General comments:

The authors investigate compound flood potential from historical TCs impacting the Shanghai region of China. They model TC-induced storm tides (surge + astronomical tide) using the Delft3D hydrodynamic model and utilize observed rainfall from nearby tidal gauges. They quantify the joint probability of rainfall and sea level using a bivariate copula, and then assess the impact of historical relative sea level rise (RSLR). The results show that the astronomic tide is the lead driver of the peak coastal water level, followed by the impact of storm surge. Relative sea level rise also significantly amplified the peak coastal water level in the study period of 1961-2018. This paper is on a topic of interest to the audience. The modeling and analysis methods are scientifically sound. The results provide helpful insights about coastal compound floods. I have a few comments that I hope the authors could address in their revision:

Overall Response: We would like to thank these detailed comments and suggestions, which are very helpful for us to improve the quality of the manuscript. In the revision, we have taken into consideration all suggestions and addressed all concerns raised. In this letter we report the point-by-point response to the comments.

Specific comments:

1. Line 20: Please change "Delft3D-Flow Flexible Mesh" to "D-Flow Flexible Mesh". To my knowledge, the Delft3D Flexible Mesh is suite software and the D-Flow Flexible Mesh is the main module of this suite.

Response: Thank you for your suggestion. We have changed "Delft3D-Flow Flexible Mesh" to "D-Flow Flexible Mesh". In section 2.4, we rephase the sentence as "The D-Flow FM module as part of the Delft3D Flexible Mesh suite solves the non-linear shallow water equations for unsteady flow and transport phenomena derived from the three-dimensional Navier Stokes equations for incompressible free surface flow (Symonds et al., 2016)."

References:
Symonds, A. M., Vijverberg, T., Post, S., Van Der Spek, B. J., Henrotte, J., Sokolewicz, M. (2016). Comparison between Mike 21 FM, Delft3D and Delft3D FM flow models of western port bay, Australia. Coast. Eng., 2, 1-12.

2. Line 21: Worth mentioning "historical" relative sea level rise as it is not immediately clear if this work is examining historical compound flooding or projecting future compound flooding.

Response: We employed historical TCs in this study and highlighted them in the abstract and rephrased this sentence to "This study employed the D-Flow Flexible Mesh model to simulate the historical peak coastal water level, consisting of storm surge, astronomical tide, and the relative sea level rise (RSLR) in Shanghai over 1961-2018."

3. Lines 35-38: The sentence beginning " As such, the joint probability theory..." does not make sense. Please rephrase.

Response: We rewrite this long sentence as follows. "As such, the joint probability theory has been incorporated into the analysis of compound flood risk to take the advantage of Sklar's Theorem (M. Sklar, 1959). According to Sklar's Theorem, any multivariate joint cumulative distribution function can be expressed in terms of univariate marginal distribution functions and a copula which describes the structure of dependency between the variables (Bevacqua et al., 2019)."

References:
Sklar, M. (1959). Fonctions de Répartition à n Dimensions et Leurs Marges. Publ. inst. statist. univ. Paris, 8, 229-231.
Bevacqua, E., Maraun, D., Vousdoukas, M. I., Voukouvalas, E., Vrac, M., Mentaschi, L., Widmann, M. (2019). Higher probability of compound flooding from precipitation and storm surge in europe under anthropogenic climate change. Science advances, 5(9), eaaw5531.

4. It is so helpful to give a figure showing the study area, location of rain gauges, and tide gauges. I am not very familiar with the geography of the region and I suspect many readers may not be either. For example, the blue background in the East China Sea would help readers to realize this study in the coastal region.

Response: In section 2.1, we have added a figure to show the locations of Baoshan rain gauge and Wusongkou surge gauge (Figure 1). We also highlight the location of Shanghai at the beginning of this section "Shanghai is surrounded by water on three sides, and the Huangpu River and Suzhou River pass through the city".

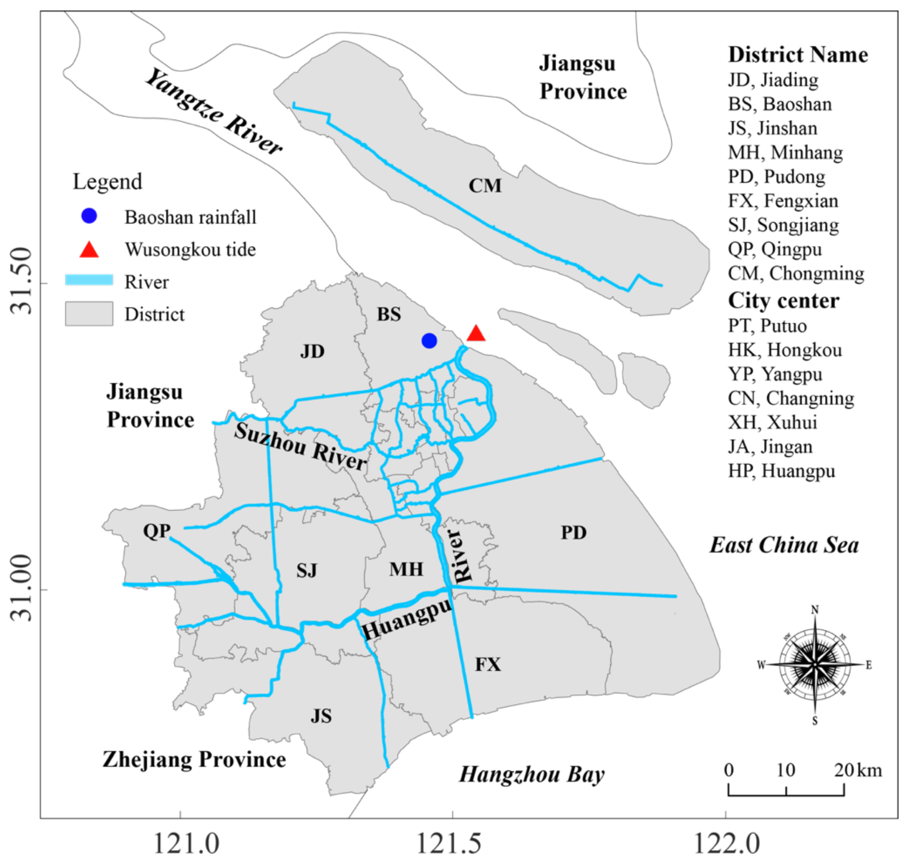

Figure1. Location map of Shanghai.

References:

Ke, Q., Yin, J., Bricker, J. D., Savage, N., Buonomo, E., Ye, Q. (2021). An integrated framework of coastal flood modelling under the failures of sea dikes: a case study in shanghai. Natural Hazards, 1-33.

5. The reader needs to know some more information about the TC hazard in Shanghai. On average, how many TCs make landfall near the region per year? How exactly were the TCs modeled since size information is missing for TCs occurring before ~2000?

Response: In section 2.1, we provided more information about the hazards in Shanghai: "The total area of Shanghai is 6,340.5 km^2 with a population of 24.87 million in 2020. The annual rainfall is around 1,200 mm. June to September are the rainy months. From late August till early September, Shanghai is frequently affected by typhoons and rainstorms (Yin et al., 2021). Storm flooding caused by typhoons is the main natural hazard in Shanghai. Shanghai's flood risk is about US $63 million/year under an optimistic scenario of a maximum protection level of 1/1000 per year (Hallegatte et al., 2013). Although the construction of flood control measures in the past 50 years has effectively reduced the risk of storm floods, TC Matsa in 2005, the 2013 TC Fitow, and the 2019 TC Lekima caused substantial losses in Shanghai. Particularly, Typhoon Winnie in 1997 led to direct economic damage of over US $100 million. During typhoon Winnie, the peak water level at Huangpu Park (city center) rose to 5.72 m, equivalent to the water level with a 500-year return period. During Typhoon Fitow in 2013, the water level at Mishidu in the inland area of the Huangpu River was recorded at WD (Wusong Datum is adopted as the reference) as 4.61 m, the highest on record (Ke et al., 2018). In the context of climate change, relative sea level rise, and urban expansion, Shanghai will face higher compound flood risk and challenges from TCs, storm surge, and extreme rainstorms in the future (Wang et al., 2018)."

In this study, we employed the Holland model to reconstruct the TCs in the past, with the Takagi and Wu (2016) empirical relation used to determine radius of maximum winds where this information was missing in the best track data. Delft3D WES (Wind Enhance Scheme), a built-in module in Delft3D, is used in this study to generate wind fields of TC scenarios. WES calculates the wind and pressure according to the Holland formula (Holland et al., 2010). It is able to generate tropical cyclone wind and pressure fields around storm center positions on a high-resolution grid. This asymmetry is caused by the use of the translational speed of the cyclone's center displacement as the steering flow, and the rotation of the wind velocity due to friction (Takagi and Wu, 2016). This model performance has been assessed based on model configuration, model calibration, grid generation and computational efficiency (Ke et al., 2019). The output of WES is suitable as input for the Delft3D-Flow model to simulate water level including the effect of storm surge.

In addition, we have added a map to show the tracks of historical tropical cyclones used in this study (Figure 2). We hope that this could help readers better understand the TCs hazards in Shanghai in the past 60 years.

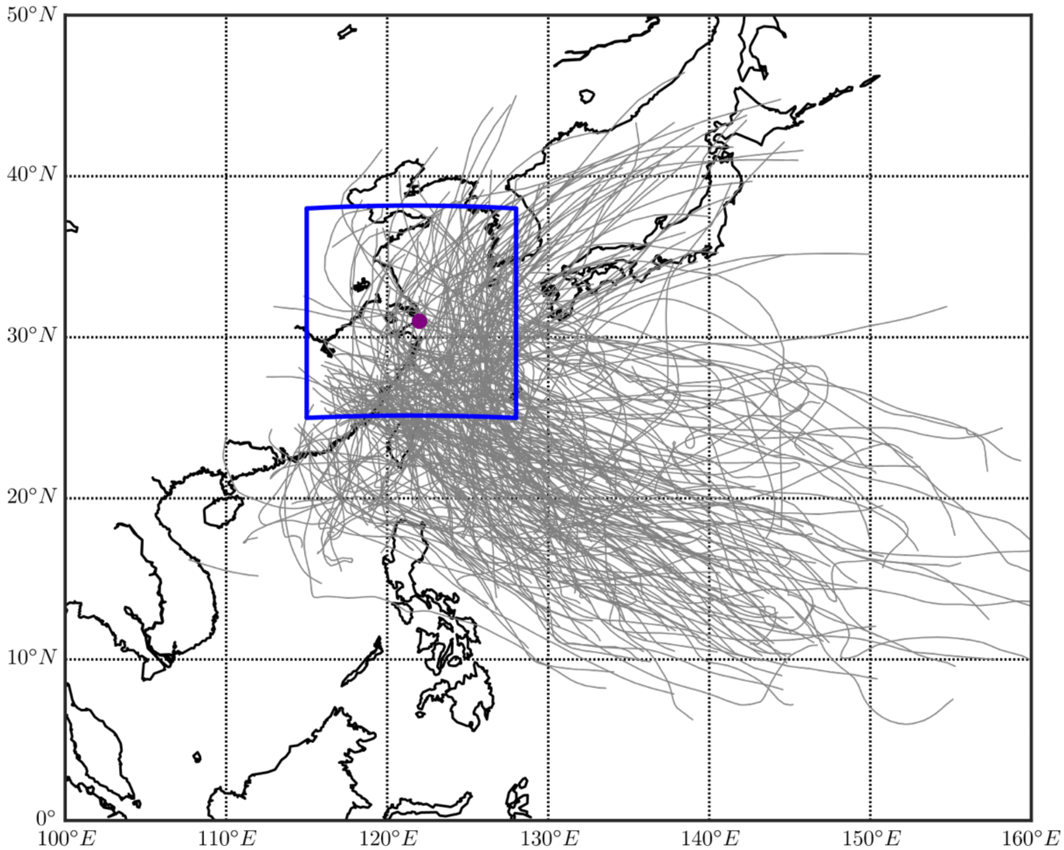

Figure 2. Location map for the area of interest. (Grey colored lines indicate major historical typhoon tracks within the region. Blue box indicates the selection criteria.)

References:
Takagi, H., Wu, W. (2016). Maximum wind radius estimated by the 50 kt radius: improvement of storm surge forecasting over the western north pacific. Natural Hazards and Earth System Sciences, 16(3), 705-717.
Holland, G. J., Belanger, J. I., Fritz, A. (2010). A revised model for radial profiles of hurricane winds. Monthly weather review, 138(12), 4393-4401.

6. Line 139: Not sure what the unit mm/yr means (millimeters per year?).

Response: It means millimeters per year.

7. It is not clear how RSLR is modeled in the study. Is the relative sea level change added to the modeled storm tides from each TC, assuming a linear relationship between storm tides and RSLR? Or is the Delft3D model run with initial increase in sea level to reflect RSLR? Either method is okay, but it needs to be explicitly stated. If RSLR is super-imposed on modeled storm tides, the authors should discuss the limitation of assuming linearity since previous studies have shown that nonlinear interactions between SLR and storm tides can significantly impact extreme water levels.

Response: Thanks for your comments. In this study, we first used the D-Flow FM model to simulate the storm tide. Then, we added the RSRL to the simulated storm tide. Though the uncertainties caused by the nonlinear interactions are important when investigating the interaction between sea level rise and storm tides under future climate change (Bilskie et al., 2016), we neglect this interaction in the present analysis.

References:
Bilskie, M. V., Hagen, S. C., Alizad, K., Medeiros, S. C., Passeri, D. L., Needham, H. F., Cox, A. (2016). Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern Gulf of Mexico. Earth's Future, 4(5), 177-193.

8. We are also missing key details about the Delft3D model. In particular, what is the minimum resolution of the mesh? How many and which tidal constituents are modeled?

Response: In section 2.4, we added the description of model domain: "The domain of the model covers the East China Sea, Hangzhou Bay, the Yangtze Estuary, and the downstream reach of the Yangtze River, ranging from 24 to 34°N and 118 to 128°E, and consists of 69,000 mesh cells. The model has been validated with observed storm tide and astronomical tide at 10 stations around Shanghai during TC Winnie in 1997 (Ke et al., 2021)." More details about model settings are presented in Ke et al. (2021).

References:
Ke, Q., Yin, J., Bricker, J. D., Savage, N., Buonomo, E., Ye, Q. (2021). An integrated framework of coastal flood modelling under the failures of sea dikes: a case study in shanghai. Natural Hazards, 1-33.

9. The authors used the "AND" scenario to develop compound flood design values. Please clarify in more detail why the "AND" scenario is more appropriate to estimates the flood hazard.

Response: Following Salvadori and De Michele (2004), Copula allow a straightforward definition of two hazard scenarios, i.e., space where pairs have a probability of occurrence greater than safety threshold, namely "AND" and "OR" scenarios (Ghanbari et al., 2021). The "AND" scenario assumes that a hazardous condition is realized when both the dependent variables, in this case peak surge and rainfall, exceed their predefined thresholds, while the "OR" scenario assumes that a hazardous condition can occur when either one of the two dependent variables exceed their predefined thresholds. In this study, we consider the "AND" scenario since we are interested in estimating the probability of peak water level and accumulated rainfall that exceed their respective thresholds at the same time (Moftakhari et al., 2019 , Ghanbari et al., 2021).

References:
Salvadori, G., De Michele, C. (2004). Frequency analysis via copulas: Theoretical aspects and applications to hydrological events. Water resources research, 40(12), W12511.
Moftakhari, H., Schubert, J. E., AghaKouchak, A., Matthew, R. A., Sanders, B. F. (2019). Linking statistical and hydrodynamic modeling for compound flood hazard assessment in tidal channels and estuaries. Advances in Water Resources, 128, 28-38.

Ghanbari, M., Arabi, M., Kao, S. C., Obeysekera, J., Sweet, W. (2021). Climate Change and Changes in Compound Coastal-Riverine Flooding Hazard Along the US Coasts. Earth's Future, 9(5), e2021EF002055.

10. Lines 239: I do not understand the sentence "The traditional approach is to assume independence between rainfall and sea level, then the independence assumption would generally lead to lower design values compared to scenarios from the copula-based method.". First, what is the "traditional approach"? If the traditional approach is to assume independence between rainfall and sea level, then the independence assumption would generally lead to lower design values compared to the "OR" scenario using the copula method. This needs to be clarified.

Response: Thanks for your comments. The “traditional approach” means the univariate statistics, which characterizes one variable only. We now directly call it univariate analysis approach. The revised sentence reads as follows: “The univariate analysis approach is to assume independence between rainfall and sea level, then the independence assumption would generally lead to lower design values compared to scenarios from the copula-based method.”

11. It would be interesting to see the impact of climate change on water level and compound floods. The authors may add some discussion related to this topic.

Response: Because we focus on examining historical compound flooding, the impact of climate change on the compound flooding is represented by the observed sea level rising.

12. It seems the process of land subsidence is not included in the relative contribution analysis. Could the authors provide some discussion about this driver?

Response: The land subsidence is included in the relative contribution analysis. The relative sea level change includes both absolute sea level rise and land subsidence.

13. The capitation of figure 5 is not enough, be more informative. Authors need to say that it is in the figure in detail not what the figure represent. For example, the yellow isolines fitted Gaussian copula.

Response: Thanks for your comments. We have rephased the figure’s caption as follows, “With RSLR (red) and without RSLR (blue) for 2 different copulas. Both peak water level (x axis) and accumulated rainfall (y axis) are presented in probability space. The red isolines are the fitted Gaussian copula, and the blue lines use a Clayton copula. Lines present the copula isolines and dots show observed data. The vertical axis on the right-hand side shows the joint probability value of isolines”. By the way, we also added the following description at the end of this paragraph: “Figure 5 shows the difference between peak water level and accumulated rainfall with RSLR and without RSLR. This indicates that different copula families can return different dependence structures. In Figure 5, both peak water level and accumulated rainfall are presented in probability space. Gaussian and Clayton copula families are used to explain the bivariate dependence between peak water level and accumulated rainfall in this study. The red and blue isolines are fitted Gaussian copulas and Clayton copulas, respectively. Neither is among the commonly used copulas in the hydrological literature. This highlights the importance of the choice of the copula, and quantifies the difference in results based on copula choice."

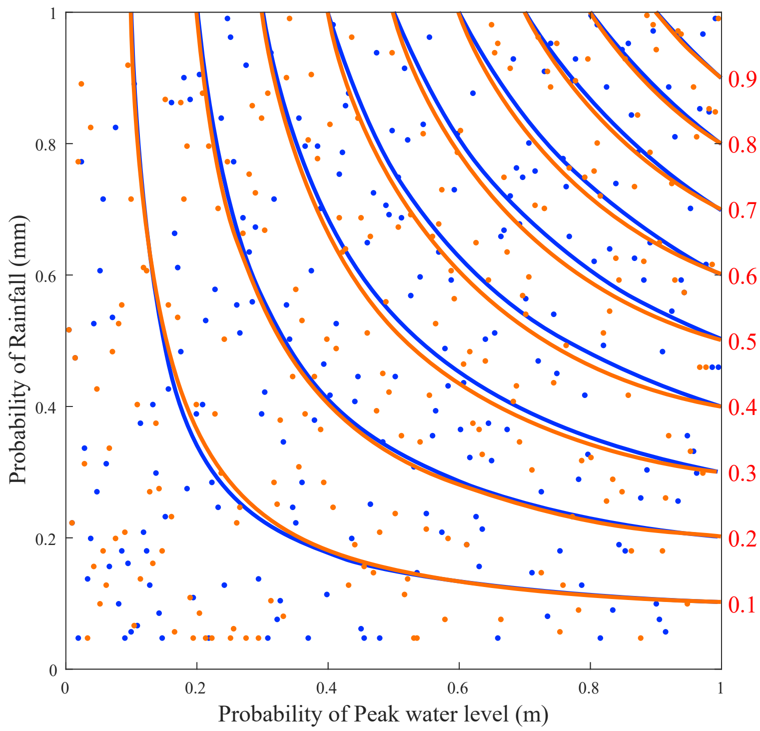

Figure 5: With RSLR (red) and without RSLR (blue) for 2 different copulas. Both peak water level (x axis) and accumulated rainfall (y axis) are presented in probability space. The red isolines are the fitted Gaussian copula, and the blue lines use a Clayton copula. Lines present the copula isolines and dots show observed data. The vertical axis on the right-hand side shows the joint probability value of isolines.

14. Please provide the summary of the significant findings in discussion part, for example, the dependency of water level and rainfall. In discussion part, the authors should make a comparison and contrast of the findings with others.

Response: Thank you for your suggestion. We have added a new discussion section to support our findings with additional references. In this new section, we discussed the dependency between the water level and rainfall, the effect of RSLR on peak water level and the multiple contributors to peak water level. We compared our findings with other researches which reported parallel results. For example, the literature shows that the correlation between rainfall and surges is generally weak, our research highlights that the correlation has a significant impact on coastal floods. Another example is that in the St Johns River in Florida, the astronomical tide contributes as much as 94% to the extreme water level (Bacopoulos, 2017). These discussions further convince the feasibility of the probabilistic modelling framework we developed in incorporating the interdependence of multiple drivers. We highlighted our key finding that the peak water level is the most dangerous hazard to Shanghai. The combination of astronomical tide, storm surge and RSLR drives the peak water level. In future research, it is essential to take into account the contribution of the tide during TCs. We expect the findings from our research to be useful for the decision-making on the adaption via coastal flood defense measures for Shanghai and other coastal cities or regions in East and Southeast Asia. The new discussion section is as follows.

4 Discussion

Coastal areas are the most densely populated and economically developed areas of many countries, and they are also the most vulnerable regions to the risk of compound floods from heavy precipitation and storm surge because of high population and property density as well as storm surge risk (Shen et al., 2019). In this study, we provide a framework that could be applied in general to coastal cities which face the constraint of unavailable water level records.

4.1 The dependency between the water level and rainfall

The dependence among different drivers of compound floods has been widely studied. For example, Zheng et al. (2013) identified significant dependence between precipitation and storm surge along the coastlines of Australia; Wahl et al. (2015) examined the enhanced dependence between precipitation and storm surge, and reported an increasing trend in compound flood risk in past decades along the coast of the US. These findings are critical to better understand the changing compound flood risk and provide important references for the evaluation of simulation-based studies.

The correlations between rainfall and storm surge are determined by various factors such as meteorological conditions and regional topography. For example, compound floods from heavy precipitation and storm surge can occur during TCs (Wahl et al., 2015; Bevacqua et al., 2019). TCs are one of the most important triggers of compound floods from heavy rainfall and storm surge in coastal regions. Even though compound floods are receiving attention, few studies have analyzed the dependency between water level and rainfall during historical TCs in China. This study enriches this stream of literature by quantifying the joint distribution of peak water level and rainfall during TCs in the Shanghai estuary region. On the other hand, it is worth noting that the record lengths of observational data in our study is relatively short and the uncertainties of simulation-based studies could be large. Therefore, further studies are needed once more observational data become available.

4.2 The effect of RSLR on peak water level

Deltas are especially vulnerable to RSLR because of their low elevations and commonly high rates of land subsidence (Wang et al., 2012; Higgins et al., 2014). Long-term tide gauge records show that global mean sea levels have risen by 1.7 ± 0.3 mm/yr over the last century (Holgate, 2007; Cipollini et al., 2017). Nearly 90% of the world's river deltas suffer the impact of RSLR, including Shanghai and Manila (He and Silliman, 2019). The accelerated rise of global sea level puts low-lying coastal regions at risk of increases in frequency and magnitude of flooding (Cazenave and Cozannet, 2014). For example, the sea level rose on average by $\sim$10 cm over the 20th century along the Italian coast, and flood frequency increased by more than seven times in the area (Kulp and strauss, 2019). Increased flooding because of RSLR, in regions that experience storm surges from TCs, further increases the vulnerability of coastal regions to inundation (Edmonds et al., 2020).

Previous studies of Shanghai reported increased risk of coastal floods due to global and local changes (Wang et al., 2012; Yin et al., 2013; Yan et al., 2016). Including the increased RSLR as we estimated over the past 58 years (0.55 m), a 4.3 m projected RSLR due to additional land subsidence along the Yangtze River delta by 2100 would result in half of Shanghai being flooded by extreme storm-water levels (Wang et al., 2012). There are serval potential carbon emission scenarios used to project sea-level rise. Regardless of the methods and emission scenarios used to estimate future sea levels, the consensus is that sea levels are rising and its rate is expected to accelerate (Wahl et al., 2017). By contrast, this paper presents a probabilistic analysis of the impact of RSLR on peak water level, accounting for the effects of sea level rise and land subsidence on coastal flooding, in Shanghai over 1961-2018. The findings from our research would provide more solid foundation for the scenario-based analysis towards future and be useful for the decision-making about the adaption via coastal flood defense measures for Shanghai.

4.3 Multiple contributors to peak water level

Coastal flooding from peak water levels is one of the most devastating natural hazards to Shanghai. A storm with strong winds and low atmospheric pressure can produce a large storm surge and large waves. A storm surge is an increase in water level above normal sea level and is a function of storm intensity, duration, size, and location (Cooper et al. 2008). Tides are an astronomical phenomenon caused by the gravitational attraction of the moon and the sun on earth's oceans, while storm surge is a meteorological phenomenon (Karim and Mimura 2008). If storm surge coincides with the astronomical high tide, these water levels superpose, and an extreme water level may be generated. Southeast Asia is highly vulnerable to, and frequently impacted by, extreme sea-level events of different origins: TCs cause severe storm surges and rainfall with potentially devastating impacts to the economy and environment and in many cases loss of human life.

Astronomical tides are deterministic and can be predicted far in advance, whereas storm surges can only be accurately hindcast from tide gauge records. Prediction of storm surge is possible days in advance of TC landfall, simulated by taking into account predicted forcing variables, such as wind stress and sea level pressure over the sea surface. Tide gauge records have been used to study sea level extremes. However, 90% of the tide gauges located in Southeast Asia have record lengths of less than 30 years. One way to overcome the absence of long tide gauge records is to employ numerical models to simulate the storm surge component (Park and Suh, 2012) using best track TC data or meteorological reanalysis results, as we have done in this study.

In this study, we demonstrate that the astronomical tide plays an important role in the total water level in Shanghai. Indeed, surges might occur at any tidal level, and are especially strong in shallow estuaries. A high tide at Wusongkou gauge would extend to downtown Shanghai causing a fluvial flood. The flood extent, depth, and duration can be exacerbated by storm surge, and consequently, the disruptive impact increases strongly (Ke et al., 2018). Astronomical tides contribute to peak water levels during TCs (Sweet et al., 2009). Bacopoulos (2017) showed that in the St Johns River in Florida, the astronomical tide could contribute as much as 94% to the extreme water level. Our study highlights that the critical components to consider in the analysis of peak water level during TCs are the astronomic tides, storm surge and RSLR. In future research, we will explore the applicability of the presented methodology to other regions where limited observational data availability has hampered a better understanding of peak water level, storm surge and potential changes related to climate variability and change.