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RESEARCH ARTICLE

The impact of Typhoon Lekima (2019) on East China: a postevent survey in Wenzhou City and Taizhou City

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Abstract Typhoon Lekima (2019) struck Zhejiang Province on 10 August 2019 as a supertyphoon, which severely impacted Zhejiang Province. The typhoon killed 45 people and left three others missing, and the total economic loss reached 40.71 billion yuan. This paper reports a postdisaster survey that focuses on the storm precipitation, flooding, landslides, and weather services associated with Typhoon Lekima (2019) along the southeastern coastline of Zhejiang Province. The survey was conducted by a joint survey team from the Shanghai Typhoon Institute and local meteorological bureaus from 26 to 28 August, 2019, approximately two weeks after the disaster. Based on this survey and subsequent analyses of the results, we hope to develop countermeasures to prevent future tragedies.

Keywords Typhoon Lekima (2019), Zhejiang Province, disaster assessment, postdisaster survey

1 Introduction

China is severely affected by tropical cyclone (TC) disasters. In an average year, approximately nine TCs make landfall over Chinese mainland and Hainan Island (Lu and Zhao, 2013), leading to 28.7 billion yuan in direct economic losses and killing 472 people on average (Zhang et al., 2009). Associated with extreme winds, rainfall, and storm surges, TCs are significant hazards in coastal areas. Nearly all coastal provinces in China are affected by TCs that make landfall, and Zhejiang Province is one of the most severely affected regions. Zhang et al. (2009) noted the most likely reason for this trend is that the average intensities of the TCs that make landfall in Zhejiang Province are higher than those of TCs in other provinces.

TC disaster assessment has been the subject of considerable attention among scientists, sociologists, and policymakers. Most studies have concentrated on the factors that led to extensive destruction or risk assessments of TCs (Willoughby and Black, 1996; Emanuel et al., 2006; Chen et al., 2009; Lei et al., 2009; Vickery et al., 2009; Fang and Shi, 2012; Lin et al., 2012; Chen et al., 2013; Fang and Lin, 2013). Some researchers have focused on postdisaster surveys of catastrophic hurricanes. An integrated postdisaster investigation for a disastrous TC is very complicated and must consider the interdisciplinary integration of issues, such as flooding, landslides, water facility failures, damaged bridges, traffic problems, life support system problems, socioeconomics, schools and public facilities, and damaged buildings (Lei et al., 2009; Li et al., 2013; Lu et al., 2017, 2018). Li et al. (2013) carried out a comprehensive investigation to understand the types, numbers, and scales of the disasters caused by Typhoon Morakot (2009). They compiled cumulative rainfall data, flooding areas, hillside disasters, affected roads, and damaged bridges over Taiwan Island during Typhoon Morakot (2019). They discussed the relationship between these disasters to identify potentially dangerous areas. Nevertheless, most disaster investigations focus on only one or two aspects of typhoon disasters. For example, Tajima et al. (2014, 2017) reported the postdisaster survey results for surge disasters caused by Typhoon Haiyan (2013) and Typhoon Meranti (2016), and a joint

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US-Japanese team investigated coastal impacts in the United States Virgin Islands after Hurricanes Irma (2017) and Maria (2017) (Cox et al., 2019). Other researchers have been concerned about the physical and mental health of the minority communities most severely affected by disasters (Mellman et al., 1995; Elliott and Pais, 2006; Eisenman et al., 2007; Lin et al., 2015; Hugelius et al., 2017).

On 10 August, 2019, Typhoon Lekima (2019) made landfall in east China as a supertyphoon and resulted in significant damage across several provinces. Zhejiang Province, in coastal southeastern China, one of the most prosperous regions in the country, was the worst-hit province. This paper reports a postdisaster survey focused on storm precipitation, flooding, landslides, debris flows, and weather services associated with Typhoon Lekima (2019) along the coastline of Zhejiang Province, China.

This paper is organized as follows. First, in Section 2, we briefly introduce the outline of the survey. Next, in Section 3, we present the disaster scenario for Typhoon Lekima (2019) in detail. Section 4 is the weather service support for Typhoon Lekima (2019) provided by the Zhejiang Meteorological Bureau. Section 5 presents a discussion of the results and our conclusions.

2 Outline of the survey

The survey was conducted by a joint survey team from the Shanghai Typhoon Institute and local meteorological bureaus from 26 to 28 August, 2019, approximately two weeks after the disaster. The researchers from Shanghai Typhoon Institute (STI), whose mission is to advance the understanding and prediction of TCs, has been collecting primary, detailed, and reliable data to rectify typhoon yearbooks for decades. They have been engaged in a TC disaster survey for more than ten years and have a large number of first-hand observation data.

2.1 Data and methods

The track and intensity data for Typhoon Lekima (2019) and TC-induced precipitation and wind data at stations from 8 August to 13 August were obtained from the China Meteorological Administration (CMA). The TC-induced precipitation contains daily precipitation, maximum 1 h precipitation, and the associated date and time. The TC-induced wind data are 3-s extreme wind speed, and the wind scale is divided into 18 grades according to the national wind scale standard released in June 2012 (GB/T 28591-2012). The TC categories follow the national standard of China (ICS 07.060), and the scale is determined by the maximum central 2-min mean wind speed, divided into six grades based on the national standard of China (GB/T 19201-2006): tropical depression (TD, 10.8–17.1 m/s), tropical storm (TS, 17.2–24.4 m/s), severe tropical storm (STS, 24.5–32.6 m/s), typhoon (TY, 32.7–41.4 m/s), severe typhoon (STY, 41.5–50.9 m/s), and super typhoon (Super TY, ≥51.0 m/s).

The damage data, including the deaths and missing, affected crop area, number of destroyed houses, and direct economic losses, were obtained from the Zhejiang Provincial Office of the Prevention of Floods, Typhoons, and Droughts. Despite uncertainties in this data set, these records provide essential information about the societal and economic effects of TCs in China (Chen et al., 2013).

The survey team employed two primary methods to acquire disaster data: visits to meteorological bureaus and interviews with residents living near the disaster area. Considering the degree of casualties and economic losses, the mudslides in Wenzhou city and urban floods in Taizhou city were the most severe disasters. Besides, Taizhou city was where Typhoon Lekima made landfall in 2019. Therefore, we chose Wenzhou and Taizhou (two cities along the coast of Zhejiang Province) as our research sites. Table 1 lists the survey locations and methods. The inset in Fig. 1 shows the locations of survey sites in Taizhou city and Wenzhou city.

2.2 Introduction of Typhoon Lekima (2019)

According to the CMA data set, Typhoon Lekima (2019) formed on 4 August, 2019 and lasted until 13 August, 2019; the typhoon ranked among the strongest TCs in 2019, with a maximum wind speed of 62 m/s and a minimum central pressure of 915 hPa, as shown in Fig. 1. Typhoon Lekima (2019) developed over the Philippine Sea and initially moved slowly northward. As the system continued to move north-westward, it entered an area of low wind shear, and rapid intensification occurred. On 7 August, Typhoon Lekima (2019) was upgraded to a supertyphoon and maintained the strength to move north-westward. The environmental conditions in the East China Sea became unfavorable for growth, causing Typhoon Lekima (2019) to weaken while slowly approaching East China. On 10 August, Typhoon Lekima (2019) made landfall in Wenling, Taizhou city, with a maximum wind speed of 52 m/s and a minimum central pressure of 930 hPa. Typhoon Lekima (2019) quickly weakened and turned to the north. On 11 August, the system shifted into the Yellow Sea and made a second landfall in Qingdao, Shandong, with a maximum wind speed of 23 m/s and a minimum central pressure of 980 hPa. Finally, Typhoon Lekima (2019) meandered across the Shandong Peninsula and the Bohai Sea, and the CMA downgraded Typhoon Lekima (2019) to a tropical depression and stopped tracking the system on 13 August.

Typhoon Lekima (2019) was the third-strongest TC to make landfall (after Typhoon Saomai (2006) and Typhoon No. 5612) since 1949 with a landfall intensity of 52 m/s. According to the damage data obtained from the Zhejiang Provincial Office of the Prevention of Floods, Typhoons,

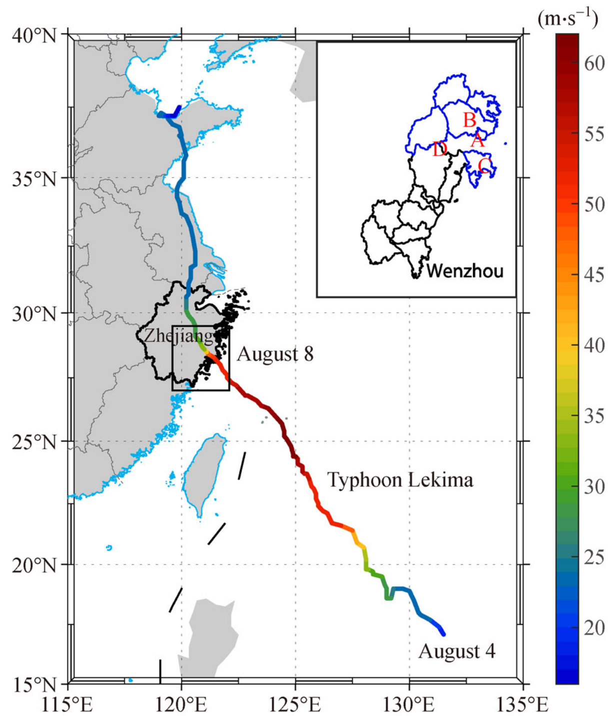

Fig. 1 Path and intensity of Typhoon Lekima (2019). Inset shows the locations of survey sites in Taizhou city and Wenzhou city. The bold line indicates the path of Typhoon Lekima (2019), and colors indicate TC intensity.

Table 1 Survey locations and methods

Location	Map mark	Method	Administrative area
Taizhou city	A	Interviews with local meteorological bureaus	Zhejiang Province
Linhai city	B	Interviews with residents living near the disaster area	Taizhou city
Wenling city	C	Interviews with residents living near the disaster area	Taizhou city
Shanzao village	D	Interviews with local meteorological bureaus and residents living near the disaster area	Yongjia county, Wenzhou city

and Droughts, 3723000 residents were affected, three people died, 4107 houses collapsed, 1110 km^2 of plants were affected, and 2130 km^2 of plants faced destruction in Taizhou city. The direct economic loss was approximately 25 billion yuan. Although Typhoon Lekima (2019) made landfall in Wenling, Taizhou city, it caused more severe damage to life in Wenzhou city, located south of Taizhou city. In Wenzhou city, 1702700 residents suffered, 36 people died, two people were missing, 181 houses collapsed, 168.03 km^2 of plants were affected, and 4.73 km^2 of plants faced total failure. The total direct economic loss reached 30 billion yuan. The different disaster situations in the two cities are related to the regional topography, which will be discussed in detail below. Field surveys and interviews with residents indicated that most of those killed died in Yongjia county, Wenzhou city. The landslides blocked a stream, water levels rose 10 m in ten minutes, and many residents could not evacuate in time to avoid injury or death. Some photos were taken at the disaster sites in Shanzao village, Yongjia county (Fig. 2).

3 Disaster statistics and causality analysis

3.1 Rainfall and wind analysis

3.1.1 Eastern China

From 8 August to 13 August, eastern China (Zhejiang Province, Jiangsu Province, and Shandong Province) experienced torrential rainfall (Fig. 3). The average rainfall in Shandong Province was 158 mm, exceeding that of Typhoon Rumbia (2018) (135.5 mm on average throughout the whole province), which is the highest rainfall ever recorded in Shandong Province. The average rainfall in Zhejiang Province was 165 mm. In the period affected by the TC, the totals at 46 rainfall stations in Shandong Province, Zhejiang Province, Jiangsu Province, Anhui Province, Shanghai, and other places reached or exceeded the historical maximum daily rainfall.

Furthermore, northeastern Zhejiang Province, the northeast

Fig. 2 Photographs of the disaster investigation field in Shanzao village, Yongjia county (Cong ZHOU, 2019-08-28 took photos). The red arrows indicate the position of the landslide.

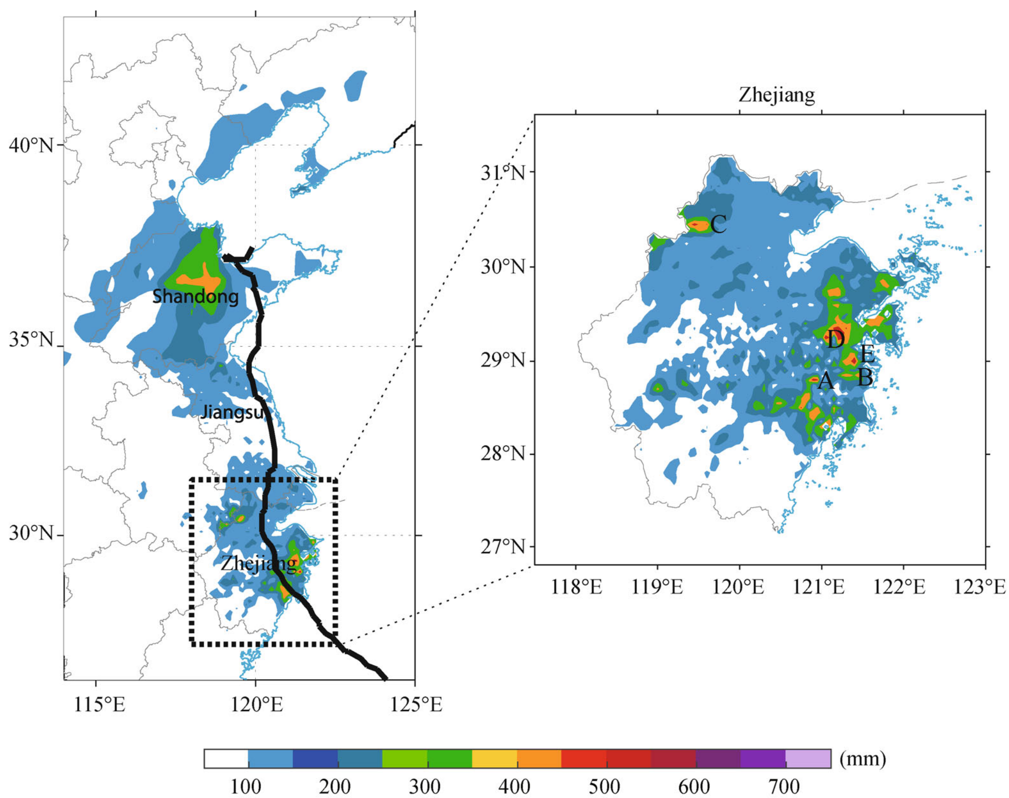

Fig. 3 The observed cumulative rainfall (mm) from 8 August to 13 August (Beijing Time) over eastern China. The colors show the amount of precipitation, and the bold black line indicates the path of Typhoon Lekima (2019). The enlarged figure shows the observed accumulated rainfall in Zhejiang Province, and the bold letters show the locations of the top five records affected by Typhoon Lekima (2019).

coast of Fujian Province, Shanghai, Jiangsu Province, northeastern Anhui Province, northeastern Shandong Province, eastern Hebei Province, and southern Liaoning Province were affected by strong winds from level 8 to level 11. The east coastal islands in Zhejiang Province, Qingdao, and Tai’an in Shandong Province experienced

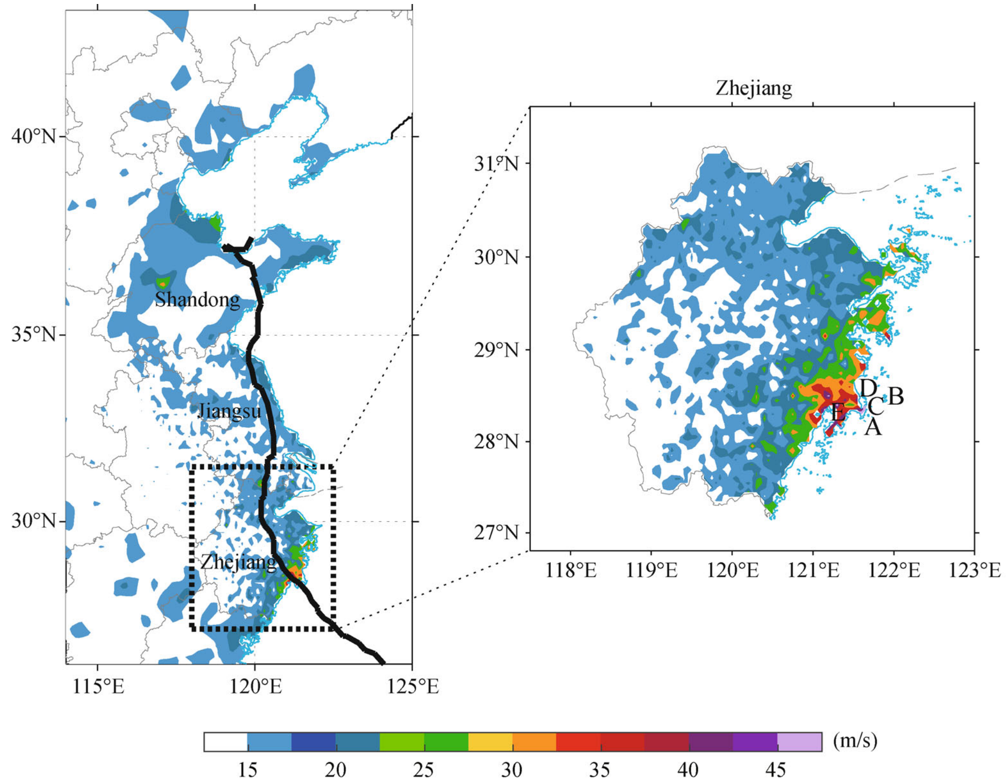

Fig. 4 The observed extreme wind speed (m/s) from 8 August to 13 August (Beijing Time) over eastern China. The colors show the wind speed, and the bold black line indicates the path of Typhoon Lekima (2019). The enlarged figure shows the wind speed in Zhejiang Province, and the bold letters show the locations of the top five records affected by Typhoon Lekima (2019).

winds from level 12 to 15. Figure 4 shows the observed extreme wind speeds from 8 August to 13 August over eastern China. On Sansuan Island (61.4 m/s) and in Nanqiao village (60.3 m/s) and Beigang (57.8 m/s) in Zhejiang Province, the wind speed even reached or exceeded level 17.

Chen et al. (2019) analyzed the relationships between TC precipitation, wind, and storm damage for Chinese mainland based on TCs over 1984–2013. The analysis shows that the maximum daily areal precipitation (MDAP) from stations with daily precipitation of 50 mm and the sum of gust wind speeds of 13.9 m/s can be used to estimate the direct damage caused by TCs. An index combining the precipitation and gust wind of a TC is defined to assess the severity of precipitation and wind (Chen et al., 2009, 2013, 2019). A total of 1401 meteorological stations were chosen to calculate the parameter based on the data completeness, representativeness, and homogeneous distribution. Figure 5 shows the locations of the 1401 stations. The combined impact index of precipitation and wind (*IPWT*) is defined as

$$IPWT = (IPT + IWT + IPT \times IWT)/2, \tag{1}$$

$$IPT = MDAP/MDAP_{\mathrm{MX}}, \tag{2}$$

$$MDAP = \max\left(\sum\nolimits_{i=1}^{npi} P_{ij}\right), \quad j = 1, \ldots, \mathrm{N}d_{p,} \tag{3}$$

$$IWT = GUST7\_T/GUST7\_T_{MX}, \tag{4}$$

$$GUST7_T = \sum\nolimits_{i=1}^{Ns_w} (GUST_i), \quad i = 1, \ldots, Ns_w, \tag{5}$$

where P_{ij} is the daily precipitation (mm) at the *i*th station on the *j*th day, np_j is the number of stations with $P_{ij} \geqslant 50$ mm on the *j*th day, and nd_p is the number of precipitation days during a TC influence period. $MDAP_{\mathrm{MX}}$ is the maximum value of *MDAP* from 1984 to 2013, and the $MDAP_{\mathrm{MX}}$, from TC Bilis in 2006, is 12679 mm. $GUST_i$ is the extreme gust wind (m/s) at the *i*th station during a TC influence period, and NS_w is the number of stations with extreme gust wind 13.9 m/s during a TC influence period. The $GUST7\_T_{MX}$ is the maximum value of $GUST7\_T$ from 1984 to 2013, and the $GUST7\_T_{MX}$ is 4481 m/s for TC Winnie in 1997.

Here, we use Chen's newest index to assess Typhoon Lekima (2019) and list the top-10 TCs to impact the Chinese mainland ranked by IPWT (Table 2). Suppose only the precipitation and wind levels of a TC are

Fig. 5 Distribution of the 1401 stations chosen to analyze the precipitation and wind.

considered. In that case, Typhoon Lekima (2019) becomes the most destructive TC ever recorded.

3.1.2 Zhejiang Province

With its long duration, Typhoon Lekima (2019) produced torrential rainfall over eastern Zhejiang Province. More than 50 rainfall stations recorded rainfall totals exceeding 500 mm, and the totals at more than 200 rainfall stations exceeded 400 mm in the four days from 8 to 13 August 2019. The enlarged figure in Fig. 3 shows the cumulative rainfall totals recorded in Zhejiang Province, with a maximum of approximately 800 mm. The precipitation area is mainly near the typhoon path on both sides. Most of the precipitation area is located in the north of Wenzhou city and Taizhou city, and precipitation was the main cause of local typhoon disasters. The top five meteorological stations with the highest rainfall totals associated with Typhoon Lekima (2019) are listed in Table 3. The observed cumulative rainfall in the Kuocang Mountains station totaled 834 mm, which broke the local record of TC-based cumulative rainfall and was the second-highest total ever recorded in Zhejiang Province (the maximum historical record is 916 mm for Typhoon Rananim in 2004). Most of the record-high rainfall totals were observed along the eastern coast of Zhejiang Province, and Taizhou city was the most affected city.

In addition to heavy rain, Zhejiang Province was also hit by strong winds. From 8 to 13 August, 2019, most areas experienced winds over 17.2 m/s (Level 8), except for parts of south western Zhejiang, and the coastal areas generally had winds over 32.7 m/s (Level 12). The coastal gale lasted for nearly 36 h, and the gale reached levels 12 to 14 for approximately 20 h. Seventeen individual gauge stations experienced winds above 51 m/s (level 16), with a maximum of approximately 61.4 m/s (level 17). The enlarged figure in Fig. 4 shows that a new maximum wind speed was recorded in Zhejiang Province, and the top five stations most affected by the winds of Typhoon Lekima (2019) are listed in Table 4. The observed extreme wind on Sansuan Island reached 61.4 m/s, reaching the second-highest level for a TC in Zhejiang Province. The maximum historical record was 68 m/s for Typhoon Saomai in 2006. The top wind speed area is concentrated where the typhoon made landfall and the area to the right of the typhoon's path. As the landing point of Typhoon Lekima (2019),

Table 2 The top 10 most damaging typhoons in China ranked by IPWT

Rank	Typhoon name	Time	Landing situation		Precipitation situation	Wind situation	IPWT	Category
			Location	Central pressure/hPa	Maximum cumulative precipitation at a station/mm	Maximum wind speed/($m \cdot s^{-1}$)		
1	Lekima	20190804	Zhejiang	930	829	61.4	1.6589	4
2	Winnie	19970818	Zhejiang	960	483	41	1.2834	4
3	Bilis	20060708	Taiwan and Fujian	980	570	42	1.1087	4
4	Amy	19620829	Taiwan and Fujian	975	446	40	0.9535	4
5	Freda	19840802	Taiwan and Fujian	988	379	40	0.793	4
6	Polly	19920827	Taiwan and Fujian	978	722	40	0.7488	4
7	Mary	19600602	Guangdong	970	439	40	0.7429	4
8	Herb	19960723	Taiwan and Fujian	970	418	29	0.7287	4
9	Joan	19590824	Taiwan and Fujian	970	417	40	0.7142	4
10	Prapiroon	20060728	Guangdong	975	418	42	0.6782	4

Table 3 The top five stations most affected by cumulative rainfall from typhoon Lekima (2019) (8–13 August, 2019)

Location	Cumulative rainfall/mm	Map mark	Administrative area
Kuocang Mountains	834	A	Linhai city, Taizhou city
Jiantou village	728.5	B	Sanmen county, Taizhou city
Tianhuangping	628.8	C	Anji county, Huzhou city
Shiliang town	613.5	D	Tiantai county, Taizhou city
Linchang	604	E	Sanmen county, Taizhou city

Source: CMA

Table 4 The top five stations most affected by extreme winds from Typhoon Lekima (2019) (8–13 August, 2019)

Station	Extreme wind/($m \cdot s^{-1}$)	Map mark	Administrative area
Sansuan Island	61.4	A	Wenlin city, Taizhou city
Nandai village	60.3	B	Jiaojiang district, Taizhou city
Beigang	57.8	C	Wenlin city, Taizhou city
Baiguo village	56	D	Luqiao district, Taizhou city
Ximen Island	55.9	E	Yueqing county, Wenzhou city

Source: CMA

Wenlin city, Taizhou city, suffered the most from the storm disaster. This survey found that the wind disaster loss in Taizhou city was relatively small, mainly due to two reasons. One is the timely evacuation of people from the landfall site and proper disaster prevention strategies; the other is that the local economy does not depend on planting crops.

3.2 Hillside and flooding disaster analysis

3.2.1 Disaster statistics

The extreme rainfall triggered floods and landslides throughout eastern Zhejiang, and most of the incidents took place in Taizhou city and Wenzhou city. Here, we focus on 3 cases: Case 1 – Case 3. Figure 6 shows pictures of (a) an aerial photo of Shanzao village, Yongjia county (Source: Sina Weibo @CCTV News), (b) Linhai ancient city (Source: Website of The Paper News), (c) an aerial photo of Linhai city on 11 August (Source: Sina Weibo @The Voice of Zhejiang), (d) an unfinished reservoir, (e) collapsed buildings (Source: Website of Caixin News), and (f) exposed tree root and channel. As most survey sites were in the drone no-fly zone, we selected some photos from the Internet. Figure 7 and Figure 8 show satellite images of Linhai city before and after the flood.

Case 1: One landslide and subsequent flash flood destroyed Shanzao village in Yongjia county (survey site D in Fig. 1) early on 10 August, killing over 30 people. With

Typhoon Lekima (2019) making landfall, the rainfall in Shanzao village exceeded 160 mm in 3 h, which caused a landslide at the entrance to the village. Figure 2 shows the landslide position and the surrounding environment. The landslide blocked a stream, which caused water levels to rise 10 m in ten minutes, and approximately 120 people were trapped in the village. Suddenly, the water level exceeded the warning level, and the barrier lake burst. Many residents could not evacuate in time to avoid injury or death; most of them were older people and children. The

Fig. 6 Pictures of (a) an aerial photo of Shanzao village, Yongjia county (Source: Sina Weibo @CCTV News), (b) Linhai ancient city (Source: Website of The Paper News), (c) an aerial photo of Linhai city on 11 August (Source: Sina Weibo @The Voice of Zhejiang), (d) an unfinished reservoir, (e) collapsed buildings (Source: Website of Caixin News), and (f) exposed tree roots and channel.

Fig. 7 Satellite images of the Lin River before and after the flood (Source: Sike website).

Fig. 8 Satellite images of Jianchuan village, Linhai city, before and after the flood (Source: Sike website).

worst-hit area was located at the bend of the stream, an area near the entrance to the village with low topography (Fig. 6(a)).

Case 2: Torrential rains caused the Lin River to swell, which results in urban flooding in the ancient city of Linhai (survey site B in Fig. 1). The ancient walls of the city, facing the Lin River, were constructed in the Jin Dynasty (265–420) and have been barriers against floods since ancient times. At 3:00 pm on 10 August, the water level of the Lin River exceeded the warning level (Fig. 7), a flood wave reached the ancient walls, and the water level reached 1.5 m (Fig. 6(b)). In addition to the ancient walls, the entire city of Linhai experienced severe urban inundation (Figs. 6(c) and 8). It took at least two days for the city to recover initially. In the survey, we found that a more significant problem for residents suffering from urban inundation was isolation from the outside world caused by power failure. At night, the sense of helplessness was magnified when there was no power or mobile phone signal.

Case 3: A flash flood caused by torrential rains affected 41 buildings in Fangxi village, 20 km from Linhai (survey site B in Fig. 1). Fortunately, the villagers were evacuated early, and no people were in the homes when they collapsed into the stream. Fangxi village is a small village with approximately 500 people located in the lower reaches of the Fangxi River, a tributary of the Yonganxi River. An unfinished reservoir was located upstream of the river (Fig. 6(d)). On the evening of 9 August, a copious amount of rain fell in the reservoir in a short period. It was then discharged directly through two temporary drainage culverts, causing damage to the lower village, which was less than 500 m downstream. In the survey, we saw that houses on the upper side of the village, on the side next to the river, were almost thoroughly washed out and covered in rubble. A three-story building not far from the village council was tilted, with its foundation and steel bars visible. Large boulders covered much of the village, as did the rubble from many collapsed houses on the sides of the river (Figs. 6(e) and 6(f)). Based on the residents' interviews, the houses were destroyed by the rocks transported by the flood (Fig. 6(f)).

3.2.2 The reasons for the hillside and flooding problems

a) Typhoon Lekima (2019) moved slowly (approximately 15 km/h) and stayed in Zhejiang Province for 20 h, maintaining a supertyphoon level for more than 1 h, strong typhoon level for 2 h, and typhoon level for 4 h. According to a damage assessment report, Typhoon Lekima (2019) was the third-strongest TC to make landfall (after Typhoon Saomai and Typhoon No. 5612). However, Typhoon No. 5612 stayed in the province for approximately 10 h, and Typhoon Saomai made landfall in the area for less than 1 h. The extreme rainfall was caused by the slow movement of Typhoon Lekima (2019) both during landfall and in the postlandfall period. The continuous formation of mesoscale convection occurred with the moisture from the southwesterly flow.

b) Landslides triggered by rains result from the combined action of hydrological, geological, topographical, soil conditions, and so on (Ma et al., 2015). As shown in Fig. 9, the terrain in Zhejiang Province is complex. The shaded colors reflect the topography (the elevation data are derived from Scripps Institute of Oceanography, University of California San Diego). The red words mark the 2 locations where landslides and flooding occurred in the Typhon Lekima (2019) period. Mountainous and hilly terrain accounts for 72% of the province. The mountainous areas with elevations above 500 m are mainly distributed in the west and south, where the terrain is steep, and the hilly topography with elevations below 500 m chiefly occurs in the central and eastern coastal areas and has relatively gentle slopes (Ma et al., 2015). The region is also characterized by complex geology. In the south-eastern portion of the region, the geology mostly comprises volcanic rocks and sedimentary rocks. The hilly and mountainous areas, such as Shanzao village, are highly prone to the occurrence of landslides during intense rainfall periods (Li et al., 2004).

c) In Zhejiang Province, there are eight river basins, including the Qiantang, Ou, Lin, Tiaoxi, Yong, Feiyun, and Ao river basins, and the famous Beijing-Hangzhou canal. In the rainy seasons of summer and fall, flooding frequently occurs, sometimes causing severe losses. In a long and narrow flat area between mountains, Linhai city is a typical inundation area in Zhejiang Province. The Ling River runs through the city, and drainage is relatively limited. When TCs bring strong winds and torrential rain, especially flooding and high tides in the Ling River, which can approach or exceed warning levels, the drainage network cannot provide sufficient discharge from the dam, resulting in floods and urban inundation.

d) Land exploration and development usually lead to landslide-prone hillside areas. For example, plantations, reservoirs, and houses can be affected. Some residents built their homes near the confluence of two rivers or on the riverbank, which are areas often affected by TCs.

4 Weather service support for Typhoon Lekima (2019)

The governments at all levels in Zhejiang Province have always prioritized TC hazards. The local meteorological bureaus focused on storm defense and disaster relief. The Taizhou Meteorological Bureau started to release TC information to the public every 6 h, beginning on 6 August. The report released included the landing site and the movement path. A formal warning was issued at 9:00 am on 8 August. The landing time, landing site, and effects of

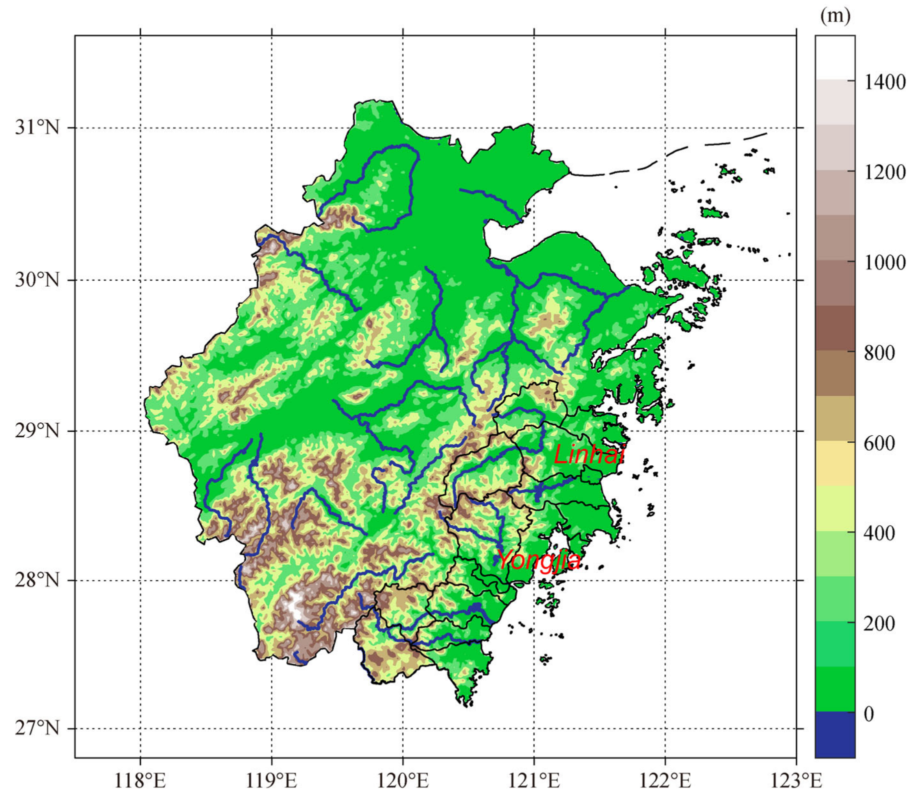

Fig. 9 Topographic relief map of Zhejiang Province. Blue lines show major rivers. The colors show the topography. The elevation data is derived from the Scripps Institution of Oceanography, University of California San Diego (available at Satellite Geodesy website). Red letters are 2 locations where landslide and flooding occurred in the Typhon Lekima (2019) period.

wind and rain were released to the public every 3 h. The rainfall totals in Yueqing city and Yongjia county surpassed those of a one-hundred-year return period. During the storm period, the Yongjia Meteorological Bureau implemented a level 4 Typhoon Emergency Response at 16:30 on 7 August and upgraded to level 2 at 08:15 on 9 August. Soon afterward, the warning was adjusted to level 1 at 11:20 on 9 August.

5 Discussion and recommendations

Typhoon Lekima (2019) led to severe disasters across eastern China. In this paper, if only the precipitation and wind level associated with TCs are considered, Typhoon Lekima (2019) is the strongest and most destructive TC in the Chinese mainland ever recorded. In particular, the TC-induced rainfall is unprecedented.

On the other hand, the extreme rainfall, complex terrain, and geological composition led to disasters in eastern Zhejiang Province. Of the three factors, the one we can forecast as accurately as possible is the first. Precisely controlled and accurate disaster information is crucial to successful disaster response. For a TC making landfall, a slower moving speed increases the duration of the precipitation, while an abnormal path makes local disaster prevention more difficult. For example, Beijing Meteorological Observatory predicted that Typhoon Maisha (No. 0509), which moved northward after making landfall in Zhejiang Province, would bring heavy rainfall to Beijing. However, there was heavy rain only in northeastern Beijing because the true path was different from the prediction. For Typhoon Lekima (2019), the path forecast's accuracy is relatively high due to the improvement of forecasting skills, while the predicted precipitation area and amount of precipitation still have some errors. Enhancing the accuracy of TC forecasts, especially the predictions of heavy precipitation in certain areas, is urgently needed. Furthermore, suppose the precipitation forecast cannot be accurate in a short period. In that case, the relevant databases related to disaster prevention should be created to offset the limited accuracy of early warning systems.

Through this survey, the effects of the catastrophes provided an essential reference for disaster prevention in the future. We noted some aspects of disaster management that need to be improved as follows.

a) As disasters occur, decision-makers often have only a limited time to react quickly. Therefore, combining modern and traditional methods to transmit information to remote mountainous areas rapidly is essential. Taking Shanzao village as an example, there was a short power outage when the landslide occurred, which delayed the rescue efficiency.

b) The public attitude toward disaster prevention should be improved by increasing the general comprehension of weather information, the ability of citizens to respond to events should be enhanced, and consultations should be provided to improve public awareness of disasters, disaster prevention, and disaster response.

c) Human-induced environmental changes should be taken into account. Global Positioning System (GPS), Geographic Information System (GIS), Unmanned Aerial Vehicle (UAV), and other modern methods should be used in disaster monitoring. To fundamentally improve the capability to reduce disaster risks, experts need to update the design standards of engineering construction and perform environmental renovation project assessments. For development in regions with weak geological conditions, the recurrence period of TC-induced wind and precipitation events should be taken into account. It is necessary to perform scenario simulations of critical areas to identify the possible typhoon risks and determine if settlements need to be relocated.

Compared with the comprehensive investigation of Typhoon Morakot (2009), we only focused on precipitation and wind caused by Typhoon Lekima (2019). We hope that future investigation teams will include experts in other fields, such as agriculture, hydrology, engineering, and insurance.

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The major areas impacted by Typhoon Lekima (2019) included Taizhou city, Linhai city, Wenling city, and Yongjia county. We used local meteorological bureaus as the basic investigation units and considered the resources of local governments. A total of 3 departments and more than 12 experts were involved in this investigation. The investigation results informed the following analysis and discussion. Thanks to the Taizhou Meteorological Bureau, the Wenzhou Meteorological Bureau, and the relevant leaders, technicians, and partners who supported and assisted in completing this investigation.

References

Chen P, Lei X, Ying M (2013). Introduction and application of a new comprehensive assessment index for damage caused by tropical cyclones. Trop Cyclone Res Rev, 2: 176–183

Chen P, Yu H Y, Xiao T L, Yan Z Q (2009). Cause analysis and preliminary hazard estimate of typhoon disaster in China. J Nat Disast, 18: 64–73 (in Chinese)

Chen P, Yu H, Xu M, Lei X, Zeng F (2019). A simplified index to assess the combined impact of tropical cyclone precipitation and wind on China. Front Earth Sci, 13(4): 672–681

Cox D, Arikawa T, Barbosa A, Guannel G, Inazu D, Kennedy A, Li Y, Mori N, Perry K, Prevatt D (2019). Hurricanes Irma and Maria postevent survey in US Virgin Islands. Coast Eng J, 61(2): 121–134

Eisenman D P, Cordasco K M, Asch S, Golden J F, Glik D (2007). Disaster planning and risk communication with vulnerable communities: lessons from Hurricane Katrina. Am J Public Health, 97(Suppl 1): S109–S115

Elliott J R, Pais J (2006). Race, class, and Hurricane Katrina: Social differences in human responses to disaster. Soc Sci Res, 35(2): 295–321

Emanuel K, Ravela S, Vivant E, Risi C (2006). A statistical deterministic approach to hurricane risk assessment. Bull Am Meteorol Soc, 87(3): S1–S5

Fang W, Lin W (2013). A review on typhoon wind field modeling for disaster risk assessment. Prog Geogr, 32: 852–867

Fang W, Shi X (2012). A review of stochastic modeling of tropical cyclone track and intensity for disaster risk assessment. Adv in Earth Sci, 27: 866–875 (in Chinese)

Hugelius K, Gifford M, Örtenwall P, Adolfsson A (2017). Health among disaster survivors and health professionals after the Haiyan Typhoon: a self-selected Internet-based web survey. Int J Emerg Med, 10(1): 13

Lei X T, Chen P Y, Yang Y H, Qian Y Z (2009). Characters and objective assessment of disasters caused by typhoons in China. Acta Meteorol Sin, 67: 875–883

Li C J, Wang Y J, Shen X H, Ye J Q (2004). Remote Sensing Survey and Integrated Investigation of Land and Resources in Zhejiang Province. Beijing: Geological Publishing House

Li H C, Hsieh L S, Chen L C, Lin L Y, Li W S (2014). Disaster investigation and analysis of Typhoon Morakot. J Chin Inst Eng, 37 (5): 558–569

Lin C Y, Chen T C, Dai C Y, Yu M L, Lu P L, Yen J H, Chen Y H (2015). Serological investigation to identify risk factors for post-flood infectious diseases: a longitudinal survey among people displaced by Typhoon Morakot in Taiwan, China. BMJ Open, 5(5): e007008

Lin N, Emanuel K, Oppenheimer M, Vanmarcke E (2012). Physically based assessment of hurricane surge threat under climate change. Nat Clim Chang, 2(6): 462–467

Lu Y, Ren F, Zhu W (2018). Risk zoning of typhoon disasters in Zhejiang Province, China. Nat Hazards Earth Syst Sci, 18(11): 2921–2932

Lu Y, Yu H, Yang Q, Xu M, Zheng F, Zhu J (2017). Post-disaster survey of Typhoon Megi in Wenzhou City. Trop Cyclone Res Rev, 6: 34–39

Lu X Q, Zhao B K (2013). Analysis of the climatic characteristics of landing tropical cyclones in east China. J Trop Meteorol, 19: 145–153

Ma T, Li C, Lu Z, Bao Q (2015). Rainfall intensity–duration thresholds for the initiation of landslides in Zhejiang Province, China. Geomorphology, 245: 193–206

Mellman TA, David D, Kulick-Bell R, Hebding J, Nolan B (1995). Sleep disturbance and its relationship to psychiatric morbidity after Hurricane Andrew. Am J Psychiatry, 152(11): 1659–1663

Tajima Y, Tomohiro Y, Benito M P, Eric C, Koji K, Hisamichi N, Mamoru M, Yuji A, Taro A, Noel M O, Ronwaldo A, William M, Justin V, Ferdinand B (2014). Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan. Coast Eng J, 56(1): 1450006-1–1450006-12

Tajima Y, John P L, Jeane C, Mizuka S, Yoshinao M, Takenori S, Dominic B, Marjorie T, Eric C (2017). Post-disaster survey of storm surge and waves along the coast of Batanes, the Philippines, caused by Super Typhoon Meranti/Ferdie. Coast Eng J, 59(1): 1750009-1–1750009-11

Vickery P J, Masters F J, Powell M D, Wadhera D (2009). Hurricane hazard modeling: the past, present, and future. J Wind Eng Ind Aerodyn, 97(7–8): 392–405

Willoughby H E, Black P G (1996). Hurricane Andrew in Florida: dynamics of a disaster. Bull Am Meteorol Soc, 77(3): 543–549

Zhang Q, Wu L, Liu Q (2009). Tropical cyclone damages in China 1983–2006. Bull Am Meteorol Soc, 90(4): 489–496