Supplementary Information for

Global compound floods from precipitation and storm surge:

Hazards and the role of cyclones

Yangchen Lai\textsuperscript{1,2,3,4}, Jianfeng Li\textsuperscript{1,3,4*}, Xihui Gu\textsuperscript{5,1*}, Cancan Liu\textsuperscript{6,3}, Yongqin David Chen\textsuperscript{7,6,3}

1. Department of Geography, Hong Kong Baptist University, Hong Kong, China
2. Key Laboratory for Geo-Environmental Monitoring of Great Bay Area, Ministry of Natural Resources, Shenzhen University, Shenzhen, China
3. Guangdong-Hong Kong Joint Laboratory for Water Security, Hong Kong Baptist University, Hong Kong, China
4. Institute for Research and Continuing Education, Hong Kong Baptist University, Shenzhen, China
5. Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, China
6. Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China
7. School of Humanities and Social Science, The Chinese University of Hong Kong, Shenzhen, China

*email: jianfengli@hkbu.edu.hk; guxh@cug.edu.cn
Illustration of the selection of minimum record length threshold based on the number of available tide gauges

In this study, we selected 18 years as the minimum threshold of record length given the consideration of the number of available tide gauges and the quality of the analysis. As shown in Figure S1a, the number of available tide gauges decreased as the minimum threshold was increased. Figure S1b shows the reduced number of tide gauges when the minimum record length threshold was increased. The number of tide gauges reduced increased obviously when the threshold was increased from 18 to 19-21 years. The numbers of available tide gauges were 297, 275, and 254 when the minimum thresholds were set as 19, 20, and 21 years, respectively. Furthermore, we would like to clarify that the 18-year threshold was used as a minimum threshold of record length to select stations with enough observations, and the total record lengths in many tide gauges were longer than 18 years. For example, there were 144 (out of 314) tide gauges with record lengths >40 years (Fig. 1b). Moreover, the expected return period of compound floods defined in our study (i.e., co-occurrences of extreme precipitation and storm surge exceeding the 98.5th percentile) was about 12 years and the joint return period was further shorter than the expected 12 years (i.e., < 4 years in most areas). Therefore, the minimum threshold of 18-year is an optimized option that balanced the number of available tide gauges and the analysis quality.
Figure S1. (a) The number of available tide gauges at specific minimum record length threshold; and (b) the reduced number of tide gauges when the minimum record length threshold was increased. The dashed grey vertical line indicates the threshold of 18 overlapping years.
Fractional contribution of tropical cyclones (TCs) and extratropical cyclones (ETCs) to extreme precipitation and extreme storm surge

The fractional contributions of TCs to extreme precipitation and extreme storm surge are shown in Figure S2. More than 40% of extreme precipitation in East Asia and northwestern Australia was associated with TCs. This percentage was lower (<30%) but still considerable on the east coast of the US (Fig. S2a). TCs contributed to more than 50% of extreme storm surge in East Asia, while this value ranged from 30-50% on the coast of the Gulf of Mexico (Fig. S2b). In East Asia and the coast of the Gulf of Mexico, contribution of TCs to extreme storm surge exceeded that to extreme precipitation, suggesting that TCs play a larger role in extreme storm surge.

Figure S3 shows the contributions of ETCs to extreme precipitation and extreme storm surge. In mid and high-latitude areas, such as Europe, the west coast of Canada, the northeast coast of the US, and southeastern Australia, the fractional contributions of ETCs to extreme precipitation and storm surge exceeded 60%. In areas where TCs are experienced frequently (i.e., southeast coast of the US, southeast China, and Northern Australia), the fractional contributions of ETCs to extreme precipitation and extreme storm surge were < 40% (Fig. S3).
Figure S2. Fractional contribution of TCs to (a) extreme precipitation, and (b) storm surge (i.e., > 98.5th percentile). Data between 1979-2012 was used to estimate the fractional contribution of TCs. Open circles denote that the fractional contributions are 0.
Figure S3. Fractional contribution of ETCs to (a) extreme precipitation, and (b) storm surge (i.e., > 98.5th percentile). Data between 1979-2012 was used to estimate the fractional contribution of ETCs. Open circles denote that the fractional contributions are 0.
The best fitting copula types

To determine the dependent structures between extreme precipitation and extreme storm surge, the best-fitting copula was selected from five copula types (i.e., normal, t, Clayton, Gumbel, and Frank copulas) for each tide gauge. The Akaike Information Criterion (AIC; Akaike, 1974) was employed to select the best-fitting copula. The Cramer-von-Mises test (Genest et al., 2009) was employed to assess the goodness-of-fit. The results show that the best-fitting copulas in most areas of the world passed the significance test level of 0.05, demonstrating that copulas are capable of constructing the dependence structure of extreme precipitation and extreme storm surge (Fig. S4).
Figure S4. The best-fitting copula type for the pairs of extreme precipitation and extreme storm surge (i.e., > 95th percentiles). Open circles (i.e., NA values) denote no copulas can significantly fit the pairs (α = 0.05).
The comparison between empirical return periods and copula-based return periods of compound floods

Figure S5 shows the scatter plot of the empirical and copula-based return periods of all tide gauges. We can see that most of points located near the diagnosed line, which means the empirical and copula-based return periods of compound floods matched well. The Pearson’s correlation coefficient is 0.83 with the p value < 0.001, which further validates the performance of copula-based return periods.
Figure S5. scatter plot of empirical and copula-based return periods. Colors denote the length of time series analyzed. Pearson’s correlation coefficient (Wilks, 2011) between empirical and copula-based return periods was assessed.
The joint return periods of compound floods with univariate extreme events exceeding the 99.5\textsuperscript{th} percentile

Figure S6 shows the joint return periods of compound floods with precipitation and storm surge exceeding the 99.5\textsuperscript{th} percentile. The expected return period is ~109 years if precipitation and storm surges were assumed to be independent. The empirical return periods of compound floods ranged from 2-32 years on the coast of the US, southern Europe, East Asia, and Australia (Fig. S6a). The empirical return periods estimation failed in some locations (i.e., open circles in Fig. S6a). This might be because the lengths of observational time series in these locations are shorter than the return periods of compound floods. The copula-based return periods of compound floods showed a similar pattern. Areas such as coast of the US, southern Europe, East Asia, and Australia experienced a higher probability of occurrence of compound floods (Fig. S6b). In locations where the empirical return periods estimation failed, the copula-based joint return periods were longer than 32 years. The Pearson’s correlation coefficient between empirical and copula-based return periods is 0.44 at a significance level of 0.001 (Fig. S6c).
Figure S6. Joint return periods of compound floods from extreme precipitation
and extreme storm surge exceeding the 99.5th percentiles. (a) Empirical return periods, (b) copula-based return periods of compound floods, and (c) scatter plot of empirical and copula-based return periods. A compound flood is the co-occurrence of extreme precipitation and storm surge exceeding the 99.5th percentiles. Open circles in (a) denote no compound flood was observed. In (c), colors denote the length of time series analyzed. Pearson’s correlation coefficient (Wilks, 2011) between empirical and copula-based return periods was assessed.
Weather patterns associated with compound floods, extreme precipitation, and extreme storm surges

The compositied maps of sea level pressure, wind field, and precipitable water content based on days where extreme events (i.e., compound flood events, extreme precipitation without an extreme storm surge, and an extreme storm surge without extreme precipitation) occurred in tide gauges Brest (western Europe), Charleston (southeast coast of the US), Takamatsu and (East Asia) are showed in Figures S7 and S8. The weather patterns associated with compound floods were characterized by deep low pressure, cyclonic wind, and high precipitable water content, simultaneously occurring around the target locations (Figs. S7a–c, S8a–c). During extreme precipitation events, the weather patterns featured abundant precipitable water; however, there was no obvious low-pressure or cyclonic wind (Figs. S7d–f, S8d–f). The occurrences of extreme storm surge events were associated with obvious cyclonic wind and deep low-pressure systems (Figs. S7g–i, S8g–i).
Figure S7. Sea level pressure and wind associated with extreme events. Composite maps of sea level pressure (shadings, hPa) and wind (black arrows) based on days where extreme events (i.e., > 98.5th percentile) occurred in (a, d, g) Brest, (b, e, h) Charleston, and (c, f, i) Takamatsu between 1948–2014. Extreme events are (a–c) compound floods, (e–f) extreme precipitation without extreme storm surge (i.e., < 95th percentile), and (g–i) extreme storm surge without extreme precipitation (i.e., < 95th percentile). Green dots indicate the locations of tide gauges.
Figure S8. Precipitable water content and sea level pressure associated with extreme events. Composite maps of precipitable water content (shadings, kg/m²) and sea level pressure (white contours, hPa) based on days where extreme events (i.e., > 98.5\textsuperscript{th} percentile) occurred in (a, d, g) Brest, (b, e, h) Charleston, and (c, f, i) Takamatsu between 1948–2014. Extreme events are (a–c) compound floods, (e and f) extreme precipitation without extreme storm surge (i.e., < 95\textsuperscript{th} percentile), and (g–i) extreme storm surge without extreme precipitation (i.e., < 95\textsuperscript{th} percentile). Green dots indicate the locations of tide gauges.
Scatter plots of the magnitudes of precipitation and storm surge

Figure S9 shows the scatter plots of the magnitudes of precipitation and storm surge. In Brest, ETCs contributed to most compound floods and extreme storm surge events (Fig. S9a), while almost all compound floods in Takamatsu were associated with TCs (Fig. S9c). For the tide gauge Charleston in the southeast of the US (where the contribution of TCs and ETCs to compound floods were comparable; i.e., ~47%), TCs contributed to the most extreme compound floods, and ETCs caused a number of compound floods that were second only to the most severe flood (Fig. S9b).
Figure S9. Scatter plots of precipitation (mm) and storm surge (m) for tide gauges (a) Brest in France, (b) Charleston in the US, and (c) Takamatsu in Japan. The colors of points (boxes) denote different types of extreme events (zones). Extreme events associated with TCs and ETCs were denoted by rhombuses and triangles, respectively. The smaller open circles denote other events.
References:

