Sea-Level Rise Driving Increasingly Predictable Coastal Inundation in Sydney, Australia

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Abstract

As global mean sea level (GMSL) continues to rise, thresholds corresponding to coastal inundation impacts are exceeded more frequently. This paper aims to relate sea-level rise (SLR) observations and projections to their physical on-the-ground impacts. Using a large coastal city as an example, we show that in Sydney, Australia, frequencies of minor coastal inundation have increased from 1.6 to 7.8 days per year between 1914 and present day. We attribute over 80% of the observed coastal inundation events between 1970 and 2015 to the predominantly anthropogenic increases in GMSL. Further, we find that impact-producing coastal inundation will occur weekly by 2050 under high- and medium- emission/sea-level rise scenarios, and daily by 2100 under high emissions. The proportion of tide-only coastal inundation events (i.e. where no storm surge is required to exceed flood thresholds) will increase with SLR, such that most coastal inundation events, including those considered historically severe, will become a predictable consequence of SLR and astronomical tides. These findings are important for coastal managers as frequency, severity and predictability of inundation impacts can all now be related to the amount of SLR (e.g. a planning allowance or SLR projection). By incorporating known historical inundation events, this allows contextualization, visualization and localization of global SLR and the changing nature of future coastal inundation risk.

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Key Points:

- Coastal inundation in Sydney, Australia is now happening nine times more often than it would be if global mean sea-level rise had not occurred.
- Future coastal inundation events defined by current impact thresholds will be mainly tide-driven, with minimal role for ocean, weather and climate variability.
- We develop a framework for generating projections of frequency, severity and predictability of coastal inundation *impacts*, to inform adaptation.

Abstract

As global mean sea level (GMSL) continues to rise, thresholds corresponding to coastal inundation impacts are exceeded more frequently. This paper aims to relate sea-level rise (SLR) observations and projections to their physical on-the-ground impacts. Using a large coastal city as an example, we show that in Sydney, Australia, frequencies of minor coastal inundation have increased from 1.6 to 7.8 days per year between 1914 and present day. We attribute over 80% of the observed coastal inundation events between 1970 and 2015 to the predominantly anthropogenic increases in GMSL. Further, we find that impact-producing coastal inundation will occur weekly by 2050 under high- and medium- emission/sea-level rise scenarios, and daily by 2100 under high emissions. The proportion of tide-only coastal inundation events (i.e. where no storm surge is required to exceed flood thresholds) will increase with SLR, such that most coastal inundation events, including those considered historically severe, will become a predictable consequence of SLR and astronomical tides. These findings are important for coastal managers as frequency, severity and predictability of inundation impacts can all now be related to the amount of SLR (e.g. a planning allowance or SLR projection). By incorporating known historical inundation events, this allows contextualization, visualization and localization of global SLR and the changing nature of future coastal inundation risk.

Plain Language Summary

As sea levels rise, the daily highest tide reaches higher and further inland and as a result we see coastal flooding more frequently. Coastal flooding is when roads, carparks, walking paths, gardens, and in more extreme cases, homes and businesses, are impacted by high sea levels. Using Sydney, Australia as an example, we find that most coastal flooding events we observe today would not have happened without human-caused sea-level rise. Further, coastal flooding is expected to occur in Sydney on average once per week by 2050, and every day by 2100 if high greenhouse gas emissions continue. In the past, the most severe coastal flooding impacts, such as flooding of main roads and private property only occurred with large coastal storm events. However, we find that these severe floods will occur much more frequently as sea levels continue to rise, as they will eventually occur on the daily high tides. As the timing and heights of daily high tides are driven by the sun, moon and the seasons, these severe coastal floods will

become very predictable. This will have implications for the coastal and emergency managers tasked to deal with this changing risk.

1 Introduction

Global mean sea level (GMSL) continues to rise at an accelerating rate due to anthropogenic climate change (**IPCC, 2019**). Specifically, increased greenhouse gas emissions are responsible for 70% of the observed global sea-level rise (SLR) since 1970 (**Slangen et al., 2016**). This leads to increasingly frequent extreme sea-level events due to these events occurring against a background SLR trend (**Oppenheimer et al., 2019**). Sea-level variability observed at tide gauges comprises multiple components, including SLR, astronomical tides (e.g. as presented in tide tables), the effects of climatic, meteorological and oceanographic phenomena, and vertical land motion (**Woodworth et al., 2019**). Furthermore, there is large regional variability in the meteorological and climatological processes, as well as in astronomical tides, that contribute to extreme sea levels around the Australian coast (**McInnes et al., 2016**). Storm surges (**Callaghan & Power, 2014**), tsunami (**Beccari, 2009**), meteotsunami (**Pattiaratchi & Wijeratne, 2015**) and sea-level anomalies coinciding with high astronomical tides (**Hanslow et al. 2019, Maddox 2018a**) all have been associated with past impact-producing extreme sea-level events.

In many low-lying locations, SLR has led to a reduction in the gap between typical high tide marks and inundation thresholds (freeboard), causing smaller and more frequent sea-level anomalies (i.e. with respect to the changing mean) to result in inundation (**Sweet & Park 2014**). This occurrence of typically minor or 'nuisance' (**Moftakhari et al., 2018**) inundation and its impacts are expected to become more frequent into the future (**Moftakhari et al., 2018**; **Jacobs et al., 2018**). Recent studies in Australia (**Hague et al., 2019; Hanslow et al., 2019; Hanslow et al. 2018**) and internationally (**Sweet et al., 2018**; **Sweet et al., 2016**; **Ray & Foster, 2016**) have documented frequent, typically minor, coastal inundation impacts, occurring multiple times per year and at elevations that can now be reached by the day-to-day astronomical tides. However, the causes, trends, future projections, and economic and environmental impacts of these frequently occurring coastal inundation events remain largely unstudied in the Australian context, and to a lesser extent, globally. Notably, **Ray and Foster (2016)** were first to attribute specific coastal inundation events (via the exceedance of an impact-based threshold) as being due to astronomical tides alone. Henceforth, we adopt their terminology and refer to this phenomenon as 'tide-only' inundation. We deliberately avoid the terminology of 'tidal inundation' and 'high tide flooding' as these terms have been used in the Australian and international contexts to mean minor coastal inundation, occurring predominantly, but not exclusively, due to astronomical tides (e.g. **Habel et al., 2020; Moore & Obradovich, 2020; Hino et al., 2019; Hanslow et al., 2019**; **Hanslow et al., 2018**; **Sweet et al., 2018; Dahl et al. 2017; Sweet et al., 2016**).

Critical environmental thresholds in natural and human systems, including for coastal inundation are typically fixed (although may change as human developments creates different exposures to inundation) rather than relative to a changing background signal (**Harris et al., 2018**). **Habel et al. (2020)** state that for sea level projections to be useful for planning, they must consider local coastal inundation impacts including those due to astronomical tides. Ultimately, this means to monitor coastal inundation due to extreme sea levels, one must consider metrics that are defined based on consequence rather than likelihood. The errors produced by using likelihood are exacerbated by the trend in the sea level timeseries as events of a given consequence become increasingly likely due to SLR. Despite this, most studies on sea-level extremes in the Australian (**McInnes et al., 2013**; **McInnes et al., 2009**; **Church et al., 2006**; **Manly Hydraulics Laboratory [MHL], 2011**; **Department of Environment Climate Change and Water [DEECW], 2010**; **Haigh et al., 2014a**; **Haigh et al., 2014b**) and international (e.g. **Oppenheimer et al., 2019**; **Buchanan et al., 2017**; **Wahl et al., 2017**; **Hunter et al., 2017**; **Marcos et al., 2015**, **Arns et al., 2013**; **Menendez & Woodworth 2010**) literature consider annual recurrence intervals (ARIs) or annual exceedance probabilities (AEPs) without specific reference to observed coastal impacts. Recent studies (e.g. **Hague et al., 2019**, **Hanslow et al., 2019**) show that coastal flooding occurs multiple times per year in parts of Australia. By construction, ARIs or AEPs, as they are commonly used, typically ignore annual or sub-annual coastal floods such as these, and others that may be caused by tides. Whilst there are notable cases where return periods of one year or less were considered in Australia (**MHL, 2011**; **DEECW, 2010**; **Church et al., 2006**), these are not standard practice. Even then, the thresholds chosen by these studies remained based on the probability of an event rather than its impacts. This means that even if these ARIs could be related to a specific set of impacts or an historical extreme sea-level event st, they will not be relevant in the future as SLR causes a change in the underlying probability distribution. Therefore, we adopt an impact-based perspective to relate observed and projected SLR to changes to their expected physical impacts on coastal communities.

Here we adapt a recently developed impact-based methodology (**Hague et al., 2019**) to analyze historical and projected future coastal inundation events in Sydney, Australia. By considering a variety of inundation thresholds, including the current highest-on-record observation, we show that the occurrence of coastal inundation in Sydney will become increasingly predictable and almost entirely driven by astronomical tides rather than storm surges.

2 Data Requirements and Sources

In order examine trends in coastal inundation, both reports of impacts of coastal inundation and long sea level height records are required. Whilst the methodology and analysis could be applied anywhere the relevant data exist, Sydney, Australia provides an excellent case study due to the abundance of both impact and tide gauge data. Note that the method of **Hague et al. (2019)**, which is employed here, has some broad similarities to other contemporaneous studies that have sought to define impact-based sea level thresholds or models for coastal inundation due to high still water levels (**Habel et al., 2020; Moore & Obradovich, 2020; Hino et al., 2019**). Coastal inundation impacts around Sydney have also been well-documented in the scientific literature (**Hanslow et al., 2019**), government reports (**Watson & Frazer, 2009**; **Jacobs, 2012**; **Jacobs, 2014**; **Jacobs, 2015**; **Jacobs, 2016**; **Maddox, 2018b**; **Maddox, 2019**), on social media (e.g. **Witness King Tides, 2020**) and by local coastal scientists (P. Watson, pers. comm.; D. Hanslow, pers. comm.). **Table 1** documents the dates of occurrence and the nature of coastal inundation impacts and the source of the information. **Figure 1** shows a map of the locations and a small selection of images of inundation events documented in **Table 1**.

The longer the sea level height record available is, the more robust it is for detection of linear and non-linear changes due to SLR against long-period climatic variability (**Watson, 2018**; **Haigh et al., 2014c**). The Sydney region has one of the longest tide gauge records in the Southern Hemisphere (**Marcos et al., 2015; Watson, 2011**) with digitized hourly data available since 1914 at Fort Denison (**Hamon, 1987**). Data for Fort Denison, Camp Cove and Botany Bay were sourced from the Bureau of Meteorology Tides Unit databank, of which portions are available from GESLA-2 (**Woodworth et al., 2017**) and/or University of Hawaii Sea Level Center (**Caldwell et al., 2015**). The primary dataset used in this study, from Fort Denison, can be wholly reproduced by concatenating the GESLA record with the UHSLC Research Quality data to the end of 2018. This data has temporal resolution of 1 hour and consists of digitized historical records and, more recently, Lanczos-Cosine filtered data, all referenced to a common datum (**PSMSL, 2020**; **Holgate et al., 2013**; **Hamon 1987**). To account for changes in reporting precision throughout the digitized record, and the implications this may have on the consistency of event threshold exceedances through time, all observations have been rounded to the nearest centimeter. Data for Patonga, Port Jackson, Port Hacking, and Bundeena were provided by Manly Hydraulics Laboratory (MHL), which was filtered to hourly frequency for comparability to the Bureau of Meteorology data. The MHL data, along with Camp Cove and Botany Bay, were only used for purposes of establishing whether Fort Denison data was representative of regional sea level (e.g. within 100km of the gauge).

Table 1: Known dates of coastal inundation events in the Sydney region, with associated daily maximum sea level heights from Fort Denison and description of impacts, flood level (refer ***Section 2****) and information source. Abbreviations for sources: W&L (2008) is* ***Watson and Lord (2008)****, W&F (2009) is* ***Watson and Fraser (2009)*** *and WKT (2020) is* ***Witness King Tides (2020)****. Social media includes Twitter, Instagram and YouTube sources.*

Date	Sea Level	Flood Level	Impacts	Source
26/11/2007	1.98 m	Low-impact	Inundation of jetty and wave overtopping from passing ferry at Fort Denison.	W&L (2008)
14/12/2008	2.16 m	Minor	Jetties and gardens flooded at Browns Bay.	WKT (2020)
15/12/2008	2.12 m	Minor	Roads flooded at Botany, Oatley.	W&F (2009), P. Watson (pers. comm.)
12/01/2009	1.96 m	Low-impact	Carpark flooded at Putney. Paths and/or parks flooded at Hunters Hill, Sydney Harbour, Oatley, Woolooware.	W&F (2009), P. Watson (pers. comms.)
05/06/2012	2.21 m	Moderate	Roads and paths flooded at Haberfield.	P. Watson (pers. comms.)
14/12/2012	1.96 m	Low-impact	Paths flooded at Tempe, Bayview, Farm Cove, Mosman.	WKT (2020)
12/01/2013	2.07 m	Minor	Roads flooded at Como.	WKT (2020)
02/01/2014	2.20 m	Moderate	Flooding of jetties and/or gardens at Browns Bay, Little Wobby Beach, Arncliffe, Palm Beach; paths at Meadowbank, Wooloomooloo; buildings at Bayview and Elizabeth Bay; roads at Akuna Bay; Botany.	WKT (2020), Jacobs (2014), P. Watson (pers. comms.)
03/01/2014	2.15 m	Minor	Flooding of carpark at Brooklyn; roads at Mona Vale, Botany.	WKT (2020), Jacobs (2014) P. Watson (pers.

				comms.)
04/01/2014	2.18 m	Minor	Flooding of roads at Ku Ring Gai; carpark at Hornsby Heights.	WKT (2020)
14/06/2014	2.19 m	Minor	Paths flooded at Kirribilli.	WKT (2020)
13/01/2017	2.16 m	Minor	Paths and gardens flooded at Farm Cove.	Social media
05/12/2017	2.23 m	Moderate	Paths and gardens flooded at Farm Cove.	Social media
06/12/2017	2.27 m	Moderate	Flooding of major roads at Haberfield, Ku Ring Gai; paths and/or gardens at Farm Cove, Elizabeth Bay; jetties at Kurraba Point.	WKT (2020), P. Watson (pers. comms.)
07/12/2017	2.07 m	Minor	Roads flooded at Botany.	Maddox (2018b)
03/01/2018	2.26 m	Moderate	Major roads flooded at Ku Ring Gai, Tempe, Earlwood.	Maddox (2018b), Social media

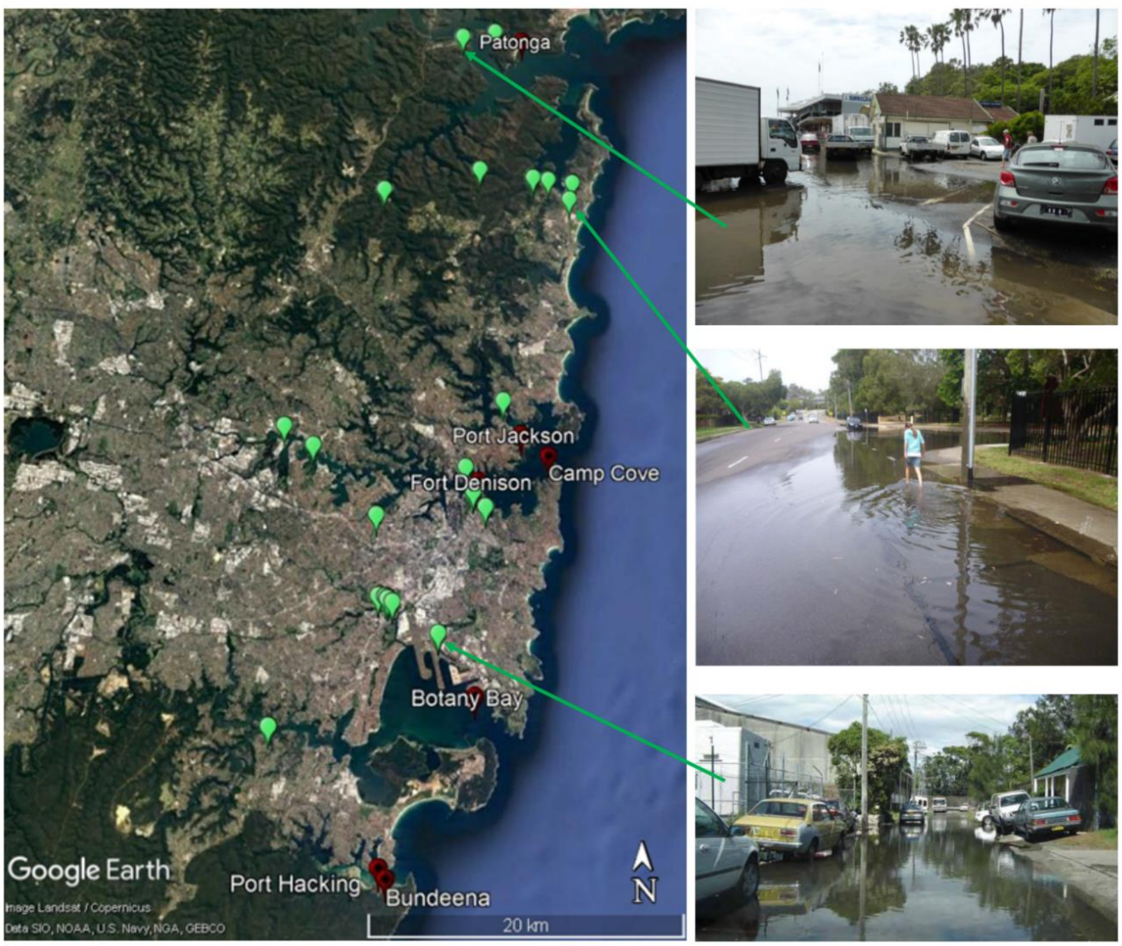

***Figure 1**: **Observational data sources and examples.** (**a, left**) Locations where coastal inundation impacts have been observed and been used for determination of impact-based*

*thresholds (green markers) and position and name of tide gauges (red and black markers). Images of impacts associated with minor inundation on 3 February 2014 at Hawkesbury River Train Station carpark (**b, upper right**) and Mona Vale (**c, right centre**), and at Botany on 15 December 2008 (**d, lower right**). Arrows mark these locations on the map. Images from **Witness King Tides (2020)**, **Jacobs (2014)** and **Watson and Frazer (2009)** respectively.*

3 Defining impact-based thresholds for the Sydney region

An assumption of the approach of **Hague et al. (2019)**, and indeed all other studies that define impact-based thresholds, is that the water levels recorded at the tide gauge are representative of the water levels at the locations where impacts are reported. **Hague et al. (2019)** argued that broadscale events with similar regional impacts implied that the tide gauges heights were locally representative, however, the high data density of the Sydney region allows this assumption to be examined empirically. We find that very strong correlations ($R > 0.95$) exist between the daily minimum, mean and maximum sea levels at Fort Denison and other nearby tide gauges, as well as in the monthly mean and maximum timeseries ($R > 0.90$). We also find that the same high sea-level events elicit impacts in multiple locations around the Sydney region, indicating that inundation is not localised and hence not likely due to local effects. This is expected from a physical perspective as the Sydney region comprises predominantly drowned river valley estuaries which have only mild attenuation of the tidal signal away from the oceanic source of sea-level variability (**Hanslow et al., 2018**). Hence, variations in water levels recorded at the Fort Denison tide gauge are highly representative of those in the broader Sydney region. Notably, the 6th December 2017 coastal inundation event saw impacts right along the New South Wales coast including at Coffs Harbour, Newcastle, Gosford, Woy Woy, Moruya and Batemans Bay (P. Watson pers. comm.), as well as in the Sydney region (**Table 1**). Sydney is also considered to be tectonically stable – thus, the differences between absolute and relative sea levels have been historically small (**Burgette et al., 2013**) and projected to remain small into the future (**Kopp et al., 2014**). Therefore, impact-based thresholds can be determined by matching historical and modern records of documented instances of coastal inundation at various sites around Sydney (**Figure 1**) to the synchronous Fort Denison tide gauge observations.

Minor and moderate thresholds were defined so that impacts associated with exceeding these thresholds align with impacts prescribed to the minor and moderate classifications used by the Australian **Bureau of Meteorology (2013)** for riverine flood warnings. Moderate level impacts include flooding of major roads and flooding of buildings above the floor level. Minor level impacts are typically analogous to those of 'nuisance' or 'high tide' flooding discussed in the international coastal literature (**Moftakhari et al., 2018**; **Sweet et al., 2016**; **Ray & Foster, 2016**; **Sweet & Park, 2014**) where low-lying residential streets, paths, jetties, carparks and parklands are submerged. Finally, low-impact inundation was defined to encompass inconvenient coastal floods that cause disruption by impacting bicycle and walking paths, jetties and boat ramps, but without the road closures and property damage impacts of minor floods. The lowest sea-level value associated with each impact is defined as the impact-based threshold for that inundation classification. With reference to **Table 1**, the lowest sea level associated with inconvenient floods of paths and gardens is 1.96m, the lowest level at which flooding of roads is reported is 2.07m, and the lowest level associated with flooding of buildings and/or major roads is 2.20m. Hence, these levels correspond with the low-impact, minor and moderate impact-based thresholds, respectively.

4 Historical inundation frequencies

The exceedance of impact-based thresholds is commonly used as a proxy for the occurrence of historical coastal inundation even when records of impacts do not exist (e.g. **Moore & Obradovich, 2020**; **Hague et al., 2019**; **Hanslow et al., 2019**; **Hino et al., 2019**; **Thompson et al., 2019**; **Sweet et al., 2018**; **Dahl et al., 2017; Ray & Foster, 2016**; **Strauss et al., 2016**; **Sweet & Park, 2014**). Therefore, estimates of historical coastal inundation days are simply the number of days per year where the daily maximum (hourly) sea-level observation is equal to or exceeds the relevant impact-based threshold. A key aim of this study is to investigate the changing frequency and predictability of these coastal inundation events. To do this we define 'tide-only inundation' quantitatively as when the daily highest astronomical tide exceeds a coastal inundation threshold (**Sweet et al., 2018; Ray & Foster, 2016**). Tide-only inundation frequencies are calculated the same way as for coastal inundation, except it is the daily hourly maximum predicted tide height, rather than the observed (still water) sea level height, that is compared to the impact-based threshold.

There are two main data completeness criteria utilized in this study, and they are applied sequentially. The first relates to the computation of the daily maximum sea-level value and the second relates to the computation of the yearly number of days above said daily maximum. For a daily maximum sea-level value to be defined there must be no missing hourly sea-level observations on that (UTC) day. If a day is missing one or more hourly sea-level values the whole day was assigned a null value and is considered missing for purposes of computing the daily maximum. The second criterion is that, for an annual count exceeding the impact-based threshold, **WMO (2017)** states that for a count parameter (e.g. exceedance of a threshold) to be calculated for a given time period at least 70% of the data must be available. Furthermore, the guidelines advise that, if the data is not 100% complete, counts should be calculated using ratios of available data in the averaging period. Based on this an adjusted exceedance count is applied to all years with at least 70% data completeness. In practice this means that if a year has 10% missing data and has 9 days where the daily maximum sea level exceeds the impact-based threshold throughout remainder of the year (i.e. the 90% of the record where data is not missing), then the adjusted exceedance count is 10. If a year has less than 70% data completeness it not considered further in the analysis. It is this adjusted exceedance count that is reported and analyzed in this study. These adjusted annual counts are then rounded to the nearest whole number. This is consistent with the methodology of **Hague et al. (2019)**. This analysis is conducted for the whole observational period 1914 – 2018, with only two years, 1914 and 1930, excluded from the analysis under this second criterion.

Astronomical tides are highly predictable (**Pugh & Woodworth, 2014**) and thus can be generated many years, even decades or centuries, in advance, provided local changes in astronomical tides (e.g. as described by **Haigh et al. 2019**) are small. Astronomical tide predictions were generated using R's TideHarmonics package (**Stephenson, 2016**), to hourly resolution. We compared results from several common tidal analysis packages – TideHarmonics, UTide (**Codiga, 2011**) and TTide (**Pawlowicz et al. 2002**), as well as the Bureau of Meteorology's in-house tidal analysis software. We found the choice of package to have negligible impact on the results, so chose TideHarmonics for computational efficiency and reproducibility of results. When analyzed against hourly predictions generated by other analysis packages, TideHarmonics had correlations of 0.987 or greater, linear regression coefficients of between 1.0002 and 1.0172 and absolute average differences of between 0.0049 and 0.0553 m. Harmonic constituents were derived using hourly data over an epoch of 1986-2005, the baseline period used for recent climate change projections (**IPCC, 2019**). As this period is greater than 18.6 years it is sufficiently long to capture the key variability of the tidal cycle relevant to this analysis (**Haigh et al., 2011**). Predictions were then propagated from these constituents over the relevant period, 1914 – 2018 creating a hindcast to be used for the historical analysis.

As tide predictions issued by the Bureau of Meteorology (and many other oceanographic agencies globally) are reported with respect to a temporally invariant datum, changes in mean sea level must be considered. The tide predictions used in this analysis comprise mean sea level in each year and the astronomical tide oscillating about that mean. The exact specification of historical mean sea level can influence results of analysis of tide-only inundation frequencies. Since that mean is changing due to SLR, for this analysis astronomical tides are derived as per above with the **Dangendorf et al. (2019)** GMSL reconstruction used to specify the historical mean of each year. Compared to other options such as polynomial or linear fits to the observed tide gauge data, this has the benefit of capturing non-linear or non-polynomial variations in GMSL, which have been observed in the Fort Denison tide gauge record (**Watson 2011**). Furthermore, global, rather than local, MSL was used because increases in this parameter have been directly attributed to anthropogenic climate change (**Slangen et al. 2016**). For a geologically stable gauge such as Sydney, the difference between these will reflect the differences between anthropogenic sea level rise at the global and local scale, oceanographic and meteorological variability at different time scales (for example, due to El Niño), and sampling issues. Published estimates suggest that SLR in Sydney is likely to be close to the GMSL change in the long term, differing by less than 10% (**McInnes et al. 2015**). As the global trend continues to increase the difference between the GMSL and local MSL trend is likely to diminish so the choice matters less as sea levels rise in the future. The reconstruction was expressed with respect to the observed 1986-2005 mean from the Fort Denison sea level records. This allows a more straightforward approach to attribution in the counterfactual analysis (**Section 5**). One downside of using the reconstruction is that it ends at 2015 is that predicted historical tides cannot be generated after this year. There is no missing data in the predicted tides, so all years from 1914 to 2015 are included for calculation of tide-only inundation.

The resulting calculations show that all severities of coastal inundation are occurring more frequently, compared to a century ago (**Figure 2**). Frequency counts of low-impact and minor inundation increased from averages of 11.6 and 1.6 days per year over 1914-1933 to averages of 22.8 and 7.8 days per year over 1999-2018, respectively. The frequency of moderate coastal inundation also increased, occurring twice in the 1914-1933 period but 16 times in the 1999-2018 period. Much of this increase is likely due to the rapid emergence of tide-only inundation. At the low-impact level, (reconstructed) tide-only inundation occurred three days in total during the 1914-1933 period but averaged 13.4 days per year between 1996 and 2015. Despite never occurring prior to 1991, 19% of all minor coastal inundation days over the 1996-2015 period could have occurred without an additional contribution from oceanographic or meteorological factors.

These tide-only results are averages and if one considers a specific event, the non-tidal residual may have raised or lowered the predicted astronomical tide to either exacerbate or mitigate impacts of coastal inundation. However, considering the 13.4 days per year (1996 to 2015) of low-impact tide-only inundation we find that on average 8.8 (65%), coincided with a day of coastal inundation (i.e. the astronomical tide and observed sea level both exceeded the impact-based threshold). Tide-only inundation occurred at 67% of the rate of coastal inundation over the 1996-2015 period, up from 1.4% over the 1914-1933 period. This indicates that the contribution of tides to impact-producing extreme sea levels, and the associated inundation, has dramatically increased over the last century.

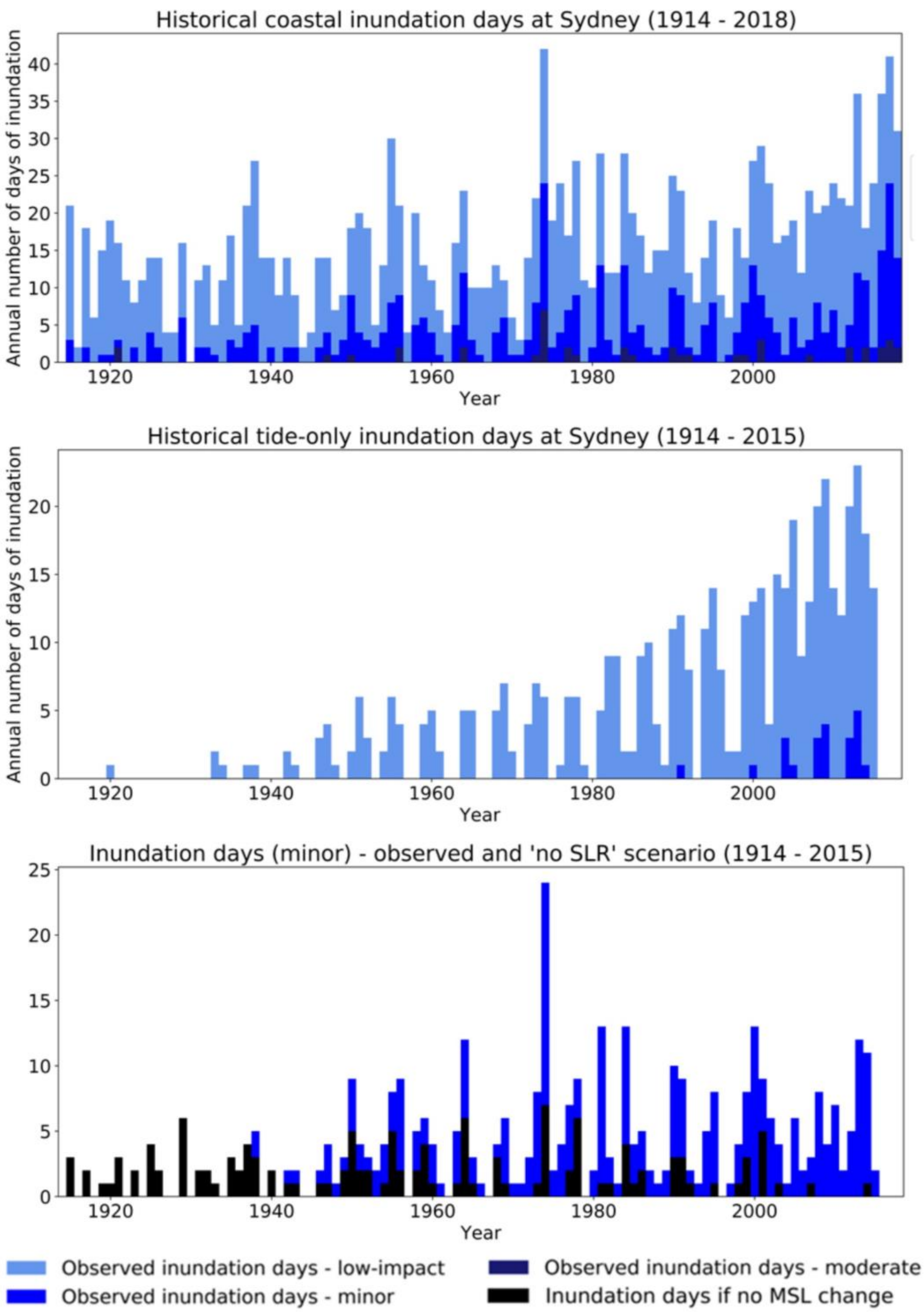

Figure 2: Historical inundation frequencies (a, upper) *Observed frequency (days per year) of low-impact (light blue), minor (overlaid, medium blue) and moderate (overlaid, dark blue) coastal inundation (1914 – 2018), from tide gauge observations.* ***(b, middle)*** *Observed frequency (days per year) of low-impact (light blue), minor (overlaid, medium blue) and moderate (overlaid, dark blue) tide-only inundation (1914 – 2015), from the* ***Dangendorf et al. (2019)*** *reconstruction plus astronomical tide timeseries.* ***(c, lower)*** *Observed frequency (days per year) of minor*

*coastal inundation (medium blue), as per a), and, overlaid, estimated frequency (days per year) of minor coastal inundation under 'no SLR' scenario (black), from counterfactual analysis as described in **Section 5**.*

5 Attribution of coastal inundation to SLR

In order to consider the role that SLR has played in the increase in coastal inundation frequency we consider an alternate reality (i.e. a counterfactual analysis) where MSL does not change from the 1914-1933 value – i.e. the first 20 years of the Fort Denison observations. This was achieved using the following method. Residuals of the observed sea levels from Fort Denison were calculated, using the predicted tides generated as per the above (i.e. using the **Dangendorf et al. 2019** specification of GMSL changes). These residuals were then added to the 1914-1933 mean, to make the counterfactual time series without the contribution of rising GMSL. Analysis of exceedance of the new timeseries was carried out in the same manner as for coastal inundation (**Section 4**), as the daily maximum hourly sea-level values in the counterfactual were compared to the impact-based thresholds. As the residuals are calculated using the predicted tides, this analysis is constrained by the length of the reanalysis which concludes in 2015.

This paper then follows the methodology of **Strauss et al. (2016)** by defining the counterfactual sea-level timeseries (i.e. the 'no SLR' scenario) as a reference state and the observed timeseries as the new (i.e. under SLR) state, in the fraction attributable risk framework of **Stone and Allen (2005)**. The Fraction Attributable Risk (FAR) is calculated as:

$$FAR = \frac{(P_{with\ SLR} - P_{without\ SLR})}{P_{with\ SLR}} = 1 - \frac{P_{without\ SLR}}{P_{with\ SLR}} = 1 - \frac{1}{RR}$$

Where $P_{without\ SLR}$ is computed as mean of coastal inundation days in the observed timeseries over a reference period, divided by the 365 days per year. $P_{without\ SLR}$ is computed as the mean of coastal inundation days in the counterfactual ('no SLR') time series over the same reference period, divided by the 365 days per year. The period of 1996-2015 is used as it is the last 20 years of the counterfactual timeseries.

The trend in GMSL has been largely attributed to anthropogenic climate change, especially since 1970 when greenhouse gas emissions are reported to be responsible for 70% of the observed trend (**Slangen et al., 2016**). Comparing the exceedance count in the 'no SLR' timeseries to that of the observed sea level timeseries (**Figure 2c**) shows the degree to which climate change, via the change in GMSL, has already increased coastal inundation risk in Sydney. Of the 248 days since 1970 when the minor inundation threshold was exceeded, 203 (82%) days of coastal inundation wouldn't have occurred without SLR. Specifically, the widespread minor coastal inundation around Sydney's central and northern suburbs on 2-4 January 2014 (**Jacobs, 2014**; **Witness King Tides, 2020; Figure 1b-c**) and flooding of Botany on 15 December 2008 (**Watson & Frazer, 2009**; **Figure 1d**) did not occur in the 'no SLR' scenario, even at a low-impact level. Overall, minor coastal inundation occurred nine times more often between 1996 and 2015 as a direct result of SLR. Considering fraction attributable risk (FAR) framework (**Stone & Allen 2005**), we find that 88.9% of minor inundation and 83.3% of low-impact inundation could be attributed to SLR, with risk ratios of 9.0 and 6.0 respectively. Thus, we can conclude that if a low-impact or minor coastal inundation event happened in the 1996-2015 period, the event was made more likely (**Lewis et al., 2019**) by SLR. It is worth noting that coastal inundation frequencies have increased over this recent period, and hence, the FAR of an event today is likely higher than the value calculated using this 20-year mean.

Interestingly, we found a decrease in coastal inundation frequency over time in the 'no SLR' scenario (**Figure 2c**), indicating some factors have mitigated against the effects of global SLR on coastal inundation frequency changes. Some possible factors include storminess (**Marcos et al. 2015**; **Menendez & Woodworth 2010**), and tidal range (**MHL, 2011**; **Mawdsley et al., 2015**; **Harker et al., 2019**) which previous studies have found to all be decreasing at Sydney. Whilst there are many potential causes of tidal amplitude changes (**Haigh et al., 2019**), **Harker et al. (2019)** found Sydney's observed tidal range reduction was potentially related to channel dredging rather than SLR. However, overall the combined effect of these factors was small compared to the effect of SLR and will become increasing less important as the trend accumulates.

6 Future projections of inundation and extreme sea level frequencies

A key objective of this study was to derive projections of impact-producing extreme sea-level event frequencies. For this purpose, a baseline sea-level climatology was defined using all daily maximum hourly sea levels recorded over the 1986-2005 period (the baseline period used by **IPCC 2019**), which is effectively equivalent to an empirical probability density function (PDF). For each year in the **IPCC (2019)** projection period of 2006-2100 a new climatology was defined by increasing every daily maximum hour sea level observation in the baseline climatology by the amount corresponding to a specified RCP projection increment for the year in question. This is equivalent to shifting the mean of the probability density function to higher sea levels and assuming no change to the variance. The average number of days where this adjusted timeseries exceeds the relevant impact-based thresholds is then considered the estimate of coastal inundation days for the year in question. This process is repeated for every year and for each RCP SLR scenario considered – the 5th, 50th (median) and 95th percentiles of RCPs 2.6, 4.5 and 8.5.

The estimation of future frequencies of tide-only inundation was different to the distribution-shifting method used for coastal inundation. As discussed in **Section 4**, the highly predictable nature of tides allowed a tidal hindcast to be derived over a historical period. For the projections of tide-only inundation we implement a similar process for future tides, using the GMSL estimates (5th, 50th and 95th percentile for RCPs 2.6, 4.5 and 8.5) from **IPCC (2019)** to specify the future mean sea level about which the astronomical tides oscillate. Future annual counts of tide-only inundation (**Figure 3**; **Table 1**) can thus be estimated in the same way as historical counts (**Section 4**), as the number of days per year where the highest hourly tide prediction value exceeds the relevant impact-based threshold. A feature of this method is that by using harmonic analysis extending to 2100, key tidal variability on 4.4-, 8.9-and 18.6-year cycles (**Haigh et al., 2011**) is included.

Future climate change will further increase the frequencies of all severities of coastal inundation (i.e., from low-impact to highest-on-record) becoming tidally driven by 2100, and in many cases earlier. Considering the median estimates and 90% confidence intervals (90% CI) under RCP 8.5, we find that low-level inundation will occur 128 days each year (90% CI: 85 – 186) by 2050 and daily by 2100 (90% CI: 301 – 365). By 2050, 70 (90% CI: 40 – 114) days of minor inundation and 21 (90% CI: 9 – 44) days of moderate inundation are anticipated each year. End-of-century estimates are for daily (90% CI: 301 – 365 days) minor floods of which almost all, 347 (90% CI: 204 – 365) days each year, will also exceed the moderate inundation impact-based threshold.

As SLR continues, the proportion of coastal inundation events that are due to astronomical tides alone (i.e. 'tide-only' inundation) will increase, as demonstrated in the convergence between the coastal inundation and tide-only inundation curves in **Figure 3**. Under RCP 8.5, predicted tides are expected to exceed the low-impact inundation threshold 132 (90% CI: 86 – 184) days per year by 2050 and daily (90% CI: 359 – 365) by 2100. For the minor threshold, 69 (90% CI: 28 – 112) and 365 (90% CI: 314 – 365) days of exceedance are expected each year, by 2050 and 2100 respectively. Comparing these results to the earlier results presented for coastal inundation projections, indicates that effectively all low-impact and minor flooding will be due to astronomical tides alone. For moderate inundation, it takes until after 2050 for inundation to become completely tidally driven, with only 7 (90% CI: 0 – 32) days' highest tide exceeding the moderate threshold each year by 2050. However, by 2100 we expect 358 (90% CI: 201 – 365) days per year where the daily high tide exceeds the moderate inundation threshold. As tidal predictions can be generated many years in advance (i.e. out to 2100) through harmonic analysis, coastal inundation frequencies in Sydney therefore become a predictable consequence of SLR and tides with minimal role for ocean, weather and climate variability (e.g. storm surges, ENSO).

This predictability also extends to much higher inundation thresholds, such as that associated with the current highest-on-record observation of 2.40 m (recorded 25 May 1974). Considering RCP 8.5, coastal inundation exceeding this current record is estimated to occur 234 (90% CI: 70 to 359) days per year by 2100. Whilst the 1974 observed sea level was associated with a surge of 54 cm, this level will be exceeded by astronomical tides alone as early as 2061 (90% CI: 2052 – 2075) under RCP 8.5. Over the 2081 – 2100 period, we estimate that tide-only inundation will occur at 97% (90% CI: 79% - 103%) of the rate of coastal inundation of this severity. This means that it likely, under RCP 8.5, by 2100 more that 60% of all days will have a daily high tide exceeding the present-day highest-on-record record observation. This demonstrates that even considering a threshold of highest-on-record sea level, coastal inundation will become almost exclusively driven by daily tides and become highly predictable many years in advance by the late-21st century. Whilst tidal amplitudes are expected to continue decreasing slightly (**Harker et al., 2019**; **Devlin et al., 2017**) these changes are negligible compared to SLR projections. For example, **Devlin et al. (2017)** estimate a 2.5 mm decrease in tidal range per meter of SLR. As such, there is very little uncertainty in these coastal inundation estimates beyond the well-quantified and documented uncertainty in mean SLR projections (**Kopp et al. 2019**).

In order to assess the robustness of the tidal inundation projections derived using the harmonic analysis method, similar timeseries were derived by applying the distribution-shifting method used for coastal inundation to a tidal prediction distribution over the 1986-2005 period. We derived low-impact, minor and moderate inundation frequencies under the 5th percentile, median and 95th percentile estimates of RCP 8.5 projected GMSL, under the distribution-shifting method to allow direct comparison to the nine tide-only inundation curves in **Figure 3** (black lines)**.** The distribution-shifting method could not reproduce interannual variability in tidal inundation frequencies due to the periodic nodal cycles not being resolved by resampling the climatology. Aside from this, the results were very similar suggesting that the different and independent methods of calculating coastal and tidal inundation are robust. We found the mean difference in total exceedances between the two methods to average 0.18% over the 2007-2100 period, with the largest difference being 0.42% and the least difference being 0.08%. The Pearson's correlation co-efficient between the two methods' resultant timeseries vary between 0.9969 and 0.9992 and slopes vary between 0.9574 and 1.0011. This reinforces the predictable nature of future coastal inundation, as SLR means inundation becomes increasing tidally driven.

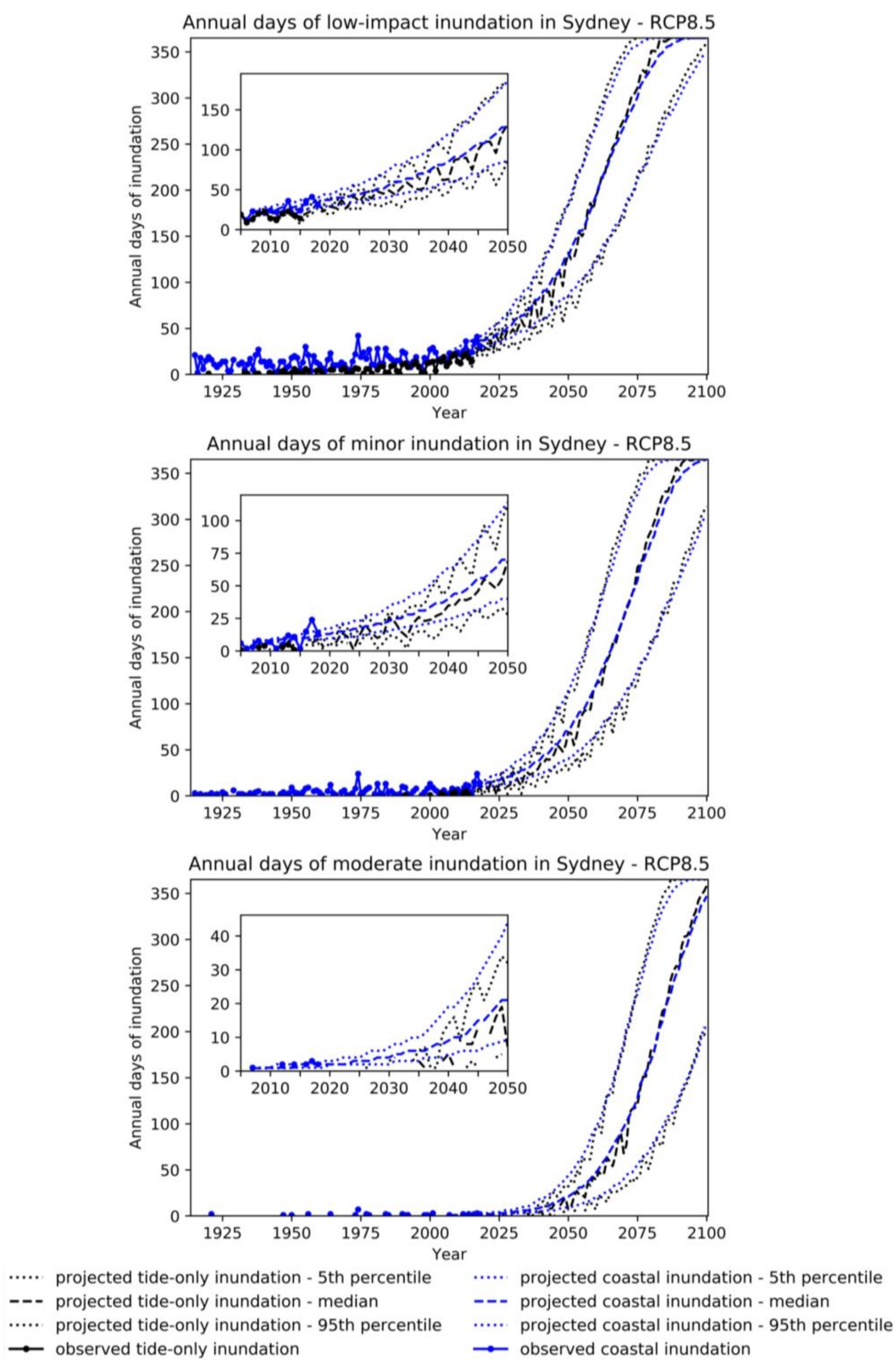

Figure 3: Future inundation frequencies in a historical context. *Observed frequency (solid line with markers) and projected future frequency under RCP8.5 (median estimate: dashed lines, 5th and 95th percentile estimates: dotted lines) of low-level (upper), minor (middle) and moderate (lower) coastal (blue) and tide-only (black) inundation.*

7 Implications for adaptation – emergence times, ARIs, emission reductions and predictability

A key application of this analysis is the ability to estimate emergence times, the first year when coastal inundation will occur at a specific frequency (e.g. weekly, daily, 100 days per year). This assists in further relating projections to impacts and provides insights into tipping points and the exponential nature of SLR impacts (**Taherkhani et al., 2020**). Emergence times are intended to be a tool for policymakers and impacts scientists to help contextualize the increasingly frequent coastal inundation that is expected in the next 80 years. The projected emergence year of various inundation frequencies, and whether these frequencies have already been reached, are presented in **Table 2**.

Global greenhouse gas emissions are following RCP 8.5 more closely than any other scenario (**Peters et al., 2013**; **Hayhoe et al. 2017**). Therefore, considering the differences between high and low emissions scenarios may also enable cost-benefit analysis of various adaptation and mitigation strategies (**Table 2**). For example, we found 8,100 days of moderate coastal inundation will occur in the 2020 – 2100 period under RCP 8.5 (median estimate). Following the lower-emission scenarios of RCP4.5 or RCP 2.6 resulted in 4,414 and 5,807 fewer days of inundation, reductions of 54% and 72%, respectively, considering median estimates. Crucially, we also found that frequent coastal flooding is inevitable in Sydney, even if rapid reductions of greenhouse gas emissions occurs and future emissions track closer to RCP4.5 or RCP2.6. For example, the emergence of weekly minor inundation is expected by the 2070s in the 95th, 50th and 5th percentile estimates in all RCP scenarios (**Table 2**). However, considering the median estimates, weekly minor flooding occurs by the 2050s in all scenarios. This means that adaptation, or acceptance of a higher inundation risk, will be necessary even with strong emission reductions.

Analyzing the differences between emergence times shows the acceleration in the frequency of inundation. Considering all minor and moderate inundation scenarios in **Table 2**, it takes an average of 19.9 years for the annual frequency to increase from 10 days per year to 30 days per year, but only another 12.3 years to reach weekly frequency, a 62% increase in rate. The higher the emission scenario the larger the increase in rate; 85% under RCP 8.5, 40% under RCP 2.6. These results are consistent with an earlier study (**Sweet & Park, 2014**) that identified 30 days per year as a tipping point for frequent coastal flooding in the United States. At 30 days per year frequency, the average ratio of coastal inundation days to tide-only inundation days is 0.76; at 52 days per year the ratio is 0.84. This further shows that future coastal inundation frequencies are more closely related to predictable tides and SLR than the frequency of large sea-level anomaly events (e.g. storm surges).

ARIs are commonly used to assess long-term risks of extreme sea-level events to inform policy (**Buchanan et al., 2017**; **McInnes et al., 2015**; **DECCW, 2010**). However, from a risk management perspective it is also instructive to consider future risks to assets impacted by present-day extreme sea levels. Therefore, we estimate future changes in the frequency of exceedance of 1914-2008 ARI levels (**DEECW, 2010**; **Figure 4**), using the same distribution-shifting methodology as above. This historical 1-year ARI is 2.16 m, the 10-year ARI is 2.27 m and 100-year ARI is 2.36 m (**DEECW, 2010**). Under RCP 8.5, we expect the daily maximum sea level to exceed the 1914-2008 1-year ARI 28 (90% CI: 12 – 52) days per year by 2050. By 2100 this increases to 349 (90% CI: 221 – 364) days per year. We find the 1914-2008 10-year ARI is exceeded 7 (90% CI: 3-19) and 306 (90% CI: 138-363) days per year by 2050 and 2100 respectively. The 100-year ARI is exceeded 2 (90% CI: 0.62 to 6) days per year by 2050 and 247 (90% CI: 82 to 359) days per year by 2100. This means that the 1914-2008 100-year ARI will be exceeded on 3,633 (90% CI: 1,059 – 7,560) days between 2020 and 2100, with over 99% of these days occurring after 2050 and over 90% after 2070. If the 1914-2008 100-year ARI is used to assess 21st century coastal inundation risk under RCP 8.5, the risk is underestimated by a factor of more than 3,600.

When considering lower emissions scenarios, large reductions are also seen in projections of exceedances of the historical 100-year ARI (**Figure 4c**). For example, the number of days where the 100-year ARI is exceeded is 39% lower under RCP 4.5, and 43% lower under RCP 2.6 compared to RCP 8.5 between 2020 and 2050, considering median estimates. However, the largest reductions are seen by comparing late-century projections. Reductions in the number of days where the 100-year ARI is exceeded post-2050 are 76% under RCP 4.5 and 90% under RCP 2.6, compared to RCP 8.5, considering median estimates.

The increasing predictability of the occurrence of coastal impacts demonstrated in this study is important for adaptation, as it will likely necessitate a shift in how society manages coastal risk and inundation events. For example, as illustrated by **Ray and Foster (2016)**, the precise timing and duration of when inundation due to tides will occur can be determined decades in advance. In some parts of the world, including Sydney, it is now not necessary to rely on only short-term sea-level forecast models (e.g. **Allen et al., 2018; Taylor and Brassington 2017**) to predict when impact-producing extreme sea levels may occur. However, these models will be important in forecasting the severity of inundation, especially in cases where sea-level anomalies are large. However, we have shown that even events that have been historically very rare will occur on hundreds of days each year, due to tides alone, by 2100. This means that dealing with the impacts of these events will require greater proactivity or adaptation rather than simply a responsive approach, dealing with consequences of presently unusual, extreme events as they occur.

These important findings for adaptation strategies all support the movement towards an impact-based approach for coastal risk assessments rather than considering sea-level allowances (e.g. **Hunter, 2012**; **McInnes et al., 2015**) or amplification factors of statistical metrics of extreme sea levels (e.g. **Buchanan et al., 2017**). In general, sea-level allowances tell the policymaker how high they need to elevate coastal assets to keep inundation risk constant. This is impractical for most purposes as elevating all roads, homes, business and recreational spaces is prohibitively expensive, or physically impossible. Using amplification factors, the policymaker would typically be confined to considering an event that is statistically extreme (e.g. the 100-year ARI), regardless of whether this level is associated with the impacts of concern. Emergence times and emission scenarios can provide information on the possible timeframes required for adaptation decisions to be made and can also enable the cost-benefit approach used to make these decisions in a more intuitive way. Consider the example of managed retreat of coastal communities (e.g. **Alexander et al., 2012**; **Wrathall et al., 2019**). If a local government or community has decided that they plan coastal retreat in the future, how to do they know when the time has come to relocate? Without an impact-based perspective and knowing the current and future frequency of impacts, there is a risk of relocating too early (unnecessary displacement of a community) or too late (location becomes uninhabitable and community disperses to other places). A solution within the framework of emergence times could be the setting of a threshold of a certain frequency of inundation of a certain severity (e.g. 30 days per year of moderate flooding) and planning for retreat by the time those conditions are projected to occur. This allows the unique circumstances and vulnerability (vertical land offsets, tidal range, storm frequency) of each location to be fully considered. More broadly, the utilization of the impact-based perspective directly enables a practical cost-benefit analyses of various adaptation and mitigation pathways when combining local asset (e.g. **Hanslow et al., 2018**) or economic loss (e.g. **Hino et al., 2019**) information.

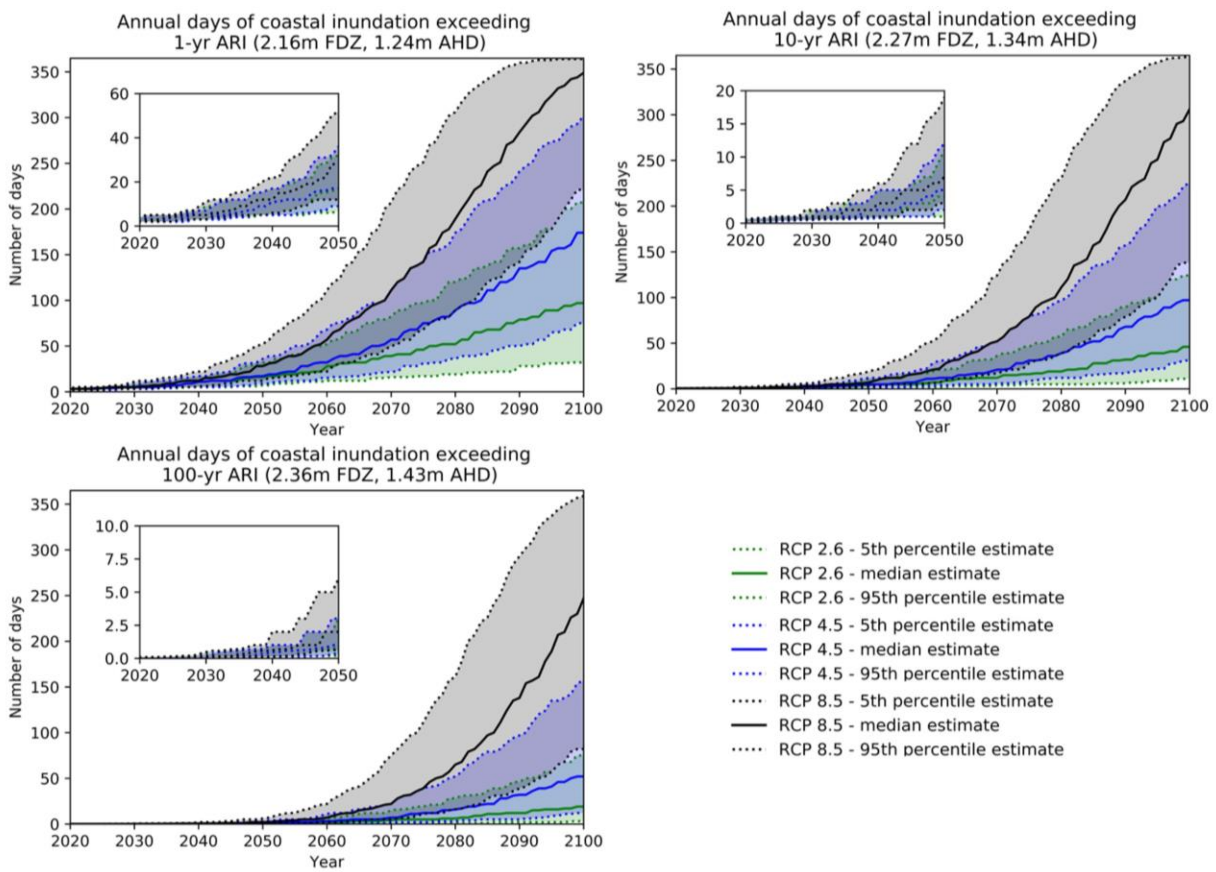

***Figure 4: Future projections of frequencies of present-day extreme sea levels**. Projections of the number of days when present-day (**DEECW, 2010**) 1-year (upper left), 10-year (upper right) and 100-year (lower left) Annual Recurrence Intervals (ARIs) are exceeded under RCP 2.6 (green), RCP 4.5 (blue) and RCP 8.5 (black) emission scenarios from 2020 – 2100. Shading indicates 90% confidence interval.*

***Table 2*: *Emergence Times*.** *Emergence times of regular coastal inundation (at different levels of impact) under different greenhouse gas emission scenarios using Representative Concentration Pathways (RCPs) with 5th, 50th (median) and 95th percentile estimates for each scenario. An asterisk (*) indicates that this frequency was observed prior to the projected emergence year.*

RCP	Inundation Level	Percentile	Days per year of inundation						
			10	30	52	100	183	300	365
2.6	Low-level	5th	2007*	2021*	2043	2074			
		50th	2007*	2015*	2031	2051	2078		
		95th	2007*	2011*	2025	2040	2060	2086	
	Minor	5th	2021*	2052	2078				
		50th	2015*	2038	2053	2074			
		95th	2011*	2030	2042	2057	2076		
	Moderate	5th	2067						
		50th	2047	2069	2085				
		95th	2037	2054	2065	2079	2099		
4.5	Low-level	5th	2007*	2021*	2042	2064	2091		
		50th	2007*	2015*	2032	2049	2069	2093	
		95th	2007*	2012*	2025	2040	2057	2075	
	Minor	5th	2021*	2049	2066	2086			
		50th	2015*	2038	2051	2066	2084		
		95th	2012*	2031	2042	2054	2069	2087	
	Moderate	5th	2059	2082	2097				
		50th	2046	2063	2073	2087			
		95th	2037	2052	2060	2071	2084		
8.5	Low-level	5th	2007*	2020*	2038	2054	2071	2090	
		50th	2007*	2015*	2030	2044	2059	2075	2094
		95th	2007*	2011*	2024	2037	2050	2064	2081
	Minor	5th	2020*	2044	2056	2069	2083	2099	
		50th	2015*	2035	2045	2057	2069	2083	2100
		95th	2011*	2029	2038	2048	2059	2071	2087
	Moderate	5th	2051	2066	2075	2085	2098		
		50th	2041	2054	2062	2071	2082	2094	
		95th	2034	2046	2053	2061	2070	2081	2094

8 Conclusions

We have shown that already-observed global mean sea level rise has caused frequencies of coastal inundation in Sydney, Australia to increase by a factor of nine. Further, we have found that this projected SLR will lead to increasingly frequent and increasingly predictable coastal inundation this century, with impacts such as flooding of roads, paths, parks and private property. Under high emissions scenarios, coastal inundation of at least minor level, which presently occurs approximately seven days per year, will occur on average weekly by 2050 and every day by 2100. Sea levels occurring during the majority of these inundation events will be higher than any of those observed in 104 years of tide gauge observations at Fort Denison. When considering sea levels associated with low-impact, minor and moderate inundation, exceedances of these thresholds become a predictable consequence of SLR and tides with minimal role for ocean, weather and climate variability. This finding is particularly important for considering the applicability of climate change science to adaptation decision to manage the impacts of climate change. Whilst weekly minor inundation is effectively unavoidable by the 2070s without adaptation measures, reduced global emissions can result in large reductions in the frequency of coastal inundation projected for Sydney, especially in the late 20th century. This analysis has highlighted that whilst still of some use, many current coastal risk assessment tools such as amplification factors and SLR allowances are inadequate to make and implement evidence-based policy at the local and regional scale. An impact-based perspective, such as that developed in this study, is therefore required to ensure that the on-the-ground impacts of SLR, which provide the motivation for such adaptation, can be more holistically considered in coastal risk assessments.

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B.H., S.M and R.R conceived the study, while B.H. carried out the analysis and wrote the initial manuscript draft. All authors contributed to the interpretation of results, the refinement of the analysis, and distillation of the manuscript.

Fort Denison sea level data is available from the GESLA-2 database (Woodworth et al. 2017) at https://www.gesla.org/, and from the University of Hawaii Sea Level Center database (Caldwell et al. 2015) at ftp://ftp.soest.hawaii.edu/uhslc/rqds. Botany Bay tide gauge data is available from the GESLA-2 database (Woodworth et al. 2017) at https://www.gesla.org/. Data for Patonga, Port Jackson, Port Hacking and Bundeena are described in Maddox (2019). Global mean sea level reconstruction data is described in Dangendorf et al., (2019). Global mean sea level projection data is described in IPCC (2019) and Oppenheimer et al. (2019).

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