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RETURN PERIOD AND THE TREND OF EXTREME DISASTROUS RAINSTORM EVENTS IN ZHEJIANG PROVINCE

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Abstract: A provincial Disaster-causing Rainstorm Severity Index (DRaSI) is introduced to quantify the relationship between rainfall and its disastrous impacts on Zhejiang province of China, shortened as ZJ-DRaSI. ZJ-DRaSI is set up based on the DRaSI for single stations in combination with the coverage of rainstorms. The probability distribution function (PDF) of ZJ-DRaSI between 1971 and 2015 can be well fitted by the Wakeby Distribution with five parameters. It is found that decadal (e.g. 10yr, 20yr, and so on) return period values of ZJ-DRaSI related to typhoons are generally lower than that of non-typhoon events, implying that disastrous non-typhoon events have a higher frequency of occurrence. The extreme typhoon events have a significant cycle of 22.5 years, while the non-typhoon events have a significant cycle of 15 years. Both are currently at the high-value phase. The annual extreme value of ZJ-DRaSI exhibits an increasing trend of approximately 15% every 10 years.

Key words: extreme disastrous rainstorm event; probability distribution; return period; trend
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1 INTRODUCTION

Rainstorm is one of the most severe meteorological disasters in Zhejiang Province of China (Chen[1]). With the development of the society and economy, the number of entities affected by natural disasters is increasing rapidly. As a result, the extent of the impact and the level of damage caused by disasters are both enhancing. In recent years, this case holds true for extreme disastrous rainstorm events for its frequent occurrence.

Researchers have conducted extensive studies on the extreme precipitation events occurring in different regions of China (Fu et al.[2]; Hu et al.[3]; Ren et al.[4]; Zheng et al.[5]; Zhang and Wei [6]; She et al.[7]; Bao[8]; Zhang and Cui[9]; Yang et al.[10]; Wang et al.[11]). Previous studies mainly focused on the extreme tendency of precipitation elements. Some were conducted based on several extreme precipitation indices recommended by organizations such as the World Meteorological Organization (Ren et al.[4]), while others focused on such topics as the total regional precipitation, the days of rainstorm and the maximum daily precipitation[6]. These studies have drawn numerous valuable conclusions. Gao and Xie summarized the methods to define an extreme precipitation event as follows[12]: (1) The precipitation events occurring at a relatively low frequency can be determined using the percentile threshold method. (2) The precipitation events significantly deviating from the norm can be determined based on the times of precipitation anomaly greater than the standard deviation. (3) A disastrous rainstorm is defined when the precipitation event caused severe social and economic losses as well as casualties. According to the national standard of China (GB/T 28592-2012), an event with a total precipitation greater than 50 mm in 24 hours is defined as a rainstorm event. However, not all rainstorms are disastrous. Whether a rainstorm will cause disaster depends not only on the extent and intensity of the precipitation but also on the natural environment as well as the social and economic conditions. Disaster is the result of the combined effect of the disaster-causing factors, the environment where the disaster is formed and the disaster-bearing bodies (Shi[13]; Chui and Shi[14]). Therefore, to deepen the knowledge about the disastrous rainstorms is of direct guiding significance to disaster prevention and reduction.

In this paper, a provincial Disaster-causing Rainstorm Severity Index (DRaSI) which is closely related to the damages caused by rainstorms in Zhejiang is defined, and the methods of evaluating multi-year return periods of disastrous rainstorm events are established. The long-term trend of disaster-causing rainstorm events will also be investigated.

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2 DEFINITION OF PROVINCIAL RAINSTORM EVENT AND DATA SOURCES

A provincial rainstorm event is defined when there is at least one day with 10% of stations in the specific province recorded daily precipitation greater than 50 mm. The construction of meteorological stations in Zhejiang began in the 1950s and was basically completed in the 1970s, at which time there was generally one meteorological station in each county. In other words, the meteorological data recorded since the 1970s are comparable and can thus be used to study provincial level meteorological events in Zhejiang.

Based on the precipitation data recorded at 62 county-level meteorological stations (Fig. 1) in Zhejiang between 1971 and 2015, 140 typhoon rainstorms and 286 non-typhoon rainstorms are chosen using the aforementioned criteria. Annual counts of the rainstorm events are shown in Fig. 2a, with a maximum of 8 for typhoon events and 13 for non-typhoon events. Both typhoon and non-typhoon events are at a low occurrence stage since 2010. Non-typhoon rainstorms mainly occur in the frontal system of the annually first rainy season (April to May) and Meiyu period (June to July), followed by easterlies systems in August and September. Severe convective weather is also a contributor. The monthly distribution (Fig. 2b) indicates that non-typhoon rainstorms appeared most in June with 75 times, accounting for 26% of the total, followed by May with 51 times (18%). 9% to 13% of non-typhoon rainstorms occurred in April, and almost the same in July, August and September. Typhoon rainstorms mainly occur in the months from May to October. Among them, most occurred in August, with 54 times accounting for 39%, followed by September and July with 33 times (24%) and 31 times (22%), respectively.

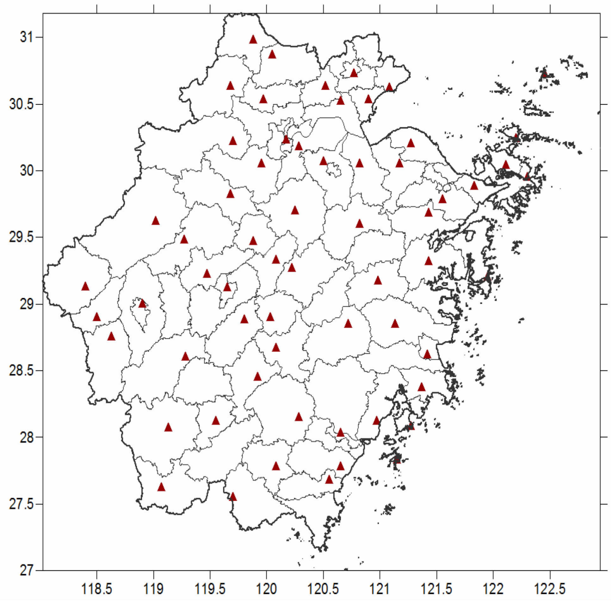

Figure 1. Distribution of the county-level meteorological stations in Zhejiang Province used in this study.

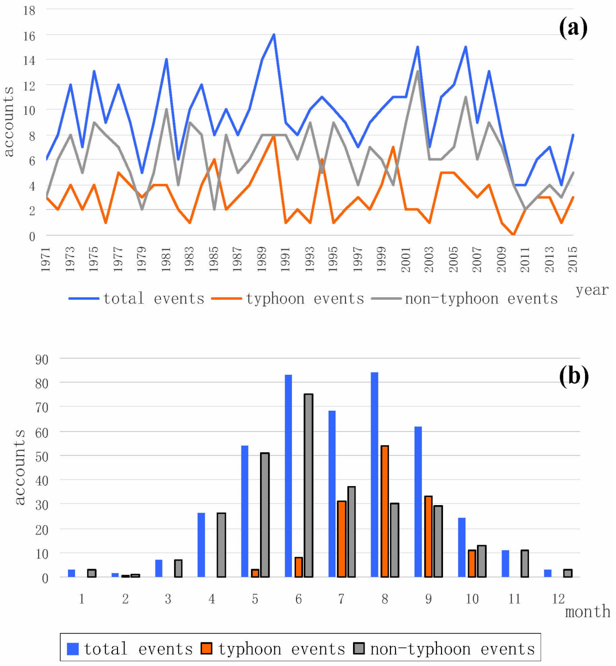

Figure 2. The annual (a) and monthly (b) distribution of the provincial level rainstorm events in Zhejiang.

3 PROVINCIAL DISASTER-CAUSING RAINSTORM SEVERITY INDEX FOR ZHEJIANG (ZJ-DRaSI)

3.1 *Definition of ZJ-DRaSI*

The relationship between the damages and disaster-causing factors of the rainstorms needs to be analyzed in order to set up the ZJ-DRaSI. According to Chen et al. [15] and the local standard "*Technical Specification for the Assessment of Risk Level of Rainstorm Processes*" (DB33/T2025-2017) in Zhejiang province, a model for determining the DRaSI of single stations is established as follows[15]:

$$I_f = 0.38\frac{R_{\mathrm{all}}}{\overline{R}_{\mathrm{all}}} + 0.30\frac{R_{\max}}{\overline{R}_{\max}} + 0.32\frac{R_{\mathrm{d}}}{\overline{R}_{\mathrm{d}}} \tag{1}$$

where I_f represents the DRaSI of single stations, R_{all} represents the total precipitation of that station in one rainstorm (unit: mm), $R_{\max}$ represents the maximum daily precipitation (unit: mm), and R_{d} represents the rainstorm days (unit: days). $\overline{R}_{\mathrm{all}}$, $\overline{R}_{\max}$ and $\overline{R}_{\mathrm{d}}$ are constants equal to the average values of the sample data used in the present study.

Based on the damage data of rainstorm events, Chen et al. classified the single station DRaSI into four levels as shown in Table 1[15]. Rainstorms at Level 1 (mild) generally lead to water-accumulated in low-lying areas and landslides in mountainous areas. When the DRaSI reaches Level 2 (relatively severe) and level 3 (severe), low-lying areas are prone to be flooded, secondary disasters (e.g., mountain torrents, mudslides and landslides) will be easily induced, with level 3 more serious than level 2. Level 4 (extremely severe) rainstorm

Table 1. DRaSI levels of single station.

Level (extent) of impact	Level 1 (mild)	Level 2 (relatively severe)	Level 3 (severe)	Level 4 (extremely severe)
I_f value	[0.8, 1.3)	[1.3, 1.9)	[1.9, 2.9)	⩾2.9

will cause severe waterlogging in urban and rural areas and secondary disasters occur easily.

To evaluate the severity of a provincial rainstorm event, both the intensity and extent of the rainstorm with different disaster intensity should be considered. Therefore, an integrated DRaSI of level k (=1, 2, 3, 4, as in Table 1) for a specific provincial rainstorm event can be defined by:

$$I_k = 0.5\left(\frac{A_k}{A'_k} + \frac{S_k}{S'_k}\right) \quad k = 1, 2, 3, 4 \qquad (2)$$

where A_k denotes the ratio of the amounts of stations at k-level to total station amounts, representing the relative area where k-level DRaSI is obtained during a specific provincial rainstorm event. A'_k is a constant, equal to the average value of A_k (Table 2) of all provincial rainstorm events. S_k represents the provincial average DRaSI at k-level during a specific provincial rainstorm event and S'_k is a constant, equal to the average S_k of all provincial rainstorm events (Table 2).

Table 2. Values of A_k' and S_k' at various levels.

Level (k)	1	2	3	4
A_k' value	10%	8%	6%	5%
S_k' value	1.0	1.4	2.1	3.4

Then, the provincial DRaSI for Zhejiang (ZJ-DRaSI) is designed as follows:

$$I = W_k I_k \qquad k = 1, 2, 3, 4 \qquad (3)$$

where W_k represents the weight coefficient for each level, determined by analytical hierarchy process (Tang and Feng[16]; Chang and Jiang[17]; Hosking and Wallis[18]). The analytical hierarchy process determines the weight coefficient by establishing an analytic hierarchy model to construct the judgment matrix, then calculates the characteristic value. Based on the sample data, the weight coefficients from level 1 to level 4 are 0.0553, 0.1175, 0.2622 and 0.565, respectively.

3.2 *Probability distribution function of ZJ-DRaSI*

ZJ-DRaSI is calculated for all the 426 provincial rainstorm events since 1971 (Fig. 3). There are 63 typhoon events accounting for 45% and 150 non-typhoon events accounting for 52% with ZJ-DRaSI <0.2. 45 (31%) typhoon events and 85 (29%) non-typhoon events have a ZJ-DRaSI between 0.2 and 0.5. In addition, 25% of typhoon events and 20% of non-typhoon events have a ZJ-DRaSI >0.5. The ZJ-DRaSI value of typhoon Fitow in 2013 is the greatest one, up to 2.86. The greatest value of non-typhoon events is 2.79, corresponding to the rainstorm event from June 8 to 18, 1994.

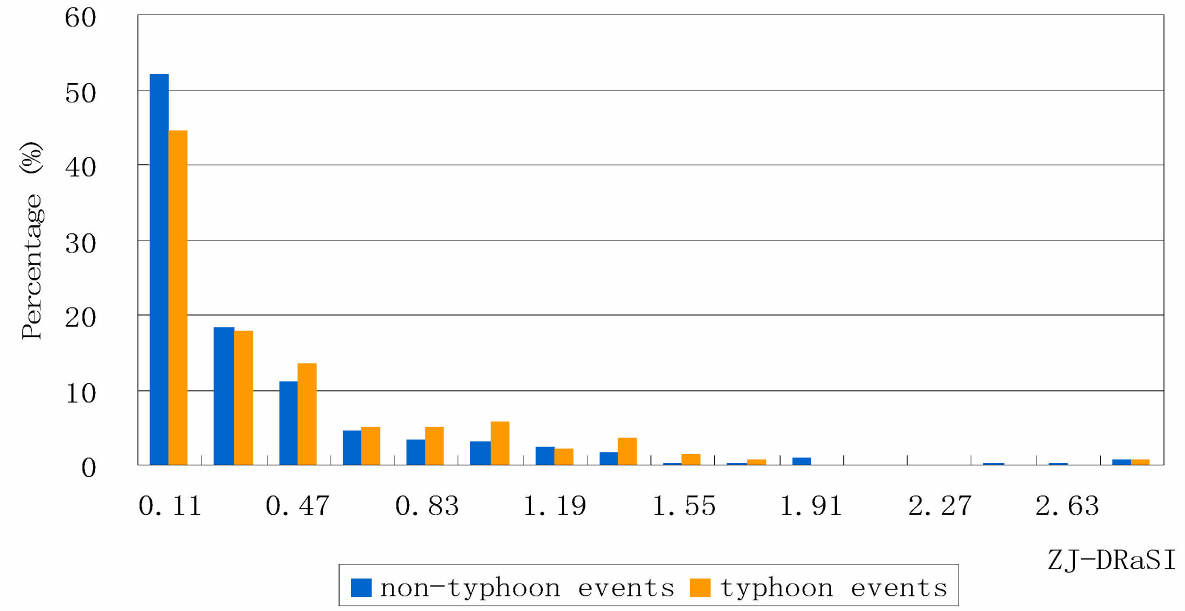

Figure 3. Binned distribution of ZJ-DRaSI during 1971 and 2015.

The Wakeby distribution was defined by Thomas in 1976[19], and has the following attributes: (1) With suitable parameter values, Wakeby distribution can mimic the extreme value distribution, the logarithmic normal distribution and the logarithmic Gamma distribution. The generalized Pareto distribution is only a special case of Wakeby distribution. (2) Wakeby distribution has five parameters, more than the common statistical distributions. This large number of parameters allows Wakeby distribution to adopt various shapes, thereby resulting in a better goodness of fitting. (3) Some cases of Wakeby distribution have an upper trailing tail and "outliers" that suit occasional high values. Therefore, Wakeby distribution is chosen to fit the probability distribution of ZJ-DRaSI.

The analytical equation of Wakeby distribution can only appear in the form of an inverse function. For a continuous sequence of numbers, the cumulative probability distribution function (CPDF) is as follows:

$$F(x)=P(X\leqslant x)=\int_{-\infty}^{x} f(t)\mathrm{d}t \quad -\infty<\chi<\infty \tag{4}$$

The inverse function of Wakeby distribution is as follows:

$$x(F)=\mu+\frac{\alpha}{\beta}[1-(1-F(x))^{\beta}]-\frac{\gamma}{\delta}[(1-(1-F(x))^{\delta}] \tag{5}$$

where μ is position parameter; α and γ are size-related parameters; and β and δ are shape-related parameters.

Based on the significance test of Kolmogorov statistics, the parameters for typhoon rainstorm events are fitted with the L-moment approach, while for non-typhoon and all rainstorm events, the method of least squares is used. Detailed values are shown in Table 3. As shown in Fig. 4, the probability distribution of ZJ-DRaSI can be well fitted by Wakeby distribution.

Table 2. Values of A_k' and S_k' at various levels.

	Estimated parameters				
	M	α	γ	β	δ
Typhoon rainstorm events	0.0272	−0.1986	1.2434	0.3877	0.1328
Non-typhoon rainstorm events	0.0299	0.0035	−0.3600	0.2183	0.3600
All rainstorm events	0.0251	−0.5340	2.6835	0.5925	−0.1010

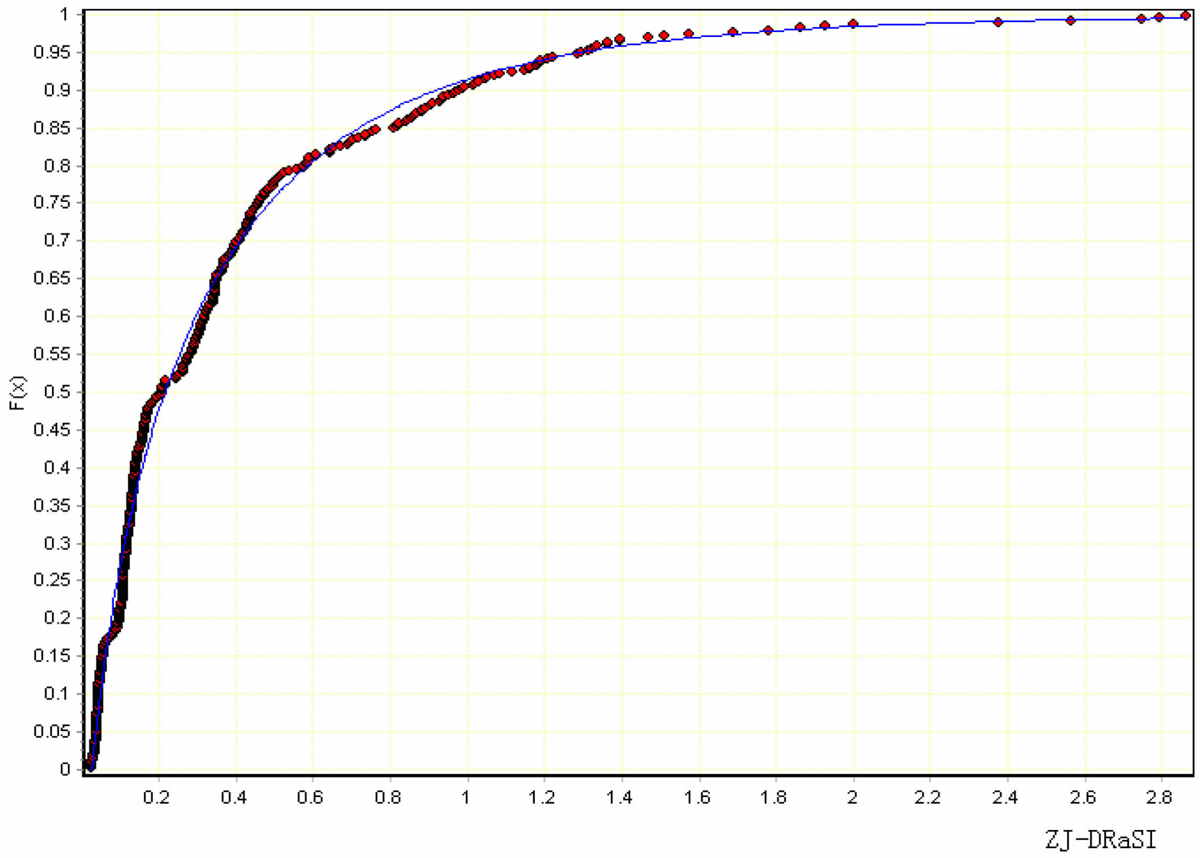

Figure 4. Fitted probability distributions of ZJ-DRaSI for all the rainstorm events. Solid line: the fitted Wakeby distribution. Dots: ZJ-DRaSI for all the rainstorm events.

4 RETURN PERIOD AND TREND OF EXTREMELY DISASTROUS RAINSTORM EVENTS

4.1 *Probability distribution function of ZJ–DRaSI*

Sequence of annual extreme disaster-causing rainstorm events can be obtained based on the highest ZJ-DRaSI each year. There are 17 years of extreme rainstorm events caused by typhoons and 28 years by others. When having a look at the annual extreme ZJ-DRaSI values for typhoon and non-typhoon cases respectively, it is found that the inter-annual changes of extreme ZJ-DRaSI values for typhoon cases is relatively larger than those of non-typhoon cases. For typhoon cases, there are 21 years which are less than 0.5, with a minimum of 0.01 (Typhoon Meranti, No.1010), and 14 years (31%) which are greater than 1.0, with a maximum value of 2.86 (Typhoon Fitow, No.1323). For non-typhoon cases, the maximum ZJ-DRaSI is 2.79 (1994) and minimum value is 0.12 (1978). The annual extreme ZJ-DRaSI for non-typhoon cases mainly appears in the annually first rainy season or the Meiyu season from late-May to mid-July, which accounts for 80% (36 years) in the past 45 years. This kind of rainstorms generally lasts for a long time, say 5-10 days or even sometimes about 20 days, which can be with some short breaks. The remaining 20% (9 years) are mainly caused by the easterlies system or low pressures with inverted troughs. The durations are generally 2-5 days with relatively small ZJ-DRaSI values (less than 0.5 for 7 of the 9 years).

The annual extreme sequence of ZJ-DRaSI is analyzed using Harmonic analysis method, and it is found that: (1) Extreme typhoon rainstorm events have a most significant cycle of 22.5 years and are currently at the high-value stage; in addition, they have a short cycle of 2.5 years (Fig. 5a). (2) Non-typhoon rainstorm events have a most significant cycle of 15 years and are currently in the oscillating period of the high-value area (Fig. 5b). (3) When all the disaster-causing rainstorm events are included, they are found to have a most significant cycle of 22.5 years and are currently at the high-value stage.

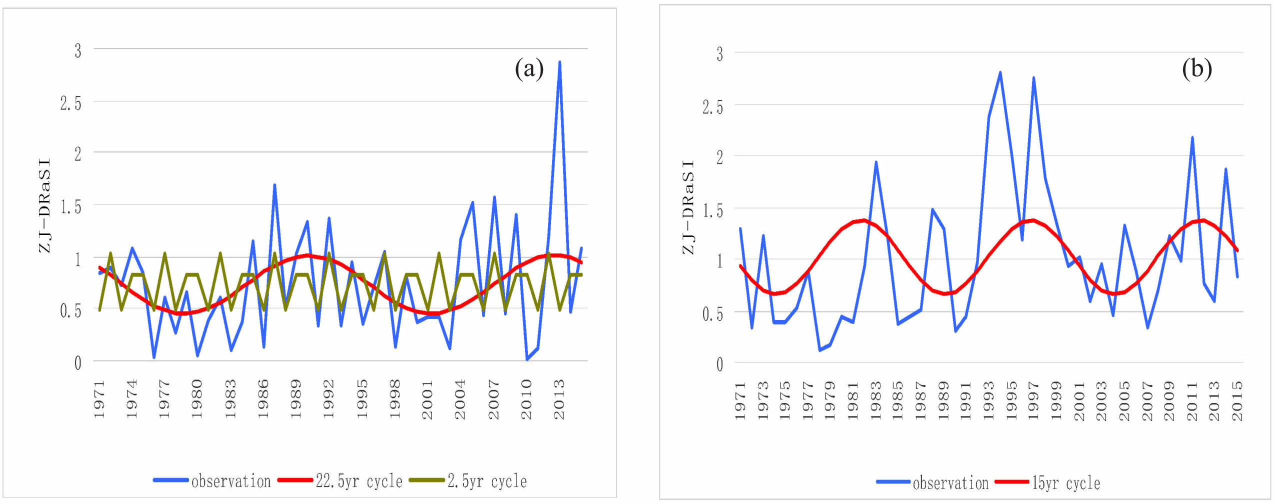

Figure 5. Harmonic analysis of the annual extreme ZJ-DRaSI. (a) typhoon rainstorm events; (b) non-typhoon rainstorm events.

4.2 *ZJ–DRaSI for different return periods and evaluation of severe rainstorm events*

When calculating the ZJ-DRaSI for different return periods, a maximum value is generally selected from the sample data for each year. However, when the sample data are insufficient or the samples are highly random, multiple values can be selected for each year. It is quite common for non-typhoon rainstorm events occurring several times in one year, so it is reasonable to select one maximum ZJ-DRaSI for each year to do the return period analyses. However, the typhoon events have a relatively high randomness with some years suffering from severe precipitation-related disasters several times while other years quite few. Therefore, the return period analysis for typhoon rainstorm events is adjusted as follows.

For a known cumulative probability distribution function $F(x)$, the return period R corresponding to a certain value x can be calculated using the following equation:

$$R=1/(1-F(x)) \quad (6)$$

When a non-single value is used for each year, R should be multiplied by the annual probability of the event (λ),

$$R' = \lambda * R \quad (7)$$

The ZJ-DRaSI corresponding to a given return period R is

$$X(R) = G(1-(1/\lambda * R)) \quad (8)$$

where G represents quantile function, i.e., the inverse function of the cumulative probability distribution function.

With Wakeby probability distribution, the extreme ZJ-DRaSI of each year is selected to study the return period values (Table 4) for all and non-typhoon rainstorm events. The fitting root-mean-square errors are 0.0852 and 0.06179 for non-typhoon and all the rainstorm events respectively, both having a significance level of 95%. For typhoon rainstorm events, all 140 samples are included in the fitting by Wakeby probability distribution. The return period values of ZJ-DRaSI are calculated for 10, 20, 30, 50 and 100 years according to formula (7) and (8) and listed in Table 4.

Table 4. ZJ-DRaSI of various types of disaster-causing rainstorms with return periods of 10, 20, 30, 50 and 100 years.

Return period	10 years	20 years	30 years	50 years	100 years
Typhoon rainstorm events	1.6	1.8	1.9	2.1	2.2
Non-typhoon rainstorm events	2.0	2.5	2.7	3.0	3.3
All rainstorm events	2.1	2.6	2.8	3.1	3.5

It can be observed from Table 4 that the ZJ-DRaSI values of typhoon events are generally lower than those of non-typhoon rainstorms, by approximately 0.5 to 1. These results imply that non-typhoon rainstorms have a more significant impact than typhoon rainstorms, which might be due to their long durations, although their rainfall intensity are generally weaker.

The return period of the top 10 events are calculated and listed in Tables 5 and 6 for typhoon and non-typhoon events respectively. Among the top 10 typhoon events, seven occurred after 2000. Among the top five, four typhoons landed in Fujian or at the border between Zhejiang and Fujian. Thus, the typhoons landing in Fujian can have severe impact on Zhejiang, which is located in the right-hand side of the storm track. The confluent airflow and the elevated local topography is favorable for heavy rainfall in that situation. Some extreme events are related to the interaction between the inverted typhoon trough and cold air intrusion. The ZJ-DRaSI of typhoon Fitow (No.1323) has a return period of more than 100 years, exceeding that of typhoon Gerald (No.8712) by 70%. The extremely heavy rainstorm and high tide level during Fitow result in severe waterlogging and water accumulation in urban and rural areas in northern Zhejiang, and the farmlands in that region were flooded for a long period of time. The city of Yuyao was waterlogged for nearly a week. According to the statistics published by the Zhejiang Civil Affairs Bureau, Typhoon Fitow resulted in a direct economic loss of 58.1 billion yuan, which is the largest economic loss that has ever occurred in Zhejiang as a result of a typhoon since 1951.

Table 5. Return periods of the top 10 typhoon rainstorms.

Typhoon code & name	ZJ-DRaSI	Return period	Typhoon code & name	ZJ-DRaSI	Return period
1323 Fitow	2.86	Over 100 years	0713 Wipha	1.36	6 years
8712 Gerald	1.69	15 years	9216 Polly	1.36	6 years
0716 Krosa	1.57	10 years	9015 Abe	1.33	5 years
0505 Haitang	1.51	8 years	0509 Matsa	1.32	5 years
0908 Morakot	1.40	7 years	1211 Haikui	1.19	4 years

Table 6. Information related to the top 10 non-typhoon rainstorms.

Year	Start time (mmdd)	End time (mmdd)	Mean precipitation in the entire province (mm)	Maximum daily precipitation at the county-level meteorological stations (mm)	Number of casualties	Number of injured people	Direct economic loss (100 million *yuan*)	ZJ-DRaSI	Return period
1994	0608	0618	334	165	62	86	47.5	2.79	32
1997	0621	0713	362	163	13	139	69.8	2.75	30
2011	0603	0621	332	212	0	0	30.3	2.56	22
1993	0614	0706	345	130	64	376	42.82	2.38	16
1995	0619	0707	272	122	40	40	38.45	2.0	10
1998	0612	0627	256	173	18	236	23.21	1.86	8
1999	0623	0630	135	135	11	12	20.38	1.78	7
2014	0620	0629	233	142	4	1	24.02	1.47	5
1988	0611	0623	222	192	17	35	6.95	1.39	4
1989	0627	0708	193	135	46	278	5.13	1.30	4

Among the top 10 non-typhoon rainstorm events, eight occurred in the 1990s and two after 2010 (Table 6). The heaviest one appeared between June 8 and 18, 1994 during the Meiyu season. Its ZJ-DRaSI has a return period of 32 years. The losses information listed Table 6 tells us that the ZJ-DRaSI is corresponding quite well to the damages. In particular, the economic losses increase essentially with the increasing ZJ-DRaSI. Therefore, it is reasonable to use the ZJ-DRaSI as an index to describe the regional disastrous rainstorm events in Zhejiang.

4.3 *The trend of extremely disastrous rainstorm events*

The linear trend fitting of annual extreme ZJ-DRaSI (Fig. 6) shows that the severity of extremely disastrous rainstorm events is increasing in the past 45 years, at a significance level of 98% (99%) for non-typhoon (all) events. Decadal mean values of ZJ-DRaSI are 0.58 (1970s), 0.88 (1980s), 1.65 (1990s), and 0.98 (2000s), respectively, for non-typhoon events. Thus, 1990s is the worst period in Zhejiang. Annual maximum ZJ-DRaSI of typhoon rainstorms increases by approximately 10% every 10 years, with decadal mean being 0.60 (1970s), 0.73 (1980s), 0.64 (1990s), and 0.88 (2000s), respectively. Anyway, the reliability test showed that the linear uptrend is not significant for typhoon events.

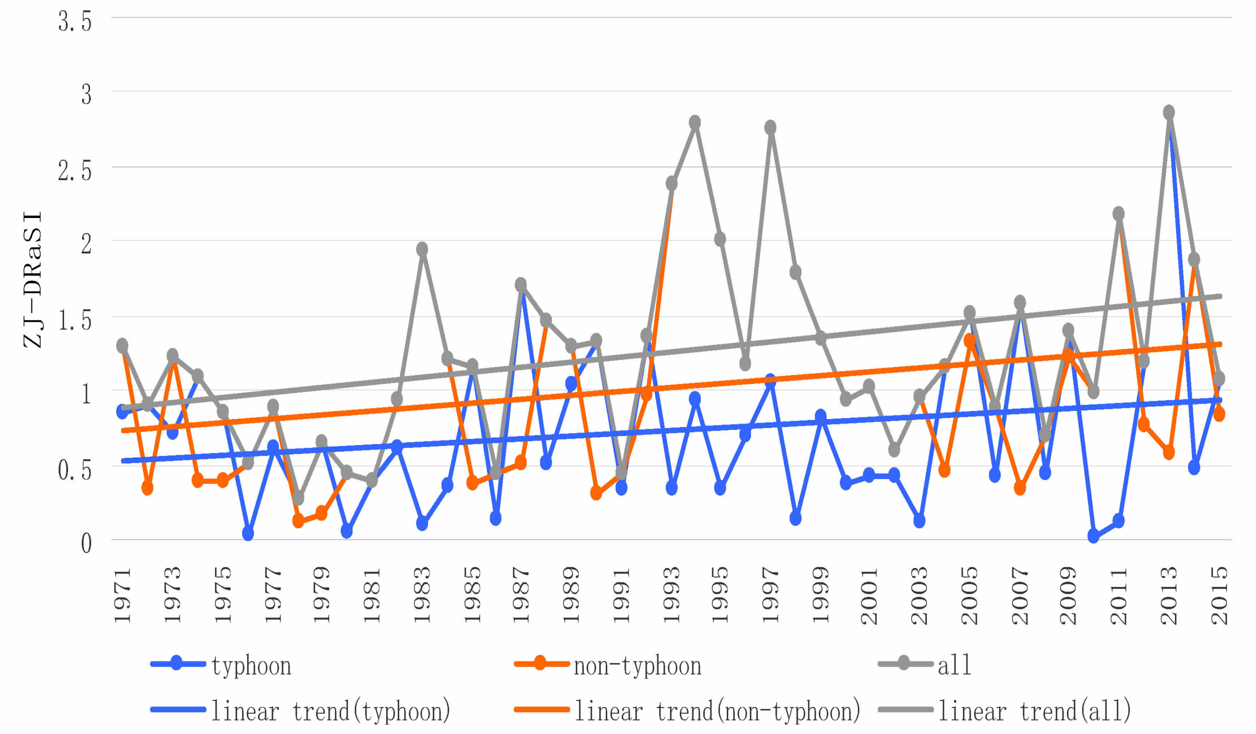

Figure 6. Tendency of the annual extreme intensity of rainstorm events.

To further analyze the long-term tendency of rainstorm events with various intensities, the quantile thresholds of ZJ-DRaSI corresponding to various quantiles (20%, 80%, 90% and 95%) are calculated using the Wakeby probability distribution function for consecutive 10-year periods (1971–1990, 1976–1995, 1981–2000, 1986–2005, 1991–2010 and 1996–2015) (Fig. 7). The smaller the quantile threshold is, the smaller the impact. And vice versa. It can be seen that both typhoon and non-typhoon rainstorm events do not have significant tendency of variation at the lower quantile threshold (20%), whereas both have an increasing trend at the upper quantile thresholds (80%, 90%, and 95%). The 80% quantile threshold of typhoon rainstorms increases from 0.60 to 0.79, while that of non-typhoon rainstorms increases from 0.41 to 0.69. 95% quantile thresholds of typhoon and non-typhoon rainstorms increase from 1.05 and 0.95 to 1.42 and 1.39, respectively.

5 CONCLUSIONS AND DISCUSSION

In combination with the areal coverage of rainstorms, a method for calculating the provincial Disaster-causing Rainstorm Severity Index (DRaSI) in Zhejiang is proposed based on the DRaSI of single stations. The ZJ-DRaSI of 426 rainstorm events that occurred between 1971 and 2015 is calculated, and the periodicity, return period and long term tendency of extreme rainstorm events are further analyzed. The results are as follows:

(1) The ZJ-DRaSI defined takes into account the intensity of a rainstorm, the extent of impact and the relationship between a rainstorm and the damage. The higher the ZJ-DRaSI is, the more serious the damage caused in Zhejiang by the rainstorm.

(2) The ZJ-DRaSI and its annual extreme value can be fitted well with the five-parameter Wakeby

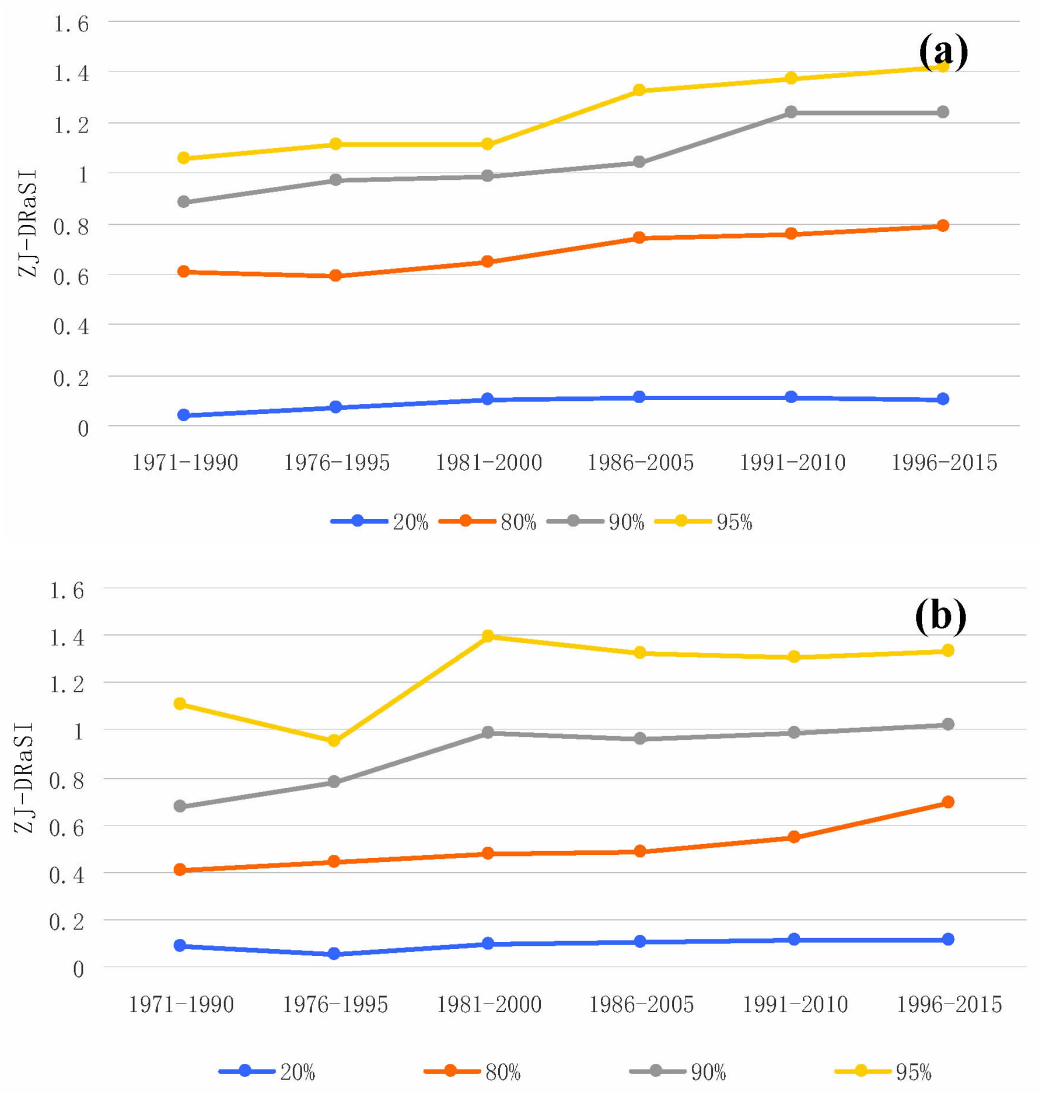

Figure 7. Quantile thresholds of ZJ-DRaSI in consecutive decades. (a) typhoon rainstorms; (b) non-typhoon rainstorms.

distribution. The ZJ-DRaSI of non-typhoon rainstorms, which is corresponding to various return period, is greater than that of typhoon rainstorms, while inter-annual variability of non-typhoon rainstorm events is lower than that of typhoon rainstorms. That is to say, typhoon rainstorms are characterized by their extreme impact, whereas the impact of non-typhoon rainstorms has a higher frequency of occurrence.

(3) Extreme disaster-causing typhoon rainstorm events have a long-term cycle of 22.5 years and a short-term cycle of 2.5 years. Extreme rainstorm events other than typhoon events have a significant cycle of 15 years. Both typhoon and non-typhoon events are currently in the high-value phase of their significant cycles. Annual extreme ZJ-DRaSI exhibits an increasing trend in the past 45 years, implying the impact of extreme rainstorm events is becoming more severe.

Natural disaster is an outcome of the interaction among disaster-formative environment, disaster bearing bodies and disaster-causing factors. The vulnerability and exposure of hazard bearing bodies are changing constantly with the development of society and economy. The characteristics of factors causing disaster also change with climatic conditions. Therefore, the catastrophability of rainstorms under time-varying condition is worthy of future research.

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