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EL NINO/SOUTHERN OSCILLATION SIGNALS IN THE GLOBAL TROPICAL OCEAN

Fu Congbin (符淙斌), *Dong Dongfeng* (董东风)

Institute of Atmospheric Physics, Academia Sinica, Beijing

Ralph Slutz, and *Joseph Fletcher*

Cooperative Institute for Research in Environmental Sciences (CIRES)

University of Colorado, Boulder, CO 80309

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ABSTRACT

The monthly mean sea surface temperature data of 6 areas are used to study the El Nino/Southern Oscillation signals in the global tropical ocean. These areas are in the 5°N-5°S latitude zone at 1) eastern Pacific (110°-140°W), 2) western Atlantic (30°-50°W), 3) eastern Atlantic (10°W-10°E), 4) western Indian Ocean (30°-50°E), 5) central Indian Ocean (70°-90°E) and 6) far western Pacific (120°-140°E), and the data cover the 120-month period of December 1968 to November 1978.

A power spectrum analysis shows that the characteristic time of the El Nino/Southern Oscillation (about 3-4 years) appears not only in the eastern Pacific but also in other areas of the tropics except for the western Pacific, where the spectrum is of white noise. The amplitude of oscillation in the eastern Pacific is about 4 times larger than the others, making the El Nino/Southern Oscillation signal the strongest in this area. According to a cross-spectrum analysis, there is no time lag between the variation in the central Indian Ocean and that in the eastern Pacific. These two areas oscillate simultaneously and comprise the main feature of the El Nino/Southern Oscillation. Other tropical areas are related with time lags, as shown by correlation and coherence calculations.

It should be noted that the sea surface temperature in the eastern Pacific oscillates in phase with that in the Indian Ocean, while the pressure oscillations in these two areas are out of phase with each other, according to the Southern Oscillation definition. It is suggested that the Southern Oscillation cannot be explained simply by the sea surface temperature anomalies.

Variations in the far western equatorial Pacific do not have the time scale of the El Nino/Southern Oscillation, perhaps because it is a buffer zone between the monsoon system and the trade wind system.

I. INTRODUCTION

The El Nino/Southern Oscillation is seen as a strong signal standing out above the noisy background of short-term climate variation. The characteristic time scale of the El Nino/Southern Oscillation (the duration of one cycle) ranges from 2 to 7 years, about 3-4 years on the average (Lockyer and Lockyer 1904, Julian and Chervin 1978, Fu and Su 1981, Chen 1982, and Rasmusson and Carpenter 1982). This characteristic time is mainly calculated from sea surface temperature, sea level pressure, and other data mainly in the Pacific, although it can be correlated with many of the global features named "teleconnection" (e.g. Bjerknes 1969, Horel and Wallace 1981). By studying the mean tropospheric temperature and 200 hPa height data, Horel and Wallace (1981) have pointed out that the El Nino/Southern Oscillation signal appears not only in the Pacific sector, but also throughout the tropics. It is worthwhile to look further at the sea surface temperature data for the El Nino/Southern Oscillation signal in the global tropical ocean, and to study the relationships between different areas. This is the main subject of this paper. The data sets used are described in Section II. Section III gives briefly the calculation method for one- and two-dimensional spectrum analyses. Section IV presents the main results about the oscillation in the 6 areas and their relationships. Finally the conclusions are given in Section V.

II. DATA SOURCE

The monthly mean sea surface temperature data used in this paper are taken from the "Historical Sea Surface Temperature Project" (HSSTP) marine data files which are available from the U.S. National Climatic Data Center. The period analysed is from December 1968 to November 1978, which is thought to be of good quality.

The areas defined to describe the regional features of the global tropics (5°N-5°S) are shown in Fig. 1. The longitude ranges of each area are:

Area 1:	eastern Pacific	110°W-140°W.
Area 2:	western Atlantic	30°W-50°W.
Area 3:	eastern Atlantic	10°E-10°W.
Area 4:	western Indian Ocean	30°E-50°E.
Area 5:	central Indian Ocean	70°E-90°E.
Area 6:	far western Pacific	120°E-140°E.

The mean values of temperature departures along the equator in the longitude ranges defined above were calculated separately for each area.

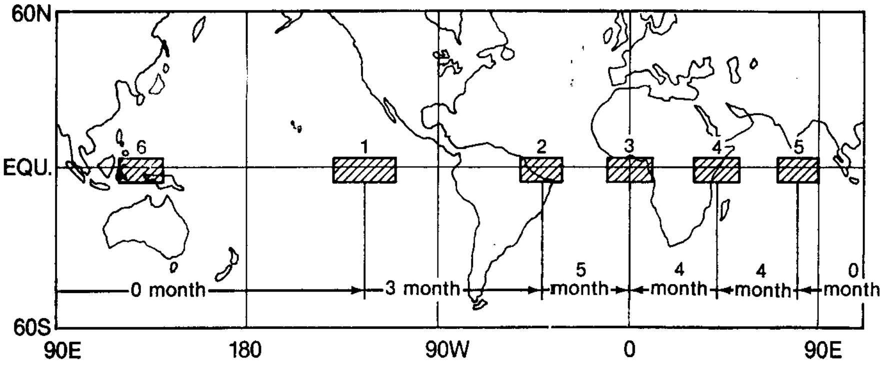

Fig. 1. Six areas in the global tropics studied in this paper. 1: eastern Pacific; 2: western Atlantic; 3: eastern Atlantic; 4: western Indian Ocean; 5: central Indian Ocean; 6: western Pacific.

III. SPECTRUM ANALYSES

A power-spectrum analysis using the Fourier Transform of windowed correlation coefficients (both auto- and cross-correlations) is applied in this paper (for details see references Fu and Su 1981, Bath 1974). Here only the main formulas are given.

The formula for a one-dimensional spectrum calculation is

$$S(K)=\frac{2}{m}\sum_{\tau=0}^{m} R(\tau)\cos\frac{K\tau\pi}{m}\cdot D_{\tau}\cdot\delta_{\tau}, \qquad (1)$$

where m is maximal lag; $R(\tau)$ is the auto-correlation coefficient at the time lag τ; D_τ is the "lag window" operator,

$$D_\tau = \cos^2 \frac{\tau\pi}{2m}, \tag{2}$$

δ_τ is the "lag window" width factor,

$$\delta_\tau = \begin{cases} 1/2 & \tau = 0,\ m \\ 1 & \tau \neq 0,\ m. \end{cases} \tag{3}$$

$S(0)$ is the estimate of zeroth spectrum term which equals that of infinite wave length (the mean), $S(m)$ is the estimate of the highest spectrum term calculated, i.e. the shortest wave decomposed from the series; $S(K)$ for $K=1,2,\ldots,\ m^{-1}$ are estimates of the middle-spectrum terms.

The formula for a bivariate spectrum calculation is

$$\Gamma(K) = \frac{1}{m} \sum_{\tau=-m}^{m} R(\tau)\, e^{-\frac{ik\tau\pi}{m}} = C_0(K) + iQ(K), \tag{4}$$

where the cospectrum

$$C_0(K) = \frac{2}{m} \sum_{\tau=0}^{m} R_{c\tau} \cos \frac{K\tau\pi}{m} \cdot D_\tau \cdot \delta_\tau \tag{5}$$

and

$$R_{C\tau} = \frac{1}{2}(R_\tau + R_{-\tau}) \tag{6}$$

$$R_\tau = \frac{1}{N-\tau} \sum_{i=1}^{m-\tau} X_i Y_{i+\tau} \tag{7}$$

$$R_{-\tau} = \frac{1}{N-\tau} \sum_{i=1}^{m-\tau} X_{i+\tau} Y_i . \tag{8}$$

For the orthogonal spectrum

$$Q(K) = \frac{2}{m} \sum_{\tau=1}^{m-1} R_{S\tau} \sin \frac{K\tau\pi}{m} \cdot D_\tau, \tag{9}$$

where

$$R_{S\tau} = \frac{1}{2}(R_\tau - R_{-\tau}) . \tag{10}$$

Coherence, a measure of the correlation between two time series as a function of frequency range (K), is

$$CH(K) = \frac{Q^2(K) + C_0^2(K)}{S_x(K) \cdot S_y(K)}, \tag{11}$$

where $S_x(K)$, $S_y(K)$ are the estimates of the spectrum at frequency K for variables x and y respectively, and $0 \leqslant CH \leqslant 1$. The phase spectrum, a measure of the phase relationship between x and y, is

$$\theta(K) = \arc\tan\left[\frac{Q(K)}{C_0(K)}\right]. \tag{12}$$

For convenience, in the case of using monthly mean data, we have

$$\theta(K) = \frac{m}{\pi} \frac{\theta(K)}{K} \Delta t, \qquad K = 1, 2, \cdots, m,$$

where $\Delta t = 1$ (month) shows the month of lag between x and y as the function of K, N, the number of samples, is 120 and the maximal lag is 24. Only the smoothed values of the spectrum estimate are given as a function of frequency (or period) on the diagrams.

IV. MAIN RESULTS

1. *Characteristics of the Oscillation in 6 Areas of the Global Tropics*

Periodicity

Figure 2 gives the spectra of the 6 areas defined in Fig. 1, with the lower limit for 95%

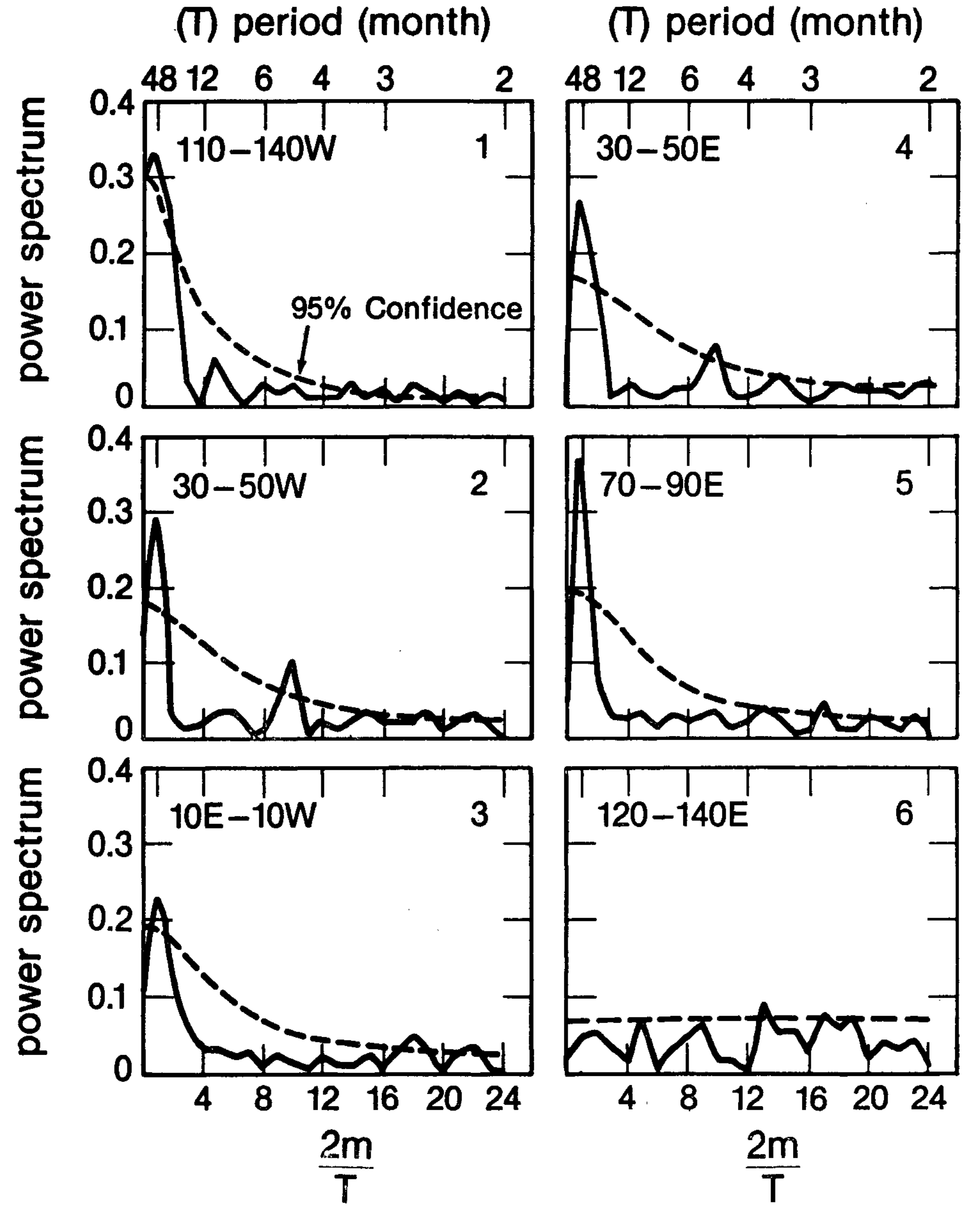

Fig. 2. Spectra of monthly mean temperature in six areas. The dashed line shows the lower 95% confidence limit (annual variation supposed to be filtered out).

confidence indicated by the dashed line. The major features to be seen are as follows:

a) All these regions show a well-marked low-frequency (or long-period) oscillation with the peak at about 3–4 years, except for area 6 which displays nearly "white noise". The major period obtained here is close to the characteristic time of the El Nino/Southern Oscillation index given by Lockyer and Lockyer (1902) (3.8 years) and Fu et al. (1977), and Chen (1982) (36.6–42.7 months). The spectrum power in the low-frequency range appears stronger in areas 1 (eastern Pacific) and 5 (central Indian Ocean), both of which are above 0.30. This indicates that the El Nino/Southern Oscillation signal appears not only in the eastern Pacific, but also in most parts of the tropics except for the western Pacific. It is strongest, however, in the eastern Pacific and central Indian Ocean.

b) There is also a short-period oscillation (of about 2–3 months) reaching the 95% confidence in the first area (eastern Pacific), and an oscillation with a period of about 5 months in area 2 (western Indian Ocean) and area 4 (western Atlantic). Such oscillations are worthy of further study for understanding the air-sea interaction in the tropics.

Relative amplitude of oscillation

To concentrate on the low-frequency oscillation associated with the El Nino/Southern Oscillation, a low-pass filter (Gaussian filter) was applied to the monthly mean time series of the 6 areas to filter out the two short-period oscillations mentioned above. Fig. 3 shows the low-pass filtered curves in the 6 areas as labeled at the end of each curve. The characteristics of the low-frequency oscillations in these areas can be summarized as follows:

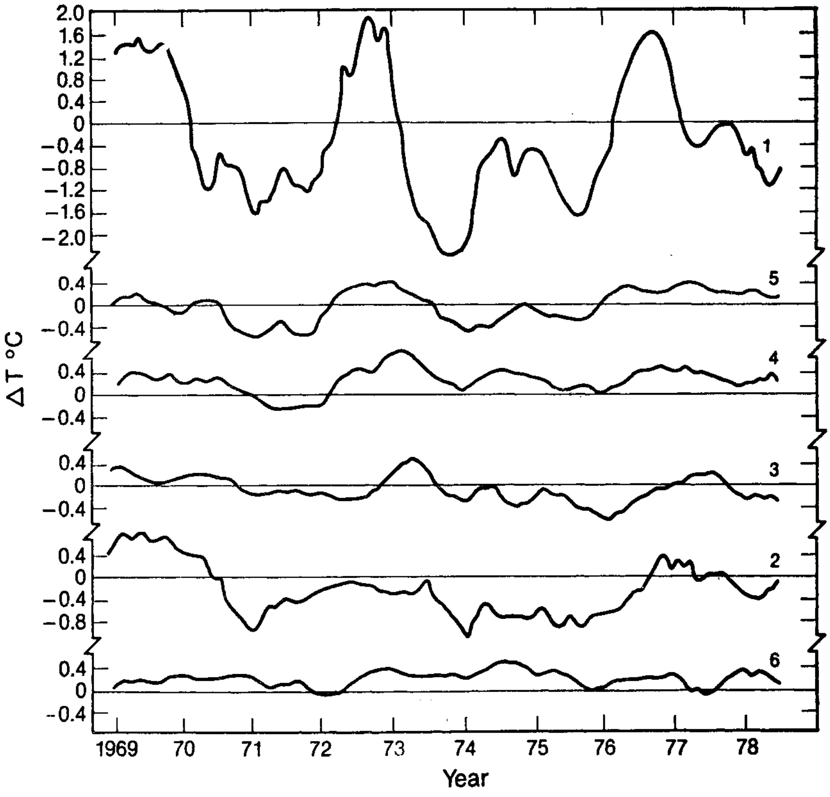

Fig. 3. Low-pass filtered curves of monthly sea surface temperature anomalies in six areas.

a) There is a well-distinguished El Nino/Southern Oscillation signal in the eastern Pacific, related to the three major El Nino events in the years of about 1969–1970, 1972–1973 and 1976–1977, with maximum temperature anomalies about 2°C. The anti-El Nino in 1974 is also very strong, having maximum anomalies about -2°C on the average.

b) This type of oscillation also appears in the Indian Ocean (areas 5 and 4), the eastern Atlantic (area 3), the western Atlantic (area 2) to a certain extent, but not in the western Pacific (area 6). However, the amplitude of oscillation in the eastern Pacific is about 4 times larger than in the other areas. We don't know why it is so strong in the eastern equatorial Pacific.

c) The figure also shows some time lag relationships between the oscillation in the eastern Pacific and that in the others. This is examined in the next paragraph.

2. *The Coupling between Oscillations in the* 6 *Areas*

Cross-correlation

Figure 4 gives diagrams of cross-correlation coefficients between area 1 and the others as

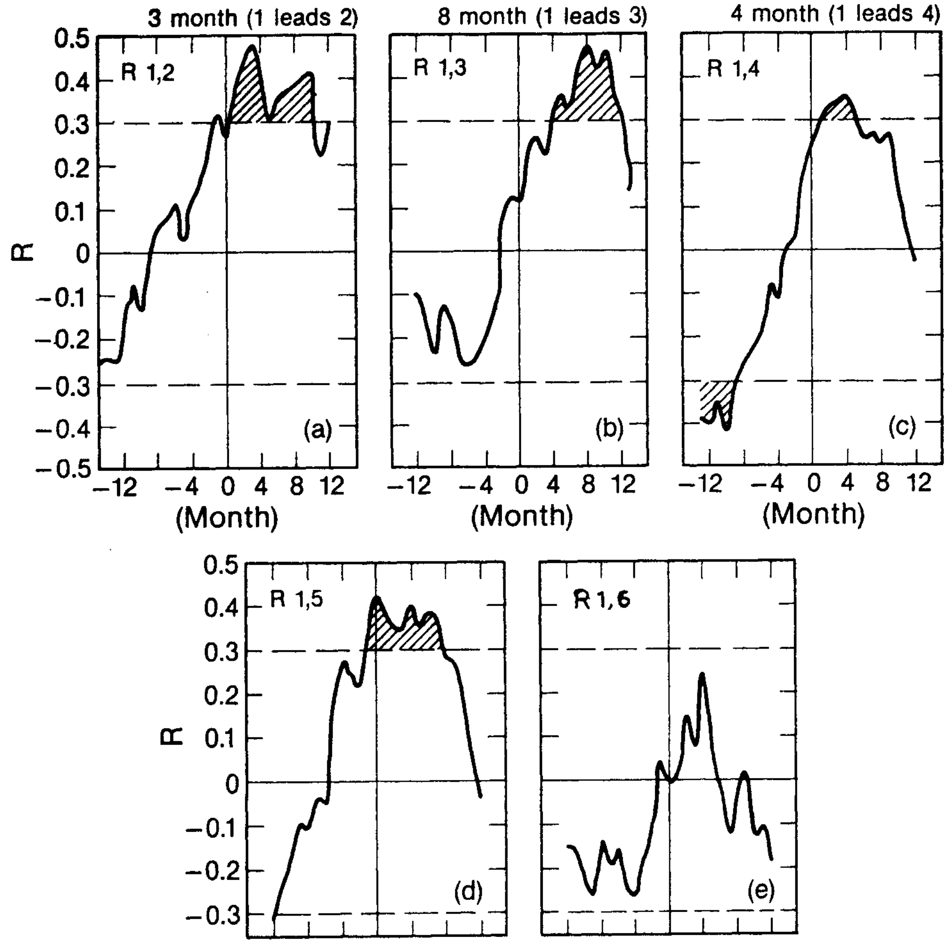

Fig. 4. Cross-correlation coefficients between area 1 and other areas as the function of time lag (−12 to+12 months). Positive numbers mean that area 1 leads. Shaded areas indicate the range reaching 95% confidence.

a function of time-lag (–12 to +12 months: positive numbers mean that area 1 leads the others and vice versa).

The main features of Fig. 4 are as follows:

a) Figure 4 (d) shows that the maximum correlation coefficient between area 1 and area 5 is about 0.42, occurring at zero time lag, although there are also some other effects at different lags. It is an important phenomenon that the temperature in the eastern Pacific oscillation is in phase with that in the central Indian Ocean. However, as shown by the classical Southern Oscillation concept of Walker, the pressure oscillations in these two areas are out of phase with each other (Berlage, 1966).

The disagreement between the oscillation of the surface pressure field and that of the surface temperature field of these two areas sets an obstacle to the conventional explanation of the Southern Oscillation from the surface temperature distribution (Bjerknes, 1969).

Now let us examine the reality of the above statistical results:

According to Bjerknes (1966, 1969) and others, the following relationship exists in the eastern Pacific: warm SST is related to low pressure, and more rainfall. According to Weare (1979), the following relationship exists in the Indian Ocean, although it is rather weak: warm SST is related to high pressure, and less rainfall. According to Rasmusson and Carpenter (1983), Fu and Fletcher (1982), Pant and Parthasarathy (1981), and others, the statistical relationship between the SST in the eastern Pacific and Indian monsoon rainfall is: warm SST in the eastern Pacific is related to less rainfall in India. Fig. 5 summarizes these three results.

less rainfall		more rainfall
↑		↑
high pressure	←A→	low pressure
↑		↑
warm SST	←B→	warm SST
Indian Ocean		Eastern Pacific

Fig. 5. Schematic diagram of correlations between rainfall, surface pressure and surface temperature in the areas of the eastern Pacific and Indian Ocean.

This combination of the three independent analyses confirms what has been observed here, that between these two areas the oscillations of the surface temperature fields are in phase but the oscillations of the surface pressure fields are out of phase. It is suggested that the pressure oscillation in India-Pacific areas (or Southern Oscillation) cannot be simply explained from the surface temperature anomalies only.

Static equilibrium is often used to explain the relationship between surface temperature and surface pressure. According to this relationship, a warm surface would be favorable to the development of a low pressure system and vice versa. On the other hand, the development of a low-pressure system would produce more cloudiness which would diminish the absorption of radiation and thus decrease the surface temperature. So the net result would depend on the balance between these two factors.

In the same way, high-pressure systems with less cloudiness would increase the absorption of radiation and thus increase the surface temperature. The relationship between surface temperature and surface pressure in the Indian sector is perhaps of this case.

b) The temperature oscillations of areas 1, 2, 3, 4 and 5 are all in phase, with different time lags as shown in Figs. 4 (a), (b), (c) and (d). For the maximum correlation coefficients, the time lags between area 1 and areas 2, 3 and 4 are three, eight, and four months respectively.

Since there is no time lag between areas 5 and 1, the same lags apply to the relationships between area 5 and the others.

From the above statistical results, it is very likely that the El Nino/Southern Oscillation signal exhibited mainly in the eastern Pacific and central Indian Oceans could be propagated into other parts of the tropics in some special way which we don't yet know. One way would be eastward propagation from area 1 to area 2 and area 3. Another way would be westward propagation from area 5 to area 4 and area 3, as schematically marked in Fig. 1. In about 8 months the Southern Oscillation could be spread to almost the whole tropics.

c) For the surface temperature data that were examined, there is no significant correlation between the eastern and the western Pacific, as shown in Fig. 4(e).

Coherence

Figure 6 gives the squared-coherency spectrum between area 1 and the other areas as a function of period, and shows clearly:

a) There is very good low-frequency coupling between area 1 and areas 2, 3, 4, 5 with a period of about 3–4 years, the characteristic time of the El Nino/Southern Oscillation.

b) Although the annual variation has been filtered out by using deviation from the long-term monthly mean in the spectrum analysis, there is still a strong coupling relationship between area 1 and area 6 with a period of about 12 months. It may be still a reflection of annual variation signal which is supposed to be filtered. But in the calculation, this type of coupling also appears in the coherences between areas 1 and 2, and between areas 1 and 3.

c) It is very interesting that the El Nino/Southern Oscillation signal does not appear in the temperature variation in the western equatorial Pacific. It can be seen from the low-pass filtered curve of area 6 in Fig. 3 that the temperature in the western equatorial Pacific is above the average (the climatological value for the data sets is for the period 1940–1970, a 30-year mean; WMO, No.208, Tp 108 TN. NO. 84) during nearly the whole period analyzed in this paper, and there is no apparent periodicity as shown by Fig. 2(e).

Figure 4(e) shows that this area has a negative correlation with that of area 1 in the case it leads about 4 months. This agrees with the finding of Rasmusson and Carpenter (1982): the negative anomalies in the western Pacific occur earlier than the warming in the eastern Pacific.

The independence of the surface temperature variation in the western Pacific from the El Nino/Southern Oscillation time scale represents perhaps its transient feature in the buffer zone between the monsoon system and trade wind system. The strong annual variation both in the surface wind field and the surface temperature field dominates the characteristics of this area. However, it in no manner means that this area is unimportant in the El Nino/Southern Oscillation, because it is very likely that the characteristic time of the Southern Oscillation is just a compound harmonic oscillation between the annual variation and some other oscillation. This is still a major issue in El Nino/Southern Oscillation studies.

Another possibility to explain this feature is that the sea-surface temperature in this area is too uniform and appears to be less variable than in the others. Donguy and Dessier (1982) pointed out that the sea temperature in the western Pacific is not a reliable parameter, while the surface salinity does show an El Nino-like variation.

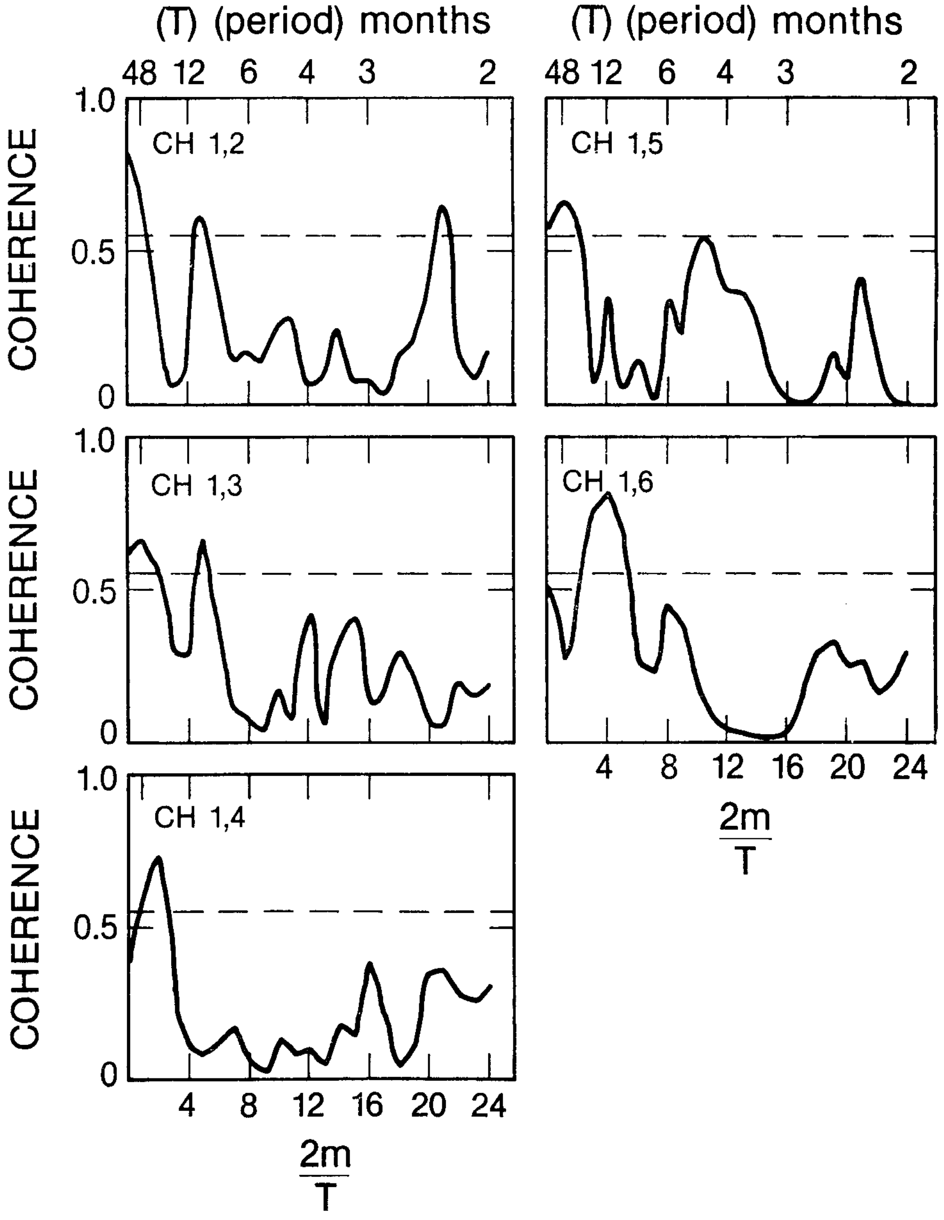

Fig. 6. Coherence spectra between area 1 and others as a function of period and frequency. The dashed line indicates the 95% confidence level.

V. CONCLUSIONS

Since the El Nino/Southern Oscillation is so important in the global atmospheric circulation and in climate variation, and is considered to be the main component of tropical atmospheric circulation, having strong teleconnections with the circulation in middle and high latitudes, a study of the El Nino/Southern Oscillation signal in different areas of the global tropics would be helpful for understanding the whole story of the El Nino/Southern Oscillation and its prediction.

The main conclusions that can be made from only one parameter, the sea-surface temperature in the tropics, are as follows:

a) The El Nino/Southern Oscillation signal (quasi 3–4 year's oscillation) appears not only in the eastern Pacific but also in most of the tropics except for the western Pacific;

b) The El Nino/Southern Oscillation signal is the strongest in the eastern Pacific, where it has an amplitude about 4 times larger than those in the other areas.

c) There is no time lag between the oscillation in the eastern Pacific and that in the central Indian Ocean, but there are different time lags when compared with the other three areas. This indicates that the El Nino/Southern Oscillation originally exists mainly in the Indian-Pacific area and perhaps propagates both eastward and westward into other parts of the tropics.

d) According to the classical definition of the Southern Oscillation, the surface pressure oscillation in the Indian Ocean is out of phase with that in the eastern Pacific, while the surface temperature oscillation in the Indian Ocean is in-phase with that in the eastern Pacific. It is suggested that the Southern Oscillation can not be simply explained by pressure changes driven only from surface temperature anomalies.

e) Non-correlation of surface temperatures between the western Pacific and the eastern Pacific indicates perhaps an independence of the western Pacific area, a buffer zone between the trade-wind system and the monsoon system, where the strong annual variation of both wind field and temperature field dominates atmospheric circulation. In that region there is a strong interaction between the annual variation and the other time-scale oscillations. This is a very challenging question in the study of the El Nino/Southern Oscillation. It should be checked carefully by studying other variables in this area.

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