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THE TROPICAL VERY LOW-FREQUENCY OSCILLATION ON INTERANNUAL SCALE

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ABSTRACT

This is a review on the studies of tropical very low-frequency oscillation (VLFO) on interannual scale, mainly on the recent researches undertaken by Chinese scientists which are not well known outside of the country.

This paper summarizes the basic features of VLFO in the tropics, the characteristic time and spacial structure of oscillation, especially the new concept of Low Latitude Oscillation consisted of two components: the well-known Southern Oscillation (SO) and the so-called Northern Oscillation (NO). A large number of evidences have been provided to illustrate the relationship between VLFO in tropics and the climate variation in China, such as the long-term variation of north Pacific high, the frequency of typhoon and the cyclone over the East China Sea, the summer monsoon rainfall in Yangtze valley basin and the cold summer disaster in Northeast China, and so on. Finally throw some lights on the nature of VLFO on interannual scale.

I. INTRODUCTION

The low-frequency oscillation is one of the major characteristics of tropical ocean-atmosphere system and displays also somewhat in the higher latitudes. Studies on the origin and maintenance, the amplitude and the phase propagation of such slowly varying motion and their physical mechanisms are of great importance for understanding the predictability of tropical weather and climate.

Recent studies have brought into sharp focus on two kinds of low-frequency oscillation. One is the 30 to 60 day mode on intraseasonal scale, i. e. the eastward propagating planetary wave shown up in sea level pressure, upper troposphere winds, outgoing long-wave radiation, and so on. (e. g. Madden and Julian, 1971; Weickmann, 1983 and Anderson, J. R. et al, 1984). The other is the interannual oscillation associated mainly with the El Nino/Southern Oscillation phenomenon (e. g. Rasmusson and Wallace, 1983; Cane, 1983).

Although there are some evidences showing the possible connections between these two modes (Lau and Chen, 1986), we, in this review, focus mainly on the VLFO on interannual scale but with more wide view than the ENSO phenomenon, especially on the researches undertaken by Chinese scientists in recent years. Only a few of the papers appeared in western journals will be referred when it is necessary.

II. SOME BASIC FEATURES OF VERY LOW-FREQUENCY OSCILLATION (VLFO) IN THE TROPICS

Although the study on low-frequency oscillation in the tropics on interannual scale can be traced back to late last century (Hildebrandsoon, 1897), only recently such a very low-frequency oscillation was well documented by a great number of evidences, according to the ever growing global data sets.

1. *Characteristic Time Scale of Low-frequency Oscillation*

The 40 month low-frequency oscillation in the tropical ocean and atmosphere was found firstly in the study on the relationship between the long-term variation of North

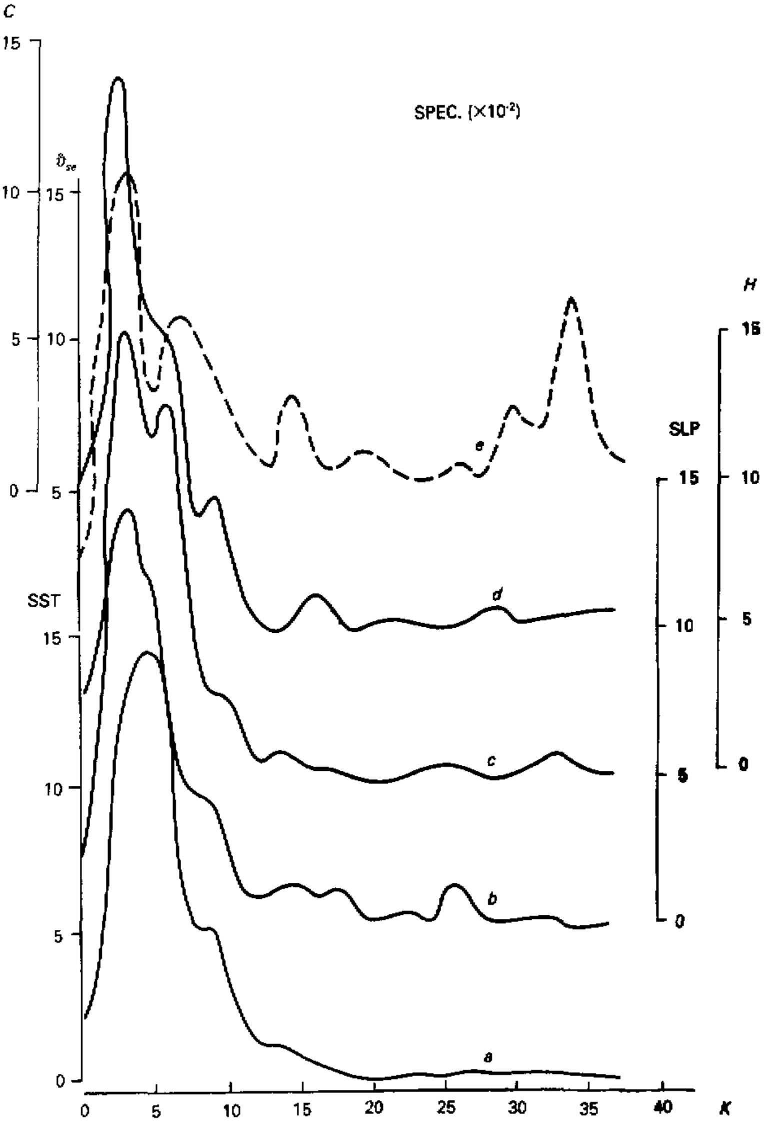

Fig. 1. Power spectrum of first eigenvector of EOF for variables of sea surface temperature (a), sea level pressure (b), humidity (c), θ_{se} (d) and cloudiness (e).

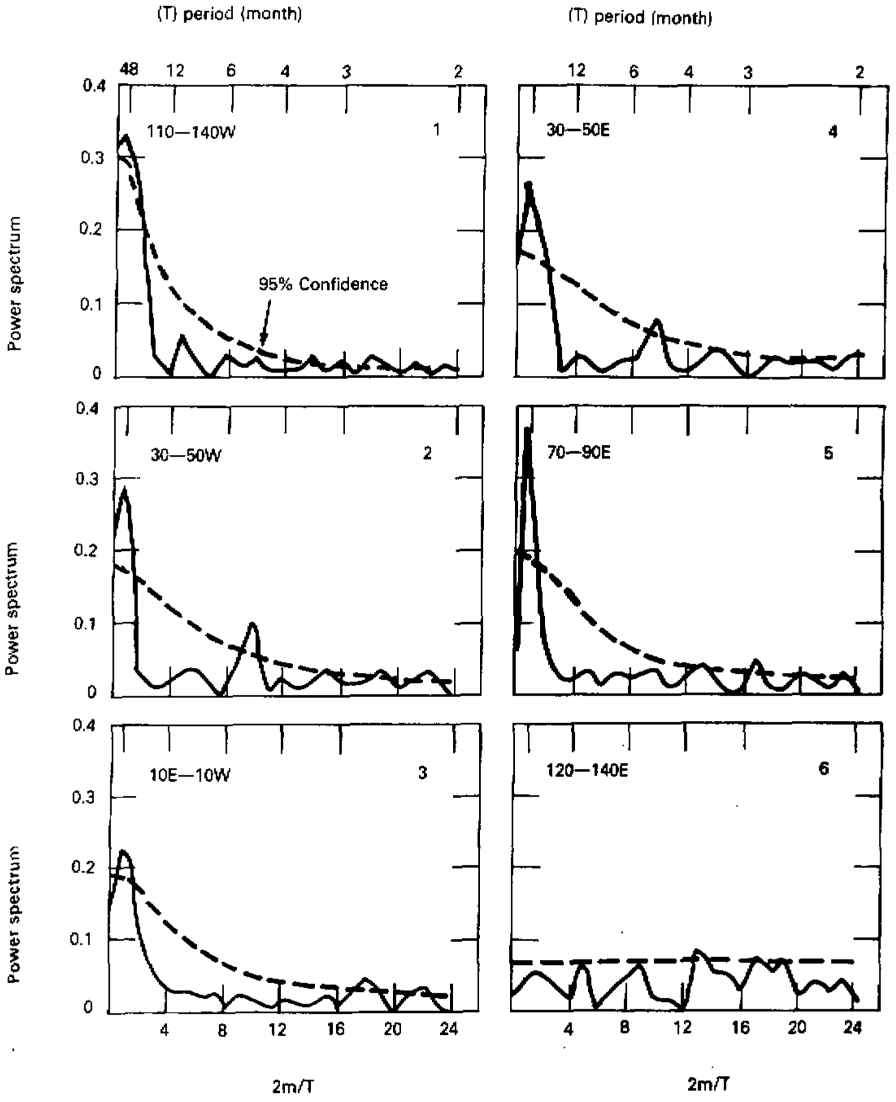

Fig. 2. Power spectrum of SST in six areas along the equator.
1:110–140°W; 2:30–50°W; 3:10°E–10°W; 4:30–50°E;
5:70–90°E; 6:120–140°E.

Pacific high and the SST anomalies in the equatorial Pacific (Fu, et al, 1977). Later on, many studies (i. e. Yan and Chen, 1982; Li and Huang, 1984; Xu, 1987) provided more evidences of the existence of such low-frequency oscillation. The Fu and Su (1981) analysed more completely 4 oceanic parameters: SST anomalies in the equatorial cold tongue, the intensity of north equatorial current (NEC), north equatorial counter-current (ECC), the south equatorial current (SEC), and 4 atmospheric parameters: intensity of north Pacific high, intensity of equatorial low, index of meridional circulation over the tropical Pacific and the index of zonal circulation along the equatorial plane and presented clearly the behavior of LFO in the Pacific area. Recently, through the analyses of time coefficient of first eigenvectors of main surface parameters in the global tropics, the low-frequency oscillation is further documented. Their spectra show the oscillation frequency ranging from 3.5 years to 4.2 years for the 30-year records. (see Fig. 1) (Fu and Dong, 1986).

2. *Regional Features of VLFO*

Since most studies on the low-frequency oscillation focus on the Pacific area, the regional characters of VLFO in the different areas of tropics present some interesting results (Fu, et al, 1987). From the spectra of SST anomalies in six areas in the tropics: eastern Pacific (110°W–140°W), western Atlantic (30°W–50°W); eastern Atlantic (10°E–10°W); western Indian Ocean (30°E–50°E); central Indian Ocean(70°E–90°E) and the far western Pacific (120°E–140°E),it is observed that a well-marked very low-frequency oscillation with the peak at about 3–4 years in most part of the tropics, except for the far western Pacific which displays nearly "white noise" (Fig. 2). But the amplitude of oscillation in the eastern Pacific is about 4 times larger than that in the other areas, indicating the most strong signal over there. The phase spectrum analyses show further the propagation feature from Indian-Pacific area towards both east and west. In about 8 months the VLFO could be spread out to almost whole tropics.

The independence of variation in the far western Pacific represents its transient feature between monsoon system and trade wind system.

By using complex EOF analysis, Fu and Su revealed the information flow of VLFO in the global tropics (Fu, et al, 1987).

3. *Coupling Oscillation of Ocean and Atmosphere*

Since the VLFO has its strongest signal in the tropical Pacific as described in previous sections, the coupled oscillation in the tropical Pacific ocean-atmosphere system has been mainly studied recently (Fu and Su, 1981). The cross-spectrum analysis between oceanic and atmospheric parameters in the tropical Pacific shows a well-marked coupled oscillation. The oceanic variations precede usually the atmospheric ones, suggesting that the ocean probably plays an important role in the low-frequency oscillation as a low-pass filter. In addition, among all the oceanic parameters, the SST shows maximum coherence with the atmosphere, implying the thermodynamic feature of oceanic effect on the atmosphere. It is interesting that the equatorial countercurrent (ECC) seems to play an important role in the tropical Pacific Ocean as portrayed by Fig. 3. It is understood that the velocity of ECC is about three times of that of the SEC and NEC. Its mass transfer is about the same order as the Kuroshio and Gulf stream. Therefore although ECC is a shallow current, its high speed and large amount of mass transfer could bring about the transfer of surface warm water from west to east. It is probably more sensitive to the variation of surface wind stress, because it sandwiches between SEC and NEC.

Another interesting thing which can be seen from the cross-correlation coefficient as the function of time lag in Fig. 4, is that the response time of Walker circulation to the ECC is only about 1–2 seasons, but the response time of ECC to the Walker circulation is much slower than the former (about 1.5 year). Only the persistent forcing from the atmosphere can produce significant oceanic response. In other words, in the long-term process, the ocean has the ability to accumulate the energy of high frequency atmospheric forcing and then transforms it into the energy of low-frequency oscillation.

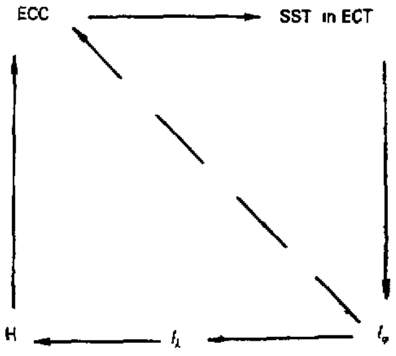

Fig. 3. A schematic diagram showing the role of equatorial counter-current in VLFO.

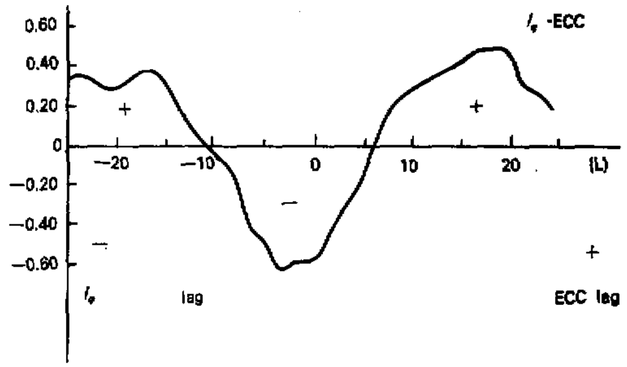

Fig. 4. Time lagged correlation between the index of zonal circulation along the equatorial plane and the intensity of equatorial counter-current in Pacific.

III. LOW LATITUDE OSCILLATION AND ITS TWO COMPONENTS OF VLFO IN THE SEA LEVEL PRESSURE FIELD

The VLFO in the sea level pressure field, showing an out of phase east-west seesaw, was firstly discoverd in last century (Hildebrandsoon, 1897) and was named "Southern Oscillation" (SO) by Walker in early 1920's (Walker, 1923), because the major oscillation centers are located to the south of the equator.

However such east-west out of phase oscillation appears not only in the Southern Hemisphere, but also in the Northern Hemisphere. Recently a new Southern Oscillation picture calculated from a more complete data sets shows a subcenter of negative correlation to the north of the equator in the eastern Pacific around the center of north Pacific high.

By analysing the sea level pressure in the north Pacific (to the north of 10°N), Chen (1984) discovered the east-west out of phase oscillation over there and named it "Northern Oscillation", as a counterpart of the Southern Oscillation (Fig. 5) and pointed out the relationship between NOI and rainfall in the tropical Pacific and the SST in the eastern equatorial Pacific (Chen and Zhang, 1984). Fu and Ye (1987), by using global data set, especially the data over the world ocean (COADS, 1984), verified further the existence of so-called Northern Oscillation (NO), and studied the relationship between Southern Oscillation and Northern Oscillation.

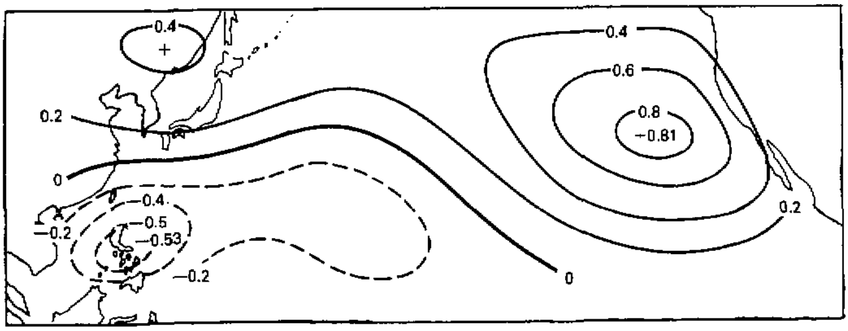

Fig. 5. Simultaneous correlation coefficients of Northern Oscillation Index (NOI) with pressure over the north Pacific.

The first eigenvector of EOF analysis of sea level pressure in global tropics shows clearly a well-marked east-west out of phase oscillation with the zero line along the dateline and four oscillation centers located both to north and south of the equator respectively. One pair of centers to the south of the equator shows the well-known Southern Oscillation. To the north of equator, there is another pair of centers representing the so-called Northern Oscillation, although it is weaker than the one to the south of equator (Fig. 6). An one-point correlations based on the stations of Darwin and Manila show also two components of east-west oscillation, providing more evidence for the existence of both Southern Oscillation and Northern Oscillation on annual scale.

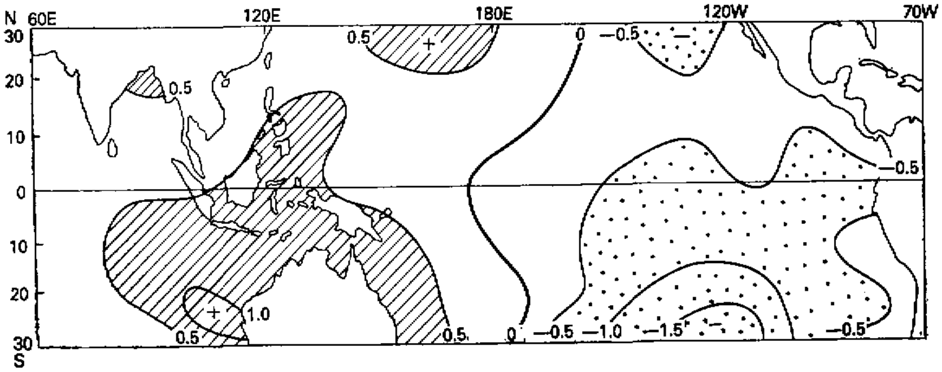

Fig. 6. First eigenvector of EOF of sea level pressure for all seasons.

However, it was observed that the Northern Oscillation exhibits a significant seasonal variation, showing the strong signal only in the northern winter. In the transient seasons, there seems to be a northwest-southeast cross-equator oscillation, a cross-mixing of SO and NO, superimposed on the typical Southern Oscillation. An analysis on the relationship between SO index and NO index indicates that there is a high coherence in the low frequency range (3–4 years) and an almost out of phase relationship in the "higher" frequency range (period shorter than a year).

From the comparison of mean sea level pressure fields with the correlation maps, it is observed that in general the positive correlation area at the western side of SO and NO occupies almost the entire equatorial low pressure zone from Indian Ocean to western Pacific, while two separated negative correlation centers are located at around the north Pacific high and south Pacific high respectively. The seasonal evolution of correlation fields seems to be associated in certain extent with that of the sea level pressure fields. Therefore the nature of NO and SO could be looked upon as a reflection of the interannual variability of three action centers: the equatorial low, the north Pacific high and the south Pacific high.

In accompanying the variation of pressure field, the variations of moisture field, the cloudiness, the θ_{se} and the sea surface temperature fields all show VLFO features. In the cloudiness field, it displays mainly the east-west shift of the strongest convection area around the dateline. While in the moisture, θ_{se} and SST fields, it displays respectively mainly the alternative appearence of warming and cooling, moist and dry and moist unstable and the depression of unstability over the central and eastern equatorial Pacific. The opposite trend appears in the subtropics both in north and south Pacific.

As mentioned in Section II, such a very-low frequency oscillation appears also in the variation of equatorial ocean currents and that of some atmospheric circulation indices. (Fu and Su, 1981).

It was concluded that the VLFO is basically an integrated behavior of tropical ocean-atmospheric system. It does not show branching phenomenon symmetric to the equator, except for the pressure field. Therefore the new concept of "Low-Latitude Oscillation" (LLO) was proposed (Fu and Ye, 1987). While the so-called "Northern Oscillation" and the

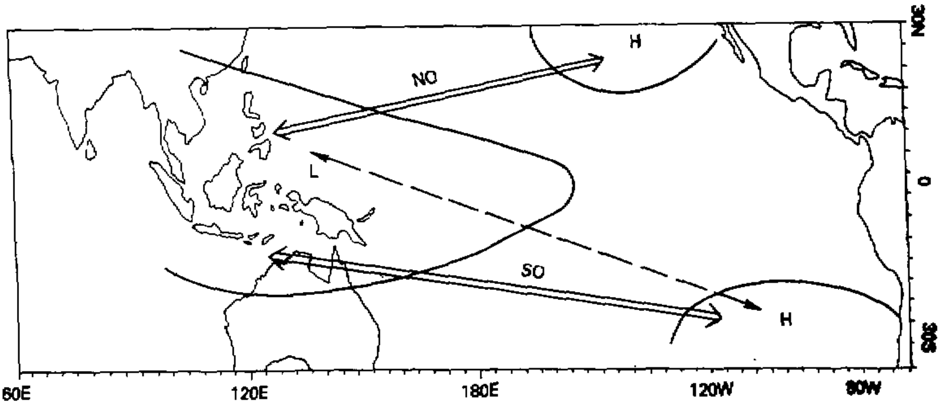

Fig. 7. A schematic map of Low Latitude Oscillation consisted of Southern Oscillation and Northern Oscillation.

well-known "Southern Oscillation" can be looked upon as its two components in the pressure field only. The time coefficient of first eigenvector of sea level pressure field of global tropics was defined as the low-latitude oscillation index (LLOI), which has very high correlation with the first eigenvector of SST over global tropical ocean ($r=0.84$) (Fu and Ye, 1987), showing that the LLO is mainly an ocean-atmospheric coupled phenomenon. Fig. 7 gives schematically the physical picture of so-called Low-Latitude Oscillation.

IV. LOW FREQUENCY OSCILLATION OF THE SO-CALLED EQUATORIAL WARMING POOL AND THE CLASSIFICATION OF ENSO WARMING

The study on SST anomalies has long been focused in the eastern equatorial Pacific area, the so-called "equatorial cold tongue" (ECT). Recently more attention is given to the warmest area in the west-central Pacific, the so-called "equatorial warming pool" (EWP) (Fu, Diaz and Fletcher, 1986). It is observed that although the annual variation of SST in EWP is much smaller than that of ECT, its interannual variation is of the same order as that in the east. The ratio of standard deviation over annual amplitude of SST over there is 3, (Fu et al, 1986) much larger that in other equatorial regions, indicating the strong interannual signal in the equatorial warming pool region.

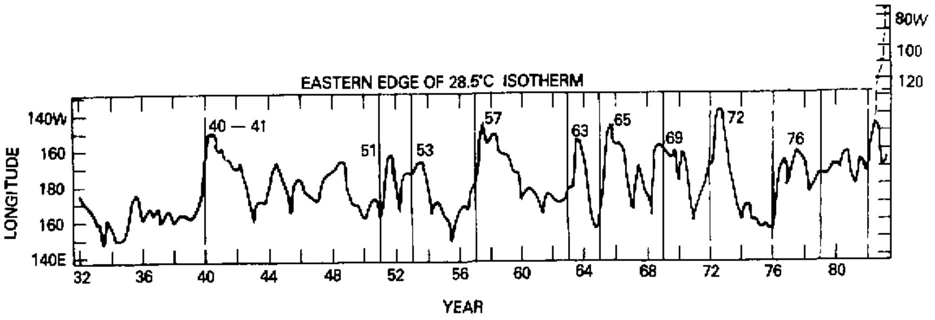

Fig. 8. Time evolution of eastern edge of 28.5°C isotherm of sea surface temperature along the equatorial Pacific (4°N–4°S), numbers indicate the onset years of ENSO events.

The longitude of the eastern edge of 28.5°C isotherm, which is chosen as the reference boundary of warming pool and as a good indicator of the shift of the strong tropical convection, shows an significant low-frequency oscillation with the main period obout 40 months and presents a strong ENSO signal. It was observed that the eastward migration of 28.5°C isotherm was a common feature for all the El Nino events so far observed in their developing stage, not only for the 1982–1983 event as explored by Rasmusson, et al (1983) (Fig. 8).

The extent of eastward migration varies from event to event (Fu et al, 1986). In the strong events, such as 1940—1941, 1957, 1965, 1972 and particularly in 1982, it extends eastward as far as east of 150°W and lasts longer (i. e. it remains to the east longer) than during the weak events. The westward retreat of this warmest water prior to the onset of *most of the ENSO events seems to be another precursor of El Nino development.*

According to the observed SST profiles along the equatorial Pacific during the past 12 ENSO events and then the principle patterns of SST profiles derived from EOF analysis, the equatorial warming associated with El Nino events could be classified as three main patterns.

Profile 1 (1957, 1965, 1972 and 1982 events). much warmer than normal to the east of dateline, slight below normal in the west, the warmest water extending to about 150-160°W.

Profile 2 (1963, 1969). warmer than normal almost everywhere, especially in the west and central Pacific. The warmest area extends to the east of dateline, but not as far as profile 1.

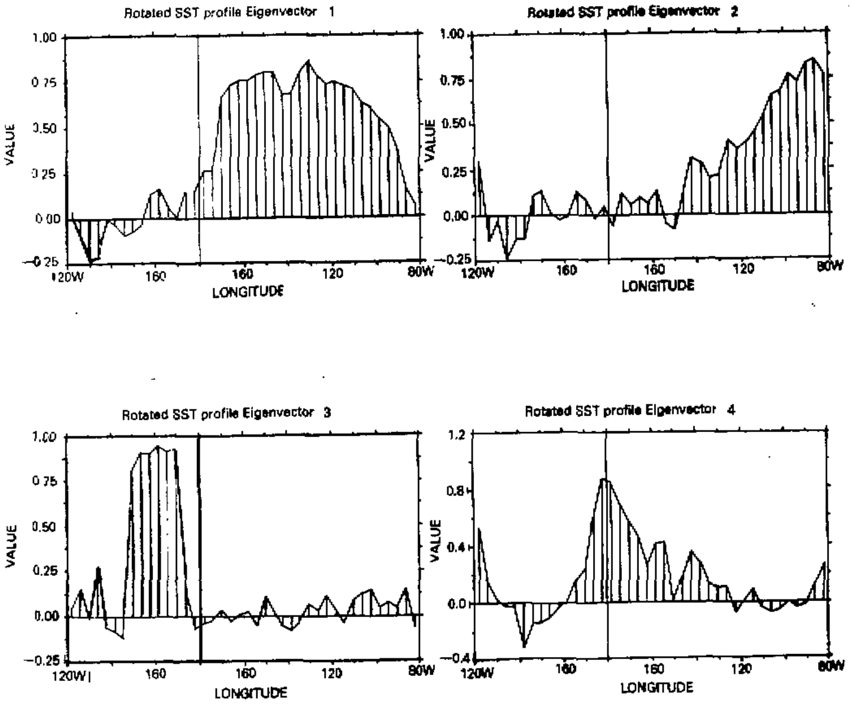

Fig. 9. First four rotated eigenvectors of SST profiles along the equatorial Pacific.

Profile 3 (1976). warmer than normal being restricted in far east Pacific, slightly below normal in the west and near normal in the central area. The warmest water is located in its mean position.

These three types of profile reflect the relative contribution of EWP and ECT to the ENSO morphology. Fig. 9 shows the first four rotated eigenvectors of SST profiles along the equatorial Pacific during ENSO episodes.

There are also good relationship between the east-west migration of warming pool and the tropical convection area and the extent of equatorial westerlies, indicating a positive ocean-atmospheric feedback process.

V. THE EFFECTS OF VLFO ON INTERANNUAL CLIMATE VARIATION IN CHINA

A great deal of researches about the effects of large-scale tropical air-sea interaction on climate variability in China have been undertaken in recent years. (Pan, 1987; Zhang et al., 1984; Zhang, Y., et al, 1985; Zeng, et al, 1987; Chen, 1977; Wang et al , 1984; Fu, 1986, 1987; Tao, 1987; Shi and Zhou, 1983). Some of major results are outlined as follows:

1. *The Long-term Variability of Western Pacific High Associated with the SST Anomalies in the Eastern Pacific*

The western Pacific high is one of the most important weather systems and the action centers effecting the weather and climate in East China. The shift of main rainbelt, the behavior of ITCZ and the related typhoon activites, the track of extratropical cyclone, the temperature distribution in midsummer, and so on, are strongly dependent on the behavior of the western Pacific high, being related to such features as the intensity, the position of ridge, the westward extension, the seasonal north-south shift, etc. (Tao and Hsu, 1962; Tao and Chu, 1964). The Chinese weather forecasters have long been searching for the main control factors of this huge high system and its long-range prediction (Liao, 1976). The results presented here provide a promising way along this direction.

The observational studies revealed a pronounced time-lag coupling between oscillations of the intensity and westward extension of the western Pacific high and SST anomalies.

Fig. 10 presents the time variation of the monthly mean intensity of the western Pacific high defined by the area index: the number of grid points embraced by this high pressure system(5880 contour at 500 hPa) and the SST anomalies in the eastern equatorial Pacific (defined by the mean of SST departure in the area of 10°S–5°N, 110–140°W). An in-phase oscillation between these two curves with some time lag can be seen clearly from this figure: when the SST is warm, the subtropical high strengthens and vice versa. Both of them have the oscillation period about 42 months. Therefore the frequency of their coupling is for the same period with maximum coherence of about 0.77. The cross-correlation and the phase spectrum indicate that the variation of the subtropical high lags behind that of the SST by 5–6 months.

The position of the western edge of this high system (defined by the degree of westward extension) shows a similar relationship with the SST in the equatorial Pacific, i. e. when the SST is warm, the subtropical high extends westward and vice versa. Therefore, when there is an anomalous warming of SST in the equatorial Pacific in winter, the western Pacific high in the following summer is stronger and has a more westward extension and vice versa.

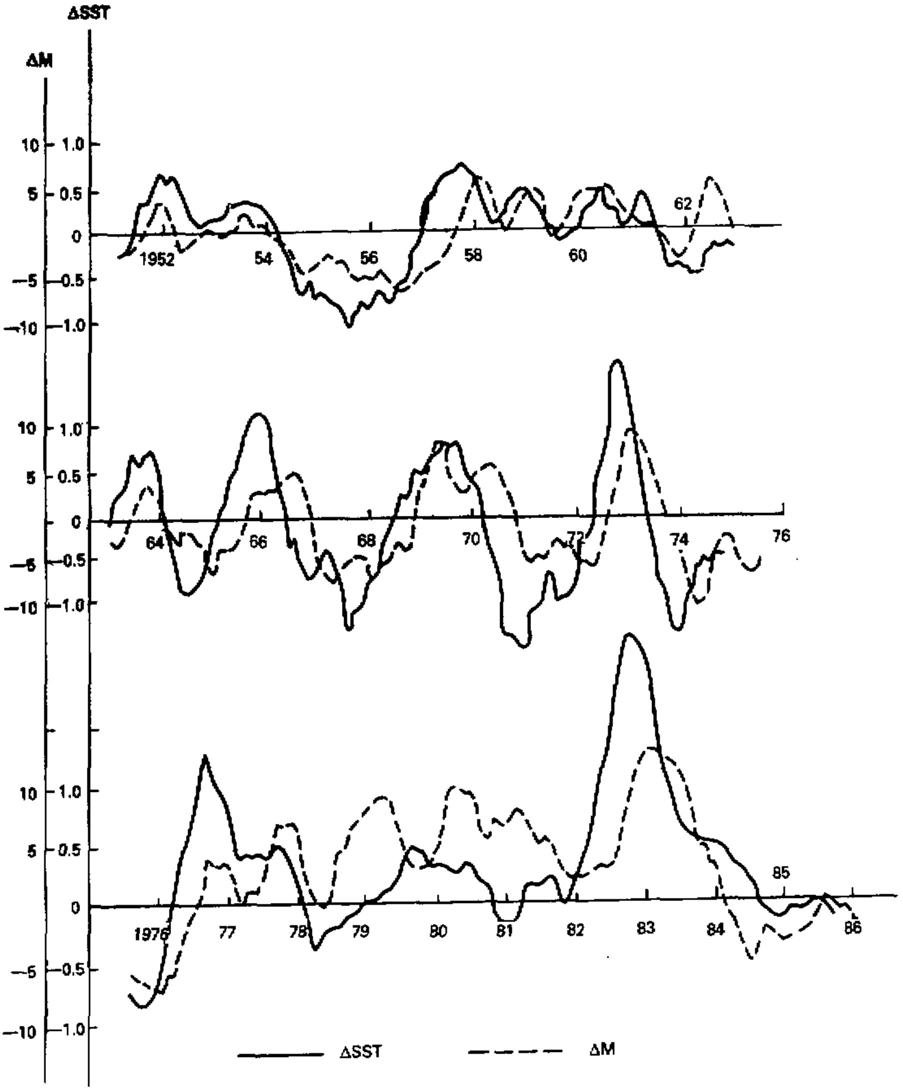

Fig. 10. 6-month running mean of the intensity of western Pacific high (ΔM) and the SST anomalies in the eastern equatorial Pacific (ΔSST).

This important finding not only gives a clue to understanding the physical causes of long-term variation of the western Pacific high, but also provides a basis for its prediction.

Analyses on the variation of the distributions of time lag correlations between the SST anomalies in the eastern equatorial Pacific and the surface pressure anomalies of the whole north Pacific show that the variation in intensity of the subtropical high in the eastern Pacific leads that of SST and in turn the variation of SST leads that of the intensity of subtropical high in the western Pacific, the half cycle is of about 20 months. Therefore a complete cycle would be about 40 months (Chen, 1984). (Fig. 11).

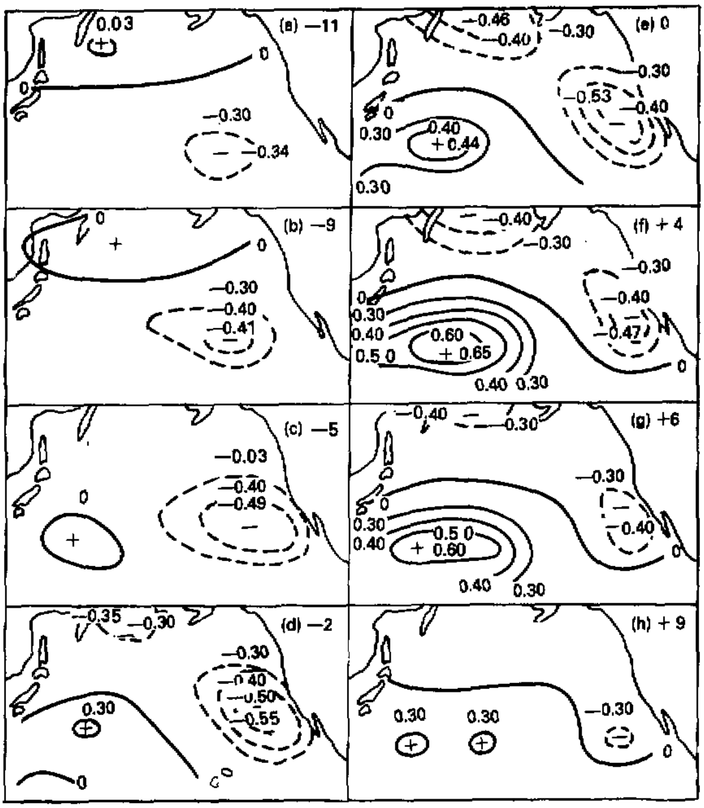

Fig. 11. Evolution processes of lag correlation between SST in the eastern equatorial Pacific and sea level pressure over the north Pacific.

How do the SST anomalies in the equatorial Pacific affect the behavior of the western Pacific high? Calculations from routine rawinsonde data (Fu, 1979a and 1979b) and evidence deduced from satellite measurements of cloudiness(Fu, 1979c) show that the patterns and intensity of mean meridional circulation and the east-west vertical circulation along the equatorial plane are quite different during warm and cold SST periods.

Along the equatorial plane, there is no closed cell during the warming SST in the western Pacific, because of less east-west gradient. While in the anomalously cold period, the east-west vertical circulation develops into a major cell which is the so-called Walker circulation.

Along the meridional plane, there is a Hadley circulation in each hemisphere respectively during warming SST period. While in the anomalously cold SST period, there appears in each hemisphere a vertical circulation, the flow of which is in opposite direction to the typical Hadley cell. It was named "anti-Hadley cell or "Equatorial cell'. Therefore there is a contrary tendency between these two types of vertical circulation. In the case of warming SST, the zonal circulation weakens, but the meridional circulation strengthens which has a strong descending flow in the subtropics corresponding to a strong subtropical high; while in the case of cold SST, the zonal circulation strengthens and the meridional circulation weakens and transforms into anti-Hadley circulation which makes a negative contribution to the Pacific high (Fig. 12). This might be a physical/synoptic explanation of the coupled oscillation between SST anomalies and the variation of the Pacific high.

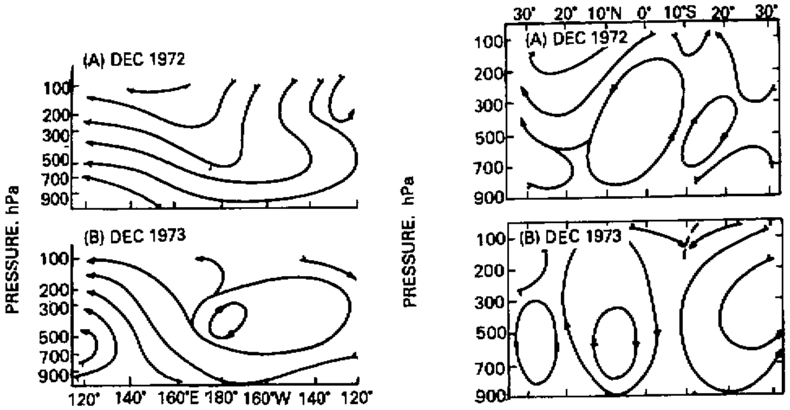

Fig. 12. The mean meridional circulation over the Pacific (a) and the mean zonal vertical circulation (b) along the equatorial plane for the Dec. 1972 and Dec. 1973.

The simulation results of the mean meridional circulation under the anomalous SST in the eastern Pacific are very similar to the observational evidence (Ji and Chao, 1979; Xin, 1981; Zhang and Zeng 1986; Chao, 1986). Wu (1987) recently applied ECMWF model to test the effect of SST anomaly in tropics and found that an enhance of Hadley circulation related to El Nino is mainly through the enhance of convergence of moisture and sensible heat towards the tropics, including positive feedback between tropical diabatic heating and direct mean meridional circulation.

According to above results, one can make use of the SST data in the tropical Pacific in previous 5–6 months to estimate the variation trend of the intensity and the westward extension of western Pacific high. The experiments in forecasting operation in Chinese NMC Long-Range Prediction Division during past 10 years have got a fairly good result (Fu and Zeng, 1986; Zhang, 1986).

In addition, a set of fitting curves are also developed for the correlation between the SST anomalies in some key regions in north Pacific and the other characteristics of western Pacific high, such as the latitude of ridge line, the northern boundary of high, and so on, to make the statistical forecasting of high pressure system (Fu et al, 1979).

2. *Summer Monsoon Rainfall in East China*

As mentioned above, the western Pacific high is one of the control factors affecting the summer monsoon rainfall in East China. Therefore it is expected that the summer monsoon rainfall would be linked in certain extent with the SST anomalies in the eastern Pacific (Tao and Chen, 1985; Guo, 1987; Zhang et al., 1985; Xu, 1985). The simultaneous correlation between the summer monsoon rainfall of China and SST anomalies in the eastern equatorial Pacific for the period June through August shows clearly a general tendency towards less rainfall in most parts of the country during the onset year of El Nino, with an especially significant area being in the central part of the country; while during cold SST years, there is a general wet tendency except in the areas in the northern part of the Northeast, in the Northwest, and in the southern part of South China which have the opposite sign. This indicates that the dry monsoon occurred not only in India, but also very often in China during El Nino years. This consistent oscillation between the China monsoon and the Indian monsoon during El Nino years is one type of interannual variation of the Asian monsoon system, different from the out-of-phase oscillation between them within the monsoon system in non-El Nino years (Fu and Fan, 1983).

Focusing on the lower and middle reaches of the Yangtze River basin,an important agricultural area in China, Fig. 13 presents the variation of summer monsoon rainfall in this area for the period of 1951–1984. A dry monsoon occurred in the onset years of each El Nino event except the year of 1969.

Another interesting fact is that there is more chance of wet monsoon than the dry monsoon in the year following the El Nino onset. A frequency distribution of occurrences of 5 classes of drought and flood indices in lower and middle reaches of Yangtze River valley in the following summer of El Nino onset since 1900 shows that the probability of wet monsoon occurred in that area is about 4 times that of dry monsoon (Fu, 1985).

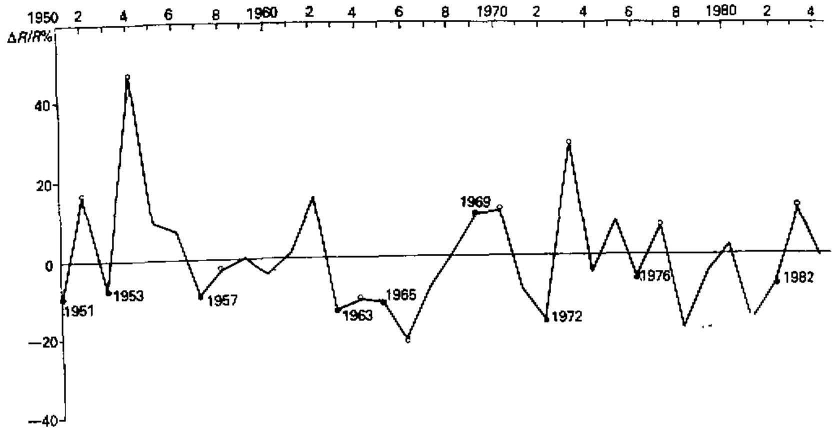

Fig. 13. Variation of summer monsoon rainfall in lower and middle reaches of Yangtze River valley.
○ onset year of ENSO.

3. *Cold Summer in Northeast China*

During the last two decades,cold summers occurred every three or four years in Northeast China, when summer temperature is persistent below normal in most of that region with the crop production reduced by 15% on an average. It was found that the summer temperature in Northeast China has correlated with the SST in eastern equatorial Pacific in certain extent (i. e. Research Group on cold summer in Northeast China, 1979; Zhang and Zeng, 1984). Fig. 14 gives the summer temperature index in Northeast China since 1941. The shaded bar indicates the ENSO event. The interesting thing is that all the severe cold summer years are the years of El Nino onset, such as 1941, 1957, 1965, 1969, 1972 and 1976.

Back to the records since 1860, of the thirty cold summers in Northeast China identified during 1860 to 1980, 16 were concurrent with El Nino years and the 12 either preceded or followed an El Nino year (Wang, 1984). As shown by the first EOF of Pacific SST, there is a negative area in the northeast Pacific and a positive area in the eastern equatorial Pacific. The cold summer in Northwest China seems to be related to the cold SST in the northwest Pacific as the counterpart of warm SST in the equator.

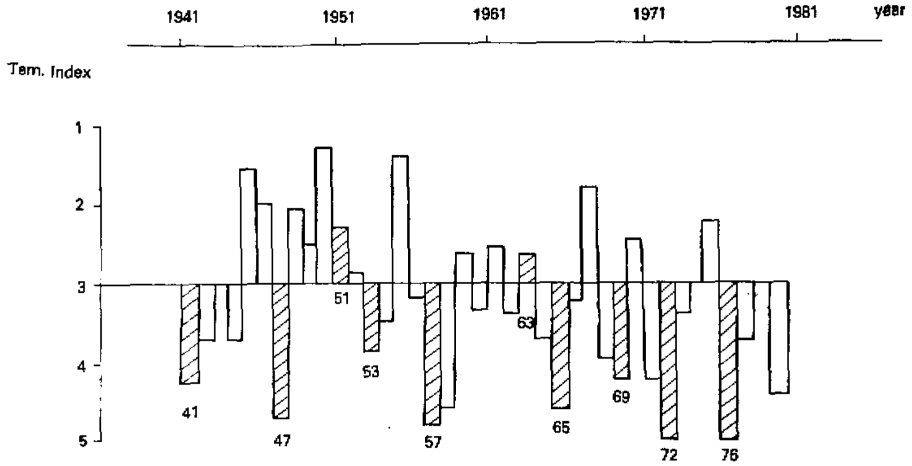

Fig. 14. Cold summer disaster index in Northeast China for the period 1941–1979 (the shaded bar indicates onset year of ENSO).

4. *Typhoon Activities in Western Pacific*

The typhoon activities in the western Pacific are related in certain extent to the ITCZ over there which largely depends on the western Pacific high. Therefore a statistical out-of-phase relationship between the frequency of typhoon and the SST anomalies in the eastern Pacific is found: when the SST in the eastern Pacific is warm, there is less typhoon in the western Pacific, and vice versa. That means there is less typhoon during El Nino years (Pan, 1982; Li, 1985; Xie et al, 1985). This relationship can be explained by the variation of Walker circulation associated with SST anomalies: when the SST is cooling in the eastern Pacific, the rising branch of Walker circulation develops strongly in the western Pacific which is favorable to the active ITCZ over there and vice versa.

5. *Frequency of Cyclogenesis over the East China Sea*

The interannual variability of frequency of cyclogenesis over the East China Sea is found to be linked with the Southern Oscillation and also to the El Nino. The cross-spectrum of high-pass-filtered time series of the cyclogenesis and the Darwin pressure anomalies shows a peak at about 5 years for which Darwin pressure leads about 2 months (Hanson and Long, 1985). This relationship seems to be an manifestation of teleconnection between El Nino/ Southern Oscillation and mid-latitude circulation. The warm equatorial temperature and anomalous deep convection in the central Pacific are associated with a deepening and broadening to the west of the Aleutian low, thus increasing the potential for storm formation over the East China Sea. On the other hand, the more frequent appearence of cyclone over the East China Sea is favorable to the deepening of Aleutian low.

VI. ABOUT THE POSSIBLE MECHANISM FOR MAINTENANCE OF TROPICAL VLFO ON INTERANNUAL SCALE

At present, there are still strong argument about the maintenance mechanism of such a low frequency oscillation in the tropical air-sea system.

As one side of this argument, a theory of free oscillation of coupled atmosphere-ocean system has been developed. According to this theory, the tropical VLFO is controlled mainly by the system's own physical properties and feedback processes, but not forced by the external forcing. For instance, Mcwilliams et al (1977) found several damping oscillation with the time scale of years in the tropical Pacific air-sea system. Wright (1979) showed in a simple model that a positive feedback relationship between the atmospheric circulation over the equatorial Pacific and the sea surface temperature over there can account for the observed statistical behavior of SO. Manabe and Hahn (1981) have simulated the SO with remarkable realism using the observed SST variation in the period of 1960 to 1976. Some primary studies indicate the stochastic effect of anomalous SST in tropical ocean on atmospheric oscillation. (Shi and Lu, 1984 and Yan and Pen, 1987).

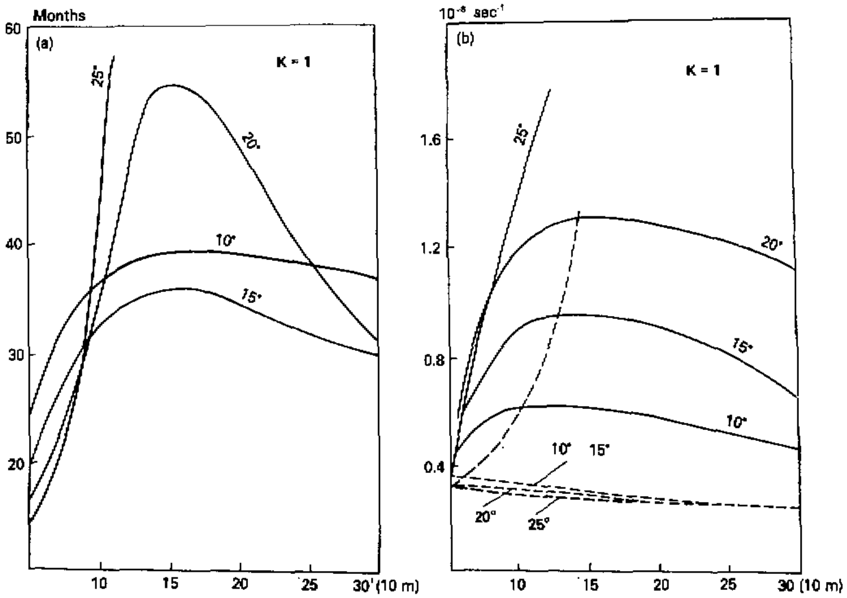

Fig. 15. The period and growth rate of the oscillation in the ocean-atmospheric system as the function of latitude and depth of mixing layer (for wave number K=1).

Another multi-year oscillation theory on tropical ocean-atmospheric system (Ji, 1982) suggested that in a latitudinal mean linear model with consideration of only the oceanic mixing layer coupled with atmosphere, the oscillation with the period of monthly scale develops, while if the processes not only in the mixing layer but also in the deeper ocean are considered, a longer period oscillation(3–4 years in low latitude) will be excited in the ocean-atmosphere system.

The main results from this model study show the period and growth rate of the oscillation in the ocean-atmospheric system as the function of latitude, depth of mixing layer and the wave number.

The range of oscillation period is about 20–50 months, i. e. 2–4 years, very close to the observed VLFO period. The growth rates of periodic solutions (real part of complex roots for the equations, solid line) are much larger than those of periodic solutions (real root, dashed line) (Fig. 15a). For instance, at latitude 15°, depth 100 m, e-folding time is about 10 seconds (40 months). So quasi-periodic variation in the observational data can be found.

The maximum of growth rates of periodic solutions show that the fluctuations will increase at some depth more rapidly than any others, i. e., the depth about 100–150 m. The corresponding period is 30–40 month. This result implies that the growth rate of oscillation does not increase monotonically with depth of mixing layer, but it has a maximum for a depth about 100 m. The fluctuation with period of three years grows most rapidly (Fig. 15b). It is also significant because the 3–4 years oscillation exists in the observational evidence.

The above analysis indicates that the periods of socillation in air-sea coupled system vary basically in the range of 2–4 years for different depth of mixed layer, latitude and latitude wave numbers. This is a very low-frequency oscillation in the coupled ocean-atmospheric system formed by the slowly varied thermo-dynamical processes and various feedback processes. Above results have been further examined by a numerical experiment in an ocean-atmospheric coupled model (Xin, 1983).

As other side of this argument, several hypotheses have been proposed. The relationship between the solid earth rotation change and El Nino /Southern Oscillation indicates a possible mechanism of VLFO related to the external forcing (Chao, 1984).

Under the assumption that the entire planet(the earth-atmospheric system) is a closed dynamical system, and the atmosphere and the earth could exchange angular momentum. In such a system, any accelerations of the atmosphere would occur simultaneously with a deceleration of the earth. The length of day (LOD) is used to be a measure of planet's spin rate.

Ren et al (1985) observed that since 1956, four strong El Nino events, i. e. 1957, 1969, 1972 and 1976 have occurred in the minimum of earth rotation speed and the event of 1965 and 1963 occurred around the minimum.The SST variation in the eastern equatorial Pacific lags behind that of earth rotation speed about 14 days on average. It is suggested that the slowing down earth would accompany the acceleration of the atmosphere which produces the increasing westerlies in mid-latitude and pushing the system moving equatorward resulting in the decreasing of trade wind system which is favorable to the development of equatorial warming. While on the other hand, the warming equator would strengthen the Hadley circulation and then the westerlies. The increase of angular momentum of westerlies will slow down the earth further. Obviously there is no mechanism to have a negative effect in causing the acceleration of the earth rotation again to form the oscillation. It is necessary to have some feedback processes within the ocean-atmospheric system, even it is forced initially by the external factor.

In summary, the tropical ocean-atmosphere system is characterized by a very low frequency oscillation which is closely related to the interannual climate variability in global tropics and even in the mid-latitude. However the mechanism on the formation and the maintenance of such a low frequency oscillation is still a labyrinth where scientists could find plenty of scope for their talents.

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