# Intraseasonal and Interannual Modes of Atmosphere-Ocean System Over the Tropical Western Pacific

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## 1. Introduction

The importance of the wave-CISK mechanism on the 30-60 day oscillation has been verified by the results of numerical models (Hayashi and Sumi, 1986; Hayashi and Golder, 1986; Lau and Peng, 1987; Yamagata, 1987, *etc.*). Since the intraseasonal oscillation was fairly well simulated using numerical models in which the sea surface temperature (SST) was fixed, it has been understood that this oscillation is an atmospheric phenomenon which is excited by the dynamics of the tropical atmosphere itself and there is no need to regard it as being an air-sea coupled system. However, there still remain some differences between the simulated and observed oscillations. One of them is the shift of simulated intraseasonal oscillations toward higher frequencies as compared to those observed. In recent numerical model studies, Miyahara (1987) estimated the effect of SST on tropical intraseasonal oscillation by varying the CISK parameter as functions of longitude and latitude. Sui and Lau (1989) shows that the lower boundary forcing due to heat flux from the ocean surface destabilizes the mobile wave-CISK mode. Thus some studies focus on the role of tropical SST as a lower boundary in destabilizing the intraseasonal mode.

The existence of the intraseasonal variations of tropical SST is already reported by Krishnamurti *et al.* (1988) and so on. We further found that the tropical SST exhibits a coupling with outgoing longwave radiation (OLR) on the same time scale with a phase difference of 10-20 days (Murakami, 1988; Kawamura, 1988). This fact is suggestive of not only the importance of the dependence of the 30-60 day oscillation on SST but also air-sea interaction in this time scale. It is still uncertain, however, how the air-sea coupling in the intraseasonal time scale is different from that in the interannual time scale which is represented by the ENSO and QBO.

The objective of this research, therefore, is to investigate phase relationships among SST, zonal wind at 850mb and high-cloud cover (HCC), providing a measure of active convection similar to OLR, in the warm pool region of the western Pacific on intraseasonal and interannual time scales. We extracted dominant phase relationship of the air-sea coupling in two time scales, using the complex EOF (CEOF) analysis.

## 2. SST and eastward-propagating intraseasonal mode

We first examine the relationships between the SST over the western Pacific and the eastward-propagating large-scale disturbance having an 30-60 day mode. The 10-day averaged SST data used were regularly collected by the Japan Meteorological Agency. Figure 1a indicates the climatological mean OLR field, which was obtained from the NMC/NOAA, for the northern summer (May-

October) over the period from 1979 through 1984. Deep convective areas are observed in a belt extending from the Indian to the western Pacific Ocean. We divide the equatorial western Pacific sector (0°-10°N, 130°E-180°), where SST is very warm, into five blocks (10°latitude by 10°longitude) as shown in Fig. 1b and compute lag-correlations between 10-day mean SST and OLR averaged over each region during the above period. Figure 2 depicts the spatial distributions of lag-correlation coefficients between the tropical OLR anomalies from the Indian Ocean through the central Pacific and the SST in a key region (0°-10°N, 130-160°E), where significant correlations were detected. Here negative lag denotes that the variation in OLR precedes that in SST and one lag is equivalent to 10 days. Weak positive OLR anomalies cover the key region and extend to the central Pacific at lags of -2 and -1. On the other hand, negative anomalies are located in the region from the Indian Ocean to the maritime continent and progress eastward from negative through positive lags. At a lag of +2 (20 days), significant negative anomalies expand into the equatorial western Pacific. The above results show that the SST over the equatorial western Pacific and the eastward-propagating disturbance interact with an intraseasonal time scale, and that the SST is above normal to the east of the eastward-propagating 30-60 day mode disturbances.

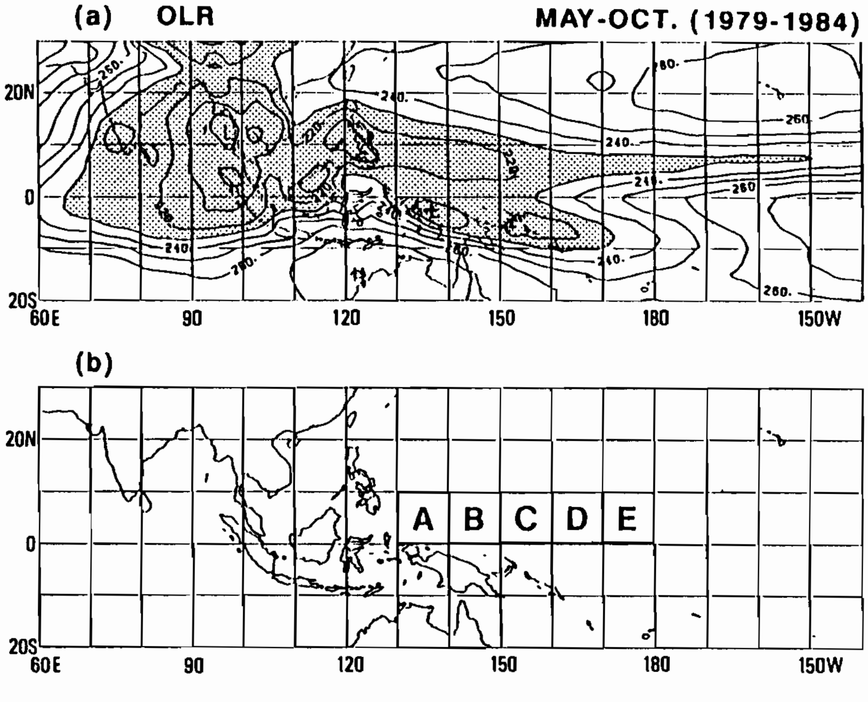

Fig. 1 (a) Climatological mean OLR field for the northern summer over the period from 1979 through 1984. The contour interval is $10Wm^{-2}$ and areas less than 230 $Wm^{-2}$ are shaded, indicating the most active convection. (b) Location of five regions selected in computing lag-correlations between the 10-day mean SST and OLR.

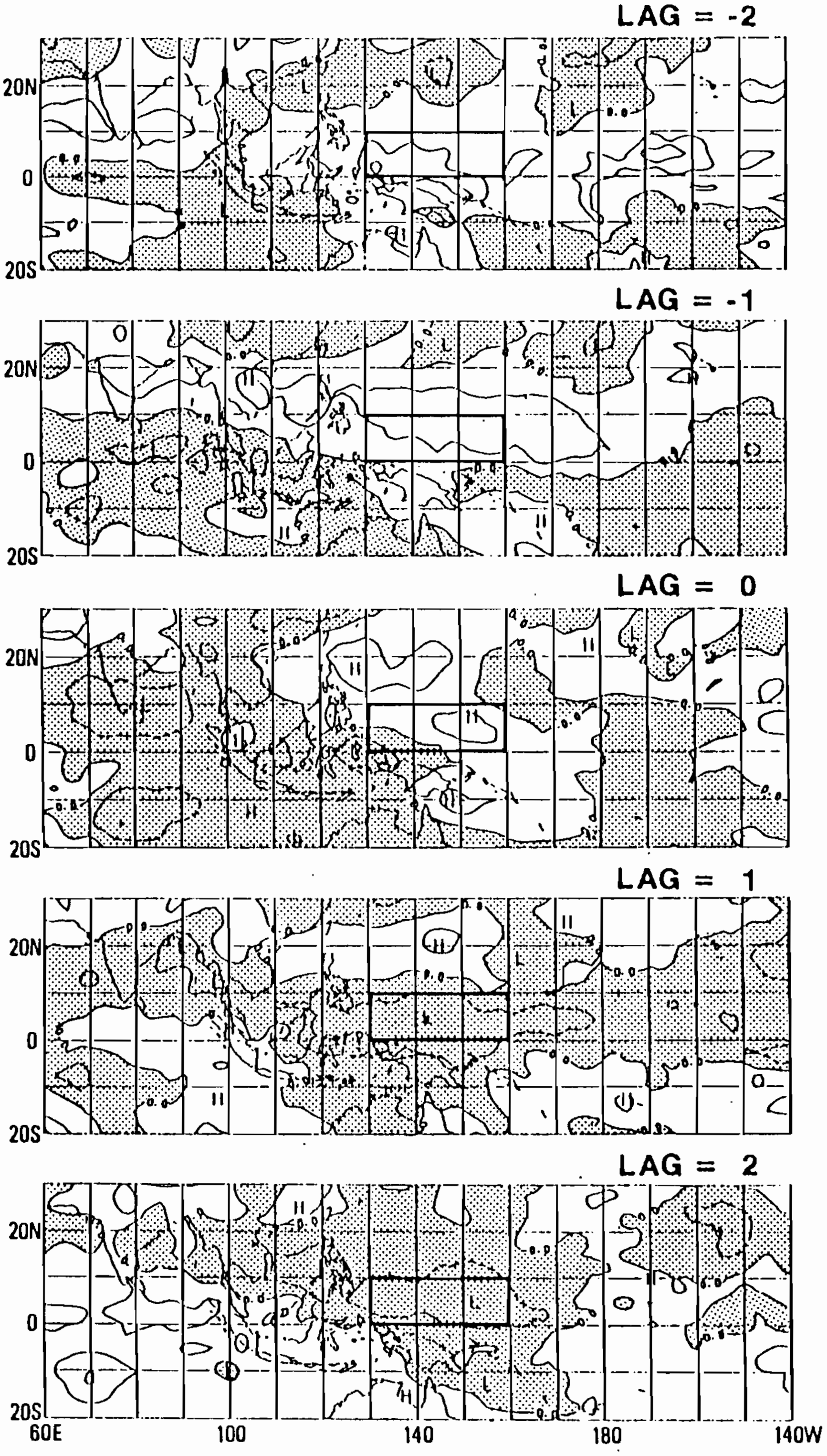

Fig. 2 Lag-correlation patterns between the OLR anomalies in tropical regions and SST anomalies in the key region (0°-10°N, 130-160°E) shown by the rectangle. Positive lag implies that the variation in SST precedes that in OLR and one lag is equivalent to 10 days. The contour interval is 0.2 and negative values are shaded.

Although Emanuel (1987) and Neelin *et al.* (1987) suggested that evaporation-wind feedback mechanism leads to the eastward propagation of intraseasonal disturbance using numerical model which SST is fixed, the high SST located to the east of eastward-propagating disturbance also provides a favorable condition for the disturbance to propagate eastward. It can be considered that the intraseasonal variations are easily modified by air-sea interaction and as a result have spectral peaks in wide (30 to 60 day) period range if we take account of such an air-sea interaction as the reduced incoming solar radiation and active turbulent mixing accompanying the large-scale disturbance result in a decrease of SST.

Figure 3 displays the time series of the 10-day mean SST (solid line) and OLR (dashed line) averaged over the key region for the northern summer (May-October) during the 6 year period (1979-1984). The coupling of SST and OLR on the intraseasonal time scale is more notable in the northern summer during 1979 when the 30-60 day oscillation of tropical convection was dominant. The SST in the key region fluctuates between 29.0 and 29.5°C during this period. In contrast, although the SST was above 29.5°C during 1981, the 30-60 day oscillations in both the OLR and SST were not very dominant. Rather, the SST in the equatorial western Pacific exhibited a 20-30 day oscillation and fluctuated in phase with OLR during the northern summer of this year. Thus the air-sea coupling in the 30-60 day time scale seems to be weak during the northern summer of 1981. It is of interest that the periodicity in the intraseasonal oscillation tends to be short for the 1981 when the air-sea coupling appears to be weak.

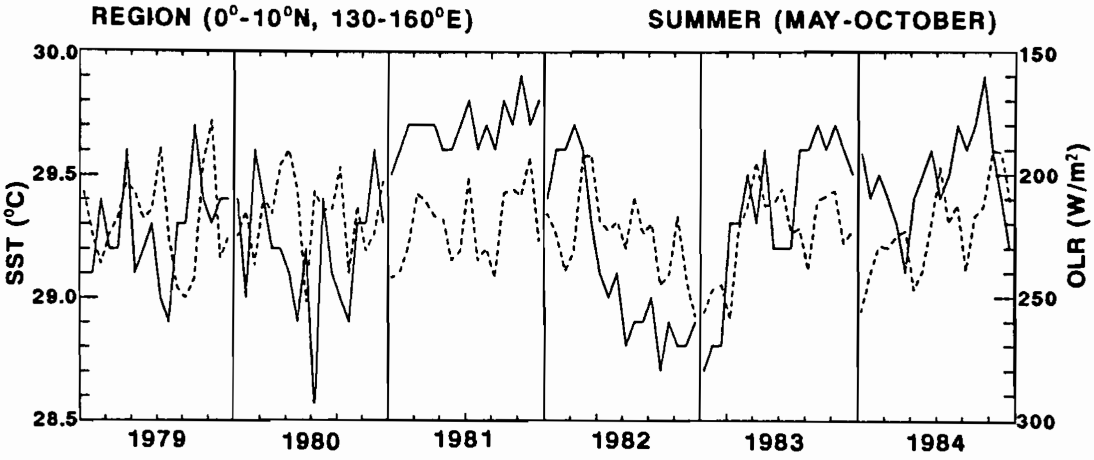

Fig. 3 Time series of the 10-day mean SST (solid line) and OLR (dashed line) in the key region (0°-10°N, 130-160°E) during the northern summer (May-October) for the period from 1979 through 1984.

## 3. Phase relationships among SST, HCC and zonal wind at 850mb

Figure 4 shows time series of HCC, SST and 850mb*u* for two time scales in the key region during the 7 year period 1980-1986. We utilize the GMS high-cloud cover data defined as a fractional ratio of cloud pixels at a 1°latitude by 1°longitude area, whose top height is above 400mb. The maximum value of HCC is 10.0. Daily 850mbu data are derived from global analyses by ECMWF. The intraseasonal component is here evaluated as departures from the smoothed data (interannual component) using a 90-day weighted running mean. It is deduced that the amplitudes and phases of SST, HCC and 850mb*u* vary with longitude even over the tropical western Pacific, though both components have a general nature of propagating eastward. Hence time series of the three variables (SST, HCC and 850mb*u*) in two time scales in regions A and E are also indicated in Figs. 5 and 6, respectively. For the intraseasonal component in region A, the periods of large amplitude of all three variables are the 1979 period and 1984/85 period. The amplitude of the intraseasonal component in region E is smaller than that in region A. In contrast, the amplitude of the interannual component in region E tends to be larger than that in region A. Thus it is observed that the regions where two components are dominant are different each other.

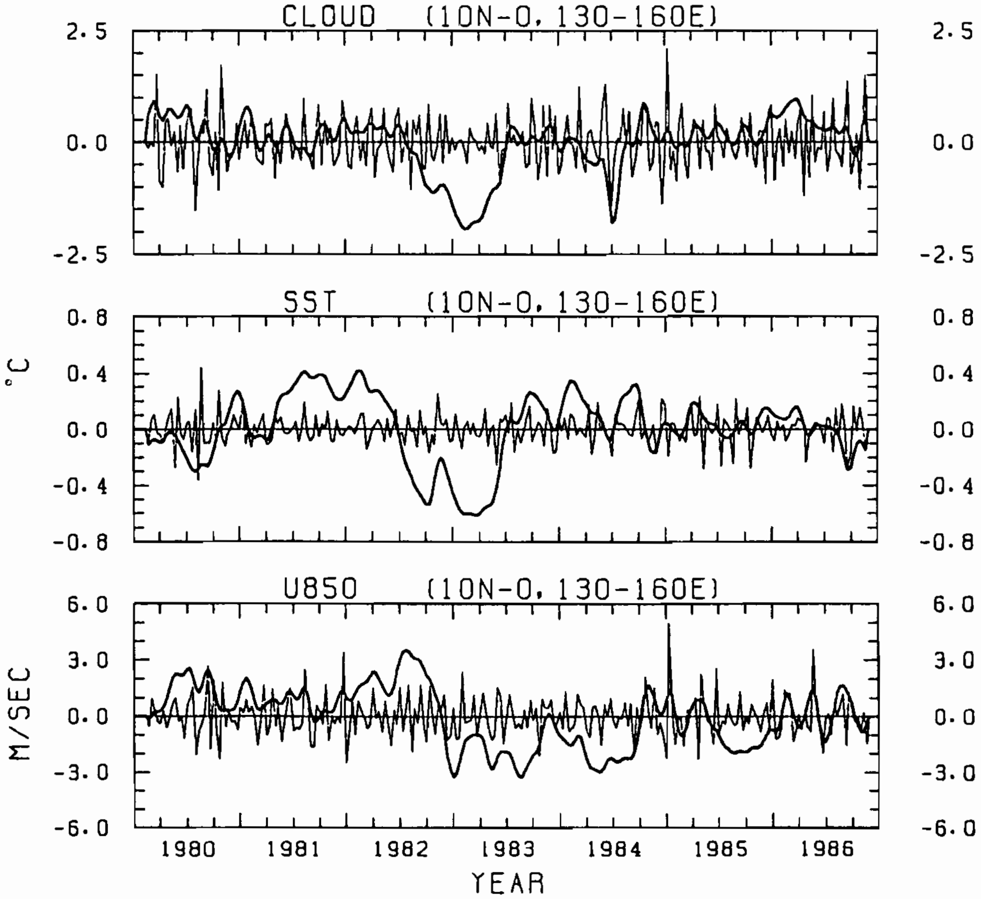

Fig. 4 Time series of HCC, SST and 850mb*u* in the key region for intraseasonal component (thin line) and interannual component (thick line).

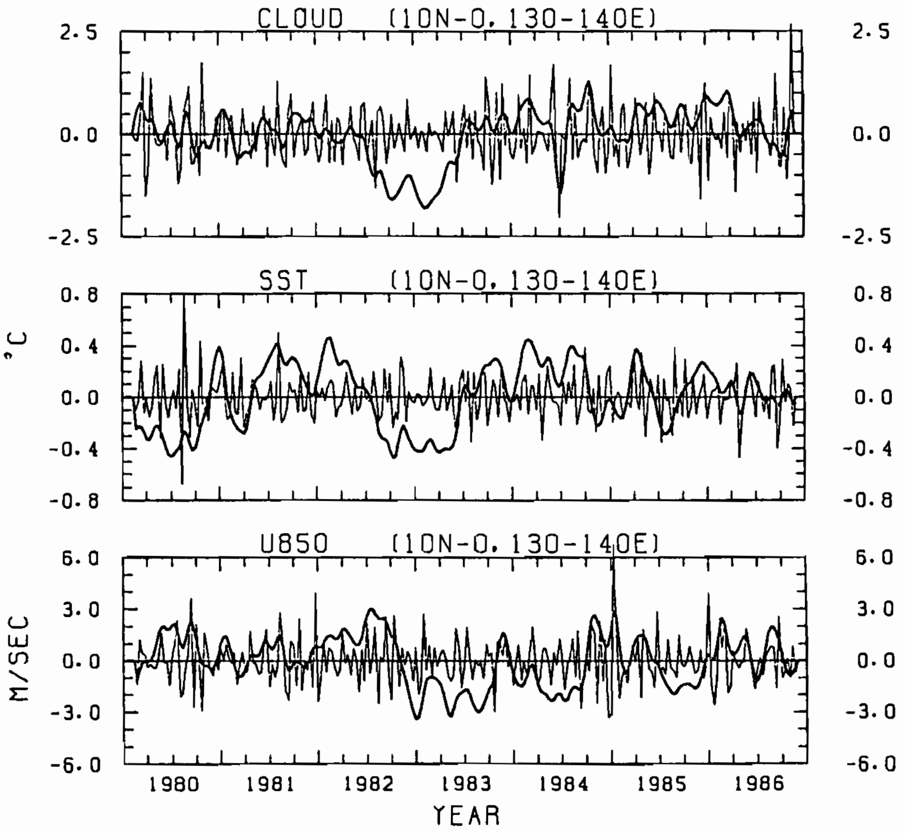

Fig. 5 As in Fig. 4, but for region A.

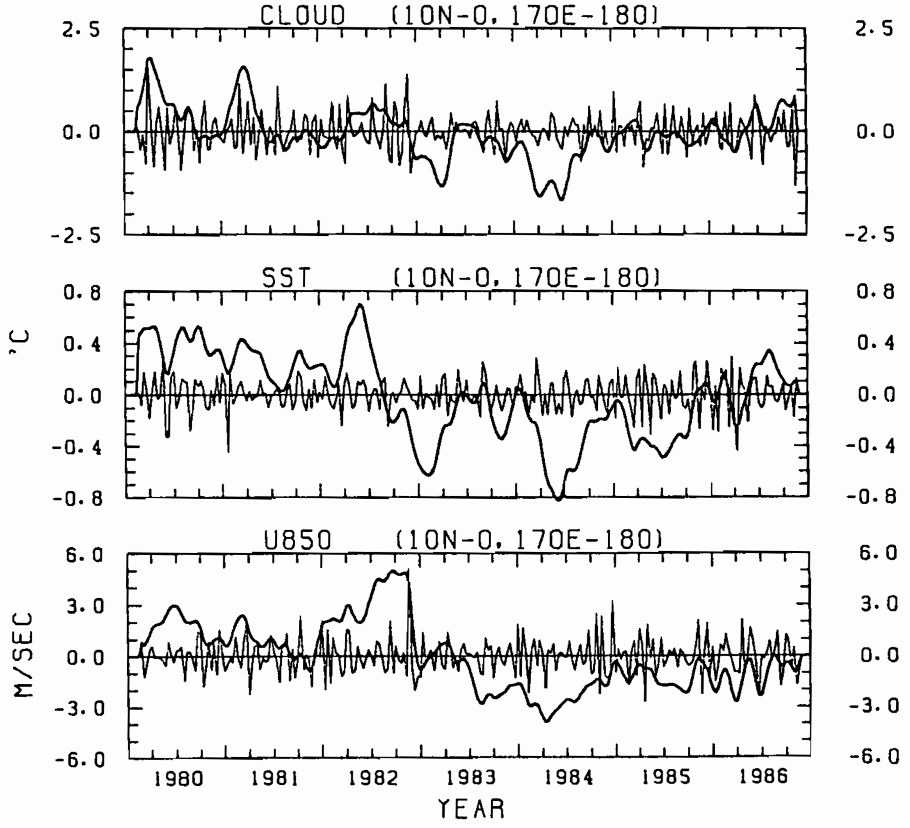

Fig. 6 As in Fig. 4, but for region E.

We next examined statistically phase relationships among three variables on each time scale in regions A, E and key region, using the CEOF analysis. Complex time series $X(j,t)$ is obtained by Hilbert transform of $x(j,t)$, the normalized time series of each variable $j$. $X(j,t)$ is expand into the sum of EOFs as follows.

$$X(j,t) = \sum_{m=1}^{3} F_{mt} B_m{}^*(j)$$

where the asterisk implies complex conjugation, $B_m(j)$ represents the complex eigenvector of the $j$-th variable for the $m$-th mode, and $F_{mt}$ is the complex coefficient for $B_m(j)$. Considering only three variables, we solve the eigenvalue problem of the 3x3 complex correlation matrix (Hermite matrix). We should refer to Barnett (1983) if more detailed explanation is needed. The amplitudes $A(j)$ and phases $P(j)$ of the first CEOF modes for the intraseasonal and interannual time scales in each region are shown in Fig. 7. We can obtain $A(j)$ and $P(j)$ as

$$A(j) = [B_m(j)\, B_m{}^*(j)]^{1/2},$$
$$P(j) = \tan^{-1} [\mathrm{Im}\, B_m(j) / \mathrm{Re}\, B_m(j)].$$

Here the first CEOF modes for the intraseasonal and interannual time scales are called the intraseasonal mode and interannual mode, respectively.

The intraseasonal mode has a similar tendency in all regions. In this mode the HCC is almost in phase with 850mb*u*, that is, the maximum of HCC is in accord with that of westerly wind at 850mb, while the SST leads HCC by around 140°-170°. If we notice the key region where the variance is largest in all regions, it can be seen that the amplitude of SST is somewhat smaller than that of HCC or 850mb*u* and phase difference between SST and HCC is about 140°. This means that in the intraseasonal time scale the HCC (or westerly wind at 850mb) couples with SST with a phase shift of 10-20 days. The above result is consistent with the results of previous observational studies (Kawamura, 1988; Murakami, 1988).

On the other hand, in the interannual mode the amplitude of SST is almost as large as that of HCC and the SST leads HCC by around 10°-30°. Further it is seen that the phase of 850mb*u* shifts obviously from regions A to E, that is, in region A the phase lag between SST and 850mb*u* is about 80°, whereas in region E the 850mb*u* comes to lag SST by only about 20°. Since the interannual mode includes the time scales of the ENSO and QBO, it is inferred that the SST over the western Pacific is anomalously high and then the HCC reaches its maximum about 1-3 months later. The maximum of westerlies at 850mb lags that of HCC by 3-7 months for the key region and by within 1 month for region E. The variance of the interannual mode tends to become large from the western Pacific eastward to the dateline. The above results are summarized as a schematic diagram as shown in Fig. 8.

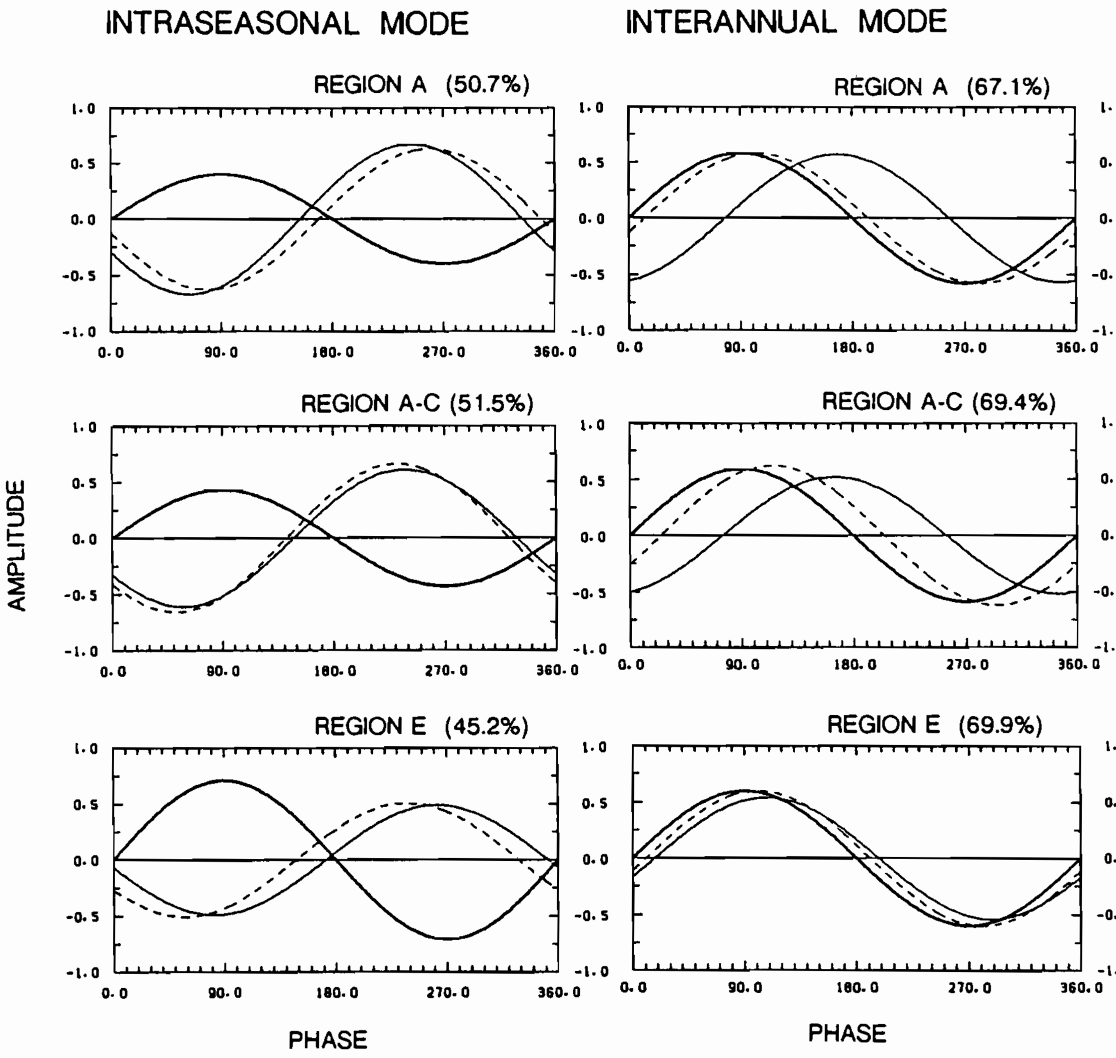

Fig. 7 The amplitudes and phases (degrees) of SST, HCC and zonal wind at 850mb on the intraseasonal and interannual modes. The SST, HCC and 850mb*u* are denoted by thick, dashed and thin lines, respectively. Note that the ratio of the explained variance of the total variance, expressed as percentages, is also shown for each region.

## 4. Summary and discussion

This paper addresses the question of air-sea coupling in the warm pool region of the western Pacific on intraseasonal and interannual time scales. We make investigation into phase relationships among SST, HCC and zonal wind at 850mb in two time scales using the CEOF analysis.

It is first found that there exist the remarkable differences of air-sea coupling in intraseasonal time scale from in interannual time scale. The intraseasonal mode reveals similar tendencies over the tropical western Pacific. In this mode the SST is approximately out of phase with HCC and

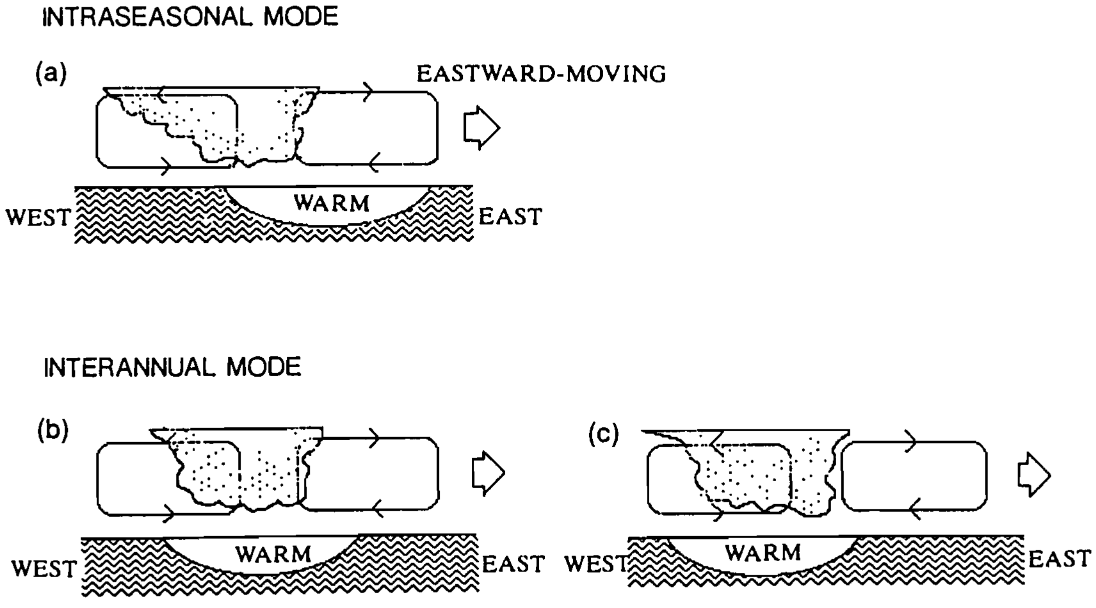

Fig. 8 Schematic diagrams displaying the phase relationship of air-sea coupling on (a) the intraseasonal mode for the key region and on the interannual mode for (b) the key region and (c) region E.

850mb$u$. The existence of high SST located to the east of eastward-propagating 30-60 day disturbance favors its further eastward propagation. This mode is very similar to the advective mode presented by Lau and Shen (1988) with respect to phase relationship. Their mode requires an east-west SST gradient. However, the intraseasonal mode defined in this paper exists in the warm pool region where the east-west SST gradient is so small. The intraseasonal variations of SST in the warm pool region, therefore, are probably caused by the mechanism of incoming short-wave radiation and turbulent mixing in ocean mixed layer rather than east-west SST advection. The importance of air-sea interaction for intraseasonal oscillations cannot be denied, though the amplitude of SST is somewhat smaller than of the other variables.

It is also found that the air-sea coupling in interannual time scale varies with longitude over the tropical western Pacific. The interannual mode is that the SST leads HCC by about 20° but the phase of 850mb$u$ is different in each region. The SST-HCC negative feedback may not be essential to this mode because the SST and HCC tend to be in phase. Since the variances of this mode are large from the western Pacific eastward to the dateline, it is understood that an atmospheric interannual mode propagating eastward over the western Pacific gradually intensifies large-scale air-sea coupling. Although the variances of interannual mode are larger than those of intraseasonal mode, it may be natural that the air-sea coupling like the ENSO event is stronger than that in intraseasonal time scale.

Although we examined statistically phase relationships of air-sea couplings on two time scales only over the western Pacific, we will further understand the air-sea couplings of eastward-propagating modes in two time scales if a similar analysis is applied in the eastern Pacific and Indian Oceans.

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# WESTERN PACIFIC INTERNATIONAL MEETING AND WORKSHOP ON TOGA COARE

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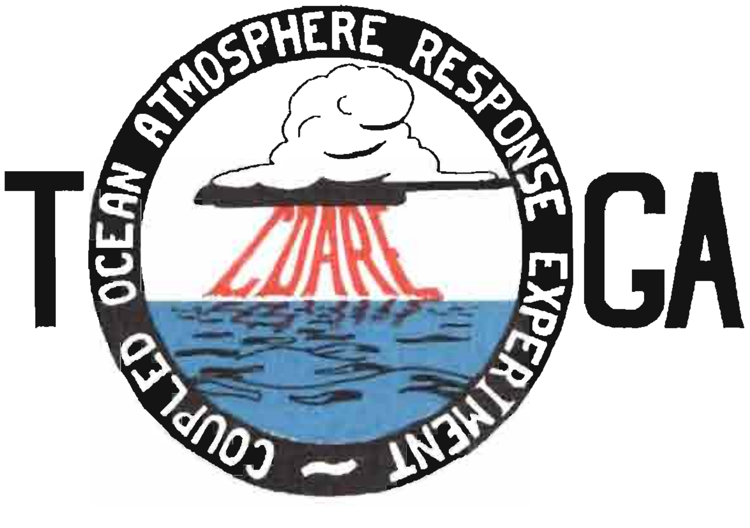

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