

Spatial–temporal distribution of storm surge damage in the coastal areas of China

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Abstract Storm surges account for increasing economic losses and casualties (including death and missing) because of sea-level rise and growing population in coastal areas. China is one of the several countries severely affected by storm surge disasters. In this study, the annual variation and geographical distribution of direct economic losses and casualties caused by storm surge in coastal areas of China were analyzed based on the losses database. The results show that: (1) the frequency of the tropical storm surges over the past 65 years has risen remarkably with a significant trend, while the frequency of extra-tropical storm surges does not display this trend; (2) the annual casualties caused by storm surge have decreased, with Zhejiang, Fujian, and Guangdong provinces suffering the highest casualties from storm surge; and (3) the annual direct economic losses present no obvious trend, with Guangdong, Zhejiang, and Fujian experiencing the highest direct economic losses from storm surge. Taking GDP and the gross ocean production into consideration, their loss rates show an obvious decreasing trend over the past 25 years. Although population and exposed value have increased rapidly in coastal areas, the casualties and economic loss rate show a decreasing trend, suggesting that disaster reduction measures by the Chinese government have had a significant effect in storm surge disaster prevention.

Keywords Storm surge disaster · Direct economic losses · Casualties · Spatial–temporal distribution

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1 Introduction

Storm surge disasters have been responsible for a large number of deaths, and statistical results show that more than 2.6 million people may have drowned because of storm surges during the past 200 years (Nicholls 2003). According to the official estimate, the most destructive storm surge disaster was caused by Cyclone Nargis in the Indian Ocean, which claimed the deaths of more than 138,000 people and economic damage of over USD 10 billion (Fritz et al. 2009). People and the exposed inundation-prone coastal areas are facing a severe threat of storm surge (Zachry et al. 2015), which is also one of the most serious marine disasters in China causing great economic losses and casualties. More than 18,000 km of coastline in China, extending from the south to the north, is influenced by frequent storm surges, including tropical and extra-tropical storm surges. For example, the 9711 storm surge was caused by the combined effect of Typhoon Winnie and local high tides, killing 342 people and causing a direct economic loss of RMB 28.7 billion, which is the greatest loss caused by a storm surge event in China since 1949 (State Oceanic Administration of China 1997).

Various studies have focused on the trends in hurricane damages in the USA (Pielke and Landsea 1998; Pielke et al. 2008) and in China (Xiao and Xiao 2010; Zhang et al. 2009), but little is known about the influence of storm surge disaster damages (Vinet et al. 2012). Over the past 20 years, the coastal zones of China have become the main area of economic development. For example, the gross ocean production (GOP) (capital) of the Zhejiang Province was RMB 37.3 billion in 1990 and reached RMB 3756.8 billion in 2013 (GDP deflator not considered). In the context of global climate change, sea-level rise (Hoffman et al. 2010), and the rapid increase in exposure, it is crucial to find out how storm surge damage varies across the coastal areas of China, whether it shows an increasing trend in economic losses, and what the relationship between the frequency, intensity, and loss of storm surge disasters is and whether there is a trend. In this study, based on collected multi-source data of storm surge damage in the coastal areas of China, we analyze the inter-annual changes in storm surge frequency, the spatial distribution of the storm surge disaster damage, and examine the trends of direct economic losses and casualties. Based on the current situation in China, the potential reasons for variations in casualties and economic losses are also analyzed.

2 Data sources

With the rapid process of urbanization in the coastal areas of China, the focus has increasingly been on disaster prevention and mitigation. The Department of Civil Affairs of China began releasing data on loss caused by natural hazards since 1983, but loss data on marine disasters were not included at first. The State Oceanic Administration of China (SOA) issues loss data caused by marine disasters through the marine disaster bulletin, which primarily includes the casualties, direct economic losses, and affected population and areas. The National Marine Environmental & Forecasting Center of China began field surveys after serious storm surge disasters occurred in coastal areas, forming storm surge disaster investigation reports that include detailed descriptions of the loss data. Based on these, the center published a book called the “Chinese Marine Disasters Four Decades Compilation” (Yang et al. 1991), which systemically recorded typical historical storm surge disasters. These records provide first-hand information on how storm surges affect the society and economy in the coastal areas of China.

Table 1 Multi-source data of storm surge damage

Data source	Time series	Description
Chinese marine disasters four decades compilation	1949–1990	Includes frequency records 1949–1990
The marine disaster bulletins	1989–2013	Includes frequency, casualties, direct economic loss, affected population and areas
The marine economy statistical bulletins	1994–2013	Includes the GOP from 1994

Based on these materials (listed in Table 1), the storm surge loss database was established (no damage data are available for Hong Kong, Macau, or Taiwan) from 1989 to 2013, including typhoon and extra-tropical storm surge disasters. The marine economy statistical bulletins, which include the annual GOP data issued by the SOA, were also collated from 1994 to 2013.

3 Frequency

Frequency and intensity are key indicators for evaluating the severity of a storm surge. Previous researches (Chan and Liu 2004; Chan and Shi 1996; Webster et al. 2005) found that the tropical cyclones in the Northwest Pacific Ocean showed an increasing trend before the 1970s, but have decreased since then. Some tropical cyclones making landfall do not cause storm surge disasters, and the frequency of storm surge events does not coincide with the frequency of tropical cyclones. From 1949 to 2013, there were a total number of 451 typhoon storm surges recorded in the coastal areas of China, with an average of 6.9 times per year. The highest number of typhoon storm surges in a year was 19 in 2004. There were 13 years when typhoon storm surges occurred more than 10 times per year. Two typhoon storm surges occurred during 1949, 1952, 1955, and 1957, which is the lowest recorded among the years. The frequency analysis of the storm surges over the past 65 years shows a remarkable rise with a significant trend (Fig. 1).

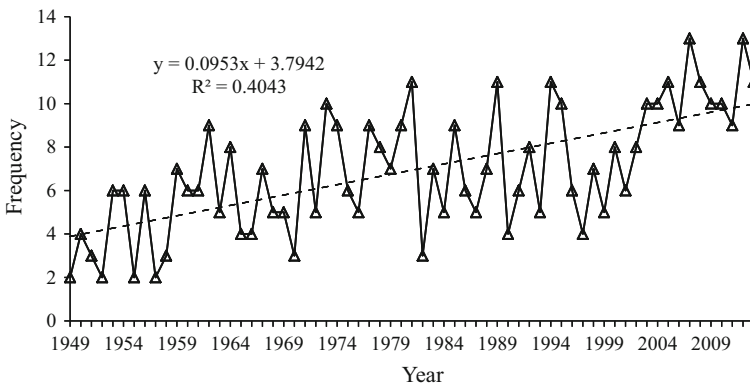


Fig. 1 Frequency of typhoon storm surges in the coastal areas from 1949 to 2013 (solid line) and its trend (dashed line)

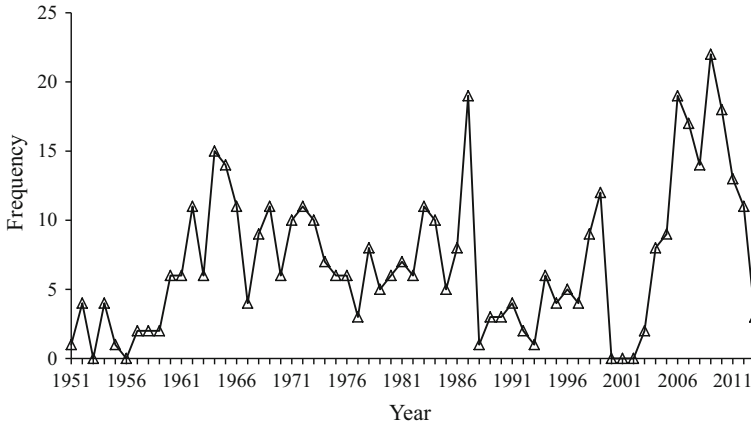


Fig. 2 Frequency of extra-tropical storm surges in the coastal areas from 1951 to 2013

There were a total number of 443 reported extra-tropical storm surges in the coastal areas of China from 1951 to 2013, with an average of seven times per year. Extra-tropical storm surges occurred more frequently in the 1960s and 1970s than in the 1950s. The highest frequency was 22 times a year in 2009, but there was no significant trend (Fig. 2). Although extra-tropical storm surges occurred more frequently than typhoon storm surges, the extra-tropical storm surges had a lower intensity and resulted in smaller losses. More

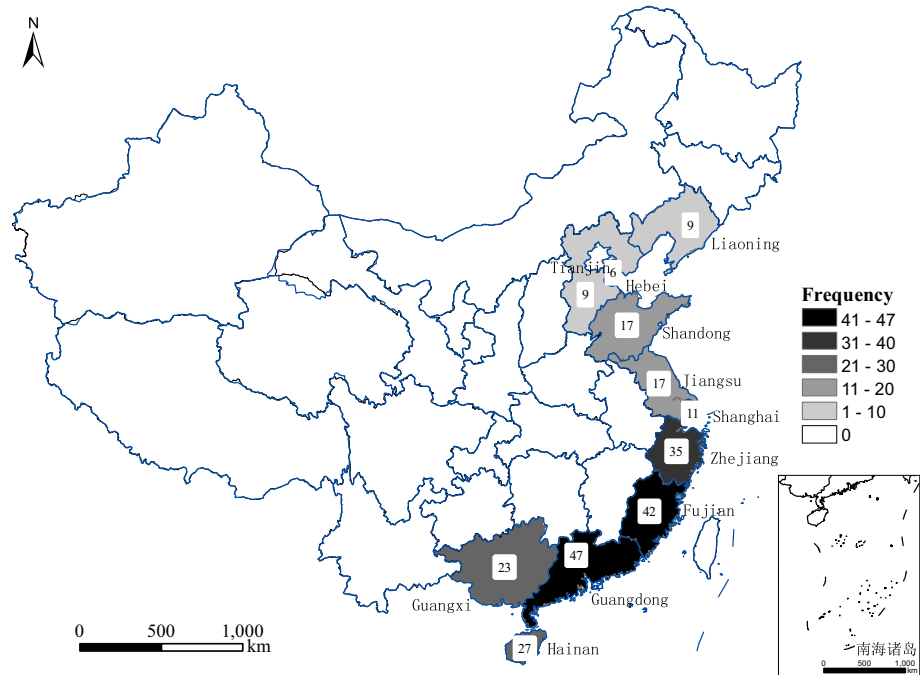


Fig. 3 Total frequency of storm surge events between 1989 and 2013 in each coastal province of China

than 95 % casualties and economic losses are caused by typhoon in storm surge events comparing with extra-tropical storm surge, and the most catastrophic storm surge disasters were all caused by typhoons. The frequency of storm surge event in each coastal province between 1989 and 2013 is shown in Fig. 3. The results show that Guangdong, Fujian, and Zhejiang are the top three suffering most from storm surge events, followed by Hainan, Guangxi, Jiangsu, Shandong, Shanghai, Hebei, Liaoning, Tianjin, and storm surge event happened in the south is much more frequent than that in the north.

4 Casualties

Figure 4 shows the time series of casualties caused by storm surges from 1989 to 2013, revealing a total number of 4351 deaths over the past 25 years, with an average of 174 casualties per year. The highest death rate occurred in 1994 with up to 1240 casualties. The historical records show that the storm surge caused by Typhoon Fred resulted in 1216 deaths in the Zhejiang Province. The casualties exceeded 500 in 1989 and 1996. There were no casualties in 2011 or 2013. In general, the number of casualties has decreased, as shown in Fig. 4, especially in recent years.

Based on the collected data, we individually counted the casualties caused by storm surges in the each coastal province from 1989 to 2013 as shown in Fig. 5. Zhejiang ranked highest with 1962 casualties, followed by Fujian, Guangdong, Shandong, Hainan, Guangxi, Jiangsu, Shanghai, Tianjin, and Hebei. Zhejiang, Fujian, and Guangdong contributed more than 80 % of the total casualties. The storm surge induced by Typhoon FRED, which is one of the most serious storm surge events in the history of Zhejiang Province, caused 1198 death in 1994. Specially, we could find that there were no casualties or missing persons from storm surges in Liaoning Province during 1989–2013. However, Typhoon Gloria in 1949 induced a great storm surge, causing 175 deaths in Liaoning Province, which was the most serious storm surge in the past 100 years in Liaoning.

The central and local governments pay much more attention to storm surge disaster preparedness and planning than before, and local officials may lose their position should they be slow to respond and inadequate in their efforts. Many measures have been taken for storm surge disaster mitigation. There are two major reasons contribute to the decreasing casualties caused by storm surges:

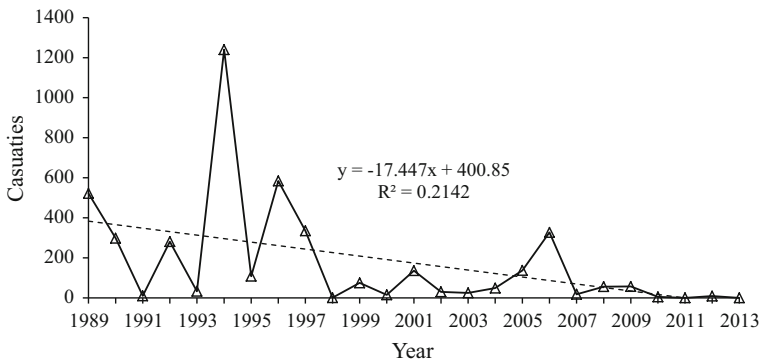


Fig. 4 Casualties caused by storm surge disasters in China from 1989 to 2013 (solid line) and its trend (dotted line)

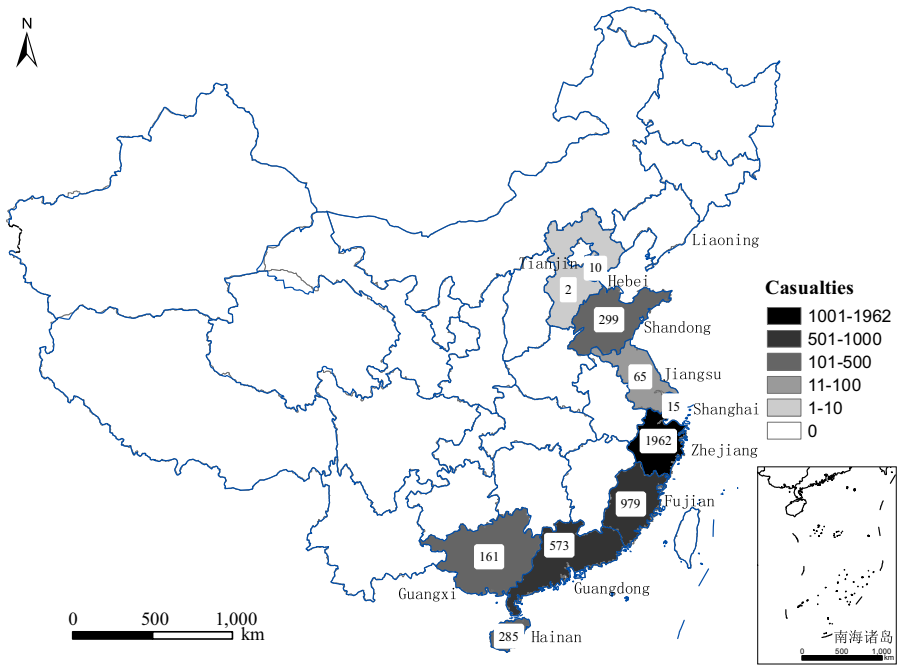


Fig. 5 Distribution of casualties caused by storm surge disasters in the coastal provinces of China

- (a) The establishment of “province–city–county” three-level emergency response mechanism: To cope with storm surges, Marine Disaster Headquarter of China was established in 2012 in response to storm surge disaster in coastal provinces such as Zhejiang. Local oceanic administration built communication channels with other government agencies, such as meteorological administrations and water resource administrations, to obtain scientific support for decision making. Fishers on the sea are being tracked uninterruptedly by BeiDou navigation satellite. Once a storm surge event is predicted, they would be called back 24–72 h prior to the event happens.
- (b) Strengthened early-warning capability: The early-warning system is able to predict cyclone tracks, affected areas, and surge scenarios more accurately and timely. This brings enough time for evacuation and greatly reduces casualties caused by storm surges.

5 Direct economic losses

The economic loss caused by the storm surge disasters is much greater than any other marine disaster in China. The average annual economic loss caused by storm surges is RMB 16.412 billion from 1989 to 2013. As shown in Fig. 6, the annual economic loss presents no notable tendency. The highest annual loss occurred in 2005, reaching RMB 42.28 billion. Eleven typhoon storm surges occurred in this year, and nine of them resulted in great losses based on the records of the marine disaster bulletin in 2005. In contrast, the

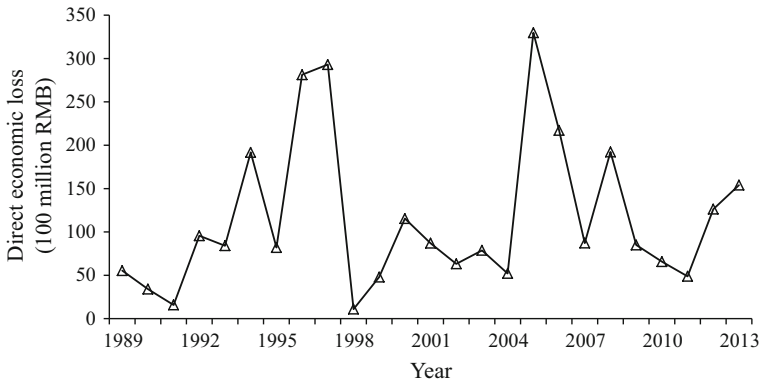


Fig. 6 Direct economic losses caused by storm surge disasters from 1989 to 2013

lowest annual loss occurred in 1998 with RMB 1.497 billion of direct economic loss. The annual economic loss in 1994, 1996, and 1997 exceeded RMB 30 billion, which was twice the average annual economic loss.

To identify whether there is a detectable trend in the economic loss caused by storm surge disasters, we divided the annual direct economic loss by GDP in each year. The loss ratio of GDP caused by storm surge disasters has a remarkable decreasing trend compared with the direct economic losses as shown in Fig. 7. The average loss ratio of GDP is approximately 1.34 ‰, and this number has reduced to approximately 0.2 ‰ over the past 5 years. Furthermore, we take the GOP as an indicator to validate this trend, adding the annual direct economic loss itself, and obtain the loss rate of the GOP. As shown in Fig. 8, the loss rate of the GOP shows a decreasing trend, which is statistically significant at the 95 % level, and behaves the same way as the loss ratio of GDP. The average loss rate of GOP is approximately 2.17 ‰, and this number averaged at approximately 2 ‰ over the past 5 years. We can therefore conclude that, taking the rapid economic growth of the coastal areas into consideration, there is a clear decreasing trend in the direct economic loss ratio caused by storm surge events.

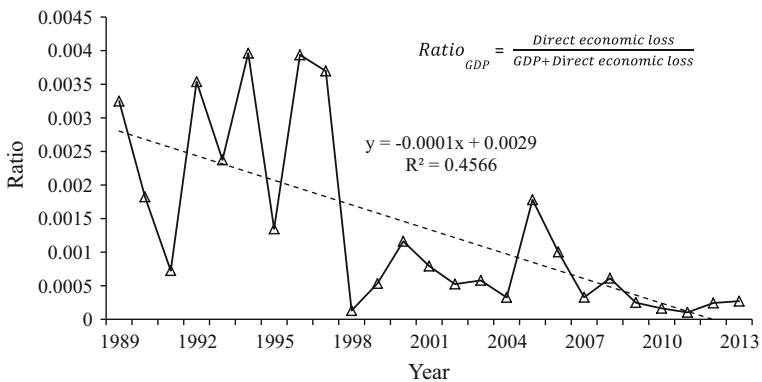


Fig. 7 Direct economic loss ratio of GDP caused by storm surge disasters from 1989 to 2013 (solid line) and its trend (dotted line)

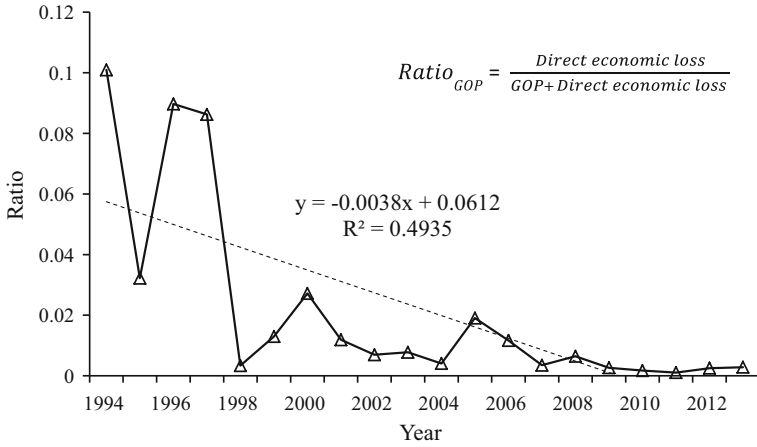


Fig. 8 Direct economic loss ratio of GDP caused by storm surge disasters from 1994 to 2013 (solid line) and its trend (dotted line)

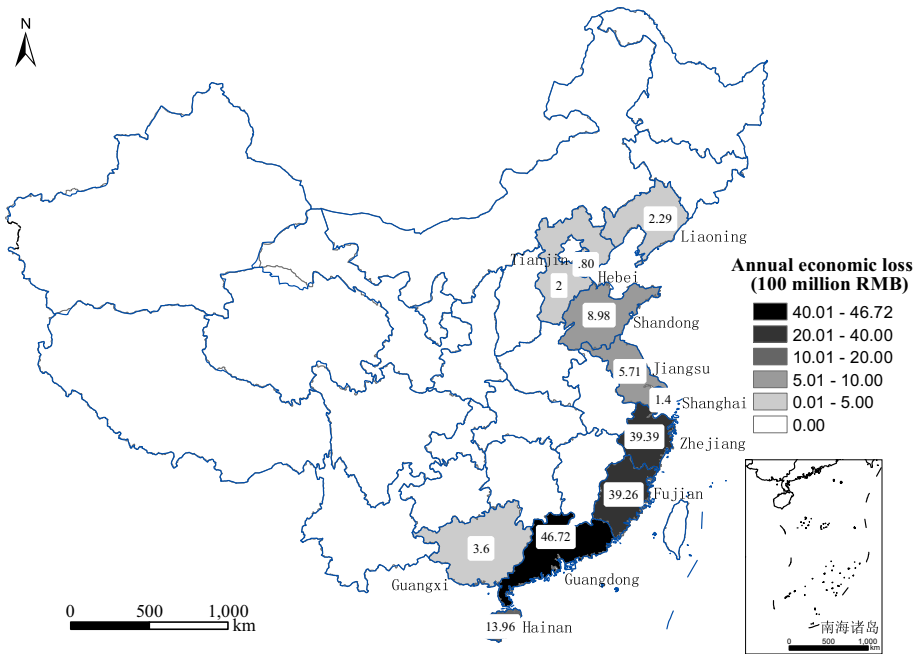


Fig. 9 Annual mean direct economic losses caused by storm surge disasters for each coastal province in China

The direct economic losses exhibit clear geographical distribution characteristics in the coastal areas of China as shown in Fig. 9. The 11 provinces in the coastal regions of China have all experienced economic loss from storm surges. Guangdong, Zhejiang, and Fujian are the three provinces that have suffered the most severe direct economic losses from

storm surge disasters. The losses in these three provinces account for over 75 % of the total economic losses among all the coastal provinces, and they each have an average annual expected loss of more than RMB 3.9 billion. The next highest losses occurred in Hainan, Shandong, Jiangsu, Guangxi, Hebei, and Tianjin. The Pearl River Delta has the most advanced marine economy in China. Typhoon and storm surges occur fairly frequently here, bringing great economic losses to these areas. The coastal area of Zhejiang has a large tidal range. Surges often coincide with the astronomical tide causing severe storm surge disasters, resulting in large economic losses. Storm surges in Liaoning, Hebei, and Tianjin are less severe and cause lower economic losses.

In the past decades, Chinese government has taken great efforts to reduce losses from storm surge events by following engineering and non-engineering measures:

- (a) Improving public awareness and prevention skills to storm surge disasters: China sets up the National Day of Disaster Prevention and Reduction to attract the society's attention to disasters. Emergency drills, propagandas, and education on storm surge were held more frequently in coastal communities. By these efforts, local people in coastal areas accumulated more experience in coping with storm surge events.
- (b) Strengthening the capacity of monitoring, forecasting, and early warning for storm surge disasters: More than 100 tidal observation stations that are distributed in the coastal area from the south to the north have been built in recent years. The forecasting and early-warning systems were developed covering the whole coastal area of China to ensure targeted measures could be applied before storm surge event happens.
- (c) Construction of dike or seawall: The storm surge disaster induced by Typhoon Winnie in the Zhejiang Province in southeast China resulted in the launch of the project "Thousand miles of sea dike" to deter future inundation caused by storm surges. Standard seawall was constructed along the coastline according to designed water level. Similar seawall has been built for protection against storm surges in the coastal areas of Jiangsu and Fujian. Besides, mangroves were planted in the coastal areas of Guangxi and Guangdong provinces as a natural barrier to minimize the influence of storm surges.

6 Conclusions and discussions

Based on historical storm surge disaster records of the past 25 years, this study analyzed the spatial–temporal distribution of storm surges, and corresponding losses and casualties. The frequency of tropical storm surges over the past 65 years shows a remarkable increase with a significant trend, while the frequency of extra-tropical storm surges does not show a clear trend and the annual frequency of extra-tropical storm surges is significantly greater than that of previous years.

The number of casualties caused by storm surges has a clear decreasing trend. The economic loss caused by storm surges remains constant and displays no trend, whereas the loss ratio of the GOP and GDP shows a clear decrease. The decrease in the number of casualties and loss rate shows that China's efforts on storm surge disaster prevention and mitigation since the 1990s have been effective. In terms of spatial distribution, the southern coast suffered more from storm surges than the north. The southern coast of China experienced greater losses from storm surge disasters than the northern coast, and the former is mainly

Table 2 Order of frequency, casualties and direct economic loss in each coastal province caused by storm surge

Frequency		Casualties		Direct economic loss	
Order	Name	Order	Name	Order	Name
1	Guangdong	1	Zhejiang	1	Guangdong
2	Fujian	2	Fujian	2	Zhejiang
3	Zhejiang	3	Guangdong	3	Fujian
4	Hainan	4	Shandong	4	Hainan
5	Guangxi	5	Hainan	5	Shandong
6	Jiangsu	6	Guangxi	6	Jiangsu
6	Shandong	7	Jiangsu	7	Guangxi
8	Shanghai	8	Shanghai	8	Liaoning
9	Hebei	9	Tianjin	9	Hebei
9	Liaoning	10	Hebei	10	Shanghai
11	Tianjin	11	Liaoning	11	Tianjin

affected by typhoon storm surges while the latter by extra-tropical storm surges. Frequencies are positively correlated with casualties and direct economic losses caused by storm surge events in coastal areas, as shown in Table 2. These provide solid bases for the planning and implementation of regional storm surge disaster risk reduction activities and measures.

In recent years, Chinese government has taken a variety of actions to reduce the storm surge risk in coastal areas. From the year 2011, the SOA started the “Marine disaster risk assessment and zoning” project to identify the inundation-prone area. Emergency shelter was built in safety place for people threatened by storm surges. The “National Model Community of Marine Disaster-reduction” project was implemented to improve the prevention and mitigation capacity of marine disaster for local governments, especially for communities or counties in coastal areas from 2012. Property insurance and reinsurance were introduced to reduce the economic losses (Shi et al. 2013). For example, fishery mutual insurance has been widely accepted in coastal province of China, which is heavily subsidized by governments (subsidies >80 % of the premium). All of these actions reduce the influence of storm surges in China, and these experiences can be helpful for other developing countries suffering from storm surge disaster.

While population and exposed value have increased in coastal areas, the casualties and economic loss rate show a decreasing trend, and great efforts have been made by the Chinese government in improving storm surge disaster prevention. Population growth will persist, and the development in exposed regions will continue to play a major role in terms of storm surge exposure (Berz 2005), and the capabilities of storm surge disaster mitigation will need to be strengthened.

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