Interdecadal and Interannual Variations of the South China Sea Summer Monsoon:

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1. Introduction

It has been found that the South China Sea summer monsoon (SCSSM) has variations with periods ranging from interdecadal to intraseasonal. This paper presents a summary of the interdecadal and interannual variations and their possible physical mechanisms/processes. The intraseasonal variations have been explored by some other studies (e.g. Mao and Chan 2004) and will therefore not be considered in this paper.

2. Interdecadal variations

A prominent interdecadal signal is the Pacific Decadal Oscillation (PDO) (e.g. Mantua et al. 1997). In addition, the El Niño/Southern Oscillation (ENSO) has also been observed to go through interdecadal changes (e.g. Wang 1995). These two oscillations are found to be related to the monsoon rainfall over South China (SC), the results of which are presented in this section. These rainfall data are used as a proxy for that over the South China Sea (SCS) because the latter does not have such long records.

2.1. Data

The rainfall data include those at Hong Kong, Macao and Guangzhou for 92 years from 1910-2001. Monsoon rainfall is defined as the average of the May and June rainfall for these three stations (SCMR). Only these two months are chosen because of the "hybrid" nature of the rain-bearing systems in April. The choice of these three stations is because the correlation coefficients of these three stations with the Guangdong monthly rainfall averaged over 47 stations are significant above the 99% confidence level.

The PDO index is taken from Mantua's website (see Mantua et al. 1997) and is equal to the leading empirical orthogonal function (EOF) of SST anomalies (January to March) in the North Pacific Ocean poleward of 20^{o}N. A Niño-3 SST index is defined as the January to March SST averaged over the central Pacific (5^{o}S-5^{o}N, 90-150^{o}W) to represent the effect of ENSO. The SST data for 1910-1949 are extracted from U.K. Meteorological Office GISST2.3 dataset, and for 1950-2001 from the US Climate Prediction Center. Reanalyses of monthly 500-hPa geopotential height from 1950-2001 are produced from the NCEP/NCAR reanalyses.

2.2. Interdecadal variations of SCMR

Based on the Z-index (Ju et al. 1997), and using half a standard deviation ($|Z| > 0.5$) as the threshold (the Z-index is normalized to make the category simple), the 92 years can be stratified into three groups: 31 dry, 37 normal and 24 wet. According to the PDO shifts (1925, 1947 and 1977) (e.g., Mantua et al. 1997), the number of dry or wet monsoon years is found to be different during these three epochs (Table 1). Note the existence of an interdecadal variation, from a more frequent occurrence of dry monsoon years during 1925-1946 to the opposite in the next epoch (1947-1976), and then back to more dry monsoon

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years again after 1977. It is obvious that these changes match the PDO shifts very well, with a high PDO phase corresponding to more dry monsoon years, and vice versa. A wavelet analysis of the SCMR suggests that during the entire 92 years, most of the wavelet transform coefficients that alternate between positive and negative values are around 16-32 yr except for 1920s-1940s when the main peak is larger than 32 yr (not shown).

TABLE 1. Dry or wet monsoon years during each of the three PDO epochs. El Niño years: parentheses, La Niña years: underlined, EN+1 years: boldfaced and LN+1 years: italicized.

Epoch	1925-1946	1947-1976	1977-1995
Dry	1925, 1926, 1929, 1930, 1932, 1933, 1935, 1937, 1938, 1939, 1945	*1949*, **1954**, **1958**, 1961, (1963), 1967	**1977**, **1980**, *1985*, **1988**, 1990, (1991), (**1994**), **1995**
Wet	1927, 1940, 1944	*1950*, *1951*, *1955*, (*1957*), 1959, **1966**, 1970, (1972), **1973**, *1975*	(1982), *1989*, **1992**, 1993
Ratio of dry/wet	11/3	6/10	8/4

2.3. Possible relationships among SCMR, ENSO and PDO

The results in Table 1 suggest the existence of a possible linkage among the SCMR, ENSO and PDO. Based on the wavelet analysis, the scale-weighted sums of the wavelet transform coefficients within periods of 16-32 yr and 32-64 yr of PDO, ENSO and SCMR are examined (Fig. 1). The important feature is that PDO and ENSO are strongly correlated (0.71) on decadal timescales. Indeed they are nearly phase locked. It appears that SCMR has a close association with ENSO/PDO at both periods, being –0.59/-0.71. Similar results are obtained for the 32-64 yr period (not shown). These results suggest the SCMR may be highly related to PDO and ENSO at decadal timescales such that a high PDO/El Niño (low PDO/La Niña) phase pattern is associated with a deficient (above-normal) SCMR.

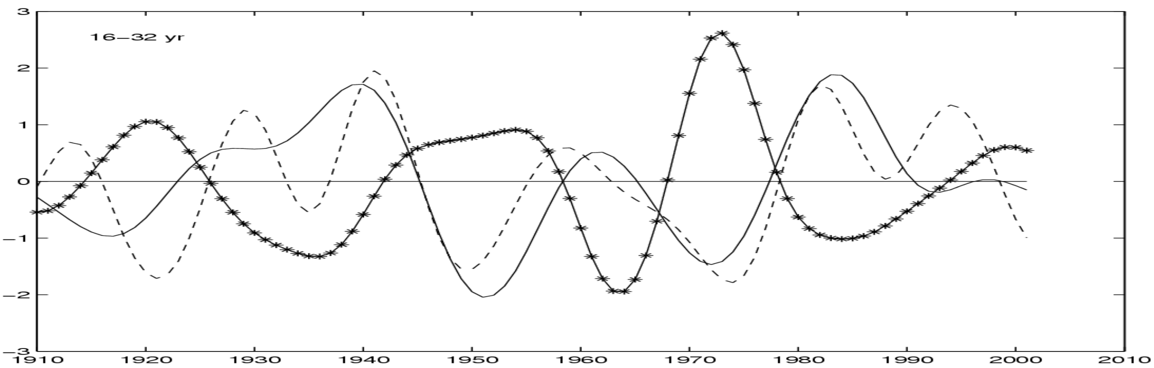

Fig. 1. The normalized reconstructed time series of SCMR (solid with *), PDO (solid) and ENSO (dash) at period of 16-32 yr.

To verify this hypothesis, for each of the years between 1950 and 1995, the ENSO condition and the category of SCMR (wet, normal or dry) are examined. It is found that the best relationship exists for the years after an El Niño (EN+1) or La Niña (LN+1) event (Table 2). The variation of the SCMR is more (less) "predictable" when both ENSO and PDO are in phase (out of phase). When an in-phase situation occurs, the SCMR tends to be below normal or normal during high PDO phase/EN+1 events, but above normal or normal during low PDO phase/LN+1 events. On the contrary, the trend of SCMR has no preference in an out-of-phase situation (i.e. high PDO/LN+1 or low PDO/EN+1). These results suggest a strong coupling between PDO and ENSO in affecting the SCMR. It appears that when these two forcings are in phase, the SCMR is highly related to these forcings. However, when they are out-of-phase, one forcing can be stronger than the other or their effects can cancel each other. As a result, the "predictability" becomes low.

TABLE 2. Comparison of the conditions of SCMR during different ENSO/PDO phases. A, N and B denote the above-normal, normal and below-normal SCMR. EN+1 and LN+1 represent the year after an El Niño and a La Niña event respectively.

	Low PDO	High PDO
EN+1	**A:** 2/7 (1966, 1973)	**A:** 1/9 (1992)
	N: 4/7 (1952, 1958, 1964, 1969)	**N:** 3/9 (1978, 1983, 1987)
	B: 1/7 (1954)	**B:** 5/9 (1977, 1980, 1988, 1994, 1995)
LN+1	**A:** 5/8 (1950, 1951,1955,1957,1975)	**A:** 1/3 (1989)
	N: 3/8 (1965, 1971, 1974)	**N:** 1/3 (1996)
	B: 0/8	**B:** 1/3 (1985)

2.4. Physical mechanism

The reason for the SCMR being more predictable in some years than in other years relative to the phase relationship between ENSO and PDO is likely to be in the intensity of the subtropical high associated with these two oscillations. Consider the high PDO phase situation. In this case, the North Pacific SSTA is below normal (e.g. Mantua et al. 1997). If a warm ENSO event occurs during the high PDO phase, the SSTA over the western equatorial Pacific as well as the Philippine Sea is also below normal. Thus, these two anomalies superpose on each other to give a below-normal SSTA over the Philippine Sea and the tropical western North Pacific. Associated with this distribution of SSTA are the anticyclonic anomalies associated with the mature phase of the warm ENSO event (Wang et al. 2000) and the PDO that will be enhanced through the mechanism discussed in Chang et al. (2000). Since the subtropical high tends to persist for a relatively long period of time, the enhanced subtropical high will likely extend westward into the SCS in the early summer, which would result in a weak summer monsoon over SC.

On the other hand, if a cold ENSO event occurs, the SSTA over the western equatorial Pacific as well as the Philippine Sea are above normal. Therefore, depending on which one dominates, the SSTA could either be positive or negative. Furthermore, because cyclonic anomalies are associated with the mature phase of the cold event, but for the high PDO phase, the flow should be anticyclonic, the subtropical high is weaker. In fact, the two circulation anomalies might cancel each other, which results in a low predictability of the intensity of the subtropical high, and hence the intensity of the summer monsoon over SC.

The scenarios for the low PDO phase are just the reverse. That is, during the LN+1 situation, the cyclonic anomalies of the PDO are superposed onto those associated with the cold ENSO event so that the subtropical high is very weak, which then results in a stronger summer monsoon, and hence an above-normal SCMR.

2.5. Summary

These results suggest that the interdecadal variability of the SCMR is determined at least partly by the phase relationship between PDO and ENSO. However, only when these two oscillations are in phase can such a variability be more deterministic.

3. Interannual variability

The purpose of this part is to investigate how the onset time of the SCSSM may be affected by remote SST anomalies over the Pacific associated with ENSO.

3.1. Data

The data used in this study are mainly from the NCEP/NCAR reanalysis. The ENSO is represented by the Niño3.4 SST anomalies (5°S-5°N, 170-120°W). The monthly mixed-layer ocean temperature (0/400m) data on a 2° latitude x 5° longitude grid are obtained from the Scripps Institute of Oceanography. From the ocean dynamics point of view, the thermocline depth could be roughly represented by the 20°C isotherm within the thermocline layer (Kessler 1990). To estimate the depth of this isotherm, the mixed-layer ocean temperature (0/400m) datasets are interpolated to 1 m x 1 m vertical resolution using cubic splines, and the ocean heat content (OHC) above the thermocline could then be obtained.

3.2. Monsoon onset date

The 850-hPa zonal winds over the central and southern part of the SCS (110-120ºE, 5-15ºN), is used to determine the onset pentad, which is defined as the first pentad after mid-April when the 5-day mean value of the 850-hPa zonal winds is westerly over the central and southern part of SCS and lasts for more than two pentads. An early or late monsoon onset date (MOD) can then be classified using pentad 28th (P28) as the threshold (Table 3).

TABLE 3. Classification of MOD. EE, NE, NN, NL and EL represent extreme early onset (< 27 pentad)), early to normal onset (=27 pentad), normal onset (=28 pentad), late to normal onset (=29 pentad), and extreme late onset (> 29 pentad)).

EE (<P27)	1956, 1960, 1966, 1971, 1972, 1974, 1976, 1984, 1985, 1994, 1996, 1999, 2000, 2001
NE (=P27)	1957, 1961, 1979, 1980, 1981, 1986, 1995
NN (=P28)	1962, 1964, 1977, 1989, 1990, 1992, 1997
NL (=P29)	1955, 1958, 1965, 1967, 1969, 1978, 1983, 1988, 1998
EL (>P29)	1959, 1963,1968, 1970, 1973, 1975, 1982, 1987, 1991, 1993

3.3. ENSO cycles associated with OHC and MOD

The longitude-time sections of OHC composites along the equator show that, for the early onset cases (Fig. 2a), in year –2[1], positive (negative) OHC anomalies exist over the eastern (western) equatorial Pacific, which is typical of the mature phase of an EN event. The negative OHC anomalies then propagate eastward and reach the central equatorial Pacific (CEP) by the winter of year -1 (Dec -1 to Feb 0), signifying the mature stage of La Niña (LN). At this time, OHC anomalies over the western equatorial Pacific (WEP) have become positive. These positive anomalies begin to propagate eastward towards the end of year 0. These results suggest that early onset cases mostly occur from an EN type in year -2 or -1 to the LN type in year 0. Almost the exact reverse occurs for the late onset cases (Fig. 2b), although the eastward propagation of the positive OHC anomalies is not as strong. In fact, the maximum positive OHC anomalies appear to remain in the central equatorial Pacific during the winter of year -2 and year -1. Nevertheless, it is apparent that these late MOD cases are associated with an EN type that follows from a LN type.

[1] Year 0 is defined as the year in which the MOD of a particular type is considered. Year (-n) refers to *n* year(s) before, and year (n) *n* year(s) after, year 0.

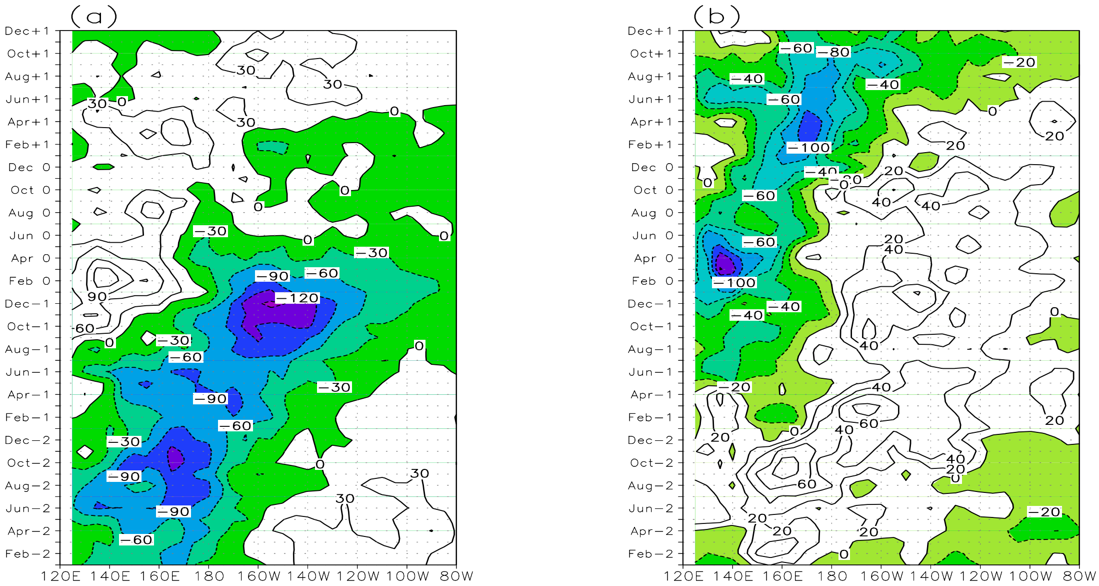

Fig. 2. Longitude-time section of OHC composites (unit: 10^8 J m^{-2}) averaged over 4°S-4°N for (a) E onset years and (b) L onset years. Year 0, +1, and –1 (–2) refer to the monsoon onset year, the year after, and the year (two years) before. Shaded areas indicate negative values.

This conclusion is further demonstrated from the fact that 11 out of 14 early onset cases occurred either during an LN year or the year after an LN event (LN+1) (Table 4), and 8 out of 10 late onset cases are associated with either an EN event or the year after an EN event (EN+1). These results suggest that changes in the SCSSM onset date may be tuned to the ENSO cycle, with late and early onsets taking turns. In other words, variations of MOD appear to follow the ENSO cycle. For example, from an LN event to an EN event, the SCSSM experiences an NE (normal to early) or E (early onset) onset and then an NL (normal to late) or L (late) onset, e.g. 1956-58, 1971-73, 1974-78, 1984-87, and 1995-98. Likewise, from an EN event to an LN event, the onset time sequence reverses, e.g. 1968-71, 1982-85, 1986-89, 1991-96, and 1997-2001.

TABLE 4. ENSO event and MOD. LN, LN+1, EN, EN+1, neutral refer to, respectively, the La Niña year, the year after La Niña, the El Niño year, the year after El Niño year, and non-ENSO year. The years in parentheses are those in which a switch to the other phase of the ENSO occurs.

	Early onset (14 cases)	**Late onset (10 cases)**
LN/LN+1	1956, 1971, 1974, (1972), 1976, 1984, 1985, 1996, 1999, 2000, 2001	1975
EN/EN+1	1966, 1994	1963, 1968, (1970), (1973), 1983, 1987, 1991, 1993
Neutral	1960	1959

3.4. Physical mechanism

A possible mechanism for the interannual variation of the onset date of the SCSSM could be as follows. Consider a case of a late monsoon onset in year 0. Two years before (year –2), it is related to a pre-EN onset situation (see Fig. 2b) so that warm sub-surface water over the WEP propagates eastward while sub-surface water over the eastern equatorial Pacific tends to be cold. As the warm sub-surface water continues to move eastward as Kelvin waves, the cold water is displaced poleward, so that the negative correlation along the

South American coast decreases. The cold water then propagates westward as a Rossby-wave response. When the cold water reaches the western North Pacific, it weakens the warm pool and hence intensifies the subtropical high. The strengthening of the subtropical high leads to an enhancement of the easterlies and hence stronger upwelling and cold sub-surface water. Persistence of the strengthening of the subtropical high also results in its westward extension and hence a weak winter monsoon (the case for EN+1; Li and Mu 2002) and then a late summer monsoon onset (year 0, EN+1). A persistent subtropical high results in an increase in insolation and hence an increase in SST. This would weaken the subtropical high, or the development of cyclonic anomalies. The other half of the cycle then repeats.

3.5. Summary

These results suggest that the interannual variability of the MOD very much relates to the ENSO cycle. Further, the physical mechanism presented is consistent with that from the last section in that the subtropical high appears to be a dominant factor in controlling the SCSSM. Any mechanism that can modify the strength of the subtropical high is likely to produce an effect on the SCSSM.

4. Summary and discussion

This paper shows the existence of large interdecadal and interannual variabilities of the SCSSM. The former is apparently related to the coupling between the forcings from PDO and ENSO while the latter is largely due to variations in ENSO. The proposed mechanisms related to ENSO are consistent with each other. The results suggest that in certain situations, it is possible to predict the onset and intensity of the SCSSM.

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