TROPICAL SEA SURFACE TEMPERATURE ANOMALY AND INDIAN SUMMER MONSOON*

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ABSTRACT

The time series of the sea surface temperature (SST) anomaly, covering the eastern (western) equatorial Pacific, central Indian Ocean, Arabian Sea, Bay of Bengal and South China Sea (SCS), have been analyzed by using wavelet transform. Results show that there exists same interdecadal variability of SST in the tropical Pacific and tropical Indian Ocean, and also show that the last decadal abrupt change occurred in the 1970s. On the interannual time scale, there is a similar interannual variability among the equatorial central Indian Ocean and the adjacent three sea basins (Arabian Sea, Bay of Bengal and South China Sea), but the SST interannual changes of the Indian Ocean lagged 4—5 months behind that of the equatorial central-east Pacific. Meanwhile, the interannual variability and long-range change between SST anomaly and Indian summer monsoon rainfall in recent decades have been explained and analyzed. It indicates that there existed a wet (dry) period in India when the tropical SST was lower (higher) than normal, but there was a lag of phase between them.

Key words: SST (sea surface temperature) anomaly, variability, monsoon rainfall, wavelet transform

I. INTRODUCTION

Through the implementation of TOGA (tropical ocean and global atmosphere) 10-year plan during 1985—1994, the interdecadal variability that occurred in ENSO (El Nino/Southern Oscillation) ocean-atmosphere interaction has been found (Graham 1994; Trenberth 1995). This variability caused that the traditional ENSO prediction pattern could not be used since the 1980s, and the forecasting of coupled model and observation of SST anomaly were in discrepancy from 1992 to 1995 (Qian 1997; Ji et al. 1996). In the late of 1970s, the tropical Pacific experienced an abrupt interdecadal warming and changes of atmospheric circulation. This phenomenon was referred to as interdecadal variation (Wang 1995). Up to now, many researches focused on the interannul and interdecadal

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variability on both eastern equatorial Pacific and Atlantic SST anomalies, but the data series was limited in recent several decades so that it can not well illustrate the SST and climate interdecadal-centurial variability. Further work should improve in three aspects: (1) to study the interannual and interdecadal variability of SST anomalies in different basins, especially in the Indian Ocean and the adjacent sea basins; (2) to rebuild the data series with the time scale of several hundred years and use it to study SST or climate interdecadal variability; and (3) due to the relationship between the South Asian summer monsoon and ENSO events, their spatial-temporal phase relationship and their interaction should be studied further. To efficiently compare the spatial-temporal characteristics of different basins over tropical ocean, especially the features of SST variations the wavelet transform has been used to analyze the time series of SST anomaly in different tropical basins. The wavelet coefficients associated with different time-scales can well illustrate SST variation relation between basins. Meanwhile, there is a close linkage between the SST interannual/interdecadal variability in the tropical ocean and the intensity of the Indian summer monsoon rainfall.

II. DATA AND METHODOLOGY

The data came from three sources.

(1) SST data for 47 years used in this paper were monthly $2^\circ \times 2^\circ$ latitude/longitude grid for 1950—1992 and monthly $1^\circ \times 1^\circ$ latitude/longitude grid for 1993—1996, which came from US National Centers for Environmental Prediction (NCEP). Thus, we have a global 564-month SST data set from January 1950 to December 1996. In order to analyze interannual/interdecadal variability, we calculated monthly SST anomalies related to observed 564-month SST time-series in different areas. As we know, the strongest signal of SST variation was in equatorial central-eastern Pacific. However, one can express this signal by using average SST anomaly of different domains such as NINO1+2, NINO3 and NINO4 in US Climate Diagnostics Bulletin, and other domains NINOC and NINOW given in Chinese Climate Monitoring Bulletin. As shown in Table 1 we choose six domains in the different parts of the tropical Indian Ocean and tropical Pacific to form 6 time-series. INDIAN and NINOW and NINOC express the equatorial central Indian Ocean area, equatorial western Pacific and equatorial central-eastern Pacific (Angell 1981) respectively. To reveal SST interannual/interdecadal variability over South Asian monsoon region we also choose another three domains, i. e. Arabian Sea, Bay of Bengal and South China Sea (SCS). Each domain is given in Table 1. The SST time-series from 1950 to 1996 can be got based on the average of all grids in the domain.

(2) ENSO index time-series in the past 527 years. To reveal ENSO interdecadal variation by using longer data, the measured data in recent more than 100 years are used to find the relationship between the ENSO events and other factors. By this relationship one can obtain the proxy data to present historical ENSO events. If one can make scientific combination of different proxy data to represent the ENSO events, this reconstructure of ENSO index series by using these proxy data can assure its quality on longer period. Wang (1988; 1992) combined 8 proxy data to reconstructure 114 El Nino events occurring during 1470—1989. However, the equatorial Pacific SST anomalies should include two aspects of

cold and warm, i.e. El Nino events and La Nina events. Including two aspects of cold and warm the data series can reflect the interdecadal variability in past several hundred years. Therefore, Wang (personal communication) used East Asian summer low-temperature data series, typhoon numbers on China Continent (Wang 1988), the relationship between Southern Oscillation and tree rings over western North America (Lough and Fritts 1985), to rebuild Southern Oscillation Index based on dryness/wetness grades in China (Zhang et al. 1989), drought in Australia (Nicholls 1988), dryness in North China (Guo 1992), and Quinn (1978) rebuilt the historical record of El Nino events for last 527 years. To represent time series of the equatorial Pacific SST anomaly, observed data in recent years and proxy data should be written as index form. The relation between the grade or domain SST anomaly and index can be explained as follows: (a) the strong El Nino event or SST anomaly (SSTA) >1°C was defined as 1; (b) the moderate El Nino event or SSTA>0.5°C but <1°C was defined as 0.5; (c) the strong La Nina event or SSTA<-1°C was defined as -1; (d) the moderate La Nina event or SSTA<-0.5°C but SSTA>-1°C was defined as -0.5; and (e) other case was defined as 0°C.

Table 1. Different Domains of SST Anomalous Time-Series

Code	Region	Domain
NINOC	central-eastern Pacific	0—10°S, 180—90°W
NINOW	western Pacific	0—10°N, 140°E—180
INDIAN	equatorial central Indian	0—10°S, 71—95°E
ARABIAN	Arabian Sea	9—17°N, 55—65°E
BENGAL	Bay of Bengal	11—17°N, 83—93°E
SCS	South China Sea	7—15°N, 111—117°E

(3) Recent 100-year Indian summer monsoon rainfall departure data (June—July—August rainfall in every year) for 1871—1986 came from Guo (1992).

All of data series except the rainfall data have been analyzed by wavelet transform. As been known in recent years, the continuous wavelet transform has been applied in signal detection of climatic time series (Lau and Weng 1995). The principle of wavelet transform is to project time series signal on a wavelet basis. The wavelet transform $W(s, t)$ is defined as the convolution of a time series with a wavelet basis. By varying the wavelet scale s and the localized time t, one can construct a picture showing the amplitude variation with time. The wavelet basis is also called as analyzed wavelet. We choose "Mexican hat" as analyzed wavelet to detect the signals that are included in NINOC region SST anomaly time series.

III. SST ANOMALY SIGNAL DETECTED BY WAVELET TRANSFORM

According to the different domains shown in Table 1, we have calculated 6 SST anomalous monthly time-series. From these SST anomaly time-series we can distinguish interannual variations ranging from 2 to 7 years, but it is not easy to determine

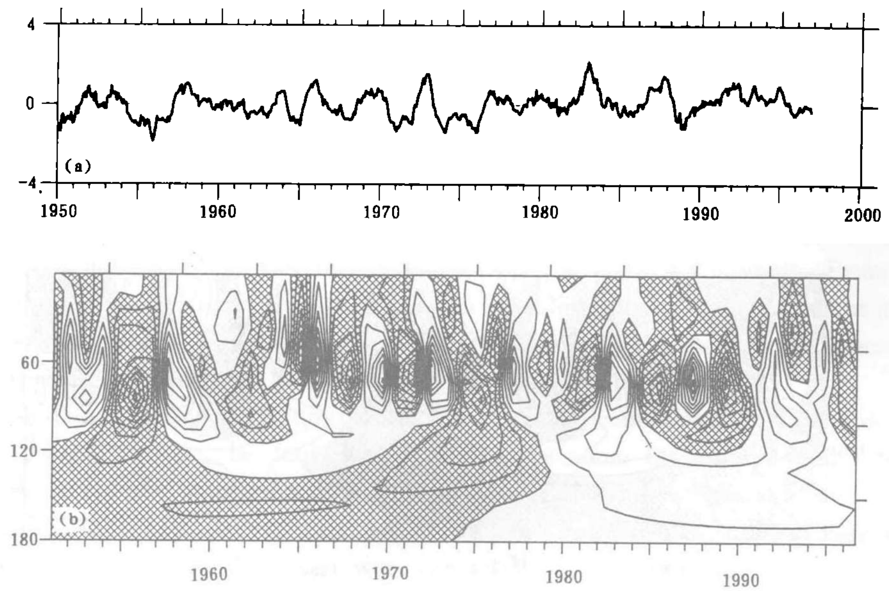

Fig. 1. (a) SST anomaly time series of NINOC domain for January 1950 to December 1996 (unit: ℃) and (b) local wavelet coefficients of NINOC domain (unit: 1). the left ordinate axis is the period (in month) corresponding to each wavelet scale from 1 to 180 months. the bottom abscissa axis is time (in year). the shaded areas represent negative wavelet coefficients.

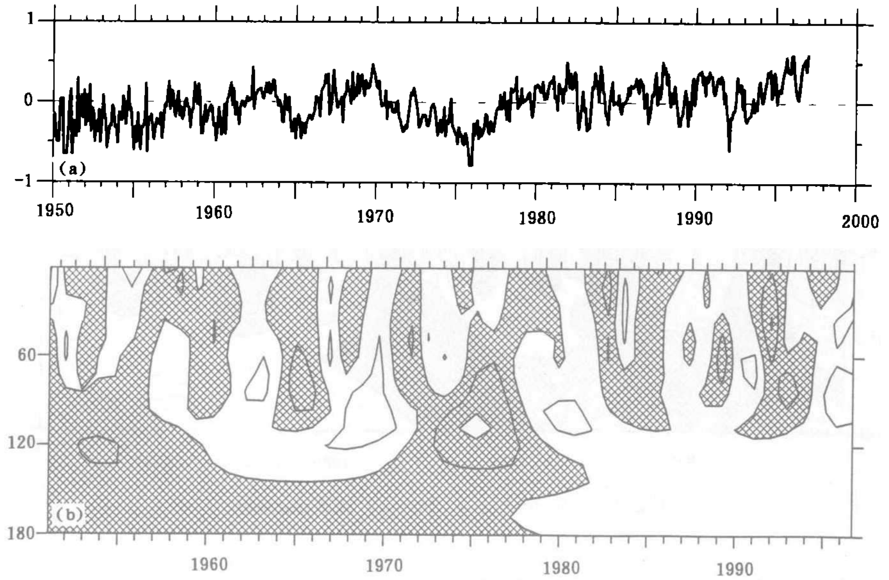

Fig. 2. As in Fig. 1. but for NINOW domain.

interdecadal changes. Thus, a wavelet transform is applied to detect the different scale signals occurring in six SST time-series. The wavelet transform coefficients are associated with different scales and times as shown in Fig. 1b — Fig. 4b. Based on the wavelet coefficients we can explain some features of SST variations in different domains as

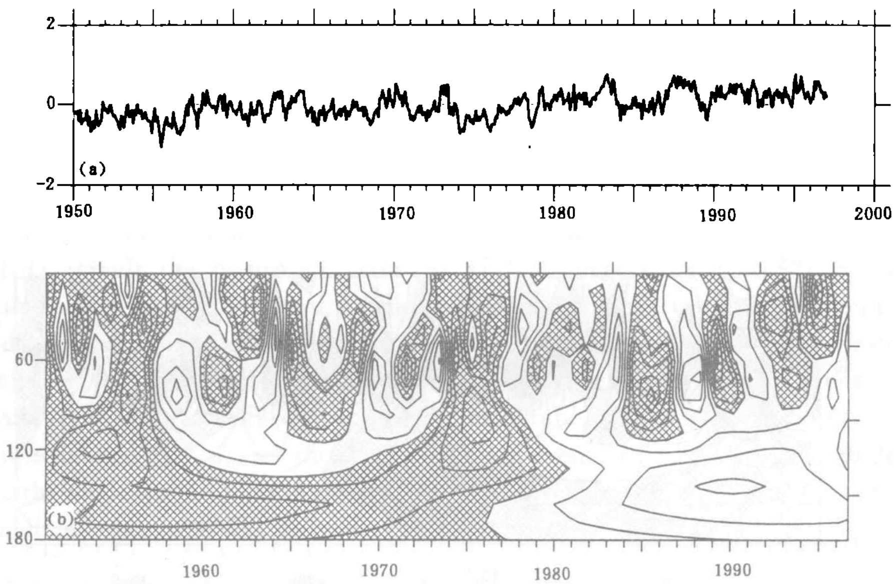

Fig. 3. As in Fig. 1, but for INDIAN domain and the unit is 0. 5.

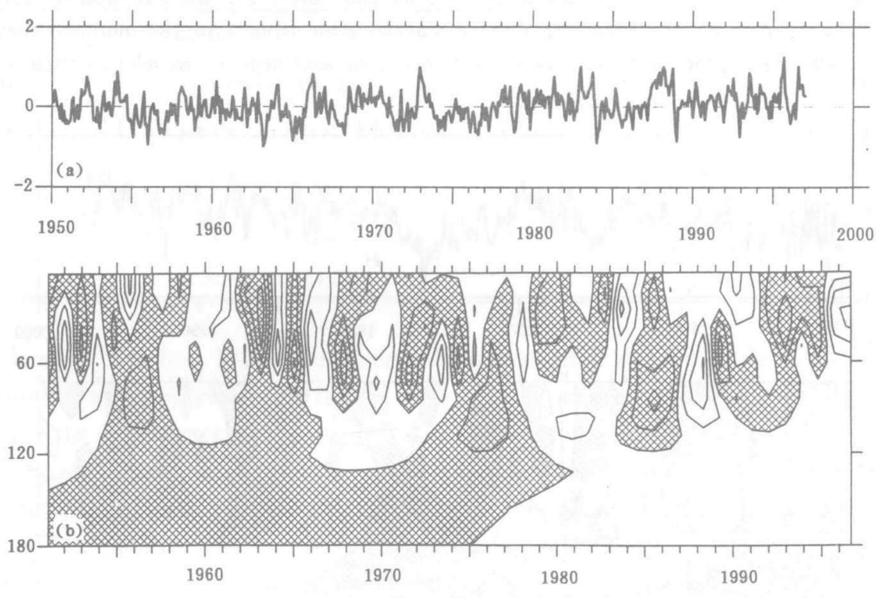

Fig. 4. As in Fig. 1, but for SCS domain.

follows:

(1) NINOC domain. As shown in Fig. 1b strongest signals are located in the 60-month (5-year) scale and the SST anomaly of this scale is called as interannual variation. As we have noted in Fig. 1b there are interdecadal time scale that is longer than 120 months and interannual time scale of 2—3 years (28-months) in the eastern equatorial Pacific SST anomaly. On the interdecadal time scale, negative SST departure occurred in pre-1977 and positive SST departure occurred in post-1977. The SST difference between 1950—1977 and 1978—1996 has reached 0. 4—0. 5°C (not shown). This difference can

express the interdecadal change of ocean background state. On the interannual time scale, however, there are some regular variations on SST anomaly time scale. At the larger magnitudes of SST wavelet coefficients, three obvious anti-El Nino events regularly occurred in 1955, 1975 and 1995. On the other hand, we also note that there is 2—3 years' variability in some time ranges, such as in 1960s to early 1970s but not in later 1970s to 1980s.

(2) NINOW domain. Comparing Fig. 2 and Fig. 1, we can find that the amplitude of SST anomaly in NINOW domain is 1/4 as small as that of NINOC domain. From different time-scales, it can be found that the variation on interannual time-scale is not absolutely same between them, but it is consistent between the two domains on interdecadal time-scale, especially for negative SST anomalies occurring in 1955 and 1975.

(3) Indian domain. If we compare the wavelet coefficients between Indian domain and NINOC domain, it can be found that there were same interannual and interdecadal variations except the amplitude in which the latter was larger than the former. On the interdecadal time-scale the SST in the Indian domain transformed from cool period to warm period in 1977 as well. There were several same negative departure periods between them, such as 1955, 1975, 1985, 1989 and 1995.

(4) SST variations in Arabian, Bay of Bengal and SCS domains. Figures 4a and 4b are SST anomaly time-series in the SCS domain and its wavelet transform coefficients are associated with different scales and times. SST variations and their wavelet transform coefficients in Arabian and Bay of Bengal were similar to that of the SCS domain. The result indicates that the interdecadal SST variations and their transform time from cool period to warm period in the three domains were similar to that of Indian and NINOC domains. Another phenomenon, five cold processes occurring in 1955, 1965, 1975, 1985 and 1995 can be seen in the three figures, i. e., the interdecadal cool SST anomalies once

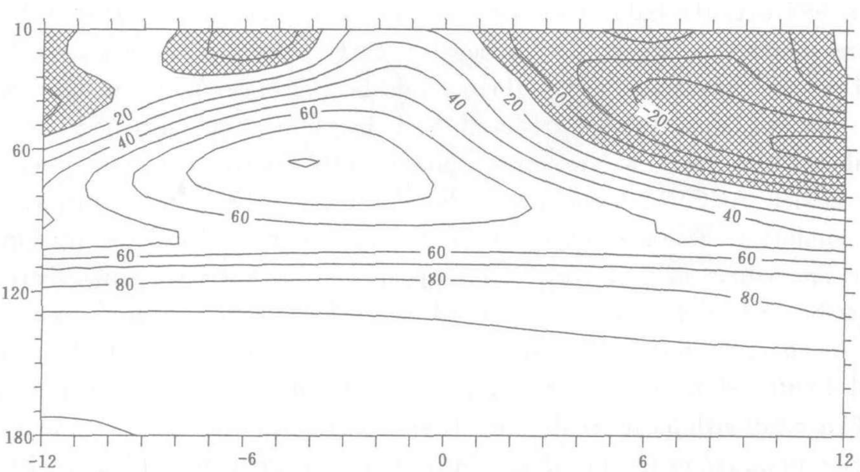

Fig. 5. Lead and lag correlation coefficients between Indian and NINOC domains on the different time-scale based on wavelet coefficients of Fig. 3b and Fig. 1b (unit: 0. 01), the left ordinate axis is the period (in month) corresponding to each wavelet scale from 1 to 180 months, the bottom abscissa axis is lead (positive) or lag (negative) time (in month), the negative time represents that Indian SST anomaly series lagged behind that of NINOC.

per 10-years.

In comparison of the wavelet coefficients of the SST anomaly in different domains, we can find that stronger signals occurred in the NINOC region and Indian domain. In order to identify the phase relationship of Indian and NINOC domains, we calculated lead and lag correlation coefficients between them based on wavelet coefficients of the different time-scale as shown in Fig. 5. As seen in Fig. 5, there is a 4—5 month lag correlation between them on the interannual time-scale (70—80 months), i. e. SST anomaly in the eastern equatorial Pacific started earlier than that of the equatorial Indian Ocean by 4—5 months and their correlation coefficient was higher than 0. 8. There was also high correlation on interdecadal time-scale (longer than 120-months).

IV. SST ANOMALY AND INDIAN SUMMER MONSOON RAINFALL

The changes of atmospheric circulation caused by temperature contract over land and sea with seasons are called as monsoon in determined areas. Due to the relationship between the monsoon and rainfall, the summer monsoon is also understood as the start and end of rainfall. From this definition the rainfall will be larger than normal if the summer monsoon is stronger. Recently, the study made by Chattopadhyay and Bhatla (1996) based on the yearly summer monsoon rainfall over the whole Indian region for 1901—1990 found that the ENSO event usually occurred in the year of deficient monsoon rainfall (dry), but the anti-ENSO event appeared in the year of plentiful monsoon rainfall (wet). Due to a reasonably strong relationship of SST anomalies between Indian Ocean and eastern equatorial Pacific, we have noted that on the interannual time-scale the Indian summer monsoon is weaker (stronger) when SST is a positive (negative) anomaly. Obviously, if assuming that there are no anomaly temperature and moisture changes over land with season, the land-sea temperature contract is only determined by abnormal variation of SST over the Indian Ocean and the adjacent sea basins. So that if the land-sea temperature contract is larger, that is negative SST anomaly occurring over the Indian Ocean and eastern equatorial Pacific, there would be a stronger Indian summer monsoon. Recently, You and Qian (1997) introduced the Indian Ocean and Pacific SST anomalies at the typical El Nino and La Nina event phases into a two-layer atmospheric general circulation model (AGCM) to simulate the low-level atmospheric circulation anomaly, the result was similar to that of the observation. During the phase of El Nino (La Nina) event period, the anomalous westerly (easterly) appeared in the low-level atmosphere over the tropical Pacific and anomalous wind toward (departing from) equator occurred in the Southeast Asian. This simulation can explain the effect of the SST anomaly in the Indian Ocean and Pacific on monsoon circulation and its possible impact on summer monsoon rainfall. This relationship can be also clearly seen in Fig. 6, showing the summer (June—September) rainfall anomalies in Indian, with black columns representing the El Nino and shaded columns representing the La Nina. From Fig. 6 it can be seen that the weaker Indian summer monsoon rainfall occurred when the SST was positive anomaly and the stronger rainfall appeared in negative SST anomaly.

The relationship between the interannual SST anomaly and yearly Indian summer monsoon rainfall has been studied by many researchers (Guo 1992; Chattopadhyay and

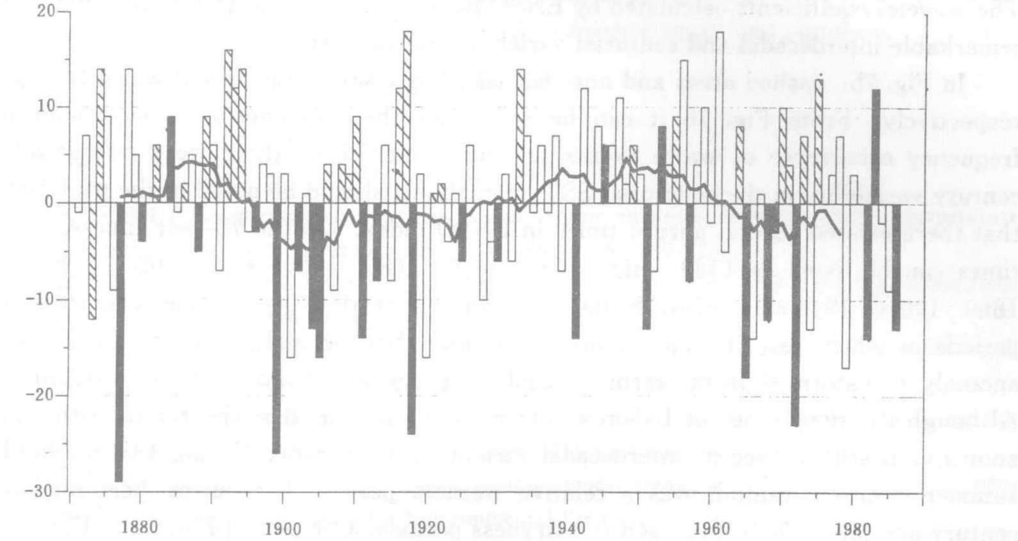

Fig. 6. Summer monsoon (June—September) rainfall anomalies in Indian region for 1871—1986, black columns represent the El Nino and shaded columns represent the La Nina, the thick solid line gives a 9-year running mean of rainfall anomaly.

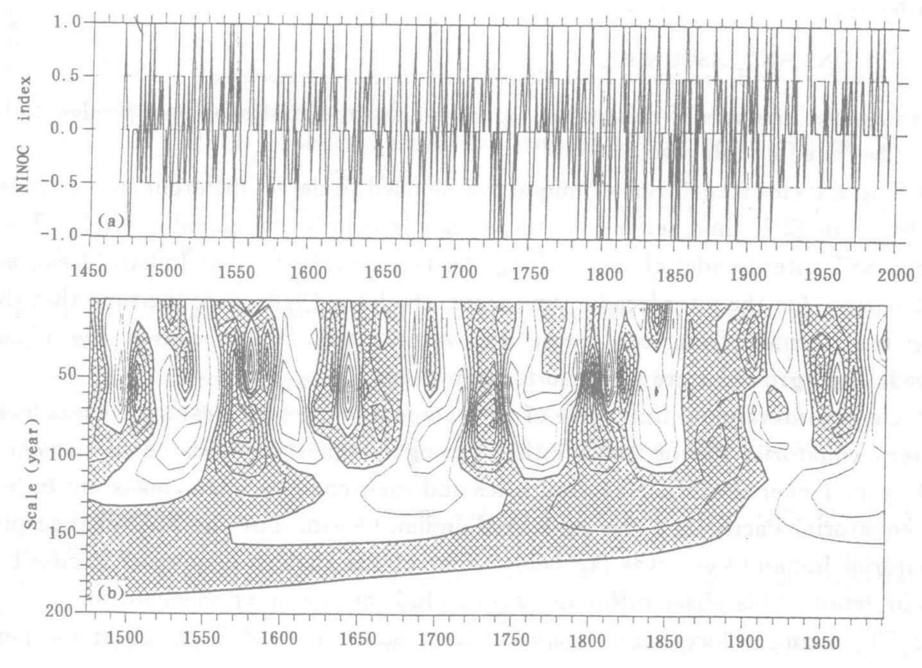

Fig. 7. (a) ENSO index time series for 1470—1996, (b) local wavelet coefficients of ENSO index (unit: 0.2), the left ordinate axis is wavelet scale, the bottom abscissa axis is time (in year), the dashed areas represent negative wavelet coefficients that mean cold SST.

Bhatla 1996), their results were basically in consistency. On the other hand for interdecadal changes, we use the ENSO index (Fig. 7) provided by Prof. Wang Shaowu to analyze its relation with the long-range change of the Indian summer monsoon rainfall.

The wavelet coefficients calculated by ENSO index shown in Fig. 7b indicate that there are remarkable interdecadal and centurial variability in the past 500 years.

In Fig. 7b, dashed areas and non-dashed areas represent cold and warm SST periods respectively. From Fig. 7b it can be seen that there obviously is periodicity in the frequency occurrence of warm events or cold events, i. e. there were interdecadal and century variability in the equatorial SST anomaly. It should be noted in the past 500 years that there existed several abrupt times in ENSO index. On the 70-year time-scale, these times can be listed as 1560, mid 1590s, 1620, 1680, 1720, mid 1740s, 1790s, 1830, 1860, 1900s, 1940 and 1970s. From 1470 to 1990, on the 70-year time-scale there were 7 periods in which the El Nino events were more than normal. Since this century, SST anomaly transformed from warm to cool in 1930s and from cool to warm in 1970s. Although the time-series of Indian summer monsoon rainfall is shorter than that of SST anomaly, it still can see its interdecadal variability (in Fig. 6). During 1930—1950 Indian summer monsoon rainfall was a relative wetness period, but during beginning of this century and later 1960s it crossed two dryness periods. Comparing Fig. 6 and Fig. 7 we can see that Indian summer monsoon rainfall not only has same interdecadal variation as SST anomaly but also has phase difference between them. The interdecadal variation of Indian summer monsoon rainfall may be also the result of impact of long-term SST anomaly and other factors.

V. CONCLUSIONS AND DISCUSSION

Through the analysis of this paper, some conclusions and problems needed to further study can be listed as follows:

(1) The wavelet transform technique can be used to detect different time scale signals that included in SST time series and these signals can be compared as well. There are consistent SST interdecadal changes along the tropical Pacific and Indian Ocean and the adjacent basins. On the interdecadal time scale, the later 1970s were the time that the SST anomaly transformed from cool state to warm state. What causes the change of interdecadal background state needs to further study.

(2) On the interannual time scale of SST anomaly, the strongest signal was located in the eastern equatorial Pacific and another stronger signal was located in the equatorial Indian Ocean. Generally, the SST anomalies and their changes were consistent in both the eastern equatorial Pacific and the equatorial Indian Ocean, but the SST change phase in the equatorial Indian Ocean was lag behind that of the eastern equatorial Pacific by 4—5 months in detail. This phase difference may include an unknown mechanism.

(3) The stronger (weaker) Indian summer monsoon rainfall occurs at the period of cool (warm) SST in the both eastern equatorial Pacific and Indian Ocean. This relationship can be explained by land-sea temperature contract over the two oceans and Asian Continent.

(4) The relationship between the Indian summer monsoon and the SST anomaly in the eastern equatorial Pacific has been studied by many researchers, e. g., Webster and Yang (1992) analyzed the relationship between the South Asian monsoon and ENSO events by using detailed data. Recently, Yang and Lau (1997) introduced the SST and the

surface moisture anomalies into AGCM to detect their direct effect on the South Asian monsoon. All of these impacts on monsoon need to further study and simulate.

The ENSO index was provided by Prof. Wang Shaowu.

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