonal wind speeds in the central North Pacific implies that meridional Ekman advection may contribute to the SST propagation to a extent. Therefore, we examine quantitatively how the SST variations can be explained these two mechanisms, by using a simple heat budget equation.

For simplicity, we will focus on how the observed SST variations can be explained by atmospheric net heat flux and meridional Ekman advection, and ignore possible contributions from SST advection due to geostrophic currents and active roles of vertical entrainments of thermocline waters to the mixed layer. Furthermore, we assume that the variability can be expressed as $T(x, y)\exp(-i\omega t)$, where ω is the angular frequency, and T is the complex amplitude of temperature. Consequently, we can obtain a linearized heat budget equation as follows;

$$T = \frac{1}{r + i\omega}\frac{1}{\rho H}\left(\frac{Q}{c_p} + \frac{\tau^x}{f}\frac{\partial \overline{T}}{\partial y}\right),$$

where r is the damping rate due to Newtonian cooling, Q the net heat flux, τ^x the zonal wind stress, H the mixed layer thickness, $\overline{T}(x, y)$ the background SST field, and f is the Coriolis parameter. Notice that the ambiguities of r and H do not influences the relative strength of the heat flux and Ekman advection contributions. Here, we assume H to be 100 m, and r to be 2 years.

The seasonality shown above has indicated that the thermal forcings of the mixed layer mainly occurred only in the winter season. This seasonality is taken account by setting the amplitudes of τ^x and Q as a one quarter of the respective regression coefficients onto the PC-1 of the PXCEOF observed in the winter season.

Figure 3 shows modeled spring SST amplitudes and phases along with the observed ones, which are the regression coefficients of the spring SST onto the PC-1 of the PXCEOF. In general, the modeled SST successfully reproduced the major features of the amplitudes and phase distributions around the propagation path. However, the modeled amplitudes does not show a prominent trough along the propagation path which is observed as the contours of 0.2° and 0.4°C in the western Pacific around 20°N. Nevertheless, the amplitude and phase distributions along the propagation path reveals a remarkable similarity between the observation and model (**Fig. 4**).

The complex amplitudes of the modeled SST are given by the sum of the contributions of the heat flux and Ekman transport. By examining these terms, it is shown that the contribution of the heat flux is larger through the most of the path, while the contribution of the Ekman advection become comparable in the central North Pacific, resulting in the large model amplitudes there.

5. Summary and Discussion

In the present study, the seasonality of the SST propagating signal from the Philippine coast to the central North Pacific has been revealed. The SST signal is the most prominent in the spring season, and weakest in the fall. Similar signature has been observed in the subsurface temperature in the upper 120 m, which approximately corresponds to the wintertime mixed layer. Thus, the memory of the SST signature is likely to be stored in the subsurface temperature through the year. The atmospheric propagating signals from the western North Pacific to the central North Pacific have been detected in the wind speeds, and net, latent, and sensible heat fluxes in the winter season. Weaker signature is also found in the zonal wind speeds over the central North Pacific. A simple local heat budget model taking account of air-sea heat flux and meridional Ekman advection due to zonal

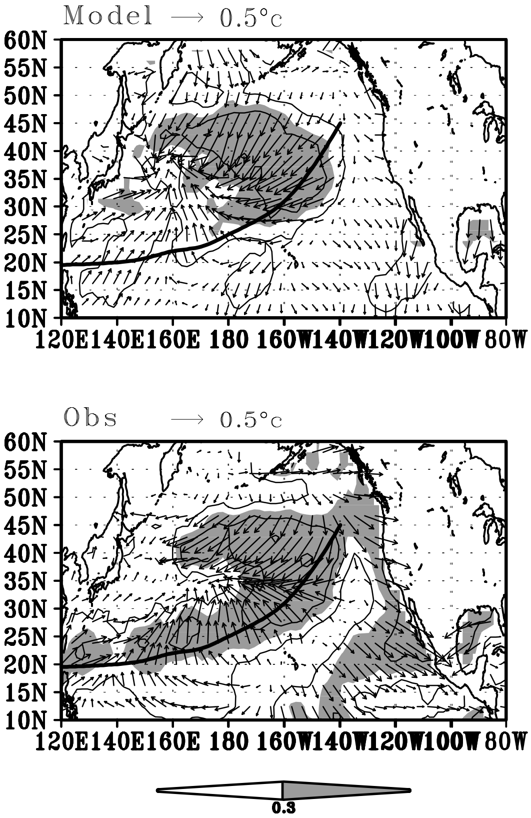

Figure 3. Modeled SST complex amplitudes (upper) and observed SST springtime regression coefficients (lower). The absolute amplitude is shown by the contour, shade and arrow length, and phase is shown by the angle of the arrows. Contour interval is 0.2°C, and amplitudes larger than 0.3°C are shaded.

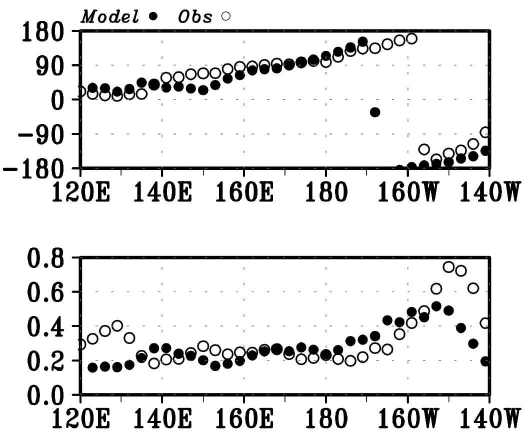

Figure 4. Phases (upper) and amplitudes (lower) of the modeled (closed circle) and observed (open circle) SSTs along the propagation path.

wind stresses produces similar amplitude and phase distributions to those observed. The model result has suggested that the heat flux is the dominant forcing for the SST propagation, and meridional Ekman advection contribute to yield SST amplitude maximum in the central North Pacific.

It is not known what mechanism causes the propagating signatures in the meridional winds and air-sea heat fluxes. However, we speculate that the meridional advection of the heat and humidity in the surface boundary layer may be responsible to the in-phase relation between the surface meridional wind speed and latent and sensible heat fluxes in the western North Pacific. The meridional advection should be effective across a steep meridional gradient, and hence the presence of the subtropical front just south of the propagation path may play an important role for the relation between the meridional wind and heat fluxes. It is noteworthy that the seasonal evolution of the subtropical front is parallel to the occurrence of the propagating signals in meridional winds and heat fluxes; they are prominent in the winter season.

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