Assessing the characteristics and drivers of compound flood events ~~Compound flood potential~~ from storm surge and heavy precipitation in coastal China

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Abstract. The interaction between storm surge and concurrent precipitation can cause greater flooding impacts than either in isolation. This paper investigates the potential compound effects from these two flooding drivers along the coast of China. Statistically significant dependence between them exists at the majority of locations that are analysed, but the strength of the correlation varies spatially and depending on how extreme events are defined. In general, we find higher dependence at the south-eastern tide gauges (TGs) (latitude < 30°N) compared to the northern TGs. Seasonal variations in the dependence are also evident. Overall there are more sites with significant dependence in the typhoon season, especially in the summer. Accounting for past sea level rise further increases the dependence between flooding drivers and future sea level rise will hence likely lead to an increase in the frequency of compound events. We also find notable differences in the meteorological patterns driving compound and non-compound events. Compound events at south-eastern TG sites are caused by low-pressure systems with similar characteristics across locations, including high precipitable water content (PWC) and strong winds that generate high storm surge. Based on historical disaster damages records of Hong Kong, compound flood events account for the vast majority of damages and casualties, compared to univariate flooding events, where only one flooding driver occurred. Given the large coastal population and low capacity of drainage systems in many Chinese urban areas, these findings highlight the necessity to incorporate compound flooding and its potential changes in a warming climate into risk assessments, urban planning, and the design of coastal infrastructure and flood defences.

Keywords. Compound flood, Storm surge, Precipitation, China

1 Introduction

Floods are among the costliest and deadliest disasters globally (Hu et al., 2018). In recent years, a series of devastating compound flooding events occurred, such as Hurricane Isaac in 2012, Typhoon Haiyan in 2013, Hurricanes Irma and Florence in 2018, and Typhoon Lekima in 2019. Despite improvements in flood defences, flood forecasting, and warnings, these flood events caused devastating impacts, in parts due to the limited understanding of compound floods in coastal regions. Flooding along the coast can arise from three main sources: 1) extreme sea levels (comprised of storm surge, high astronomical tides, and/or waves (coastal flood)); 2) river discharge (fluvial flood); and 3) direct surface run-off from rainfall (pluvial flood) (Hendry et al., 2019). Floods in coastal areas are frequently caused by more than one driver, none of which have to be extreme themselves, but the corresponding impacts when they coincide are often much greater than from either flood driver occurring in isolation (Leonard et al., 2014; Zscheischler et al., 2018; Hao et al., 2018). Exploring the probabilities of compound flood events and understanding their driving processes is important for flood mitigation and risk reduction in a warming climate (Wahl et al., 2015).

A growing number of studies investigated compound flooding in recent years. At the global scale, dependence between storm surge and river discharge has been investigated based on observational data (Ward et al. 2018) and model hindcasts (Bevacqua et al., 2020; Couasnon et al., 2020). The relationship between storm surge and wind waves was assessed by Marcos et al. (2019). At the regional scale, compound flood assessments have been undertaken for Australia (Zheng et al.,2013; Zheng et al.,2014; Wu et al., 2018), the USA (Wahl et al., 2015), the UK (Svensson and Jones, 2002, 2004; Hendry et al., 2019), and Europe (Petroliagkis et al., 2016; Paprotny et al., 2018; Bevacqua et al., 2019; Ganguli and Merz, 2019). Other studies focused on specific locations, such as the Netherlands (van den Hurk et al., 2015); Fuzhou, China (Lian et al., 2013); Taiwan, China (Chen and Liu, 2014), or the North Sea (Khanal et al., 2019). Most of these studies investigated the dependence between two hazards, such as storm surge and river discharge, storm surge and waves, or storm surge and rainfall.

For China, a comprehensive regional assessment of compound flooding is currently missing. Low-lying coastal areas (elevation less than 10 m) in China only account for 2% of the national land, but account for more than 12% of the national population (Liu et al., 2015; Fang et al., 2020). At the same time, these areas are experiencing frequent coastal disasters from tropical cyclones (TCs) and storm surges, among others. Coastal flooding has caused more than US$ 71 billion direct economic losses and 4,376 fatalities in China from 1989 to 2014 (Fang et al., 2017). Flood risk is likely increasing in China due to climate change (most notably sea level rise), as well as human factors (e.g. human-induced subsidence) (Fang et al., 2020; Jiang et al., 2020; Wu et al., 2005; Wu et al., 2017). Meanwhile, fast urbanisation in China has led to more people and economic assets exposed to hazards (Fang et al., 2018; Du et al., 2018), and has also prompted irrational urban planning, increased areas of urban impervious surface, and low capacity drainage systems (Cheng, 2020). For example, the capacity of the local drainage system of Shenzhen City is designed to drain the surface runoff associated with a 2-year return period (Urban Planning & Design Institute of Shenzhen, China, 2008). As drainage facilities are often under-designed and/or have not been upgraded, surface runoff during storms frequently exceeds the drainage capacity resulting in flooding damages in low-lying areas (Qin et al., 2013). Despite the relevance of compound flood risk for coastal China, the associated probabilities and driving mechanisms have not been explored at broad spatial scales at the national level.

A limited number of studies have assessed different aspects of compound flooding for China. Lian et al. (2013) and Xu et al. (2014) investigated the joint probability, using copulas, of extreme precipitation and storm tide and associated changes for Fuzhou city. Both studies showed that the joint impacts from surge and precipitation were much higher than from each individually; this is currently ignored in the design of flood defences. Xing et al. (2015) analysed joint return periods of precipitation and runoff in the upper Huai River Basin in China. Ye et al. (2018) estimated compound hazard severity of TCs considering extreme wind and precipitation. Changes in storm surges and precipitation in China have also been investigated separately, showing significant increases in extreme precipitation in parts of the southwest and south China coastal areas (Zhai et al., 2005). Similarly, significant increases in sea level extremes have been reported (Feng et al., 2014; Feng et al., 2019), and attributed to both changes in mean sea level (MSL) and in the wind driven storm surge component (Feng et al., 2015). However, these previous studies were mostly local, they neglected seasonal characteristics, and weather circulation patterns driving compound events were not assessed. In this study, we use the most comprehensive records of storm surge and precipitation to investigate dependencies and incidences of compound flooding associated with storm surge and heavy precipitation along the coast of China, as well as the large scale weather systems causing compound events.

In this context our three main objectives are to: 1) identify and collate compound events from storm surge and precipitation, and analyse~~s~~ their dependence~~identify and collate compound events from storm surge and precipitation, and analyse their dependence, including the role of sea level rise and seasonality~~; 2) examine how the strength of dependence between storm surge and precipitation is influenced by seasons and threshold selection~~understand the driving weather patterns of compound/non-compound events~~; and 3) identify the driving weather patterns of compound/non-compound events~~compare damages caused by compound and non-compound events~~.

2 Data

Most tide gauge (TG) data are kept confidential in China; thus, we obtained hourly sea-level data of 11 TGs with at least 20-year lengths along the Chinese coast from the University of Hawaii Sea Level Center (Caldwell et al., 2015). Locations of TGs and the time series' lengths are shown in Fig. 1. The stations are located south of the Shandong peninsula in China, where tropical cyclone impacts are most severe. Nine of the 11 TG stations have about 20 years of data (1975-1997), Xiamen and Hong Kong have 46 years (1954-1997) and 52 years (1962-2014), respectively.

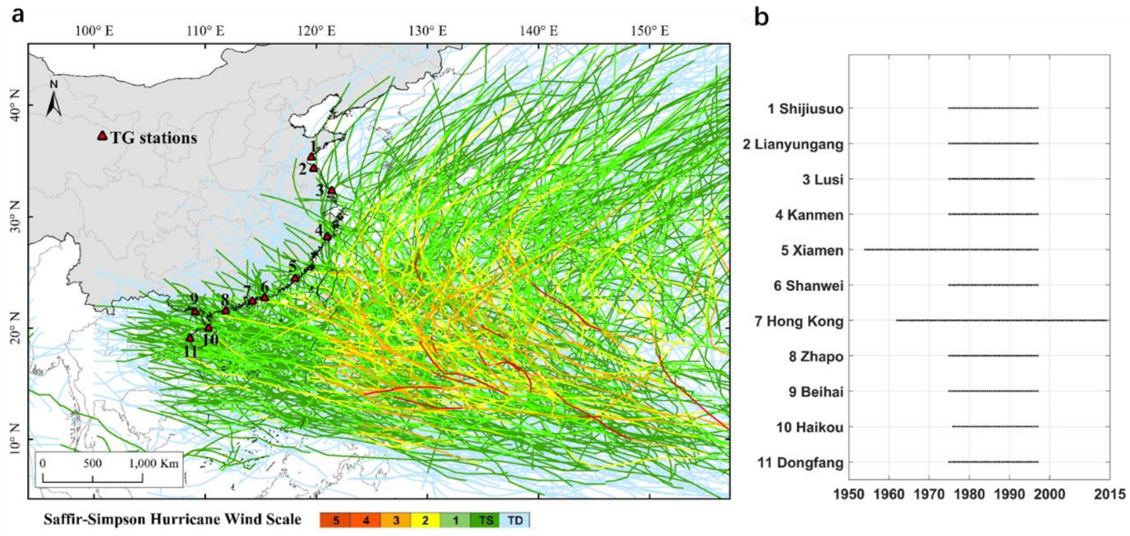

Fig.1 (a) Locations of 11 tide gauges and historical typhoon tracks for different intensities (only 1975-1997 shown here); (b) time periods covered by hourly data at the 11 tide gauges

Storm surge is extracted using the MATLAB t_tide package (Pawlowicz et al., 2002) by applying a year-by-year harmonic tidal analysis with 67 constituents. ~~It~~ This also effectively removes the ~~annual mean sea level, namely, removing~~ MSL influence including the long-term trend in MSL as well as the year-to-year and decadal variability. The data has been checked for common errors and 75% completeness of each year is required. An offset in the Hong Kong data is adjusted by shifting the earlier data by 1.02 cm, following Ding et al. (2002).

Cumulative daily precipitation records from 1951-2015 are collected from China Meteorological Administration. The closest meteorological station is chosen to match each TG station, and the distance between them is less than 25 km for 9 out of 11 TGs (TG2 with 29 km and TG8 with 34 km) ~~are less than 25 km distance~~. The time series of precipitation observations are usually longer and more complete than TG observations; thus TG data availability determines the lengths of overlapping periods available for the dependence analysis presented here.

To identify weather patterns typically associated with compound and non-compound events, sea surface pressure (SLP), precipitable water content (PWC), and wind fields are used from the Twentieth Century Reanalysis Project Version 2c (Compo et al.,2011).

~~To compare impacts caused by compound and non-compound events, we employ a typhoon database developed by Yap et al. (2015), which includes historical typhoon records from 1951 to 2012, with the main focus on Hong Kong, Taiwan, and the south-eastern Chinese coastal provinces of Zhejiang, Fujian, Guangdong and Hainan. The database contains information of 853 typhoons in total, with records of direct normalized economic loss (in US$), death toll, and number of people affected.~~

3 Methodology

3.1 Selecting compound events

The combination of storm surge and precipitation can exacerbate the flood impacts in different ways (Wahl et al., 2015). First, both heavy precipitation and extreme sea levels (storm surge with high tides) can coincide, leading to more severe floods. This often happens during typhoon events. Second, impacts of a storm surge already causing flooding will increase when significant precipitation occurs at the same time, although the precipitation itself may not be considered extreme. Third, a moderate storm surge can block freshwater water drainage and high precipitation occurring at the same time can lead to more serious flooding (as compared to the same rain event coinciding with low sea level). To capture all of those mechanisms, we investigate the relationship of storm surge and precipitation for two distinct cases: in Case 1 we select extreme storm surge events and the corresponding precipitation within ± 1 day of the surge; in Case 2 we select extreme precipitation events and the corresponding storm surges within ± 1 day of the precipitation (Fig. 2).

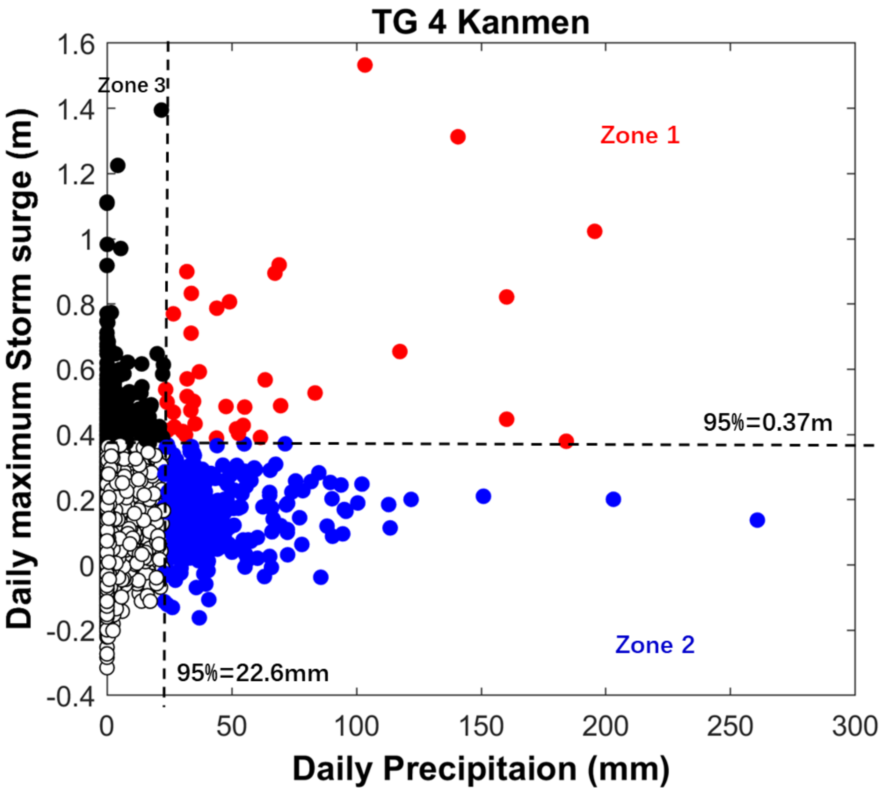

Fig. 2 Daily maximum storm surge plotted against daily maximum precipitation for threshold of 95%. Case 1 indicates Zone1 and Zone3. Case 2 indicates zone1 and zone2. Red dots (plotted in Zone 1) show the events with potential for compound flooding (i.e. joint occurrence of high storm surge and heavy precipitation), whereas blue (Zone 2) and black (Zone 3) dots define the non-compound events (i.e. high storm surge or high precipitation only, respectively)

We use the peaks over thresholds (POT) method to select extreme events. The POT method refers to selecting events over a high threshold within a certain time span. The annual maximum approach is widely used for sampling extreme events. However, it would be not appropriate here as time series of 9 out of 11 TGs in China only have around 23 years of data, which would lead to small sample sizes. Furthermore, the second or third largest values in a given year may be larger than the annual maximum in another year (Coles et al., 2001; Arns et al., 2013). To test the sensitivity of the results to the threshold selection, we employ thresholds related to eight percentiles ranging from 95% to 99.5%, i.e., 95%, 96%, 97%, 98%, 98.5%, 99%, 99.25% and 99.5%. Independence of the POT sample was achieved using a declustering time of 3 days. We also test how the inclusion of sea level rise affect the compound events (in Section 4.2).

3.2 Dependence analysis

Kendall's rank correlation coefficient τ is employed to measure dependence between storm surge and precipitation. In Case 1, storm surges sometimes could occur without any precipitation, and this leads to ties (i.e., several zero values) affecting the dependence analysis. We use the same method as suggested in Kojadinovic (2010) and Wahl et al. (2015) by assigning ranks randomly, repeating the procedure 100 times and calculating the average rank correlation. To better understand the influence of seasonality, dependence is assessed for the full year as well as for summer (June to August), autumn (September to November), and the typhoon season (July to October) separately.

We also assess how compound event frequencies are affected by MSL rise along coastal China. The effects of MSL are initially removed during the harmonic tidal analysis. In order to assess the compound effects under nonstationary conditions, we repeat the analysis but keep the MSL influence and extract surge events by only removing the tidal influence, i.e., total water level minus tide. Then we re-count the numbers of compound events (i.e. falling in Zone 1 in Fig. 2) with MSL included.

3.3 Weather patterns

To investigate the meteorological patterns that drive compound and non-compound flood events, sets of the two types of events are selected based on a threshold of 98%. Compound events refer to joint occurrences of high storm surge and heavy precipitation (Zone 1 in Fig. 2). Non-compound events refer to only high storm surge (Zone 2 in Fig. 2) or only heavy precipitation (Zone 3 in Fig. 2). SLP, PWC, and wind fields on the days are selected to match days when compound/non-compound events occurred, then they are averaged into composites to represent reference synoptic-scale weather patterns favouring compound events.

~~3.4 Losses associated with compound and non-compound events~~

~~In order to quantify the differences in impacts causes by compound and non-compound events, we employ historical damage records. We take Hong Kong (TG 7) as an example; it also has the most historical damage data available, from 1962 to 2012. The other ten TGs cannot directly be linked to the damage database, as the typhoon database from Yap et al. (2015) only collected damage records at province level. Therefore, to compare damages caused by compound and non-compound events, we match the days when the selected compound/non-compound events (separated in the same way as for the synoptic weather type analysis) occurred with records in the database including information of death toll, people affected, and economic losses.~~

4 Results

4.1 Dependence between storm surge and precipitation

Figure 3 demonstrates dependence between storm surge and precipitation in Case 1 and Case 2, also indicating the impact of the thresholds (95% to 99.5%) which can influence the correlation. For Case1, south coastal China, which is more affected by TCs (Fig. 1), exhibits higher dependence than the northern part. Overall, Case 1 dependence is also higher than Case 2 dependence and we identify more locations with significant dependence, 11 TGs in Case 1 and 7 TGs in Case 2, respectively.

Haikou (TG10) shows the highest positive dependence for both cases among all TGs. Kanmen (TG4) shows the second highest positive dependence for Case 1, and also shows relatively high dependence in Case 2. Lianyungang (TG2) and Beihai (TG9) show insignificant dependence for both cases, indicating that a limited number of compound events occurred at those sites (Fig. 3c and 3d). Shanwei (TG6) and Zhapo (TG8) show high positive dependence in Case 1, but insignificant dependence in Case 2, meaning that high storm surge is often accompanied by high rainfall but not the other way round. The opposite is true for Lusi (TG3) which has positive dependence in Case 2, but insignificant dependence in Case 1.

At most locations the dependence increases when higher thresholds are used to sample extremes (Fig. 3c and 3d). There are exceptions however, for example, Haikou (TG10) in Case 2 shows higher dependence with a threshold of 99% than 99.5%. At some TGs dependence becomes insignificant due to small sample sizes when thresholds are very high, indicating the trade-off between bias and variance in the threshold selection. Thresholds for compound events are very localized and highly dependent on the underlying data and various methods exist to select bivariate extremes (Salvadori, et al., 2016); we did not compare those methods here as it would go beyond the scope of our study.

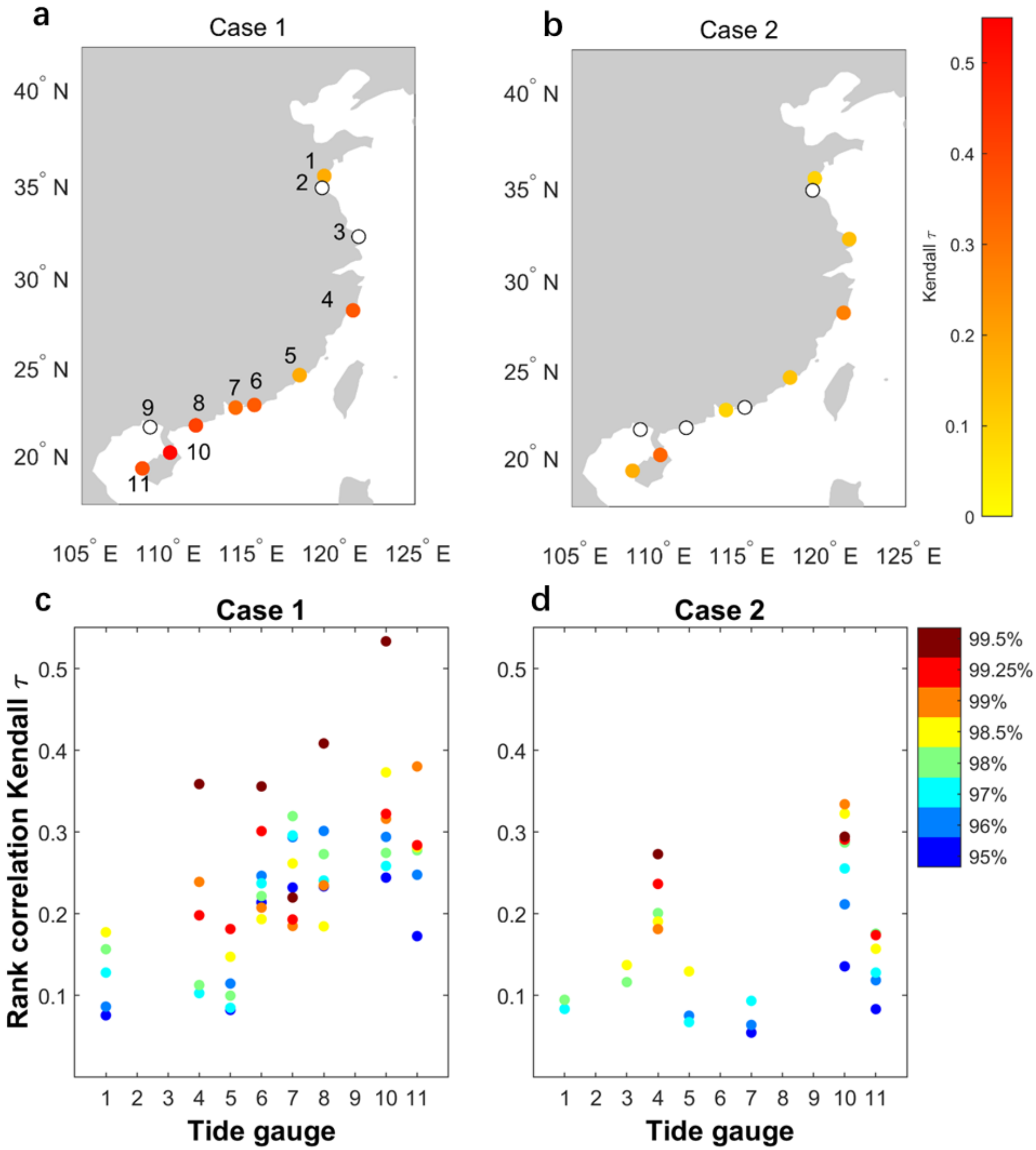

Fig. 3 Kendall’s tau between storm surge and precipitation for thresholds from 95% to 99.5% for Case 1 (a and c) and Case 2 (b and d). Maximum dependence was plotted for Case 1 and Case2 in a) and b), white dots refer to insignificant dependence (10% level). Only significant results at the 90% confidence level are shown in c) and d).

4.2 Effects of sea level rise on compound event frequencies

8 out of 11 TGs show an increase of compound events when MSL influence is included (Fig. 4), number of compound events of TG 10 (Haikou) remain unchanged. For example, at Lianyungang (TG2) and Beihai (TG9), only one compound event is identified when MSL is removed, while this number increases to 22 and 26, respectively, with MSL included. It indicates that coastal China will experience an increasing frequency of compound flood events with future MSL rise. This is in line with Moftakhari et al. (2017) and Bevacqua et al. (2019), who also report that SLR will lead to more compound events. SLR not only increases the probability of coastal flooding from storm surges (Buchanan et al., 2017), but also poses an additional threat for coastal communities susceptible to compound events. Meanwhile, other flood drivers, such as precipitation, river discharge, waves, and TCs, can also exhibit nonstationarity leading to increased (compound) flood risk (Kundzewicz et al., 2019). Observations from the last five decades and numerical model studies (Lai et al., 2020) indicate a slowdown of TCs, which would likely favour more extreme rainfall during the events as compared to fast-moving TCs.

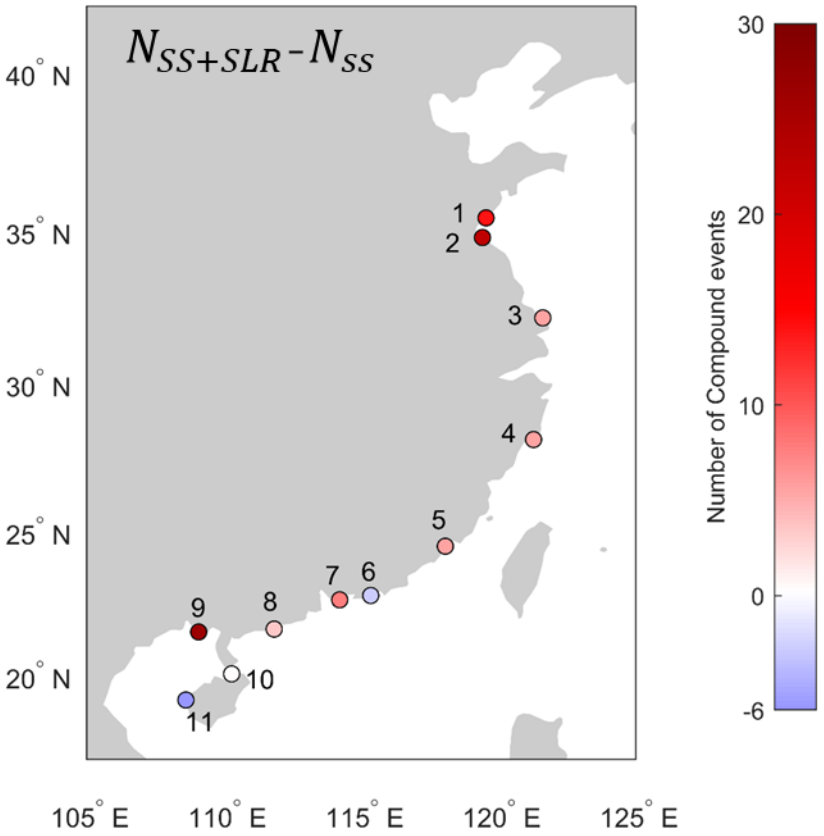

Fig. 4 Counts of compound events between storm surge and precipitation with/without sea level rise at threshold of 98% (falling in Zone 1 in Fig. 2). N_{SS+SLR} indicates compound events between storm surge considering historical sea level rise trend. N_{SS} indicates compound events between storm surge by removing annual mean sea level.

4.3 Seasonal variation

To better understand the timing of events leading to joint dependence throughout the year (as identified in Section 4.1), the influence of seasons is investigated. TCs are active over the western North Pacific during July to October (He et al., 2015). Thus, four periods are considered: typhoon season (July-October), summer (July-August), autumn (September-November), and whole year. The seasonal dependences for different thresholds in the POT sampling are displayed in Fig. 5. Lianyungang (TG2), Lusi (TG3), and Beihai (TG9) show insignificant dependence for both cases and all seasons and thresholds, they ~~and~~ are therefore not included.

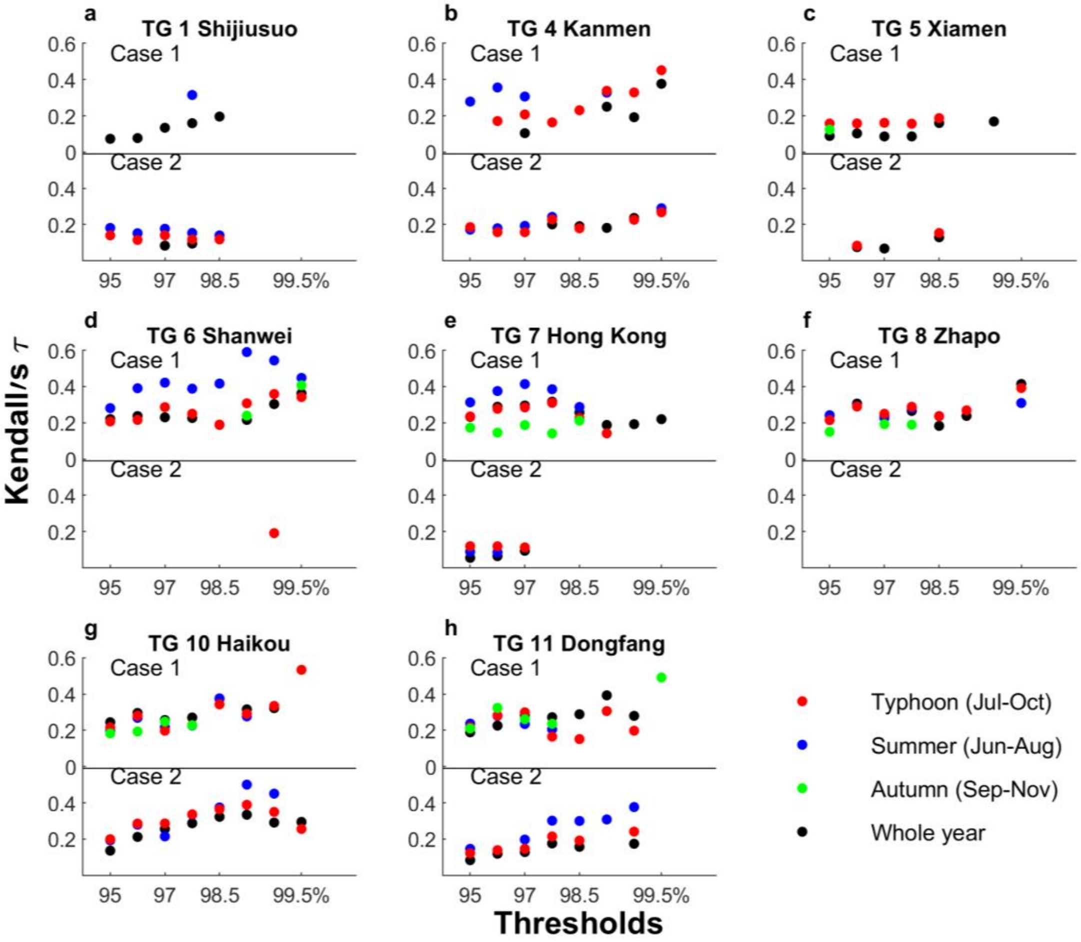

Fig. 5 Kendall's tau between storm surge and precipitation in summer, autumn, the typhoon season, and the whole year for different thresholds used in the POT sampling for Case 1 (a) and Case 2 (b) (Only significant dependences at the 90% confidence level are shown).

For Case 1, multiple TGs show stronger dependence in summer and in the typhoon season compared to the whole year, such as Kanmen (TG4), Shanwei (TG6), and Hong Kong (TG7). Compared to Case 1, there are fewer locations with significant dependence for Case 2. Shanwei (TG6) and Zhapo (TG8) show insignificant dependence in Case 2, while significant positive dependence is found in Case 1. For most TGs, dependence varies with the increase of thresholds. However, for multiple TGs, such as Kanmen (TG4), Shanwei (TG6), Zhapo (TG8), Haikou (TG10), and Dongfang (TG 11) dependence continuously increases with higher thresholds. Again, for some TGs, dependence becomes insignificant for high thresholds, e.g. Hong Kong (TG7), indicating the importance of threshold selection, especially when records are short.

TGs from Kanmen (TG4) to Dongfang (TG11) are most affected by TCs, and show high dependence for Case1, especially in summer and in the typhoon season. Xiamen (TG5), is an exception, likely because Taiwan Island weakens the intensity of cyclones before reaching Xiamen. Stronger dependence in autumn is found for southern TGs (latitude < 25°N), such as Hong Kong (TG7), Beihai (TG9), and Dongfang (TG11), where typhoons still occur autumn. The dependences in typhoon season are similar with the whole year, which indicates that most compound events occur in the typhoon season. For example, 80% compound events (Zone 3 in Fig. 2) for Hong Kong (TG7) and 97.5% for Haikou (TG10) occurred in the typhoon season. South-east coastal China is not only affected by TCs, but also by summer monsoon precipitation from the Northwest Pacific Subtropical High. The summer monsoon brings continuous precipitation since June to August in southern China. Thus, the dependence is higher in the summer compared to the typhoon season. It has been reported that an abrupt increase of intense typhoons occurred in September after the mid-2000s for south China (He et al., 2016), which could affect the seasonality of compound events. However, from the results shown in this study, this pattern is not captured due to limited observation (most observations end in 1997).

4.4 Links to weather patterns

We derived composite plots of synoptic conditions of SLP, PWC, and wind fields that drive compound (both high storm surge and heavy precipitation) and non-compound events (high storm surge or heavy precipitation only) across coastal China. To illustrate the results, we focus on Kanmen (TG4) and Shanwei (TG6) on the east and south coast of China, which both have been frequently affected by typhoons (Fig. 6 and Fig. 7). Results for the other nine stations are shown in Supplementary Figs. S1- S9. Based on the thresholds we selected to identify compound and non-compound events (see Method 3.3), we identify 15 compound events for Kanmen (TG4) and 21 events for Shanwei (TG6), respectively.

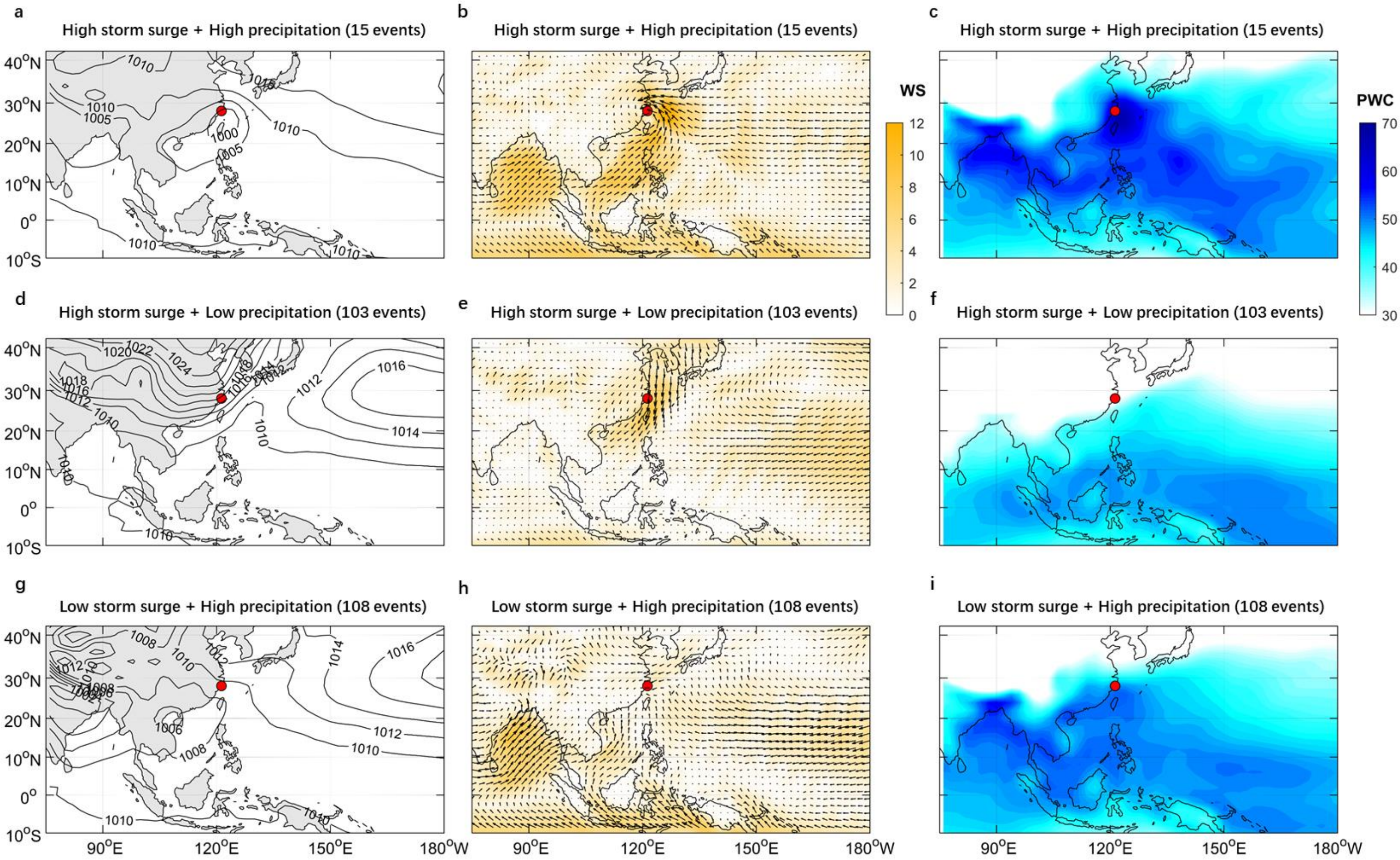

Fig. 6 Meteorology conditions for Kanmen (TG 4): (a, d, g) sea-level pressure (mbar), (b, e, h) wind speed (m/s) and direction (grey arrows), and (c, f, i) precipitable water content (PWC, kg m^{-2}) during (a, b, c) compound events with high storm surge and high precipitation, (d, e, f) for non-compound events with high storm surge and low precipitation, and (g, h, i) non-compound events with low storm surge and high precipitation.

The meteorological patterns in SLP, PWC, and wind fields are distinctly different across the three event types. At Kanmen (TG4), compound events are associated with a well-defined low-pressure system with strong east-west and south-westerly winds transporting moist air toward the south-eastern coast of China (Fig. 6a-c). Non-compound events with only high storm surge exhibit a distinct pressure gradient along the coast (Fig. 6d). As expected, the wind speed is much stronger along the coast for this case (Fig. 6e) compared to the one where only precipitation is high (Fig. 6h), and the northern high wind drives moist air away from the site of interest. The differences in PWC patterns for compound and non-compound events are more pronounced (Fig. 6c, f, i). There is low PWC for the type of only high storm surge events (Fig. 6f), while high PWC from the Bay of Bengal and cross-equatorial flow is observed for the other two types of events.

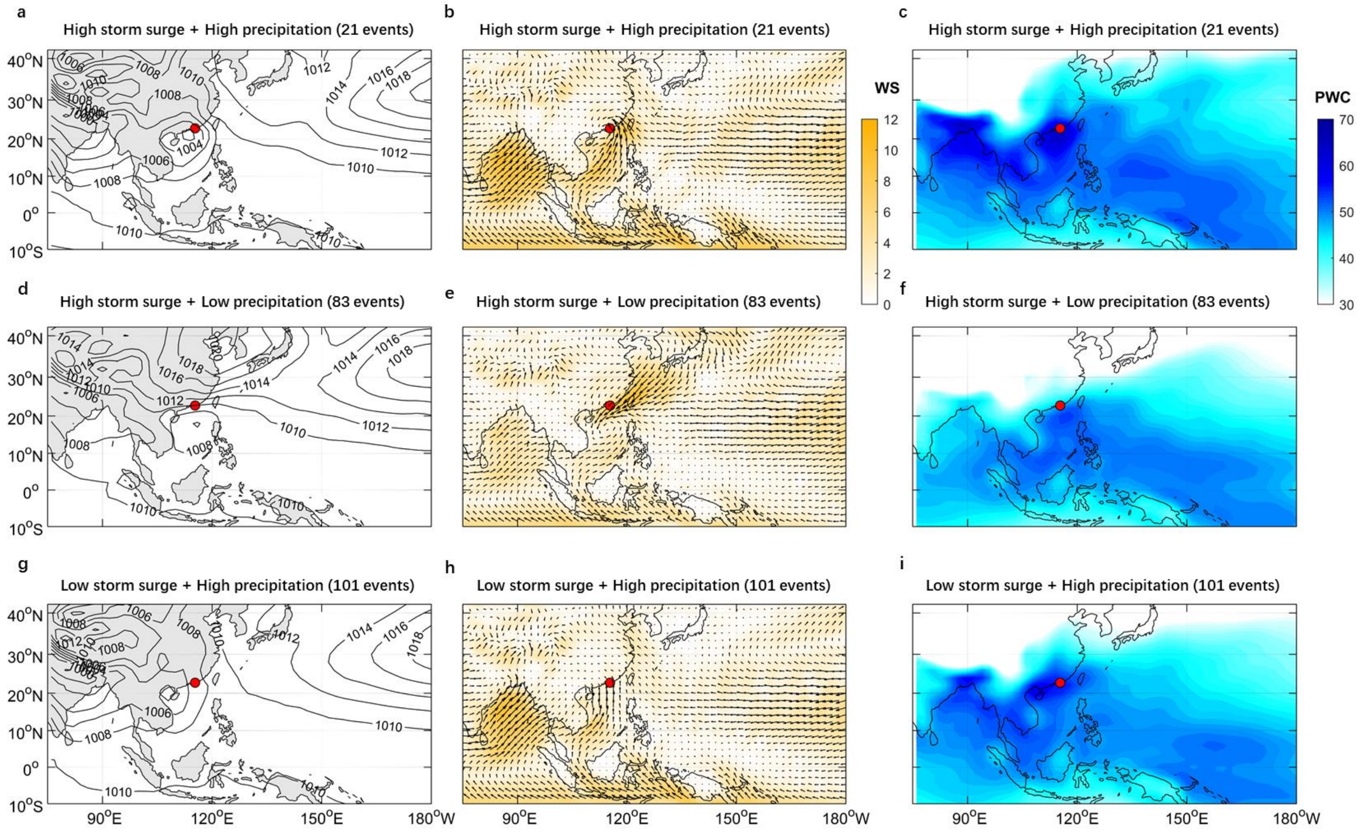

Fig. 7 Meteorology conditions for Shanwei (TG 6): (a, d, g) sea-level pressure (mbar), (b, e, h) wind speed (m/s) and direction (grey arrows), and (c, f, i) precipitable water content (kg m-2) during (a, b, c) compound events with high storm surge and high precipitation, (d, e, f) for non-compound events with high storm surge and low precipitation, and (g, h, i) non-compound events with low storm surge and high precipitation.

At Shanwei (TG 6), similarly to Kanmen, the meteorological patterns in SLP show a cyclone-structure for both compound events and non-compound events with only high storm surge (Fig. 7a and 7d). For events with high storm surge only, there is a distinct pressure gradient and strong wind speed (Fig. 7e). The PWC is low for the high storm surge events and high for compound and precipitation only events (Fig. 7c, f, i). For precipitation only events, flows from the Bay of Bengal and cross-equatorial flow is observed, and south-eastern wind drives moist air to the site of interest for compound events and high precipitation only events (Fig. 7b and 6h).

The results for other stations are similar (Supplementary Figs. S1-S9). For compound events, synoptic weather patterns for south-eastern TG sites (latitude < 30°N) show similar low-pressure systems carrying intense PWC and causing strong wind. For northern TGs, such as TGs 1-3 (Supplementary Figs. S1- S3), the low-pressure systems are less developed compared to other TG sites. As most typhoons make landfall along the south-eastern China coasts, their intensity decreases when they move from south to north (see also Fig. 1).

~~4.5 Impacts caused by compound and non-compound flood events~~

5 Discussions

~~To understand impacts caused by compound and non-compound events, we calculated death toll, people affected, and economic losses for both classes of flooding events. Here we identify compound and non-compound events in the same way we did for the synoptic weather type analysis. The impact data base does not include information on all events that we identified, as not all of them led to significant impacts or the impacts were not recorded. A total number of 42 compound flood events (HH) are identified for Hong Kong, 135 events with high surge and low precipitation (HL), and 160 events for low surge and high precipitation (LH). As shown in Fig. 8, compound flood events caused 225 deaths, affected 26,718 people, and led to US$ 221 million in damages. Non-compound flood events caused 63 deaths, affected 4623 people, and caused US$ 0.16 million recorded damage. Hence, compound flooding events contributed 78% of the reported causalities, 85% of the people affected, and almost recorded damage.~~

The findings presented here are consistent with previous studies conducted for other regions, such as USA (Wahl et al., 2015) and Europe (Ganguli and Merz, 2019). On the one hand, significant dependence exists between various flood hazard drivers which should be taken into consideration when drainage systems and other flood mitigation infrastructure are designed. This is of particular importance for coastal China, as China was the country with the fastest growing amount of artificial impervious areas between 1985-2018 and now ranks first globally in terms of total impervious area (Gong et al., 2019). On the other hand, our results indicate that the frequency of compound events is increasing for coastal China under climate change, in particular sea level rise, which is also in line with previous studies (Moftakhari et al., 2017; Bevacqua et al., 2019). Additional drivers of climate change and variability could further exacerbate the associated flood impacts (Liu et al., 2018). There is evidence, for example, that ENSO has an impact on the dependence between storm surge and precipitation in Australia (Wu and Leonard, 2019). Hence, future research should focus on the interaction between climate processes (e.g., El Nino and/or rising temperatures) and different flooding drivers, such as precipitation, river discharge, waves, and TCs, and their joint occurrences as well as the associated impacts. The latter are often hard to quantify without using computationally expensive hydrologic and hydraulic models, which are usually limited to local applications as opposed to the larger regional assessment conducted here. However, we can use a damage database for Hong Kong as a case study to explore past impacts of extreme events that were either compound or non-compound events from a flooding point of view. ~~To understand impacts caused by compound and non-compound events, we take Hong Kong as the case , w~~We employ ~~-~~a typhoon disaster database developed by Yap et al (2015) with records between 1962 and 2012, and ~~we~~ consider ~~by calculating~~ death toll, people affected and economic losses. ~~The other ten TGs cannot directly be linked to the damage database, as the database only collected damage records at province level. Here w~~We identify compound and non-compound events in the same way we did for the synoptic weather type analysis, then match the days when the selected compound/non-compound events occurred with records in the database including damage information. Thus, there are 315 events identified as compound (44 events in zone 1 in Fig. 8) and non-compound (116 events for zone 2 and 155 events for zone 3 in Fig. 8) events for Hong Kong. The damage database does not include information on all events that we identified, as it is a historical typhoon disaster damage dataset. Among them, 168 events are not matched to typhoon historical records, and they are all non-compound events. 68% of those unmatched events (115 events) are identified as low storm surge and high precipitation, ~~it might be caused by short-term heavy precipitation happened due to strong~~and hence more likely related to convective ~~processes~~rainfall events. It also~~for~~ indicates that not all those events lead to significant damages or the damages were not recorded. As shown in Fig. 8b, compound flood events caused 227 deaths (average 5 deaths per event), affected 29,550 people (672 affected people per event), and led to US$ 221 million (US$ 5 million per event) damages. Non-compound flood events caused 65 deaths (average 0.24 deaths per event), affected 6469 people (23.87 affected per event), and caused US$ 0.92 million (US$ 0.003 million) recorded damage. ~~It could be seen that~~ Hence, compound flooding events contributed 78% of the reported causalities, 82% of the people affected, and ~~almost~~the vast majority of recorded damages. It is difficult to exactly quantify compound and non-compound effects, as reported historical damage records could contain inaccuracies and inconsistencies, such as various reported numbers from different sources and incomplete information. ~~Meanwhile~~Furthermore, the typhoon damages not only result~~s of~~from flooding due to heavy rainfall and storm surge, but also include damages from other effects, such as gale~~ for example~~. From the perspective of disaster system theory (Shi et al., 2020), it is also related to vulnerability and human activities. Due to the complexity of damage records themselves, unfortunately, there is no straightforward way to disentangle the fraction that each hazard contributed to the recorded damages, but nevertheless the analysis highlights the importance of compound flooding events in causing damages in highly urbanized areas. ~~. The compound effects need further analysis if more reliable damage datasets are available.~~

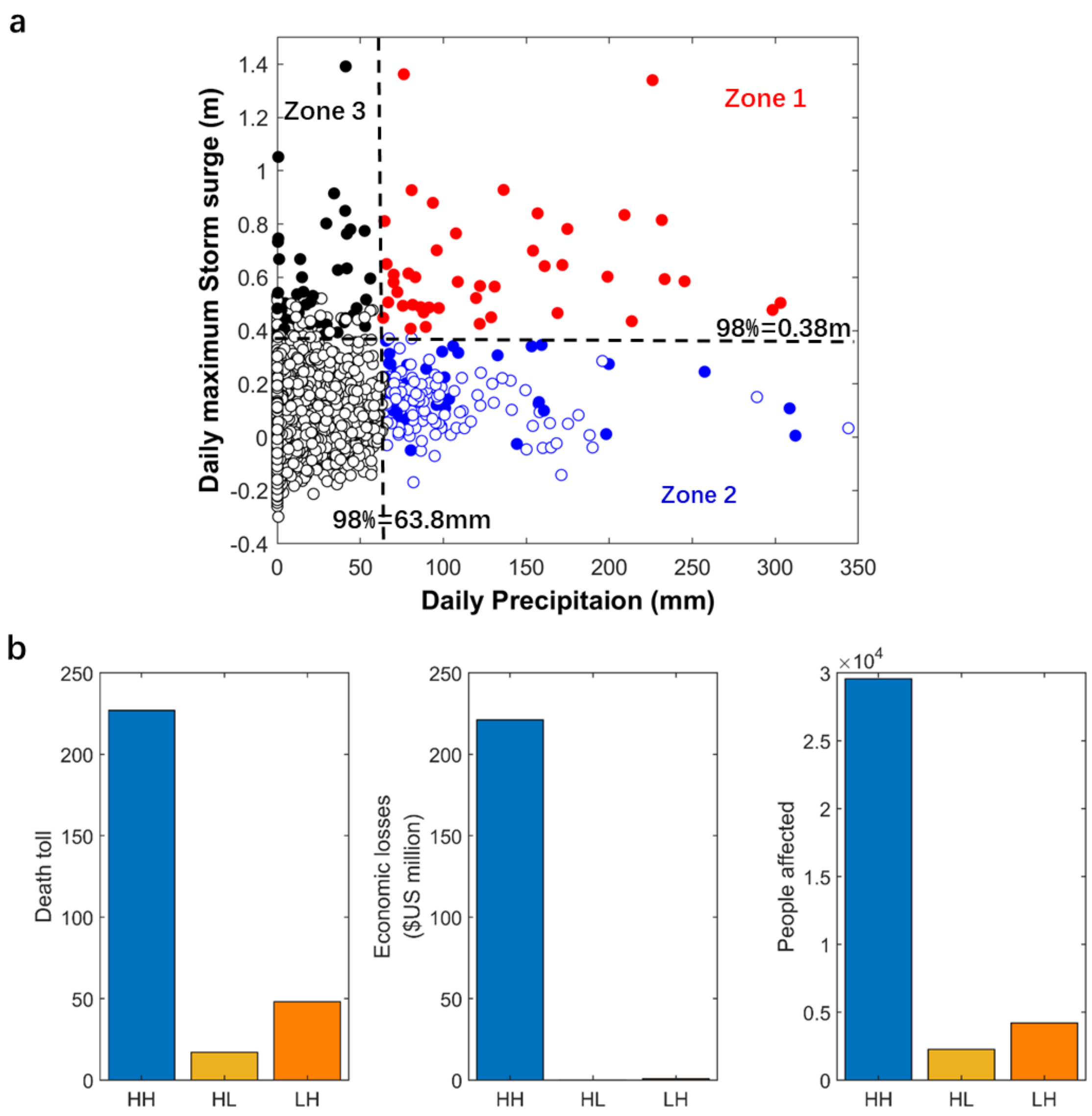

Fig. 8 a) Daily maximum storm surge plotted against daily maximum precipitation for threshold of 98% for Hong Kong. Filled dots indicate events were linked to typhoon historical damage records. b) damages by compound (HH: high storm surge and high precipitation) flood and non-compound flood events (HL refers to high storm surge and low precipitation; LH refers to low storm surge and high precipitation) in Hong Kong.

~~5~~ 6 Conclusions

In this study, we demonstrate that compound flood events comprised of high surge and heavy precipitation can occur along major stretches of coastal China. The results show that significant dependence exists between the two flood drivers at many locations, especially at sites in lower latitudes (latitude < 25°N). The dependence varies when using different thresholds in the event sampling and is also affected by seasonality. The latter shows that compound events occur more often during the typhoon season, especially in summer. In terms of weather patterns, compound events at south-eastern TG sites (latitude < 30°N) are caused by low-pressure systems of similar characteristics carrying intense PWC and causing strong winds that generate storm surges. For Hong Kong, we find that compound flooding events were responsible for the vast majority of the recorded casualties and damages, as opposed to flooding events where only one driver was extreme. We also find SLR plays an important role ~~for increasing~~ in causing more frequent ~~occurrence of~~ compound events. As SLR keeps rising, it will keep exacerbating the compound effects of flood drivers.

One of the main limitations of this study is the relatively small number of tide gauge sites and limited length of the time-series available, especially from TGs. For now, publicly accessible datasets considered here constitute the most comprehensive collection of hourly sea level data along Chinese coasts. There is an urgent need for longer data sets to be used in order to better assess compound flood risk, especially for south-east China coasts which are prone to TCs. Here we only consider two drivers of flooding, precipitation and storm surge. The role of other flooding drivers needs to be further explored, as well as compound effects under nonstationary conditions, including bivariate frequency analysis, assessing the relationship to climate indices, and the implications for flood risk management. The latter is particularly important, given the low capacity of drainage systems in many Chinese urban areas.

Ignoring compound effects likely leads to an underestimation of flood risk in coastal China, particularly along the south-eastern coasts. It is therefore crucial that coastal cities and urban planning authorities address compound flood effects (including additional drivers such as river discharge or waves) when designing coastal infrastructure and flood defences or developing adaptation plans to combat the negative impacts of climate change.

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Competing interests. The authors declare that they have no conflict of interest.

Data availability. This study relies entirely on publicly available data from 1) hourly sea-level data of 11 TGs with at least 20-year lengths along the Chinese coast from the University of Hawaii Sea Level Center; 2) cumulative daily precipitation records from 1951-2015 are collected from China Meteorological Administration.;3) meteorological data from the 20th Century Reanalysis, Version 2c, obtained from the National Oceanic and Atmospheric Administration website; 4) historical damages records from a typhoon database developed by Yap et al. (2015) including historical typhoon records from 1951 to 2012.

Supplementary. Meteorological patterns for associated with compound and non-compound events at the other 9 TGs (not shown in the manuscript) are shown in the supplementary.