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ORIGINAL PAPER

A study into the spatiotemporal distribution of typhoon storm surge disasters in China

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Abstract

In this study, we collected the data of 172 typhoon storm surge disasters that occurred in China during 1983–2018 to show the temporal and spatial distribution of their frequency and damage. Our results indicated that: (1) there was an increase in the frequency of typhoons storm surge disasters during 1983–2018, and 98% of these disasters occurred from June to October; (2) the damage decreased over time, especially after 1997; (3) the frequency and damage caused by typhoon storm surge disasters were higher in the southern and eastern regions than in the northern regions; (4) Guangdong, Fujian, and Zhejiang experienced the highest disaster occurreneces and damages, and the number of disaster occurrences and damages in these three regions accounted for approximately 57% and 80% of the total disaster occurrences and damages, respectively. Furthermore, we mainly analyzed the spatiotemporal characteristics of typhoon storm surge disasters from three aspects: contributors and damage records of extreme typhoon storm surge disasters, mitigation measures, and tropical cyclone tracks. These findings and analyses can help disaster managers improve their understanding of typhoon storm surge disasters and strengthen protection in disaster hotspots and sensitive months.

Keywords Typhoon storm surge disaster · Spatiotemporal distribution · Direct economic loss and fatalities · Disaster mitigation

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1 Introduction

A storm surge is an abnormal water rise caused by cyclones having low pressures and strong winds (Muis et al. 2016; Helderop and Grubesic 2019a). Given the cyclone types, i.e., tropical cyclones (e.g., typhoons and hurricanes) and extratropical cyclones, storm surges are divided into tropical storm surges (also known as hurricane surges or typhoon storm surges) and extratropical storms surges (Grinsted et al. 2013; Needham et al. 2013; Suh et al. 2015; Tadesse et al. 2020). Tropical cyclones having lower pressures and higher wind speeds can typically induce higher surges than extratropical cyclones (Resio and Westerink 2008). In China, storm surges induced by tropical cyclones are officially called typhoon storm surges. A combination of typhoon storm surges, astronomical tides, and (or) ocean waves can lead to typhoon storm surge disasters (TSSDs), leading to the damage caused by coastal flooding, destruction of engineering structures in coastal regions, and disruption of fisheries (Yang et al. 2016; Wang et al. 2018).

As social, climatic, and geomorphic factors change, coastal areas globally face significant challenges in dealing with TSSDs (Helderop and Grubesic 2019b). In 2017, 37% of the global population lived in coastal communities (UN-DESA Ocean Conference 2017), and this percentage is still growing (He et al. 2014; Neumann et al. 2015; Meng et al. 2017; Gao and Wang 2020). Meanwhile, the ocean economy is continually growing (Winther et al. 2020). In general, currently, more population and assets are in the potential zones of TSSDs than before. Climate change can impact TSSDs with respect to two main aspects: sea level and tropical cyclones (Helderop and Grubesic 2019b). Under the influence of climate change, ice melting and thermal expansion are responsible for sea level rise (Overpeck et al. 2006; Rahmstorf 2007; Lin et al. 2012; Haigh et al. 2016), which increases the total water level during a TSSD (Fang et al. 2016b), leading to increased coastline exposure (with respect to coastal flooding) and higher coastal flooding risk (Hallegatte et al. 2013; Lloyd et al. 2016). Hallegatte et al. (2011) estimated the economic loss of future 100 year coastal flooding in the absence of protection, suggesting that it would increase by 33% under 25 cm of the mean sea rise in Copenhagen. As for the changes in tropical cyclones' frequencies and intensities under the influence of climate change, there has been uncertainty (Moon et al. 2019). However, broad studies consistently show a decreasing trend in the frequency and an increasing trend in the intensity (Knutson et al. 2008, 2010). These tropical cyclone changes are likely to increase typhoon storm surges in the future (Dasgupta et al. 2009). Additionally, land subsidence is expected to lower the ground level and reduce seawall protection ability, which is likely to worsen TSSDs in the future (Wang et al. 2012).

In China, TSSDs, as the most destructive marine disasters, impact all 14 province-level administrative coastal regions and cause far more losses than any other marine disaster (Gao et al. 2014). According to the Bulletin of China Marine Disaster (BCMD) (2014–2018) (State Oceanic Administration of China 1989–2018), TSSDs caused a direct economic loss of 4.32 billion RMB in 2018. The direct economic loss ratio of TSSDs to marine disasters reached 99% in 2005; the average loss ratio in the 2014–2018 period was 89%. Such huge damages highlight the need to manage TSSDs. One of the critical aspects for reducing impacts is to understand their temporal and spatial evolution.

Many studies have investigated the spatiotemporal distribution of TSSDs on a regional scale, paid more attention to typhoon storm surges or storm surge disaster patterns at the national level, and mainly analyzed spatiotemporal distribution patterns from the mitigation measures across China.

Most studies have focused on the distribution of one or several coastal regions, and few have discussed the distribution at a national level in China. For example, Sun et al. (2013) analyzed the spatiotemporal patterns of TSSDs in Guangxi, and Gan et al. (2012) showed patterns along the south China coastal regions. Such studies related to a small spatial scale failed to show changes over large coastal regions and gave little advice for disaster prevention at the national level. Some studies have focused on the frequency and intensity of typhoon storm surges. For example, Shi et al. (2020) mapped different risk levels of storm surge zones in China by assessing the intensities of storm surges. Feng et al. (2018) used hourly sea level data from four tide gauges to show the spatiotemporal patterns of storm surges in the Bohai Sea. Fang et al. (2016a) illustrated the interannual variability of typhoon storm surges during 1951–2012 and monthly variability during 1949–1997. These studies aimed at typhoon storm surges and were not responsible for showing the spatiotemporal distribution of TSSDs.

Additionally, some studies have partially shown the spatiotemporal distribution of TSSDs at the national level. For example, Hou et al. (2011) showed the temporal frequency of intense TSSDs (wherein the total water level of a tide gauge station exceeds the local warning tide level by more than 80 cm during a typhoon storm surge) between 1949 and 2009 across China. Shi et al. (2015) and Fang et al. (2017) showed the nationally interannual frequency of TSSDs over the past 60 years. Xie and Zhang (2010) showed the interannual and monthly frequency of TSSDs that occurred between 1989 and 2008 over China. These studies mainly provided a spatiotemporal frequency of TSSDs and overlooked the distribution of TSSD damages. Wang et al. (2021) showed the spatiotemporal distribution of the frequency and damage of storm surge disasters during 2000–2019 in China, but they lacked to show a separate spatiotemporal distribution of TSSDs. Furthermore, previous studies mainly analyzed the spatiotemporal distribution from the implemented mitigation measures (e.g., Fang et al. 2017), but more related factors should be explored.

This study aimed to show a complete spatiotemporal distribution of the frequency and damages of TSSDs in China and analyze characteristics of the frequency and damage distributions. TSSDs are caused by complex interactions between typhoon storm surges and coastal region vulnerabilities, along with the prevention and mitigation abilities applicable for these regions. Possible factors for spatiotemporal patterns are multiple and complicated. Considering the scope limitations of this study, we analyzed the spatiotemporal characteristics mainly from three aspects: contributors and damage records of extreme TSSDs, mitigation measures, and tropical cyclone tracks. The remainder of this paper is organized as follows. Section 2 describes the study area, data sources, and methods used. Section 3 presents the study results for China's coastal regions (1983–2018). The discussion and conclusions are presented in Sects. 4 and 5, respectively.

2 Data and methods

2.1 Study area

There are 14 province-level administrative regions in the coastal area of China, which stretch tropical, subtropical, and temperate climate zones (Su et al. 2015). There is an area of 194,045 km^2 that has an elevation of less than 10 m in China's coastal area, accounting for 14.6% of the land area in the 14 coastal regions (Liu et al. 2015). Because there were no disaster records in Hong Kong, Macao, and Taiwan in our data sources,

Fig. 1 11 coastal regions of the coastal area in China

we selected the remaining 11 coastal regions as our study area (Fig. 1). In this study, to describe the spatial patterns easily, the 11 coastal regions are divided into northern regions (Liaoning, Hebei, Tianjin, and Shandong), eastern regions (Jiangsu, Shanghai, Zhejiang, and Fujian), and southern regions (Guangdong, Guangxi, and Hainan).

These 11 coastal regions are densely populated and economically developed in China. In these 11 coastal regions of mainland China, the coastal population increased by 17%, and the overall population increased by 10% from 2000 to 2018 (National Bureau of Statistics of China 2019). In 2018, the proportions of the population and the gross regional product of these 11 regions were approximately 45% and 50% in mainland China (National Bureau of Statistics of China 2019). Topography is an essential factor that impacts typhoon storm surges (National Oceanic and Atmospheric Administration 2021). Discussing how topographic factors impact TSSDs in detail is beyond the scope of this study. However, some examples are provided to briefly describe the local features of coastal regions for TSSDs. Bays with lambdoid shapes are liable to gather seawater, thereby enhancing the surge (Zhao et al. 2016). This local feature appears in many coastal regions, such as the Leizhou Peninsula in Guangdong (Liu et al. 2018b), Tieshan Bay in Guangxi (Chen and Qiu 2000), Hangzhou Bay in Zhejiang (Shi et al. 2008), and Minjiang estuary in Fujian (Xia et al. 2014). In estuaries, the total water levels rise by a combination of upstream floods, typhoon storm surges, astronomical tides, and waves, leading to considerable damages in coastal regions; for example, "Imbudo Typhoon" triggered a TSSD in the Pearl River Estuary of Guangdong (Ma and Hu 2004).

The Bohai Sea, Yellow Sea, East China Sea, and South China Sea are marginal seas of the western Pacific Ocean (Shi and Wang 2012; Wu et al. 2015), and most tropical cyclones that trigger TSSDs in China are generated in the northwestern Pacific Ocean (Ling et al. 2011). Over the past few decades, there has been a decreasing trend in the frequency of tropical cyclones in the northwestern Pacific (Xiao and Xiao 2010; Yin et al. 2013). However, due to climate change, the intensity of tropical cyclones is likely to increase in the northwestern Pacific (Yasuda et al. 2014). In addition, China's coastal sea level rise increased 3.3 mm per year during 1980–2018, and it will continue to increase to a value between 68 and 166 mm in the next 30 years, according to the Bulletin of China Sea Level (2018). Owing to the long coastlines and complex coastal environment (Wang et al. 2016; Liu et al. 2018a), the Chinese disaster managers are concerned about the occurrences of TSSDs.

2.2 Data sources and methods

To show the spatiotemporal distribution of the frequency and damage of TSSDs at the national level, the following data of TSSDs were required: times of TSSD occurrences (years and months), total damages in China, affected regions, and individual affected region's damages. The first official storm surge forecast was issued in China in 1974 (Wang et al. 2003). However, because of the lack of damage information between 1974 and 1982, the data period was selected from 1983 to 2018 (no available data for 1987). Thus, the data of 172 TSSDs were collected for the period 1983–2018. The collected disaster data for 1989–2018 were obtained from the BCMD (State Oceanic Administration of China 1989–2018), and the data for 1983–1988 were obtained from the book of the Collection of Storm Surge Disaster Historical Data in China 1949–2009 (Yu et al. 2015). For some disasters lacking information about the affected region's damages in the BCMD, the missing information was supplemented from the Bulletin of Guangxi Marine Ecological Environment Status (Oceanic Administration of Guangxi 2008–2009), along with the book data source, after checking the consistency of the data of total damages. It is worth noting that one TSSD could affect multiple coastal regions, or its duration could span two months (from the end of one month to the start of the following month). Hence, the total number of occurrences of TSSDs in the 11 coastal regions and 12 months was 324 and 180, more than the number of 172 TSSDs at the national and year level. The gross domestic product (GDP) and consumer price index (CPI) data were obtained from the China Economic and Social Big Data Research Platform (http://data.cnki.net/YearData/Analysis). The landfall sites of tropical cyclones were collected from the BCMD and book data source; the missing data of landfall sites in some disasters were supplemented from the Yearbook of Meteorological Disasters in China (China Meteorological Administration 2007–2018). Tropical cyclone track data were obtained from the Best Track Dataset (Ying et al. 2014), which was obtained from the China Meteorological Administration Tropical Cyclone Data Center (http://tcdata.typhoon.org.cn/zjljsjj_zlhq.html). The data sources are presented in Table 1.

If we analyze economic loss trends of natural disasters, normalizing economic losses is necessary because the social and economic situation of affected areas is changing (Chen et al. 2018). In this study, the direct economic loss from each TSSD was normalized using the most frequent inflation ratio, CPI (Fischer et al. 2015), which is consistent with the normalization method in the study of Fang et al. (2017), analyzing the trend of direct economic losses of storm surge disasters. We took 2018 as the base year, and the direct economic losses in other years were adjusted to values of 2018 using Eq. (1):

Table 1 Data sources and related information

Data sources	Time scales	Data information	Other information
BCMD (State Oceanic Administration of China 1989–2018)	1989–2018	Occurrence time Affected regions Total damages Individual affected region's damages Landfall sites of tropical cyclones	It lacks data of individual affected region's damages and landfall sites in some disasters
Collection of Storm Surge Disaster Historical Data in China 1949–2009 (Yu et al. 2015)	1983–2009	Occurrence time Affected regions Total damages Individual affected region's damages Landfall sites of tropical cyclones	It includes all related information and supplements missing damage data in the BCMD
Bulletin of Guangxi Marine Ecological Environment Status (Oceanic Administration of Guangxi 2008–2009)	2008–2009	Occurrence time Affected regions Total damages Individual affected region's damages Landfall sites of tropical cyclones	It supplements missing damage data in the BCMD
Yearbook of Meteorological Disasters in China (China Meteorological Administration 2007–2018)	2007–2018	Landfall sites of tropical cyclones	It supplements missing landfall site data in the BCMD
China Economic and Social Big Data Research Platform	1983–2018	GDP CPI	It includes GDP and CPI information
Best Track Dataset (Ying et al. 2014)	1983–2018	Such as longitude and latitude per 6-h	It provides 172 tropical cyclone tracks

$$L_{y(2018)} = L_y \times \frac{\prod_{y+1}^{2018} CPI}{100^{(2018-y)}} \tag{1}$$

where $L_{y(2018)}$ is the adjusted direct economic loss from year y to 2018; L_y is the recorded direct economic loss of year y ($y = 1983, 1984, \ldots 2017$), and CPI is the consumer price index (preceding year = 100).

The average adjusted annual direct economic loss per disaster from year y to 2018 ($L_{yp(2018)}$) is given as follows:

$$L_{yp(2018)} = \frac{L_{y(2018)}}{N_y} \tag{2}$$

where $N_y\left(N_y = 1, 2, \ldots\right)$ is the number of TSSDs in year y.

3 Results

3.1 Temporal distribution of TSSDs

As shown in Fig. 2a, despite the fluctuation in the number of TSSDs from 1983 to 2018, there was an increasing trend in the frequency during this period, especially after 2005. According to the calculation of the average annual number of disasters, it was approximately seven from 2005 to 2018, while it was only about three disasters per year before 2005. The highest peak occurrence was in 2013 (11 disasters), and three years (2012, 2008, and 2005) showed the second-highest occurrences, with approximately nine disasters per year. However, except for 1987 (no available data), 1984 and 1988 had the lowest number

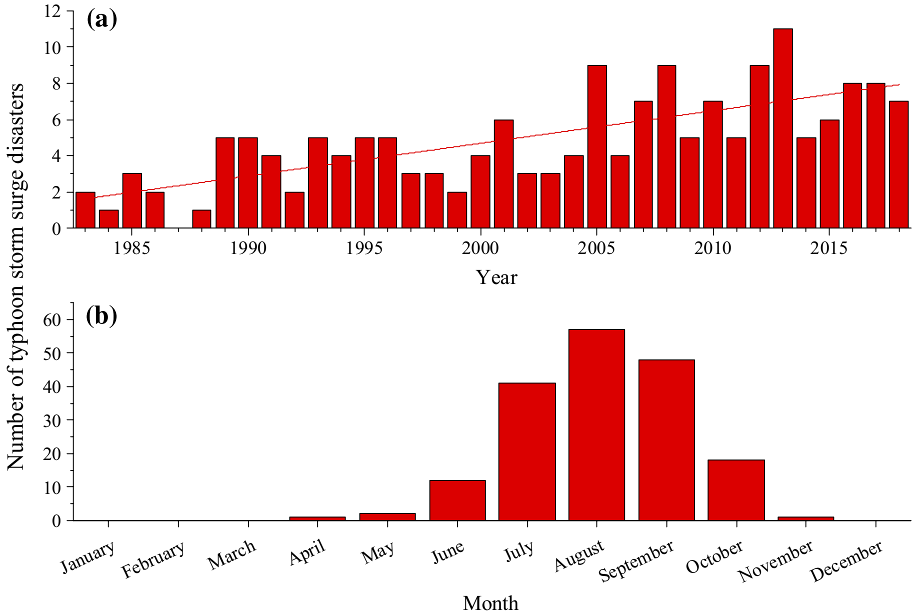


Fig. 2 Frequency-time variations of TSSDs: **a** Number of TSSDs per year (red line indicates the linear trend); **b** Number of occurrences of TSSDs per month

of disasters, with only two disasters with complete disaster data occurring in these two years. The monthly distribution of disasters is shown in Fig. 2b. As seen in the figure, all TSSDs occurred between April and November, and 176 occurrences from June to October, accounting for 98% of the total disaster occurrences in 12 months. August witnessed the peak, with over 30% (57 occurrences) of the total disasters occurring in this month.

The temporal distribution of the direct economic loss caused by TSSDs is shown in Fig. 3. There was a significant decrease after 1997, while there was a fluctuation with an upward trend during 1983–1997 (Fig. 3a). According to the calculation of the average direct economic loss before and after 1997, it was less after 1997 (12.7 billion RMB) than that in the pre-1997 period (20.9 billion RMB). The highest and second-highest losses

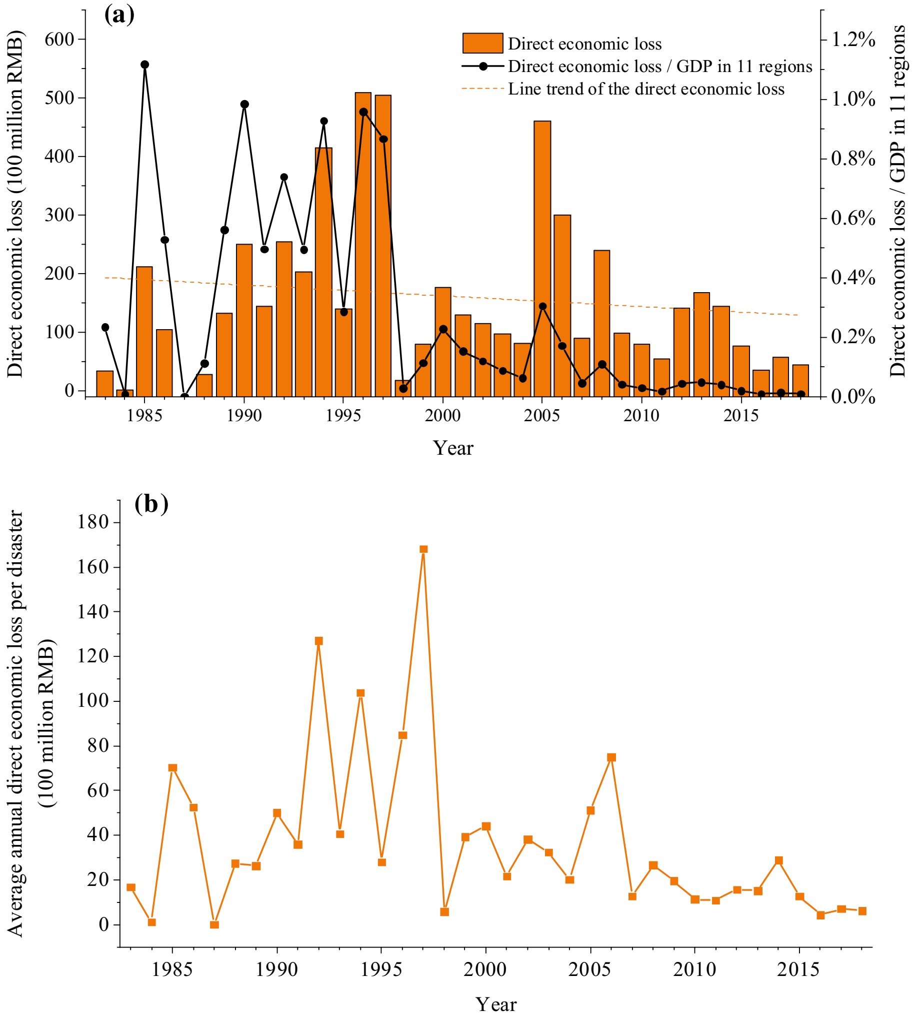


Fig. 3 Direct economic loss-time variations of TSSDs: **a** Direct economic loss and the ratio of the direct economic loss to GDP in 11 regions per year; **b** Average annual direct economic loss per disaster

occurred in 1996 and 1997, respectively, while the third-highest losses were recorded after 1997 (in 2005). The ratio of direct economic losses to GDP decreased significantly after 1997 (Fig. 3a). By calculating average ratios before and after 1997, results showed that the average ratio before 1997 was 0.6%, which was higher than the average ratio of 0.08% after 1997. Although the direct economic loss in 2005 (46.1 billion RMB) was close to the value in 1996 (50.9 billion RMB), the ratio in 2005 (0.3%) was approximately one-third of that in 1996 (0.9%) (Fig. 3a). However, the average annual direct economic loss per disaster trend (Fig. 3b) was very similar to the direct economic loss trend (Fig. 3a); the few observed differences in these two trends were unneglectable. For example, the highest annual direct economic loss was reported in 1996 (Fig. 3a), while the highest average annual loss per disaster occurred in 1997 (Fig. 3b). This characteristic was related to the frequency and intensity of TSSDs in different years, as discussed in Sect. 4.

As for annual fatalities (Fig. 4), a significant decrease from 1983 to 2018 was found. Based on the calculation of the average number of fatalities during 1983–2018 and 2010–2018, it was 159 fatalities between 1983 and 2018, while it dropped sharply to four fatalities from 2010 to 2018. The highest number of fatalities was reported in 1994 (1240 fatalities), accounting for 22% of the total fatalities (5528 fatalities). The second and third highest number of fatalities occurred in 1990 (663 fatalities) and 1997 (537 fatalities), and around 80% (4571 fatalities) of the total number of fatalities occurred in the 1983–1997 period. Similarly, the average annual number of fatalities per disaster peaked in 1994 (310 fatalities); the highest average annual number of fatalities per disaster was only 1.2 between 2010 and 2018.

3.2 Spatial distribution of TSSDs

In Fig. 5a and b, the spatial distributions show marked variations in the 11 regions. Among the 11 regions, southern and eastern regions were affected far more than the northern regions (Fig. 5a). The high-grade group (Guangdong, Fujian, and Zhejiang) accounted for 57% (185 occurrences) of the total number of disaster occurrences in the 11 coastal regions, with the highest proportion of 22% (73 occurrences) being in Guangdong (Fig. 5b). With fewer occurrences than the above three provinces, 34% (109 occurrences) of the total number of disaster occurrences in the 11 coastal regions were in the medium-grade group

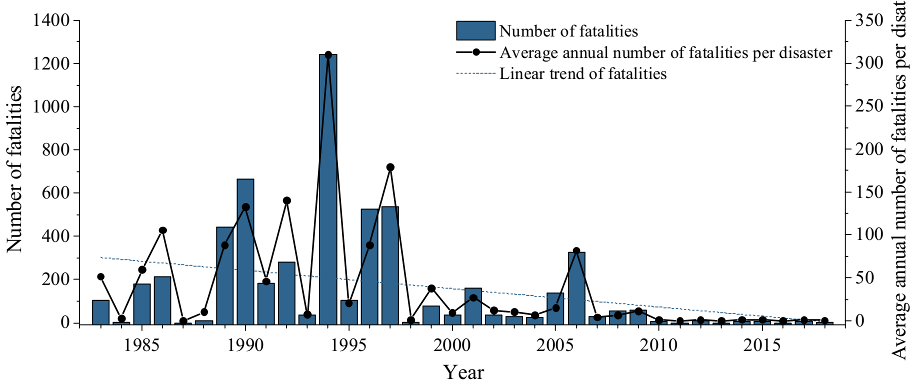


Fig. 4 Number of fatalities per year and the average annual number of fatalities per disaster

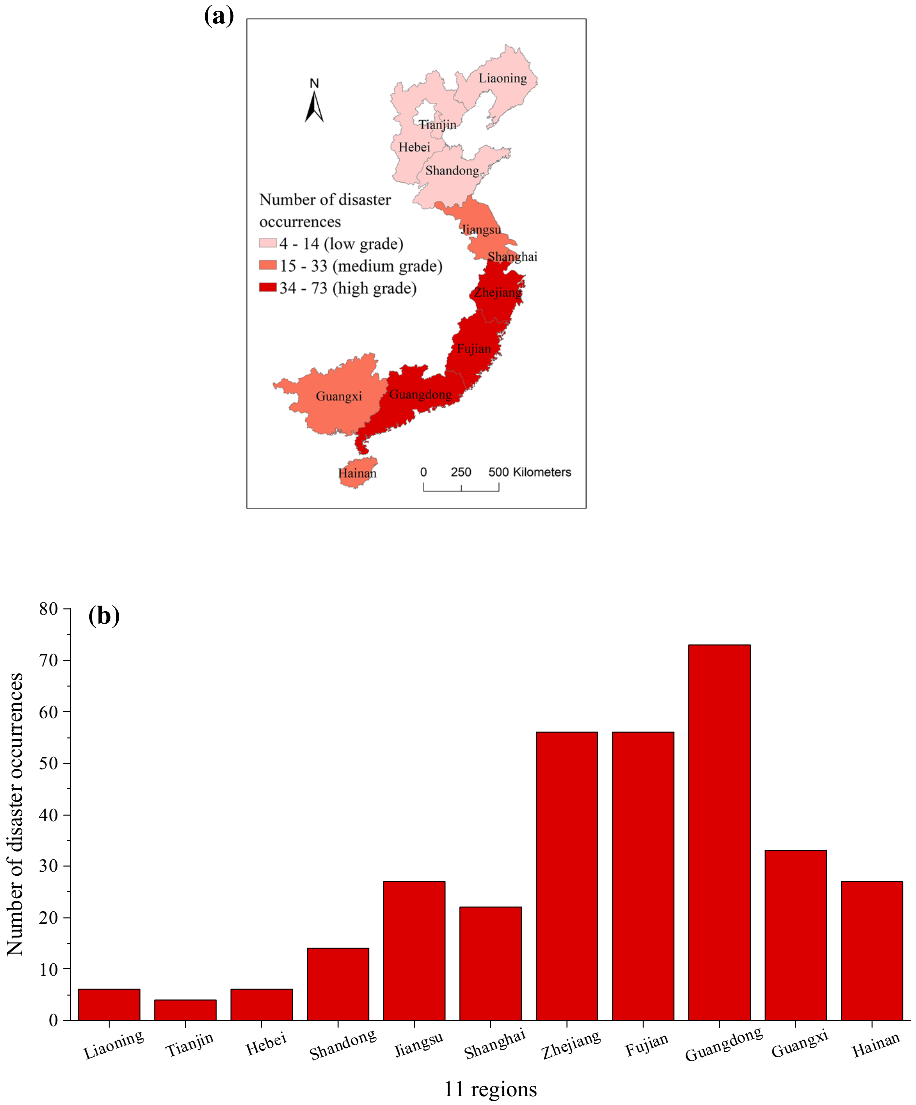


Fig. 5 Frequency-region variations of the number of disaster occurrences in 11 coastal regions: **a** Spatial distribution of the number of disaster occurrences; **b** The number of disaster occurrences per region

(Guangxi, Hainan, Jiangsu, and Shanghai). The number of disaster occurrences in the remaining four northern regions (Liaoning, Hebei, Tianjin, and Shandong) accounted for less than 10% (30 occurrences) of the total number of disaster occurrences.

As seen in Fig. 6, the direct economic loss in the high-grade group (Guangdong, Zhejiang, and Fujian) accounted for more than 75% (435.2 billion RMB) of the total direct economic loss (561 billion RMB), and the proportion of over 30% (190 billion RMB) in Guangdong was the highest. Within the three southern regions, Guangxi experienced the lowest direct economic losses. Shandong had the highest direct economic losses among the

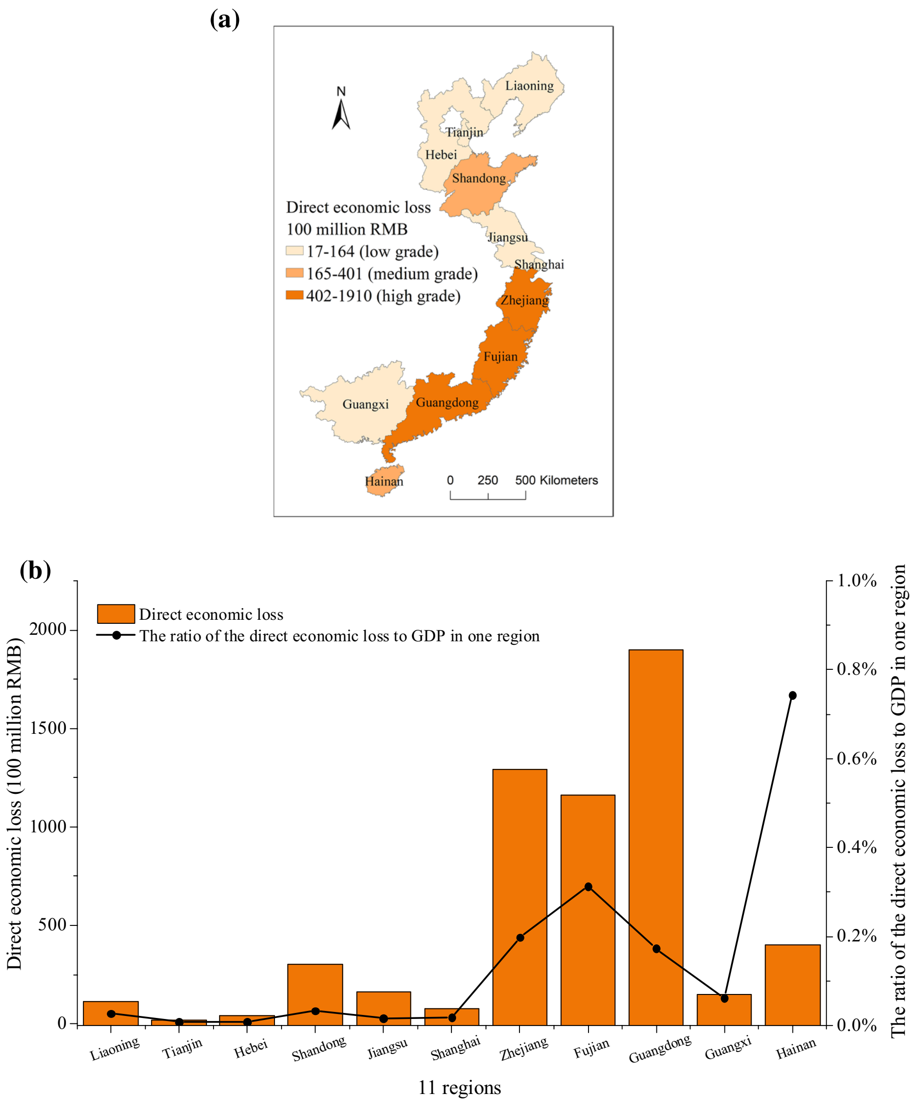


Fig. 6 Direct economic loss-region variations of TSSDs: **a** Spatial distribution of direct economic loss in 11 coastal regions; **b** Direct economic loss and the ratio of the direct economic loss to GDP per region

four northern regions. The highest ratio of direct economic loss to GDP was observed in Hainan (Fig. 6b).

TSSDs in the high-grade group (Zhejiang, Fujian, and Guangdong) caused approximately 80% (4452 fatalities) of the total number of fatalities across the 11 coastal regions (Fig. 7). The highest number of fatalities was 2417 in Zhejiang, far more than that in any other region. The medium-grade group consisted of a southern region (Hainan), an eastern region (Jiangsu), and a northern region (Shandong). Three northern regions (Liaoning, Tianjin, and Hebei) and an eastern region (Shanghai) were all in the low-grade group, with a total of 152 fatalities.

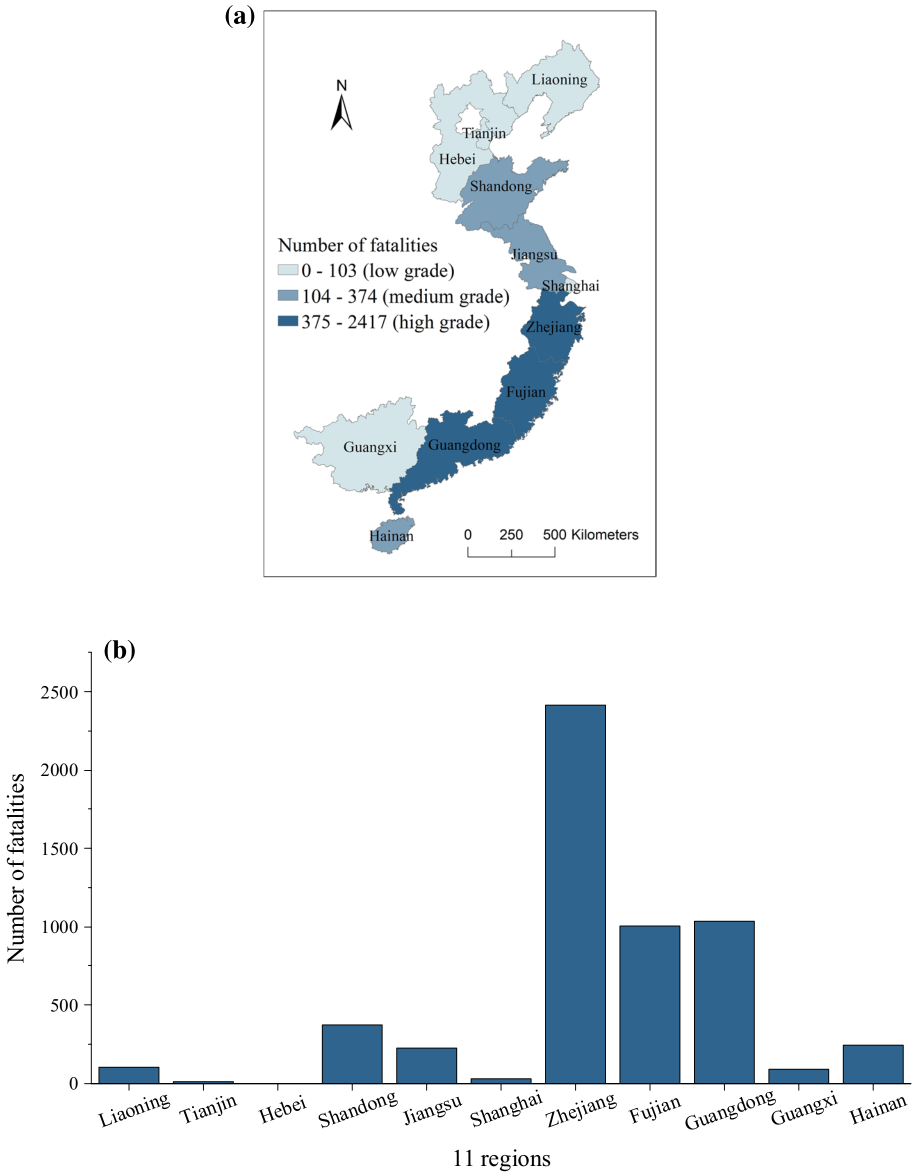


Fig. 7 Fatality-region variations of TSSDs: **a** Spatial distribution of fatalities in coastal 11 regions; **b** Number of fatalities per region

4 Discussion

Temporal trends of TSSDs in this study are consistent with previous studies (Table 2). Notably, previous studies have focused on the total damage distribution of storm surge disasters (typhoons and extratropical storm surge disasters) at the national level and overlooked the spatiotemporal damage distribution of TSSDs.

Table 2 Temporal result comparisons between this study and previous studies

Temporal trend	Results in this study	Results in previous studies
Interannual trend	An increasing trend in the TSSD frequency from 1983 to 2018, especially after 2005 (Fig. 2a)	An increasing trend in the TSSD frequency since 2000 (Fang et al. 2017); A remarkable rise in the TSSD frequency in the past 65 years (Shi et al. 2015)
Monthly trend	Around 98% of TSSDs occurring between June and October during 1983–2018 (Fig. 2b)	Around 93% of TSSDs occurring between June and October during 1989–2008 (Xie and Zhang 2010)

Table 3 Data of extreme TSSDs, including the direct economic loss and number of fatalities

Year	Disaster ID	Direct economic loss (100 million RMB, 2018 values)	Number of fatalities
1985	8509	171.27 (78.9%)	162 (91.0%)
1992	9216	260.36 (99.5%)	280 (100%)
1994	9417	267.20 (62.6%)	1216 (98.1%)
1996	9615	313.63 (59.9%)	279 (52.9%)
1997	9711	415.52 (80.0%)	444 (82.7%)
2005	0518	175.12 (36.9%)	25 (18.2%)
2008	0814	170.12 (69.1%)	26 (46.4%)

In Table 3, the percentages are the damages caused by extreme disasters in the table to the total damages in corresponding years

The monthly frequency of TSSDs can most likely be attributed to the monthly variation in tropical cyclone occurrences in the northwestern Pacific. In the northwestern Pacific, over the past 30 years, approximately 80% of tropical cyclones have been reported between June and October (Chen et al. 2019), explaining why most TSSDs occurred in the same period.

With respect to the temporal distribution of disaster damage, some years suffered from outstandingly huge damages, which are likely to be caused by the severity and number of extreme TSSDs. Severe damages have occurred in some years (1985, 1992, 1994, 1996, 1997, 2005, and 2008), owing to one or two extreme disasters (shown in Table 3). Several factors contribute to extreme TSSDs: high intensity tropical cyclones, typhoon storm surges combining with an astronomical high tide, and the destruction of seawalls during disasters. For example, when the "Fred" tropical cyclone made landfall with a central pressure of 950 hpa in 1994, its typhoon storm surge combining with an astronomical high tide increased the sea water level, leading to 520 km of ruined seawalls and 1216 deaths, which was the highest number of fatalities among 172 disasters (Le 2000). Without combining with the astronomical high tide, intense tropical cyclones can also trigger extreme TSSDs, e.g., the "Sally TSSD" in 1996 (Tai et al. 2009). In 1996, extreme damages were likely attributed to several disasters, with relatively high losses. For example, according to the direct economic loss records from data sources, the highest total loss occurred in 1996 because of three disasters, with a total loss of 47.4 billion RMB. Although the most severe disaster occurred in 1997 (with the highest loss of 41.55 billion RMB) among 172 disasters, the annual loss in 1997 was lower than that in 1996 (Fig. 3a). However, the average annual direct economic loss per disaster in 1997 was higher than that in 1996 (Fig. 3b).

There was a significant decrease in damage after 2000 (Figs. 3a, 4). The reasons behind this phenomenon are complicated and multifaceted, and it is challenging to find direct evidence that reduces TSSD damages. We attempt to discuss the factors related to mitigation measures adopted from the beginning of the twenty-first century in China to analyze this decreasing trend. In this study, mitigation measures are discussed from three aspects: technical factors, engineering, and non-engineering mitigation measures.

In China, storm surge forecasting began in the early 1970s (Liu and Wang 1989; Li and Nie 2017). The China Ocean Yearbook (China Ocean Yearbook Compilation Committee 1986–2017) reports that at the beginning of the twenty-first century, significant advances in the resolution of numerical storm surge forecasting were made, and a refined numerical forecasting system for storm surges covering the entire coastal sea of mainland China has been established. In addition, advanced warning systems make disaster information easily accessible to the public. Coastal people can get the forecasted and real-time disaster information through many approaches, such as the phone, broadcast, television, and website (China Ocean Yearbook Compilation Committee 1986–2017). Thus, people can protect themselves and their assets during TSSDs. Advanced forecasting and warning systems (Ying and Yi 2018) can effectively mitigate TSSDs.

The seawall is an essential component of engineering mitigation measures. However, some seawalls that face poor maintenance and low protection standards are likely to be destroyed during TSSDs, amplifying the disaster impacts. From the end of the twentieth century, the Chinese government built seawalls with high protection standards and reinforced the weaker sections in coastal areas. For example, the government launched a “Thousand kilometers of seawalls” project, and newly built seawalls could achieve the defense standard of a 100 year return period flood for cities in Zhejiang since 1997 (Zhang 1999). Likewise, the Jiangsu government started seawall construction and improvement work in 1998 (Chen and Zhao 2019). Over the past 20 years, there was an increase in the ratio of the seawall length to the coastline length, with a peak of approximately 60% (Ma et al. 2014); Guangdong had the highest ratio of over 90% (Luo et al. 2015).

Non-engineering measures, including implementing regulations and guidance documents, establishing official agencies for disaster management, and strengthening public awareness, are also essential for disaster mitigation (Fang et al. 2017). Two official documents offer risk assessment methods and disaster response strategies for TSSDs called “Storm surge, Tsunami, Sea Wave, and Sea Ice Disaster Emergency Response Plans” and “Technical Guidelines for Risk Assessment and Zoning of Storm Surge Disasters.” Simultaneously, warning water levels, the index for the warning systems, have been approved in coastal regions based on the new specification “Specification for warning water level determination (GB/T 17,839—2011).” In 2011, the establishment of the National Marine Hazard Mitigation Service aimed at supporting marine disaster prevention and emergency platform operations and encouraged more coastal regions to set up related agencies for disaster risk reduction. In 2018, China implemented institutional reforms and established the Ministry of Emergency Management, which significantly improved the country’s emergency response ability during disasters. In addition, the government raises public awareness of TSSDs through many activities, such as holding emergency drills and promotional lectures. Moreover, increased marine emergency shelters, growing rescue teams, and comprehensive marine disaster reduction demonstration communities can improve disaster response performance (Xin et al. 2012; Zhang et al. 2013).

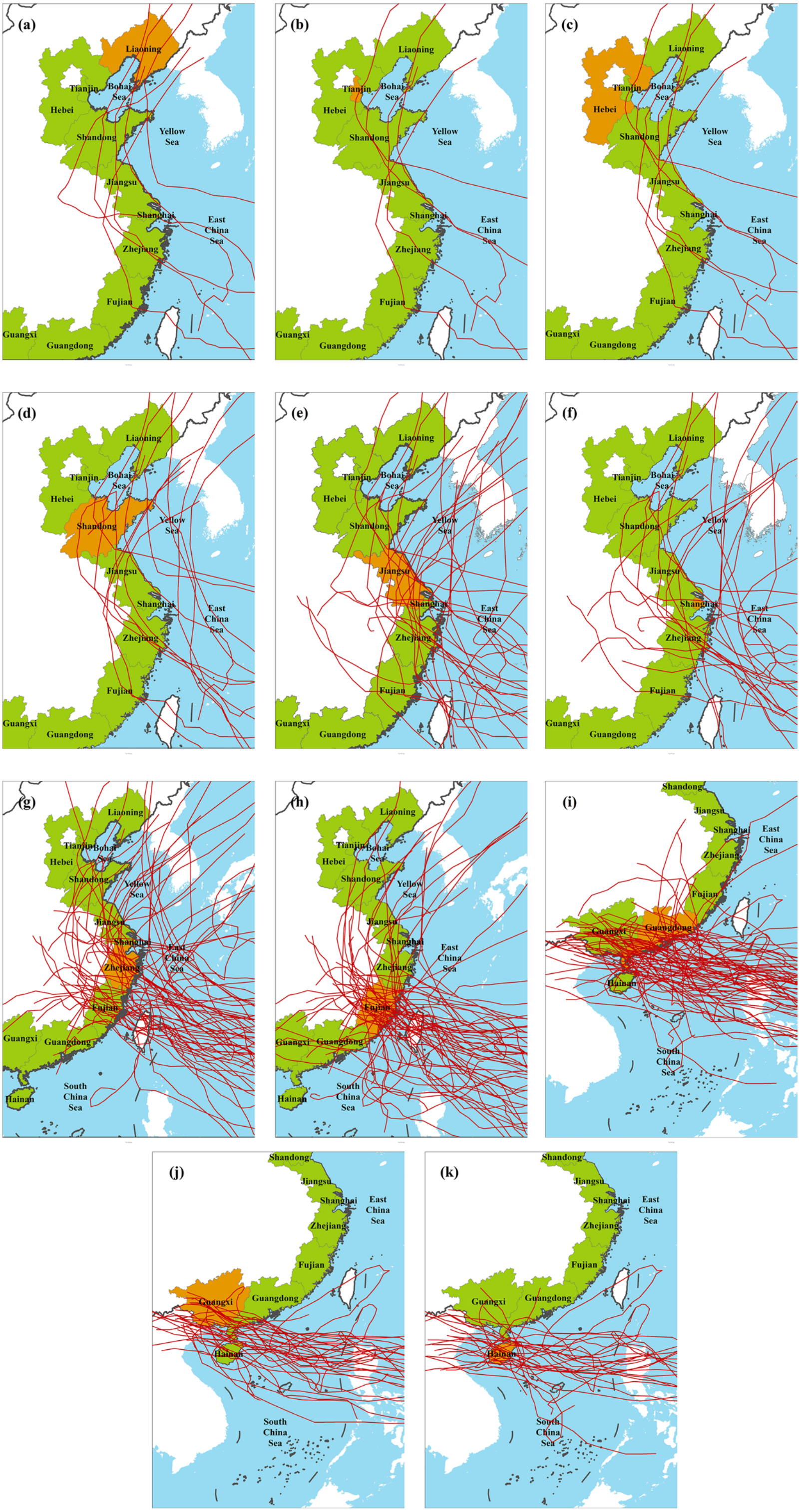
From the perspective of tropical cyclones, many attributes are related to the TSSDs, such as intensities, wind field positions, and tracks (Colle et al. 2010; Booth et al. 2016; Zhang et al. 2019). Given the scope limitations of this study, we introduced the tracks of 172 TSSDs and analyzed what kinds of tropical cyclone tracks (with landfall sites and shifting directions) could trigger TSSDs in 11 coastal regions. The tracks of tropical cyclones that triggered TSSDs in each coastal region are shown in Fig. 8. For the 11 coastal regions (Fig. 8), more than 90% of TSSDs were triggered by landfalling tropical cyclones, and over 70% of the landfall sites were in Zhejiang, Fujian, and Guangdong. The landfall tropical cyclones shifted northward, triggering TSSDs in more coastal regions (eastern and northern regions). As seen in Fig. 8, more tropical cyclone tracks passed by the southern and eastern regions than the northern regions, consistent with the spatial frequency patterns of TSSDs (Fig. 5).

For the northern regions (Liaoning, Tianjin, Hebei, and Shandong) affected by TSSDs (Fig. 8a–d), the tracks had a clear northward shift from the eastern landfall sites (Fujian, Zhejiang, Jiangsu, and Shanghai) to the northern regions. In addition, some tropical cyclones, moving along the coastline from the East China Sea to the Yellow Sea, triggered TSSDs in Shandong and Liaoning (Fig. 8a, d). Tropical cyclones triggering TSSDs in four eastern regions can be categorized into three types (Fig. 8e–h): shifting westward from landfall sites to inland areas, shifting northward from the landfall sites to northern regions, and shifting northward from the East China Sea to the Yellow Sea. For TSSDs in the southern regions (Guangdong, Guangxi, and Hainan), the tropical cyclones were dominated by tracks having a westward shift from the southern landfall regions (Fig. 8i–k). Approximately 88% of TSSDs in Guangdong and Hainan were triggered by landfall tropical cyclones, with landfall sites located in these two regions (Fig. 8i, k). TSSDs in Guangxi were mainly triggered by tropical cyclones that shifted westward to Guangxi's coastal area after their landfall in Guangdong or Hainan (Fig. 8j).

As for the spatial damage distribution, Guangdong, Fujian, and Zhejiang were the three most affected regions and experienced the most severe damage. The highest number of fatalities was recorded in Zhejiang because the "Fred" TSSD (Disaster ID: 9417) caused far more fatalities than any other disaster in the last three decades (Table 3). The highest direct economic loss was observed in Guangdong due to the highest tropical cyclones (42%) along its coastline and its highest GDP among the 11 regions. Although the frequency of TSSDs in Shandong was in the low-grade group (Fig. 5a), the damage was in the medium-grade group (Figs. 6a, 7a). The two most severe disasters (Disaster IDs: 8509 and 9216 in Table 3) were responsible for Shandong's damages, which accounted for over 50% of the TSSD damages in Shandong between 1983 and 2018. Higher defense standards and reasonable maintenance of seawalls in Shanghai could be one of the reasons for the low-grade damage (Figs. 6a, 7a) despite the medium-grade frequency (Fig. 5a) (Zhang et al. 2008).

5 Conclusions

This study presented a complete spatiotemporal distribution of TSSDs in 11 coastal regions of China during the 1983–2018 period. The main findings were as follows: (1) the number of TSSDs increased over time, while the damage decreased significantly over the past three decades; (2) most disasters occurred from July to September; (3) the southern and eastern regions were affected more (with respect to the frequency and damage of


(a)
Liaoning
Tianjin
Bohai Sea
Hebei
Shandong
Yellow Sea
Jiangsu
Shanghai
East China Sea
Zhejiang
Fujian
Guangxi
Guangdong
(b)
(c)
(d)
(e)
(f)
(g)
(h)
South China Sea
Hainan
(i)
(j)
(k)

◀ **Fig. 8** Tracks of tropical cyclones triggering TSSDs and affected regions (orange regions): **a** Liaoning; **b** Tianjin; **c** Hebei; **d** Shandong; **e** Jiangsu; **f** Shanghai; **g** Zhejiang; **h** Fujian; **i** Guangdong: **j** Guangxi; **k** Hainan

TSSDs) than the northern regions. Multiple factors (e.g., climate, topography, and social factors) can influence TSSDs. In this study, three main aspects were introduced to analyze spatiotemporal patterns of the frequency and damage. Two aspects, i.e., contributors and damage records of extreme TSSDs and mitigation measures, have been analyzed for the spatiotemporal damage distribution. Another aspect was the tropical cyclone track, and we have analyzed tropical cyclone tracks that triggered TSSDs in each coastal region to help understand the spatial frequency distribution. In addition, the monthly frequency of TSSDs was consistent with the monthly variations of tropical cyclones in the northwestern Pacific. Spatiotemporal patterns provide essential information in disaster hotspots and sensitive months, reminding disaster managers to strengthen protection in specific regions and months. From a future-based perspective, we should analyze and quantify relationships between more related factors and TSSDs to improve disaster management performance and reduce disaster damage.

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Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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