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EFFECT OF TROPICAL CYCLONE PRECIPITATION ON ALLEVIATING THE DROUGHT SITUATION IN THE SOUTHEAST COASTAL REGIONS OF CHINA DURING SUMMER AND AUTUMN: USING THE IMPROVED OBJECTIVE SYNOPTIC ANALYSIS TECHNIQUE

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Abstract: To quantitatively study the role of tropical cyclone precipitation (TCP) on alleviating the drought in the southeast coastal region of China (SCR) during summer and autumn, the objective synoptic analysis technique (OSAT), improved for consistency and rationality, was used to separate the TCP data on the summers and autumns of 1963-2005 on the basis of daily precipitation data from stations and tropical cyclone best track data. After defining the season drought index, the actual drought distribution and the assumed drought distribution without TCP were acquired. The results showed that within 1 000 km from the southeast coastline of China, TCP accounted for 11.3% of natural precipitation (NP). Without TCP, the drought index in the SCR during summer would have increased from 0.2 to 0.6 or even above 1.0 in some regions whereas the drought index during autumn would have increased from 0.4 to 0.6 or above 1.2 in some regions. The impact of TCP on drought decreases progressively from the southeast coastline to the inland regions. The TCP proportion (TCPP) showed a significant negative correlation with the drought index in many regions of the southeast, and the significant region is wider in autumn than in summer. TCP relieved the drought most significantly within a range of 0-500 km from the southeast coastline. This drought relief showed different characteristics for the interannual variability in summer and autumn, and the cross wavelet transform indicated that the impact of TCP on drought mainly lies in 2-4-year time scales. In particular, there was a significant effect during the summers of 1977-1985 and in the autumns following that of 1985. Therefore, TCP has indeed largely alleviated drought in the SCR during summer and autumn.

Key words: tropical cyclone; precipitation; drought; objective synoptic analysis technique
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1 INTRODUCTION

Of the natural disasters associated with meteorological extreme events, drought causes the largest losses (Wilhite[1]) and deaths (De et al.[2]) all over the world. In summer and autumn, even though there is ample precipitation in the southeast coastline regions of China (SCR), drought still occurs in these regions. Conversely, summer and autumn are tropical cyclone (TC) seasons and TCs bring ample precipitation to the SCR. What is the contribution of TC precipitation (TCP) to natural precipitation (NP) in the SCR? To what extent does TCP alleviate the drought situation in the SCR? In order to obtain reliable data to discuss these issues, credible TCP data need to be extracted from the NP data and a quantitative drought standard needs to be defined.

Both subjective and objective methods can be used to extract TCP. In China, the subjective method usually is the expert subjective method used by the Shanghai Typhoon Institute. This data set has been used in various studies such as that by Cheng et al. [3], who revealed the downward trend of TCP between 1960 and 2003. The objective methods are primarily of two types. One is based on station precipitation data or satellite-retrieved data, which is used to classify the precipitation within a fixed or changed circle into TCP (Rodgers[4]; Englehart and Douglas[5]; Lau et al.[6]; Li and Zhou [7]). The other is the objective synoptic analysis technique (OSAT), which is based on station precipitation data and was developed by Ren et al. [8], Wang et al.[9] and Ren et al.[10]. The idea behind OSAT is to imitate the process by which a weather forecaster manually analyzes a synoptic map. Compared with simply setting an influencing range for a TC, OSAT first selects several natural rainbelts and then selects TC

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rainbelts according to the relative positions of the TC center and these rainbelts. Therefore, the asymmetry of TC precipitation can be captured, which is more consistent with the actual situation. This method has been used to analyze TCP in China. For example, Ren et al.[11] and Wang et al.[12] reported a decreasing trend of TCP influencing China, while Zhang et al. [13] emphasized the increasing trend of the average rainfall per TC in southeast China.

Concerning drought research in China, based on different drought indexes (Yuan and Zhou [14]; Heim[15]; Keyantash and Dracup[16]), several conclusions have been reached. For example, for all of China, the drought area has had an increasing trend since 1980 (CMA[17]) and the heavy drought situation has become increasingly serious from the late 1990s (Yu et al.[18]). In North China, the drought area has increased from 1951 to 2003 (Zou et al.[19]). Except for those studies focusing on all of China or North China, in recent years, the drought in South China has generally caused some concern (Jian et al.[20]; Zhang et al.[21]; Guo and Zhi[22]; Huang et al.[23]). Guo and Zhi discovered that, in summer and autumn, the area of 106°–115°E, 23°–32°N is more likely to experience drought[22]. Huang et al. emphasized that, in South China, droughts have become more serious in spring and autumn, while the opposite is true in summer and winter[23].

These studies have focused on TCP and drought separately. To study the quantitative influence of TCP on alleviating the drought situation, we extracted TCP using OSAT. However, we found that several procedures used by OSAT needed to be improved. As an algorithm designed to solve a practical problem, it should be consistent; the same result should be arrived at using different programs coded with the same algorithmic flow. In addition, it should be reasonable; the result should not be in obvious disagreement with the actual situation. Based on these two requirements, we made five improvements to OSAT resulting in the improved objective synoptic analysis technique (IOSAT).

To evaluate the drought situation, the standard of the percentage of the precipitation anomaly, which was proposed by the Institute of Atmospheric Physics, Chinese Academy of Sciences, was used in this paper (IAP, CAS [24]). This standard takes into account the different seasons and different arid and humid regions in China and is easy to use. Based on this standard, the drought index, H, was defined to obtain a quantitative distribution of the drought situation in China.

Section 2 introduces the data and method, including the basic steps of OSAT and the five improvements in IOSAT. Section 3 presents the result and analysis, and Section 4 gives a summary of the study.

2 DATA AND METHOD

2.1 *Data*

IOSAT requires daily station precipitation data and TC track/intensity data to derive TCP. The former data set used in this paper is from the National Meteorological Information Center of the China Meteorological Administration (CMA). We chose 684 stations, which included more than 20 years of records from a total of 756 stations. The TC track and intensity data set is from the CMA tropical cyclone data center (Ying et al. [25]) and contains four records per day. The time range of both data sets is 1963-2005.

2.2 *Procedures of OSAT*

The basic idea of OSAT is to analyze a synoptic map with processes imitating the manual operations of a weather forecaster. Suppose that on a daily surface weather map, the precipitation distribution and the position of a TC center are labeled. To analyze TCP, a weather forecaster usually takes two steps: first, based on the structure of the precipitation distribution, the daily precipitation field is separated into several independent rainbelts and some scattered precipitation stations; and second, according to the forecaster's experience and the relationship between the TC center and the independent rainbelts and scattered precipitation stations, the weather forecaster visually determines which rainbelts are associated with a given TC.

As in the case of a weather forecaster, OSAT also takes two steps: first, it separates the independent natural rainbelts; and then, it distinguishes the TC rainbelts. See Fig.1 for the process and data dependencies and Ren et al.[10] for further details.

2.3 *IOSAT*

As mentioned in the introduction, OSAT, which is designed to solve a practical problem, needs to be both consistent and reasonable. In particular, the outputs should be independent of the coding following the processing of OSAT, and the result should not obviously disagree with the actual situation. After a careful analysis of OSAT, we found that the algorithms of 1.2 (selecting the most potential rainbelt centers) and 1.4 & 1.5 (roughly & carefully defining the edges of the rainbelts) in Fig.1 were not strict and could lead to inconsistent results. In addition, step 2.1 (selecting potential TC rainbelts) in Fig.1 was unreasonable in some cases.

2.3.1 IMPROVING THE SELECTION OF THE MOST POTENTIAL RAINBELT CENTERS (MPRCS)

When MPRCs are being selected, if there are, for example, three stations with the same raining (precipitation) rate of neighborhood stations (RRNS), the selected MPRCs will be affected by the order of the selection, which may affect the outcome of the final separation (e.g., three stations located at the three vertexes of a triangle with sides of 250 km, 250 km, and 400 km, Fig.2).

Improvement: When the RRNSs of two stations are the same, the one with more precipitation should be preferentially selected as MPRC.

2.3.2 IMPROVING THE ROUGHLY AND CAREFULLY DEFINED

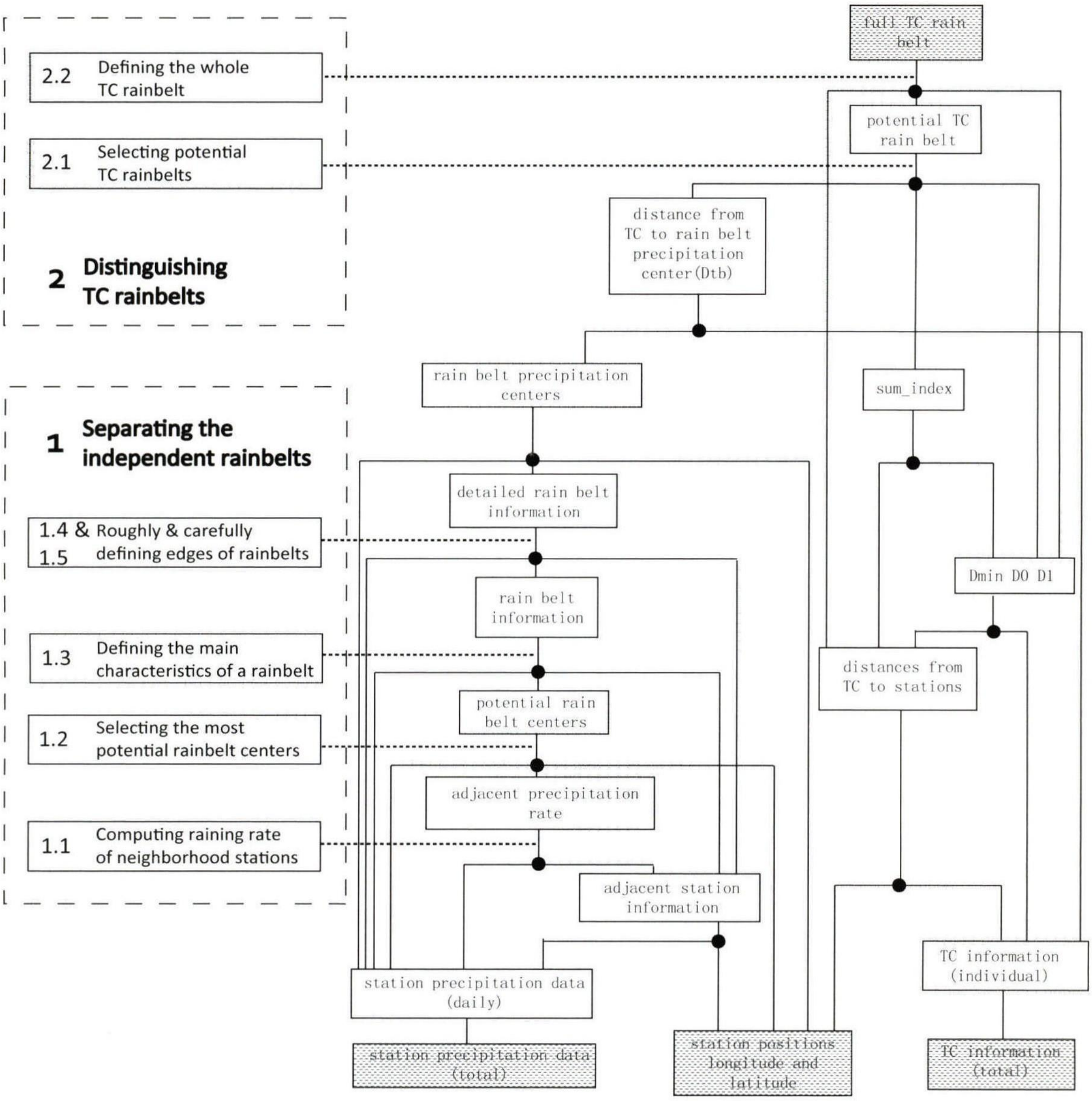

Figure 1. Flowchart of OSAT with the steps listed on the left and the data dependencies listed on the right.

Figure 2. Inconsistency caused by selecting the MPRCs.

EDGES OF THE RAINBELTS

This section includes two improvements. First, when a station has the same number of neighborhood stations for different rainbelts (NSDRs), the assignment of this station depends on the sequence of the for-loop.

Improvement: When a raining station has several greatest numbers of NSDRs simultaneously, this station should be added to the rainbelt containing the closest neighborhood station.

Second, in OSAT, a station is added to a rainbelt immediately as long as it meets the requirements. However, this may lead to inconsistently separated rainbelts, which are affected by the order of the cycling. As shown in Fig.3, the positions of stations and the distribution of precipitation are completely symmetrical. If the program cycles from station A to station B, it will add station A to rainbelt 1. Then, because the distance between station A and B is smaller than that between

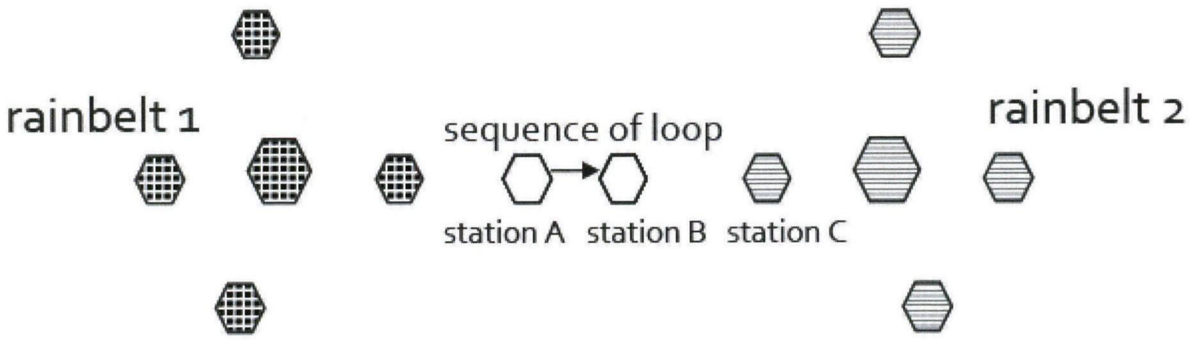

Figure 3. Inconsistency caused by cycling and adding at the same time.

station C and B, station B will also be included in rainbelt 1. Therefore, a symmetrical pattern leads to unsymmetrical rainbelts. This is neither consistent nor reasonable.

Improvement: When the edges of the rainbelts are being defined, the stations that qualify for addition to the rainbelts should not be added until a cycle of the for-loop has finished, rather than adding them to the rainbelts immediately.

2.3.3 IMPROVING THE SELECTION OF POTENTIAL TC RAINBELTS

There are two improvements in this section. The first concerns the unreasonableness caused by the station density. According to Ren et al.[10], a rainbelt can be defined as a potential TC rainbelt when it satisfies one of the following two criteria:

$$D_{tb} < D_0 + D_{min}\,, \tag{1}$$

$$\sum v(k) \geqslant 8.0, k=1, \cdots, M_l\,, \tag{2}$$

where D_{tb} is the distance between the TC center and the rainbelt-weighted-precipitation center; D_0 is a radius of the absolute TCP; D_{min} is the minimum distance between the TC center and a station; the station score $v\ (k)$ is a piecewise function of D_{min} and the distance between station k and the TC center; M_l is the rainbelt l's stations number; see Ren et al.[10] for details.

Criterion (2) relates to the station density, which may lead to unreasonable results. In Fig.4, assume that the precipitation of rainbelts 1 and 2 is completely symmetrical and that the station density of rainbelt 2 is greater than that of rainbelt 1. It is obvious that $\sum v(k)_{rainbelt\ 1} < \sum v\ (k)_{rainbelt\ 2}$. Then, if $\sum v\ (k)_{rainbelt\ 1} = 5$ and $\sum v\ (k)_{rainbelt\ 2} = 10$, rainbelt 2 will be selected as a potential TC rainbelt while rainbelt 1 will not. In this case, two rainbelts with the same precipitation have a $\sum v\ (k)$ proportional to the station density in the rainbelts, which is unreasonable.

Improvement: We use the number of neighborhood stations, $n(k)$, to indicate the density of a station, k. By defining $\bar{n}$ as the average of the number of neighborhood stations for all the stations, $\frac{n(k)}{\bar{n}}$ denotes the relative density of station k. Then, the new criterion can be written as $\sum v\ (k)\cdot\frac{\bar{n}}{\max(n(k),1)} \geqslant 8.0$, which includes the spatial case of $n(k) = 0$.

Second, the minimum of the distances between the TC center and the stations (D_{min}) in criterions (1) and (2) is also unreasonable, which is illustrated in Fig.5. Assume the TC center moves from A to B and the intensity of the TC remains unchanged. Then, at point A, D_{min} = 200 km, and according to criterion (1), the rainbelt in Fig.5 is a potential TC rainbelt. At point B, D_{min} = 0 km (the TC has just landed), and according to criterions (1) and (2), the rainbelt in Fig.5 is no longer a potential TC rainbelt. In this case, in spite of having the same TC intensity, the TC influence circle becomes smaller while landing. This is unreasonable.

Improvement: For a simple approach, just deleting Dmin in conditions (1) and (2). This hotfix has a drawback that the influence of long distance TCs may be omitted, which should be improved in future work.

2.4 *Selection of parameters in IOSAT and data matching*

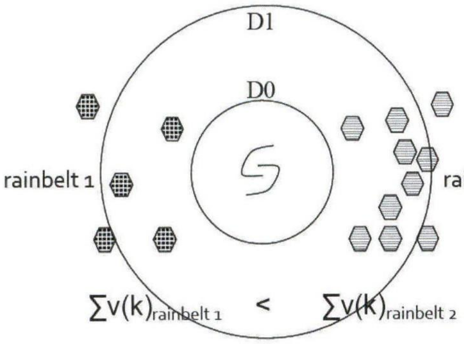

Figure 4. Unreasonable behavior caused by station density.

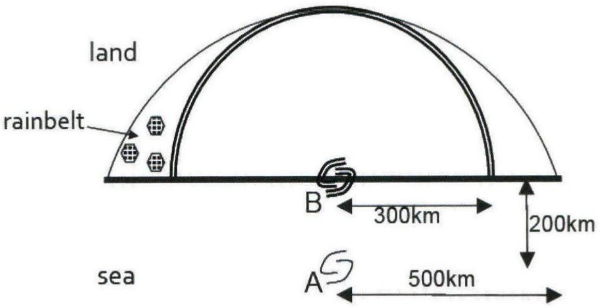

Figure 5. Unreasonable behavior caused by D_{min}.

In this study, the parameters used in IOSAT were set as follows: the critical distance for defining neighborhood stations was 200 km; the lower bound distance, d_c, for selecting the most potential rainbelt centers was 300 km; the threshold of the raining rate of the neighborhood stations, R_0, for selecting the most potential rainbelt centers was 0.3; the threshold, P_0, for distinguishing large and small amounts of precipitation was 5 mm; and the total times for roughly and carefully defining the edges of the rainbelts was 5. In addition, $\bar{n}$ calculated according to the positions of the 684 stations was 9.5.

In OSAT, when the number of neighborhood stations of a raining station is 0, the raining rate of the neighborhood stations for this station is not defined. In this case, we set it to 0.

Because there are four TC records and only one precipitation record each day, we match the precipitation data with the valid daily mean TC data. If the four records of the maximum wind speed of a TC in a day are missing and only the positions of the TC are measured, we set the parameters D_0 and D_1 for this day to the lowest levels. Moreover, if there are several TCs simultaneously influencing China in a day, we define the TC rainbelts of that day as the union of each TC rainbelt. This can be done by analyzing each TC rainbelt individually and then combining the analysis results.

2.5 *Defining the seasonal drought index H*

According to the standard of the Institute of Atmospheric Physics, Chinese Academy of Sciences[24], the drought severity can be measured by the percentage of the seasonal precipitation anomaly, which is defined as the percentage of the precipitation anomaly $\frac{R_{\text{station, year, season}}-\bar{R}_{\text{station, season}}}{\bar{R}_{\text{station, season}}}\times100\%$, where R is the precipitation at a station in a season in a certain year and $\bar{R}$ is the annual average precipitation of that station in that season (See Table 1).

Table 1. Standard of drought according to the seasonal charts of climate disasters in China (1951-1990)[24].

	Seasonal precipitation (mm)	Drought (%)	Heavy drought (%)
Summer (JJA)	50-199	-15 to -40	<-40
	200-600	-20 to -45	<-45
	>600	-25 to -50	<-50
Autumn (SON)	45-200	-10 to -30	<-30
	>200	-25 to -50	<-50

Based on the above standard, we defined the drought index H as H = 0 if there was no drought at the station in the season for that year; H = 1 if there was drought; and H = 2 if there was heavy drought. According to this definition, the distribution of drought over stations and seasons and years can be obtained. In addition, we defined the summer and autumn drought index as the sum of the two seasons' drought indexes.

3 RESULTS

3.1 *Characteristics of NP and TCP*

To investigate the annual variation of TCP in SCR in summer and autumn, the region within 1 000 km of the southeast coastline of China was divided into 0.25° × 0.25° latitude-longitude grids, and a bilinear interpolation was applied to TCP and NP to derive their area sum, area average, and time series. The southeast coastline in this study was defined as the coastline from Dongxing in Guangdong Province to Shanghai.

As shown in Fig.6, NP, TCP, and the ratio of TCP to NP (i.e., TCP proportion, TCPP) all exhibit downward trends, of which the annual variations of TCP and TCPP are similar. The downward trends are consistent with the studies of Cheng et al.[3] and Ren et al. (Ren et al.[11]; Ren et al.[26]). TCPP ranges from approximately 4% (1982, 1983, and 1998) to more than 20% (1985 and 1994). On average, TCPP in SCR in summer and autumn is 11.3%, which is similar to the 12% estimated by Rodgers et al. [4] using passive microwave satellite observations in the North Pacific Ocean.

As for the spatial distribution shown in Fig.7, TCP is primarily distributed in SCR and decreases quickly in the northwestward direction. This distribution is consistent with that of Ren et al.[26] and Wang et al.[12]. TCPP is greater than 30% along the southeastern coastline of China, greater than 6% in the southeastern regions of China, and less than 2% on the northwestern side of the Heihe-Tengchong Line. The Heihe-Tengchong Line is an important population dividing line. To its southeastern side lies 94.4% of the population and 91.5% of the grain planting area in China (Hu [27]). It is assumed that TCP is of great significance to agricultural production in summer and autumn.

3.2 *Influence of TCP on the drought situation: Spatial distribution*

As shown in Fig.8, in summer, the lower reaches of the Yellow River and the Yangtze River experience drought to some extent and the Hetao area experiences heavy drought (Fig.8a). The drought situation in autumn is generally more serious than that in summer, especially

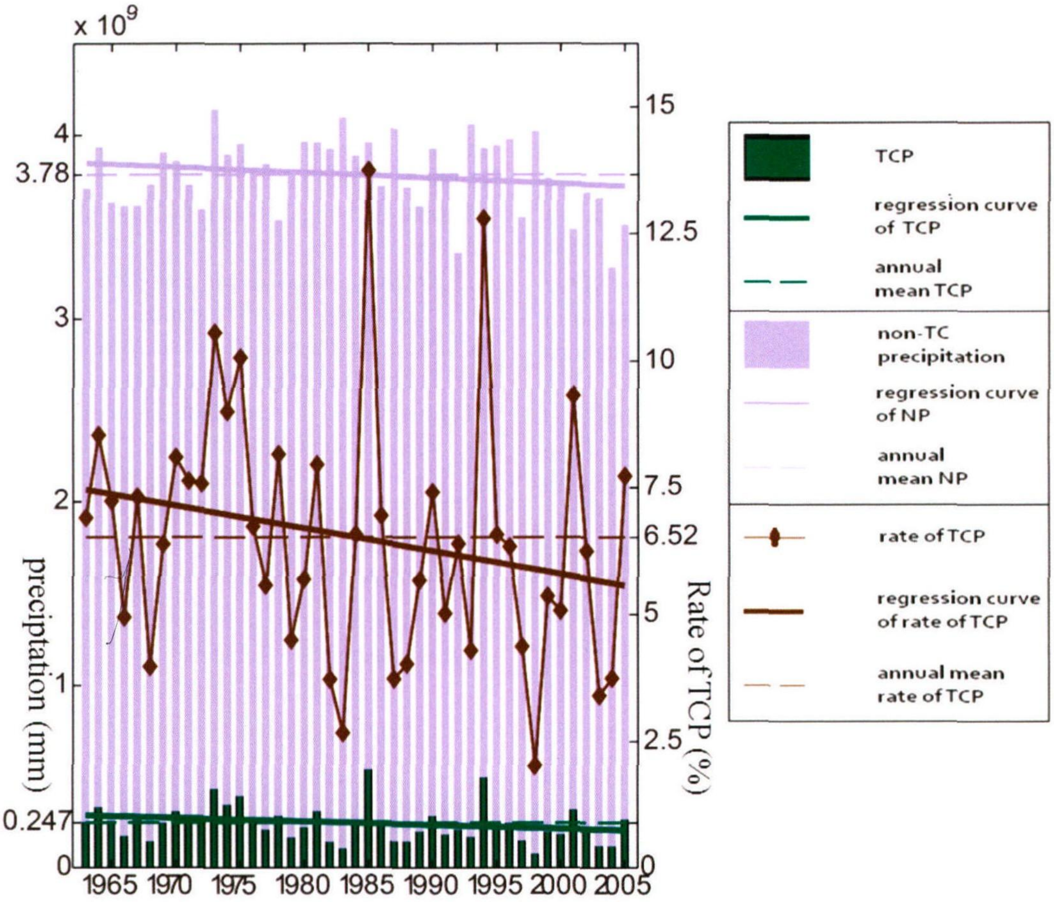

Figure 6. Annual precipitation in summer and autumn within 0-1 000 km of the southeast coastline of China during the time period of 1963-2005.

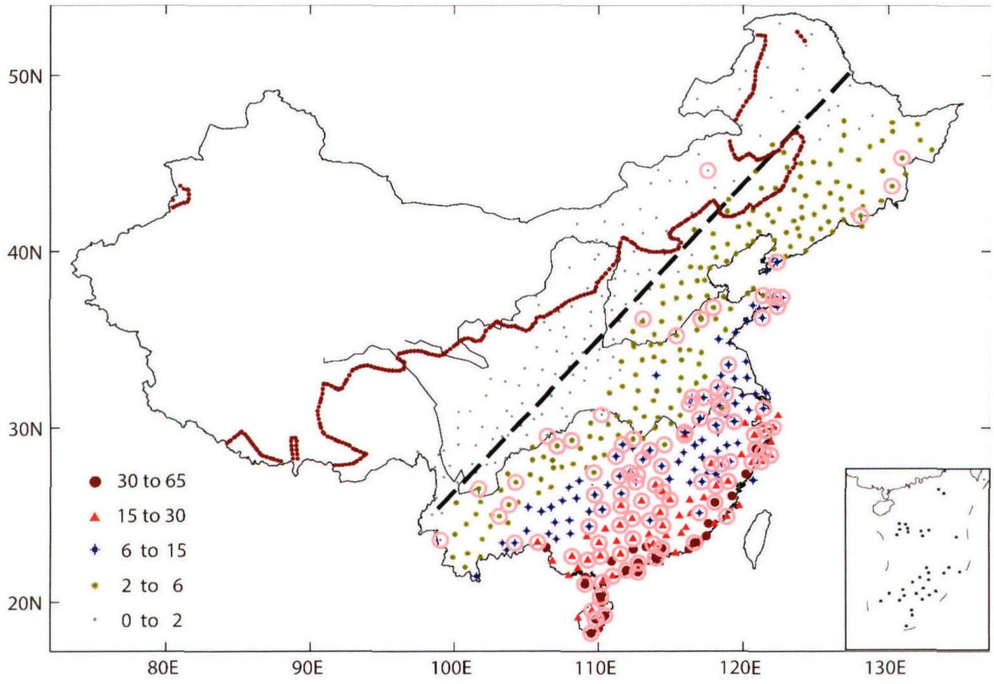

Figure 7. Spatial distribution of annual mean TCPP (unit: %). The dashed line is a demarcation line beginning in Heihe in Heilongjiang Province in the northeast and stretching to Tengchong in Yunan Province in the southwest. The dotted line marks the 400 mm NP line. The labels with large circles indicate a statistical negative correlation between the summer and autumn annual TCPs and drought indexes (at the 0.10 significance level).

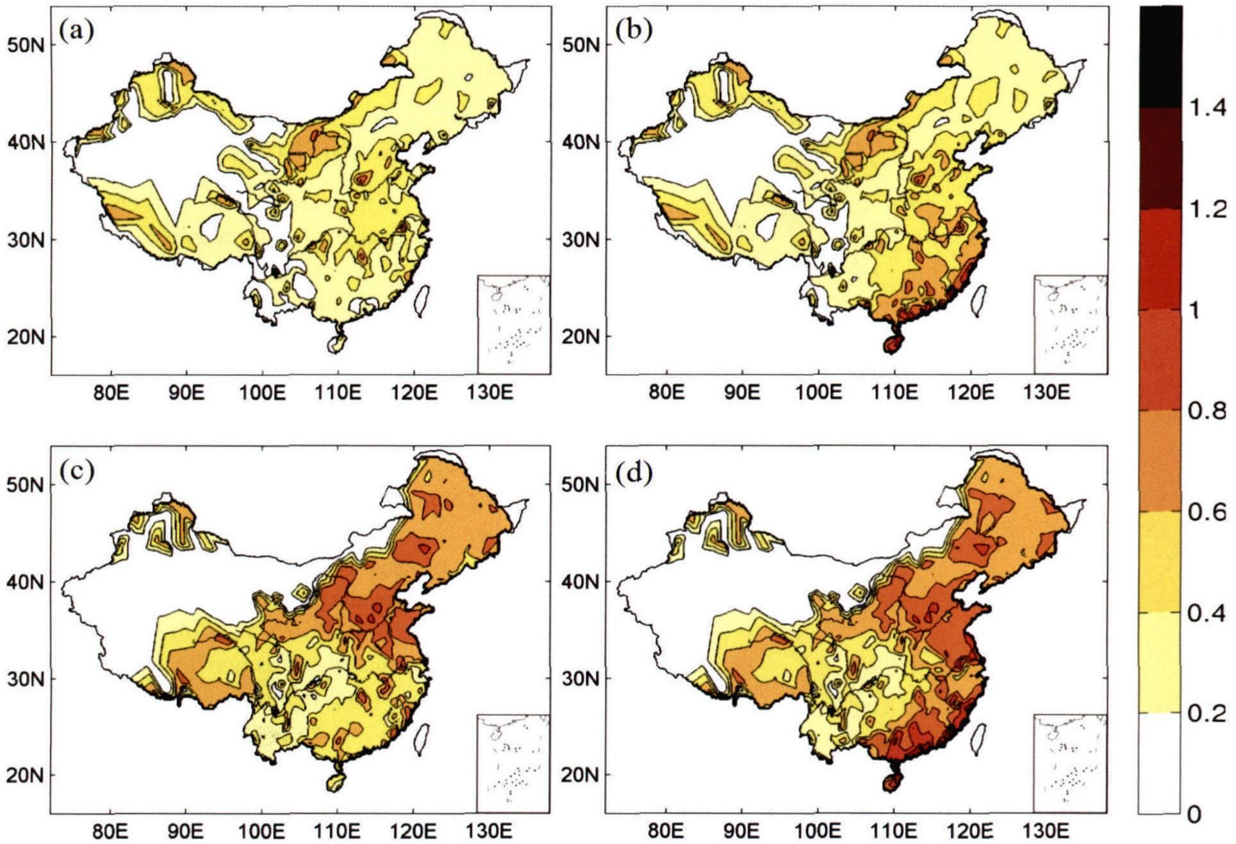

Figure 8. Spatial distribution of the annual mean summer and autumn drought index in China averaged over 1963-2005: (a) summer; (b) fictitious non-TCP summer; (c) autumn; and (d) fictitious non-TCP autumn.

in the middle and lower reaches of the Yangtze River and in the Daxingan Mountains (Fig.8c). If there is no TCP, the drought regions would be greatly extended in southeast China. In summer without TCP (Fig.8b), the drought index would increase from 0.2 to more than 0.6 and would be greater than 1.0 in some southeast coastal regions. In autumn without TCP (Fig.8d), the drought index would increase from 0.4 to more than 0.6 and would be greater than 1.2 at some stations in SCR. Conversely, in the Yellow River and inland areas, the drought situations are similar with and without TCP. Therefore, TCP is indispensable to SCR in summer and autumn.

The correlation between the TCPP and the drought index is shown in Fig.9. The distribution of the correlation is similar to that of TCP, which decreases from southeast to northwest. In summer, the influence area extends beyond the Heihe–Tengchong Line and is larger than that in autumn. The significantly negatively correlated stations in summer are primarily located in the Zhejiang and Guangdong coastal areas and in the junction area of Jiangxi and Henan Provinces. In autumn, in addition to the mentioned stations, the stations on Shandong Peninsula and Hainan Island also show significant negative correlations. Further, the correlation between TCP and drought index led to similar results (Fig.7, big circles). In summer and autumn, most of the stations with TCPPs of more than 6% passed the significance test, which implies that the larger TCP in summer and autumn results in lower occurrences of drought situations.

3.3 *Influence of TCP on the drought situation: Temporal distribution*

Figure 10 shows the ratio of the fictitious non-TCP drought index to the actual drought index and the annual change in the drought situation at different locations. The decreasing importance of TCP in alleviating the drought situation is shown in Figs.10a and 10e. In summer, it decreased more quickly than in autumn. However, regardless of the season, the ratio decreased to less than 1.5 at 500 km and nearly 1 (indicating that TCP has no influence on the drought situation) at 1 000 km. The annual indexes (Figs. 10b-10d and 10f-10h) show that TCP primarily influences the drought situation in the 0-500 km area. In the 500-1 000 km area, TCP influences the drought situation only during certain individual years, e.g., the summers of 1975 and 1985 and the autumns of 1969 and 1995. In the 1 000-1 500 km area, except for the autumn of 1985, the influence of TCP on the drought situation can be neglected. In general, the influence of TCP on the drought index in summer is larger than that in autumn, which could be attributed to the relatively smaller drought index in summer.

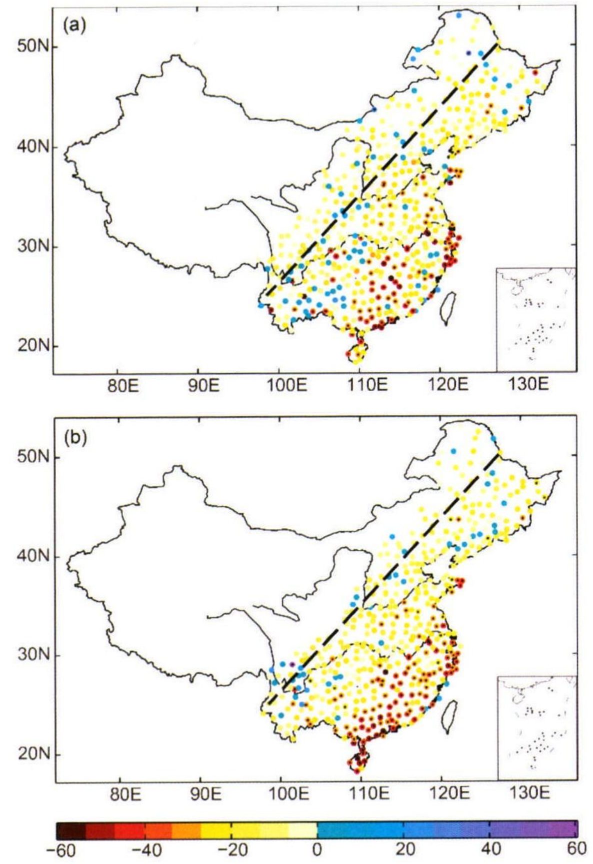

Figure 9. Correlation between TCPP and drought index: (a) summer and (b) autumn. Circles with black points indicate that the correlation passes the significance test at a level of α= 0.10. Only stations with seasonal TCP of more than 0 are shown in this figure.

In addition to the previously mentioned characteristics, Figs.10b and 10f also show that the period of annual variation of the drought situation within the 0-500 km area in the summer is longer than it is in the autumn after 1985. A wavelet analysis can reveal such periodic characteristics and show both the frequency domain and the temporal domain information of a time series. See Torrence and Compo [28] and Grinsted et al.[29] for detailed information and examples in atmospheric science. Fig.11 illustrates that the summer drought index has a period of 2 years between 1975 and 1982 and a period longer than 11 years; however, the longer period cannot be confirmed due to the series length. The autumn drought index has a 3-year period after the 1980s. In the cross wavelet spectrum, TCP and the drought situation are consistent with each other at 6-7-year periods and at a 2-4-year period around 1980, which passes the significance test. In autumn, they are consistent with each other at a 3-4-year period after the end of the 1980s. Therefore, the drought index, TCP, and their cross wavelet spectrum all exhibit interdecadal variation and show different features in summer and autumn. The influence of TCP on the drought situation is primarily at a period of 2-4 years, which may be modulated by the El Niño Southern Oscillation; e.g., Rodgers et al.[4] found that there is usually a positive anomaly in TCP in El Niño years due to the eastern extension of the monsoon trough.

4 DISCUSSION AND SUMMARY

Compared with the fixed or changed circle approach mentioned in the introduction, OSAT has the advantage of being able to capture the asymmetric characteristics of TC rainbelts. In general, the basic idea of OSAT is to use a non-standard cluster analysis to define independent rainbelts based on station precipitation data and to estimate the impact of a TC on these rainbelts to separate out the TCP. In Section 2.3, IOSAT was proposed with five improvements according to the requirements of being consistent and reasonable. To further improve this method, detailed TC structure information or large-scale circulation information can be used or the influencing radius of TC can be carefully redefined, e.g., approximately two thirds of TC hard rain occurred in the moving direction of TC; therefore, an asymmetric influencing radius could be determined.

Using IOSAT, TCPs for the 684 weather stations in China from the period of 1963-2005 were determined. Then, via the definition of the drought index H, the drought situation and the supposed non-TCP drought situation for China in summer and autumn were quantified. The analysis shows the following. (1) In summer and autumn, within a range of 1 000 km from the southeast coastline, TCP accounted for 11.3% of NP and decreased northwestwardly from more than 30% to less than 2% west of the Heihe-Tengchong Line. (2) Without TCP, the summer drought index in SCR would have increased from 0.2 to 0.6 or even more than 1.0 in some regions, while the autumn drought index would have increased from 0.4 to 0.6 or more than 1.2 in some regions. The impact of TCP on drought decreases progressively from the southeast coastline inland. (3) TCPP showed a significant negative correlation with the drought index in Zhejiang, Guangdong, Hainan, Jiangxi, and Henan Provinces, and this region is wider in autumn than in summer. (4) As for the temporal change, TCP primarily relieved drought within the area 0-500 km from the southeast coastline and had only a limited influence on drought within the area 500-1 000 km from the coastline. (5) The wavelet power spectrum exhibited different decadal variations for TCP and the drought index, and the impact of TCP on drought primarily lies in 2-4-year time scales, especially during the summers of 1977-1985 and in the autumns after 1985.

The percentage of the precipitation anomaly was selected in this paper to calculate the drought situation. Its advantages are that it is easy to calculate and to understand; however, the influences of temperature, the underlying surface, and the drought's cumulative processes have not been directly considered. In addition,

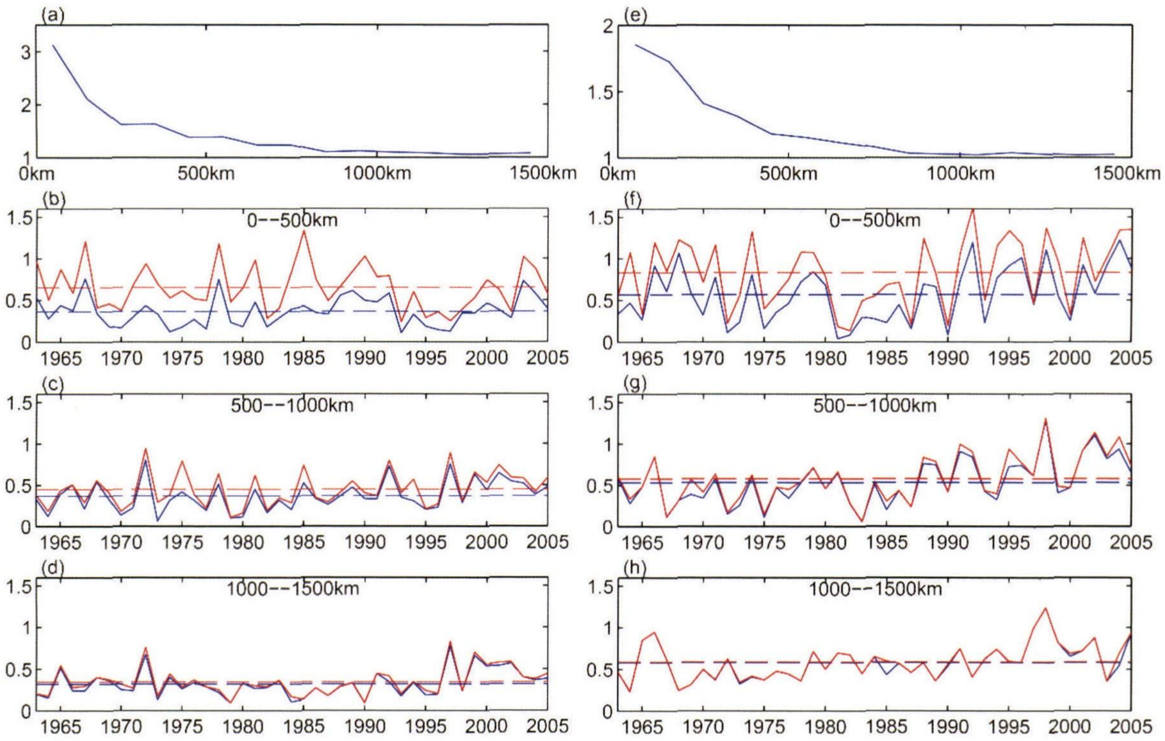

Figure 10. (a) Ratio of the fictitious non-TCP drought index to the actual drought index in summer. The x-axis indicates the distance to the coastline from Dongxing in Guangdong Province to Shanghai. The result is calculated at 100 km intervals. (b) The actual drought index (blue line) and the fictitious non-TCP drought index (red line) within 500 km of the coastline in summer. (c) Same as (b), except for 500–1 000 km. (d) Same as (b), except for 1 000–1 500 km. (e)-(h) Same as the left column, except for autumn instead of summer.

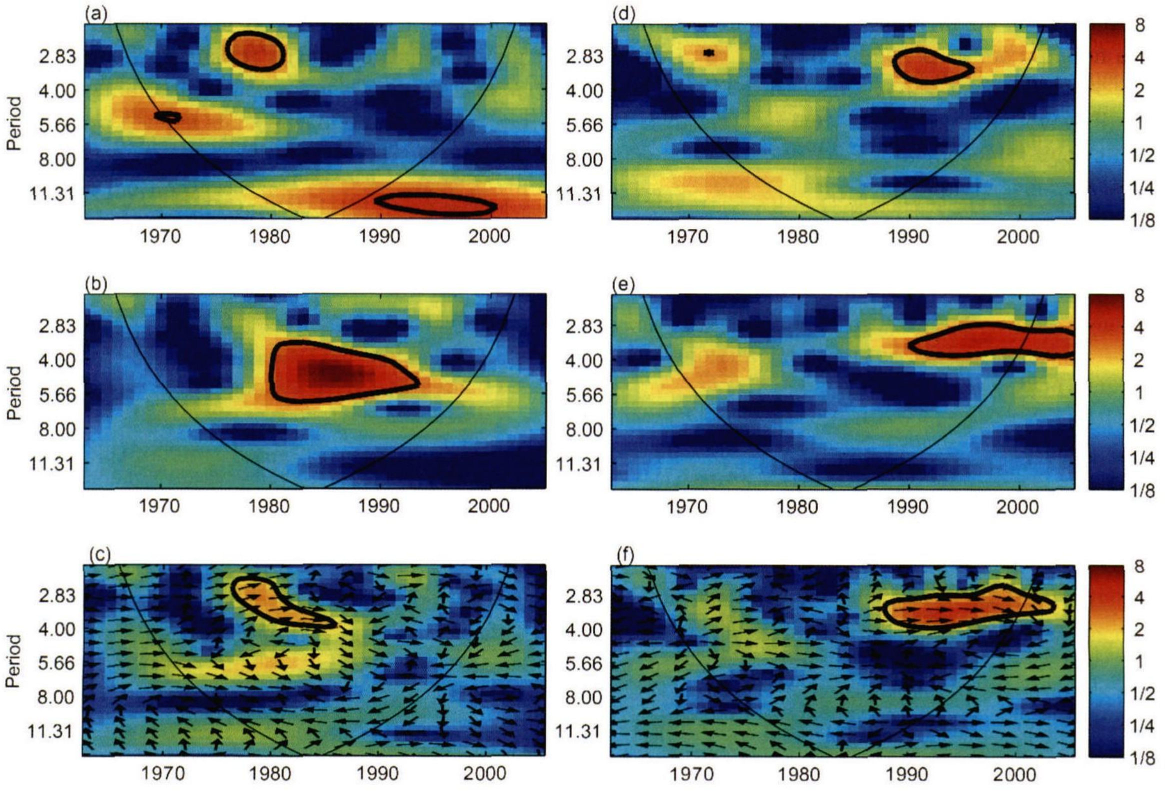

Figure 11. (a) Wavelet power spectrum of the drought index 500 km within the coastline in summer using the Morlet wavelet. The thick black line designates the 5% significance level against red noise. The area outside the thin black line is distorted by edge effects. (b) Same as (a), except for TCPP. (c) Cross wavelet transform of the two previous time series. Arrows represent the relative phase relationship (with in-phase pointing right). (d)-(f) Same as the left column, except for autumn instead of summer.

drought can be classified into four categories (Mishra and Singh[30]): meteorological drought, hydrological drought, agricultural drought, and socio-economic drought. Therefore, the drought index should be selected based on the specific application, and our conclusions require further study.

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