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THE PROPAGATION CHARACTERISTICS OF INTERANNUAL LOW-FREQUENCY OSCILLATIONS IN THE TROPICAL AIR-SEA SYSTEM

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ABSTRACT

The time series of sea surface temperature(SST), sea level pressure (SLP), zonal wind (U) and total cloudiness (CA), for the period of 1950–1979, over a 8°×8° grid-point latitudinal belt between 32° S and 32°N are made from COADS (Comprehensive Ocean–Atmosphere Data Set). The time harmonic analysis and power spectra analysis show that there exist quasi-biennial oscillation (QBO), three and half years oscillation (SO), five and half years oscillation (FYO) and eleven years oscillation (EYO) in these time series. The main propagation characteristics of these interannual low-frequency oscillations are as follows:

(1) The variance analysis of SST shows that there is an active region of QBO and SO (with maximum variance), coming from the southwestern part of the subtropical Pacific, stretching eastward up to the west coast of South America, and then northward to the eastern equatorial Pacific. The QBO and SO disturbances of SST follow the same route and cause the anomaly of SST (El Nino and period of cold water) in the eastern equatorial Pacific.

(2) Either the QBO or SO of SST can cause El Nino events, although it is easier when they are situated in the same phase of warm water at the eastern equatorial Pacific. The FYO of SST seems to be a standing oscillation. It plays an important role on the formation of strong El Nino events or strong cold water events.

(3) The QBO and SO of U propagate eastward along the equator. The origin of QBO and SO may at least be traced as far as the western Indian Ocean. While they propagate along the equator, it strengthens two times at 90° E and the western Pacific, respectively. Like SST, the FYO of U is somehow a standing oscillation.

(4) The Oscillations of U have a good coupling relationship with those of SST, while they propagate. When the QBO and SO of SST move to the east side of the eastern equatorial Pacific, it is the time for the QBO and SO of U to enter into the east part of the western Pacific.

It is clear that, when we do research work on the formation of El Nino events, our consideration would not be confined to the tropics, it should cover the subtropical region in the southern Pacific. The features of the circulation and other oceanic states in this area are very important to the El Nino events.

I. INTRODUCTION

Recently, the research on the low-frequency oscillations with periodicities longer than one year (VLFO) in air-sea system has become one of the major concerned problems in the fields of synoptic and dynamical meteorology. Some scientists take the low-frequency oscillations with 30–60 day period as a physical consideration for the medium-range or monthly forecast, and take VLFO as a physical foundation for the intraseasonal/interannual forecast. By now, the significant oscillations which have been recognized with periodicities longer than one year are quasi-biennial (QBO), three and half years, five and half years and eleven years. For simplicity the last three oscillations are denoted here as the SO, FYO and EYO, respectively.

The QBO was discovered first by Reed (1964) in the lower stratosphere. It was also found in the index of Southern Oscillation and the Indian monsoon rainfall (Bhalme and Jadhav, 1984). Yasunari (1985) found the QBO in the 200 hPa and 700 hPa zonal wind (U) and pointed out that the propagation of QBO is eastward along the equator. It is thought that the QBO results from the eastward propagation of the anomalous Walker circulation. In this paper, the activities of QBO in the air-sea system will be investigated. The variability and evolution of QBO and the coupling relationship between air and sea will be discussed in another paper (Chen, Yan and Wang, 1987).

Lots of research work on SO has been done. Although the Southern Oscillation and the El Nino event have a period varying from two to seven years, still some people refer the SO to as the main period of ENSO. For convenience, the three and half years oscillation is still denoted as SO. In other words, the word SO means the oscillation with a three and half years period. Krishnamurti, Chu and Iglesias (1986), Yasunari (1985; 1987a, b) investigated the SO propagations of pressure and zonal wind and found that in the atmosphere, they are eastward moving waves with the zonal wave number 1. The phase distribution shows that the SO of zonal wind appears firstly over the Indian Ocean, but the SO of pressure, according to Yasunari (1987b), probably originates in middle Asia and may be caused by the variability of snow and ice in high latitudes. However, by now there is not much research work on the SO in the air-sea systems with a same data set. The activities of SO are discussed in the paper. The evolution and coupling relationship of the air-sea system will be reported in another paper (Chen, Yan and Wang, 1987). Few investigations concerned with the FYO have been done. Bhalme et al (1984) found the existence of FYO in SOI and the Indian monsoon rainfall, with its confidence better than 95%. However, the structure and the propagation of FYO are not thoroughly understood yet. It is one of our interests to get an insight into these aspects.

The Comprehensive Ocean-Atmosphere Data Set (COADS) is now available. The elements used here are the sea surface temperature (SST), Sea level pressure(SLP), zonal wind (U) and the total cloudiness(CA). The period of 1950–1979, with most complete data, is chosen and original 2°×2° mesh is simplified to 8°×8° mesh.

II. DATA AND COMPUTATIONAL PROCEDURE

The simplified data set of SST, U, SLP and CA for the period of 1950–1979 (360 months in total) over 8°×8° grid-point mesh are made firstly from the COADS. The south and north boundary lines are 32° S and 32°N, respectively. There are still some years without data, even though we have chosen the best data period. We have to fill up the data gaps by means of time linear interpolation in each time series. If the number of missing data is more than 3 (three monthly means), we change the method to use the zonal linear interpolation. It was proved that this interpolation method can make a satisfactory, complete time series. In order to eliminate the seasonal tendency, we take off the climatical means, and so only the anomalies are discussed here.

Applying the time harmonic analysis method to each time series at each grid-point, we find the maximum amplitudes concentrate over some periods. They are two years, three and half years, five and half years and eleven yeras, respectively. In the equatorial region, the oscillation of SST also has maximum amplitude over these four periods, located mainly in the Pacific Ocean (figure is not shown). Those of U are located from the Indian Ocean eastward to the central Pacific, and so are those of CA.

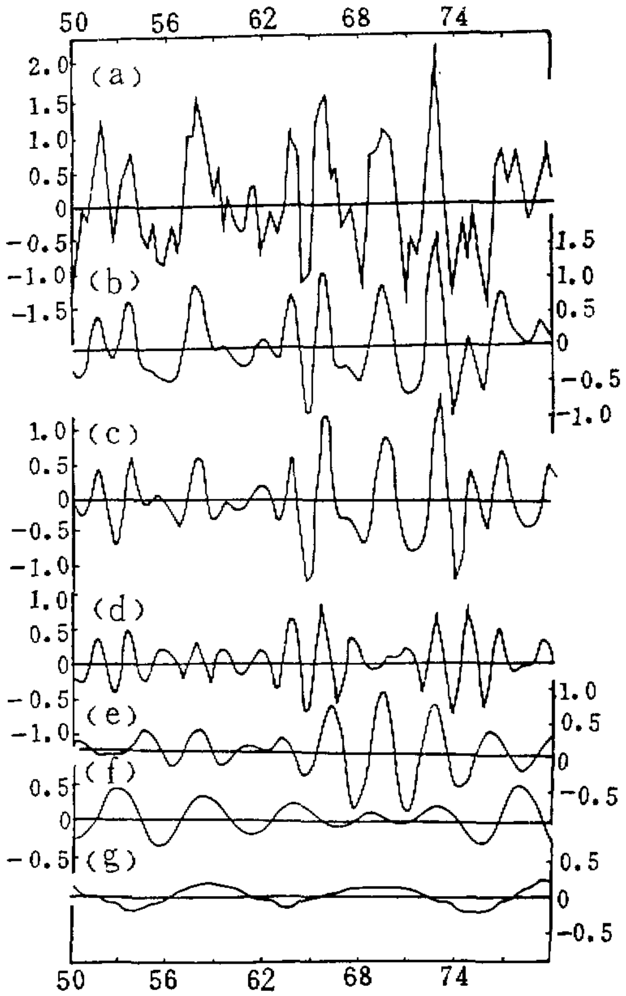


Fig. 1. The average (174° W–78°W, 0°N) time series of SST for different oscillations.
(a) actual curve of SST; (b) resultant curve of QBO, SO and FYO; (c) resultant curve of QBO and SO; (d) curve of QBO; *(e) curve of SO; (f) curve of FYO;* (g) curve of EYO.

In order to filter out each oscillation component, we apply the filter formula developed by Murakami (1979) with the central periodicities of 24, 42, 66 and 132 months for QBO, SO, FYO and EYO, respectively. As an example, we give a comparison between the time series of SST anomaly in the eastern equatorial Pacific (174°W-78°W) and the variations of oscillation components (Fig. 1). From the actual variation (curve (a)), it can be seen that the positive anomalies in 1951, 1953, 1957-1958, 1963, 1965-1966, 1969, 1972, and 1976-1977 are distinctive, and all these years are El Nino event years. Also the negative anomalies in 1950, 1952, 1954-1956, 1960, 1962, 1964, 1967-1968, 1971, 1973 and 1975 are the period of cold water. Curves (d)-(g) represent the components of QBO, SO, FYO and EYO, respectively. It is seen that the amplitudes of QBO, SO and FYO are of the same order, indicating their same importance. Except for 1969, there is always a peak of QBO (curve (d)) responding to each positive anomaly of actual SST (curve (a)). It is clear that QBO is very important to the formation of El Nino event. The variation of SO (curve (e)) shows some peaks in 1957, 1965-1966, 1969, 1972 and 1976 (El Nino years) and curve (f) (FYO) has peak in 1953, 1958, 1963 and 1972, implying their importance to the El Nino event. However, the variation of EYO (curve (g)) is rather small, no significant contribution to El Nino or period of cold water. Curve (c) represents the resultant of QBO and SO. Although curve (c) can basically reflect the actual positive SST anomalies (curve a), the intensity of signals is much weaker than the actual. Moreover, the nagetive anomalies in some cold water years, such as 1958 and 1962, do not appear in curve (c). However, curve (b), representing the resultant of QBO, SO and FYO, can reflect the years of strong El Nino and cold water much better than curve (c). We suggest that the FYO should be an important factor to determine the intensity of El Nino events and to cause the cold water events. Its function is different from those of QBO and SO, and can not be ignored.

Fig. 1 shows some reasonable results, and also implies our computation is reliable. The following discussion is based on these oscillation components.

III. THE VARIANCE DISTRIBUTIONS OF INTERANNUAL OSCILLATIONS

The variance distribution of oscillation components for 360 months period is shown in Fig. 2, which indicates the activity features of each oscillaton for each meteorological element (SST, U, SLP and CA). The following discussion is classified according to different oscillations.

QBO:

The most significant feature of SST-QBO is the existance of a maximum variance belt over the southern Pacific. This maximum belt originates in the western part of the southern subtropical Pacific, stretches eastward to the west coast of South America, then turns northward to the equator and goes straight along the equator to the middle Pacific. The maximum variance center is off the west coast of South America, where the QBO in the ocean is most active. Chen et al (1987) found the QBO of SST propagates anticlockwise along this belt, and makes great contribution to the warming or cooling of the sea water. There are still some other maxima with less values of SST variance located alongside the shore of East Asia (close to the region of Kuroshio) and California cold current area.

The QBO variance distribution of U differs from that of SST. There are two maxima along the equator, located in the equatorial Indian Ocean (70°-90°E) and in the area between 140°E and 160°W (with a center near 169°E). Besides, in the equatorial area, with large value variance of SST, the variance of U is small. In all subtropical oceans, there are some high value QBO centers of U, indicating the subtropics is also an active area. This is different from the QBO in stratosphere, where the QBO of U decreases poleward from the equator, and becomes very weak in the subtropics.

No maximum QBO of SLP is found near the equator. But in the subtropics of both hemispheres, the maximum QBO of SLP is almost coincided with that of U, indicating the QBO is very active in the subtropics.

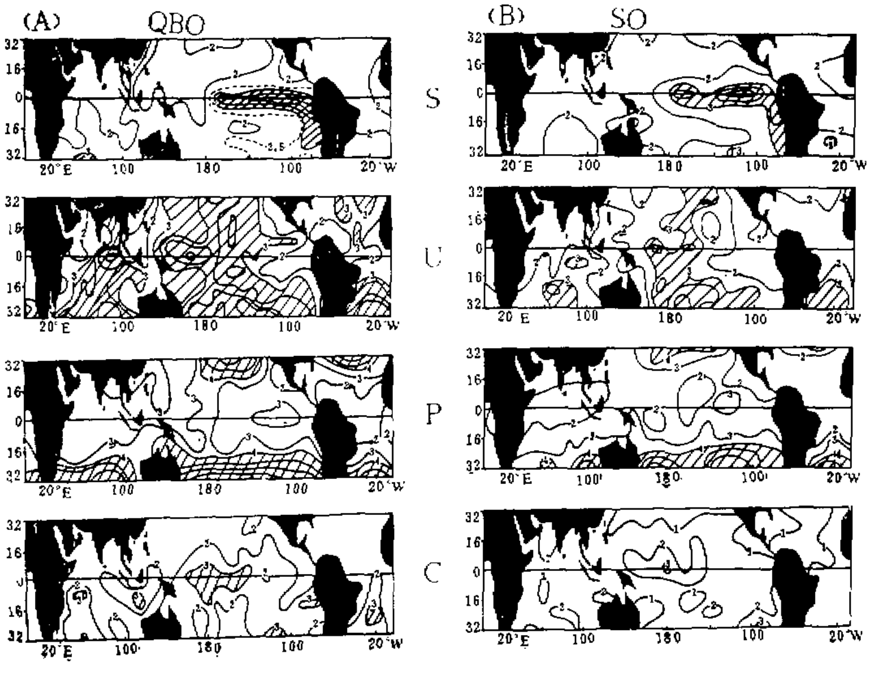
The maximum QBO of CA concentrates in the central equatorial Pacific. As we know, the rainfall there is very sensitive to El Nino events, and consequently, the QBO of CA is very active there.

SO:

As defined previously, SO here means the oscillation with a three and half years period. In general, the variance distribution of SO is similar to that of QBO. As for SST, the maximum belt lies in the eastern equatorial Pacific, alongside the west coast of South America and in the subtropical southern Pacific. The SO of SST, like the QBO, is very active in this belt. The SO maxima of U are located not only in the equatorial Indian Ocean, the western and central Pacific, but also in the subtropical southern Indian Ocean, and the subtropical Pacific in both hemispheres. Again, only in the subtropics southern and northern Pacific can the maxima SO of SLP be found. And the SO maxima of CA are only seen in the central equatorial Pacific with variance values less than those of QBO

FYO:

The variance distribution of FYO is different from those of QBO and SO. The variance maximum of SST exists in the eastern equatorial Pacific (180°W–140°W), but there



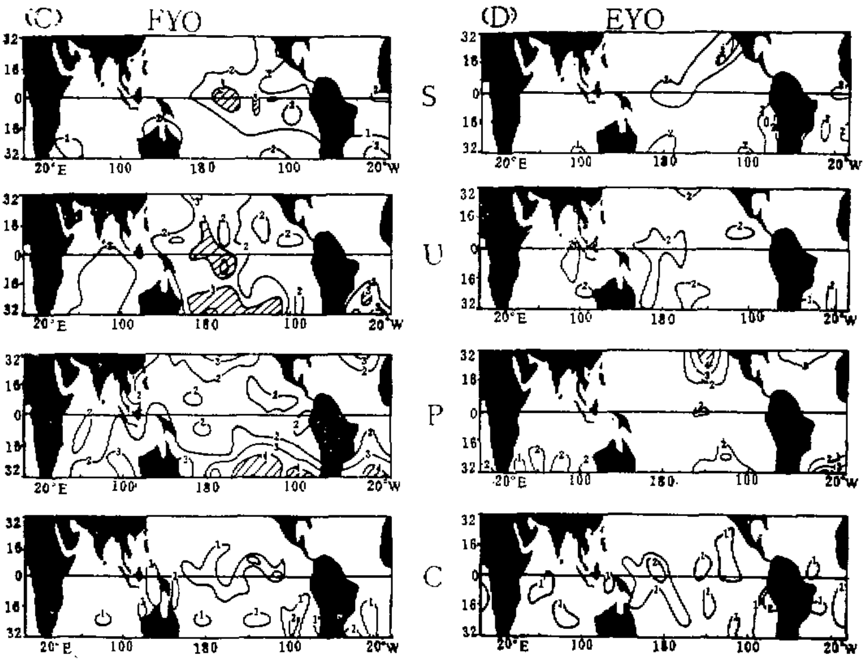


Fig. 2. The variance distribution of the four oscillations for SST, U, SLP and CA.
2A: QBO; 2B: SO; 2C: FYO; 2D: EYO. The unit is 0.1 (°C, m/s, hPa, decile) and the interval is 1.0 (°C, m/s, hPa, decile), shadings indicate regions of greater than 0.3 for SST, U and CA, and 0.4 for SLP.

are two maxima of U, with almost the same order of value, in the central equatorial Pacific and the subtropical southern Pacific, respectively. The distribution of FYO variance of SLP is similar to those of QBO and SO, with high value variance in the subtropical southern/northern Pacific. The FYO variance maximum of CA, like QBO and SO, lies in central equatorial Pacific, but extends eastward to 100°W.

EYO:

The variance of EYO is relatively small. The variance maxima of SST and SLP concentrate alongside the North America coast. The center of SST lies close to Mexico and stretches southwestward to the central Pacific.

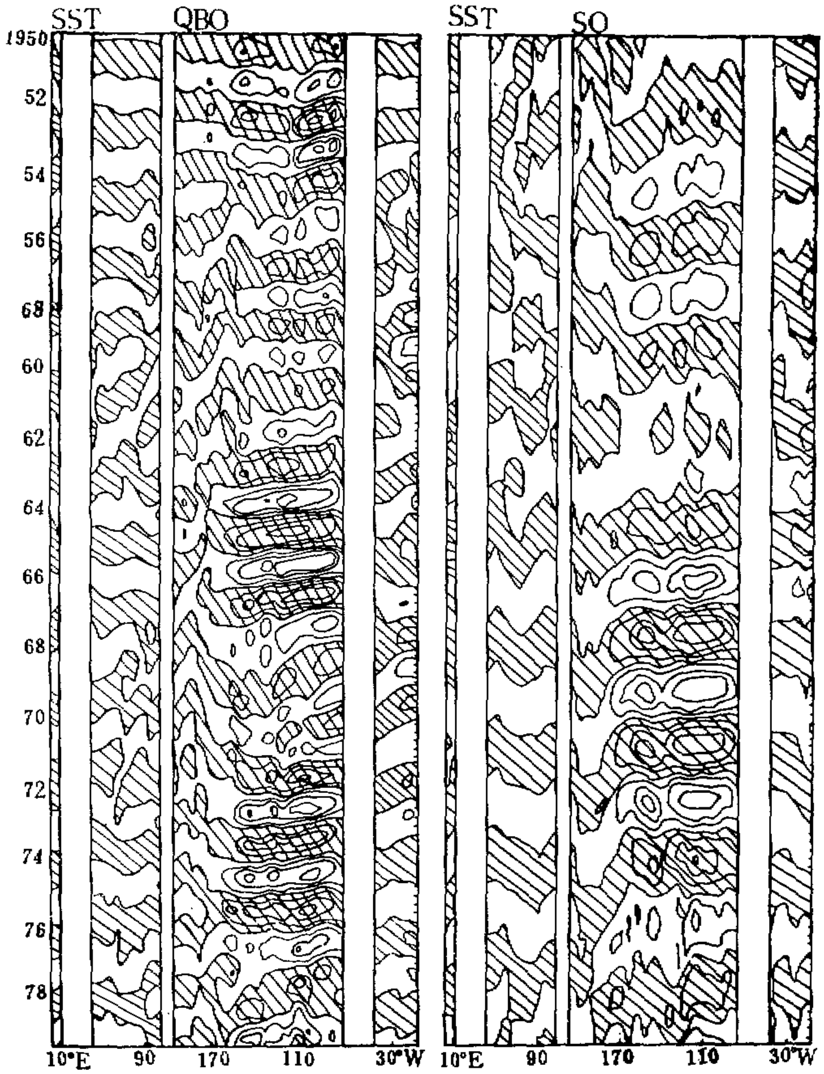
Like FYO, the EYO of U and CA is significant over the central equatorial Pacific.

In summary, each of the four oscillations has different active areas. The activities of QBO and SO are similar to each other. For instance, the QBO and SO of SST both have an active area, coming from the west part of the subtropical southern Pacific, stretching eastward to the west coast of South America, then turning northward to the equator and spreading westward to the central Pacific. The activities of U are confined to the Indian and western/central equatorial Pacific, and those of SLP are confined to the subtropical southern/northern Pacific. However, the FYO of SST and U concentrates in the central equatorial Pacific.

The propagation route of oscillations is usually within the active areas, and that will be discussed in the next section.

IV. ZONAL PROPAGATION OF THE OSCILLATIONS

The SO and QBO propagations of U and SLP have been investigated by some meteorologists. However, no one has been concerned with the oscillations with periods longer than three and half years, and used a data collection combining information in both sea and air systems. The COADS contains elements in both atmosphere and oceans for a



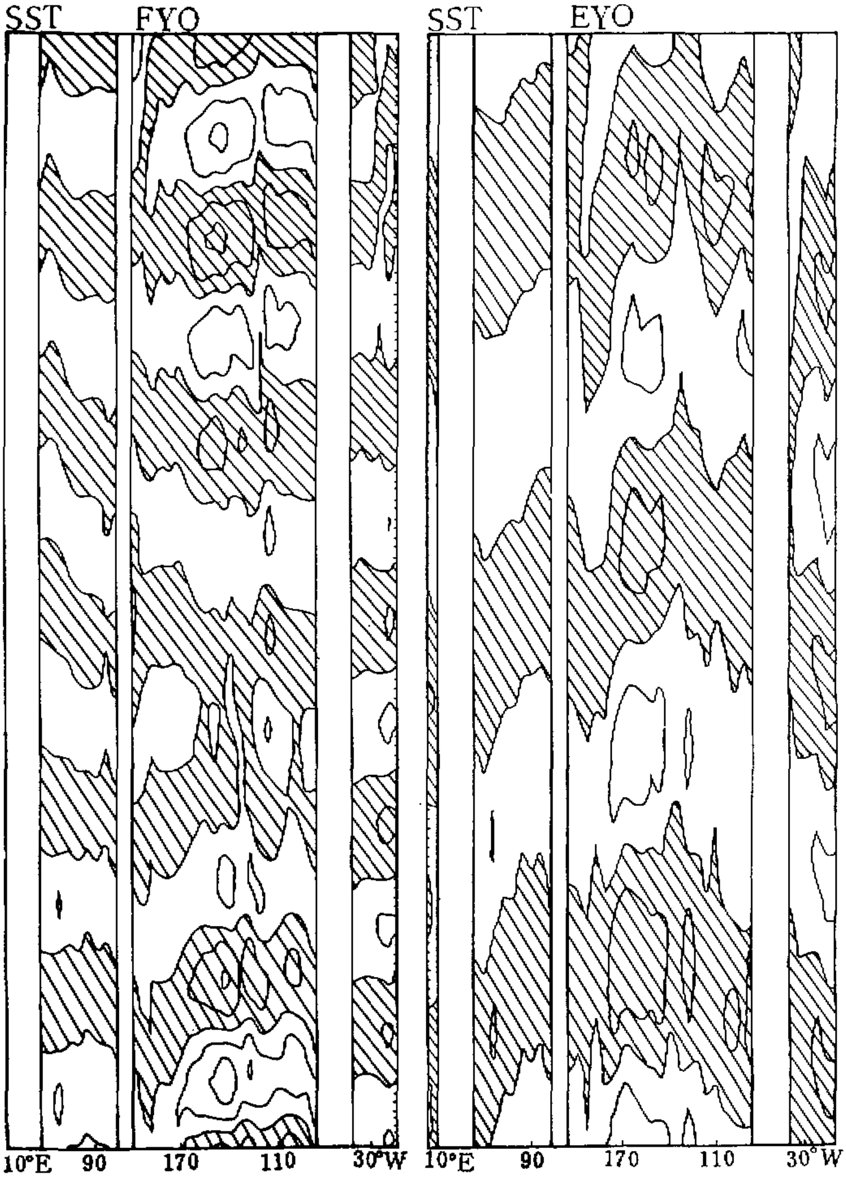


Fig. 3. Time-longitude cross-section of SST oscillations along equator. The interval is 0.3°C. Negative values are shaded.

period longer than 30 years. That provides us means to investigate the problem just mentioned. Since the oscillations of SLP are very weak near the equator, our concern is only with the propagation of SST and U.

Figs. 3a and 3b are the time-longitude sections along the equator of the four oscillations of SST. The QBO and SO propagate westward in the equatorial Pacific east of 160°E and this is also the propagation direction of the most El Nino events. To the west of 160°E the propagations of QBO and SO in the Pacific and the Indian Ocean are eastward, although there are Borneo and Sumatra between the two oceans and the oscillation amplitude is rather small.

In the equatorial Atlantic Ocean, however, the propagation of QBO seems westward, while that of SO is still eastward. The eastward propagation over the central equatorial Pacific is rather quick. It takes only three or four months to get to the central Pacific from the South America coast. It is also seen that there are two oscillation centers located in 100°-120°W and the central Pacific. The centers of SO are even more pronounced, especially during 1963-1975. The east center is caused obviously by the oscillations propagating northward alongside of the west coast of South America. But the mechanism to cause and maintain the center in the central Pacific is not clear yet. The QBO and SO act differently in different periods. For instance, the QBO was very active in 1952-1955, 1962-1967 and 1971-1976, and the SO was very active in 1963-1975 with maximum amplitudes of 0.9-1.2°C.

Over the equatorial Pacific, the propagation direction of FYO is ill-defined. Sometimes, such as in 1963-1967, it is a little eastward. Sometimes, such as in 1971-1975, it is slightly westward. Moreover, it seems a bit eastward in the Indian Ocean. So, it can be believed that the FYO is basically a standing wave with the oscillation center in the central Pacific (170°E-160°W). This center is also a maximum of variance, indicating that the FYO is very active there. The amplitude of FYO has a maximum about 0.6°C and the mean value is greater than 0.3°C most of the time.

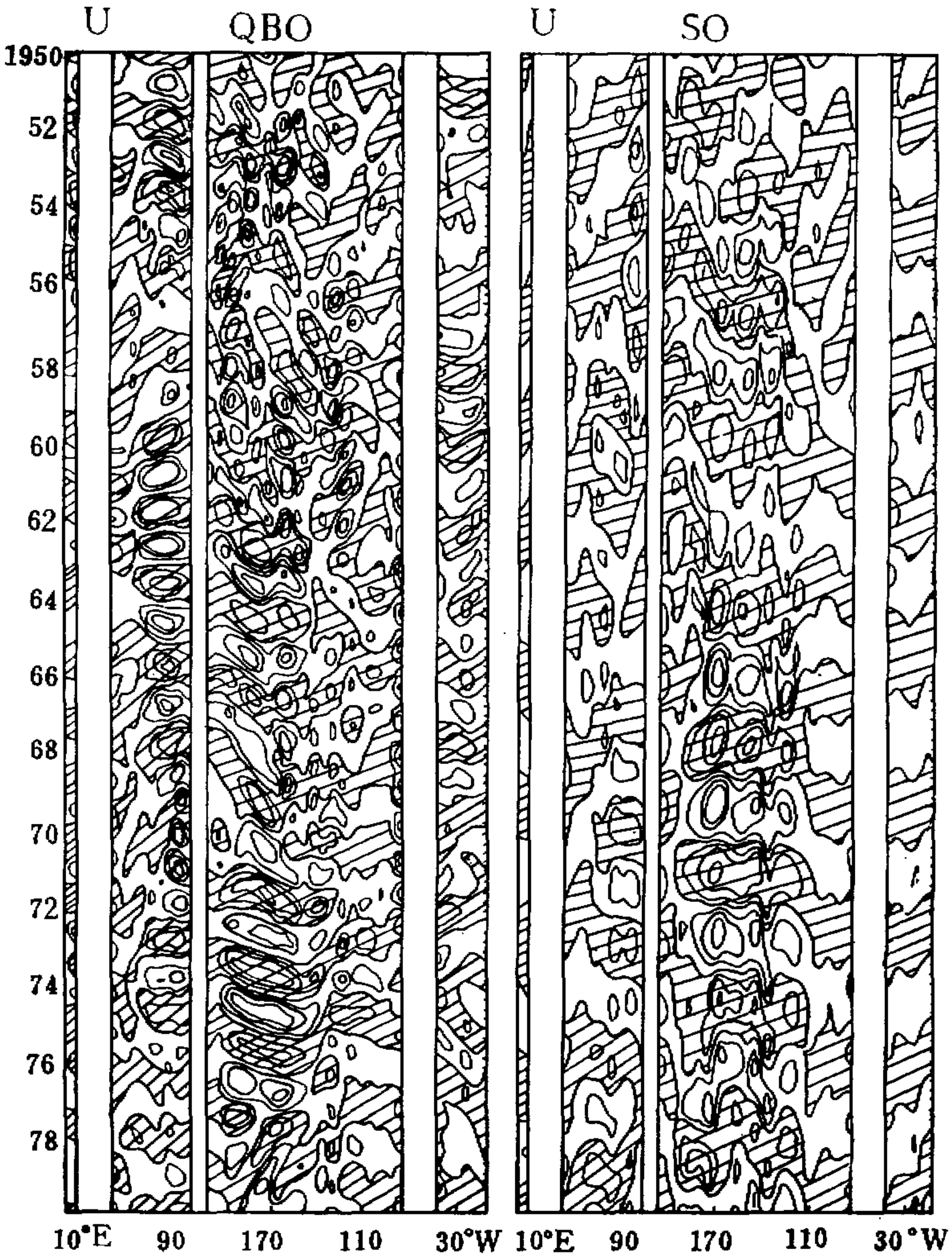
Although there are only three circles of EYO in the whole 30 year period, the westward propagation in the Indian Ocean is obvious (just opposite to the propagation of FYO). However in the Pacific, it moved westward in the fifties and sixties, and eastward in the seventies. The EYO, like the FYO, can also be classified as a standing wave with the oscillation center in the central Pacific and a comparatively small amplitude about 0.3°C.

Fig. 4 is a time-longitude diagram of U oscillation along the equator. The oscillations (QBO, SO and FYO) are active between 0°E and 160°W, but they are weak in Western Hemisphere. That is in agreement with the 30-60 day oscillation. The QBO propagates eastward distinctively in the eastern equatorial hemisphere, but hardly move in the Western Hemisphere, especially in the eastern equatorial Pacific. Even more, it moves westward in some years, such as 1954-1956, 1967-1973. That is also the way in which the 30-60 day oscillations of OLR propagate. Murakami et al (1986) claimed that the low-frequency oscillation of OLR moves eastward in the Eastern Hemispheric equatorial area and is ill-defined in the other hemispheres. The QBO has three oscillation centers in the Eastern Hemisphere, located in 70°-90°E (the equatorial Indian Ocean), 110°E· (the western equatorial Pacific) and the central Pacific, respectively. This is similar to the variance distribution of U (see Fig. 2).

As for SO, its propagation is eastward in the region west of 110°W. Again, there are three maximum centers of SO like QBO, but the two centers in the equatorial Pacific are further eastward than those of QBO.

Yasunari (1986) found the QBO and SO amplitudes of U vary from time to time.

For example, in the periods of 1971–1977 and 1980–1985, the QBO of U was active with larger amplitude, so was SO in the periods of 1969–1973 and 1982–1985. This feature



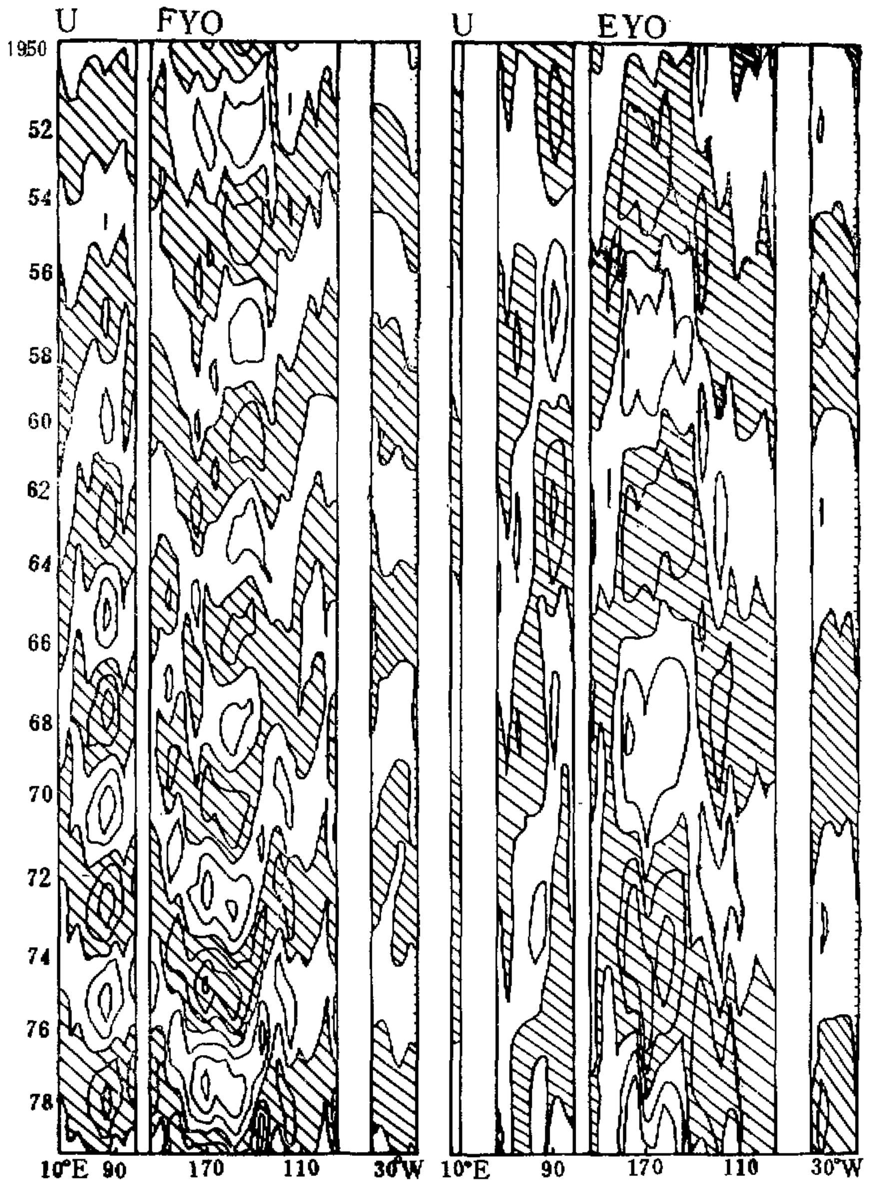


Fig. 4. Same as Fig. 3, but for U.

also appears in Fig. 4, with large QBO amplitude in 1951–1955, 1961–1966, and 1971–1977 and in the periods of 1953–1959 and 1964–1975 for SO. So the stronger periods proposed by Yasunari coincide with ours except for the stages before 1968 in our results and after 1979 in his. Combining two works we get the strong periods in 1951–1955, 1961–1966, 1971—1977 and 1980—1985 for QBO, 1953—1959, 1964—1975 and 1982—1985 for SO. The reason of periodical variation in QBO and SO needs further study and it also should be noticed that the strong/weak periods of SST and U, not only QBO but also SO, are consistent with each other. This periodical variation is the characteristic in ocean-atmosphere system. They are coupled quite well.

The FYO of U propagates apparently eastward in west of 140°W, and a slightly westward in eastern Pacific of 78°-140°W. It has two oscillation centers located at 90°E and in the central Pacific separately. When the oscillation approaching to 90°E, it becomes stronger. After that it decreases rapidly and finally it becomes stronger again near the central Pacific. The oscillation amplitude is very small in the area between 90°E and the central Pacific. It seems that the two oscillation centers fluctuate separatively, i.e., they are standing waves. It should be noted that the FYO of U is different from that of SST. While the FYO of SST in the equatorial area fluctuates in almost the same phase, the FYO of U in Indian Ocean is out of phase with that in the western and central Pacific. So the FYO of U is characterized by the zonal wavenumber 1.

The EYO of U is hardly in propagating, with maximum amplitude centers, located to the east of 90°E and the central Pacific, respectively. Like the FYO, the EYO is characterized by the zonal wavenumber 1, too.

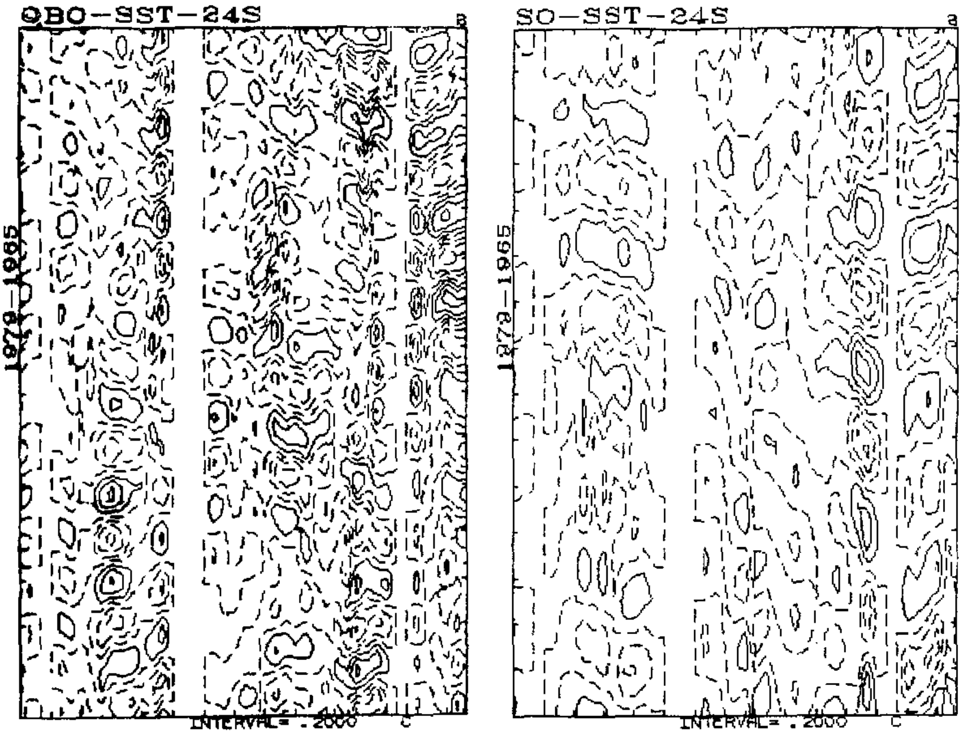


Fig. 5. Time cross-sections of SST oscillations along 24°S from 1965 to 1979. Dashed lines are negatives. (a) QBO, (b) SO.

In summary, the central Pacific is the most active area for the four oscillations of U. The next one is the Indian Ocean near 90°E, which is the origin of the QBO and SO and also the center of all oscillations. However, the mechanism to stimulate the oscillations in these oceans is not understood yet. That deserves further investigation.

As the propagation of oscillations in the subtropics is concerned, it is believed that the SO of SLP propagates eastward. i. e., as the same in the equatorial region. Our results show that the propagations of QBO and SO are eastward in subtropics, especially the oscillation of SLP in the latitude between 32°S-32°N. However, there seems some phase difference between the oscillations of U in the subtropics and the equator. Here, more details are given to the oscillations of SST in the subtropics.

Fig. 5 (a) and (b) are the time cross-sections of SST near 24° S. It is clear that both QBO and SO propagate eastward in the subtropical Pacific, that is just opposite to the case near the equator. There often exist some QBO centers in the central subtropical Pacific, and alongside the western South America coast. The latter is also the location for SO center. Whenever the QBO or SO of SST approaches to the western coast of the South America (in the subtropics), the disturbance always strengthens. And the disturbances in the subtropics appear usually three months earlies than those near the equator (see Fig. 3). This will be discussed in more detail in next section (or refer to the authors' another paper, 1987). We suggest that the disturbance of SST near the equator be caused by the one which propagates eastward to the west coast of South America and then turns to the north alongside the coast. While the disturbance is moving northward, it is getting stronger and stronger. In the last section, it is shown that the variance of QBO and SO for SST has a high value belt. The location of that belt is quite well coincided with the propagation trace. It indicates that the anomalous high SST in the eastern equatorial Pacific may originate from the subtropical southern Pacific.

V. THE MERIDIONAL PROPAGATION OF SST OSCILLATIONS

To illustrate the suggestion that the oscillation of SST will turn to the north when it arrives at the west coast of South America, we investigate the time-longitude cross-section of SST oscillation along 86°W (close to the west coast of South America). Figs. 6a, 6b are for the period of 1965–1979, because the situation during 1951–1964 is quite similar. Fig. 6a is for the QBO of SST. We can see that the propagation of QBO is northward except for the period of 1975–1978, when the QBO is still northward to the north of 16°S. While the oscillations propagate northward, most of them are getting stronger and reach their peaks near 8°S-0°. Still a few cases behave differently, increase first, reach the peak near 24°S, then decrease and finally increase again to the north of 16°S.

Fig. 6b shows the meridional propagation of SO for SST. The SO propagates northward and strengthens while it moves. The maximum is near 8°S.

The propagation speed can also be estimated from Figs. 6a, 6b. It usually takes 3–6 months from 24°-32°S to the equator, i.e., the speed is about 5–8 degrees of latitude per month.

In the Northern Hemisphere, the oscillation can reach as north as 8°-16°N, but it becomes very weak there. No southward propagation is found in this hemisphere.

A time cross-section of SST oscillations averaged for the longitude between 170°E-134°W is given in Fig. 7. It is seen from Fig. 7a that the QBO during 1970–1975 is obviously southward from the equator. However, it can not be found in other years. Also the oscillations in the subtropics and the equator are out-of-phase, especially in the southern Pacific west of 110°W. So, it can be thought that most of the QBO oscillations in the subtropical southern Pacific are locally developed by and large, although the influences from the equator still exist. Fig. 7b is for the SO. The anomaly signs in the equator and the subtropics are almost opposite, and there is no obvious meridional propagation. These facts indicate that the oscillations of SST in the subtropical southern Pacific are locally developed, except that part of QBO is stimulated by the oscillation propagating from the equator.

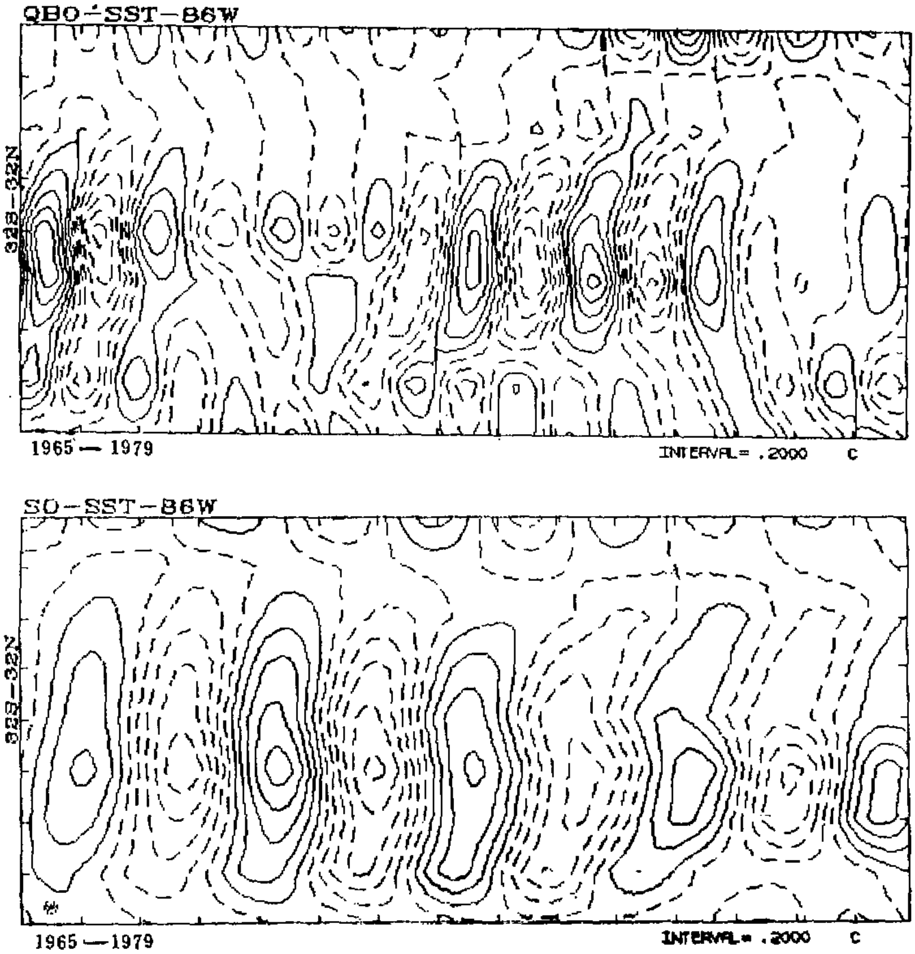


Fig. 6. Time-latitude cross-section of SST oscillations along 86°W.
(a) QBO; (b) SO. Dashed lines are negative.

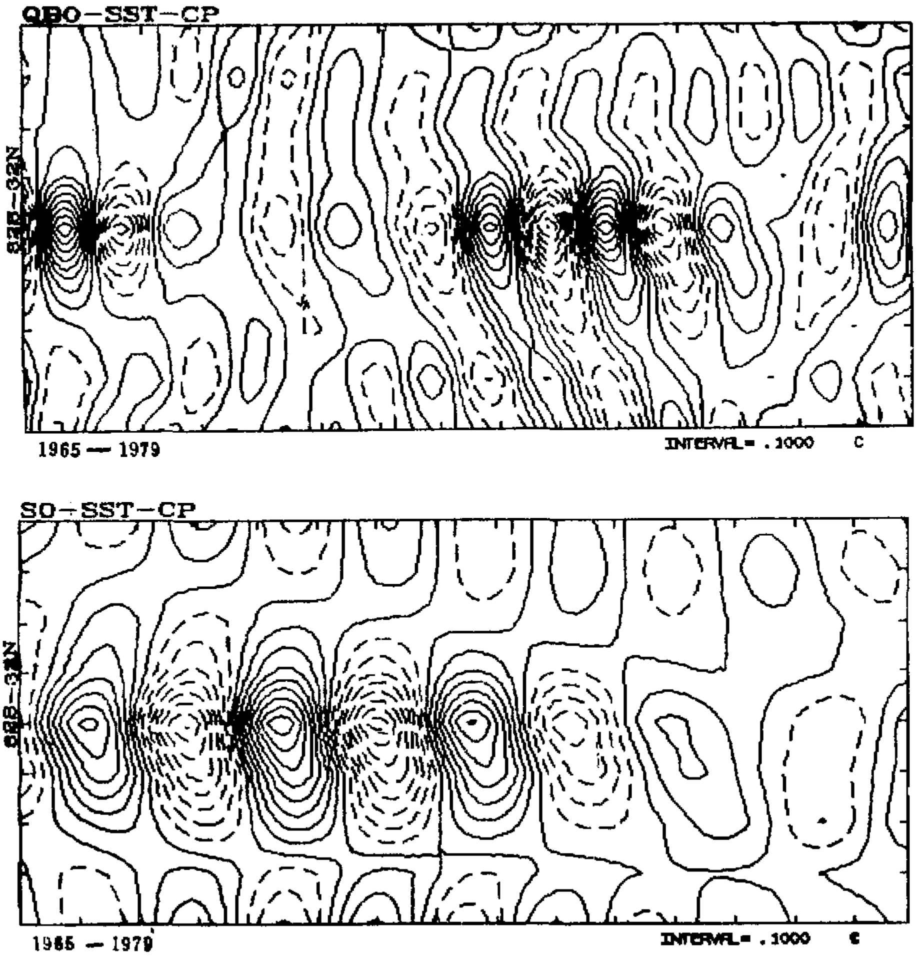


Fig. 7. Same as Fig. 6, but along central Pacific of 178°E-134°W.

VI. CONCLUSIONS

It is shown that the COADS data are very useful for investigating the interannual variations of the sea-air systems. The following conclusions can be drawn:

1) It is found from the QBO and SO variance distributions of SST that the active area (high value of variance) originates from the subtropical southwestern Pacific, stretches eastward up to the coast of the South America, and then turns northward and spreads out in the eastern equatorial Pacific. The QBO and SO of SST also propagate from the subtropical southwestern Pacific (QBO partly from the western equatorial Pacific), then go anticlockwise to the eastern equatorial Pacific, causing an anomalous SST there. The time for propagating from the southwestern Pacific to the central equator is just the periodicity for each oscillation,

2) Either the QBO or SO can cause an El Nino event, although it can be easier for them working together. The FYO is a standing wave, and it is also important for forming the El Nino event and the cold water period. The QBO and SO situation of SST in the subtropical southwestern Pacific and the FYO situation in the eastern equatorial Pacific may be used as a clue for predicting the El Nino event one or two years in advance.

3) The QBO and SO of U near the equator and in the subtropics propagate eastward basically. The origin of oscillations can be traced up to the western Indian Ocean. They usually get stronger near 90°E and the east side of the western Pacific, while they move eastward along the equator. The FYO of U seems to be a standing wave, like that of SST.

4) The coupling relationship between the oscillation of SST and U is consistent. When the QBO and SO of SST propagate into the east end of the eastern Pacific, the anomaly centers of QBO and SO for U arrive in the east part of the western Pacific. In author's another paper (1987), the coupling relationship is discussed in more detail by means of extended EOF method and the lag-correlation analysis.

There is no doubt that our consideration should include the circulation systems and the ocean conditions in the subtropic southwestern Pacific, not just near the equator if we want to predict the El Nino event. During 1982–1983, there happened a particular El Nino event. It is a pity that our data set does not cover this event. Whether our conclusions are valid for that event is still a question. And that is what we will do in the future.

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