NOTES AND CORRESPONDENCE

Relationships between Summer Rainfall over China and Ocean Temperatures in the Tropical Western Pacific

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Abstract

Aspects of the associations between summer (June–August) rainfall over China and ocean temperatures in the ‘warm pool’ region in the tropical western Pacific have been examined. This has been achieved with precipitation records for 160 stations and sea surface temperature data from the COADS covering the 40-year period 1951–90.

The spatial distribution of the rainfall-SST correlations were found to vary considerably according to location of the SST target area. There were significant positive associations between the interannual variation of summer rainfall in the lower part of the Yangtze River valley and SST in the 10–20°N, 120–130°E Marsden square. To the north, over the Huaihe River valley, the correlations assumed opposite signs. When the SST over the Marsden square to the southeast (*i.e.*, 0–10°N, 130–140°E) was considered, the correlations became very small and were not significant. For the period considered here, there appears to be little synchronous connection between the Southern Oscillation Index and summer station precipitation in China.

Our results differ from those that have been obtained with data periods shorter than we use here. The findings suggest that the nature of the association between summer rainfall and ‘warm pool’ temperatures exhibit multi-decadal variability and, in particular, underwent a change in about 1970.

1. Introduction

In recent years, much scientific attention has been focussed on the role that the western tropical Pacific may play in atmospheric and oceanic variability on time scales of months to years. A manifestation of this was the establishment of TOGA COARE, three goals of which were to describe and understand (i) the principal processes responsible for the coupling of the ocean and the atmosphere in the western Pacific warm-pool system, (ii) the principal atmospheric processes that organise convection in the warm-pool region, and (iii) the multiple-scale interactions that extend the oceanic and atmospheric influence of the western Pacific warm-pool system

to other regions and *vice-versa* (Webster and Lukas, 1992). In this paper, we examine the nature and extent to which ocean conditions in the warm pool region appear to be associated with summer rainfall over China. Summer precipitation and temperature are very important determinants of agricultural output in China, this being particularly true in the Yangtze and Yellow River valleys as these can be regarded as the economic centre of the country.

The El Niño phenomenon has impacts on temperature and rainfall over a significant portion of the globe. A recent review by Liu and Ding (1992) of much work undertaken by Chinese scientists indicates that El Niño events are often accompanied by reductions in summer rainfall in eastern and northern China and by reductions in typhoon occurrence.

Fig. 1. Correlations ($\times 100$) between summer (June–August) station rainfall and SST in the Marsden square $10\text{--}20^\circ\text{N}$, $120\text{--}130^\circ\text{E}$ over the period 1951–90. Correlations significantly different from zero (95 % confidence level) are shown in **bold**. The contour interval is 20, the zero contour is bold, and negative contours are dashed.

Fig. 2. Correlations ($\times 100$) between summer (June–August) station rainfall and SST in the Marsden square $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$ over the period 1951–90. Correlations significantly different from zero (95 % confidence level) are shown in **bold**. The contour interval is 20, the zero contour is bold, and negative contours are dashed.

However, Liu and Ding point out that there are inconsistent findings between many of the published papers, and they attribute this to the inherent complexity of the phenomenon, small sample sizes, and different definitions and analysis techniques. Many of the studies which take a broad global view indicate little or no precipitation signal over China (*e.g.*, Ropelewski, 1992). The results of Huang and Wu (1989) and Huang and Sun (1992) show that, while there is a relationship between summer rainfall in the Yellow and the Yangtze Rivers with ENSO events (or east tropical Pacific sea surface temperature (SST)), the relationships are not overwhelming. Indeed it is clear (*e.g.*, from Fig. 1 of Huang and Sun) that the extreme years are *not* associated with ENSO. Wang and Li (1990) mentioned eastern Pacific SST and the location and intensity of the west Pacific high as important determinants of Chinese rainfall. However, they found that (only) 23 of the 33 El Niño events during the last 100 years were accompanied by below-average rainfall in the north China region. They also found that in the 2–3 year frequency band, to the south of 42°N , there was a positive correlation between precipitation and the Southern Oscillation Index (SOI), with the latter leading by 2–5 months. By contrast, the correlation became *negative* to the north of 42°N and the SOI lagged by up to 10 months.

These findings reinforce the comments made by Liu and Ding (1992) in connection with the complexity of the associations. Hence much variance remains to be explained by other processes and it may be that regional, rather than quasi-global, anomalous surface conditions are, in some cases, more important forcing agents. It is this possibility that we

approach here. It should be emphasised that the system we are dealing with is one of immense complexity and it is often difficult to suggest *a priori* the sign of the response of regional SST anomalies on rainfall. Aside from the potential to set up wavetrain patterns, changes in ocean temperatures can induce a number of possibly competing responses. For example, Liang *et al.* (1995) commented that cooler ocean temperatures and (hence) increased land-sea thermal contrast have been identified with greater monsoon circulation intensity. On the other hand, such cool temperatures may lead to decreased evaporation, which may lead to a reduction in available moisture and a weaker monsoon.

Our aim is to address the extent to which SST variations in the ‘warm pool’ region are associated with summer rainfall anomalies over China, and how those relationships change with SST target area. We also examine the role that the Southern Oscillation may play in these associations and how the nature of the rain–SST links may have changes on multi-decadal timescales.

2. Data

In this study we have used the summer precipitation data for 160 WMO stations covering, with a reasonably uniform distribution, the entire country over the 40-year period 1951–90. (There are discontinuities at individual stations before 1951 (Liang *et al.*, 1995), and hence data prior to this time were not used.) The sea surface temperature data employed were based on the Comprehensive Ocean–Atmosphere Data Set (COADS) (Slutz *et al.*, 1985). We use the “trimmed” COADS data from 1951 to 1990. Before being used in our analysis, these data

Fig. 3. Correlations ($\times 100$) between summer (June–August) rainfall and the SOI over the period 1951–90. Correlations significantly different from zero (95 % confidence level) are shown in **bold**. The contour interval is 20, the zero contour is bold, and negative contours are dashed.

(available on $2^\circ \times 2^\circ$ grid squares over the globe) were subject to the preprocessing and weak smoothing described by Simmonds and Rocha (1991). We have also used summer values of the SOI for the period 1951 to 1990, as compiled by the U.S. Climate Analysis Center.

3. Results

There is good reason to believe that regional behaviour of the atmosphere is highly sensitive to the precise western Pacific oceanic conditions obtaining at a given time and that the specific nature of the response may be very dependent upon where the forcing is located. Indeed, one of the central foci of TOGA COARE is to examine the multiple-scale interactions that extend the oceanic influence of the western Pacific warm-pool system to other regions. Accordingly, we have examined the relationship between summer (June, July, August) rainfall over the 160 stations in China and the summer SST in the 'warm pool' region over the 40-year period. We confine ourselves here to considering the associations with SST variations in the two Marsden squares ($10^\circ \times 10^\circ$) $10\text{--}20^\circ\text{N}$, $120\text{--}130^\circ\text{E}$ and $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$. To achieve this we have calculated the temporal correlation between summer rainfall at each of the stations and the square-averaged SSTs; the coefficients are displayed in Figs. 1 and 2, respectively. For the correlations to be significantly different from zero (in a two-tailed test, $N = 40$, $df = 38$) their magnitude must be greater or equal to 0.31 (95 % confidence level) or 0.26 (90 %). In the Figures, the correlation coefficients (multiplied by 100) are presented at the locations of the various stations. Those given in **bold** indicate the coefficient may be regarded as significantly different from zero at the

Fig. 4. Partial correlations ($\times 100$) between summer (June–August) rainfall and SST in the Marsden square $10\text{--}20^\circ\text{N}$, $120\text{--}130^\circ\text{E}$ over the period 1951–90. The effect of variations in the SOI have been removed. Correlations significantly different from zero (95 % confidence level) are shown in **bold**. The contour interval is 20, the zero contour is bold, and negative contours are dashed.

95 % confidence level. Contours have been drawn through the values.

Figure 1 shows that the most striking associations between the interannual variations of summer rain and SST in the $10\text{--}20^\circ\text{N}$, $120\text{--}130^\circ\text{E}$ 'square' (immediately to the east of the Philippines) are found in the lower part of the Yangtze River valley. The correlations are overwhelmingly positive and many are significant. To the north, over the Huaihe River valley the correlations assume opposite signs. This picture changes dramatically when one considers the associations with SST in the Marsden square to the southeast (*i.e.*, $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$). Figure 2 shows that the magnitude of the correlations decreases markedly, and very few achieve statistical significance.

As indicated above, there is considerable debate as to the influence that the El Niño–Southern Oscillation phenomenon has on summer rainfall in China. To cast light on this we have calculated the correlations between the interannual variations of station summer rainfall and the average June-to-August SOI. The result of these calculations is presented in Fig. 3, from which it can be seen that the pattern of coefficients displays only a modest amount of organization. The region of eastern China to the south of 35°N is host to predominantly negative correlations, but none of these achieve significance. In fact, at only seven stations are there significant correlations with the SOI.

It is known that in the various phases of the Southern Oscillation SST over the tropical Pacific tends to assume considerable organisation. Given this, one might ask whether the correlations pre-

Fig. 5. Partial correlations ($\times 100$) between summer (June–August) rainfall and SST in the Marsden square $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$ over the period 1951–90. The effect of variations in the SOI have been removed. Correlations significantly different from zero (95 % confidence level) are shown in **bold**. The contour interval is 20, the zero contour is bold, and negative contours are dashed.

Fig. 6. Correlations ($\times 100$) between summer (June–August) station rainfall and SST in the Marsden square $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$ over the subperiod 1972–89. Correlations significantly different from zero (95 % confidence level) are shown in **bold**. The contour interval is 20, the zero contour is bold, and negative contours are dashed.

sented in Figs. 1 and 2 are indicative of the nature of the relationships between local and regional SST *per se* or if they really owe their origin to the influence of the Southern Oscillation or, specifically, whether those correlations are dominated by El Niño events. To answer this question, we have recalculated the coefficients shown in Figs. 1 and 2, but with *partial* correlation (*e.g.*, Spiegel (1988)) to remove the effect of the SOI. The resulting plots are shown in Figs. 4 and 5. One can see that the removal of the influence of the SOI has very little effect on the patterns and hence the associations highlighted are truly quasi-regional phenomena.

4. Manifestation of multi-decadal variability in associations

The results presented above reveal that the nature of the connection between monsoon rainfall over China and synchronous SST in the warm pool depends very much on which specific forcing region is being considered. In addition, our work has revealed a somewhat different nature of the associations between ocean temperatures in the Philippines warm pool and Chinese rainfall from that found in some studies. Huang and Sun (1992) found correlations between the rain and the July ocean temperature at 150 m depth, averaged for the 137°E line from 2 to 10°N . The analysis (their Fig. 4) shows negative correlations everywhere to the south of the Yangtze as well as in the Huaihe River valley. At the same time, they showed positive correlations over most of the region centred on the Yellow River. Our plots appear to bear only a passing resemblance to this structure.

The question naturally arises as to whether these findings differ because different stations and ocean temperatures have been used, or whether the period used by Huang and Sun (1972–89) was too short or atypical in some sense. In an attempt to clarify this, we have recalculated our correlation maps, but make use of the data only for the subperiod 1972–89. The correlations plot for our $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$ square (which contains the transect along which Huang and Sun used the subsurface temperature data) is presented in Fig. 6. (For the length of data considered in these analyses ($df = 16$), coefficients must attain a magnitude of 0.47 to be considered significantly different from zero.)

The structure obtained from the short data period is very similar to that shown by Huang and Sun (1992). (Hence, in particular, one may assume little difference results from the fact that we performed our calculations with the ‘square’ average SST, while they used subsurface transect data.) Both our plots are dominated by negative correlations over the Yangtze and Huaihe River valleys and positive coefficients in the Yellow River valley. It should be pointed out, however, that the number of these which achieve significance is rather modest. It would appear that the change in the apparent relationship between the two variables is a result of our using a greater length of record.

Hence the reason our results differ from those which have been presented heretofore in the literature is that we have used a longer period of record. The very different structures of Figs. 2 and 6 suggest that the nature of the relationship between summer rainfall and ocean temperatures in $0\text{--}10^\circ\text{N}$, $130\text{--}140^\circ\text{E}$ over the later two-decade period differs

Fig. 7. Time series of anomalous summer (June–August) rainfall at Nanjing (dashed) and SST in Marsden square 0–10°N, 130–140°E (solid). The unit of the left axis is mm and of the right axis is °C.

significantly from that over the 40 years. Though not shown here, a similar finding has been made for many regions in the warm pool region.

5. Discussion

The coupled ocean-atmosphere system has many expressions of variability and that there is a rich array of such modes on decadal and longer scales. The fact that this is so sounds a caution in the interpretation of studies which are based on a specific period of data. Liang *et al.* (1995) pointed out that, for distinct periods, summer rainfall variability over China can be identified with knowledge of specific boundary conditions, but that these relationships appear to be period specific. In a similar vein, Nitta and Kachi (1994) commented that the relationship between precipitation and SST (in the Indian Ocean) appeared to change in about 1970. Our discovery of a dramatic difference between the precipitation–SST relationship in the warm pool in the periods 1951–90 and 1972–89 is consistent with that finding.

To obtain another perspective on this, we examine the summer rainfall time series at a station on the lower Yangtze, and have chosen Nanjing as typical. Figure 6 shows a (significant) correlation of -0.56 with temperature in the 0–10°N, 130–140°E box over the 1972–89 period, but this drops to 0.06 when the entire 1951–90 record is considered (Fig. 2). Figure 7 exhibits the SST and Nanjing rainfall time series for the entire period. One can see that from 1972 there is a reasonably strong out-of-phase relationship in their variations. However, prior to

about 1970 this relationship is different and the temperature and rainfall show more of a tendency to be in phase. The net effect of this is to produce the small correlation over the entire period presented above.

One important but complex process mediating between oceanic forcing and precipitation is convection. Liebmann *et al.* (1994) have recently shown that the numbers of depressions, storms and cyclones are enhanced during active periods of convection. These systems would be expected to provide a significant source of moisture for monsoonal rain over China. The processes that determine the temperature of the ‘warm pool’ and its variability and relation to convection are topics which have sparked much debate in the wake of TOGA COARE (*e.g.*, Waliser and Graham (1993), Arking and Ziskin (1994)). In comparing our results with those obtained by workers who used measures of ‘convective activity’, it must be borne in mind that there is not a linear, or even monotonic, relationship between tropical SST and convection (Waliser and Graham, 1993). Further, there may be some ambiguity as to how such activity is defined, and what some of the physical implications of the definition may be (*e.g.*, Waliser *et al.* (1993), Yulaeva and Wallace (1994)). Our point here is to stress that anomalous ocean temperatures and anomalous convective activity should not necessarily be thought of as directly related features.

It is known that the response of ocean temperature anomalies in the western Pacific is sensitive to the nature of the background flow. Our results suggest that it is also significantly sensitive to the precise location of the forcing. This is consistent with the findings of some recent modelling and observational work. Nitta (1987), among others, had suggested that there exists ‘suitable longitudes for Rossby wave generation’. Ju and Slingo (1995) have exposed the role played by the sea surface temperatures and the ITCZ in the tropical western Pacific (and the ‘warm pool’ region) in determining the strength of the Asian summer monsoon and, reinforcing these ideas, Gao *et al.* (1995) found that the meridional SST gradient along 110°W greatly influences the eastern Pacific monsoon.

6. Concluding remarks

The livelihood and wellbeing of many people depends on the timing and behaviour of the East Asian summer monsoon. To understand its interannual variations is obviously a task of great social importance as well as one of considerable scientific interest. We have shown that East Asian summer monsoon rainfall is associated with sea surface temperature conditions in the warm pool region, and that the nature of the association depends greatly on the precise location in the region. We have also found

that these relationships are effectively independent of the phase of the Southern Oscillation. Some of the results obtained here differ from those achieved by other workers using smaller data sets. In particular, the associations of rainfall and ocean temperature revealed in the 1951–1990 period appear rather different from those obtained in the later two-decade part of the period. This emphasises the fact that not only do the basic climatological parameters in the tropics undergo multidecadal variations but so, too, do the *relationships* between them. Further work is planned to reveal the mechanisms and examine the temporal stability of these links.

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夏季中国降水量と熱帯西部太平洋海面水温との関係

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1951～1990年のデータを用いて、中国大陸160地点における夏季平均(6～8月)降水量と熱帯西部太平洋海面水温(SST)変動との関係について調べた。

降水量-SSTの相関はSSTの地域によって大きく変化する。降水量と最も大きな相関を持つ海面水温領域は10–20°N, 120–130°Eで、揚子江流域の降水量と正相関、淮河流域の降水とは負相関を持つ。しかし、0–10°N, 130–140°Eの海面水温との相関は低く有意性がない。今回の解析期間に関しては、南方振動指数と降水量との関係は弱い。

以上の結果はこれまでの短期間の解析結果と異なっているが、これは降水量と海面水温との関係は数十年規模で変化していることによると思われる。特に両者の関係は1970年頃を境に異なっている。