Australian Coastal Flooding Trends and Forcing Factors

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Abstract Using the new Australian National Collection of Homogenized Observations of Relative Sea Level (ANCHORS) dataset, we assess trends in Australian relative sea levels over recent decades and subsequent coastal flooding impacts. We estimate a gauge average rate of mean sea level rise over the 1966–2019 period of 1.94 mm/yr with local variations around the Australian continent. Simultaneously, the frequency of coastal flooding impacts has increased at many major Australian cities including Sydney, Melbourne, Brisbane, Adelaide, and Perth. We find that this increase is not because storm surges are getting larger or more frequent, but because tides are reaching higher levels as they rise and fall about higher mean sea levels. This demonstrates that a major shift in the processes that lead to coastal flooding is underway, arising directly from global mean sea level rise, and is consistent with findings from the United States. This suggests that new perspectives on extreme sea levels are required, so research can be more impact-based and meet the needs of policymakers planning for these impacts. Considering extreme sea levels more broadly, we show that the seasonality of extreme sea levels is closely linked to the monthly variability in the heights of the highest tides. This framework provides a holistic assessment of coastal flood risk in Australia, based on established impact-based methodologies.

Plain Language Summary Here, we estimate how sea level rise around Australia and its implications for the frequency of coastal flood events. We estimate that sea levels have risen more than 10 cm over the 1966–2019 period, with much of this increase happening since 1993. This has led to more frequent coastal flooding in many major cities as the daily tides reach higher levels because they now rise and fall about higher mean sea levels. This means that smaller storm surges (temporary increases in water level due to severe weather), and in some locations, tides alone, can cause coastal flooding. We show that the most frequently occurring coastal flood impacts are due to tides rather than storm surges. While these events are associated with less severe impacts than those associated with much rarer, large storm surges (e.g., from tropical cyclones), they can still lead to disruption and economic costs, especially if they occur very frequently. Hence, understanding the trends and drivers of these minor floods is important for a holistic assessment of coastal flood risk in Australia. By leveraging established impact-based approaches we offer a new way to study the changing risk of coastal flooding in Australia.

1. Introduction

Sea level rise around Australia has been well-documented using a range of in situ and satellite-based datasets (Church et al., 2006; Karimi & Deng, 2020; Watson, 2011, 2020; White et al., 2014). Estimates vary spatially and are highly dependent on the record length of the datasets used, owing to accelerating global trends and interannual to decadal variability in the Australian region (Watson, 2020). Using an unhomogenized dataset, White et al. (2014) estimated an Australian national average trend in relative sea levels of 1.4 mm/yr over 1966–2009, increasing to 4.5 mm/yr for 1993–2009. These rates are a little higher than those measured using satellite altimetry for 1993–2019 period which have been estimated at 3.85 mm/yr (Karimi & Deng, 2020) and 3.4 mm/yr (Watson, 2020) for the broader Australian domain (typically 0°–50°S, 100°–165°E). Watson (2020) also investigated instantaneous velocities of four long tide gauge records, which offers a unique perspective on sea level changes. Other recent studies (e.g., Lowe et al., 2021) have also considered changes and drivers of variability on regional scales.

Sea level rise reduces the vertical distance between typical high tide levels and flood thresholds (freeboard). As such, coastal floods will increasingly occur due to smaller storm surges, or even tides alone under average meteorological and oceanographic conditions (Burgos et al., 2018; Moftakhar et al., 2015; Ray & Foster, 2016; Sweet & Park, 2014). The degree to which flood frequency will increase is dependent on greenhouse gas emission
earth’s future

pathways (Fox-Kemper et al., 2021) and whether actions can be taken to defend assets, such as raising the elevations of assets and hence, increasing flood thresholds. Under high emissions and without flood risk mitigation actions, flooding in Sydney will become regular and predictable (i.e., chronic) by mid-century (Hague et al., 2020). In Australia’s most populous state, New South Wales, Hanslow et al. (2018) estimated that the number of properties at risk of multi-annual tidal flooding would increase sixfold from 8,500 presently to 50,700 with a meter of sea level rise, which is possible later this century (Fox-Kemper et al., 2021).

Our interest is in examining the impact of these rising sea levels on changes to coastal flood frequency around Australia, especially minor flooding for which the most rapid frequency changes are currently occurring (Hague et al., 2020; Thompson et al., 2021). In this context, minor, or nuisance (e.g., Moftakhari et al., 2018), coastal flooding is when still water levels (i.e., the water levels measured by tide gauges in sheltered bays, harbors, and estuaries) cause inundation of low-lying assets such as streets or roads, paths, gardens or parks, or buildings below the floor level (Table S1 in Supporting Information S1; Hague et al., 2019). This inundation can be caused by multiple mechanisms including direct marine flooding, storm-drain backflow, and groundwater intrusion (Habel et al., 2020). We do not consider inundation due to waves on open coasts, such as described by Leach et al. (2021). While not as extreme as other floods, these minor floods have been associated with economic losses in the United States (Fant et al., 2021; Hauer et al., 2021; Hino et al., 2019; Kasmalkar et al., 2020). Across northern Australia, Hague et al. (2019) found that minor coastal flood frequencies vary spatially and are occurring multiple times per year, increasing at most key population centers. However, most Australian coastal risk studies adopt likelihood-based (i.e., using return periods or annual exceedance probabilities) approaches that either do not consider these more frequent minor floods, or that their frequencies can vary spatially (e.g., Church et al., 2006; Haigh et al., 2014; Lowe et al., 2021; McInnes et al., 2016; Pattiaratchi et al., 2018).

The motivation of this study is to assess trends in coastal flood frequency around Australia. We seek to quantify the extent to which these trends are driven by greater storminess (e.g., higher, or more frequent, storm surges) and higher tides due to sea level rise. This is achieved by combining a new national homogenized relative sea level dataset (Hague et al., 2021), with a framework that is used to define impact-based thresholds by matching reports of coastal flood impacts to the water levels at which they are reported (Section 2.3; Hague et al., 2019). Minor coastal floods are already observed frequently in many key Australian population centers, and as such robust impact-based coastal flood thresholds can be defined. Rapid increases in these minor events can be harbingers of future increases in more extreme floods (Moftakhari et al., 2017; Sweet & Park, 2014; Thompson et al., 2021). Therefore, understanding observed trends in minor flooding may offer insights into future changes in the frequency of more severe coastal floods. A further motivation of this study is to assess whether conceptual models and understanding developed from United States case studies (e.g., Sweet et al., 2018; Sweet & Park, 2014; Thompson et al., 2021) are applicable in other locations. If so, the incorporation of these impact-based insights into flood frequency changes could improve the utility of coastal risk assessments for coastal planners in other countries. As the first systematic, impact-based, assessment of coastal flood frequency changes for a jurisdiction outside the United States, our study provides an opportunity for such comparisons.

This study is the first to provide a national assessment of the changes in coastal flood frequencies that have been elicited from changes in Australian mean sea levels over the last 50 yr. We present updated estimates to mean sea level changes since 1966 and extend the impact-based approaches of Hague et al. (2019) to demonstrate resultant changes in coastal flooding at locations around Australia (Hague et al., 2021). We also consider how spatial and temporal variabilities in coastal floods are influenced by tidal modulations and storm surges, building on previous work (Eliot, 2010; Haigh et al., 2014; Hunter, 2020). As coastal flooding is related to the sum of eustatic (i.e., with respect to the center of the geoid) and isostatic (i.e., due to land motion) sea level changes, our analysis considers relative, rather than absolute, sea levels (Karegar et al., 2017; Nicholls et al., 2021). However, as Australia is broadly geologically stable the difference between relative and absolute are small compared to the magnitude of sea level rise resulting from climate change. This differs from existing work (e.g., White et al., 2014) which sought to exclude sites where vertical land motion may be enhancing or diminishing sea level rise locally. We deliberately chose to include sites where land subsidence is documented, for example, Port Adelaide (Belperio, 1993), Fremantle (Featherstone et al., 2015), and Newcastle (Watson, 2011), as these sites are likely more vulnerable to coastal flooding than they would be if there was no land subsidence occurring (Nicholls et al., 2021). In other words, we investigate trends and variability in Australian sea levels within the context of
how their impacts are felt at the coast, rather than how they relate to global sea level rise caused by climate change and natural variability alone.

2. Data and Methods

2.1. Sea Level Data

Here, we aim to provide new insights into Australian coastal sea levels and their impacts by analyzing the new Australian National Collection of Homogenized Observations of Relative Sea Level (ANCHORS) dataset (Hague et al., 2021). This dataset provides hourly observations for 38 locations around Australia with homogenization performed on annual means. It also provides the corresponding un-homogenized data, subsets of which have been provided to international databases such as GESLA (Woodworth et al., 2017) and University of Hawaii Sea Level Center (Caldwell et al., 2015).

A homogenized dataset is one that is free of inhomogeneities—sources of error due to factors other than the geophysical conditions experienced at the tide gauge. These inhomogeneities primarily occur when two (or more) shorter discrete tide gauge records are joined together to create a longer record and the individual records have differing instrumentation, geographical location (i.e., different hydrodynamic environments), definitions of tide gauge zero (i.e., datum shifts), and/or data collection processing procedures (e.g., measurement precision). Homogenization is typically a two-step process that involves the detection of jumps or steps in the data (i.e., inhomogeneities), followed by a correction applied to remove the change. The inhomogeneities were identified via “buddy checking.” This is an approach used to detect inconsistencies between two or more tide gauge records comparing the record to be homogenized with an independent well-correlated reference series (e.g., Hogarth et al., 2020). This means that data in ANCHORS have a consistent definition of mean sea level throughout the record when considering annual means.

The number of reference series available for specific times or locations, as well as the availability of metadata, are used as proxies for confidence in whether the homogenization algorithm has a low false-positive and low false-negative rate. Hence, “lower” or “higher” confidence data can be defined, with “higher” confidence data suitable for trend analysis. Only high-confidence data is utilized in this study, and hence, the Lakes Entrance ANCHORS site is not included in the analysis (Table S2 in Supporting Information S1). This higher confidence reliable ANCHORS data commences in 1966 with the number of locations with observations (and hence available reference series for buddy checking) increasing through to the late 1980s. We note that it is common in meteorological fields to use homogenization to also remove non-climatic factors, such as urbanization, local vegetation changes, or alterations to times of regular observations. For ANCHORS, local physical changes, such as subsidence or dredging were not removed as these have real and observable effects on how sea level impacts the coast. This approach means that ANCHORS is an accurate representation of sea level as observed, free of obvious error, but a small subset of the data reflect local factors which might not be a direct result of large-scale processes. For further information on the dataset see Hague et al. (2021).

2.2. Tidal Analysis

The oscillatory rises and falls of the sea surface about a mean level are typically called astronomical tides. These arise due to predictable factors, such as the gravity of the Earth-Sun-Moon system and the average seasonal cycle. This predictability can be exploited to produce tidal predictions (i.e., tide tables) or historical analyses (Hague & Taylor, 2021). Such analyses are valid over long timeframes, notwithstanding large changes to tidal patterns, such as those changes described for the United States by Li et al. (2021) and Australia by Palmer et al. (2019). This predictability comes from the ability to decompose the sea level signal into sums of sines and cosines with processes established for many decades to perform such decompositions. However, predictability does not imply simplicity, with complex interactions between key tidal constituents (the amplitudes and phases of key periodic variability in the astronomical tides) producing unique tidal regimes along the world's coastlines.

In this study we derive two sets of tidal analyses for each ANCHORS site. In both instances we use the “higher” quality data from the homogenized ANCHORS data and use TideHarmonics (Stephenson, 2017) as the tidal analysis package to generate tidal analysis values at the same hourly frequency as the input still water level
data. The purpose of the first set of analyses is to derive a constant value for tidal planes (e.g., HAT, the highest astronomical tide) and ranges, over a full nodal cycle, using the Permanent Committee for Tides and Mean Sea Level (PCTMSL) tidal datum epoch of 1992–2011 (Intergovernmental Committee on Surveying and Mapping [ICSM], 2018; Table 2). Nodal corrections, to account for the role that changes in the moon's tilt and distance from the Earth, need not be applied as the constituents were calculated over a sufficiently long period to capture the key nodal variations (Haigh et al., 2011). For a single site, this analysis method gives a single 20-yr timeseries with a constant mean (equal to the 1992–2011 mean). Applying this method results in the production of detrended analyzed tidal levels.

The second set of analyses are used to study the relative roles of tides and meteorological factors in causing coastal floods and whether these have changed as sea levels have risen. Hence these require a changing mean sea level to be defined. As we require both storm surge and tide-only flooding estimates, we adopt the “annual means” configuration of Hague and Taylor (2021). For a single site, we compute tidal analyses for each year (where 70% of hourly observations are available) separately using that year observations. In this analysis the annual mean sea level varies. This is a similar approach to that taken by Ray and Foster (2016) to estimate observed trends in tide-only inundation frequencies in the United States. This configuration also most closely matches the conceptual model used for investigating storm surge trends (e.g., Haigh et al., 2016; Hunter, 2020; Palmer et al., 2019). While Hague and Taylor (2021) note issues with this configuration's scalability between past estimates and future projections, such caveats do not apply to this study as future projections are not considered here.

2.3. Thresholds for Minor Coastal Flooding

Coastal flooding thresholds for minor floods can be defined by identifying the daily maximum still water levels recorded on all days where minor flooding impacts are reported, and taking the minimum value (Hague et al., 2019). One benefit of this approach is that threshold setting can consider flooding due to stormwater backflow (e.g., Habel et al., 2020) without complex hydrodynamic and hydraulic modeling (e.g., Prakash et al., 2019) being required for every location where thresholds are defined. Here, we updated and extended the geographic footprint of the observed thresholds derived by Hague et al. (2019). This approach matches coastal flood impact reports from social and news media to the maximum hourly sea levels on the days the impacts were reported (Table S1 in Supporting Information S1), with the minimum of these values assigned as the flood threshold (Table 2). Location-based information accompanying all flood impact reports was used to verify that flooding was due to high still water levels, rather than, for example, wave overtopping. Some impact reports have been collated and archived by the Bureau of Meteorology as part of routine monitoring and reporting on significant weather and climate and their impacts. We also utilize social media and citizen science to gain impact information on coastal hazards. Such use of these data has become commonplace in recent years (e.g., Habel et al., 2020; Moore & Obradovich, 2020), including in Australia (Harley et al., 2019; Leach et al., 2021; Pucino et al., 2021).

This represents a shift away from likelihood-based to impact-based extreme sea level metrics, noting both approaches are complementary and provide different insights. The aim here is to define a representative level at which coastal flooding impacts are felt in low-lying areas near a specific tide gauge. Due to the types of impact reports available, we focus on minor or nuisance flooding (Moftakhari et al., 2018), which corresponds with impacts, such as inundation of streets, paths, gardens, or jetties. While some moderate and major flood events (e.g., as described by Callaghan & Power, 2014) occurred in the study period, occurrences of these thresholds are too infrequent to be considered separately at this point but are included as instances where the minor flood level is exceeded. Similarly, coastal flooding may also be occurring at other locations, but a lack of coastal impact reports limits our analysis to locations where flooding has been consistently reported at this point.

To ensure robustness of our results we have defined two different classifications of coastal flood thresholds. Such thresholds could also be useful in early warning or impact-based forecast systems (e.g., Smith & Juria, 2019; Taylor & Brassington, 2017). The first set, termed high-sample thresholds, is used for coastal flood trend analysis at sites where coastal flooding is frequently reported. For these impact-based thresholds to be defined, at least 10 separate coastal floods were required, where both temporal and spatial separation is considered. This means that flooding either regularly occurs in the same location when the threshold is exceeded or exceeding the threshold leads to flooding in multiple communities proximate to the tide gauge. This requirement is only met at 10 out of the 38 ANCHORS locations at the current time. These high-sample thresholds are the focus of our subsequent analysis. It is also for this reason that our focus is on minor or nuisance flooding, rather than more extreme
flooding. There are not enough impact reports of severe flooding to meet this criterion and for higher thresholds to be defined.

A second set of thresholds, termed low-sample thresholds, are from locations where coastal flood impacts have been reported but not as frequently. These thresholds are provided for reference (for potential future work) but not used in analysis of coastal flood trends. As noted by Hague et al. (2019), an important aspect of the impact-based threshold methodology is that thresholds are not static, they are updated as more impacts are reported. Hence, the low-sample thresholds may not yet have enough impact reports to accurately estimate the still water level at which coastal flood impacts occur. An instance of where these low-sample thresholds may be an underestimate is where only the most severe coastal floods have been reported in news or social media and less impactful events have not. Conversely, overestimates of the flood thresholds may occur if flooding arises from the coincidence of high still water levels and rainfall (i.e., a compound flood), and hence the observed still water level is lower than the level required to cause flooding by itself. A higher sample of coastal flood impact events means that the likelihood of misestimating the threshold is reduced. The authors are aware of locations where regular coastal flooding occurs but is not yet documented in news or social media due to a range of factors (infrequently visited locations, flooding not recognized as notable) highlighting that flood impacts in some locations are simply not documented yet.

### 2.4. Sea Level Metrics and Coastal Flooding Terminology

We define various metrics to describe the tidal and non-tidal variability in sea levels which are listed in Table 1. These include the skew surge, the difference between the daily maximum observed sea level and the daily maximum analyzed tide (Batstone et al., 2013). We use this as a preferred alternative to the non-tidal residual (the instantaneous difference between still water and tidal levels) as it is independent of the tide level (Williams et al., 2016). This means that the estimate of the non-tidal component of sea level is not affected by local tide-surge interactions resulting in temporary changes in the times of low and high water during extreme sea level

| Metric                  | Physical interpretation                                                                 | Formulation                                                                 |
|-------------------------|-----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Still water level       | The observed water level at tide gauge, resulting from all possible geophysical factors | Hourly tide gauge observations from ANCHORS                                   |
|                         | (e.g., weather, climate, oceanic, and tectonic). Refer to Woodworth et al. (2017), for further details on specific factors |                                                                             |
| Annual mean sea level   | The average still water level observed at a tide gauge over a calendar year              | Average of all hourly tide gauge observations from ANCHORS, for years with at least 70% of hourly data points availability |
| Tide level              | The periodic rise and fall of water levels largely due to the gravity of the earth-sun-moon system and the average seasonal cycle, under average meteorological conditions | Harmonic analysis of hourly tide gauge observations from ANCHORS using TideHarmonics (Stephenson, 2017) |
| Highest astronomical tide (HAT) | The tidal plane representing the maximum possible tide level across a nodal cycle | Highest hourly value computed in the 1992–2011 tidal analysis period |
| Lowest astronomical tide (LAT) | The tidal plane representing the minimum possible tide level across a nodal cycle | Lowest hourly value computed in the 1992–2011 tidal analysis period |
| Tidal range (TR)        | The full possible variability of tide levels across a typical nodal cycle               | HAT-LAT                                                                     |
| Skew surge              | The meteorological component of the daily still water level; how much higher or lower daily weather and ocean conditions have made sea levels than would have been expected under the average conditions predicted in tide tables | Difference between daily maximum still water level and daily maximum tide level. Modified from Batstone et al. (2013) to consistently handle Australia’s mix of diurnal, semi-diurnal, and mixed daily tide regimes |
| Extreme skew surge (ESS) | The meteorological component of still water levels on the days experiencing the most extreme storm surges across a tidal epoch | Top 1% (i.e., 99th percentile) of all skew surges, across the 1992–2011 tidal analysis period (after Williams et al., 2016) |
| Freeboard               | The vertical distance between the HAT and the flood threshold (noting this can be negative); The minimum skew surge required for coastal flooding to occur if that surge coincides with the highest possible tide | Flood threshold—HAT |

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**Table 1**: Key Metrics Used in This Study, and How They Are Interpreted Physically and Calculated Mathematically
events (Figure 1a). Furthermore, we also use specific terminology to describe parameters that assess the frequency of coastal floods and the degree to which these are driven by tidal and non-tidal variability. These metrics can be used to investigate the changing roles that meteorological and tidal extremes play in modulating coastal flood frequencies around Australia. Coastal flood days result from the daily maximum still water level, the sum of the daily high tide and the skew surge, exceeding the flood threshold.

To investigate if coastal floods are becoming more tide-driven we assign each day with observations into one of four mutually exclusive and exhaustive subsets (Figure 1b), based on the daily maximum tidal level and daily maximum still water level. These represent cases of neither the still water level nor tidal level exceeding the flood threshold (Case 1), the still water level exceeding the threshold but the tidal level not (Case 2), both still water and tidal levels exceeding the threshold (Case 3), and the tidal level exceeding the threshold but the still water level not (Case 4). The two subsets of interest to us here are Cases 2 and 3, as these represent when coastal flood impacts are observed in locations with defined flood thresholds. The first subset of interest (Case 2, Figure 1b)
is where a positive skew surge is required to increase the still water level above the tidal level to exceed the flood threshold and cause flooding. This is termed “surge-driven” coastal flooding.

The second subset of interest (Case 3, Figure 1b) is termed “tide-sufficient” coastal flooding. This occurs when the still water level exceeds the flood threshold (i.e., flooding occurs) and the tide level also exceeds the flood threshold. In these cases, it is irrelevant whether a storm surge made the still water level higher than the predicted tide level, because the tide level was high enough to cause (at least minor) flooding regardless. It is worth noting the subtle difference between the definition of tide-sufficient coastal flooding and “tide-only” flooding (e.g., Hague & Taylor, 2021; Ray & Foster, 2016; Sweet et al., 2018). These studies define tide-only flooding as when the predicted or analyzed astronomical tide exceeds the flood threshold, regardless of whether the still water level does or not (i.e., regardless of whether flooding occurs). With reference to Figure 1b, this represents the sums of Cases 3 and 4 occurrences. Hence, they include in their flood counts circumstances where tidal floods are prevented by a sufficiently negative skew surge, for example, due to above-average atmospheric pressure. As noted by Sweet et al. (2018), the difference between these two definitions is typically negligible on results, as Case 4 occurrences are often much less common than Case 3 occurrences. However, in locations where tides’ influence on flooding is most pronounced (e.g., Sydney, Australia) Case 4 events can account for one-third of all tide-only (i.e., Cases 3 and 4) threshold exceedances (Hague et al., 2020). Given our focus is on determine the cause of specific floods, the benefits of having mutually exclusive and exhaustive subsets allow for more robust findings.

2.5. Analysis Periods

Due to varying records lengths in ANCHORS, we adopt a variety of analysis periods here to maximize the amount of data that can be used. This also ensures that there are sufficient data for inferences to be made across a consistent record length. In this study, statistical significance of trends is assessed by fitting linear trends using ordinary least squares regression as implemented by the SciPy package in Python (Virtanen et al., 2020). The following analysis periods and data subsets are used throughout this article:

1. 1966–present: Used to estimate recent trends in mean sea level (Table S2 in Supporting Information S1) for long records (90% completeness since 1966). Also used for plotting (but not trend estimates of) coastal and tide-only flooding frequencies.
2. 1993–present: Used to estimate recent trends in mean sea level (Table S2 in Supporting Information S1) for all records (90% completeness since 1993). This has been used by previous studies (e.g., White et al., 2014) to calculate trends over recent periods and match up with satellite altimetry data.
3. 1992–2011: Used as the reference period for the derivation of tidal planes (e.g., HAT) and other parameters (TR, ESS), and mean sea level anomalies. This is the standard Australian Permanent Committee for Tides and Mean Sea Level (PCTMSL) tidal datum epoch (ICSM, 2018).
4. 1987–present: Used as the period to calculate trends in annual coastal and tide-only flood frequencies (Table 2). This is the maximal period over which spatially consistent trends in coastal floods can be calculated over, limited by data availability at the Gold Coast and Ballina.

3. Analysis and Results

3.1. Changes in Mean Sea Levels

3.1.1. National Estimate

We calculate a mean sea level anomaly (compared to the 1992–2011 mean) for each year from 1966 to 2019, by approximating the Australian coastline as an n-sided polygon where n is the number of ANCHORS sites with at least 70% completeness in that year. We then defined straight line segments, clockwise around Australia, between each site with an annual anomaly defined in that year. The weighting given to each site was then the average length of the two adjoining line segments divided by the total length of all n-sides. The national annual mean anomaly was then calculated via the summation of the weighted anomalies. We estimate a trend, using linear ordinary least square regression, in the national annual mean sea level anomaly, of 1.94 mm/yr from 1966 to 2019, and 3.74 mm/yr since 1993 (Figure 2, Table 2). This means that on average, sea levels are 10.5 cm higher today than in 1966, with much of this increase occurring in the most recent 26 yr. This appears to agree with findings for the western tropical Pacific that saw very sudden changes in sea level in the early 1990s, with limited rise from
the 1960s to the early 1990s (Merrifield, 2011). This could also be partly a function of the state of longer decadal sea level variations at the start and end points of the analysis period.

A simple average of the individual station-based trends (i.e., not using the \( n \)-sided polygon approach) for the period since 1993 delivers a similar result of 3.78 mm/yr. Over the full 1966–2019 period, considering sites with at least 50 yr annual means defined, the simple average yields an estimate of 1.77 mm/yr, slightly lower the weighted average (1.94 mm/yr). The sea level rise estimates presented above are similar to other Australian estimates utilizing different methods, from both tide gauges (i.e., relative sea level) and satellite altimetry (i.e., absolute sea level; Karimi & Deng, 2020; Watson, 2020; White et al., 2014), and those seen globally (e.g., Frederikse et al., 2020; Palmer et al., 2021). The presence of trends in the recent period means that coastal flooding frequencies and trends defined over an epoch (Section 3.2) may be underestimated by the time-averaging inherent in the values indicated here (Watson, 2020).

### 3.1.2. Individual Station Estimates

All 38 ACORN-SL stations individually exhibited increases in mean sea level over their respective full records (Figure 3). These trends are calculated at each site via a linear ordinary least squares regression on annual means for years with no more than 30% of hourly observations in that year missing or rated as “lower confidence.” Over the recent period of 1993–2019, all these trends were statistically significant except for Melbourne and Wyndham (Table S2 in Supporting Information S1). For longer term trends, we can investigate locations where annual means are defined in 90% of the years in 1966–2019 period and data are “higher” confidence. These are sites with many reference series to facilitate detection and correction of inhomogeneities. All these records exhibit statistically significant increases in mean still water levels (Table S2 in Supporting Information S1) and are shown in Figure 3. Trends at individual sites varied from 1.26 mm/yr at Bundaberg to 3.32 mm/yr at Thevenard (Figure 2, Table S2 in Supporting Information S1).

### 3.1.3. Assessment of the Effect of Homogenization on National and Station Trends

To assess the effect that the adjustment of inhomogeneities undertaken in ANCHORS has on the estimation of the annual mean we repeat the above computation on the unadjusted ANCHORS data (Table S2 in Supporting Information S1). As confidence assessments could not be made to unhomogenized data (Hague et al., 2021), we analyze all years with at least 70% data availability. Considering the national weighted average, the mean sea level rise in this unadjusted data is very similar to that estimated using the adjusted data over both the 1966–2019 (1.89 mm/yr) and 1993–2019 (3.88 mm/yr) periods, indicating very little overall impact of homogenization on average trends, as might be expected. There are greater differences between trends in adjusted and unadjusted data at individual sites owing to adjustments made at these sites as one would expect (Table S2 in Supporting Information S1). For example, the range of trends at individual stations with at least 90% data completeness

**Figure 2.** Australian relative mean sea level anomaly calculated using polygon weighting (black line) from 1966 to 2019, with individual station anomalies shown in gray. Dashed line denotes 1992–2011 mean sea level, against which anomalies are calculated.
## Table 2

**Key Parameters and Coastal Flood Trends at ANCHORS Locations**

| Location     | Flood threshold (m) | Coastal floods | Tide-only floods | Sea level metrics (1992–2011) (m) | HAT | TR | ESS |
|--------------|---------------------|----------------|------------------|-----------------------------------|-----|----|-----|
|              |                     | Trend (days/decade) | Surge-driven days | Trend (days/decade) |                  |    |    |     |
| Booby Island | 4.2°                | 0.91            | 1.18             | 3.27                             | 1.77 | 4.2 | 4.1 | 0.30 |
| Cairns       | 3.36                | 2.82            | 4.77             | 10.23                            | 2.71 | 4.2 | 4.0 | 0.23 |
| Mackay       | 6.59°               |                 |                  |                                  |      | 6.6 | 6.6 | 0.24 |
| Gladstone    | 4.58°               |                 |                  |                                  | 4.9  | 4.7 | 0.21 |
| Booby Island | 4.2°                | 0.91            | 1.18             | 3.27                             | 1.77 | 4.2 | 4.1 | 0.30 |
| Cairns       | 3.36                | 2.82            | 4.77             | 10.23                            | 2.71 | 4.2 | 4.0 | 0.23 |
| Mackay       | 6.59°               |                 |                  |                                  |      | 6.6 | 6.6 | 0.24 |
| Gladstone    | 4.58°               |                 |                  |                                  | 4.9  | 4.7 | 0.21 |
| Bundaberg    | 3.46°               |                 |                  |                                  | 3.6  | 3.5 | 0.19 |
| Brisbane     | 2.61                | 8.00            | 7.73             | 9.47                             | 7.67 | 2.7 | 2.6 | 0.21 |
| Gold Coast   | 1.88                | 9.09            | 7.33             | 4.52                             | 8.19 | 1.9 | 2.0 | 0.20 |
| Ballina      | 1.85                | 4.03            | 8.42             | 8.48                             | 3.67 | 2.0 | 1.9 | 0.22 |
| Newcastle    | 1.94                | 12.57           | 9.98             | 15.82                            | 11.11| 2.1 | 2.0 | 0.20 |
| Sydney       | 1.96                | 7.49            | 7.35             | 5.65                             | 6.86 | 2.0 | 2.0 | 0.21 |
| Port Kembla  | 1.90°               |                 |                  |                                  | 2.0  | 2.0 | 0.20 |
| Eden         | 1.78                | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Burnie       | 1.78                | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Western Port | 3.30                | 0.46            | 3.35             | 0                                | 0    | 2.8 | 2.7 | 0.57 |
| Point Lonsdale| 1.78               | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Geelong      | 1.84°               |                 |                  |                                  | 1.3  | 1.2 | 0.34 |
| Melbourne    | 1.30                | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Portland     | 1.49°               |                 |                  |                                  | 1.3  | 1.2 | 0.34 |
| Port Adelaide| 3.13                | 0.46            | 3.35             | 0                                | 0    | 2.8 | 2.7 | 0.57 |
| Port Pirie   | 4.07°               |                 |                  |                                  | 3.4  | 3.3 | 0.71 |
| Port Lincoln | 1.9°                |                 |                  |                                  | 1.9  | 1.8 | 0.45 |
| Thevenard    | 2.22                | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Esperance    | 1.5                 | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Albany       | 1.4                 | 1.42            | 4.9              | 0                                | 0    | 1.0 | 0.9 | 0.40 |
| Bunbury      | 2.40°               |                 |                  |                                  | 1.2  | 1.2 | 0.34 |
| Fremantle    | 1.61                | 0.38            | 1.4              | 0                                | 0    | 1.3 | 1.1 | 0.36 |
| Geraldton    | 1.72                | 0.38            | 1.4              | 0                                | 0    | 1.3 | 1.1 | 0.36 |
| Carnarvon    | 2.0                 | 0.38            | 1.4              | 0                                | 0    | 1.3 | 1.1 | 0.36 |
| Onslow       | 3.1                 | 2.9             | 0.38             | 1.4                              | 0    | 1.3 | 1.1 | 0.36 |
| Port Hedland | 7.76°               |                 |                  |                                  | 7.5  | 7.4 | 0.21 |
| Broome       | 10.5                | 10.4            | 4.0              | 1.0                             | 10.5 | 10.4 | 0.17 |
| Wyndham      | 8.7                 | 8.6             | 4.0              | 1.0                             | 8.7  | 8.6 | 0.27 |

*Data from ANCHORS Project.*
throughout the 1993–2019 period is wider than with the adjusted ANCHORS data. This highlights that homogenization is important if local sea level changes are the focus.

3.2. Changes in the Nature and Frequency of Minor Coastal Flooding

3.2.1. Changes to Minor Coastal Flood Frequencies

Minor coastal floods occur at different frequencies around Australia and due to different causes (Figure 4, Table 2). Cairns, Townsville, Brisbane, Ballina, and Newcastle have experienced higher rates of tide-sufficient flooding than surge-driven flooding. Therefore, we can say that nuisance flooding is tide-dominated at these locations. Figure 4 also illustrates the important role that 4.5-, 8.9-, and 18.6-yr nodal cycles play in modulating tide heights, and hence, coastal flood risk. These cycles, which arise from the superposition of phases of higher-frequency tidal constituents, related to lunar nodal and perigean cycles, have been noted as a key factor in the heights and timing of extreme high tides (Eliot, 2010; Haigh et al., 2011). Thompson et al. (2021) noted that these tidal cycles may cause frequent coastal flooding to emerge earlier than would be expected if only changes in mean sea level were considered.

Sydney and the Gold Coast are not as far along the transition to tide-dominated minor flood regimes, however, still experience frequent tide-sufficient coastal flooding. Conversely, Melbourne, Port Adelaide, and Fremantle, only experience surge-driven coastal flooding, when storm surges occur and are large enough to combine with tide levels to exceed the defined flood threshold. These locations can be considered to have surge-dominated regimes in the present climate. Note that the classification of locations into surge-dominant or tide-dominant does not imply that tide-dominant locations have a higher proportion of floods that can be attributed to the increases in global mean sea level. The number of surge-driven days will also increase with mean sea level rise as smaller surges elicit impacts on days where tides approach but do not exceed the coastal flood threshold (Sweet & Park, 2014). The transition to tide-dominated flood regimes is expected to continue as sea levels rise, with minor flooding at Sydney expected to become almost exclusively due to tides by mid-century (e.g., Hague et al., 2020).

We find that coastal flood days are increasing across Australia but that these changes in coastal flood risk have not been spatially uniform (Figure 4, Table 2). The present-day frequencies of coastal flooding are not spatially uniform either—with Townsville, Brisbane, Ballina, and Newcastle experiencing at least 15 flood days per year on average but Cairns, Melbourne, Port Adelaide, and Fremantle experiencing fewer than 5. This demonstrates that likelihood-based metrics cannot be applied uniformly across wide spatial domains (e.g., Australia) to provide insights into coastal flooding. For example, metrics like the 99th percentile, 1-in-10-yr height, or 1% AEP do not have the same meaning from station to station in terms of the expected impacts. Furthermore, we show that observed changes in flood days are not proportional to the existing number of coastal flood days. For example, the Gold Coast has experienced a (slightly) more rapid increase in coastal flood rates than Brisbane, despite having lower baseline flood frequencies (over 1992–2011) and a (slightly) lower rate of sea level rise (Table 2, Table S2 in Supporting Information S1). This suggests that more factors are at play in determining coastal flood frequency changes than just the baseline rate of flooding and the amount of sea level rise.
Figure 3. Trends in annual mean sea levels at tide gauges around Australia over the 1966–2019 period (a, upper) and 1993–2019 period (b, lower) in mm/yr. For a mean to be calculated over the 1966–2019 period at least 50 annual means needed to be calculated. Note. The larger number of sites in the latter period where estimates of mean sea level change are available and the implications of this for the n-sided polygon method employed in the production of Figure 2. Results that are not statistically significant are not shown (refer Table S2 in Supporting Information S1).
Figure 4. Annual number of days where still water levels have exceeded minor flood thresholds at major population centers with frequently reported coastal flood impacts, 1966–2019. The height of the column represents the total number of coastal flood days observed at a location. The total number of coastal flood days are separated into two mutually exclusive and exhaustive categories: surge-driven coastal flooding (i.e., Case 2 in Figure 1b) colored in red, and tide-sufficient flooding (i.e., Case 3 in Figure 1b) colored in brown. Stippling denotes a year where a coastal flood count could not be obtained due to insufficient sea level data.
We posit that tidal range could be a factor, as the ratio of sea level rise to tidal range represents a way to characterize a signal-to-variability ratio, and hence the locations’ sensitivity to future sea level rise. This would be a possible explanation of the Gold Coast having a more rapid increase in flooding days than Brisbane, given the Gold Coast has the smaller tidal range (Table 2). Previous work has related tidal range to the typical coastal flood thresholds (Sweet et al., 2018) and to variations in annual counts of high tide flood days at a specific location (Thompson et al., 2021). However, the implications of this for flood risk across large spatial domains have not been fully explored. This has potentially profound implications for Australia’s future coastal flood risk that will be explored in future work as tidal ranges vary from 1 m to more than 10 m around Australia (Table 2).

3.2.2. Changes to Minor Flood Predictability

We find that increases in nuisance flooding are predominantly because tides are getting higher as mean sea levels rise, rather than due to storm surges getting more frequent or intense. Much of the increase in total flood days is explained by the increase in tide-sufficient coastal flood days. For example, in Ballina, the number of days of minor coastal flooding where surges were required to exceed the flood threshold have increased from 9.3 to 10.6 days/yr. Simultaneously, the number of tide-only flood days has increased from 6 to 18 days/yr. These statistics are estimated by multiplying out an ordinary least squares’ regression line of the annual coastal flood counts (Table 2). This same pattern emerges from other east coast locations, with tide-sufficient coastal floods increasing at three to four times the rate of surge-driven coastal floods at Townsville, Brisbane, Gold Coast, Newcastle, and Sydney.

Tide-only flooding has not yet occurred at Melbourne, Port Adelaide, and Fremantle (Figure 4). These locations have high extreme skew surges (ESS) and high freeboard—coastal flood thresholds remain well (e.g., 25–30 cm) above the HAT with present sea levels. This means that flood thresholds are only exceeded in more extreme weather conditions and that assets have likely been elevated to be well above HAT to account for these frequent storm surges. Flood frequencies in Melbourne are almost equal to those in Cairns, but the factors leading to coastal floods at these locations are different. Most floods in Cairns are due to tides, while no floods occur in Melbourne due only to tides currently. Therefore, the time window for flood risk in Cairns is very predictable well in advance, but much less so in Melbourne, despite floods in both locations occurring at about the same frequency. This demonstrates that while, in general, minor flooding will become increasingly predicatable as flood regimes transition from being surge-dominated to tide-dominated (Hague et al., 2020; Sweet et al., 2018), factors like storminess influence where on the continuum of flood frequency and predictability a location lies at present.

3.2.3. Sensitivity to Thresholds

Examining the difference in flood frequencies and trends between Sydney and Newcastle highlight how threshold-sensitive flood frequencies are in locations where flooding is tide driven. Sydney and Newcastle have near-identical storminess and similar tidal ranges, while the freeboard is −13 cm at Newcastle and −7 cm at Sydney. Note that freeboard (i.e., the vertical offset between the flood threshold and HAT) is negative when the flood threshold is below HAT. With relatively small tidal ranges at both locations, this 6 cm freeboard difference results in more than a doubling of tide-only flooding, and an effective doubling of coastal flooding in Newcastle (Table 2). This demonstrates the importance of defining, and regularly updating, impact-based coastal flood thresholds (Hague et al., 2019). As noted in the United States (Sweet et al., 2018), the difference between minor and moderate flood thresholds can be less than 20 cm. This means that as sea level rises, not only will the frequency of minor coastal floods increase, in a matter of decades moderate floods could occur as frequently as minor floods do today. Hence, this also highlights the importance of defining coastal flood tipping points (e.g., Thompson et al., 2021) and emergence times of frequent flooding (e.g., Hague et al., 2020). We know, for example, that areas subject to regular riverine flooding rapidly become uninsurable (Box et al., 2013). Similar shifts can be expected in coastal analogs without efforts to reduce the impacts, as sea levels rise further and accelerate (Haasnoot et al., 2021).

3.3. Seasonality of Minor Coastal Flooding Around Australia

Not only are some places more vulnerable to coastal flooding than others, but some seasons are more likely to see coastal flooding than others (Figure 5). At Cairns and Townsville, coastal flooding peaks in February. Between Brisbane and Sydney, flooding is more bimodally distributed with peaks around the summer and winter solstices. Southern Australia is more likely to see flooding in May, June, and July. However, as impact-based analysis is
limited to the 10 locations identified in Section 2.3, a more generic approach considering a statistical definition of extreme sea levels is required. Here we consider the frequency at which the 99th percentile of daily maximum still water level and tidal analysis values are exceeded (Figure 6). This corresponds, on average, to an event that occurs three to four times per year, a frequency at which flooding occurs at most locations where impact-based thresholds are defined in this analysis. We consider the seasonality in both still water level and tidal level across the baseline epoch of 1992–2011.

We show that tidal variability is the key determinant in locational variations of still water level extremes, even in locations where coastal flooding is presently exclusively surge-driven. In other words, the highest tides coincide with the period of lowest atmospheric pressure, most frequent strong cold fronts, and hence, highest monthly mean sea levels (Lowe et al., 2021). This likely arises from tidal analyses including monthly and seasonal variations in mean sea level due to climatic variability in wind and pressure patterns. Because tidal analysis is a physics-free method that involves the fitting of sums of sines and cosines to the predictable periodic variability of sea

Figure 5. Seasonality of coastal floods. Proportion of coastal flood events that occur in each calendar month over 1987–2019 at locations, where coastal flood thresholds are defined. Gray shading indicates that no exceedances were recorded in that month. Mackay and Gladstone are omitted due to too infrequent coastal floods for robust results.
level observations, any oscillatory signal of suitable period (from half-days to decades) with sufficient magnitude will be represented in the tidal analysis. Tidal variability is much more seasonally constrained than extreme sea level variability with extremes occurring in narrow ranges of months and many more months where extremes have never been recorded. Locations that experience more frequent storm surges tend to experience more extreme sea levels away from the month where extreme tide levels are most common, meaning that extreme sea level can happen at any time of the year. This also shows that while flooding at Melbourne, Port Adelaide and Fremantle requires storm surges to occur, the tides (and the mean sea level about which they rise and fall) play a strong driving role in determining in which months these storm surges are most likely to cause flooding.

Flooding is more likely to occur around the time of spring tides because the minimum surge required for the flood threshold to be exceeded is reduced. This interpretation is important because it is likely that the transition from

**Figure 6.** Seasonality of sea level extremes. Proportion of 99th percentile extreme still water level (left) and tidal (right) levels that occur in each calendar month 1992–2001. Gray shading indicates that no exceedances were ever recorded in that month.
surge-dominated to tide-dominated flood regimes may manifest as increased clustering of flood events in the months where high tides are at their highest (Thompson et al., 2021). This will mean that as flooding becomes increasingly tide-driven, which is expected with rising sea levels in the future, coastal floods will increase disproportionately in months that experience relatively more tidal extremes. An example of this is Fremantle, where the strong seasonal cycle has been well-documented (Eliot, 2012; Lowe et al., 2021). Currently, 32% of all still water level extremes occur in July at Fremantle. However, because 74% of tidal level extremes occur in July, we expect to see the proportion of floods that occur in July increase as sea levels rise and flooding becomes increasingly tidal. This represents an increase in predictability of coastal flooding, when viewed from the perspective of seasonal forecasting (e.g., Widlansky et al., 2017) and could be viewed analogously to already-observed changes in the commencement time of the southern Australia fire season (Dowdy, 2018).

4. Discussion—The Need for Impact-Based Coastal Risk Assessments in Australia

Through the adoption of an impact-based perspective on extreme sea levels, we have shown that minor and nuisance coastal floods are increasing in frequency and that these increases vary spatially. This impact-based perspective contrasts with the traditional paradigm through which Australian coastal flood risk has been viewed, where extreme sea levels are related to severe meteorological and oceanographic phenomena such as storm surges from intense extratropical lows, cold fronts, tropical depressions, and tropical cyclones (McInnes et al., 2016). Because these driving phenomena occurred infrequently, extreme sea level metrics were typically likelihood-based, with many studies (e.g., Haigh et al., 2014; O’Grady et al., 2019) investigating the levels associated with relatively infrequent return periods (e.g., 1-in-10 yr). However, we have shown that nuisance floods occur in most major population centers more frequently than these likelihood-based metrics would indicate. This could also be true for smaller population centers where impacts occur but have not been reported sufficiently to define impact-based thresholds. This highlights the importance of regular event monitoring in all vulnerable areas to develop flood thresholds. Incorporation of past, present, and future coastal flood frequencies in future coastal research, rather than only extreme sea level heights or coastal flood extents, will assist with informing coastal adaptation and flood risk mitigation in Australia.

We suggest that the way that Australian coastal scientists and practitioners assess coastal risk may need to change as the nature and causes of Australian coastal floods change. We have shown that in many locations along Australia’s east coast, predictable periodic tides that rise and fall against the backdrop of an increasing mean sea level are a key driver of coastal floods (Figure 4). In fact, locations in eastern Australia, including Cairns, Townsville, and Brisbane, already experience more days of minor flooding due to tides than days where surges are required to raise water levels above the flood threshold. Such events are not typically encapsulated in risk frameworks that assume that impactful coastal flood events are rare and always associated with severe weather. Therefore, a realignment of the metrics and analysis techniques used in coastal flood risk studies may be necessary to include these more frequent, but still impactful, coastal extremes. Importantly, we have shown that the impact-based approaches to identifying changes in nuisance flooding developed in the United States (e.g., Moftakhari et al., 2017; Ray & Foster, 2016; Sweet et al., 2018; Sweet & Park, 2014) are equally applicable outside the United States. Through the adoption of such techniques, coastal scientists worldwide, including in Australia, will be able to obtain greater insights on future coastal flood, especially when considering the emergence of increasingly frequent tidal flooding (e.g., Thompson et al., 2021).

We have shown that in many, predominantly northern and eastern, Australian locations, flooding regimes have transitioned from being mostly driven by extreme weather and storm surge events to being mostly driven by variations in tides. By its nature, this tide-only flooding is both more predictable and more frequent than flooding resulting from meteorological and oceanographic extremes. Therefore, once such flooding becomes sufficiently impactful, it likely elicits different adaptive responses (Grace & Thompson, 2020; Lawrence et al., 2020). However, different locations are at different stages in this transition. Considering Figure 4, we note that tide-only inundation has not yet occurred in some locations along Australia’s southern coastline, but it is commonplace in locations along Australia’s eastern coastline. To varying degrees along Australia’s eastern coastline, tide-only inundation has increased from being relatively rare in the 1960s and 1970s to being responsible for almost all flood events since 2000. Based on coastal flood projections for Sydney (Hague et al., 2020) and internationally (Sweet et al., 2018), we expect this transition to tide-only flooding to continue, and for tidal flooding to emerge in more places, as sea level rise continues and accelerates.
As noted internationally, there will be a point where cumulative annual economic impacts from frequent less extreme (chronic) flooding will surpass the average annual economic impacts from infrequent more extreme (acute) flooding (Paulik et al., 2021; Ghanbari et al., 2020; Moftakhari et al., 2017). Studies from the United States have further quantified economic impacts associated with non-acute coastal floods, including traffic delays (Hauer et al., 2021; Kasmalkar et al., 2020) and loss of income from an inability to access shops due to flooded car parks (Hino et al., 2019). Flooding of roads and car parks have been identified in Australia and used in our definition of coastal flood thresholds in this study (Table 2). A recent study for New South Wales (Wood et al., 2021) estimated economic costs of up to $1.3 billion (in 2019–2000 Australian dollars) every year with 30 cm of further sea level rise considering loss of inhabitable land and structural damage. Future work is required to estimate economic costs of such coastal flood impacts in Australia, and hence, the relative future economic costs of unmitigated chronic and acute coastal floods here. However, we have demonstrated that the sort of coastal flood impacts that lead to costly chronic floods are already occurring multiple times per year in many Australian population centers.

5. Conclusions

Using a new homogenized relative sea level dataset, the Australian National Collection of Homogenized Observations of Relative Sea Level (ANCHORS), we have provided updated estimates of sea level rise experienced around Australia’s coastline and explored contemporaneous changes in coastal flood frequencies, extreme sea levels and the changing roles of tides and storm surges. We estimate that relative mean sea levels are 10.5 cm higher today than in 1966, with much of this increase occurring since about 1993. This is consistent with the role of thermal expansion and melting of land ice in increasing sea levels globally and the regional manifestations of this global forcing.

Through the collection of coastal impact reports, we have defined coastal flood thresholds for many locations vulnerable to frequent minor coastal floods. The impact-based approach adopted here represents a shift away from the traditional paradigm used to investigate extreme sea levels in Australia (and by extension coastal flood risk) which focuses on decadal- or centennial-scale events. We showed that coastal flooding is happening much more frequently than the multi-annual return period metrics often used to assess coastal flood risk would imply. This is due to a reduction in the height of storm surges required to exceed flood thresholds as sea levels rise and push tides higher. In some locations this has already resulted in flooding due to tides alone, without any meteorological or oceanographic forcing beyond the tidal cycle. Given not all vulnerable locations have coastal flood thresholds defined, these findings should provide impetus to develop and maintain systems to monitor and report coastal flood impacts nationally and systematically. This will improve understanding in the ongoing transition from surge-driven to tide-driven coastal flood regimes.

We showed that the increases in local mean (relative) sea levels are driving increases in minor coastal flood frequencies, by examining the exceedances of coastal flood thresholds. We find that the number of these floods occurring due to tides (made higher by increasing mean sea level) are increasing three to four times faster than the number of coastal floods due to storm surges along the Australian east coast. This quantification extends findings established through United States-based case studies—that sea level rise is the dominant factor in driving increases in the frequency of nuisance or minor floods. This demonstrates how the drivers of Australian coastal flood risk are changing and highlights the importance of including processes that dominate sub-annual sea level variability in coastal risk assessments. While at some locations, non-tidal variability remains an important driver in determining when coastal flood events will occur, we find that everywhere the periodic tides are a strong determinant of the months in which coastal floods are more likely to occur. By incorporating changes in coastal flood frequency and the role of tides in modulating extreme sea levels, this new perspective can complement and enhance existing research on the expected heights of past, present, and future sea level extremes, and the resulting coastal flood frequencies.

Data Availability Statement

Sea level data used in this study are available at: http://dx.doi.org/10.25914/6142df37250b. Please refer to Hague et al. (2021) for further information on this dataset. Coastal impact data used to define flood thresholds are included in Table S1 in Supporting Information S1.
Acknowledgments

The authors wish to thank Brad Murphy and Grant Smith who reviewed an earlier version of this article. The authors are grateful to all individuals who have provided impact information to assist with the definition of impact-based thresholds. Ruth Reef was supported by DP180103444. Shayne McGregor was supported by Grant FT160100162. This work was also funded by the Australian Climate Service.

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