Response to Reviewers

Title: Disentangling Atmospheric, Hydrological, and Coupling Uncertainties in Compound Flood Modeling within a Coupled Earth System Model

Author Response 1st revision

Reviewer 2
Reviewer Comments:

This article presents a compound flood assessment of Hurricane Irene in the Delaware River Basin. The authors used a new two-way/tightly-coupled approach to quantify the uncertainty of different aspects without the modeling approach, such as the environmental forcing and coupling technique.

Author Response:

We appreciate the reviewer for the critical assessment of our work. We have carefully addressed the reviewer's suggestions as follows. Excerpts of the revised manuscript are provided to explain our responses to the review comments, and the full revised manuscript will be submitted in the future.

General Comments:

R2C1:

First, the authors need to highlight better the novelty of the paper since it is current version is difficult to identify clearly. For example, they say that their main goal is to assess the uncertainties in the compound flood model, but this has been done before by Muñoz et al. (2024). However, the authors mention this gap (L69-72) but fail to mention the work by Muñoz despite citing them for another reason in the discussion. Another example is their claim that the compound flood needs to be redefined to include AMC and not just TC impacts. However, Bilskie et al. (2021) and Santiago-Collazo et al. (2023) simulated CF from a TC but were preceded by an antecedent rainfall event, which affects the AMC. My point here is that the manuscript needs to go into an intensive literature review process so it can better define the knowledge gaps and cite the appropriate references. In my judgment, presenting the manuscript novelty as an uncertainty assessment of this specific model they used is not enough to impact the science community, as we expect with any manuscript in top-tier journals like this one.

Author Response:

We appreciate the thoughtful comment, which made us realize that the structure of our introduction may have led to the reviewer's assertion that the manuscript's novelty in assessing the uncertainty of this specific modeling framework has limited impact on the scientific community. We recognize the extensive studies on compound flooding (CF) uncertainty analysis in the literature (Abbaszadeh et al., 2022; Xu et al., 2023; Muñoz et al., 2022; Muñoz et al., 2024), typically based on single or dual-coupled regional/local river and coastal models. While these efforts are highly valued, our research explores a different venue by implementing global-scale regional-refined Earth System Models (ESMs) to simulate complex, multivariate extreme events.

Although ESMs are likely less accurate than regional/local models, they can offer distinct insights about CF due to several prominent features. E3SM, for example, leverages its exascale computing capabilities, provides a tightly coupled framework of multiple Earth system components (i.e., atmosphere, land, river, and ocean) across their global domains, resolves inherent physical processes, and also features interactive coupling among all model components.

Although a recent preprint (Zhang & Yu, 2024) has also demonstrated the importance of using a fully coupled ESM framework for CF modeling, our recent research (Feng et al., 2024) has performed the first integration of new features in E3SM, including two-way land-river-ocean coupling, coastal refined unstructured meshes in atmosphere, land, and river models, and 2-dimensional barotropic ocean models with a wetting and drying scheme. With the ultimate goal of using E3SM to model coastal extremes on a global scale, this study (still running globally) employs a specific TC event and a watershed as a test case. It is important to note that some of these features are relatively new in the domain of ESMs. Alongside model development efforts, it is crucial to evaluate the capability and uncertainty of ESMs in the context of CF modeling. Our developed framework is essential for a comprehensive evaluation of atmospheric, hydrological, and coupling uncertainties.

Uncertainty propagation in fully coupled ESMs remains an important topic in the Earth system modeling community. This complexity is further exacerbated by the two-way land-river-ocean coupling, where downstream models can affect upstream models at high temporal frequencies. Such uncertainty propagation has not been adequately addressed, particularly for extreme events, partly due to the lack of a fully coupled framework that integrates all model components at high resolutions and the high computational cost of running ESM ensembles. Even the study of Muñoz et al. (2024), which inspires our research in its preprint stage, does not comprehensively address atmospheric uncertainty. Although their uncertainty analysis includes a scenario that turned off rainfall, their study relies on a single set of external atmospheric forcing (i.e. ERA5) and does not account for backpropagating uncertainty from two-way coupling. Specifically, we have conducted ensemble atmosphere model simulations to assess the propagation of atmospheric uncertainty through the inherent systems.

Moreover, our study compares atmospheric uncertainty with the coupling uncertainties at both land/river and river/ocean interfaces. While it is true that such coupling techniques have been developed elsewhere, as detailed in R2C2, it remains unclear whether coupling uncertainty is significant compared to atmospheric uncertainty, due to a lack of direct comparisons.

Additionally, we address hydrological uncertainty by running a large ensemble of simulations with perturbed atmospheric forcing and other hydrological parameters, including Antecedent Soil Moisture Conditions (AMC) and two runoff generation parameters. This large ensemble enables the application of our newly proposed machine learning method and the related SHAP method to understand the relative contributions of hydrological factors. While the importance of AMC has been documented by Deb et al. (2023), none of these studies have demonstrated the role of underlying hydrological factors under different AMC conditions. Bilskie et al. (2021) and Santiago-Collazo et al. (2024) highlighted that the CF impact may be exacerbated if the CF event is preceded by antecedent rainfall, but their studies implemented the rain-on-grid method and did not account for the complex hydrological processes, such as soil moisture, infiltration, or evapotranspiration. We included this discussion in the revision.

With our ensemble run, we discovered that AMC plays a significant role, resulting in more than twice the inundated area if wetter AMC co-occurs with a wetter TC. The methodologies and findings together underscore the novelty of our study, which would not have been possible without the new E3SM framework. More importantly, our research sheds light on future directions and supports the ongoing development of more comprehensive model coupling methods.

In response to this comment, we have restructured the introduction, which begins with a more in-depth literature review on the CF studies, followed by a discussion of recent advancements in ESM model implementation and its associated uncertainties. We elaborated the existing gaps and research questions that need to be addressed. Additionally, we have more explicitly elaborated on the scope, objectives, and novelty of this study. Please see below the updated introduction starting from the second paragraph.

"Modeling CF is inherently challenging because it is triggered and impacted by the interactions of processes within multiple Earth system components, including atmosphere, land, river, and ocean, as well as the associated uncertainties (Xu et al., 2023). Traditional CF modelling is typically based on coupled hydrological models (Feng et al., 2022; Ikeuchi et al., 2017), hydraulic models (Bakhtyar et al., 2020; Bermúdez et al, 2021; Gori et al., 2020b) and hydrodynamic coastal/ocean models (Bennet et al., 2023; Kerns & Chen, 2023; Xiao et al., 2021; Ye et al, 2020) at local, regional and global scales. Over time, more sophisticated methodologies have been developed to enhance CF modeling. These include combined statistical-numerical modeling approaches (Olbert et al., 2023), deep learning (Feng et al., 2023a; Muñoz et al., 2021), data assimilation (Muñoz et al., 2022), reduced-physics ocean models (Eilander et al., 2023; Leijnse et al., 2021), new compound inundation models (Santiago-Collazo et al., 2024), and two-way river-ocean model coupling (Bao et al., 2022; Bao et al., 2024; Feng et al., 2024; Shen et al., 2024; Zhang et al., 2024). The CF modeling uncertainties can be sourced from model structures, parameters, input data, boundary and initial conditions (Abbaszadeh et al., 2022; Beven et al., 2018; Fan et al., 2021). These uncertainties may also cascade through the system (Meresa et al., 2021; Hasan Tanim & Goharian, 2021) and their contributions change dynamically over time (Muñoz et al., 2024).

A recently developed approach is the use of fully coupled Earth System Models (ESMs) to simulate compound flooding (Feng et al., 2024; Zhang & Yu, 2024). By integrating multiple earth system components in a single, tightly coupled framework, ESMs allow for predictive understanding of multi-scale flow processes and their interactions with other relevant processes involving heat, energy, biogeochemical and sediment transport, as well as their impacts on Earth's climate (Ward et al., 2020). Feng et al. (2024) performed the first fully-coupled ESM simulation for CF using the Energy Exascale Earth System Model (E3SM), by integrating recent advancements in E3SM including regionally refined unstructured meshes for atmosphere, land/river and ocean components in the global domain (Deb et al., 2024; Feng et al., 2022), two-way online land-river-ocean coupling (Xu et al., 2022b; Feng et al., 2024), and a 2-dimensional (2D) barotropic ocean model (Lilly et al., 2023).

While state-of-the-art ESMs are being implemented to simulate local extremes, this advancement can inevitably introduce additional uncertainties. Compared with regional simulations using prescribed atmospheric forcing derived from observation or reanalysis datasets, the model-simulated atmospheric forcings are more uncertain (Hersbach et al., 2020). Atmospheric forcing has critical impacts on the flood simulation (Cloke and Pappenberger, 2009; Hjelmstad et al., 2021). Specifically, the river discharge intensity, storm surge levels, and CF inundation extents are directly influenced by the TC's track and intensity, as well as the rainfall rate and timing (Gori et al., 2020a; Pappenberger et al., 2005; Zhong et al., 2010). These factors are the primary drivers of the riverine and coastal flooding dynamics. The uncertainty originated from atmospheric forcings would propagate to land, river, and ocean components through the multi-component framework (Deb et al., 2023; Blanton et al., 2020; Joyce et al., 2018). Likewise, the hydrological uncertainties in the land and river components (Giuntoli et al., 2018; Feng et al., 2023b) and the model coupling schemes can also propagate and even amplify the uncertainties. Typically, the cascading meteorological uncertainty is handled by the ensemble approach (Hamill et al., 2011; Villarini et al., 2019). Multiple realizations of a TC event with perturbed initial conditions and/or model physics represent a range of scenarios that evolve differently based on the dynamics of the models (Blanton et al., 2020). However, the cascading meteorological uncertainty has not been systematically estimated for CF modeling (Abbaszadeh et al., 2022; Xu et al., 2023). It remains unclear whether such uncertainty will amplify or diminish when constrained by the physical processes inherent in ESMs.

The cascading uncertainty in ESMs becomes even more complex with two-way interactive model coupling. In online two-way coupling, a downstream model, while receiving data from its upstream component, sends back real-time computed information at predefined time intervals, enabling bi-directional data exchange. For instance, a river model may send floodplain inundated water extent to the land surface model for estimating flood water infiltration on the floodplain (Xu et al., 2022b). Similarly, an ocean model provides its predicted water levels (Bao et al., 2022; Bao et al., 2024; Feng et al., 2024), velocities (Zhang et al., 2024) or fluxes (Shen et al., 2024) to the river model for capturing the backwater effect. While other uncertainties have been extensively discussed (Camacho et al., 2015; Feng et al., 2019; Muñoz et al., 2024; Willis et al., 2019), the uncertainty relevant to the two-way model coupling has rarely been explored because the coupling capabilities have only recently been developed. Questions are raised regarding the role of model coupling and the magnitude of related uncertainty compared to meteorological uncertainty, especially given the characteristic spatiotemporal scales invoked in land-river and river-ocean coupling. Addressing these questions is critical to refining the performance of interactively coupled ESMs, which is essential for achieving a more comprehensive understanding of the complex interactions and uncertainties associated with CF simulations. Moreover, assessing the enhancements provided by the two-way coupling schemes sheds light on the application of these couplings in future scenarios.

Furthermore, the cascading uncertainty changes with the variability and complexity of hydrological drivers represented in models, because these factors are critical for determining how precipitation is partitioned into runoff and infiltration. As rainfall initially infiltrates the soil, subsurface runoff moves slowly through the soil layers. When the rainfall intensity exceeds the soil's absorption capacity, saturation-excess water leads to surface runoff. The rate of infiltration, which determines the balance between surface and subsurface runoff, is influenced by soil properties, antecedent moisture conditions (AMC) (Ivancic and Shaw, 2015), and land cover types. The runoffs are then routed through river networks, resulting in high river discharge (Fig. 1) (Bevacqua et al., 2020). Understanding the hydrological drivers, including the sensitivity of flood responses to various conditions such as different AMC and rainfall scenarios, is crucial (Tramblay et al., 2010). These factors provide key insights for predicting different flood scenarios (Miguez-Macho and Fan, 2012; Schrapffer et al., 2020). In particular, AMC plays a critical role in the generation of peak runoff and modulating riverine flooding characteristics during heavy precipitation events (Berghuijs et al., 2019; Nanditha and Mishra, 2022). A saturated AMC can significantly amplify flood impacts compared to drier conditions. The relative importance of rainfall and AMC varies depending on the watershed area. Soil moisture becomes a more dominant factor in larger watersheds (Ran et al., 2022).

However, the role of these hydrologic drivers in cascading uncertainties sourced from atmospheric forcing has not been thoroughly investigated in the context of CF, partly due to the absence of a tightly coupled modeling system (Jalili Pirani and Najafi, 2020) or insufficient investigation into hydrological processes (Lin et al., 2024). Although Bilskie et al. (2021) and Santiago-Collazo et al. (2024) highlighted the critical consequence if CF is preceded by an antecedent rainfall event, their implementation of the rain-on-grid method does not account for the hydrological processes, such as runoff generation. Addressing these processes would require a detailed hydrological model or land surface component of ESMs. The fully coupled E3SM provides a feasible framework for quantifying the hydrological uncertainties in the CF modelling.

The above-mentioned uncertainties are complicated but must be carefully evaluated for ESMs as they will be more frequently applied for CF simulations in the context of climate change. This study focuses on exploring and disentangling the atmospheric, hydrological, and coupling uncertainties of coastal CF modeling within the coupled E3SM framework. We first provide a comprehensive description of the physical processes during a TC-induced CF event. We then evaluate the model coupling uncertainties and the cascading meteorological uncertainty using a simulation ensemble of a specific TC event. Using the atmospheric ensemble as a basis, we generated an expanded ensemble and proposed a new machine learning approach to analyze the relative contributions of different hydrological drivers to CF and how these contributions affect the accuracy and reliability of CF simulations over time. Finally, various hydrological and meteorological scenarios are used to delineate a spectrum of plausible CF outcomes in the designated region."

R2C2:

Second, the authors need to improve their introduction section so it can be more comprehensive than its current state. For example, one of the main points of discussion in the manuscript is the coupling technique that their model uses, such as the twoway/tightly coupling approach, but fails to explain to the reader (at least briefly) how this technique works and compares it with others. At a minimum, the authors should briefly define and explain this and cite a reference such as Santiago-Collazo et al. (2019). Similarly, the paragraph (L49-58) that describes the E3Sm model should be moved to methods and include more details of the model itself. Without this, the authors are expecting the reader to go into another reference to read basic details and model configuration, which is not appropriate. At a minimum, they should talk/show their numerical modeling domain, validation results and simulation set, and model assumptions. The authors only cite a paper from Feng et al. (2024) to point the reader to all the important details about the model for this study, which it should not. Furthermore, the author makes various unsupported claims that are not true. For example, (L90) said that model coupling uncertainties have not been studied before (which is not true; see Muñoz et al., 2024) since this coupling technique has been recently developed. However, the authors fail to comment on the many available models that can do this, such as SFICNS, SCHISIM, and the work done by George XU from LSU.

Author Response:

Thank you for the feedback. We are aware of the comprehensive discussion on the different model coupling approaches reviewed by Santiago-Collazo et al. (2019). We cited the reference and only briefly mentioned the limitation of the one-way coupling method on compound flooding: "Traditional modeling approaches that rely on one-way coupling between any two model components thus have a limited ability to capture CF (Santiago-Collazo et al., 2019)", as we consider their classification between two-way loosely coupling and tightly coupling is slightly different than the definition in Earth System Models (ESMs) that consider multiple components as a single modeling system. In the revision, we have further elaborated on the difference between one-way and two-way coupling:

"The cascading uncertainty in ESMs becomes even more complex with two-way interactive model coupling. In online two-way coupling, a downstream model, while receiving data from its upstream component, sends back real-time computed information at predefined time intervals, enabling bi-directional data exchange. For instance, a river model may send floodplain inundated water extent to the land surface model for estimating flood water infiltration on the floodplain (Xu et al., 2022b). Similarly, an ocean model provides its predicted water levels (Bao et al., 2022; Bao et al., 2024; Feng et al., 2024), velocities (Zhang et al., 2024) or fluxes (Shen et al., 2024) to the river model for capturing the backwater effect."

We apologize for any confusion caused, leading the reviewer to believe we made unsupported false claims about model coupling and the associated uncertainty. While some of our ideas on addressing uncertainty propagation in a coupled modeling system were inspired by Muñoz et al., 2024, their focused uncertainties using one-way coupled regional models differ from our study's focus and objectives. Specifically, our aim is to evaluate the capability and uncertainty of ESMs in simulating complex CF events. We concentrate on a different set of uncertainties inherent to the Earth modeling system, which are assessed through ensemble atmospheric simulations. In contrast, regional models are more susceptible to boundary forcing uncertainties, which are not applicable to our framework, as the coupled framework in the global domain does not require boundary forcing.

Additionally, other two-way coupled regional modeling studies (Bao et al., 2022; Bao et al., 2024; Zhang et al., 2024) primarily couple regional river and ocean models, such as WRF-Hydro, SCHISM, and ROMS. These model development studies lack the in-depth uncertainty analysis as done by Muñoz et al. (2024). The question of whether coupling uncertainty is significant, given the dominance of atmospheric uncertainty in such cases, remains unaddressed. We appreciate the reviewer's valuable recommendations and have expanded our literature review accordingly. Please see the updated introduction in our response to R2C1.

Following the reviewer's suggestion, we have relocated the detailed description of E3SM to the methodology section. We have intentionally not duplicated the mesh and result presentation in Feng et al., (2024). However, in the revised manuscript, we carefully describe the methodology being employed here, including the modeling schemes, mesh resolution, spatial and temporal scales and validation metrics. Please see below the updated Section 2.1.

"This study uses a recently developed configuration in the Energy Exascale Earth System Model (E3SMv2) (Feng et al., 2024). E3SM represents a significant advancement in Earth System modeling (Golaz et al., 2019, 2022). As a fully coupled ESM, E3SM supports dynamic exchanges and propagation of information across its different components. Additionally, several other developments have been recently implemented to further improve the modeling of coastal extremes, including the introduction of high-resolution regional-refined unstructured meshes in global river models (Feng et al., 2022; Liao et al., 2022, 2023a, b), the implementation of interactively coupled land-river-ocean models (Xu et al., 2022b; Feng et al., 2024), and the global tide model with a wetting and drying scheme in the ocean component (Barton et al., 2022; Pal et al., 2023). Compared with regional models that may provide more detailed inundation at the street level (Costabile et al., 2023; Ivanov et al., 2021), E3SM excels at coupling processes across various earth system components. This capability is crucial for capturing the complex responses of earth systems to climate change and projecting climate-driven flood hazards.

The new E3SM configuration (hereafter "E3SM coastal configuration") integrates the global three-dimensional (3D) E3SM atmospheric model (EAM), one-dimensional (1D) E3SM land model (ELM), 1D E3SM river model MOSART (MOSART: Model for Scale Adaptive River Transport), and the two-dimensional (2D) barotropic version of E3SM ocean model MPAS-O (MPAS-O: Model for Prediction Across Scales ocean model) (Fig. 2a). This configuration uses three different variable-resolution meshes to improve the E3SM's capability in modeling coastal processes. The EAM mesh features a global resolution of 100 km, with enhanced refinement to about 25 km over the North Atlantic Ocean and eastern North America. Both ELM and MOSART use a land mesh with a coarse resolution of 60 km globally, which is further refined to 30 km across the contiguous US and to 3 km within the Mid-Atlantic watersheds. The MPAS-O mesh offers the highest resolution of 250 m along the US East Coast, specifically designed to capture estuary dynamics, with a broader global resolution of around 1 km everywhere else. The global bathymetry data of MOSART and MPAS-O are sampled from the 90-m HydroSHEDS digital elevation model (DEM) (Lehner et al., 2008) and the 450-m GEBCO dataset (IOC and IHO, 2020), respectively. The river networks and flow directions are derived using HexWatershed which performs hybrid depression filling and stream burning for river routing in unstructured meshes (Liao et al., 2022, 2023a, b). The river bankfull width and depth were derived using the power law function with bankfull discharge (Andreadis et al., 2013).

The novel two-way hydrological coupling between land and river components enables E3SM to capture the infiltration of inundated river water in floodplains and, subsequently, the enhancement of subsurface runoff and evapotranspiration from saturated floodplain soils (Xu et al., 2022b). The two-way river-ocean coupling was developed for E3SM to better represent the dynamic interaction between rivers and oceans, especially during CF events (Feng et al., 2024). This new approach allows for an accurate representation of coastal backwater effects and the mutual influences of river discharge and ocean sea surface height (SSH), providing a more realistic assessment of CF hazards (Feng et al., 2022).

Using the E3SM coastal configuration, we simulated Hurricane Irene, a TC event that occurred in August 2011 and had large flooding impacts across the Mid-Atlantic region (Fig. 2b). Irene led to significant riverine and coastal flooding in the Delaware River Basin (DRB) and Delaware River Estuary (DBE) due to concurrent intense precipitation and storm surge. Following Feng et al. (2024), an ensemble of 25 EAM simulations with perturbed model parameters were performed to reproduce Irene and associated meteorological outcomes. EAM is initialized from ECMWF Reanalysis v5 (Hersbach et al., 2020) at 00:00Z 26 August 2011. Atmospheric nudging is not applied. The EAM ensemble can reproduce the TC characteristics, including the storm track and intensity (see Appendix A in Deb et al. (2024)). These "prerun" EAM simulations were then prescribed within E3SM to drive the land, river, and ocean components. EAM (in "data mode") provides atmospheric forcing to ELM and MPAS-O at a 15-min frequency. MOSART is interactively coupled with ELM and MPAS-O at the 1-hour interval via the E3SM coupler (Craig et al., 2012). The model outputs are archived at 15 minutes for EAM and hourly for ELM, MOSART and MPAS-O. We spun up ELM and MOSART from a 10-year historical simulation forced by Global

Soil Wetness Projects version 3 (GSWPv3; Kim, 2017), and MPAS-O from a 1-month simulation with the global tide model. MOSART was validated against the streamflow measurements at 6 USGS gauges along the Delaware River main channel with averaged coefficient of determination (r^2) of 0.79 and Kling–Gupta efficiency (KGE; Gupta et al., 2009) of 0.84. MPAS-O was assessed for water level at 6 NOAA tidal gauges across the DBE, showing an averaged r^2 of 0.72 and root mean squared error (RMSE) of 0.41 m. Please refer to Feng et al., (2024) for a more detailed description of the E3SM configuration and the model evaluation.

Fluvial and coastal inundations are simulated in MOSART and MPAS-O, respectively. The riverine inundation in MOSART is simulated using a macroscale inundation scheme that assumes the inundation occurs from the lower elevation to higher elevation within each grid cell (Luo et al., 2017; Yamazaki et al., 2011). Coastal inundation simulated on the MPAS-O inland mesh is aggregated onto the coarser MOSART mesh in the DRB. Within each MOSART grid cell, the inundation fraction is determined by the percentage of MPAS-O cells with a simulated water depth over 1 m. This threshold represents adjustments made to the MPAS-O inland bottom elevation data near the DRB coastline during the upscale sampling. Whenever there is a discrepancy between the inundation area from MOSART and MPAS-O in their overlapped cells near the coastline, the MPAS-O inundation is considered more accurate and will be used.

Here, the total simulated inundation extent of Irene is benchmarked against a 250-m resolution inundation extent dataset based on satellite imagery (Tellman et al., 2021). The dataset is aggregated onto the MOSART mesh for comparison. Within each MOSART cell, we compute the fraction of the observed inundation. The model performance is evaluated using flood metrics defined by Wing et al. (2017), including hit rate (HR), false rate (FR) and success index (SI)

$$HR = \frac{M_1B_1}{M_1B_1+M_0B_1}, \tag{1}$$

$$FR = \frac{M_1B_0}{M_1B_0+M_1B_1}, \tag{2}$$

$$SI = \frac{M_1B_1}{M_1B_1+M_0B_1+M_1B_0}, \tag{3}$$

where M and B are the pixels (or grid cells) from model simulations and benchmark data, respectively. The subscripts 1 and 0 represent wet (inundated) and dry cells, respectively. For all the three metrics, a score of 0 indicates poor performance, while a score of 1 represents perfect model performance. In our simulations, a wet cell is identified if the simulated inundation fraction is above a small unitless threshold of 0.02. This threshold minimizes the influence of cells that may only be marginally inundated—likely due to data and model uncertainties—thus ensuring a more reliable assessment of flood extent. The predicted flooded area (FA) is calculated by multiplying the flooded fraction by the corresponding cell area."

R2C3:

Third, the study limitations should be shown before the results section so the reader is aware of all of them before "believing" the results. For example, I was wondering about the lack of the coastal flood model (deep ocean, for example) since it was not explained in the methods, but then in the limitation section, I learned that the model configuration used in this study does not have one. It is not clear how they model the coastal flooding using their proposed framework since they do not have the coastal flood model (L443) nor use boundary conditions. Thus, I am not even sure if they model coastal processes. I also understand that the authors had a different purpose than to provide a high-resolution model, but the coarse resolution inland is producing an overestimation of the fluvial flood inland.

However, the authors said that it is prudent to overestimate the potential flooding from a flood hazard risk assessment perspective (L244-245). As a civil engineer myself, I am in complete disagreement with such a statement. It is not the same to overestimate the flood depth by a couple of inches, but to estimate areas being severely flooded, where there should not be any flood, is just a "bad model." Thus, the author's use of this type of statement represents a lousy justification for their poor validation/calibration processes. I strongly recommend going back to the MOSART model component and calibrating it to a better fit before moving forward with the manuscript. This has a big implication in their study findings since if the simulated storm was a pluvial/fluvial-dominated CF event, then the results would be overestimated greatly, including the uncertainty, since Irene was a coastal flood-dominated event.

Author Response:

Our framework indeed has the global ocean model MPAS-O integrated and run in the 25 ensemble simulations, which is described in Section 2.1. The ocean model is only excluded from the expanded ensemble simulations as explained in Section 2.4, in which case MPAS-O simulated water level provides the coastal boundary condition to MOSART (L190-193). In the revision, we included more details about the MPAS-O setup and validation. Please see our response to R2C2 for the updated Section 2.1.

MOSART has been validated against the measured streamflow at USGS gauges along the Delaware River main channel with averaged coefficient of determination (r^2) of 0.79 and Kling–Gupta efficiency (KGE) (Gupta et al., 2009) of 0.84, which is comparable to that of a high-resolution regional model using the same atmospheric forcing (Deb et al., 2024). The bias in the streamflow simulation is due to the EAM simulation of Hurricane Irene, which does not have nudging nor is its output bias-corrected in the ensemble simulation. The overestimation in FR is likely due to the bias in the MODIS satellite data, the macroscale inundation scheme in MOSART, and the 5-km resolution of the MOSART mesh. The flood extent dataset (Tellman et al. 2021) is known to likely underestimate the actual flooding area due to the uncertainty in the cloud cover removing technique, which is also reported in Zhang & Yu, 2024. Its fidelity further decreases in the upstream direction due to vegetation cover (Sexton et al., 2013). Such data, unlike high-resolution lidar data, should be only used to "benchmark" (rather than "validate") the modeled results. This was mentioned in the previous L128. The macroscale inundation scheme typically used in large-scale river models assumes no between-cell flux exchange and estimates the inundation fraction using the elevation profiles within the grid cell (Luo et al., 2017; Yamazaki et al., 2011). Such a scheme may not be sufficient to represent water depth heterogeneity within each cell and the subgrid flow dynamics given the grid resolution of 5 km. We agree with the reviewer that high-resolution local-scale models, which are able to provide street level flood prediction, consider the bias of a few inches as poor performance. However, global-scale Earth System Models (ESMs) offer their unique advantages in simulating coastal extremes, which is further elaborated in the updated introduction: "One significant advantage of ESMs is the integration of multiple earth system components in a single, tightly coupled framework across the global domain. Such a framework allows for predictive understanding of multi-scale flow processes and their interactions with other relevant processes involving heat, energy, biogeochemical and sediment transport, as well as their impacts on Earth's climate (Ward et al., 2020)." See our response to R2C1 for the updated introduction.

We agree with the reviewer that it is not appropriate to state the prudence of overestimating the potential flooding. In response, we first clarified the objective and advantage of the global E3SM in the introduction. We then added more details about the MOSART macroscale inundation scheme and the validation result in Section 2.1. Finally, in the revised Section 3.1, we provided more elaboration on this bias: "The overestimation in FR is likely due to the bias in the MODIS satellite data, the macroscale inundation scheme in MOSART, and the MOSART mesh resolution. The flood extent dataset (Tellman et al. 2021) could underestimate the actual flooding area due to the uncertainty in the cloud cover removing technique (Zhang & Yu, 2024). Its fidelity further decreases towards upstream due to the existence of vegetation covers (Sexton et al., 2013). In addition, the macroscale inundation scheme may not capture the subgrid connectivity given the grid resolution of 5 km (Xu et al., 2022b)."

Specific Comments:

R2C4:

Figure 1: remove the adjectives (e.g., large, heavy, high) for the flood drivers labels. This will make the figure more general and applicable to a broader audience.

Author Response:

Thanks. Figure 1 has been updated following the reviewer's suggestion.

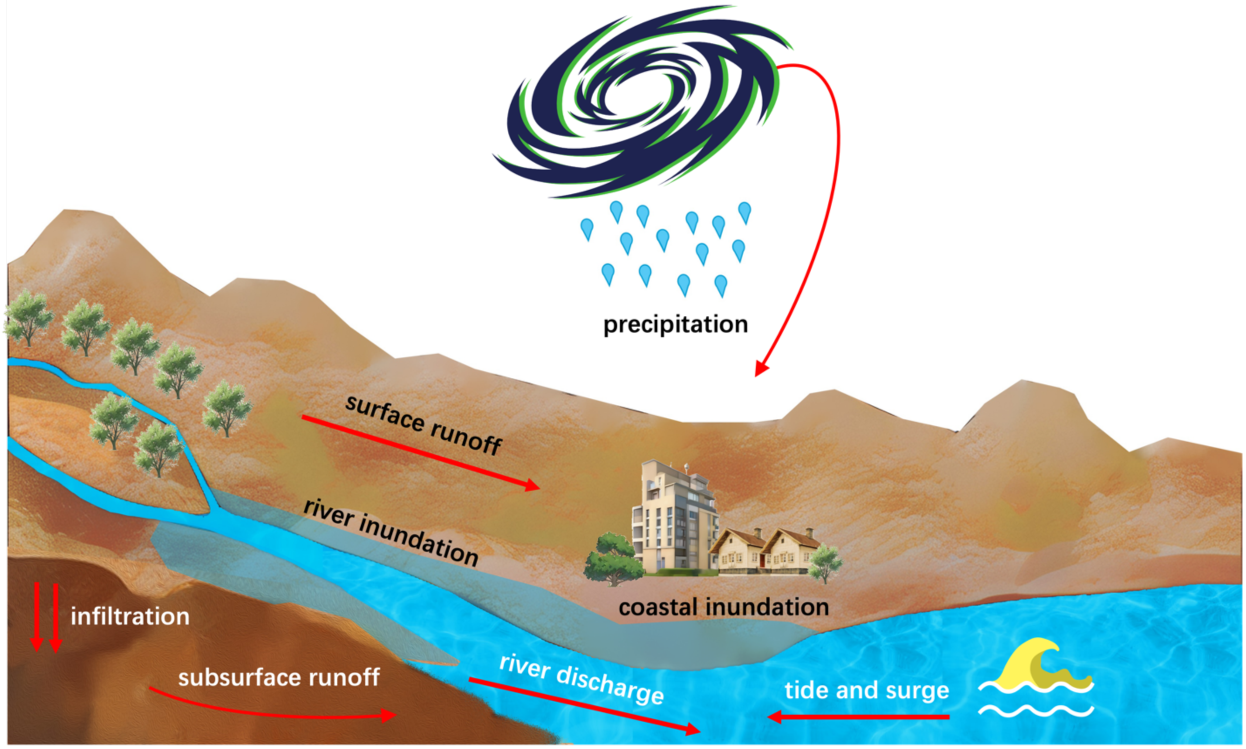

Figure 1: Compound flooding processes in a coastal river basin during a TC event. This conceptual diagram shows the key elements contributing to CF, resulting from combined riverine and coastal inundation along the river channels and adjacent coastal areas.

R2C5:

Figure 2: why are the MOSART network lines so different from the real stream network? The authors say that is a limitation but do not offer details on why.

Author Response:

We appreciate this comment. Upon checking the MOSART river network and the Delaware River streams in Figure 2b, we don't think they are very different at the 5-km resolution. In particular, we employed a rigorous way to generate the river network using HexWatershed (Liao et al., 2022, 2023a, b), a watershed and flow direction model that supports unstructured meshes for river routing models. HexWatershed employs a topology-based method to delineate river networks in the mid-Atlantic region (Lehner et al., 2008). This model generates flow direction across the domain using a combination of depression filling and stream burning algorithms. These algorithms are designed to eliminate local depressions with minimal alterations to the surface elevation, thereby producing essential flow routing parameters such as flow direction maps, channel slopes, and drainage areas. This information is complemented in the updated Section 2.1. See our response to R2C2 for the new section.

We agree with the reviewer that the original depiction of Figure 2b might lead to confusion, particularly due to the prominently displayed subbasin (HUC8) boundaries in thick black lines. Additionally, it's important to note that the Delaware streams shown in the figure, sourced directly from the Delaware River Basin Commission, were intended solely to illustrate geographic conditions and not for generating the river network. In the updated Figure 2b, we have omitted the Delaware streams and the MOSART river network. Instead, we now directly showcase the major channels of the Delaware River as derived from the HexWatershed output. We also changed to the subbasin boundaries to dashed gray lines.

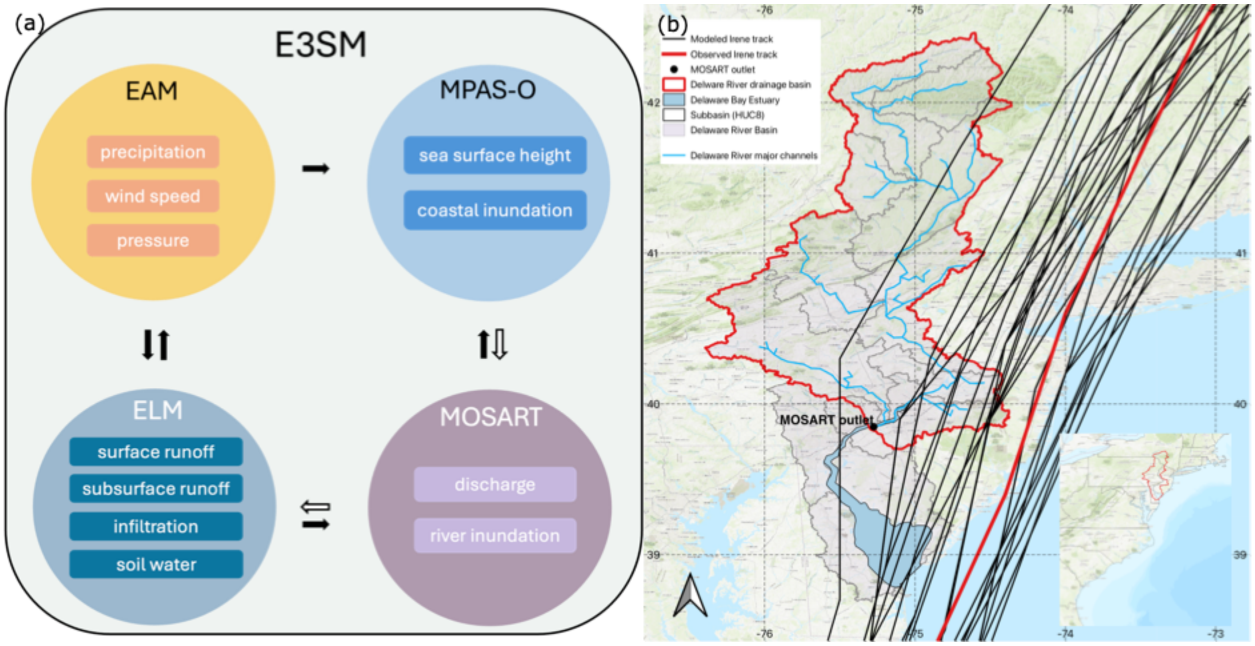

Figure 2: (a) The multi-component E3SM framework and drivers used for analyses within each model component. The black arrows represent the data flow via the one-way coupled framework. The white arrows are the new flow directions from the 2-way land-river and river-ocean models. (b) Map of Delaware river basin (DRB), Delaware bay estuary (DBE), and the observed (red) and modeled (black) Irene tracks. The topographic map in (b) is from the ESRI world topographic map (ESRI, 2012).

R2C6:

L227: The word “effectively” should not be used since the authors do not show at least a time series hydrograph, which they are multiple along the river, of its results and the observed to verify how effective the simulation was.

Author Response:

The validation metrics of MOSART and MPAS-O against observations are now provided in Section 2.1. We prefer not to show the hydrograph time series as it has already been presented in Figure 5 of Feng et al., (2024). Additionally, we have modified the first two sentences of this paragraph to present the capabilities and limitations of the models in a balanced way, focusing on what the results show rather than preemptively describing the models as successful or effective.

“In Experiment 3, the E3SM coastal configuration of E3SM employs the coupled MOSART and MPAS-O models to simulate compound riverine and coastal inundation (Fig. 4). The results indicate that MOSART can predict riverine flooding along the lower Delaware River and its upstream tributaries.”

R2C7:

L 231: does the stream network used in MOSART include the real bathymetry? If so, the data was available?

Author Response:

The delineation of the global river network and the riverbed slope of MOSART uses the 90-m HydroSHEDS digital elevation model (DEM) (Lehner et al., 2008). The river geometry parameters of bankfull width and depth were derived using the power law function with bankfull discharge (Andreadis et al., 2013) as there is no river bathymetry available for the whole watershed or globally. This information has been added to Section 2.1.

R2C8:

L283: there was no discussion/mention of the temporal scale of any model in the manuscript.

Author Response:

Sorry for the confusion. In the revision, we have clarified the model's output frequency and coupling frequency.

"EAM (in data mode) provides atmospheric forcing to ELM and MPAS-O at a 15-min frequency. MOSART is interactively coupled with ELM and MPAS-O at the 1-hour interval via the E3SM coupler (Craig et al., 2012). The model outputs are archived at 15 minutes for EAM and hourly for ELM, MOSART and MPAS-O."

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