ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE

10.1029/2023EF003993

The Influence of Future Changes in Tidal Range, Storm Surge, and Mean Sea Level on the Emergence of Chronic Flooding

Ben S. Hague[1] and Stefan. A. Talke[2]

[1]Bureau of Meteorology, Melbourne, VIC, Australia, [2]Department of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA, USA

Key Points:

- We develop a new coastal flood projection method that considers how tides and storm surges coincide, better replicating observations
- The method facilitates the first ever Australian national assessment of how flood rates may respond to future changes in tidal range and skew surges
- Percentagewise, changes in tidal range generally have a much larger impact on flood frequencies than equivalent changes in storm surge

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

B. S. Hague,
ben.hague@bom.gov.au

Citation:

Hague, B. S., & Talke, S. A. (2024). The influence of future changes in tidal range, storm surge, and mean sea level on the emergence of chronic flooding. *Earth's Future*, *12*, e2023EF003993. https://doi.org/10.1029/2023EF003993

Received 20 JULY 2023
Accepted 4 JAN 2024

Author Contributions:

Conceptualization: Ben S. Hague
Data curation: Ben S. Hague
Formal analysis: Ben S. Hague
Methodology: Ben S. Hague, Stefan. A. Talke
Writing – original draft: Ben S. Hague, Stefan. A. Talke
Writing – review & editing: Ben S. Hague, Stefan. A. Talke

Abstract Sea-level rise is leading to increasingly frequent coastal floods globally. Recent research shows that changes in tidal properties and storm surge magnitudes can further exacerbate sea-level rise-related increases in flood frequencies. However, such non-stationarity in tide and storm surge statistics are largely neglected in existing coastal flood projection methodologies. Here we develop a framework to explore the effect that different realizations of various sources of uncertainty have on projections of coastal flood frequencies, including changes in tidal range and storminess. Our projection methodology captures how observed flood rates depend on how storm surges coincide with tidal extremes. We show that higher flood rates and earlier emergence of chronic flooding are associated with larger sea-level rise rates, lower flood thresholds, and increases in tidal range and skew surge magnitudes. Smaller sea-level rise rates, higher flood thresholds and decreases in sea level variability lead to commensurately lower flood rates. Percentagewise, changes in tidal amplitudes generally have a much larger impact on flood frequencies than equivalent percentagewise changes in storm surge magnitudes. We explore several implications of these findings. Firstly, understanding future local changes in storm surges and tides is required to fully quantify future flood hazards. Secondly, existing hazard assessments may underestimate future flood rates as changes in tides are not considered. Finally, identifying the flood frequencies and severities relevant to local coastal managers is imperative to develop useable and policy-relevant projections for decisionmakers.

Plain Language Summary It is not just increases in mean sea level that cause coastal floods to become more frequent. Tidal range is the typical difference between the daily high and daily low tides that arise due to the gravity of the moon and sun acting on the Earth and how the resultant water level changes interact with coastlines. Many studies have shown that past changes in tidal range have led to observed changes in flood frequency that could not be explained by sea-level rise. Despite tidal ranges being expected to change in future, the implications of this for future flood frequencies has never been systematically assessed. We develop a new projection methodology that can consider such changes in flood risk. Our method also allows us to assess how much of an effect the way that weather and ocean patterns coincide with high tides influence how often flooding occurs. We show that for the considered Australian locations, future changes in tidal amplitude are generally expected to have a greater effect on future coastal flood rates than comparable changes in weather and ocean patterns. Understanding and accounting for potential future tidal range changes is important when formulating sea-level rise adaptation plans.

1. Introduction

Coastal floods in harbors, bays and estuaries are caused by high still water levels (SWLs) (Gold et al., 2023; Li et al., 2022; Woodworth et al., 2019). The occurrence of high water levels depends on how various phenomena coincide, including tides, storm surges, and seasonal variations in mean sea levels. Flooding occurs if the resultant water level exceeds local flood thresholds (Baranes et al., 2020; Enriquez et al., 2022; Kopp et al., 2019; Li et al., 2022; Sweet et al., 2016; Thompson et al., 2021). Variations in tides often leads to coastal flood events being clustered around high astronomical tides, even if such periods do not coincide with large storm surges (Hague, Grayson, et al., 2023; Haigh et al., 2011; Ray & Merrifield, 2019; Talke et al., 2018; Thompson et al., 2021). Long-term tidal modulations such as the 18.6 years nodal cycle also lead to variations in the heights and the likelihood of extreme flooding occurring in a given year (Baranes et al., 2020; Enriquez et al., 2022; Talke et al., 2018).

10.1029/2023EF003993

The frequencies of coastal flooding around the world have increased in response to sea-level rise (SLR) (Hague et al., 2022; Moftakhari et al., 2015; Sweet et al., 2018; Sweet & Park, 2014). SLR raises the heights of typical high tides, reducing the distance between high tide marks and flood thresholds (Dusek et al., 2022; Sweet & Park, 2014). Hence, increases in tidal range reduce the non-tidal contribution required for flooding to occur (Devlin, Jay, Talke, et al., 2017; Devlin, Jay, Zaron, et al., 2017). Tidal range also plays a key role in modulating how flood hazards change under sea-level rise. For example, locations with small tidal ranges are more susceptible to rapid changes in flood rates under SLR (Koroglu et al., 2019; Thieler & Hammar-Klose, 2000). This follows from the ratio of SLR to tidal range being higher at such locations (Ritman et al., 2022; Rueda et al., 2017). For example, for a location with 1 m tidal range, 1 m of SLR causes future low tides to be as high as today's high tides. In contrast, for a location with 2 m tidal range, the same 1 m of SLR means the future mean tide level is the height of present-day high tides.

In some locations, SLR now causes coastal flood thresholds to be exceeded due to tides alone under average weather and oceanic conditions (Dusek et al., 2022; Hague et al., 2022; Li et al., 2022; Ray & Foster, 2016; Ritman et al., 2022). A key impact of further SLR is that infrequent or rare events will become much more frequent. Many studies suggest that floods that have typically occurred once per century will likely occur every decade by mid-century, and annually before 2100, in many locations worldwide (Buchanan et al., 2017; Hunter, 2012; Taherkhani et al., 2020; Tebaldi et al., 2021). Similarly, present-day minor and nuisance flood levels may be exceeded hundreds of days per year by mid-century and daily before 2100 for current levels of exposure (Ezer, 2022; Hague et al., 2020; Ritman et al., 2022; Sweet et al., 2018; Sweet & Park, 2014; Thompson et al., 2019, 2021). These minor floods can cause disruption to transportation networks, vegetation damage, salination, and impact infrastructure (Cantelon et al., 2022; Gold et al., 2022; Hino et al., 2019; Kasmalkar et al., 2020).

The emergence and severity of chronic flooding poses a challenge to coastal management (Ghanbari et al., 2020; Gold et al., 2023; Le Cozannet et al., 2021; Moftakhari et al., 2018; Thompson et al., 2019). In many regions, the emergence of chronic flooding is expected to have a greater impact on communities than extreme floods becoming more extreme (Buchanan et al., 2019; Ghanbari et al., 2019; Moftakhari, Aghakouchak, et al., 2017; Paulik et al., 2021; Stephens et al., 2021). Unlike episodic or occasional floods, which are characterized by the severity of their impacts (Hague et al., 2022; Moore & Obradovich, 2020), chronic floods are defined by their frequency (Buchanan et al., 2019; De Leo et al., 2022; Gold et al., 2023; Sweet & Park, 2014; Thompson et al., 2019). Hence the concept of chronic flooding applies equally to minor, major or extreme floods. As they occur at lower sea levels, minor flooding will become chronic first, but eventually more extreme events will as well with continued SLR. Given the known limitations of some coastal protection measures (Nunn et al., 2021; Trace-Kleeberg et al., 2023), and absent adaptation measures, many coastal communities will eventually transition to experiencing chronic major flooding, with future timing depending on local SLR (Ghanbari et al., 2019; Hague et al., 2020; Sweet et al., 2018). This approach is embedded in coastal management frameworks in Australia, with guidelines for the State of Victoria indicating that major engineering works should only be considered if managed retreat is not a viable adaptation option (Department of Energy Environment and Climate Action, 2023).

Several recent studies have highlighted the importance of changes in storm surge magnitudes (Calafat et al., 2022; Enriquez et al., 2022; Wahl et al., 2015), tidal range (De Leo et al., 2022; Hague, Grayson, et al., 2023; Lee et al., 2017; Li et al., 2021) or both (Familkhalili & Talke, 2016; Talke et al., 2014, 2021) on extreme water levels. These changes have arisen due to changes in atmospheric processes (e.g., changes in position and intensity of storm tracks), oceanic processes (e.g., sea-level rise) and infrastructure-related anthropogenic factors (e.g., channel deepening) (Colberg et al., 2019; Devlin, Jay, Talke, et al., 2017; Devlin, Jay, Zaron, et al., 2017; Haigh et al., 2020; Lee et al., 2017; Li et al., 2021; Marcos & Woodworth, 2017; Ross et al., 2017; Talke & Jay, 2020). Changes in flood days have been attributed to changes in tidal range in both the United States and Australia, with positive trends in tidal range shown to exacerbate flood risk; decreases in tidal constituents, by contrast, may reduce chronic flooding (De Leo et al., 2022; Hague, Grayson, et al., 2023; Li et al., 2021; Pareja-Roman et al., 2023).

Despite the potential significance of sea-level variability (tides, storm surge) for flood hazards, most coastal flood hazard frameworks assume that water level variations around the average remain statistically stationary. Future water level distributions are obtained by shifting the historical distribution toward higher sea level, without any change in the shape of the distribution (Buchanan et al., 2016, 2017; Fox-Kemper et al., 2021; Ghanbari et al., 2019; Hague et al., 2020; Hunter, 2012; Kirezci et al., 2020; McInnes et al., 2013; Sweet et al., 2018; Taherkhani et al., 2020; Tebaldi et al., 2012, 2021; Thompson et al., 2019, 2021). Several studies have explored how future changes in storminess may impact sea level extremes regionally (Cannaby et al., 2016; Howard et al., 2019; McInnes et al., 2009). Similarly, some studies show that rising sea levels can influence tidal and storm surge magnitudes, and therefore flood hazards, in shallow seas (e.g., Arns et al., 2017). A recent study concluded that global-scale changes in tides, primarily due to SLR, were insignificant compared to other factors (Vousdoukas, Mentaschi, et al., 2018) suggesting that tidal non-stationarity is an insignificant factor in altered flood hazard. However, this study only modeled global-scale changes in tides, and not local or regional scale effects which have been the drivers of the largest historical tidal changes (Haigh et al., 2020; Li et al., 2021; Talke & Jay, 2020). While Ray and Foster (2016) recommended the inclusion of trends in tides be included in projections of flood frequencies, little progress has been made in projection frameworks to the present time.

This study develops a new framework to estimate the possible effect of future changes in mean sea levels and sea-level variability on flood frequencies at local and national scales. We apply our framework to assess future changes in Australian flood frequencies under various combinations of changes in mean sea level, tidal range, and storminess. This provides the first assessment of the sensitivity of chronic flood hazards to trends in tidal range and skew surges continuing, or emerging, in the future. From this assessment we identify the characteristics of locations most at-risk of large changes in chronic flood hazards in response to changes in variability.

2. Methods and Data

Our coastal flood projection framework produces timeseries of projected daily maximum SWLs under some specified climate pathway at a tide gauge location. We define a *climatological baseline period* of 1995–2014, and a *future projection period* of 2020–2150 to align with the baseline and projection periods used in the Intergovernmental Panel on Climate Change's 6th Assessment report (IPCC AR6) (Fox-Kemper et al., 2021).

The coastal flood frequency projection methodology is shown schematically in Figure 1, with further details provided in Sections 2.2–2.9. Our method is a variant of joint probability methods (Baranes et al., 2020; Batstone et al., 2013; Pugh & Vassie, 1978). It is also conceptually similar to methods used to attribute flood events to specific physical processes (Hague et al., 2020; Hague, Grayson, et al., 2023; Li et al., 2022; Ritman et al., 2022). The underpinning assumption is that a tide gauge record can be decomposed into several independent components, which are modeled separately and then recombined (e.g., Kirezci et al., 2020; Li et al., 2022; Lowe et al., 2021). Here we consider four main components: astronomical tides, mean sea level, within-year non-tidal variability and between-year (or interannual) non-tidal variability. The demarcation of these components is influenced by choices made in harmonic analysis and how long-term changes in mean sea level are represented (Hague & Taylor, 2021); thus, slightly different attributions to specific forcing may emerge, depending on specific methodology. The data produced by this study is provided in Hague (2024). These data are described in Supporting Information S1.

2.1. Historical Still Water Levels

Still water level (SWL) data are obtained from the Australian National Collection of Homogenised Observations of Relative Sea Level (ANCHORS) (Hague et al., 2021). Data over the baseline period of 1995–2014 were used to evaluate tides, storm surges, and annual mean sea level anomalies. This evaluation formed the basis for projections into the future. The locations included in the ANCHORS data set are shown in Figure 2.

2.2. Future Mean Sea Levels

Future mean sea levels are obtained from the Intergovernmental Panel on Climate Change's 6th Assessment report (IPCC AR6) (Fox-Kemper et al., 2021; Garner et al., 2021). The SLR projection closest to the published latitude and longitude for each gauge (Hague et al., 2021) was used for each respective site. We primarily focus on the SSP3-7.0 emissions scenario, following the IPCC AR6 Sea-Level Projection Tool (Garner et al., 2021). As in the tool, annual mean sea levels over the projection period of 2020–2150 were obtained through linear interpolation between the provided decadal values. In addition, we consider SSP5-8.5 to evaluate how other SLR scenarios impact the influence of increased tidal ranges and skew surges. The SLR estimates of the SSP3-7.0 and SSP5-8.5 scenarios span the sea level planning guidelines and scenarios used by Australian coastal planners (Norman &

10.1029/2023EF003993

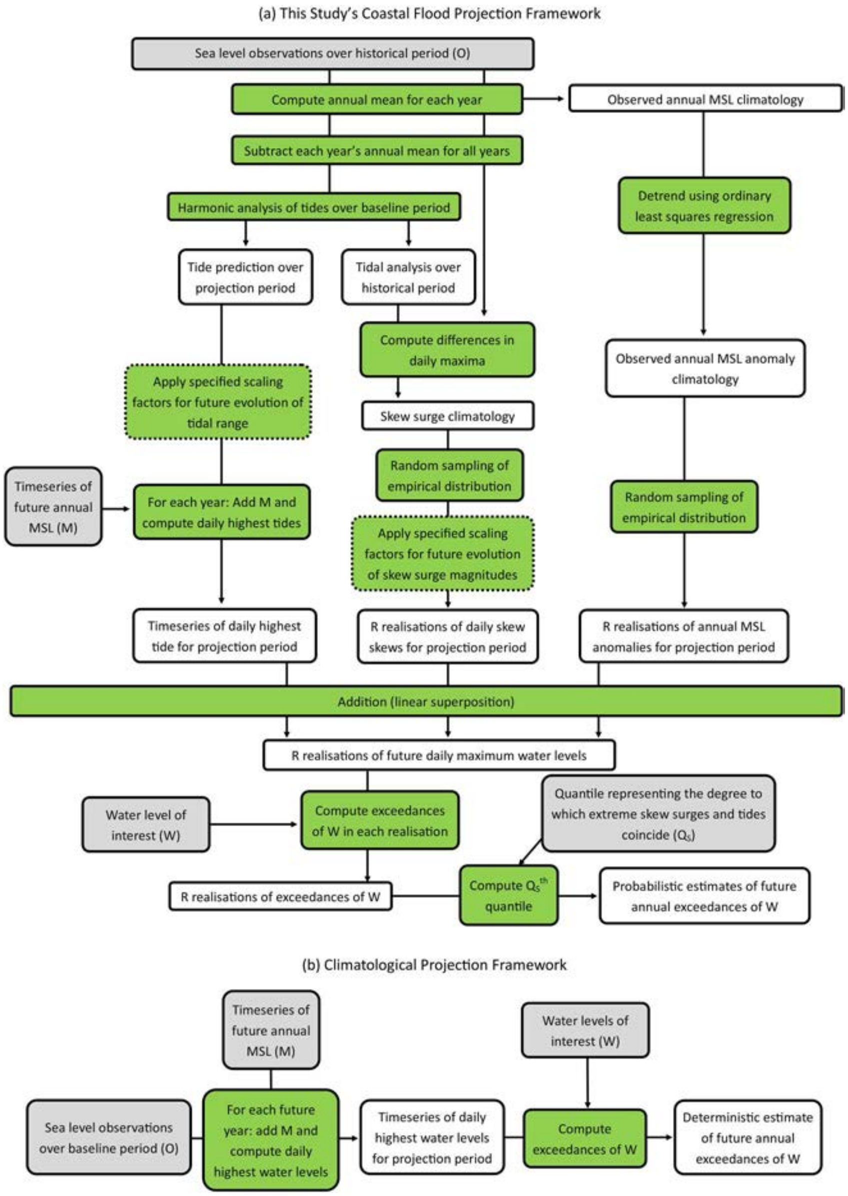

Figure 1. Schematic of the coastal flood projection method developed here (a, upper, Section 2.1–2.8) and the climatological projection methodology (b, lower, Section 2.9) used for comparisons in this study. Gray boxes are determined by the analyst, based on the specifics of the future climate storyline of interest. White boxes indicate timeseries of water levels produced during the application of the method. Green boxes denote methodological steps; solid borders indicate a step that is always performed in method. Dotted borders indicate a step that is only performed if variations in tidal ranges and skew surge magnitudes are specified in the future climate in the our framework (i.e., Section 2.10).

Gurran, 2018), and likely bound future SLR trajectories based on current emission commitments (Bamber et al., 2019; Jackson et al., 2018; Rogelj et al., 2023).

2.3. Future Astronomical Tides

Astronomical tides are the SWLs expected under average weather conditions. In this study, we considered 114 harmonic constituents, using the TideHarmonics tidal harmonic analysis package (Stephenson, 2017). We fitted the tidal model to hourly observed SWLs over the climatological baseline period (1995–2014). The corresponding annual mean sea level was first subtracted from the hourly values. This ensures that annual mean sea level contributions are not double counted when components are added together in Section 2.6. As 20 years is long

Figure 2. Locations of Australian tide gauges in the ANCHORS data set. Reproduced with author permission from Hague et al. (2021) under CC-BY 4.0 license.

enough to consider multi-annual tidal cycles (Haigh et al., 2011; Ray & Merrifield, 2019), no nodal corrections are applied.

This model of 114 constituents is used to produce a tidal hindcast over 1995–2014 baseline period, which is used to compute skew surges (Section 2.4). Additionally, a tidal forecast is produced for the 2020–2150 projection period. Each tidal prediction is made at hourly frequency, with constituent amplitudes held constant. This approach is consistent with previous coastal flood projections that have explicitly included future astronomical tides with SLR scenarios (Dusek et al., 2022; Ghanbari et al., 2019; Hague et al., 2020; Ray & Foster, 2016; Thompson et al., 2021). The maximum of (24) hourly tide heights is reported as the tidal contribution to daily maximum water levels (Section 2.6).

2.4. Future Within-Year Sea Level Variability

We represent within-year sea level variability due to short-lived meteorological, oceanographic, and (for river influenced locations) hydrologic processes using the skew surge metric. The (daily) skew surge is defined here as the difference between daily maximum observed SWL (i.e., Section 2.1) and daily maximum astronomical tide level (i.e., Section 2.3), following Hague et al. (2022). In most coastal locations, skew surges are found to be statistically independent of the tides (Baranes et al., 2020; Batstone et al., 2013; Santamaria-Aguilar & Vafeidis, 2018; Williams et al., 2016). Where surges and tides are not independent, assuming independence generally results in an over-estimation of extreme water levels and flood risk (Arns et al., 2020; Haigh, Wijeratne, et al., 2014).

Estimates of future skew surges are obtained by sampling an empirical distribution comprised of skew surges over the historical period. We compute the skew surge quantity for every day with complete observations. We first subtract the annual means from these historical SWL so that between-year sea level variability is not included in the skew surge. We generate R (here, $R = 1{,}000$) realizations of skew surges for each day in the projection period from this distribution. R is chosen as an arbitrary number that likely encompasses typical variability and enables statistics like the 5% and 95% percentiles to be assessed robustly.

The skew surge term encapsulates the water level response to all sources of short-lived non-tidal sea level forcing, including synoptic storm events, coastal circulation, local and far-field wind forcing, seasonal water temperature shifts, the inverse barometer effect, and river flow effects, both at the coast and in estuaries (Piecuch et al., 2018; Talke et al., 2021). This study adopts the common approach of not differentiating between the drivers of these non-tidal water level contributions, especially since some effects are not completely independent of each other (Hague, McGregor, et al., 2023; Li et al., 2022; Thompson et al., 2021). Instead, possible shifts in non-tidal forcing are assessed through a bulk trend in skew surge (see Section 2.9). Future efforts could investigate the influence of hydrological, meteorological, and oceanic factors on skew surge separately, especially if there is reason to believe that individual factors (such as local wind forcing or river flow) are non-stationary or trending differently from other factors. Historically, such trends have occurred; for example, over secular time scales, both the seasonal timing and magnitude of river discharge to the ocean has shifted in many river basins, both due to climate shifts and water resources management (Moftakhari et al., 2013; Naik & Jay, 2011). But, the influence on near-coastal estuarine stations is generally small during most conditions (<10 cm), even in high discharge river basins such as the Columbia River, USA (Talke et al., 2020). Similarly, the influence of channel deepening and other infrastructure development on mean river water levels is generally small near the coast, except during extreme river flood events (e.g., Talke et al., 2021). Within the Australian context considered here, river discharge magnitudes are generally small and likely have little influence on water levels at most of the coastal and near-coastal stations considered here.

The climate change impacts of mean sea level on frequent flood threshold exceedances are expected to dwarf the impact of changes in peak river flows (Ghanbari et al., 2021). Changes in rainfall and streamflow may shift annual recurrence intervals from 0.01 to 1 in a small number of locations under high greenhouse gas emission scenarios (He et al., 2022; Hirabayashi et al., 2021). In contrast, sea-level rise in the same scenario causes present-day 1-in-100-year coastal flood expected to occur annually virtually everywhere, and more than 100 days per year in many locations (Boumis et al., 2023; Fox-Kemper et al., 2021; Hague et al., 2020; Taherkhani et al., 2020; Tebaldi et al., 2021). Hence, not explicitly considering freshwater influences on chronic flood hazards should not affect the robustness of this study's findings. Nonetheless, the framework presented here could be further partitioned to examine how hydrological factors impact the emergence of chronic flooding, particularly in regions with large river-induced water level variability like tidal rivers (Hoitink & Jay, 2016).

2.5. Future Annual Mean Sea Level Variability

Our projection includes the effect of interannual variations in the annual mean sea level (AMSL). The AMSL anomaly is calculated as the difference between the observed AMSL and an ordinary least squares trendline fitted over the baseline period (i.e., 1995–2014). AMSL anomalies are assumed to be independent of tides and skew surges, and the AMSL trend (Burgos et al., 2018; Lowe et al., 2021; Ritman et al., 2022; Sweet et al., 2016). Like skew surges, estimates of future annual mean sea level variability are obtained by sampling an empirical distribution comprised of annual mean sea level anomalies over the baseline period. We then generate 1000 (i.e., R) realizations of future AMSL anomalies for each year in the projection period.

2.6. Future Still Water Levels

Projections of future daily maximum SWLs are obtained by adding the components together: projected mean sea level (Section 2.2), astronomical tides (Section 2.3), sampled skew surges (Section 2.4), and sampled annual mean sea level (AMSL) anomalies (Section 2.5). The same annual value of projected mean sea level is used for each day in a calendar year. The daily maximum astronomical tide is used as the tidal contribution to daily maximum SWLs. Each of the 1,000 different realizations of skew surges are matched to the corresponding AMSL anomaly (e.g., iteration 23 of skew surge is matched to iteration 23 of AMSL). This provides 1,000 possible future daily maximum water levels under the same predicted astronomical tide for each SLR scenario considered. The components of these future still water level timeseries are provided in Hague (2024) which is described in Supporting Information S1.

2.7. Future Flood Days

Annual flood days are the number of days in a calendar year where the daily maximum SWL exceeds a specified flood threshold (Burgos et al., 2018; Hague et al., 2020, 2022; Sweet et al., 2018; Sweet & Park, 2014; Thompson et al., 2019, 2021). Several flood thresholds are considered for each location in the ANCHORS data set. Firstly, we consider the impact-based minor flood levels defined by Hague et al. (2022). Of the 38 ANCHORS locations, 25 have a minor flood threshold defined. However, 15 of these are classified as low-sample thresholds, meaning they are based on less than 10 flood reports. The 10 locations with well-sampled flood thresholds are Cairns, Townsville, Brisbane, Gold Coast, Ballina, Newcastle, Sydney, Melbourne, Port Adelaide, and Fremantle.

These impact-based thresholds are supplemented by percentile-based thresholds so projections for all locations can be defined in a consistent way, and flood severities other than minor can be considered. Previous studies have shown that minor floods can occur 10 days per year at many locations (Hague et al., 2022). Accordingly, we consider the 97th, 99th and 99.7th percentiles of daily maximum water levels as thresholds. These are calculated from the observed SWLs over the baseline period, occurring on average 11, ~4 and 1 day/s per year, respectively. To consider more extreme floods we consider eight additional thresholds ranging from 0.1 to 0.7 m inclusive above the 99.7th percentile level, as most Australian locations have offsets between 1-in-1- and 1-in-100-year return period level of less than 0.7 m (Pattiaratchi et al., 2018; Tebaldi et al., 2021). We also consider future exceedances of the highest water level recorded over the baseline period at each location. The resultant timeseries of threshold exceedances are made available (refer Data Availability Statement).

2.8. Chronic Flood Emergence Times

Several studies have sought to quantify the number of annual flood days that are required for flooding to be considered chronic. These all agree that for flooding to be considered chronic it must occur at least several times per year (Ghanbari et al., 2020; Gold et al., 2023; Le Cozannet et al., 2021). Buchanan et al. (2019) found that a scenario where "streets may flood several times per month" led to statistically significant tendency for home-owners to consider relocation. Sweet and Park (2014) proposed a similar definition of 30 flood days per year as representing a tipping point, which once surpassed, results in chronic flooding. Most other published definitions require considerably more flood days to occur in a year for flooding to be considered chronic. For example, de Leo et al. (2022) used a definition of 100 flood days per year. Thompson et al. (2019) took a slightly different approach, defining chronic flooding to occur when nine out of 10 consecutive years produced at least 50 flood days. This definition has also been adopted by subsequent studies (Habel et al., 2020; Li et al., 2023).

The emergence time is the first year that a specified number of annual flood days occurs (Hague et al., 2020). To understand how much different definitions of "chronic" affect the results of this and previous studies, we consider four different emergence times of chronic flooding:

- The first year where 30 or more flood days occur (i.e., Sweet & Park, 2014).
- The first year where 100 or more flood days occur (i.e., de Leo et al., 2022).
- The first year where at least nine of the next 10 years have had least 50 flood days occur (i.e., Thompson et al., 2019).
- The first year where 50 or more flood days occur.

The final definition is included to assess the effect of requiring many consecutive years of flooding for it to be considered chronic (e.g., Thompson et al., 2019), rather than just a single year (e.g., the first two definitions).

2.9. Projections Considering Changes in Tidal Ranges and Skew Surges

The structure of our framework allows for straightforward modifications that consider the impact of changes in tidal range and skew surge magnitudes on coastal flood frequencies and emergence times of chronic flooding. For tides, the annual daily maximum tide levels from Section 2.3 are multiplied by some factor (with respect to mean tide level). For skew surges, this is achieved by multiplying sampled skew surge values from Section 2.4. This approach allows consideration of spatially variable trends in tide and surges if desired. We do not consider changes in the magnitude of AMSL anomalies. Whilst variability in sea surface height and AMSL may increase with climate change, further work is required to understand the flood risk implications (Widlansky et al., 2020).

To demonstrate a sensitivity testing approach, we consider increases and decreases of 1% per decade in both skew surge magnitudes and tidal amplitudes. For example, with a 1% per decade increase in tidal amplitude, a 2 m tide (above annual mean sea level) in 2020 becomes a 2.02 m tide in 2030 and 2.2 m tide in 2120. Similarly, a 0.2 m skew surge in 2020 becomes a 0.202 m skew surge in 2030 and a 0.22 m skew surge in 2120. In absolute terms, larger magnitude tides and skew surge increase more. Whilst trends in tides and surges do vary spatially in Australia (Hague, Grayson, et al., 2023; Mawdsley & Haigh, 2016), considering a spatially uniform trend enables standardized comparisons of the relative importance of future trends in sea-level, tides, and skew surge at different sites, and comparison to other sources of uncertainty in coastal flood projections.

Australian locations have been included in several global and regional studies on changes in tidal range and tidal constituents (Devlin, Jay, Talke, et al., 2017; Devlin, Jay, Zaron, et al., 2017; Mawdsley et al., 2015; Schindelegger et al., 2018; Woodworth, 2010) and two national studies (Hague, Grayson, et al., 2023; Harker et al., 2019). Schindelegger et al. (2018) found that a sea-level rise of 0.5 m produced changes of roughly −1/+2 cm in the M2 and K1 constituents in the coastal Australian ocean, depending on location. Harker et al. (2019) found small positive and negative changes in tidal amplitudes of up to 1% per decade but did not quantify how these changes impacted flood frequencies or heights of sea level extremes. A more recent study (Hague, Grayson, et al., 2023) found a much larger, 29% change, likely due to changes in the dredging regime, at one location—Lakes Entrance, Victoria. This study also found that approximately one-third of all Australian locations had statistically significant trends in the M2 constituent (the major component of tidal range in semidiurnal systems), ranging from −1.24% to +3.54% per decade. These studies justify the consideration of a hypothetical 1% per decade increases and decreases in tidal amplitudes in our sensitivity testing approach.

Fewer studies have considered changes in skew surges in the Australian region. One recent study modeled changes in extreme water levels due to changes in weather patterns (Colberg et al., 2019). The results of this study are difficult to apply within our framework for several reasons. Firstly, non-tidal residuals were used instead of skew surges. Secondly, results are expressed as absolute changes in 1-in-20-year non-tidal residual return levels rather than a multiplying factor that applies to all surge magnitudes. Thirdly, changes in ocean circulation are not considered, and they omit tides from projections. These methodological differences matter because unlike skew surge, the non-tidal residual is not independent of tides, meaning large non-tidal residuals may not be due to atmospheric factors (Williams et al., 2016). This makes it is hard to interpret the impact of changes in non-tidal residual on flood hazards without the accompanying tidal heights. A global study that included Australian locations has more useful results for our purposes. Mawdsley and Haigh (2016) found statistically significant decreases in extreme skew surge of order 1%–2% across northern Australia, and positive trends of similar magnitudes at isolated locations in the south. These results suggest changes of around 1% per decade are plausible.

2.10. Climatological Projections

Our projection method differs to the approach used by recent studies by explicitly estimating the tide, surge, and annual mean sea level components in projected water levels. Previous studies have estimated future changes in threshold exceedances under SLR. These studies define a 20 calendar-year climatology (i.e., an empirical distribution) of daily maximum SWLs. For each year and future climate pathway, all the values in this climatology are increased by some amount corresponding to the relevant SLR increment (Dusek et al., 2022; Hague, McGregor, et al., 2023; Ritman et al., 2022). The average number of annual flood days is then computed from this new climatology. This is the number of days where the daily maximum water exceeds a threshold of interest divided by the number of data-years in the climatology. This approach retains the autocorrelation structure of the water level timeseries but doesn't model surge and tide separately. We generate projections using this climatological method to understand how these methodological differences impact estimates of chronic flood emergence.

10.1029/2023EF003993

3. Results and Discussion

3.1. Impact of Coinciding Independent Tidal and Non-Tidal Water Level Contributions on Flood Frequencies

A key feature of our approach (i.e., Section 2.6) is that flood frequencies can be estimated probabilistically by taking percentiles of the R realizations (here 1000) of future annual exceedances of water levels. This enables quantification of the probability of joint events, such as the probability that large storm surges coincide with high spring tides. As also observed in other joint-probability approaches (e.g., Baranes et al., 2020), including this aleatoric uncertainty improves the replication of between-year variability like what is seen in observed flood rates (Figures S1 and S2 in Supporting Information S1). Here we primarily consider the 5th, 50th (median) and 95th percentile estimates of the possible maximum number of annual exceedances over a decade (Figure 3). This was computed by first finding the 50th, 500th, and 950th largest of the 1,000 realizations of annual flood days for each site then taking the largest annual estimate across a decade. We also provide a national median value for each of these (i.e., median of all 5th percentile estimates in Figure 3a). These probabilities are conditional on the mean sea level scenario specified, as are all other projections of future flood hazards (e.g., Thompson et al., 2021). Future changes in tides and skew surges are not considered here.

We show that variability in realized flooding is large, even when a single SLR scenario is considered (SSP3-7.0 median). For example, 26 (of 38) locations have a 95% chance of experiencing at least 1 year with 20 exceedances of the present-day once a year level (i.e., the 99.7th percentile of daily maxima) in the 2060s (Figure 3b). However, 23 of these locations have only a 5% chance of this occurring in the 2040s, two decades earlier (Figure 3g). There is a national median estimate that 12 (5%–95% range: 6–25) exceedances of the 99.7th percentile threshold will occur in at least 1 year in the 2040s. This increases to 44 (24–72) days in the 2060s and 205 (165–249) days in the 2090s.

The variability in possible flood days due to random variations in how tides and surge extremes coincide can be larger than the difference in flood days due to following a higher emission scenario. Under the SSP5-8.5 median SLR scenario, there is a national median estimate that 14 (5%–95% range: 7–27) exceedances of the 99.7th percentile threshold will occur in at least 1 year in the 2040s. This increases to 57 (34–84) days in the 2060s and 253 (215–290) days in the 2090s. The national median estimates for 2040 and 2070 sit within the 5%–95% range for SSP3-7.0 provided above and in Figure 3. Median estimates based on standard climatological projections (Section 2.10) are 13, 43, and 212 days for 2040, 2060, and 2090 respectively, under SSP3-7.0. These estimates increase to 13, 56, and 256 days under the higher SSP5-8.5 scenario. This indicates that our projection framework is unbiased with respect to the standard practice of climatological projections (i.e., Section 2.10). However, our projections that consider combinations of tides and surge (i.e., Section 2.6) can provide a possible range of values, not just a single estimate.

The sensitivity of differences in decade-dependent threshold exceedances on how tide and surge extremes coincide highlights the importance of defining risk tolerance when defining chronic flood adaptation triggers. For example, if it is decided that an adaptive action is to be taken when there is 5% chance of some flood frequency occurring, critical decisions will be required to be made decades earlier than if planners were content with waiting until there was a 50% or 95% chance of some annual flood frequency occurring. If this trigger involves anything other than a 50% probability, climatological projection frameworks based only on hazard assessments from a baseline period are unsuitable. These only provide a median estimate based on the observed coincidence of tides and storm surges at a location.

The differences in the degree to which tide and surge extremes' coincidence impact flood rates varies by location, and by the time period being considered. For example, Bunbury has the 11th smallest 5th–95th percentile range for maximum annual flood days during the 2040s but the largest 5th–95th percentile range for the 2090s. However, some locations, such as Mackay, Broome, Port Hedland, Townsville, and Darwin, have the smallest 5th–95th percentile range for all thresholds and decades (e.g., compare Figures 3c and 3i, or Figures 3b and 3h). This variability in projected flood dates is related to tidal range. The latter locations are among those with the largest tidal ranges in the ANCHORS data set (Hague et al., 2022). These large tidal ranges more strongly constrain the future frequency of flooding. This means that the coincidence of storm surges with large spring tides is less important in modulating flood days, as flooding generally occurs only on days with the very highest spring tides anyway (Hague, McGregor, et al., 2023). It is notable that the Australian locations with large tidal ranges and

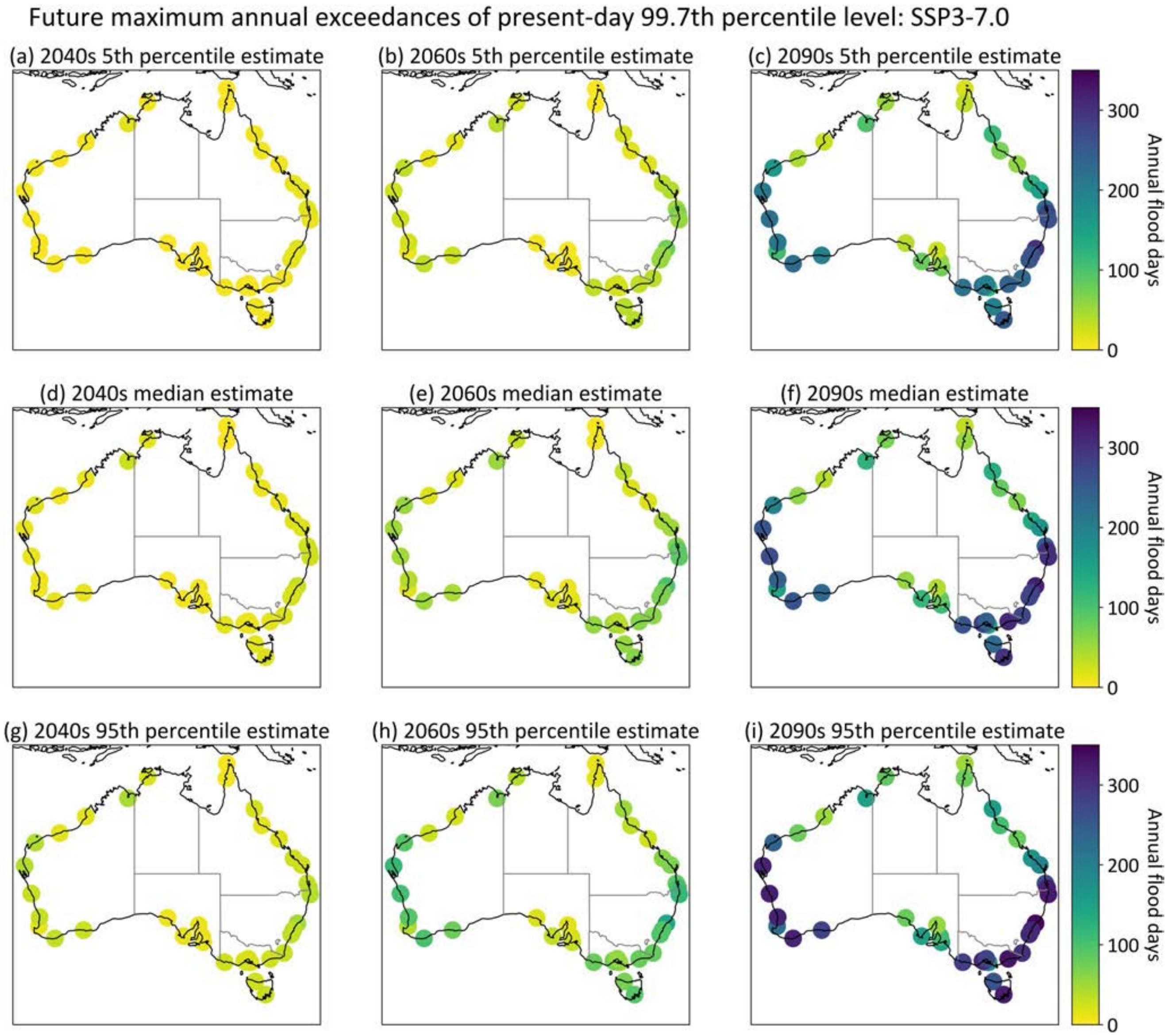

Figure 3. Projections of maximum annual exceedances of the present-day average annual maximum water level (99.7th percentile of daily maxima) for three different decades, under SSP3-7.0: the 2040s (left panels), 2060s (center vertical panels) and 2090s (right panels). The 5th (upper panels), median (center horizontal panels) and 95th (lower panels) percentile counts are provided for each decade.

less variability due to how tide and surge extremes coincide are all subject to tropical cyclone driven storm surges at present. Tropical cyclones are very often the focus when considering coastal flood risk in these locations (e.g., Haigh, MacPherson, et al., 2014; O'Grady et al., 2022). The most extreme future floods will continue to be driven by tropical cyclones. However, impacts currently associated with tropical cyclones will likely occur chronically due to tides in future.

3.2. Impact of Chronic Flood Definition on Emergence Times

There is substantial variability in emergence times of chronic minor flooding between locations, with some locations facing an imminent chronic flood threat. Based on the minor flood thresholds defined by Hague et al. (2022), Ballina, Brisbane, Gladstone, Gold Coast, Newcastle, Port Kembla, and Sydney have a 95% chance of 30 annual flood days of flood occurring at least once during the 2020 decade. In contrast, the threat is less immediate at Fremantle and Port Adelaide, where there is 95% chance that chronic flooding will not emerge until after 2050, even under high emissions scenarios. Of the 10 locations with well-established flood thresholds based on multiple observations, median estimates of the first year of 50-day-per-year flooding vary from 2020 (or earlier) (Newcastle) to 2074 (Port Adelaide). This variability in coastal flood *frequency* occurs despite relatively uniform rates of SLR and approximately uniform changes in the *heights* of sea level extremes across Australia (McInnes, Church, et al., 2015; McInnes, Monselesan, et al., 2015). Tidal variability modulates how frequency of threshold exceedances changes respond to SLR but not how extreme water level heights respond to SLR (Hague, McGregor, et al., 2023). Arguably, improving estimates of spatial variations in SLR is not very important for understanding how coastal flood frequencies will evolve this century.

Variability in emergence times of chronic minor flooding also arises from using different definitions of emergence times. Considering the median of all stations, the first year when 30 flood days is projected (Figure 4c) is 15 years earlier than the first year when 50 flood days is projected (Figure 4a). The first year of 50 minor flood days typically occurs 12 years earlier than the first year of 100 annual minor flood days (Figure 4d). Defining chronic flood emergence years as the first of nine out of 10 consecutive years where at least 50 minor flood days are projected (Figure 4b) pushes back the median estimated emergence years of chronic minor flooding by about 5 years, compared to the first year of 50 flood days. As the emergence year is defined as the first of the 9 years, the observed 5 years difference is explained by year-to-year variability in flood days (which is driven by random variations in how tide and skew surge extremes coincide). Thus, persistent chronic flooding (9 out of 10 years) requires more SLR than a single year of the same threshold (here, 50 days). Future changes in tides and skew surges are not considered here.

The dependence of emergence times on how "chronic" flooding is defined highlights the importance of identifying the most appropriate definitions of chronic flooding and what flood thresholds these pertain to. More broadly, there is a need to define appropriate adaptation triggers so science can inform coastal decision-making. For example, are single or consecutive years of extreme flood counts more likely to trigger adverse effects and/or adaptative actions? Another consideration is the relative importance of frequency and severity of floods in determining these adaptation triggers. The definitions of chronic flooding used here and by previous studies is focused on chronic *nuisance* or chronic *minor* flooding, in which flood water depths are relatively small (<20–30 cm). It is possible that increasingly frequent moderate or major flooding require adaptation measures well before minor floods occur 30, 50 or 100 days per year. For example, managed retreat has been implemented in response to recurrent hazards that have occurred less frequently than 30 days per year (Hino et al., 2017). It is important to identify the most locally relevant definition of chronic flooding as part of coastal flood hazard assessments, based on chronic flood adaptation triggers.

The effect of considering different SLR scenarios on emergence times is dependent on both the definition of chronic and the emergence time itself. The effect is generally modest. If chronic minor flooding is expected prior to 2050, considering a different scenario doesn't have much effect. For example, our projections suggest that Melbourne has a 95% chance of seeing 30 days per year of minor flooding by 2049 under SSP3-7.0 and 2047 under SSP5-8.5. If chronic minor flooding is expected to emerge only after 2050, then considering a different SLR scenario has a greater effect. For example, Port Hedland has 95% chance of seeing 30 days of minor flooding by 2114 under SSP3-7.0, or by 2104 under SSP5-8.5. The same principle applies if emergence times are delayed by considering a different definition of chronic flooding. For example, Melbourne has 95% chance of seeing 100 days per year of minor flooding by 2072 under SSP3-7.0 and 2068 under SSP5-8.5.

3.3. Impact of Changes in Tidal Range and Skew Surge Magnitudes and Sea-Level Rise Scenarios on Emergence Times

Increases (decreases) in tidal ranges and skew surge magnitudes of 1% per decade lead to larger (smaller) increases in flood frequencies than would be expected based on SLR alone. Increasing tide and storm surge magnitudes bring forward emergence times of chronic flooding (Figure 5), and increase the probability of chronic flooding emerging by a given year. In general, percentage-wise changes in tidal range have a much larger effect than the equivalent percentage-wise change in skew surge. For example, 1% per decade changes in skew surge magnitudes change emergence years of chronic flooding by one or 2 years. Such a low value suggests that even quite large changes in the daily skew surge have a quite insignificant impact on coastal flood frequencies. In contrast, 1% per decade changes in tidal amplitudes change emergence years of chronic flooding by a median of 5 years and by decades at locations with very large tidal ranges.

10.1029/2023EF003993

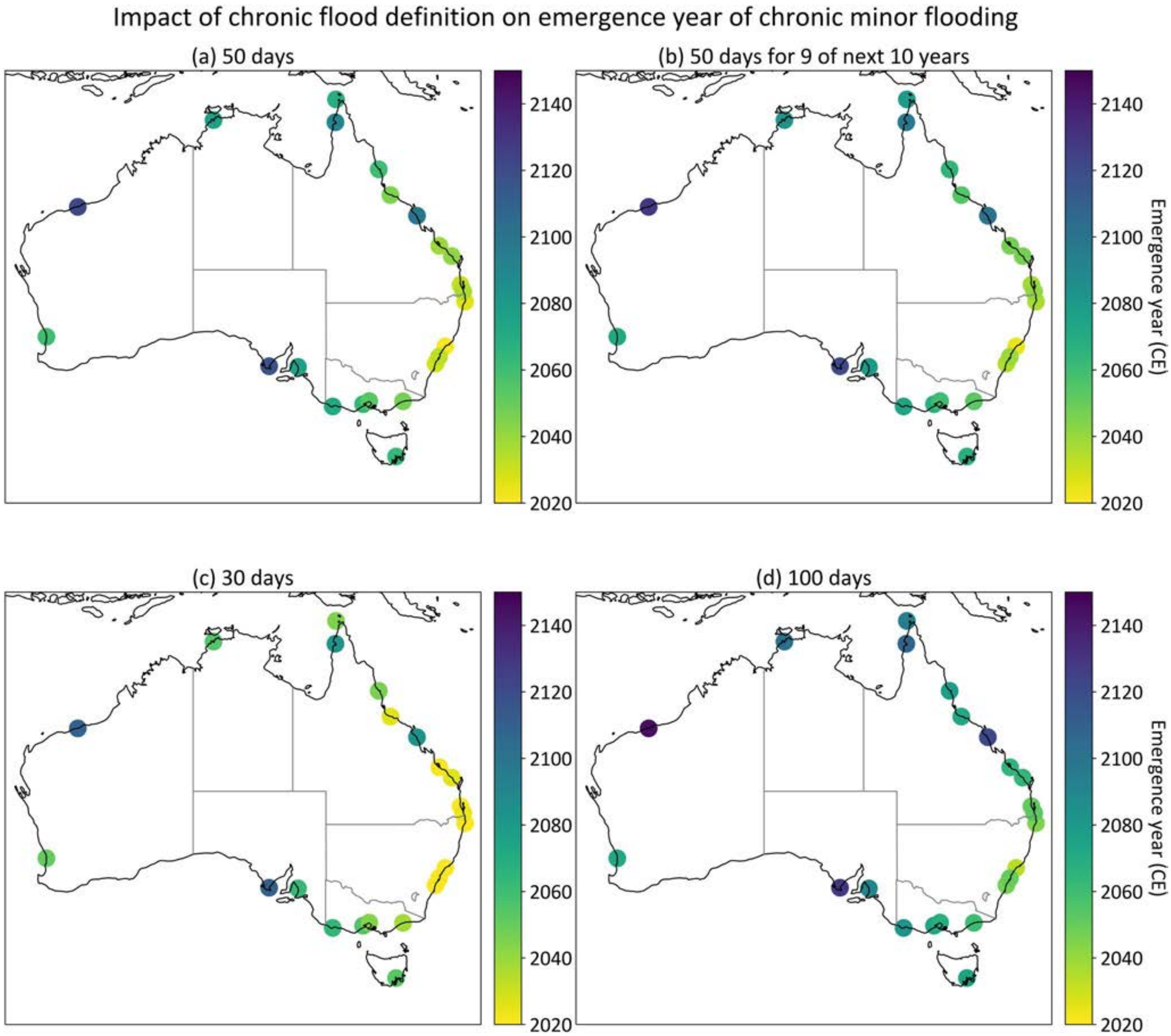

Figure 4. Impact of chronic flood definition on chronic minor flood emergence time. The median estimate of emergence year of chronic flooding based on four different definitions of emergence (a–d) based on SSP3-7.0 median SLR scenario from our projections.

Results suggest a symmetry in the sensitivity of flood frequency to changes in sea level variability. The impact of 1% decrease in tidal range has the same magnitude but different sign as a 1% increase. Thus, reducing tidal range through engineering interventions or nature-based solutions that return bathymetry and tidal inlets to pre-development depths could be a viable flood risk mitigation technique in locations where flood frequencies are sensitive to changes in tidal range (e.g., Pareja-Roman et al., 2023). Given that SLR and depth increases can strongly increase tidal range in estuaries where tidal ranges are currently damped (Khojasteh et al., 2023), our findings mean that these locations may be more at risk of future flooding than anticipated based on assumptions of stationary tidal ranges (e.g., Hanslow et al., 2018).

For 22 of the 38 ANCHORS gauges, the emergence time changes due to 1% per decade changes in tidal amplitudes are comparable to those associated with different emission scenarios. At locations with large tidal ranges, a 1% per decade increase in tidal range brings forward emergence times further than following a higher emissions scenario does. To demonstrate this, we consider the median emergence year of 50 annual exceedances of the 99th percentile under SSP3-7.0 (Figure 5). These emergence years vary from 2046 at Carnarvon and Newcastle to

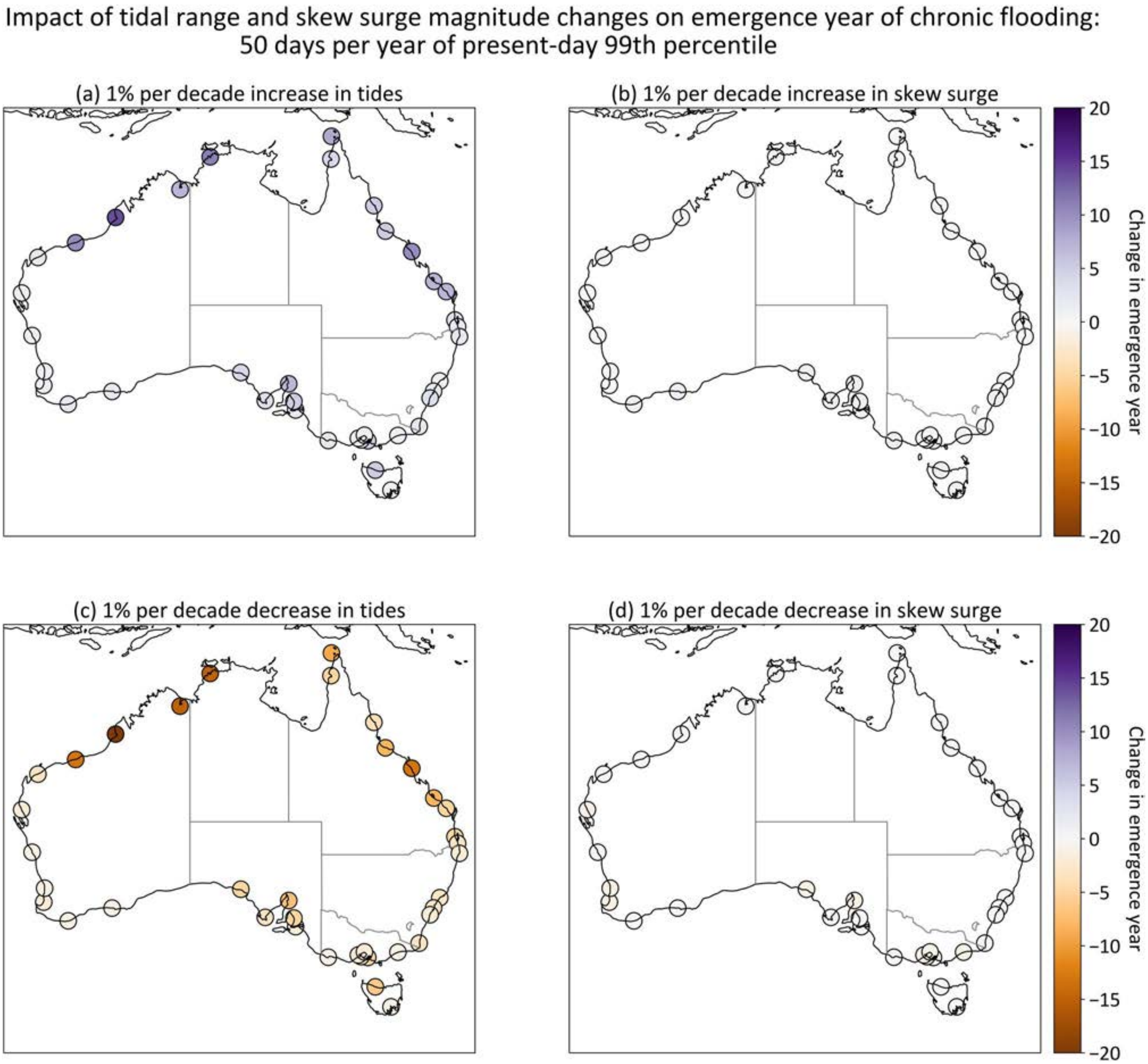

Figure 5. Change in emergence year resulting from a 1% per decade increases in tidal amplitudes (a, upper left) or skew surge magnitudes (b, upper right) and 1% per decade decreases in tidal amplitudes (a, lower left) or skew surge magnitudes (b, lower right). Brown dots denote emergence times being delayed relative to the case where no changes in tidal amplitudes or skew surge magnitudes were applied. Blue dots denote emergence times occurring earlier compared to the case where no changes in tidal amplitudes or skew surge magnitudes were applied.

2093 at Broome, with a national median of 2055. If a 1% per decade increase in tidal amplitudes is applied, the median emergence time becomes 2053. The same 2 years shift in median emergence time occurs when the SSP5-8.5 SLR scenario was considered instead of SSP3-7.0. The difference is much larger for locations with large tidal ranges. At Darwin under the SSP3-7.0 median SLR scenario, there is 50% chance of chronic flooding occurring by 2076. If the higher SSP5-8.5 median SLR scenario is considered the emergence year becomes 2072. An increase in tidal amplitudes of 1% per decade results in an emergence time of 2061—a full decade earlier than if stationary tides are considered.

The impact of changes in skew surge magnitudes on emergence times of chronic flooding is much less. For example, increasing skew surges by 1% per decade does not change the national median emergence time of 50 annual exceedances of the 99th percentile under SSP3-7.0 (Figure 5). No locations experienced a change in emergence time greater than 1 year. This includes locations such as Melbourne and Fremantle where exceedances of the 99th percentile currently occur exclusively during large storm surge event at present (Hague et al., 2022). Based on our approach (Section 2.9), a 1% change per decade in tidal amplitude means that all high tide heights (relative to annual mean sea level) increase by 1% per decade and all low tide heights decrease by 1% per decade, relative to the mean tidal level. The same applies to storm surges. It is likely that tidal range and storm surges will alter in a less spatially coherent and symmetric way, meaning these results should only be interpretated as a sensitivity test, not locally applicable projected future changes in tidal ranges.

Several flood hazard studies have considered changes other than mean sea level but have primarily focused on non-tidal, rather than tidal, sources of sea-level variability (e.g., McInnes et al., 2013; Muis et al., 2020; Vousdoukas, Bouziotas, et al., 2018; Vousdoukas, Mentaschi, et al., 2018). Furthermore, recent studies have shown that it is local, rather than global or regional, changes in tidal range that tend to be largest; nonetheless, such tidal changes are often driven by factors such as channel deepening that are occurring world-wide (Haigh et al., 2020; Talke & Jay, 2020). Local shifts in tidal properties, even if they occurred decades or a century ago, have produced the greatest impact on flood frequencies (datum exceedances) over the recent past due to sea-level rise (Hague, Grayson, et al., 2023; De Leo et al., 2022; Li et al., 2021; Pareja-Roman et al., 2023). Studies that have considered future changes in tides and their impact on flood hazards have used tidal models which do not generally resolve processes that have led to these local-scale changes, as they require detailed local knowledge (Harker et al., 2019; Schindelegger et al., 2018; Vousdoukas, Mentaschi, et al., 2018).

3.4. Impact of Flood Severities on Emergence Times

The key findings of Sections 3.1–3.3 apply regardless of the flood threshold being considered: annual flood counts are strongly modulated by whether extreme storm surges coincide with large tides, projections of chronic flood emergence years depend on how chronic flooding is defined, and changes in tides can lead to changes in these emergence years. This is observed in projections of annual flood rates and emergence times of chronic flooding for higher thresholds provided as Supporting Information S1. The risk of frequent major flooding this century is real. For example, under the SSP3-7.0 median SLR scenario there is a 50% chance that the level 0.3 m above the present-day 1-in-1-year level (i.e., 99.7th percentile) will be exceeded at least 50 times in a single year in the 2090s at many locations on the Australian east coast (Figure 5d). For Sydney, this level (i.e., 0.3 m above the 99.7th percentile) has been estimated as occurring less than once per millennium in the current climate (Watson, 2022). In other words, the present-day 1-in-1000-year level will be likely be occurring at 50 days per year before 2100 under SSP3-7.0, a 50,000-fold increase in frequency.

The main difference between results for different flood thresholds is that the emergence of chronic flooding occurs earlier for lower flood thresholds and later for higher flood thresholds. If the 99.7th percentile of daily maxima is considered as a flood threshold and the 50-day criterion is used, the emergence years of chronic flooding vary from 2054 (Newcastle) to 2105 (Booby Island), with a median of 2067 (Figure 6b). In contrast, all locations are projected to have seen chronic exceedances of the 97th percentile before 2075, with this occurring in most locations before 2042 (Figure 6a). If a threshold 0.3 m above the 99.7th percentile is considered, the median emergence year increases from 2067 to 2098 (Figure 6d). Relative differences between different locations' emergence years in Figure 5 further demonstrate the threshold-dependence of emergence years. For example, Wyndham has the earliest emergence time for chronic exceedances of the 97th percentile (Figure 6a) but ranks 7th when considering the level 0.3 m above the 99.7th percentile (Figure 6d). This means that the locations most at risk of chronic minor flooding may not be the locations most at risk for chronic moderate or major flooding. For example, based on the 97th percentile Wyndham would be assessed as most at-risk, which is a different conclusion that would be drawn if the level 0.3 m above the 99.7th percentile is used. The inconsistent emergence of chronic flooding of different thresholds means that past or recent experience may not be a good guide to where the focus for adaptation should lie.

Our findings highlight that the accuracy of flood thresholds should be a key consideration when developing flood hazard studies and assessments. For example, comparing Figures 6c and 6d shows that a 0.2 m difference in flood threshold typically causes a two -decade difference in chronic flood emergence times. The national median emergence tide of 50 days exceeding a threshold of 0.1 m above the 99.7th percentile is 2079. If the threshold is 0.3 m above the 99.7th percentile, the emergence year is 2098 instead. This observation holds for different SLR scenarios and differences in tidal trends. Under SSP5-8.5, The national median emergence tide of 50 days exceeding a threshold 0.1 m above the 99.7th percentile is 2075. This is delayed until 2092 if a 0.2 m higher

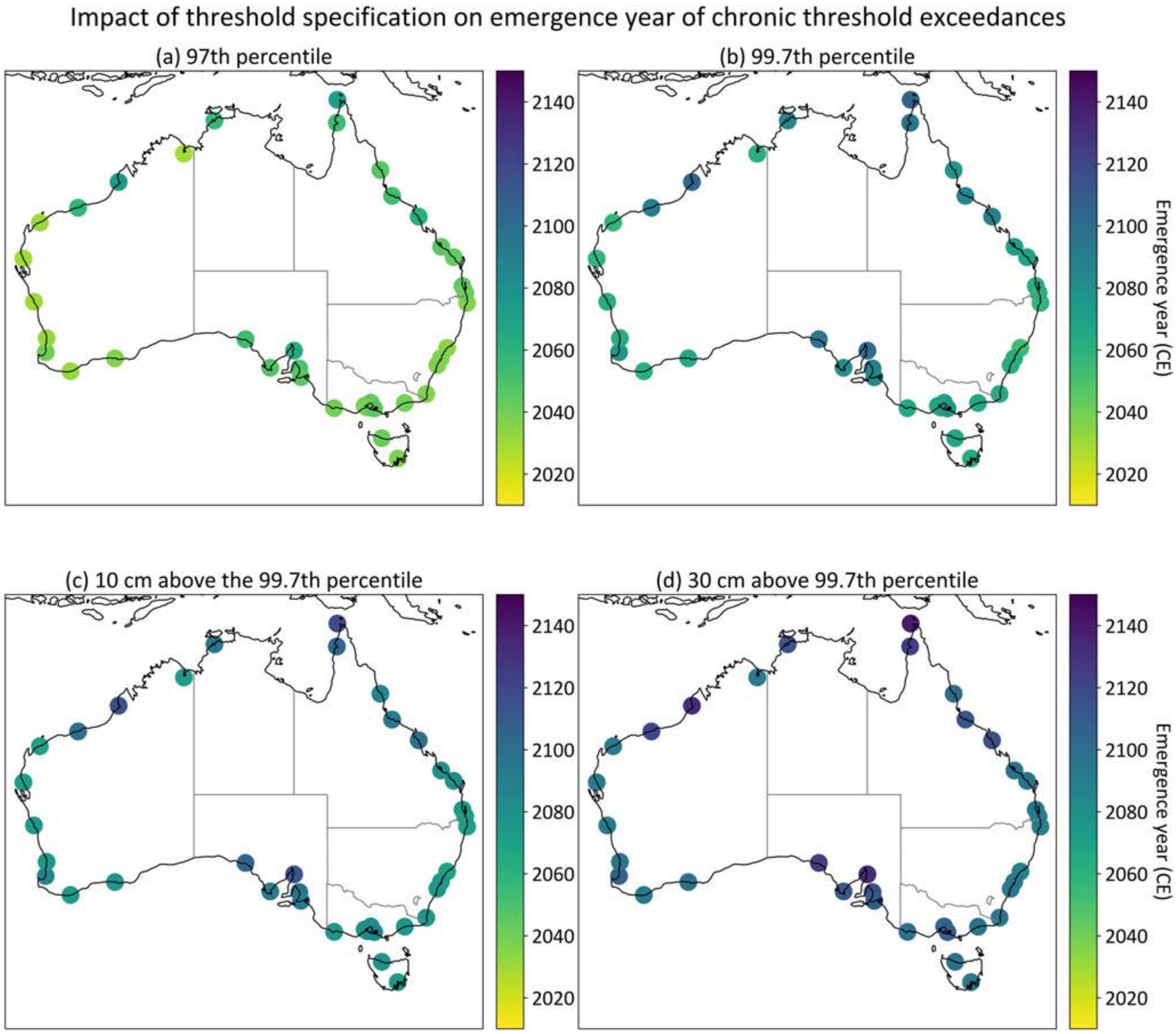

Figure 6. Impact of chronic flood threshold on the emergence year of 50 annual flood days, based exceedances of that threshold using our projection method. The median based estimate of emergence year of chronic flooding for four different definitions of emergence (a–d) based on SSP3-7.0 median SLR scenario. Locations where chronic flooding does not occur by 2150 are not indicated.

threshold is considered. Similarly, SSP3-7.0 with a 1% per decade increase in tidal amplitudes has a national median emergence year of 2075 for a threshold of 0.1 m above the 99.7th percentile. For 0.3 m above the 99.7th percentile, the median emergence time is 2095.

This threshold sensitivity means that a 0.2 m difference, uncertainty or error in flood thresholds results in projections of flood frequencies and emergence times that can be offset by two decades. Thus, locations with a relatively small, 0.2 m difference in elevation may require different planning and adaptation horizons. But, another challenge for adaptation planning is that coastal flood threshold uncertainties are typically at least 0.2 m in most coastal flood studies. For example, the frequently used 'common impact threshold' approach to estimate flood thresholds (Dusek et al., 2022; Hague, McGregor, et al., 2023; Thompson et al., 2021) has errors of 0.19 m, 0.25, and 0.39 for minor, moderate and major flood thresholds, respectively (Sweet et al., 2018). Digital elevation models (DEMs) are also used to relate water levels to their terrestrial footprints. The vertical root mean square errors of global DEMs are of order meters (Kulp & Strauss, 2018, 2021), or tens of centimeters for regional DEMs (Hanslow et al., 2018). In Australia, vertical bias of CoastalDEM is 0.11 m (Kulp & Strauss, 2018). Further work is required to understand if an uncertainty of several decades is tolerable for identifying and predicting the onset of triggers that may elicit an adaptive action, such as managed retreat (Buchanan et al., 2019; Haasnoot et al., 2013, 2021; Stephens et al., 2018).

3.5. Limitations of Methods and Results

Our projection framework also shows potential for use in understanding how other sources of non-stationarity, other than mean sea-level rise and changes in tidal range and skew surge magnitudes, may impact flood hazards. In this context, our framework is similar to the storylines approach adopted in many climate change studies (Shepherd et al., 2018). This approach develops physically plausible, self-consistent future pathways for decisionmakers by prioritizing different impact outcomes over different climate model outputs. We have demonstrated this for changes in tidal range and skew surges, but several other avenues could be explored in future work. Firstly, we have not considered the changes in magnitudes of AMSL anomalies through time (Widlansky et al., 2020). Secondly, we have discounted the possibility of local mean sea level changes differing from CMIP-based SLR scenarios due to local vertical land motion and subsidence (Karegar et al., 2017; Tay et al., 2022). Thirdly, we have not considered compound floods and possible changes to river flow, local wind forcing, and other factors that influence water level anomalies in estuaries (e.g., Moftakhari, Salvadori, et al., 2017; Wahl et al., 2015). Our work could be extended to assess the sensitivity of flood frequencies to such changes, using a percentage per decade approach like the one explored here.

Future work could also consider whether preserving autocorrelation in skew surges would improve the method. Skew surges exhibit statistically significant autocorrelation at multiple time lags (Figure S3 in Supporting Information S1), but annual mean sea level anomalies do not (Figure S4 in Supporting Information S1). Autocorrelation of tides is retained when using the approach described in Section 2.3. Similar to the convolution of distributions used in joint probability methods (Baranes et al., 2020; Batstone et al., 2013; Pugh & Vassie, 1978), the random sampling of skew surges used here does not preserve autocorrelation properties in the timeseries. Future improvements could include using an extreme value distribution for skew surge and applying an extremal index that accounts for correlation (e.g., Baranes et al., 2020; Batstone et al., 2013). Additionally, a block sampling approach may improve on the daily sampling used here. It is likely that different block lengths would need to be used for different locations due to large differences in the autocorrelation functions at each location (Figure S3 in Supporting Information S1). This has the potential to lead to inconsistencies when inter-site comparisons are made. Hence, detailed further work is required to evaluate the merits of such an approach, and is beyond the scope of this study.

4. Concluding Remarks and Opportunities for Future Work

We have presented a new way to estimate the coastal flood implications of local sea-level rise. Our approach advances upon existing coastal flood projection frameworks by considering how the coincidence of independent tidal, storm surge and AMSL extremes lead to year-to-year variability in flood frequencies. Our framework can also be used to understand the impact of future changes in sea level variability (e.g., tidal trends), not just the mean rise, on coastal flood frequencies. We find that increases in tidal range increase flood rates and bring forward emergence times, with decreases having a commensurate but opposite effect. In many cases, non-stationary tides have an equivalent effect to lowering the impact threshold or using a higher sea-level rise scenario. A similar but much reduced effect is seen for changes in skew surge magnitudes.

More generally, we present a compelling argument for improving understanding of the sensitivity to flood hazard metrics to sources of uncertainty beyond the common emission scenarios and their SLR responses. Different realizations of these sources of uncertainty can have commensurate impacts on flood frequencies as different SLR scenarios can. Applying our projection framework allows for first-pass assessments of the relative sensitivities of coastal flood frequencies to different sources of uncertainty in future changes in mean sea level and sea level variability at a tide gauge location. An example of where improvement is needed is in relating water levels to their flood impacts using digital elevation models or common impact threshold approximations. These methods can have uncertainty of at least 0.2 m, which corresponds to 20 years in chronic flood emergence times at most Australian locations. Appropriate and centimeter-accurate impact-based flood thresholds may be urgently needed to correctly identify the water levels associated with impacts of local concern.

Table 1
Projected Emergence Years of 30 Days Per Year With Exceedances of Two Different Thresholds: The Historical Period 99.7th Percentile (Left Side of Table) and the Water Level 0.2 m Above the Historical Period 99.7th Percentile (Right Side of Table)

	Historical period 99.7th percentile					0.2 m above the historical period 99.7th percentile				
Location	SSP3-7.0 median	SSP3-7.0 upper	SSP5-8.5 median	Increased TR	Increased SS	SSP3-7.0 median	SSP3-7.0 upper	SSP5-8.5 median	Increased TR	Increased SS
Albany	2052	2038	2049	2050	2051	2078	2058	2074	2076	2077
Ballina	2049	2037	2047	2047	2049	2075	2056	2070	2071	2075
Booby Island	2093	2065	2085	2085	2093	2117	2080	2103	2105	2116
Brisbane	2053	2041	2052	2051	2053	2079	2059	2074	2074	2079
Broome	2088	2065	2083	2071	2087	2106	2078	2097	2088	2105
Bunbury	2069	2051	2065	2067	2068	2091	2068	2086	2089	2090
Bundaberg	2057	2044	2053	2053	2057	2080	2061	2076	2075	2080
Burnie	2057	2042	2054	2051	2056	2083	2063	2078	2077	2083
Cairns	2065	2049	2061	2061	2065	2086	2065	2080	2080	2086
Carnarvon	2050	2036	2048	2048	2049	2076	2056	2073	2073	2076
Darwin	2065	2050	2064	2056	2065	2087	2065	2083	2075	2087
Eden	2055	2041	2053	2053	2054	2080	2060	2075	2076	2080
Esperance	2057	2042	2054	2055	2056	2081	2061	2077	2079	2080
Fremantle	2054	2041	2052	2053	2053	2079	2059	2076	2078	2079
Geelong	2059	2043	2056	2058	2058	2085	2063	2080	2083	2084
Geraldton	2054	2039	2052	2052	2053	2078	2058	2075	2077	2078
Gladstone	2059	2044	2053	2053	2059	2080	2061	2076	2073	2080
Gold Coast	2051	2038	2049	2049	2051	2076	2057	2071	2072	2076
Hobart	2054	2042	2052	2053	2054	2080	2061	2075	2078	2079
Mackay	2056	2041	2053	2055	2056	2082	2061	2077	2080	2081
Melbourne	2076	2053	2071	2065	2076	2093	2071	2087	2080	2093
Newcastle	2063	2045	2059	2062	2062	2088	2065	2083	2086	2087
Onslow	2047	2034	2045	2045	2047	2073	2054	2068	2069	2072
Point Lonsdale	2049	2035	2047	2045	2049	2075	2055	2071	2070	2075
Port Adelaide (Outer Harbor)	2058	2042	2055	2055	2057	2085	2063	2080	2082	2084
Port Hedland	2077	2059	2074	2072	2076	2097	2074	2093	2092	2096
Port Kembla	2077	2057	2073	2067	2076	2096	2072	2090	2084	2096
Port Lincoln	2053	2041	2051	2051	2053	2079	2059	2074	2076	2079
Port Pirie	2072	2053	2068	2069	2072	2093	2070	2088	2090	2093
Portland	2090	2066	2085	2083	2089	2112	2081	2103	2101	2110
Sydney (Fort Denison)	2057	2041	2054	2055	2056	2082	2061	2078	2080	2081
Thevenard	2053	2039	2051	2050	2053	2079	2058	2073	2075	2078
Townsville	2085	2063	2080	2080	2084	2104	2077	2098	2099	2103
Victor Harbor	2072	2053	2069	2068	2072	2092	2070	2087	2086	2092
Weipa	2074	2056	2071	2072	2073	2094	2072	2089	2091	2093
Western Port (Stony Point)	2086	2063	2080	2081	2085	2104	2076	2096	2099	2104
Wyndham	2064	2046	2060	2059	2064	2089	2065	2083	2082	2088

Note. Five different sets of projections to provide comparison of the relative effects on the specification of SLR scenarios, increases in tidal range (TR) and storm surge (SS) discussed in the text.

We highlight the importance of considering all sources of future changes in coastal hazards, not just emission scenario and the possible climate system responses to these. Estimates of SLR-induced tidal changes exist for many locations including Australia (Harker et al., 2019), but have not been included in projections of coastal flood frequencies. This adds another source of uncertainty not typically quantified in flood projections: the unquantified uncertainty inherent in assuming that sea level variability will not change from its present-day values. Where practical, we suggest that future projections of coastal flood heights and frequencies should dynamically model possible tidal changes, both due to alterations in the oceanic response to sea-level rise (e.g., Pickering et al., 2017; Schindelegger et al., 2018), and due to coastal management and bathymetric changes in estuaries (e.g., Holleman & Stacey, 2014; Lee et al., 2017; Talke & Jay, 2020). Tides and other long-waves such as storm surge are influenced by river flow (e.g., Kukulka & Jay, 2003; Moftakhari et al., 2013), by channel dredging and inlet modifications (e.g., Hague, Grayson, et al., 2023; Pareja-Roman et al., 2023), and by other processes that alter the roughness and geometric dimensions of estuaries (Talke et al., 2021). Hence projection frameworks that include both local and far-field responses of tides to changing conditions are needed to better project possible future flooding and the variance of possible pathways.

Our results highlight the need to consider how different responses to one element of risk can exacerbate or mitigate risks posed by another (Simpson et al., 2021). For example, channel dredging can reduce the flood threat posed by heavy rainfall and river runoff but potentially increase chronic flooding on high tides through increased tidal ranges (de Leo et al., 2022; Talke et al., 2021). Similarly, this work could also be leveraged to help make decisions around the efficacy of implementing possible flood risk mitigation measures. For example, the results of Table 1 imply that if a seawall currently protects against a 99.7th percentile water level is raised by 0.2 m, the onset of chronic flooding may be delayed by 20 years. However, this may only reduce flooding from direct overtopping, but not from backflow up storm water drains, a common pathway of nuisance flooding (e.g., Hague, Grayson, et al., 2023; Habel et al., 2020).

The use of an Australian case study increases the local significance of our results—ours are the first national estimates of changes in flood frequency for Australia. Prior to this study, sea level allowances (changes in height of present-day extremes) were the only metric for which projections were available to inform coastal decision-making. The successful implementation of the allowance approach is predicated on being able to keep pace with sea level rise through engineering interventions such that flood frequencies remain unchanged (McInnes, Church et al., 2015). Even if practical and economic, the relative benefits and risks of such engineering actions depend on location and the rate of SLR (Ghanbari et al., 2020, 2021; Hague, Grayson, et al., 2023; Stephens et al., 2021). In addition, the influence of interventions on local tidal range must also be considered to limit the chance of maladaptation occurring (Nunn et al., 2021; Schipper, 2020). Our approach does not require such assumptions, allowing for the consideration of an alternative viewpoint where coastal managers may choose for certain assets to fully depreciate and be subsequently abandoned (Haasnoot et al., 2021).

Finally, our study highlights that further work is required to properly incorporate the impacts of coinciding tide and surge extremes and changes in tidal ranges into flood hazard assessment. This includes national projections of changes in tidal range at tide gauge locations, developing centimeter-accurate flood thresholds or elevations models, and identifying the adaptive triggers that are most relevant to coastal decisionmakers. To support this, changes in *heights* of present-day extreme water levels under changes in tidal range and skew surge magnitudes should be similarly assessed as changes in their *frequency* have been here. Our results highlight the urgency of this future work being undertaken. Even without considering changes in tidal range, present-day annual extremes could occur chronically as early as the 2040s in several Australian locations. Hence, planning should already be underway for what adaptive actions will be required to protect, accommodate, or retreat from this emerging chronic flooding hazard.

Data Availability Statement

The ANCHORS data set is freely available from NCI Data Catalog (Hague, 2021) as described in Hague et al. (2021). Data produced as part of this study is available at Hague (2024) and described in Supporting Information S1. The URL for the data is: www.doi.org/10.6084/m9.figshare.24328903.

Acknowledgments

We thank the projection authors for developing and making the sea-level rise projections available, multiple funding agencies for supporting the development of the projections, and the NASA Sea Level Change Team for developing and hosting the IPCC AR6 Sea Level Projection Tool. BH's contributions to the research were funded by the Australian Climate Service, and SAT was funded by NSF Grant 2013280.

References

Arns, A., Dangendorf, S., Jensen, J., Talke, S., Bender, J., & Pattiaratchi, C. (2017). Sea-level rise induced amplification of coastal protection design heights. *Scientific Reports*, *7*, 1–9. https://doi.org/10.1038/srep40171

Arns, A., Wahl, T., Wolff, C., Vafeidis, A. T., Haigh, I. D., Woodworth, P., et al. (2020). Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts. *Nature Communications*, *11*(1), 1–9. https://doi.org/10.1038/s41467-020-15752-5

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., & Cooke, R. M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences of the United States of America*, *166*(23), 11195–11200. https://doi.org/10.1073/pnas.1817205116

Baranes, H. E., Woodruff, J. D., Talke, S. A., Kopp, R. E., Ray, R. D., & DeConto, R. M. (2020). Tidally driven interannual variation in extreme sea level frequencies in the Gulf of Maine. *Journal of Geophysical Research: Oceans*, *125*(10). https://doi.org/10.1029/2020JC016291

Batstone, C., Lawless, M., Tawn, J., Horsburgh, K., Blackman, D., McMillan, A., et al. (2013). A UK best-practice approach for extreme sea-level analysis along complex topographic coastlines. *Ocean Engineering*, *71*, 28–39. https://doi.org/10.1016/j.oceaneng.2013.02.003

Boumis, G., Moftakhari, H. R., & Moradkhani, H. (2023). Coevolution of extreme sea levels and sea-level rise under global warming. *Earth's Future*, *11*(7), 1–14. https://doi.org/10.1029/2023EF003649

Buchanan, M. K., Kopp, R. E., Oppenheimer, M., & Tebaldi, C. (2016). Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change*, *137*(3–4), 347–362. https://doi.org/10.1007/s10584-016-1664-7

Buchanan, M. K., Oppenheimer, M., & Kopp, R. E. (2017). Amplification of flood frequencies with local sea level rise and emerging flood regimes. *Environmental Research Letters*, *12*(6), 064009. https://doi.org/10.1088/1748-9326/aa6cb3

Buchanan, M. K., Oppenheimer, M., & Parris, A. (2019). Values, bias, and stressors affect intentions to adapt to coastal flood risk: A case study from New York City. *Weather, Climate, and Society*, *11*(4), 809–821. https://doi.org/10.1175/WCAS-D-18-0082.1

Burgos, A. G., Hamlington, B. D., Thompson, P. R., & Ray, R. D. (2018). Future nuisance flooding in Norfolk, VA, from astronomical tides and annual to decadal internal climate variability. *Geophysical Research Letters*, *45*(22), 12432–12439. https://doi.org/10.1029/2018GL079572

Calafat, F. M., Wahl, T., Tadesse, M. G., & Sparrow, S. N. (2022). Trends in Europe storm surge extremes match the rate of sea-level rise. *Nature*, *603*(7903), 841–845. https://doi.org/10.1038/s41586-022-04426-5

Cannaby, H., Palmer, M. D., Howard, T., Bricheno, L., Calvert, D., Krijnen, J., et al. (2016). Projected sea level rise and changes in extreme storm surge and wave events during the 21st century in the region of Singapore. *Ocean Science*, *12*(3), 613–632. https://doi.org/10.5194/os-12-613-2016

Cantelon, J. A., Guimond, J. A., Robinson, C. E., Michael, H. A., & Kurylyk, B. L. (2022). Vertical saltwater intrusion in coastal aquifers driven by episodic flooding: A review. *Water Resources Research*, *58*(11), 1–25. https://doi.org/10.1029/2022WR032614

Colberg, F., McInnes, K. L., O'Grady, J., & Hoeke, R. (2019). Atmospheric circulation changes and their impact on extreme sea levels around Australia. *Natural Hazards and Earth System Sciences*, *19*(5), 1067–1086. https://doi.org/10.5194/nhess-19-1067-2019

De Leo, F., Talke, S. A., Orton, P. M., & Wahl, T. (2022). The effect of harbor developments on future high-tide flooding in Miami, Florida. *Journal of Geophysical Research: Oceans*, *127*(7), 1–21. https://doi.org/10.1029/2022JC018496

Department of Energy Environment and Climate Action. (2023). Victoria's resilient coast: Adapting for 2100+. Retrieved from https://www.marineandcoasts.vic.gov.au/__data/assets/pdf_file/0022/662503/Victorias-Resilient-Coast-Guidelines-.pdf

Devlin, A. T., Jay, D. A., Talke, S. A., Zaron, E. D., Pan, J., & Lin, H. (2017). Coupling of sea level and tidal range changes, with implications for future water levels. *Scientific Reports*, *7*(1), 1–12. https://doi.org/10.1038/s41598-017-17056-z

Devlin, A. T., Jay, D. A., Zaron, E. D., Talke, S. A., Pan, J., & Lin, H. (2017). Tidal variability related to sea level variability in the Pacific Ocean. *Journal of Geophysical Research: Oceans*, *122*(11), 8445–8463. https://doi.org/10.1002/2017JC013165

Dusek, G., Sweet, W. V., Widlansky, M. J., Thompson, P. R., & Marra, J. J. (2022). A novel statistical approach to predict seasonal high tide flooding. *Frontiers in Marine Science*, *9*(1072792), 1–17. https://doi.org/10.3389/fmars.2022.1073792

Enriquez, A. R., Wahl, T., Baranes, H. E., Talke, S. A., Orton, P. M., Booth, J. F., & Haigh, I. D. (2022). Predictable changes in extreme sea levels and coastal flood risk due to long-term tidal cycles. *Journal of Geophysical Research: Oceans*, *127*(4). https://doi.org/10.1029/2021jc018157

Ezer, T. (2022). A demonstration of a simple methodology of flood prediction for a coastal city under threat of Sea Level rise: The case of Norfolk, VA, USA. *Earth's Future*, *10*(9). https://doi.org/10.1029/2022ef002786

Familkhalili, R., & Talke, S. A. (2016). The effect of channel deepening on tides and storm surge: A case study of Wilmington, NC. *Geophysical Research Letters*, *43*(17), 9138–9147. https://doi.org/10.1002/2016GL069494

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., et al. (2021). Ocean, cryosphere and sea level change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergover* (pp. 1211–1362). https://doi.org/10.1017/9781009157896.011.1212

Garner, G. G., Hermans, T., Kopp, R. E., Slangen, A. B. A., Edwards, T. L., Levermann, A., et al. (2021). IPCC AR6 Sea Level Projections. Version 20210809 [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.5914709

Ghanbari, M., Arabi, M., Kao, S. C., Obeysekera, J., & Sweet, W. (2021). Climate Change and changes in compound coastal-riverine flooding hazard along the U.S. Coasts. *Earth's Future*, *9*(5). https://doi.org/10.1029/2021EF002055

Ghanbari, M., Arabi, M., & Obeysekera, J. (2020). Chronic and acute coastal flood risks to assets and communities in southeast Florida. *Journal of Water Resources Planning and Management*, *146*(7). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001245

Ghanbari, M., Arabi, M., Obeysekera, J., & Sweet, W. (2019). A coherent statistical model for coastal flood frequency analysis under nonstationary sea level conditions. *Earth's Future*, *7*(2), 162–177. https://doi.org/10.1029/2018EF001089

Gold, A. C., Anarde, K., Grimley, L., Neve, R., Srebnik, E. R., Thelen, T., et al. (2023). Data from the drain: A sensor framework that captures multiple drivers of chronic floods. *Water Resources Research*, *59*(e2022WR032392). https://doi.org/10.1029/2022WR032392

Gold, A. C., Brown, C. M., Thompson, S. P., & Piehler, M. F. (2022). Inundation of stormwater infrastructure is common and increases risk of flooding in coastal urban areas along the US Atlantic coast. *Earth's Future*, *10*(3), 1–14. https://doi.org/10.1029/2021EF002139

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Haasnoot, M., Lawrence, J., & Magnan, A. K. (2021). Pathways to coastal retreat. *Science*, *372*(6548), 1287–1290. https://doi.org/10.1126/science.abi6594

Habel, S., Fletcher, C. H., Anderson, T. R., & Thompson, P. R. (2020). Sea-level rise induced multi-Mechanism flooding and contribution to urban infrastructure failure. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-60762-4

Hague, B. (2021). Australian national collection of homogenised observations of relative Sea Level (ANCHORS) [Dataset]. NCI Data Catalogue. https://doi.org/10.25914/6142dff37250b

Hague, B. (2024). Supplementary data for "The influence of future changes in tidal range, storm surge, and mean sea level on the emergence of chronic flooding" [Dataset]. Figshare. https://doi.org/10.6084/m9.figshare.24328903

Hague, B. S., Grayson, R. B., Talke, S. A., Black, M. T., & Jakob, D. (2023). The effect of tidal range and mean sea-level changes on coastal flood hazards at Lakes Entrance, south-east Australia. *Journal of Southern Hemisphere Earth Systems Science*, *73*(2), 1–15. https://doi.org/10.1071/es22036

Hague, B. S., Jones, D. A., Jakob, D., McGregor, S., & Reef, R. (2022). Australian coastal flooding trends and forcing factors. *Earth's Future*, *10*(2), e2021EF002483. https://doi.org/10.1029/2021ef002483

Hague, B. S., Jones, D. A., Trewin, B., Jakob, D., Murphy, B. F., Martin, D. J., & Braganza, K. (2021). ANCHORS: A multi-decadal tide gauge dataset to monitor Australian relative sea level changes. *Geoscience Data Journal*, *9*(2), 256–272. https://doi.org/10.1002/gdj3.136

Hague, B. S., McGregor, S., Jones, D. A., Reef, R., Jakob, D., & Murphy, B. F. (2023). The global drivers of chronic coastal flood hazards under sea-level rise. *Earth's Future*, *11*(8), 1–23. https://doi.org/10.1029/2023EF003784

Hague, B. S., McGregor, S., Murphy, B. F., Reef, R., & Jones, D. A. (2020). Sea level rise driving increasingly predictable coastal inundation in Sydney, Australia. *Earth's Future*, *8*(9), 0–3. https://doi.org/10.1029/2020EF001607

Hague, B. S., & Taylor, A. J. (2021). Tide-only inundation: A metric to quantify the contribution of tides to coastal inundation under sea-level rise. *Natural Hazards*, *107*(1), 675–695. https://doi.org/10.1007/s11069-021-04600-4

Haigh, I. D., Eliot, M., & Pattiaratchi, C. (2011). Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. *Journal of Geophysical Research*, *116*(6), C06025. https://doi.org/10.1029/2010JC006645

Haigh, I. D., MacPherson, L. R., Mason, M. S., Wijeratne, E. M. S., Pattiaratchi, C. B., Crompton, R. P., & George, S. (2014). Estimating present day extreme water level exceedance probabilities around the coastline of Australia: Tropical cyclone-induced storm surges. *Climate Dynamics*, *42*(1–2), 139–157. https://doi.org/10.1007/s00382-012-1653-0

Haigh, I. D., Pickering, M. D., Green, J. A. M., Arbic, B. K., Arns, A., Dangendorf, S., et al. (2020). The tides they are A-Changin': A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms, and future implications. *Reviews of Geophysics*, *58*(1), 1–39. https://doi.org/10.1029/2018RG000636

Haigh, I. D., Wijeratne, E. M. S., MacPherson, L. R., Pattiaratchi, C. B., Mason, M. S., Crompton, R. P., & George, S. (2014). Estimating present day extreme water level exceedance probabilities around the coastline of Australia: Tides, extra-tropical storm surges and mean sea level. *Climate Dynamics*, *42*(1–2), 121–138. https://doi.org/10.1007/s00382-012-1652-1

Hanslow, D. J., Morris, B. D., Foulsham, E., & Kinsela, M. A. (2018). A regional scale approach to assessing current and potential future exposure to tidal inundation in different types of estuaries. *Scientific Reports*, *8*(1), 1–13. https://doi.org/10.1038/s41598-018-25410-y

Harker, A., Green, J. A. M., Schindelegger, M., & Wilmes, S. B. (2019). The impact of sea-level rise on tidal characteristics around Australia. *Ocean Science*, *15*(1), 147–159. https://doi.org/10.5194/os-15-147-2019

He, Y., Manful, D., Warren, R., Forstenhäusler, N., Osborn, T. J., Price, J., et al. (2022). Quantification of impacts between 1.5 and 4°C of global warming on flooding risks in six countries. *Climatic Change*, *170*(1–2), 1–21. https://doi.org/10.1007/s10584-021-03289-5

Hino, M., Belanger, S. T., Field, C. B., Davies, A. R., & Mach, K. J. (2019). High-tide flooding disrupts local economic activity. *Science Advances*, *5*(2), 1–10. https://doi.org/10.1126/sciadv.aau2736

Hino, M., Field, C. B., & Mach, K. J. (2017). Managed retreat as a response to natural hazard risk. *Nature Climate Change*, *7*(5), 364–370. https://doi.org/10.1038/nclimate3252

Hirabayashi, Y., Tanoue, M., Sasaki, O., Zhou, X., & Yamazaki, D. (2021). Global exposure to flooding from the new CMIP6 climate model projections. *Scientific Reports*, *11*(1), 1–7. https://doi.org/10.1038/s41598-021-83279-w

Hoitink, A. J. F., & Jay, D. A. (2016). Tidal river dynamics: Implications for deltas. *Reviews of Geophysics*, *54*(1), 240–272. https://doi.org/10.1002/2015RG000507

Holleman, R. C., & Stacey, M. T. (2014). Coupling of sea level rise, tidal amplification, and inundation. *Journal of Physical Oceanography*, *44*(5), 1439–1455. https://doi.org/10.1175/JPO-D-13-0214.1

Howard, T., Palmer, M. D., & Bricheno, L. M. (2019). Contributions to 21st century projections of extreme sea-level change around the UK. *Environmental Research Communications*, *1*(9), 0–15. https://doi.org/10.1088/2515-7620/ab42d7

Hunter, J. R. (2012). A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic Change*, *113*(2), 239–252. https://doi.org/10.1007/s10584-011-0332-1

Jackson, L. P., Grinsted, A., & Jevrejeva, S. (2018). 21st century sea-level rise in line with the Paris accord. *Earth's Future*, *6*(2), 213–229. https://doi.org/10.1002/2017EF000688

Karegar, M. A., Dixon, T. H., Malservisi, R., Kusche, J., & Engelhart, S. E. (2017). Nuisance flooding and relative sea-level rise: The importance of present-day land motion. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/s41598-017-11544-y

Kasmalkar, I. G., Serafin, K. A., Miao, Y., Bick, I. A., Ortolano, L., Ouyang, D., & Suckale, J. (2020). When floods hit the road: Resilience to flood-related traffic disruption in the San Francisco Bay Area and beyond. *Science Advances*, *6*(32), 1–8. https://doi.org/10.1126/sciadv.aba2423

Khojasteh, D., Felder, S., Heimhuber, V., & Glamore, W. (2023). A global assessment of estuarine tidal response to sea level rise. *Science of the Total Environment*, *894*, 165011. https://doi.org/10.1016/j.scitotenv.2023.165011

Kirezci, E., Young, I. R., Ranasinghe, R., Muis, S., Nicholls, R. J., Lincke, D., & Hinkel, J. (2020). Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-67736-6

Kopp, R. E., Gilmore, E. A., Little, C. M., Lorenzo-Trueba, J., Ramenzoni, V. C., & Sweet, W. V. (2019). Useable science for managing the risks of sea-level rise. *Earth's Future*, *7*(12), 1235–1269. https://doi.org/10.1029/2018EF001145

Koroglu, A., Ranasinghe, R., Jiménez, J. A., & Dastgheib, A. (2019). Comparison of coastal vulnerability index applications for Barcelona Province. *Ocean & Coastal Management*, *178*, 104799. https://doi.org/10.1016/j.ocecoaman.2019.05.001

Kukulka, T., & Jay, D. A. (2003). Impacts of Columbia River discharge on salmonid habitat: 1. A nonstationary fluvial tide model. *Journal of Geophysical Research*, *108*(9). https://doi.org/10.1029/2002jc001382

Kulp, S. A., & Strauss, B. H. (2018). CoastalDEM: A global coastal digital elevation model improved from SRTM using a neural network. *Remote Sensing of Environment*, *206*, 231–239. https://doi.org/10.1016/j.rse.2017.12.026

Kulp, S. A., & Strauss, B. H. (2021). CoastalDEM v2.1: A high-accuracy and high-resolution global coastal elevation model trained on ICESat-2 satellite lidar. Retrieved from https://assets.ctfassets.net/cxgxgstp8r5d/3f1LzJSnp7ZjFD4loDYnrA/71eaba2b8f8d642dd9a7e6581dce0c66/CoastalDEM_2.1_Scientific_Report_.pdf

Le Cozannet, G., Idier, D., De Michele, M., Legendre, Y., Moisan, M., Pedreros, R., et al. (2021). Timescales of emergence of chronic flooding in the major economic center of Guadeloupe. *Natural Hazards and Earth System Sciences*, *21*(2), 703–722. https://doi.org/10.5194/nhess-21-703-2021

Lee, S. B., Li, M., & Zhang, F. (2017). Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*, *122*(5), 3917–3938. https://doi.org/10.1002/2016JC012597.Received

Li, S., Wahl, T., Barroso, A., Coats, S., Dangendorf, S., Piecuch, C., et al. (2022). Contributions of different sea-level processes to high-tide flooding along the U.S. Coastline. *Journal of Geophysical Research: Oceans*, *127*(7), 1–16. https://doi.org/10.1029/2021JC018276

Li, S., Wahl, T., Fang, J., Liu, L., & Jiang, T. (2023). High-tide flooding along the China coastline: Past and future. *Earth's Future*, *11*(e2022EF003225), 1–15. https://doi.org/10.1029/2022EF003225

Li, S., Wahl, T., Talke, S. A., Jay, D. A., Orton, P. M., Liang, X., et al. (2021). Evolving tides aggravate nuisance flooding along the U.S. coastline. *Science Advances*, *7*(10), 1–10. https://doi.org/10.1126/sciadv.abe2412

Lowe, R. J., Cuttler, M. V. W., & Hansen, J. E. (2021). Climatic drivers of extreme sea level events along the coastline of Western Australia. *Earth's Future*, *9*(4). https://doi.org/10.1029/2020EF001620

Marcos, M., & Woodworth, P. L. (2017). Journal of geophysical research: Oceans of the north Atlantic and the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, *122*(9), 7031–7048. https://doi.org/10.1002/2017JC013065.Received

Mawdsley, R. J., & Haigh, I. D. (2016). Spatial and temporal variability and long-term trends in skew surges globally. *Frontiers in Marine Science*, *3*(MAR), 1–17. https://doi.org/10.3389/fmars.2016.00029

Mawdsley, R. J., Haigh, I. D., & Wells, N. C. (2015). Global secular changes in different tidal high water, low water and range levels. *Earth's Future*, *3*(2), 66–81. https://doi.org/10.1002/2014EF000282

McInnes, K. L., Church, J., Monselesan, D., Hunter, J. R., O'Grady, J. G., Haigh, I. D., & Zhang, X. (2015). Information for Australian impact and adaptation planning in response to sea-level rise. *Australian Meteorological and Oceanographic Journal*, *65*(1), 127–149. https://doi.org/10.22499/2.6501.009

McInnes, K. L., Macadam, I., Hubbert, G., & O'Grady, J. (2013). An assessment of current and future vulnerability to coastal inundation due to sea-level extremes in Victoria, southeast Australia. *International Journal of Climatology*, *33*(1), 33–47. https://doi.org/10.1002/joc.3405

McInnes, K. L., Macadam, I., Hubbert, G. D., & O'Grady, J. G. (2009). A modelling approach for estimating the frequency of sea level extremes and the impact of climate change in southeast Australia. In *Natural hazards* (Vol. 51, pp. 115–137). https://doi.org/10.1007/s11069-009-9383-2

McInnes, K. L., Monselesan, D., Church, J., Andrew, L., & O'Grady, J. (2015). Projections (and recent trends): Marine and coasts. In *Climate change in Australia: Projections for Australia's NRM regions* (pp. 143–165).

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018). What is nuisance flooding? Defining and monitoring an emerging challenge. *Water Resources Research*, *54*(7), 4218–4227. https://doi.org/10.1029/2018WR022828

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Feldman, D. L., Sweet, W., Matthew, R. A., & Luke, A. (2015). Increased nuisance flooding due to sea-level rise: Past and future. *Geophysical Research Letters*, *42*(22), 9846–9852. https://doi.org/10.1002/2015GL066072

Moftakhari, H. R., Aghakouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Cumulative hazard: The case of nuisance flooding. *Earth's Future*, *5*(2), 214–223. https://doi.org/10.1002/eft2.186

Moftakhari, H. R., Jay, D. A., Talke, S. A., Kukulka, T., & Bromirski, P. D. (2013). A novel approach to flow estimation in tidal rivers. *Water Resources Research*, *49*(8), 4817–4832. https://doi.org/10.1002/wrcr.20363

Moftakhari, H. R., Salvadori, G., AghaKouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Compounding effects of sea level rise and fluvial flooding. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(37), 9785–9790. https://doi.org/10.1073/pnas.1620325114

Moore, F. C., & Obradovich, N. (2020). Using remarkability to define coastal flooding thresholds. *Nature Communications*, *11*(1), 1–8. https://doi.org/10.1038/s41467-019-13935-3

Muis, S., Apecechea, M. I., Dullaart, J., de Lima Rego, J., Madsen, K. S., Su, J., et al. (2020). A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. *Frontiers in Marine Science*, *7*, 1–15. https://doi.org/10.3389/fmars.2020.00263

Naik, P. K., & Jay, D. A. (2011). Distinguishing human and climate influences on the Columbia River: Changes in mean flow and sediment transport. *Journal of Hydrology*, *404*(3–4), 259–277. https://doi.org/10.1016/j.jhydrol.2011.04.035

Norman, B., & Gurran, N. (2018). In *Adapting to long term coastal climate risk through planning approaches and instruments: CoastAdapt Information Manual 5* (3rd ed.). Gold Coast: National Climate Change Adaptation Research Facility. Retrieved from https://coastadapt.com.au/sites/default/files/information-manual/IM05_Planning_instruments.pdf

Nunn, P. D., Klöck, C., & Duvat, V. (2021). Seawalls as maladaptations along island coasts. *Ocean & Coastal Management*, *205*, 105554. https://doi.org/10.1016/j.ocecoaman.2021.105554

O'Grady, J. G., Stephenson, A. G., & McInnes, K. L. (2022). Gauging mixed climate extreme value distributions in tropical cyclone regions. *Scientific Reports*, *12*(1), 1–9. https://doi.org/10.1038/s41598-022-08382-y

Pareja-Roman, L. F., Orton, P. M., & Talke, S. A. (2023). Effect of estuary urbanization on tidal dynamics and high tide flooding in a coastal lagoon. *Journal of Geophysical Research: Oceans*, *128*(1). https://doi.org/10.1029/2022jc018777

Pattiaratchi, C., Hetzel, Y., & Janekovic, I. (2018). Developing better predictions for extreme water levels. Retrieved from https://sealevelx.ems.uwa.edu.au/documents/UWA-BNHCRC_ExtremeSeaLevels_Final_Data_Report.pdf

Paulik, R., Stephens, S., Wild, A., Wadhwa, S., & Bell, R. G. (2021). Cumulative building exposure to extreme sea level flooding in coastal urban areas. *International Journal of Disaster Risk Reduction*, *66*, 102612. https://doi.org/10.1016/j.ijdrr.2021.102612

Pickering, M. D., Horsburgh, K. J., Blundell, J. R., Hirschi, J. J. M., Nicholls, R. J., Verlaan, M., & Wells, N. C. (2017). The impact of future sea-level rise on the global tides. *Continental Shelf Research*, *142*, 50–68. https://doi.org/10.1016/j.csr.2017.02.004

Piecuch, C. G., Bittermann, K., Kemp, A. C., Ponte, R. M., Little, C. M., Engelhart, S. E., & Lentz, S. J. (2018). River-discharge effects on United States Atlantic and Gulf coast sea-level changes. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(30), 7729–7734. https://doi.org/10.1073/pnas.1805428115

Pugh, D. T., & Vassie, J. M. (1978). Extreme sea levels from tide and surge probability. *Coastal Engineering*, *52*, 911–930.

Ray, R. D., & Foster, G. (2016). Future nuisance flooding at Boston caused by astronomical tides alone. *Earth's Future*, *4*(12), 578–587. https://doi.org/10.1002/2016EF000423

Ray, R. D., & Merrifield, M. A. (2019). The semiannual and 4.4-year modulations of extreme high tides. *Journal of Geophysical Research: Oceans*, *124*(8), 5907–5922. https://doi.org/10.1029/2019JC015061

Ritman, M., Hague, B., Katea, T., Vaaia, T., Ngari, A., Smith, G., et al. (2022). Past and future coastal flooding in Pacific Small-Island Nations: Insights from the Pacific sea level and geodetic monitoring (PSLGM) project tide gauges. *Journal of Southern Hemisphere Earth Systems Science*, *72*(3), 202–217. https://doi.org/10.1071/es22023

Rogelj, J., Fransen, T., den Elzen, M. G. J., Lamboll, R. D., Schumer, C., Kuramochi, T., et al. (2023). Credibility gap in net-zero climate targets leaves world at high risk. *Science*, *380*(6649), 1014–1016. https://doi.org/10.1126/science.adg6248

Ross, A. C., Najjar, R. G., Li, M., Lee, S. B., Zhang, F., & Liu, W. (2017). Fingerprints of sea level rise on changing tides in the Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*, *122*(10), 8102–8125. https://doi.org/10.1002/2017JC012887

Rueda, A., Vitousek, S., Camus, P., Tomás, A., Espejo, A., Losada, I. J., et al. (2017). A global classification of coastal flood hazard climates associated with large-scale oceanographic forcing. *Scientific Reports*, *7*(1), 1–8. https://doi.org/10.1038/s41598-017-05090-w

Santamaria-Aguilar, S., & Vafeidis, A. T. (2018). Are extreme skew surges independent of high water levels in a mixed semidiurnal tidal regime? *Journal of Geophysical Research: Oceans*, *123*(12), 8877–8886. https://doi.org/10.1029/2018JC014282

Schindelegger, M., Green, J. A. M., Wilmes, S. B., & Haigh, I. D. (2018). Can we model the effect of observed sea level rise on tides? *Journal of Geophysical Research: Oceans*, *123*(7), 4593–4609. https://doi.org/10.1029/2018JC013959

Schipper, E. L. F. (2020). Maladaptation: When adaptation to climate change goes very wrong. *One Earth*, *3*(4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., et al. (2018). Storylines: An alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change*, *151*(3–4), 555–571. https://doi.org/10.1007/s10584-018-2317-9

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., et al. (2021). A framework for complex climate change risk assessment. *One Earth*, *4*(4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

Stephens, S. A., Bell, R. G., & Lawrence, J. (2018). Developing signals to trigger adaptation to sea-level rise. *Environmental Research Letters*, *13*(10), 104004. https://doi.org/10.1088/1748-9326/aadf96

Stephens, S. A., Paulik, R., Reeve, G., Wadhwa, S., Popovich, B., Shand, T., & Haughey, R. (2021). Future changes in built environment risk to coastal flooding, permanent inundation and coastal erosion hazards. *Journal of Marine Science and Engineering*, *9*(9), 1011. https://doi.org/10.3390/jmse9091011

Stephenson, A. (2017). In *Harmonic analysis of tides using TideHarmonics* (Vol. 180). Retrieved from https://cran.r-project.org/web/packages/TideHarmonics/vignettes/austides.pdf

Sweet, W. V., Dusek, G., Obeysekera, J., & Marra, J. J. (2018). Patterns and projections of high tide flooding along the U. S. Coastline using a common impact threshold. Retrieved from https://www.tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf

Sweet, W. V., Menéndez, M., Genz, A. S., Obeysekera, J., Park, J., & Marra, J. J. (2016). In *Tide's way: Southeast Florida's September 2015 sunny-day flood*. Bulletin of the American Meteorological Society. https://doi.org/10.1175/BAMS-D-12-00021.1

Sweet, W. V., & Park, J. (2014). From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, *2*(12), 579–600. https://doi.org/10.1002/2014ef000272

Taherkhani, M., Vitousek, S., Barnard, P. L., Frazer, N., Anderson, T. R., & Fletcher, C. H. (2020). Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, *10*(1), 1–17. https://doi.org/10.1038/s41598-020-62188-4

Talke, S. A., Familkhalili, R., & Jay, D. A. (2021). The influence of channel deepening on tides, river discharge effects, and storm surge. *Journal of Geophysical Research: Oceans*, *126*(5), 1–24. https://doi.org/10.1029/2020JC016328

Talke, S. A., & Jay, D. A. (2020). Changing tides: The role of natural and anthropogenic factors. *Annual Review of Marine Science*, *12*(1), 121–151. https://doi.org/10.1146/annurev-marine-010419-010727

Talke, S. A., Kemp, A. C., & Woodruff, J. (2018). Relative Sea level, tides, and extreme water levels in Boston harbor from 1825 to 2018. *Journal of Geophysical Research: Oceans*, *123*(6), 3895–3914. https://doi.org/10.1029/2017JC013645

Talke, S. A., Mahedy, A., Jay, D. A., Lau, P., Hilley, C., & Hudson, A. (2020). Sea level, tidal, and river flow trends in the lower Columbia River Estuary, 1853–present. *Journal of Geophysical Research: Oceans*, *125*(3), 1–29. https://doi.org/10.1029/2019JC015656

Talke, S. A., Orton, P. M., & Jay, D. A. (2014). Increasing storm tides in New York Harbor, 1844–2013. *Geophysical Research Letters*, *41*(9), 3149–3155. https://doi.org/10.1002/2014GL059574.Received

Tay, C., Lindsey, E. O., Chin, S. T., McCaughey, J. W., Bekaert, D., Nguyen, M., et al. (2022). Sea-level rise from land subsidence in major coastal cities. *Nature Sustainability*, *5*(12), 1049–1057. https://doi.org/10.1038/s41893-022-00947-z

Tebaldi, C., Ranasinghe, R., Vousdoukas, M., Rasmussen, D. J., Vega-Westhoff, B., Kirezci, E., et al. (2021). Extreme sea levels at different global warming levels. *Nature Climate Change*, *11*(9), 746–751. https://doi.org/10.1038/s41558-021-01127-1

Tebaldi, C., Strauss, B. H., & Zervas, C. E. (2012). Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters*, *7*(1), 014032. https://doi.org/10.1088/1748-9326/7/1/014032

Thieler, E. R., & Hammar-Klose, E. S. (2000). National assessment of coastal vulnerability to sea-level rise: Preliminary results for the U. S. Pacific coast. *Open-File*. https://doi.org/10.3133/ofr99593

Thompson, P. R., Widlansky, M. J., Hamlington, B. D., Merrifield, M. A., Marra, J. J., Mitchum, G. T., & Sweet, W. (2021). Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, *11*(7), 584–590. https://doi.org/10.1038/s41558-021-01077-8

Thompson, P. R., Widlansky, M. J., Merrifield, M. A., Becker, J. M., & Marra, J. J. (2019). A statistical model for frequency of coastal flooding in Honolulu, Hawaii, during the 21st century. *Journal of Geophysical Research: Oceans*, *124*(4), 2787–2802. https://doi.org/10.1029/2018JC014741

Trace-Kleeberg, S., Haigh, I. D., Walraven, M., & Gourvenec, S. (2023). How should storm surge barrier maintenance strategies be changed in light of sea-level rise? A case study. *Coastal Engineering*, *184*(April), 104336. https://doi.org/10.1016/j.coastaleng.2023.104336

Vousdoukas, M. I., Bouziotas, D., Giardino, A., Bouwer, L. M., Mentaschi, L., Voukouvalas, E., & Feyen, L. (2018). Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. *Natural Hazards and Earth System Sciences*, *18*(8), 2127–2142. https://doi.org/10.5194/nhess-18-2127-2018

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., & Feyen, L. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, *9*(1), 1–12. https://doi.org/10.1038/s41467-018-04692-w

Wahl, T., Jain, S., Bender, J., Meyers, S. D., & Luther, M. E. (2015). Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, *5*(12), 1093–1097. https://doi.org/10.1038/nclimate2736

Watson, P. J. (2022). Determining extreme still water levels for design and planning purposes incorporating Sea Level rise: Sydney, Australia. *Atmosphere*, *13*(1), 95. https://doi.org/10.3390/atmos13010095

Widlansky, M. J., Long, X., & Schloesser, F. (2020). Increase in sea level variability with ocean warming associated with the nonlinear thermal expansion of seawater. *Communications Earth and Environment*, *1*(9), 1–12. https://doi.org/10.1038/s43247-020-0008-8

Williams, J., Horsburgh, K. J., Williams, J. A., & Proctor, R. N. F. (2016). Tide and skew surge independence: New insights for flood risk. *Geophysical Research Letters*, *43*(12), 6410–6417. https://doi.org/10.1002/2016GL069522

Woodworth, P. L. (2010). A survey of recent changes in the main components of the ocean tide. *Continental Shelf Research*, *30*(15), 1680–1691. https://doi.org/10.1016/j.csr.2010.07.002

Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., et al. (2019). Forcing factors affecting sea level changes at the coast. *Surveys in Geophysics*, *40*(6), 1351–1397. https://doi.org/10.1007/s10712-019-09531-1