Response to Reviewers

Title: Understanding the Compound Flood Risk along the Coast of the Contiguous United States

Author Response 1st revision

Reviewer 2
Reviewer Comments:

This work has proposed a compound flood (CF) risk assessment (CFRA) framework for coastal regions in the contiguous United States (CONUS). Compound flood is a significant research topic, and this study is timely to contribute to expand the literature. Overall, this work reads smooth and has included great simulations and analysis. Below are some comments on the manuscript.

Author Response:

We would like to sincerely thank the reviewer for the valuable comments and recommendations. We have carefully addressed the reviewer's suggestions as follows, and we will provide the revised manuscript during the revision iteration.

R2C1:

1. The scientific question was not quite clear. Is the objective to build a framework for assessing compound flood risk or to understand the risk across the U.S. coast? When reading the manuscript, it feels like the former was the main objective.

Author Response:

We appreciate the reviewer's comment. The major objective is to build the framework that can assess both compound flood hazard and exposure. Based on the framework, we provide an analysis to understand the risk across the US coasts. To better define the scientific question, in the introduction of the revision we first provide a general definition of CFRA before discussing details. Please note that we changed "data-based" and "physics-based" to "statistics-based" and "dynamics-based", respectively, according to the suggestion of another reviewer.

"Compound flood risk assessment (CFRA) is critical for flood planning, management, timely emergency response and decisions. CF risk has substantial spatial variabilities since the CF drivers and the CF risk dependence on the drivers are affected by the local conditions (Wahl et al., 2015), such as the characteristics of local basins that affect runoff generation, river routing (Hendry et al., 2019), synoptic weather systems, and storm characteristics (Seneviratne et al., 2012). CFRA can be classified into statistics-based and dynamics-based approaches. Statistics-based CFRAs rely on statistical modeling and define the CF hazard as the frequency of a CF event. Dynamics-based CFRAs use numerical simulations that can represent the spatiotemporal variabilities of CF drivers and how various CF drivers interact."

The objective is then defined at the end of the introduction:

"The objectives of this study are threefold: (a) to develop a new CFRA framework based on both statistical analyses and a large-scale river model that is coupled with a global ocean model reanalysis product; (b) to provide a holistic hazard and exposure risk assessment of the compounding fluvial and coastal flooding along the CONUS coastline, and (c) to understand the uncertainties in both statistics-based and dynamics-based CFRAs."

R2C2:

2. Line 160-165: "We consider Q and SS to be dependent of each other when they display a significant positive correlation (p-value<0.05)." Can we ignore the dependence if the p-value is smaller than 0.05. The authors need to better justify the selection of p-value.

Author Response:

Although 0.05 is a common choice, the p-value in this study is determined following a few previous studies in the CONUS domain (Ghanbari et al., 2021; Moftakhari et al., 2017). We justified the selection of p-value in the revision.

"The significance level is set as 0.05 following previous studies of statistics-based CFRAs (Ghanbari et al., 2021; Moftakhari et al., 2017)."

We agree that the choice of p-value is critical for determining dependence and would be a source of uncertainties in statistics-based CFRAs, which may be classified as model structure uncertainty (Table 1). This is now mentioned in Section 2.2.1.

"Moreover, model structure uncertainties always exist in statistical models, such as the selection of marginal distribution functions and dependence on level of significance."

R2C3:

3. Line 170-175: Which copula did the authors choose to quantify the dependence and why?

Author Response:

Thanks for the comment. For each MOSART cell, we perform the same analysis to select copula from the same 24 candidates following the instructions provided by Moftakhari et al., 2017. Given the total number of grid cells, it is tedious to provide the copula name for each grid cell. But in the revised manuscript, we elaborated on the selection of copula:

"For each MOSART coastal cell where Q and SS are dependent, the copula function is selected from 24 candidate families following the instructions provided in Moftakhari et al., 2017, using the R-package "copula" (Kojadinovic & Yan, 2010)."

R2C4:

4. Line 53: change "not available" to "unavailable"

Author Response:

We have revised it as suggested.

R2C5:

5. Line 87: “has accounted”

Author Response:

We have revised it as suggested.

R2C6:

6. Line 108-111: Why did the authors use GRFR runoff forcing? ERA5 land and NLDAS also provide runoff.

Author Response:

Thanks for the comment.

The GRFR runoff forcing is a well-calibrated and bias-corrected global dataset, which has shown excellent performance of simulating extreme streamflow events (Yang et al., 2021). The NLDAS land forcing was also tested but resulted in lower model performance. It remains a major challenge to quantify the uncertainty in runoff and streamflow simulation of Earth system modeling. Fully addressing such uncertainty is beyond the scope of this study. In response to this comment, we elaborated on the selection of the GRFR forcing:

“The GRFR forcing has shown excellent performance of simulating extreme streamflow events (Yang et al., 2021).”

and added a remark for this uncertainty in the discussion (Section 4.2):

“As quantifying the uncertainty of simulated runoff and streamflow in ESMs remains challenging (Lawrence et al., 2019), fully addressing such uncertainty in CFRAs is beyond the scope of this study.”

R2C7:

7. Fig.7’s caption is unclear. “Figure 7: The Kendall's correlation coefficient ($\boldsymbol{\tau}$).” What is this $\boldsymbol{\tau}$ and how to define it?

Author Response:

We apologize for the confusion. The caption of Figure 7 (now Figure 10) is edited with more details. Please note that the order of the figures is changed as we split each of the original Figure 3, 4 and 6 into two separate figures to increase clarity.

We have also changed the color scheme to a perceptually uniform one as suggested by the other reviewer. We added the label for the colormap in subfigure (a) and added the x and y labels in the subplot of subfigure (b). The subfigure (d) has been removed in all spatial maps.

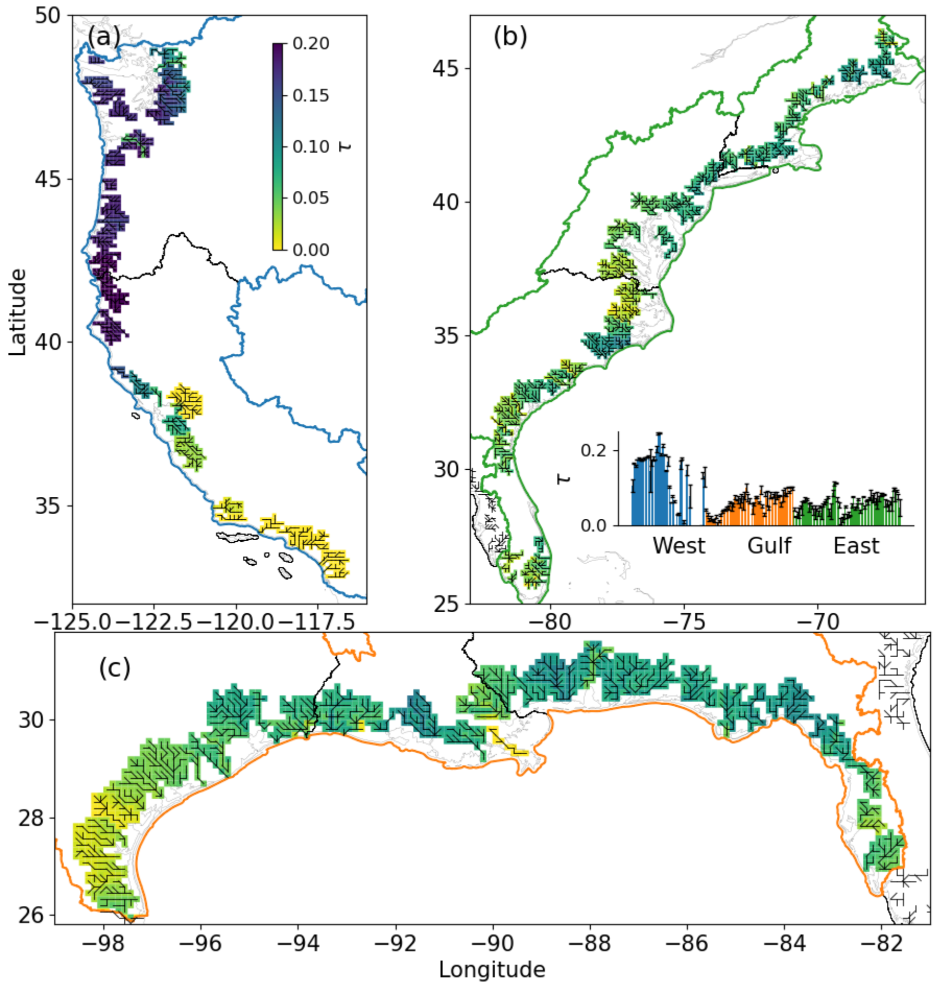

Figure 10: **The Kendall's correlation coefficient (τ) computed for each MOSART coastal cell using the corresponding Q and SS (Section 2.1). The insert in subplot (b) illustrates the basin-averaged τ provided in the counter-clockwise order of the river basins along the West, Gulf and East coastlines with the error bars representing the corresponding standard deviation.**

R2C8:

8. Fig.8's caption is also unclear. Please specify each term and variable for (PQ,SS) in the figure.

Author Response:

Thanks. We added more information in the caption of Figure 8 (now Figure 11) to increase clarity.

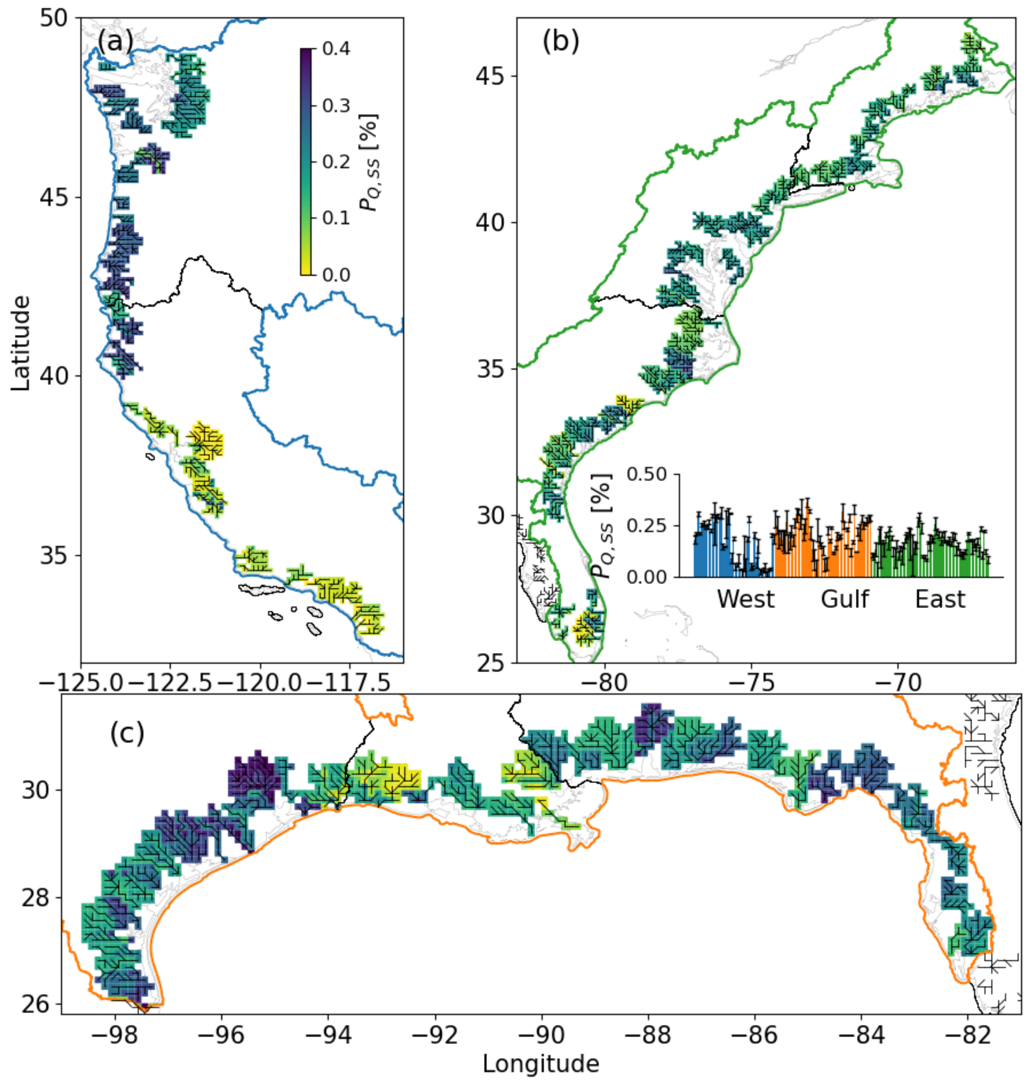

Figure 11: The joint exceedance probability ($P_{Q,SS}$) computed for each MOSART coastal cell using Eq. 3 (Section 2.1). The insert in subplot (b) is the basin-averaged $P_{Q,SS}$ provided in the counter-clockwise order of the river basins along the West, Gulf and East coastlines with each error bar representing the corresponding standard deviation.

R2C9:

9. In terms of storm surge events, is it possible to identify storm surge caused by tropical cyclones, extratropical cyclones etc.? How well is GTSM data validated by observations? Given the GTSM products are forced by ERA5 data, it would be useful to validate the GTSM's storm surge.

Author Response:

We appreciate the reviewer comment.

The storm surge events are selected using a peak detection algorithm (Feng et al., 2022), which is based on the signal processing technique and extracts the extreme event that has a peak level over 95th percentile. This method cannot distinguish between tropical cyclones and extratropical cyclones, as the magnitude of storm surge is influenced by various characteristics of the TC event, such as air temperature, air pressure, wind speed, and wind directions, and their interaction with local environments (Lin and Chavas, 2012).

The total water level has been validated globally in a previous study using gauged data (Muis et al., 2020). Its good performance is also implied in our supplementary information. The storm surge is validated by Dullaart et al., 2020 using several historical events driven by both tropical and extratropical cyclones. This information is added to the revised manuscript to increase clarity.

"The total water level in GTSM has been validated globally against gauged measurements (Muis et al., 2020) and the storm surge has been validated using historical events driven by tropical cyclones and extratropical cyclones (Dullaart et al., 2020)."

R2C10:

10. Figs 2-4: I would suggest that the authors add labels for geographical locations/states. It is hard to know where the locations are in these figures.

Author Response:

Thanks for the suggestion. We added labels of the state names to Figures 2, 3 and 5 of the revised manuscript.

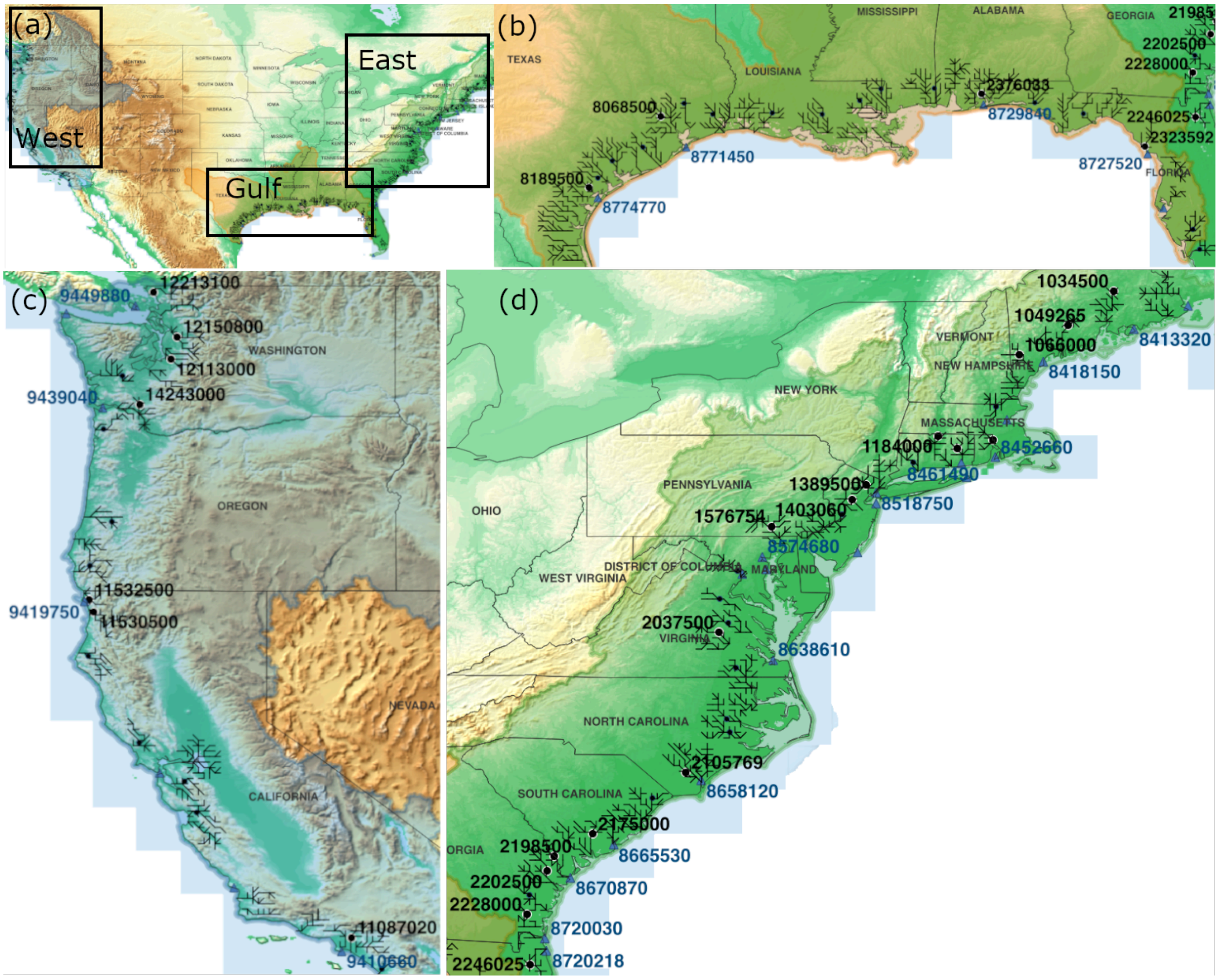

Figure 2: Study domain and observations overlaid on the USGS 3D elevation map (U.S. Geological Survey, 2019). The black and blue circles represent the USGS and NOAA gauges, respectively. The gauges used for identifying uncertainties are labeled with the gauge ID. The black solid lines are the coastal river network that consists of at most seven cells from each river outlet.

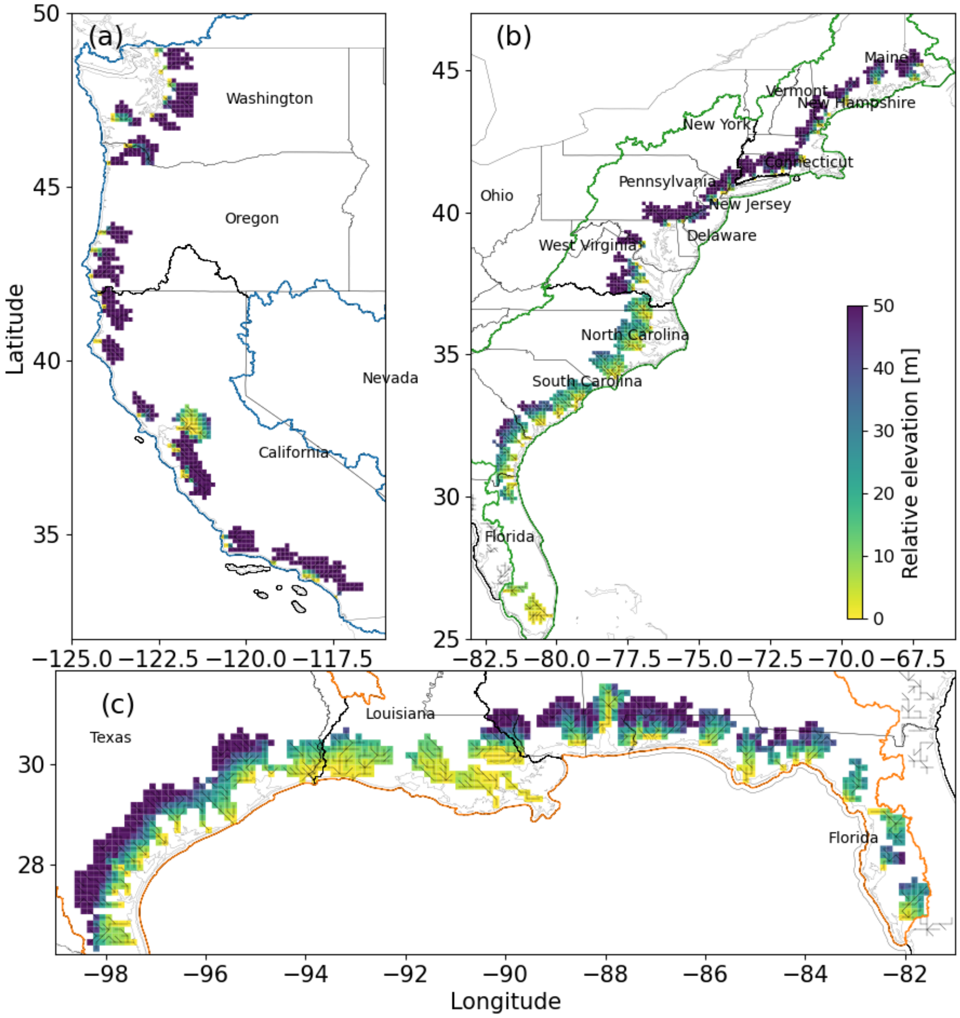

Figure 3: The relative riverbed elevation along the (a) West coast, (b) East coast and (c) Gulf coast. The river networks within the MOSART coastal cells are shown as black solid lines.

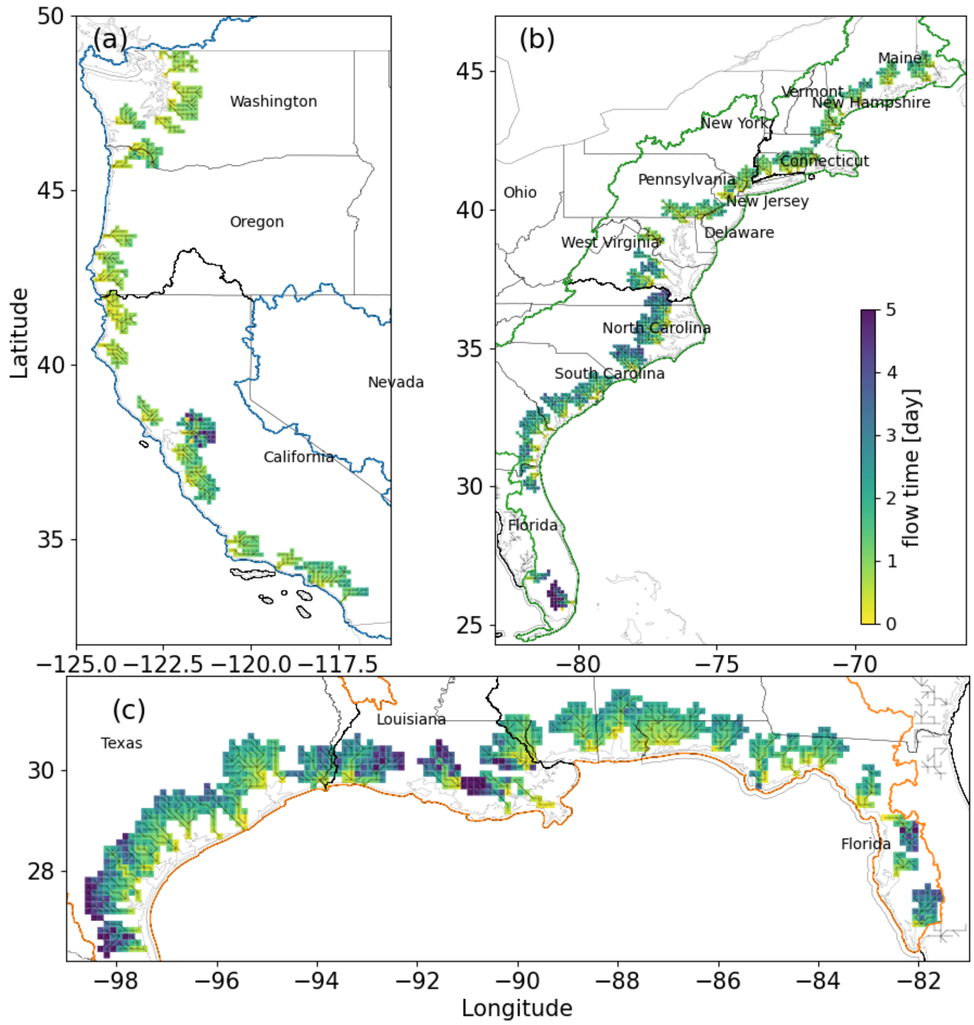

Figure 5: The flow time of river discharge at the MOSART coastal cells along the (a) West coast, (b) East coast and (c) Gulf coast. The river networks within the MOSART coastal cells are shown as black solid lines.

R2C11:

11. While it is not reported in this work, the authors could add discussions on the compound flood risk in the future given the climate projection.

Author Response:

We appreciate the reviewer's insight and have provided a discussion on the impacts of climate change on the CF risks at the end of Section 4.1.

"The broader definition of CF can be expanded to include the interaction between CF drivers and climate drivers (Zscheischler et al., 2020). Global warming will likely increase the frequency of extreme precipitation (Alfieri et al., 2016), the intensity of river discharge (Bermúdez et al., 2021) and storm surge

(Camelo et al., 2020), and the duration of the fluvial and coastal flooding (Feng et al., 2022). All these factors contribute to the exacerbation of CF risks, as both marginal and joint exceedance probabilities will increase. Moreover, climate change has the potential to alter the characteristics or distributions of CF drivers. For instance, the dependence between storm surge and precipitation is enhanced by climate warming, which increases the CF hazard (Wahl et al., 2015). The elevated sea level will move the backwater extent further upstream, increasing the CF exposure (Kulp and Strauss, 2019). Given the uncertainty of climate change, Earth System Models (ESMs) should be increasingly used to understand the potential impacts of different socioeconomic pathways on the CF risk."

R2C12:

12. In Section 3.2 CFRA, it would be better to add more discussions on the results across different coastal regions and the reason why there is spatial discrepancy in the results such as joint exceedance probability. Is the discrepancy in the risk across different regions due to differences in extremes Q or in SS (e.g., storm type, frequency or track), or in both?

Author Response:

Thanks. We added a new paragraph to discuss the inter-and intra- variabilities of the CF hazard and the reasons. Please note that Figures 4, 6, 8 and 10 are the previous Figures 3, 4, 6 and 8, respectively.

"The spatial variabilities of the CF hazard can be attributed to the inherent variability in both streamflow and storm surge. As implied by the spatially varied relative importance of Q, SS and riverbed elevation (Fig. 4), hydrological patterns exhibit substantial variation among river basins depending on river topology, basin characteristics and other geomorphological factors. Storm surge is also influenced by local factors of coastal topography, bathymetry and storm characteristics. These combined factors result in varying frequencies, durations, and correlations of fluvial and coastal flooding. For instance, in the western Gulf coast, the rivers experience more frequent extremes (Fig. 8c); however, these extremes show low correlation with SS, leading to a low dependence (τ) (Fig. 10c). Similarly, the inter-basin variabilities depend on the spatial heterogeneity of basin characteristics. The timing and magnitudes of the streamflow peaks typically vary significantly between upstream gauges and the outlet (Fig. 6), and between smaller streams and major rivers, resulting in different values of P_Q and τ."

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