JOURNAL OF COASTAL AND RIVERINE FLOOD RISK

Review and rebuttal of the paper

Sea-level rise and increasing variability are accelerating record-breaking coastal floods across the Global North

Hague et al.

Editor handling the paper: Jeremy D. Bricker

The reviewers remain anonymous.

Round 1
Response to reviewers (in red)

Reviewer A:

The manuscript shows a global analysis on extreme sea levels. The authors concluded that the main attribution of the global extreme sea level is mean sea level rising (SLR) (in the past decade) in 21st century. The methodology seems sound and the results are justified.

However, the scientific contribution or societal relevance is not clearly established. It is arguable to say that this is the first global study to find out that SLR increased the most extreme record-breaking coastal flooding (which is stated in Section of Discussion, Line 21). The extreme sea level may not potentially lead to coastal flooding. The climate interventions (including mitigation and adaptation) and flood defense may change the relationship of extreme sea levels and coastal floods. Regarding this, there are limited literatures mentioned in the current version. Therefore, it is recommended to further investigate or show the relationship between extreme sea level and coastal flooding at global scale.

We have added extensive discussion justifying the use of 'record flooding' as inferred from our analysis of record tide gauge observations in **Section 2.3**:

"Linking to sea level extremes to their impacts is critical for the development of hazard information across a range of timescales (Mahmoudi et al., 2024; Moore & Obradovich, 2020). For some locations, studies have identified sea levels associated with past impactful sea level extremes (e.g., Ezer, 2022; Habel et al., 2020; Hague et al., 2020, 2022; Hino et al., 2025; Thiéblemont et al., 2023). Impact-based flood thresholds have been systematically defined by national agencies for use in forecasting and warning services in the United States (Dusek et al., 2022) and Australia (Holmes et al., 2025). It is commonly accepted that exceedances of such thresholds can be considered 'coastal floods' (e.g., Ghanbari et al., 2019; Hague et al., 2023; Thompson et al., 2021). Hence, through the comparison of current record to impact-based flood thresholds and past impactful events, we can generate conclusions that pertain to flooding, rather than records, which are statistics of sea level timeseries. As a first pass, we compare the current record maximum sea levels at gauges identified in Section 2.1 to the minor flood level defined for GESLA gauges following the approach of the National Oceanographic and Atmospheric Administration's National Ocean Service (Hague et al., 2023). We find that the highest recorded sea level exceeds this minor flood level at 92% of locations with defined thresholds. These thresholds are associated with errors of order tens of centimeters (Hague et al., 2023; Sweet et al., 2018), smaller than the multi-metre vertical errors associated with global digital elevation models (Kulp & Strauss, 2019; Yamazaki et al., 2017) often used to identify land heights subjected to flooding during extreme sea levels.

Global studies have noted that the most extreme storm surges (and hence, record sea levels) have been associated with deaths in many parts of the world (Bouwer & Jonkman, 2018; Needham et al., 2015). Specifically, we note that numerous locations in our study have had coastal flood impacts (associated with record, or below-record levels) documented in the peer-reviewed literature. The impacts associated with record sea levels at UK sites are included in the SurgeWatch database (Haigh et al., 2015), and impacts of extreme sea levels at many Australian gauges (Bunbury, Darwin, Melbourne, Port Adelaide, Sydney and Townsville) have also been documented (Hague et al., 2020, 2022, 2024). The link between extreme sea levels and flood impacts is well-established in the United States as well – with studies presenting imagery and mapping of historical sea level-driven flooding for tide gauge locations considered here including Honolulu (Habel et al., 2020), Annapolis (Hino et al., 2019), Charleston (Román-Rivera & Ellis, 2018), and Sewells Point (Ezer, 2022). These supplement numerous US studies which leverage official impact-based flood thresholds used by the US NOAA National Weather Service (Li et al., 2022; Li, Wahl, Piecuch, et al., 2023; McKeon & Piecuch, 2025; Moftakhari et al., 2018; Sun et al., 2023). Whilst such thresholds are not perfect (e.g., Hino et al., 2025; Moore & Obradovich, 2020), using them is preferred to the common alternative practice (e.g., Muis et al., 2018; Taherkhani et al., 2020; Wahl et al., 2015) of assuming that statistical measures of extreme sea levels (e.g., the '1-in-100-year' return level) imply the occurrence of coastal flooding (Mahmoudi et al., 2024; Rasmussen et al., 2022)."

In addition, the authors should highlight the research significance and the implication of the expected results in the section of 'Introduction'. I recommend the authors to indicate future research and how future research can be built upon the current research to achieve greater impact (in discussion) and also discuss how we should use the current research findings.

Thank you for this comment. We have made a few changes to hopefully address your concerns.

First, we have provided more background on the existing relevant literature in the Introduction:

"The impact of sea-level rise and changes in storminess on various measures and aspects of coastal flood hazards have been well documented. An increase in the frequency of exceedances of impact-based flood thresholds has been identified in the United States (Li, Wahl, Piecuch, et al., 2023; Moftakhari et al., 2015; Sweet & Park, 2014), Australia (Hague et al., 2022), China (Li, Wahl, Fang, et al., 2023), and Pacific small island states (Ritman et al., 2022). This has been accompanied by changes in estimated return periods of extreme sea levels (Menéndez & Woodworth, 2010; Palmer et al., 2024). Both of these phenomena exhibit substantial variability due to within-year (Barroso et al., 2025; Merrifield et al., 2013) and between-year (Enriquez et al., 2022; O'Grady et al., 2025; Sweet et al., 2024) modulations in tides and climate. However, unlike for Although climate change's impact on record temperatures (Coumou et al., 2013) and rainfall l(Lehmann et al., 2015) is well-established, no previous studies have not assessed whether observed climate change induced sea-level rise has already increased the frequency of record setting sea levels."

Second, we have presented the key results in the Introduction and discussed their significance with respect to the existing literature:

"We find that in the 2010s, new record sea levels were set at double the rate expected if there was no climate change or variability. This is significant because it shows that sea level rise's impacts on the most extreme events is a present-day problem, not just a future problem as often implied in the scientific literature and reports (Boumis et al., 2023; Fox-Kemper et al., 2021; Hermans et al., 2023; Ranasinghe et al., 2021). Further, we show that the largest contribution to these changes is mean sea level rise, not changes in sea level variability, although the extent to which is this the case varies by geographic region. Whilst this doesn't diminish the significance of earlier studies which showed changes in storm surges have been significant in some regions (e.g., Calafat et al., 2022), we show that at the global scale this effect is secondary to that of sea-level rise."

Finally, we have included discussion on how the results should be used and also opportunities for future research in the Discussion section, in two sections:

1. "Future work could quantify this statement to present projections of the excess of records metric developed here. This would offer decision-makers a different perspective on changes in sea level extremes under SLR, supplementing the existing allowances (Woodworth et al., 2021) and amplification factors (Hermans et al., 2023; Tebaldi et al., 2021) which respectively consider changes and height and frequency of sea levels of specific present-day frequencies. Excess of records shows potential as a hybrid metric that reflects both changes in frequency and intensity of extremes."
2. Future work on projections of excess of records could assess whether regions where changes in storm tide are prominent remain this way under future SLR, or whether they will conform to the broader pattern of SLR-dominated increases in record-setting.

Anyway, the authors referred to 'recorded sea level' to 'recorded coastal floods' across the manuscript. This should be furthered justified, either by literature review or additional research.

See above discussion on flooding and extremes.

Therefore, I would recommend a major revision.

Besides, there are some minor errors in the manuscript. It is recommended to check language and clarity in general since some sentences are too long and complex to understand.

- Page 1 Line 29: remove letter 'l'

This has been removed.

- Page 2 Line 28: check grammar

We changed 'that' to 'than'

- Page 3 Line 9-10: repetitious text on ' exceeds of records' (previous section has explained it)

We have removed this sentence – thanks for noting

- Page 5 Line 3: six region or five region? Please double-check it.

Five. Thanks for picking this up – have fixed.

Reviewer B:

This manuscript presents a comprehensive analysis of a global sea level dataset to evaluate changes in the height and frequency of record sea levels worldwide. The study is well-written, clear, and methodologically sound. It provides sufficient detail on the analytical approach and clearly explains the assumptions made throughout the work.

The paper addresses an important scientific question and offers compelling evidence for the significance of incorporating historical sea level rise when evaluating coastal flood risk. The results are well-presented and thoroughly analyzed, with illustrative examples from specific locations and a thoughtful regional breakdown.

My only suggestion pertains to the discussion section, where the authors imply that not incorporating sea level rise (SLR) into coastal flood risk assessments is a common assumption. This statement could benefit from clarification—perhaps by specifying the geographic or contextual scope in which this assumption tends to hold. In my experience, many coastal risk assessments do account for SLR, although societal perspectives and policy frameworks can influence this practice. A more nuanced framing would strengthen the discussion.

Overall, this is a strong and timely contribution to the field. I recommend it for publication in the journal.

Thank you for your kind review. We have re-written the second paragraph of the discussion in response to your feedback:

" Many studies view changes in the height of sea-level extremes as a future problem, whereas we have shown that this is already occurring. This view has pervaded the literature in two main ways. First, prominent publications on future changes in extreme sea level heights do not assess whether similar changes have already occurred due to historical sea-level rise. This includes the Intergovernmental Panel on Climate Change's 6th Assessment Report (IPCC AR6) (Ranasinghe et al., 2021) and other highly-cited studies (Hallegatte et al., 2013; Nicholls et al., 2021; van der Wijst et al., 2023). Second, perhaps more implicitly, it has become a standard assumption that coastal hazards or sea level extremes averaged over a historical period extending decades into the past can be considered representative of 'present-day' conditions (Kirezci et al., 2020; Tebaldi et al., 2021; Vousdoukas et al., 2018; Wahl et al., 2017). This occurs despite well-documented contemporaneous increases in MSL and storm-tides which mean 2020s conditions are worse than those in a baseline period centred on the 1990s or 2000s. (Calafat et al., 2022; Dangendorf et al., 2019; Hamlington et al., 2024; Slangen et al., 2016).Applying MSL offsets to express extreme sea levels relative to the current year (Hague et al., 2024; Hermans et al., 2023) is a way to resolve this and ensure that recent changes in MSL and extremes are correctly identified as already having occurred, rather than projected to occur in future."

Reviewer C:

At the end of the intro, it would be nice to have an outline of the paper. In section xxx we calculate xxx, and so on.

Thanks – we have added this:

"In Section 2, we outline the data used in this study, the definition of the 'excess of records' metric and linking sea level extremes to coastal flooding. In Section 3 we present results, focussing on global trends and regional variations thereof, as well as an assessment of the data's representativeness of the broader Global North. In Section 4, we discuss key implications of our work for the coastal hazards research community to enhance offering to support coastal decision-making. We also highlight opportunities for future work and the benefits of conducting this, particularly around developing projections of the 'excess of records' metric."

Are you really studying only coastal floods? Or coastal water levels in general? Recommend replacing "flood" with "water level" or "sea level".

We have added a section (2.3) that explains how our analysis can be used to reasonably infer information on coastal floods, following previous studies and conventions:

"Linking to sea level extremes to their impacts is critical for the development of hazard information across a range of timescales (Mahmoudi et al., 2024; Moore & Obradovich, 2020). For some locations, studies have identified sea levels associated with past impactful sea level extremes (e.g., Ezer, 2022; Habel et al., 2020; Hague et al., 2020, 2022; Hino et al., 2025; Thiéblemont et al., 2023). Impact-based flood thresholds have been systematically defined by national agencies for use in forecasting and warning services in the United States (Dusek et al., 2022) and Australia (Holmes et al., 2025). It is commonly accepted that exceedances of such thresholds can be considered 'coastal floods' (e.g., Ghanbari et al., 2019; Hague et al., 2023; Thompson et al., 2021). Hence, through the comparison of current record to impact-based flood thresholds and past impactful events, we can generate conclusions that pertain to flooding, rather than records, which are statistics of sea level timeseries. As a first pass, we compare the current record maximum sea levels at gauges identified in Section 2.1 to the minor flood level defined for GESLA gauges following the approach of the National Oceanographic and Atmospheric Administration's National Ocean Service (Hague et al., 2023). We find that the highest recorded sea level exceeds this minor flood level at 92% of locations with defined thresholds. These thresholds are associated with errors of order tens of centimeters (Hague et al., 2023; Sweet et al., 2018), smaller than the multi-metre vertical errors associated with global digital elevation models (Kulp & Strauss, 2019; Yamazaki et al., 2017) often used to identify land heights subjected to flooding during extreme sea levels.

Global studies have noted that the most extreme storm surges (and hence, record sea levels) have been associated with deaths in many parts of the world (Bouwer & Jonkman, 2018; Needham et al., 2015). Specifically, we note that numerous locations in our study have had coastal flood impacts (associated with record, or below-record levels) documented in the peer-reviewed literature. The impacts associated with record sea levels at UK sites are included in the SurgeWatch database (Haigh et al., 2015), and impacts of extreme sea levels at many Australian gauges (Bunbury, Darwin, Melbourne, Port Adelaide, Sydney and Townsville) have also been documented (Hague et al., 2020, 2022, 2024). The link between extreme sea levels and flood impacts is well-established in the United States as well – with studies presenting imagery and mapping of historical sea level-driven flooding for tide gauge locations considered here including Honolulu (Habel et al., 2020), Annapolis (Hino et al., 2019), Charleston (Román-Rivera & Ellis, 2018), and Sewells Point (Ezer, 2022). These supplement numerous US studies which leverage official impact-based flood thresholds used by the US NOAA National Weather Service (Li et al., 2022; Li, Wahl, Piecuch, et al., 2023; McKeon & Piecuch, 2025; Moftakhari et al., 2018; Sun et al., 2023). Whilst such thresholds are not perfect (e.g., Hino et al., 2025; Moore & Obradovich, 2020), using them is preferred to the common alternative practice (e.g., Muis et al., 2018; Taherkhani et al., 2020; Wahl et al., 2015) of assuming that statistical measures of extreme sea levels (e.g., the '1-in-100-year' return level) imply the occurrence of coastal flooding (Mahmoudi et al., 2024; Rasmussen et al., 2022)."

The data used seem to be relative SLR, so do not take into account land subsidence at each station. What is the effect of this?

We have added the following passage to **Section 2.1**:

"As it is relative sea-level rise (i.e., where subsidence is included) that leads to coastal impacts (Lionello et al., 2021; Nicholls et al., 2021; Tay et al., 2022), we do not seek to remove the effect of vertical land motion. Despite not including the impacts of subsidence, satellite altimeters produce comparable estimates of sea-level rise on the global scale (Dangendorf et al., 2019; Frederikse et al., 2020). It worth noting that both measurement systems can be prone to errors, meaning that differences are not always simply due to vertical land motion (Ray et al., 2023)."

The title indicates "worldwide", but the data are limited to coasts of the global north. The title should be adjusted to realize this.

This is a good point and we have made this change – thanks for highlighting this. We have also included the following passage in **Section 2.1**:

"These gauges are almost exclusively in the Global North, due to a smaller number of operational stations available for the GESLA dataset in the Global South (Haigh et al., 2022). This is unfortunate, given the largest populations exposed to coastal flooding and the impacts of sea-level rise are in the Global South (Bouwer & Jonkman, 2018; Hanson et al., 2011; Strauss et al., 2021; Tay et al., 2022)."

Give more information about the tide gauges used. What are their recording intervals? Are they low passed filtered (either physically or in post processing)? What is the cutoff frequency?

Thank you for highlighting this omission. We have added the following sentence in **Section 2.1**:

"Processing of the data is described by Haigh et al. (2022), we make no further adjustments or conduct additional processing. This is consistent with other studies using the GESLA dataset (Calafat et al., 2022; Cheynel et al., 2025; Hague et al., 2023)."

Can some comparison be made between the gauge-based SLR studies here, with absolute SLR determined from satellites?

We have included the following paragraph in **Section 2.1** to include discussion on relative and absolute sea levels and comparisons made by other studies:

"Tide gauges measure water levels relative to a fixed datum on land. In GESLA this is usually a low water datum, but the precise information is provided in the metadata accompanying the dataset. Regardless, increases in mean sea level as measured at tide gauges can be caused by land sinking (termed 'subsidence') or ocean levels rising (termed 'sterodynamic sea level rise) (Wang et al., 2021). As it is relative sea-level rise (i.e., where subsidence is included) that leads to coastal impacts (Lionello et al., 2021; Nicholls et al., 2021; Tay et al., 2022), we do not seek to remove the effect of vertical land motion. Despite not including the impacts of subsidence, satellite altimeters produce comparable estimates of sea-level rise on the global scale (Dangendorf et al., 2019; Frederikse et al., 2020). It worth noting that both measurement systems can be prone to errors, meaning that differences are not always simply due to vertical land motion (Ray et al., 2023)."

What are the datums that each of the tide gauges are referenced to? How are these corrected for subsidence?

As noted above, the following sentence has been added in the manuscript:

" In GESLA this is usually a low water datum, but the precise information is provided in the metadata accompanying the dataset."

It would be informative and build confidence in the results if all stations were presented similarly to Fig 1, in an appendix.
This is good suggestion. As there were 247 sites we have provided (along with other data) via an electronic repository.

Line 29 does not make sense "more sites have data for recent years that years a long way in the past."

This should have been " more sites have data for recent years ***than*** years a long way in the past". Thanks for pointing this out.