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

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Abstract

In the first such quasi-global assessment we show that heights of record-breaking coastal floods have already increased due to climate change. In the 2010s the rate of record setting extremes in the Global North was more than double that expected in a stationary climate. 80% of these increases can be attributed to changes in mean sea level, the remaining portion is attributed to changes to storm surges and tides.

Keywords

Coastal flooding, sea-level extremes, sea-level rise, storm surges.

1 Introduction

Global mean sea levels (MSLs) are rising and accelerating due to anthropogenic climate change (Hamlington et al., 2024; Slangen et al., 2016). In some regions, changes in storm surges and tides have compounded the resultant increases in extreme sea levels (Calafat et al., 2022; Li et al., 2021; Morim et al., 2025). The most extreme coastal floods already have the potential to expose millions of people and billions US$ of infrastructure and assets to flooding (Hallegatte et al., 2013; Nicholls et al., 2021). Coastal flooding is expected to become the most costly economically of all climate hazards without effective adaptation to ongoing sea-level rise (SLR) (van der Wijst et al., 2023).

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 et al., 2023a; Moftakhari et al., 2015; Sweet & Park, 2014), Australia (Hague et al., 2022), China (Li et al. 2023b), 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 temperatures

(Coumou et al., 2013) and rainfall (Lehmann et al., 2015) previous studies have not assessed whether observed climate change induced sea-level rise has already increased the frequency of record setting sea levels.

We analyse the Global Extreme Sea Level Analysis (GESLA) tide gauge dataset (version 3) (Haigh et al., 2022) to assess changes in heights and frequency of record sea levels worldwide. We construct counterfactual timeseries to assess the contributions of changes in mean sea level (MSL) and storm-tides (the combined effects of storm surge and tides) on record flood changes, and to account for changing timeseries lengths. 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 this is 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 broader scales this effect is secondary to that of sea-level rise.

In Section 2, we outline the data used in this study, the definition of the 'excess of records' metric and link 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 offerings to support coastal decision-making. We also highlight opportunities for future work and the benefits of conducting this, particularly around developing the 'excess of records' metric.

2 Methodology

2.1 Data identification and processing

We identify tide gauge timeseries with at least 50 years of hourly or more frequent observations from the Global Extreme Sea Level Analysis (GESLA) version 3 (Haigh et al., 2022) that are assessed as having no obvious issues with quality and classified as located in coastal regions. We remove duplicates by discarding any gauge which has a shorter timeseries than another within 0.1° latitude or longitude. We exclude any data points with a 'use in analysis' flag of 'do not use'. For sites with multiple observations in an hour, we take the first observation in every hour to be the hourly sea level to allow fair comparisons between the gauges. All years with less than 70% complete observations are removed. Gauges are only retained if the resultant timeseries continues to meet a minimum data requirement of at least 50 years. This results in 247 tide gauges suitable for use in this study. 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). 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).

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 is 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).

2.2 Defining the 'excess of records' metric

For each of the 247 tide gauges we compute annual mean and maximum sea levels. The mean is the simple average of all hourly observations in a calendar year and the maximum is the highest of all hourly observations in a calendar year. A record-breaking event occurs when the annual maximum in the calendar year in question exceeds the annual maximum in all previous years (Figure 1). We identify years when record-breaking sea levels occur at each gauge both directly from observations, and from a timeseries of annual maxima with the corresponding annual means subtracted. The latter is referred to as a counterfactual where MSL is held constant, and allows quantification of the role of the combined effects of storm surge and tides ('storm-tide') on record-setting, by removing the effects of MSL changes (Wahl et al., 2017).

As evident in Figure 1, record-breaking sea levels become rarer the longer the annual maxima timeseries gets, even if sea levels are rising. The expected stationary rate of a record being set in a given year is the reciprocal of the timeseries length up to and including that year (Power & Delage, 2019). Here, stationary refers to a stochastic process whose statistical properties, such as mean and variance, do not change over time. For example, in the tenth year of observations there is 10% chance of the record being set in that year due to random chance. In the fiftieth year, there is a 2% chance of the record being set in that year due to random chance.

Each location has different timeseries lengths (of at least 50 years) and more sites have data for recent years than years a long way in the past. To account for this, we develop a metric we term the 'excess of records'. This is computed by the difference between the observed number of records over some period (n_{obs}) and the number of records expected over the same period under stationary conditions ($n_{stationary}$), divided by $n_{stationary}$ and expressed as a percentage:

$$Excess\ of\ records = \frac{n_{obs} - n_{stationary}}{n_{stationary}} * 100\%$$

Global and regional excesses of records are computed by summing the number of records that occur in each calendar year across the subset of gauges and divide this by the sum of stationary annual probabilities. We can apply the same concepts to the counterfactual where MSL does not change (but storm-tide can) to compute the excess of records for the counterfactual case.

Excess of records can be illustrated by considering 60 tide gauges each in their 20th year of observations and five of the 60 gauges observe a record-breaking sea level. The probability of a single tide gauge breaking their record in its twentieth year, if the probability doesn't change from year to year (i.e., assuming stationarity), is 0.05 (i.e., 5%). Hence, with 60 tide gauges all in their 20th year we would expect three gauges to break records (as 0.05 multiplied by 60 is 3). However, as we have observed five of 60 gauges, we have an excess of records of +67% (as 5, the observed value, minus 3, the stationary value, is 2, which is then divided by 3 to get 0.67). This approach assumes independence between gauges, and we assess the validity of this in the next section.

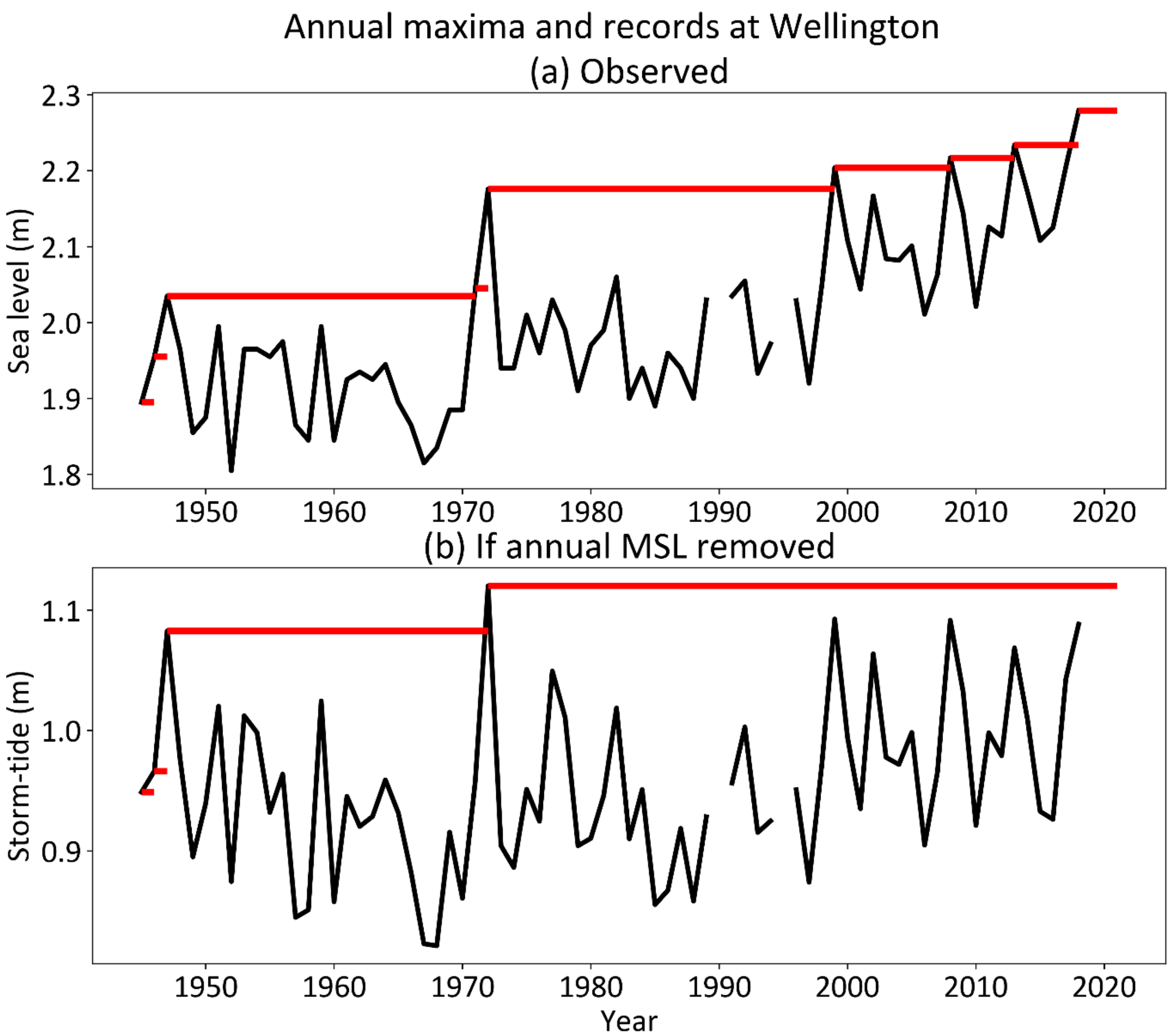

Figure 1: Example of record sea level (red line) and their relationship to annual maximum (black lines) at Wellington, New Zealand. The relationship is shown (**a**) as observed, and (**b**) under a counterfactual with annual mean sea level removed.

2.3 Linking sea level extremes to coastal floods

Linking 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, et al., 2023a; 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).

3 Results

3.1 Global trends

The frequency at which records are broken is accelerating (Figure 2a). In the 2010s, record-breaking floods occurred at 227% of the base rate expected under stationary conditions, where mean and variance of sea level do not change from year-to-year. The 2010s excess of records is substantially higher than previous decadal averages: 59% in the 2000s, 39% in the 1990s and 12% in the 1980s. Fitting a quadratic trend to global average annual excess of record values from 1970 to 2021 yields higher correlation and lower root mean square error than fitting a linear trend over the same period. This indicates acceleration of record setting over the same period that MSL has been accelerating (Dangendorf et al., 2019).

Much of the excess of records observed in the 2010s is due to increases in MSL, although increases in storm-tides have also contributed (Figure 2a). If observed storm-tide changes had occurred but annual MSLs had not increased, only one-fifth of the observed increase would have been observed in the 2010s. Hence, about four-fifths of the observed excess of records can be primarily attributed to changes in MSL. This result is also obtained for the 2000s decade. Changes in the 1990s and 1980s were primarily driven by MSL changes as the decadal average excess of records due to storm-tide only changes were 0.01% in the 1990s and -10% in the 1980s. Negative 'excess of records' means that records occurred less frequently than would be expected under stationary conditions. Hence, reductions in the effect of storm-tides on record-setting were offset by increases in MSL in the 1980s.

The prevalence of records being set in recent decades is also evident in analyses of the year in which the highest-on-record sea level was set (Figure 2b). For example, as 27% of the observational data fall within 21st century, we would expect that 27% of all locations would have set their highest-on-record sea levels during the 21st century in a stationary climate. We found that 47% of locations set their current highest-on-record sea level in the 21st century, almost double the expected stationary rate. Had changes in MSL not occurred (but changes in storm-tide had), only 34% of locations would have had their current highest-on-record observation set in the 21st century. This shows that changing MSL accounts for three-quarters of the greater-than-expected number of highest-on-record sea levels occurring in the 21st century.

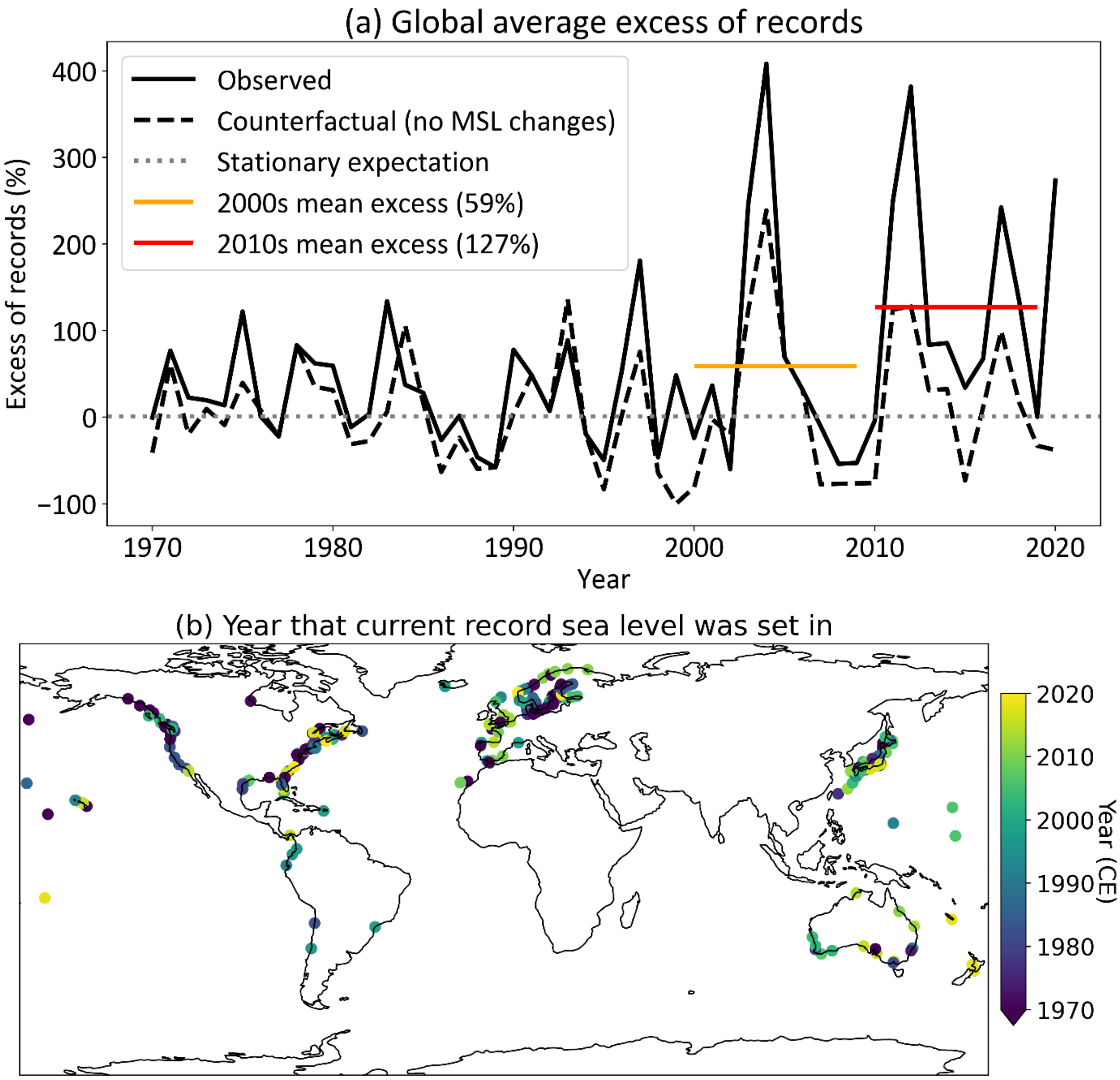

Figure 2: (a) Rates of record-setting as observed (black solid) and under counterfactual where MSL did not change (black dashed), expressed as the 'excess of records', the proportion of the rate expected under a stationary (non-varying) climate (grey dotted line) (b) the year in which that current highest-on-record sea level was observed.

3.2 Regional variations to broad-scale trends

The frequency, timing and dominant driver of the excess of records also varies by geographic location. We consider five regions which combined include 96% of all gauges in this study: North America (United States and Canada; 83 gauges; Figure 3a), Japan (65 gauges, Figure 3b), Nordic countries (Sweden, Finland, Denmark and Iceland; 48 gauges; Figure 3c), Western Europe (France, Great Britain, Spain and Germany; 25 gauges; Figure 3d), and Australia (15 gauges; Figure 3e). The 2010s was the only decade that saw positive excesses of records in all regions. Western Europe recorded the largest decadal excess of records with 218%, followed by Japan (166%), the United States (128%) and Australia (107%). Canada and Nordic countries saw much smaller excesses, of 24% and 8% respectively. Of all regions, Australia has the largest proportion of highest-on-record sea levels occurring in the 21st century. Of its 15 gauges, 10 set records in 2000 or later.

Considering gauges in the Nordic countries highlights that increases in storm-tides can be sufficient for an excess of records to occur, even without changes in MSL. For example, MSL at the gauges in the region has fallen between the 1970s to 2010s, yet records were broken more frequently than expected in a stationary climate in the 2010s (Figure 4a). This could be due to large increases in storm surges in Nordic countries (Tadesse et al., 2022) compensating for the falling

MSL due to Glacial Isostatic Adjustment (Kopp et al., 2014). This can be seen in the positive excess of records for the 2010s in Figure 4b.

Considering gauges in the USA shows that the opposite is also true: increases in MSL can also be sufficient for records to occur, even if storm surges or tides have become less extreme. For example, in the counterfactual where MSL remains constant US gauges would have experienced a 24% deficit (i.e., negative excess) of records (Figure 4b). However, there was an observed 128% excess of records (Figure 4a). In many US regions, extreme storm have increased a greater rate than MSL (Morim et al., 2025). However, the 2010s saw a minimum in the 18.6-year tidal amplitude cycle which is known to reduce the heights of extreme water levels (Enriquez et al., 2022; Thompson et al., 2021). This suggests that higher rates of MSL and extreme storm surge change in the US could have been offset by the 2010s having smaller tidal extremes. This supports extending a key property of chronic flood hazards to record flooding: tides modulate the ability for storm surge extremes to lead to flooding (Hague et al., 2023).

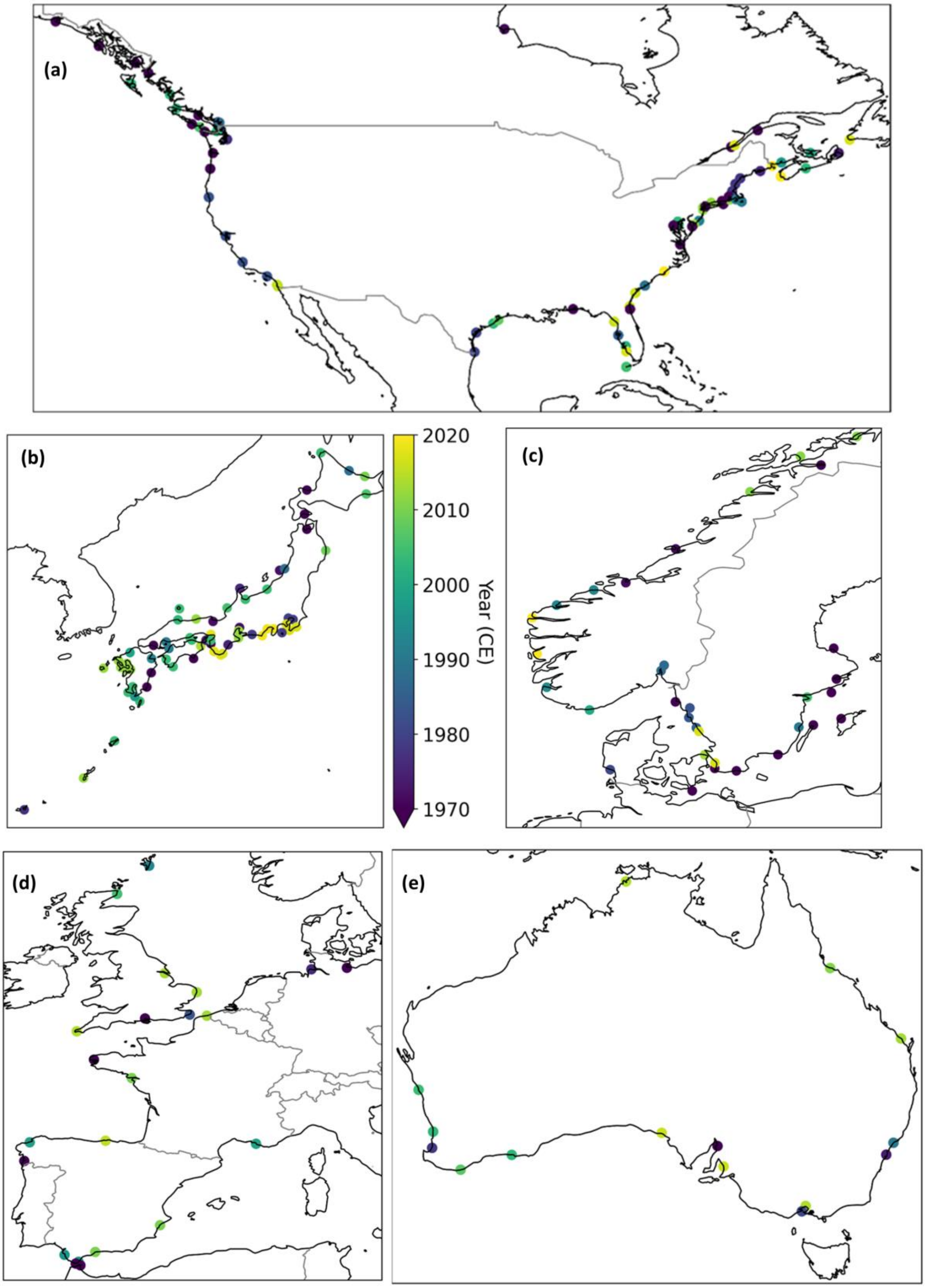

Figure 3: The year in which that current highest-on-record sea level was observed in regional subsets – (a) North America (only contiguous US and Alaska shown), (b) Japan, (c) Nordic countries (excluding Reykjavik, Iceland gauge), (d) Western Europe (excluding French Overseas Territories), (e) Australia.

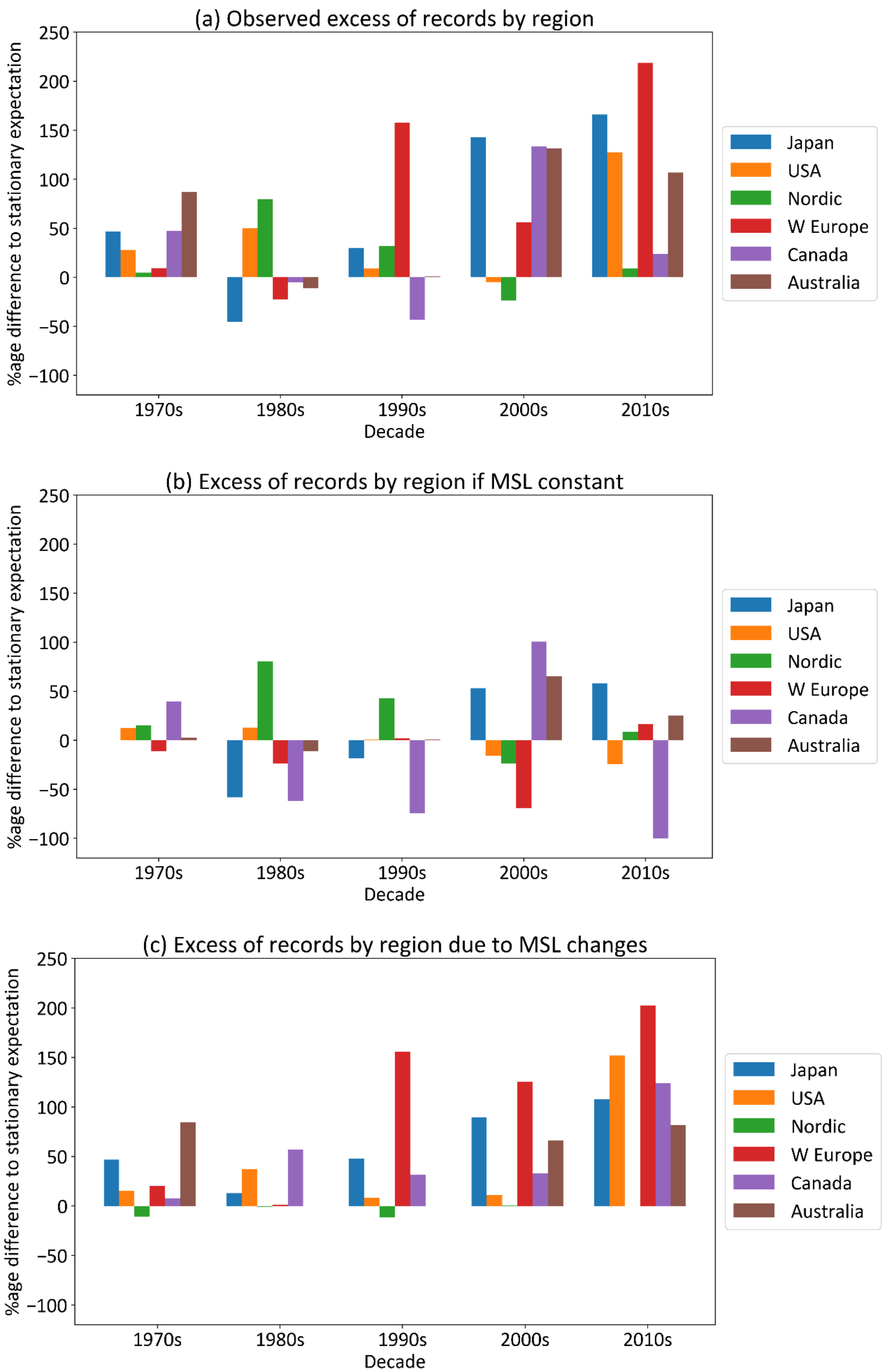

Figure 4: Excess of records, broken down by regions as described in the text for (**a**) observed sea levels, (**b**) counterfactual sea levels where observed MSL changes, showing impacts of changes in storm-tides, and (**c**) differences between (**b**) and (**a**), showing impacts of changes in MSL.

3.3 Sensitivity assessment of results to inter-gauge dependence

The GESLA dataset has highly variable spatial density across the global domain. This leads to some global regions being better represented than others in the dataset. One such region experiencing a very severe storm surge event in a particular decade could bias our results to suggest a greater proliferation of global record setting in that decade. We therefore wish to test whether correlation between gauges used in this study is a reason to doubt our finding that "in the 2010s the rate of record setting extremes in the Global North was more than double than expected in a stationary climate".

We develop two further subsets of the 247 gauges included in the analysis. First, we find a subset of 144 such that each gauge has no more than a 0.7 correlation (i.e., 50% explained variance) with any gauge in the subset. The gauges comprising this subset are determined using a recursive process where the gauge with the highest Pearson's R correlation (above 0.7) with another gauge is removed from the subset. When a subset is formed such that all gauges have R<0.7 the recursion is ended. We also repeat this process for a correlation of 0.5 (i.e., 25% explained variance), producing a subset of 85 gauges.

Whilst the exact excess of record varies, both subsets still return results consistent with the 2010s having a rate of record setting extremes in the Global North more than double than expected in a stationary climate. The R<0.7 subset gives an excess of records for 2010s of 112% and 47% for the 2000s. The R<0.5 subset gives values of 150% for the 2010s and 21% for the 2000s. This compares to the full set of gauges which give 127% and 59% respectively.

4 Discussion

Our results have global implications for coastal hazard risk assessments. We have extended recent results for the Pacific basin (Sweet et al., 2024), to show that increases in sea level extremes have already occurred across all well-gauged regions worldwide. SLR-driven increases in nuisance or minor impact coastal flooding are well established (Moftakhari et al., 2015; Sweet & Park, 2014), but this is the first quasi-global study to show that SLR has also increased the most extreme record-breaking coastal flooding. This has several implications for the validity of common assumptions that underpin extreme sea level analyses that aim to inform coastal risk assessments and adaptation.

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.

We have also shown that even if increases in storm surges have matched or exceeded rates of SLR in some regions (Calafat et al., 2022; Morim et al., 2025), on a global scale SLR is already the primary driver of increases in record-breaking coastal floods. Given projections of SLR imply much larger increases in extreme water levels than projections of storm-tides do (Vousdoukas et al., 2018), this primacy of SLR in increasing flood hazards is expected to continue. 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 in 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.

Finally, it remains a common assumption that improved predictions of storm surges (i.e., without reference to MSL or tidal changes) can materially improve coastal risk assessments (Bernier et al., 2024; Rashid et al., 2024). Our results suggest that storm surge projections must be combined with SLR information and tides to adequately inform both present-day and future coastal hazard assessments (Horsburgh et al., 2021; Tiggeloven et al., 2021). 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.

5 Conclusions

This study highlights changes in coastal flood severity are "now problems", despite prominent studies generally viewing these as "future problems". This suggests that "present-day" extremes and flood risk are likely underestimated, as these have been determined from historical data that does not include the recent observed changes in extreme sea levels demonstrated here. Heights of coastal sea level extremes have increased over recent decades, particularly in the 21st century. In the 2010s, records were broken at more than twice the rate that would be expected under stationarity (i.e., if sea level was not rising and there were no material changes in storm surge magnitudes and tidal ranges). Four-fifths of the observed increase in record-breaking coastal floods was due to increased mean sea level, with the remaining one-fifth due to changes in storm surges and tides. The impact of changes in sea level variability (i.e., related to storm surges and tides) is more noticeable on regional scales. For example, changes in variability have matched or exceeded rates of SLR in Nordic countries.

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Author contributions (CRediT)

BSH: Conceptualization, Data curation, Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing.

DGU: Conceptualization, Writing – original draft, Writing – review & editing.

DAJ: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

DJ: Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Data access statement

The GESLA dataset can be downloaded from www.gesla.org. Data and additional figures generated in this study can be downloaded from the following repository: www.doi.org/10.26180/30472118.

Declaration of interests

The authors report no conflict of interest.

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