Climatic drivers of extreme sea level events along the coastline of Western Australia

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Key Points

- Coastal sea level records were analyzed to isolate the processes responsible for extreme sea level events along Western Australia.
- Low-frequency contributions to sea level variability (seasonal and interannual) were large and comparable to tides and surges.
- Interannual variability explained clustering of extremes with strong links to global climate cycles.

Abstract

Accurate prediction of coastal flooding requires a detailed understanding of all individual contributions to sea level variability and how they interact to trigger Extreme Sea Level (ESL) events. In this study, we focus on the expansive (~10,000 km) coastline of Western Australia, a region that experiences large latitudinal gradients in met-ocean sources of sea level variability, as a case study to investigate the mechanisms responsible for ESLs and trends over the past 54 years (1966-2019). Using long-term sea level records from tide gauges and satellite altimetry, we explore how different contributions to sea level variability at different timescales (from hourly to interannual) interact to generate ESLs. We observe that all individual, non-tidal contributions to ESLs (i.e., atmospheric surge, seasonal and interannual variability) are of similar magnitude (of order 10 cm) along the entire coast, and comparable to the tidal variations in the micro-tidal southwestern region. The results reveal the important role that seasonal and interannual sea level variability plays in generating ESLs, with these low-frequency contributions being relatively large compared to typical global values. With mean sea level having risen by ~10 cm over this 54-year study period, sea level rise was also identified as making an increasingly significant contribution to observed increases in the frequency ESLs. Overall, due to the comparatively large magnitude of low frequency sea level contributions (seasonal and longer), the Western Australia coast provides a useful case study to investigate how sustained periods of elevated sea level will impact coastlines worldwide more generally in the future.
1 Introduction

Extreme sea level events (ESL) are a primary driver of coastal flooding along most coastlines worldwide (Wahl et al., 2017, Vousdoukas et al., 2018, Ruggiero et al., 2001, Rueda et al., 2017). An ESL event is usually triggered by positive interactions between multiple individual components of sea level variability that occur over a wide range of timescales (from seconds to decades and longer), including: tides, atmospheric surges, seasonal and interannual sources of water level variability, wave runup and long-term mean sea level trends (Merrifield et al., 2013, Serafin et al., 2017, Melet et al., 2018, Woodworth et al., 2019). The superposition of mean sea level rise (SLR), which has averaged ~3 mm year\(^{-1}\) globally in recent decades (but even exceeding 10 mm year\(^{-1}\) in some regions) (Church et al., 2013) makes ESL events more likely, and their frequency and magnitude have been increasing at varying rates worldwide (Vitousek et al., 2017, Vousdoukas et al., 2018). These regional variations in the atmospheric and oceanic drivers of individual sea level contributions can lead to substantial spatial and temporal variability in sea level variations that must be accounted for when forecasting ESLs for a specific coastal region (Menéndez and Woodworth, 2010). Therefore, to develop robust predictions of the probability of ESL events for a given coastal region first requires establishing a detailed understanding of the role that different sea level contributions play in driving ESLs (Serafin and Ruggiero, 2014, Méndez et al., 2007, Marcos and Woodworth, 2017, Losada et al., 2013).

The expansive (~10,000 km long) coastline of Western Australia experiences diverse sources of sea level variability along a latitudinal gradient due to regional variability in its dominant met-ocean drivers (McInnes et al., 2016, Pattiaratchi and Eliot, 2009) (Figure 1). The northwest coast experiences a large semi-diurnal tidal regime (range exceeding 8 m in some coastal regions), whereas the southwest coast experiences micro-tidal diurnal tidal conditions (mean range only ~0.5 m) (Eliot, 2012). These tidal ranges are also modulated at long (interannual) timescales by an 18.6 year lunar nodal (more important in the southwest) and the 4.4-year lunar perigean subharmonic (more important in the northwest). The influence of the 18.6 lunar nodal cycle can be especially important in the microtidal southwest where it can modulate tidal ranges by up to ~10 cm, equivalent to 20-30% of the mean tidal range (Eliot, 2010). The tropical northwest is one of the most active tropical cyclone regions in the world, experiencing an average ~5 cyclones each year (Goebbert and Leslie, 2010), which can episodically generate large atmospheric surges during the austral summer months (and transmit these along the coast to the south as coastally trapped waves).
Similarly, the southwest coast can also experience large surges during extra-tropical storms that are common in winter months (Eliot and Pattiaratchi, 2010). At longer timescales (seasonal-to-interannual), sea level variability along Western Australia is strongly influenced by its unique poleward-flowing eastern boundary current system (the Leeuwin Current) that generates seasonal sea level fluctuations of 10s of centimetres via geostrophic balances along the shelf, with a peak in sea level during the months of March to June (Feng et al., 2003, Ridgway and Godfrey, 2015). The strength of the Leeuwin Current can also vary strongly over interannual timescales due to the influence of the El Niño-Southern Oscillation (ENSO) cycle that transmits sea level anomalies between the Pacific and Indian Oceans (Wijffels and Meyers, 2004, Merrifield et al., 2012).

A number of global studies have mapped the relative importance of individual sea level contributions that contribute to ESLs around the world and have identified how ESL statistics have evolved over the past century (e.g., Losada et al., 2013, Merrifield et al., 2013, Menéndez and Woodworth, 2010). However, further work is needed to understand how individual sea level contributions will interact over time (on an event-by-event basis) to generate ESLs, which will importantly require improving understanding of the underlying regional oceanic and atmospheric processes that are responsible for driving ESLs now and in the future. The diverse sources, patterns and timescales (including phasing) of sea level variability along the Western Australia coastline, combined with the background long-term SLR trends, serves as a useful global case study to investigate how different atmospheric and oceanic processes interact to drive ESLs along a single continuous coastline.

In this study we analyse long-term tide gauge records over the past 54 years (1966-2019) and satellite altimetry observations (recent 26 years) to investigate how different oceanic and atmospheric processes interact to trigger ESL events along the Western Australia coastline. Using these observations, we assess how the frequency of ESL events have been changing over the past 54 years and isolate the mechanisms responsible for these trends. Through our analysis we identify how global climate cycles trigger interannual clustering of ESL events and how regional SLR is increasing the probability of extremes. We discuss implications for how the results can be used to help understand and forecast ESLs over different timescales.
2 Data and methods

2.1 Data sources

Historical sea level records were obtained at 7 locations along the Western Australia (WA) coastline based on tide gauge observations available from the WA Department of Transport (https://catalogue.data.wa.gov.au/dataset/tide-stations) (Figure 1). Although there are several additional tide gauges along the WA coastline, the 7 sites analysed here were chosen because they each contained a near-continuous record of hourly sea levels over the past 54 years between 1966-2019, with each site containing between 84-99% valid data over the study period. Sea levels from each tide gauge (available at an hourly interval) were adjusted from lowest astronomical tide to the Australian Height Datum (AHD), defined based on the mean sea level over the period 1966-1968, hence coinciding with roughly the start of the analysis period) using the offset from an adjacent survey benchmark. We note that using the historical tide gauge data, we are strictly assess relative sea level changes; however, in Section 3.1 and Supporting Information, we also consider absolute sea level trends, as estimated by satellite altimetry and find comparable agreement over the study period (see also White et al., 2014). By assessing sea level variations using tide gauge data, we focus specifically on identifying the mechanisms responsible for variations in total sea level (still water level) and thus do not consider potential wave-driven sources of coastal flooding (i.e. contributions from wave runup) in this study.

Regional patterns in annual (seasonal) and interannual sea level variability in the south-eastern Indian Ocean surrounding Western Australia were analysed using gridded monthly-averaged satellite altimetry data at 0.25° resolution available from SSALTO/DUACS (available at https://www.aviso.altimetry.fr/en/data) for the period 1993-2016. Relationships between interannual sea level variability and climate state (i.e. El Niño – Southern Oscillation) were evaluated based on the Southern Oscillation Index (SOI) and the Multivariate ENSO Index (MEI) (available at https://www.esrl.noaa.gov/psd/enso/). Other climate indices were also initially considered (e.g. the Dipole Mode Index associated with the strength of the Indian Ocean Dipole) but were found to be weakly correlated with interannual sea level variability and are thus not discussed here. Finally, atmospheric forcing variability (i.e. surface air pressure) were obtained over the period 1979-2019 using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis, available hourly on a 30 km grid (available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), with data extracted from each grid cell nearest each tide gauge.
2.2 Decomposition of sea level variability

The hourly sea level time-series $\eta(t)$ as a function of time $t$ at each tide gauge was decomposed into three fundamental contributions as:

$$\eta(t) = \eta_{MSL}(t) + \eta_T(t) + \eta_{NTR}(t)$$

where $\eta_{MSL}$ is the mean sea level trend over the record, $\eta_T$ is the tide contribution and $\eta_{NTR}$ is the non-tidal residual. A number of approaches have been proposed to decompose the contributions of coastal sea level variability (e.g., Merrifield et al., 2013, Melet et al., 2018), which are generally similar, but can use subtly different definitions and analysis approaches. In this study we adopt a similar approach to Serafin et al. (2017). The mean sea level trend contribution ($\eta_{MSL}$) was determined from a linear regression of the annual-averaged sea level over the record. To determine the contribution of the astronomical tide ($\eta_T$), a tidal harmonic analysis using UTIDE (Codiga, 2011) was applied using 63 constituents, with the annual ($S_a$) and semi-annual ($S_{sa}$) tidal constituents removed since the astronomical contribution of these long-period constituents are negligible (order 1 mm at these latitudes) (Lisitzin, 1974) relative to the much larger (order 10 cm) annual contribution of non-tidal seasonal sea level variations forced by large-scale atmospheric and oceanic processes (discussed further below).

The non-tidal residual sea levels ($\eta_{NTR}$) were thus obtained by subtracting the mean sea level trend ($\eta_{MSL}$) and tidal contribution ($\eta_T$) from the measured sea level time-series ($\eta$).

The non-tidal residual sea level time-series ($\eta_{NTR}$) was then further decomposed as:

$$\eta_{NTR}(t) = \eta_A(t) + \eta_i(t) + \eta_{SS}(t)$$

where $\eta_A$ is the seasonal (annual) contribution, $\eta_i$ is the interannual contribution, and $\eta_{SS}$ is the high-frequency ‘storm surge’ contribution. The seasonal contribution $\eta_A$, including the amplitude and phase, was obtained by fitting annual (12 month) and semi-annual (6 month) harmonics to the $\eta_{NTR}$ time-series using a least squares approach, with the semi-annual harmonic included to account for some nonlinearity of the seasonal cycle (Merrifield et al., 2013). The interannual variability ($\eta_i$) was defined by subtracting the seasonal contribution ($\eta_A$) from $\eta_{NTR}$ and then monthly-averaging the resulting data to remove daily to weekly variations (e.g., due to atmospheric surges, etc.) (Serafin et al., 2017).
The ‘storm surge’ contribution ($\eta_{SS}$) was defined as the remaining high frequency (i.e. daily to weekly) contributions to the non-tidal residual sea levels, which are commonly associated with atmospheric storm surges at weather band frequencies of order day-to-week. To reduce the potential for some tidal contamination that is not completely removed in the $\eta_{NTR}$ signal, a 40-hour moving average filter using a Hamming weighting function was applied to the $\eta_{SS}$ time-series. We note that while $\eta_{SS}$ will be referred to as a storm surge contribution based on the frequencies of this variability (as is commonly done), it is important to acknowledge that other high frequency sources of sea level variability (order weekly or less) would be incorporated in this contribution, e.g. coastally-trapped waves, high-frequency variability in the Leeuwin Current (including encroaching eddies), etc. (Woodworth et al., 2019).

Local atmospheric contributions to storm surges are, in general, influenced by surface air pressure fluctuations (i.e. the ‘inverse barometer effect’) and wind stress effects (wind setup). While the static sea level response to atmospheric pressure changes (inverse barometer effect) can be readily estimated from the hydrostatic pressure adjustment as 

$$\eta_{IB} = \left( \bar{P}_{atm} - P_{atm} \right) / \rho g$$

(Ponte, 1994), where $P_{atm}$ is atmospheric pressure (with the overbar denoting the long-term mean), $\rho$ is the seawater density, and $g$ is gravity, the response to wind stresses is often much more complicated due to how it depends on coastline orientation to winds, tidal currents, Coriolis, local bathymetry, and other factors (Bode and Hardy, 1997). Given that a detailed investigation of the mechanics of storm surge responses is beyond the scope of this study, we instead adopt a simple approach that explores the links between $\eta_{SS}$ and the local atmospheric pressure variability, given that atmospheric pressure and wind variability tend to be closely related. For consistency with the definition of $\eta_{SS}$, high-frequency fluctuations (e.g. diurnal and shorter) were filtered from the hourly pressure time-series by applying the same 40-hour moving average filter (Hamming weighting function). A lagged correlation analysis between atmospheric pressure and $\eta_{SS}$ was then applied at each site, with significance levels computed based on the effective degrees of freedom computed from the record length divided by the autocorrelation time-scale (Emery and Thomson, 2001). In addition, the dominant time-scales of atmospheric pressure and surge variability were assessed by computing variance-preserving spectra $\sigma^2(f)$. 

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spectral density), expressing how signal variance is distributed in logarithmic frequency space (Emery and Thomson, 2001).

Finally, the hourly reconstructed sea level time-series (sum of all separate contributions, $\eta_M + \eta_t + \eta_s + \eta_{SS}$) were compared to the original sea level records to confirm that the approach accurately captured the observed sea level variability, including extreme events. The residual error for all sites, defined based on computing the Normalized Root Mean Squared Error (normalized by the local range of the water level records) ranged between 1-3% across all sites (Table 1).

2.3 Extreme event analysis

Extreme sea level events were defined as the top 2% of the hourly sea level values recorded at the tide gauges within the record that were separated by at least 3 days to avoid duplicate counting of individual events. For each extreme event, the instantaneous breakdown of the individual sea level contributions that were responsible for the event were recorded. Over the 54-year period, the annual frequency of extreme events was evaluated, as well as the mean contribution of individual sea level contributions to the extreme events occurring each year.

To assess how the probability of extreme events varied over the record, a nonstationary extreme value analysis was used based on a Generalized Extreme Value (GEV) distribution for annual maxima values:

$$
\Psi_{GEV}(x \mid \xi) = \exp \left[-\left(1+\xi(x_c)\left(\frac{x-\mu(x_c)}{\sigma(x_c)}\right)\right)^\frac{1}{\xi(x_c)}\right],
$$

for $1+\xi\left(\frac{x-\mu}{\sigma}\right) > 0$

where $\mu(x_c)$ is the location parameter, $\sigma(x_c) > 0$ is the scale parameter, and $\xi(x_c)$ is the shape parameter, which are (in general) allowed to vary as a function of a covariate $x_c$ (e.g. time). By comparison, in a conventional stationary extreme value analysis the parameters $\mu$, $\sigma$, and $\xi$ are treated as constants, which assumes no changes in the statistical properties that govern the frequency of extremes over time. The analysis was specifically implemented using the Process-Informed Nonstationary Extreme Value Analysis (ProNEVA) tool, which estimates the parameters (including uncertainties) using a Bayesian approach with Markov Chain Monte Carlo sampling (refer to Ragno et al. (2019) for details). While it is possible to account for the nonstationary behaviour by assuming various functional relationships with $x_c$.
for the location, scale and shape parameters, we chose to assess simple linear functions of these parameters with covariate $x_c$ given the length of the data records. Given that the analysis was based on block (annual) values, we focused on assessing how longer-term (> 1 year) sources of variability in the records influenced exceedance levels and return intervals, focusing specifically on time ($t$) and climate indices (i.e. SOI) as the co-variates $x_c$. Therefore, the analysis first focused on investigating how exceedance levels and return intervals varied in a nonstationary analysis with time over the 54-year record, in which the location ($\mu$) and scale ($\sigma$) parameters were modelled as linear functions of time and the shape ($\xi$) parameter was treated as constant following Ragno et al. (2019). To investigate how exceedance levels and return intervals varied with SOI, we performed the nonstationary analysis on the linearly-detrended annual maximum sea level data with SOI as the co-variates, and also treated the location and scale parameters as linear functions and the shape parameter as constant.

3 Results

3.1 Contributions to sea level variability

To illustrate the sources of sea level variability that occur along the WA coastline, Figure 2 shows an example of the decomposition of the individual sea level contributions at Fremantle (FM). Over this 54-year period, each individual contribution to sea level variability at FM is of the same order of magnitude (10 cm). At FM, the relative mean sea level rise was 13 cm over the 54 years (~2.5 mm year$^{-1}$ on average), with other sites experiencing a similar rise of 8-13 cm over this period (Table 1). We note that in Supporting Information (Table S1), we also place these relative rates into absolute rates of sea level change through trends calculated from the satellite altimetry record during a shorter period when data is available (1993-2019), in which we generally obtain comparable rates among all sites (within uncertainty estimates). Interannual contributions to sea level variations are large (maximum range up to ~40 cm), with seasonal variations also significant (~20 cm range) (Figure 2b). The monthly maximum tidal elevation varies between ~20-40 cm (Figure 2e), with an interannual modulation of the tidal range (~10 cm) apparent that is associated with 18.6 year lunar nodal cycle (Haigh et al., 2011, Eliot, 2010). Storm surge contributions at FM extend up to 50 cm (Figure 2d).

The tidal contribution ($\eta_T$) varies along the coast, but is generally small along the western and southern coasts (i.e. at sites ES-CN), with a typical range (defined as $2\sigma_T$, where
\( \sigma_T \) is the standard deviation of the tidal contribution) being \( \leq 50 \) cm (Table 1). A minimum tidal range occurs in the southwest (FM and BU sites) where the typical range is only 32 cm. The tidal contribution becomes considerably larger in the northwest at PH, with a typical range of \(~250~\) cm.

The storm surge contribution (\( \eta_{SS} \)) generally follows an opposite pattern to the tide, with the typical range of surge variability largest along the western and southern coasts (typical range 20-23 cm), and decreasing in the northwest (CN and PH) (Table). At PH in the tropics, the typical surge range is only 12 cm; however, the site also occasionally experiences the largest surge contributions during episodic tropical cyclone events. Variance preserving spectra of the storm surge contribution show that the variance is most concentrated at time-scales of 1-2 weeks (Figure 3b). The variance in atmospheric pressure shows a general decreasing trend from south to north, with the variance peaks at similar 1-2 week time-scales, which falls within the ‘synoptic weather band’ that is known to be dominant at 1-2 weeks along the Western Australia coast (e.g., Lowe et al., 2012, Smith et al., 1991). The peaks in atmospheric pressure variance occur at slightly shorter period, which is consistent with the order hours-day lag between atmospheric pressure and surge that is often observed at other coastlines (Ponte, 1994, Woodworth et al., 2019). The static sea level response (\( \eta_{IB} \), inverse barometer effect) predicted from local atmospheric pressure anomalies (see Section 2.2) is strongly correlated with the storm surge contribution (\( \eta_{SS} \)) along the southern and southwestern coasts from ES to GN (\( R_{IB} \approx 0.7-0.8 \)), but decreases to \( R_{IB} \approx 0.3 \) in the northwest (PH) where the surge variance is also smallest (Figure 3b). However, a linear regression of \( \eta_{IB} \) and \( \eta_{SS} \) (Supporting Information Figure S2) indicates that the simple sea level response estimate of \( \eta_{IB} \) underpredicts the absolute magnitudes of \( \eta_{SS} \) by 50-60% in the south and southwest (ES to FM) and by as much as 80% in the northwest (~80%). Therefore, while the consistency in time-scales between the atmospheric variability and \( \eta_{SS} \) indicates that local atmospheric forcing is a major driver of the storm surge contribution, other more complex sea level responses (e.g. dynamic sea level responses to the atmosphere, wind setup, etc.) are also likely major contributors to \( \eta_{SS} \). Finally, variability in the surge contribution each year (annual standard deviation) is generally poorly correlated with SOI (Table 3), with correlations \( R_{surge-SOI} \leq 0.2 \) at sites in the south and southwest (ES to FM) and reaching only 0.35 in the north (PH). For the southwestern region of Australia in particular, inter-annual
variability in storm activity is known to be shaped by other climate indices, especially the Southern Annular Mode (Raut et al., 2014, Cuttler et al., 2020).

The seasonal sea level cycle (ensemble-averaged monthly mean sea levels) reaches maximum values ~3 months earlier along the north-western coast (PH) during the austral autumn (Feb-Mar), compared to along the south-western and southern coast (from FM to ES) where maximum values occur during the austral winter (May-June) (Figure 4a). For sites from GN and further south, the frequency of extreme events per month displays a similar pattern to the monthly mean water levels (Figure 4b), with highest frequencies occurring during approximately June. Sites further north (PH and CN) are more likely to experience extreme events earlier in the year. For CN, this annual pattern of the frequency of extreme events roughly follows the annual sea level cycle. However, for PH there are two periods each year when there is an enhanced probability of an extreme event: Mar-Apr and Sept-Nov. The Mar-Apr peak coincides with the peak in the monthly mean water level at PH (similar to the other sites). The anomalous peak in Sept-Nov is due to the dominant role of tides at PH, with a cycle of perigean spring tides (i.e. “King Tides”) occurring during this time of year that acts to slightly elevate the spring tidal range by 10-20% relative to annual mean values (not shown).

The regional patterns in the seasonally-averaged sea level anomalies obtained via satellite altimetry (Figure 5) indicate that the annual sea level cycle is amplified adjacent to the coast (within a few 100 km from the coast) and shows a generally consistent response along the entire WA coast (for individual monthly-averaged maps refer to Supporting Information Figure S3). There is some phase lag evident in the minimum / maximum values between the northwest and southwest sections of the coast (with an abrupt shift occurring near the North West Cape near 22°S); which is particularly pronounced during the austral summer months (Dec-Feb) (Figure 5a). These patterns are consistent with the monthly-averaged sea level records (Figure 4a), where at CN and PH (either near or to the north of the North West Cape) the annual sea level cycle leads the sites in the southwest by ~3 months.

Long-term variations in sea level (annual-averaged, detrended values) are substantial and approximately in phase along the entire coast (Figure 6b). These variations are strongly correlated with SOI (Figure 6a) with $R_{SOI} \approx 0.8$ (Table 1), with elevated water levels during La Niña periods (i.e. SOI > 1) and lower water levels during El Niño periods (i.e. SOI < -1). The interannual variations in water level are similarly strongly correlated with MEI ($R_{MEI} \approx -0.8$, Table 1). Given the consistency in relationship between SOI and MEI, all results that follow will focus on SOI. Maps of regional sea level averaged during La Niña (SOI > 1) and El Niño
(SOI < -1) periods reveal a large-scale response (scales of order 100s to 1000s of km) within the south-eastern Indian Ocean off Western Australia (Figure 7).

### 3.2 Drivers and trends of extreme sea level events

Using Fremantle (FM) again as an illustrative example, Figure 8a reveals a clustering of years with a high frequency of extreme events, followed by a clustering of years when only a minimal number (or no) extreme events occur (individual results showing the trends at all sites are included in Supporting Information Figures S4-S9). There is also an apparent increasing trend in the annual frequency of extreme events over the 54-year record that becomes apparent in 5-year moving-average. There were many years prior to approximately 2002 when no extreme events occurred (12 years out of this 36-year portion of the record) (Figure 8). However, after 2002, extreme events have been occurring each year (2-5 events per year based on the 5-year moving average), including reaching a maximum of 10 events in 2011 that coincide with a large La Niña.

For every year when at least one extreme event occurred, it is possible to compute how individual sea level components contributed to an extreme event (expressed as the mean percent contribution to the extreme events for each year). At FM, both tide and surge make the greatest contribution to each extreme event (typically averaging 30-50% and 20-30% for tide and surge, respectively, over the record). The fact that tides make an important contribution at FM despite its microtidal range simply means that the extremes (defined based on hourly water levels) tended to occur within a day during higher stages of the tidal cycle. Over the 54-year period, the mean sea level trend makes an increasingly important contribution to extreme events, contributing ~15% by the end of the record. The seasonal sea level cycle contributes on average 10-20% to the extreme events, and while periodic, indicates that the extremes tended to occur during elevated portions of the cycle, consistent with the phasing agreement between Figure 4a and b. The interannual contribution, while generally small (on average contributing up to 20% over the record), plays an important role in triggering the clustering of extreme events. Years with a relatively high (low) number of extreme events tend to occur when there are positive (negative) interannual water level contributions. An example of a strong positive interaction occurred during the 2011-2013 period, when a strong La Niña occurred that elevated mean water levels along the WA coast; when combined with the mean sea level rise that occurred since 1966, this generated a high frequency of extreme events during 2011-13. Conversely, during the strong El Niño during 2015-16 a strong negative interaction occurred, where the reduced interannual mean sea level...
contributed to reducing the frequency of extreme events, thus playing a role in countering the influence of mean sea level rise.

We note that interannual variations in the frequency and magnitude of ESLs within a given year may also be influenced by interannual modulations of the tidal range over the record due to the 18.6 year lunar nodal cycle (Figure 2e). To quantify the influence of these tidal modulations relative to interannual mean sea level variations, we assess how both the annual maximum sea level and the annual number of ESL events correlates with both the interannual contribution to mean sea level and the phase of the 18.6 year tidal cycle (the latter based on computing the annual standard deviation of the tidal contribution to define a tidal range envelope). The annual maximum sea level is moderately correlated with the interannual sea level contribution ($R_{\text{interannual}}$ ~0.3-0.5 across the sites, Table 2), but not significantly correlated with the tidal range envelope ($R_{\text{tide}}^\text{env}$ generally <0.2, $p > 0.05$, Table 2).

The annual number of ESLs is even more strongly correlated with the interannual sea level contribution ($R_{\text{interannual}}$ generally 0.5-0.6, Table 2), but again not significantly correlated ($p > 0.05$) with the tidal range envelope ($R_{\text{tide}}^\text{env}$ generally <0.2, Table 2).

Some regional differences in the contributions to extreme events are also apparent along the WA coast, which are reflected in the mean contributions to the annual maximum event (Figure 9a) as well as the overall (single) maximum event observed over the 54-year period (Figure 9b). In the far north at PH where the mean tidal range is large (~3 m), tides make the greatest percent contribution to an annual maximum sea level event (Figure 9a). In the southwest from GN to BU, the contributions of both the seasonal and interannual water level variations are relatively large (~20% contribution). At these locations, tides make a lesser contribution and atmospheric surges a greater contribution. The patterns of the contributions to the total (overall) maximum event are generally very similar (Figure 9b).

### 3.3 Changes to the probability of extreme events

Using data from FM, Figure 10a shows how the return level curves (computed using the nonstationary extreme value analysis described in Section 2.3) have changed at regular intervals during the 54-year period, revealing a continuous increase in the return level magnitudes at a given return period over time. This includes a projected return level curve at 2048 assuming trends in the ESL statistics continue at the same rate (Figure 10a). These results can also be expressed as effective return level curves that show how events of a given return period evolve over the record (Figure 10b). For example, based on these lines of
constant return period, the 50-year event predicted in 1968 near the start of the record (1.12 m AHD) is approximately equivalent to a 10-year event in 2018.

Given the strong relationship between interannual variability in sea level and ENSO state, it is also possible to investigate how return level curves are predicted to differ between La Niña and El Niño years, i.e. by replacing time with SOI as the co-variante (Figure 10c). There are large differences in the return level curves between periods classified as having La Niña (SOI>1) and El Niño (SOI<1) conditions. The 50-year event during El Niño conditions is equivalent to a ~5-year event during La Niña conditions (Figure 10d). Interestingly, the vertical offset in the return level curves between El Niño (SOI<1) and La Niña (SOI>1) conditions (difference in return level magnitudes of $\Delta RL_{\text{ENSO}} \sim 0.2$ m) is larger than the differences to the curves of $\Delta RL_{50\,\text{yr}} \sim 0.1$ m that have occurred over the past 54 years due to mean sea level rise (Figure 10c); and in fact more comparable to the difference predicted between the start of the record and at 2048 ($\Delta RL_{40\,\text{yr}} \sim 0.2$ m).

4 Discussion

By decomposing the individual contributions to sea level variability within tide gauge and satellite altimetry records, our results have revealed how different atmospheric and oceanic processes (over a wide spectrum of timescales) contribute to driving ESL events along the Western Australia coastline. The relative importance of these processes varies spatially along this extensive stretch of coastline, in part due to large differences in tidal range between the north and south, as well as moderate differences in storm surge variability (Table 1). The appreciable magnitude of the low frequency (seasonal and interannual) sources of sea level variability is particularly noteworthy and more uniformly distributed along the entire coastline, which leads to sustained periods of anomalous sea level (up to 10s of centimetres) that can have a profound influence on the occurrence of ESLs. These low frequency sea level contributions are especially important along the microtidal southwestern region where they are of comparable magnitude to the tide.

The seasonal and interannual fluctuations in mean sea level are closely linked to the dynamical state of the Leeuwin Current, thus revealing an interesting connection between the probability of ESL events with the large-scale dynamics of an ocean boundary current system in this region. This contribution of sea level variability arises from remote generation sources of the Leeuwin Current in northern Australia that are primarily driven by the seasonal reversal of monsoon winds that initially creates a large pulse of elevated sea level within the

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Gulf of Carpentaria that then propagates counter-clockwise around Australia towards Tasmania; as well as a secondary contribution from the large seasonal cycle of surface heat fluxes on the northwest shelf of Australia (Ridgway and Godfrey, 2015). The amplitude of the seasonal sea level cycle along Western Australia (0.10-0.15 m) is thus relatively large when placed in a global context; however, there are also other regions that experience seasonal cycles of similar magnitude, e.g. off India (Dhage and Strub, 2016) and in areas within the South China Sea (Amiruddin et al., 2015). However, for the southwestern region of Australia, where the equivalent mean tidal amplitude (i.e. half of the range) is only ~0.2 m, these seasonal water level fluctuations make a significant contribution to the occurrence and timing of ESL events each year.

Interannual sources of sea level variability were likewise found to play a major role in driving the clustering of ESLs within particular years, which can be associated with two main drivers: 1) extended periods of anomalous mean sea level driven by the ENSO cycle and 2) the phase of the 18.6 year lunar nodal tidal cycle that regulate the maximum tidal ranges that occur in a given year. Our results indicate that the former played a much more important role in driving interannual variability in ESLs (Table 2) over this 54-year study period. ENSO is a dominant global driver of interannual climate variability, which drives particularly large sea level anomalies (±20 – 30 cm) across the tropical Pacific that increases coastal flooding risk (Muis et al., 2018). A portion of the energy associated with these Pacific sea level anomalies becomes transmitted into the Indian Ocean through the Indonesian seas, where coastal Kelvin waves transmit these anomalies along a waveguide along the WA coast (Cai et al., 2005), which in turn modulates the strength of the Leeuwin Current (Feng et al., 2003). Our results indicate that these ENSO-driven sea level anomalies have a particularly profound influence on coastal flooding risk along the micro-tidal regions of the southwest coast of WA; for example, increasing the 100-year extreme sea level event by ~20% between El Niño and La Niña conditions (Figure 10d).

The interannual modulation of tidal range driven by the 18.6 year lunar nodal tidal cycle is known to be relatively large along the southwestern WA coast (Eliot, 2010, Haigh et al., 2011), causing tidal ranges to vary by 20-30% (Figure 2e). This cycle last peaked along this coast in ~2006 and subsequently reached a minimum near the end of the study period in ~2015 (also coincident with El Niño conditions). However, the results suggest that the phase of the 18.6-year tidal cycle was a poor predictor of the likelihood of ESLs occurring within a given year, with interannual variations being much more strongly associated with ENSO-driven mean sea level variability. Nevertheless, we do acknowledge that the length of the 54-
year record may also mask a secondary role of decadal variability in tides, given the clearly large influence of ENSO (including major La Niña and El Niño during the latter decade of the record). Looking into the future, the next peak in lunar nodal tidal cycle will occur in ~2025, at which time any elevation of mean sea level due to La Niña conditions may put the WA coastline at elevated coastal flooding risk.

Over the 54-year study period, mean sea level rose by a total of 8-13 cm along the WA coastline (Table 1), or at an average rate of ~2-3 mm year\(^{-1}\), which is comparable to the global mean rate of sea level rise over the same period (Church et al., 2013). This mean sea level trend made an increasingly important contribution to ESL events, especially along micro-tidal regions of the WA coast (i.e. from Fremantle to Esperance) (Figure 8b, Figure 9b). By the end of the study period (end of 2019), ~20% of the contribution to ESL events at Fremantle can be attributed to the mean sea level rise over the period. Based on the nonstationary return level analysis for Fremantle (Figure 10b), the mean sea level trend has increased the effective return level for the 100-year event by ~10%.

While the present study focuses on a hindcast analysis of the mechanisms responsible for driving ESLs (including temporal and regional trends), the results can provide insight into the trajectory of ESLs into the future. Given that the various individual contributions to ESLs can be forecast with varying degrees of skill over different timescales, this has important implications and provides opportunities for predicting coastal flooding risk for this region into the future. Given the importance of low-frequency (seasonal and longer) contributions to ESL events along this coast, many of these contributions can be accurately forecast far in advance. At decadal timescales, the role of long-term variations in tidal range driven by the 18.6-year lunar nodal tidal cycle can be accurately forecast indefinitely into the future based on tidal harmonics alone. Similarly, mean sea level rise can be forecast relatively accurately in the near-term (e.g. of order decades) (Church et al., 2013). The important role of seasonal to interannual sea level contributions to ESLs, also provides some unique opportunities for making robust forecasts of periods of elevated coastal flooding risk well in advance. Miles et al. (2014) and McIntosh et al. (2015) evaluated the ability of a global sea level forecast model (spanning Pacific and Indian Oceans) to predict sea level anomalies at various lead times (assessing periods up to 8 months in advance in those studies). These studies specifically identified the WA coastline as one of a few regions worldwide having a high forecast skill (correlation skill >0.6) over long lead times of 6-8 months (see Figure 3 in Miles et al. (2014) and Figure 3 McIntosh et al. (2015)). Of all mechanisms considered, only the atmospheric surge contribution cannot be forecast with long lead times, given its dependency on resolving
individual storms in the weather band that can generally only be robustly predicted up to order a week in advance. Nevertheless, storm surges alone are not primarily responsible to ESL events along this coast, contributing on average ~25% across all sites to an annual maximum event (ranging from a 10-40% contribution depending on site). On this basis, the development of future coastal flooding risk models (including practical Early Warning Systems) for this coast, could take advantage of the fact that most of the processes responsible for ESLs can be accurately predicted months in advance, which could then combine probabilistic approaches to incorporate uncertainty around the storm surge contribution.

5 Conclusions

The analysis of long-term water level observations along the extensive Western Australia coastline has revealed how different sources of water level variability interact to regulate the frequency and trends in ESL events, including how regional gradients in the dominant met-ocean drivers of such events (e.g. ranging from macrotidal in the north to microtidal in the south) explain patterns along the coast. Long-term sources of water level variability (seasonal to interannual) were identified as making particularly large contributions to ESLs, which are both large (relative to typical global averages) and can make a significant contribution to the total sea level variability, especially in the southwestern region of Australia where tidal ranges are small (microtidal). Within this southwestern region, all of the major individual contributions to ESLs (tide, surge, seasonal and interannual) tend to vary by a similar magnitude (of order 10 cm, Table 1), making it important to understand how all of these factors contribute to historical trends in ESLs and how the frequency of ESLs will likely change into the future. With sea level rise over this 54-year study period (~10 cm) now of similar magnitude to other sources of cyclic water level variability, sea level rise was also identified as making an increasingly significant contribution to modern trends in ESLs. Overall, due to the comparatively large magnitude of long-term sea level contributions (seasonal, interannual and longer), the Western Australia coast can provide a useful case study of how sustained periods of elevated sea level will impact coastlines worldwide more generally.

While the focus of this study has been on examining the historical drivers of ESLs, the results provide a foundation for the development of new tools to predict how the frequency of ESLs will evolve in the future. Given the capacity to forecast these individual contributions to sea level in advance range from effectively limitless (i.e. tides and the annual
cycle) to order days-to-weeks (i.e. surges that depend on resolving individual storms), these uncertainties in individual contributions will influence uncertainties in predictions of ESLs in very different ways. Recent developments in tools to predict future coastal flooding by ESLs (e.g., Vousdoukas et al., 2018, Anderson et al., 2019, Vitousek et al., 2017) describe promising approaches to integrate deterministic predictions with probabilistic forecasts of individual contributions (each with varying levels of forecast skill). As the present study focused only on drivers of ESLs based on offshore total sea level (still water level) variability, there are also opportunities to consider all contributions to total water level variability at the coastline by incorporating predictions of wave runup (e.g., Serafin et al., 2017, Melet et al., 2018). Given the complex nature of the Western Australia, with numerous offshore reef systems (ranging from coral to rocky) that provide significant sheltering from offshore waves, the development of tools that include wave runup will be more complicated compared to open sandy coastlines where such analysis has previously focused.

Finally, the knowledge developed to understand coastal flooding risk along Western Australia can support future studies of the drivers of erosion along this coast, given the strong connections between extreme sea levels and coastal erosion. Recent studies of coastal erosion along Western Australia have highlighted the important role that seasonal and interannual water levels can play in driving shoreline variability (Segura et al., 2018). This is especially the case for the large portion of the Western Australia coastline that receives some degree of wave attenuation from reefs and other coastal topography, which in turn reduces the influence of wave-runup on beach erosion cycles (from individual storm to seasonal variations). Overall, the Western Australia coastline can act as a valuable test bed for assessing how coastlines generally respond to sustained sea level changes, due to the major influence of long-term sources of sea level variability.

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8 Tables

Table 1. Summary of the sea level variability statistics by individual contribution, the residual of the reconstructed sea level (Normalised Root Mean Square Error, NRMSE), and correlation of annual-averaged sea level variability with climate indices ($R_{SOI}$ and $R_{MEI}$ for SOI and MEI, respectively). The MSL ‘Trend’ represents the mean sea level rise that has occurred over the 54-year study period. ‘Max range’ represents the difference between the maximum and minimum sea level over the full record. ‘Typical range’ denotes a representative range based on $2\sigma$, where $\sigma$ is the standard deviation of the sea level variability over the full record.

| Site | MSL Trend [cm] | Seasonal Max [cm] | Typical range [cm] | Interannual Max [cm] | Typical range [cm] | Tide Max [cm] | Typical range [cm] | Surge Max [cm] | Typical range [cm] | Residual NRMSE (%) | $R_{SOI}$ | $R_{MEI}$ |
|------|----------------|------------------|-------------------|---------------------|-------------------|---------------|-------------------|---------------|-------------------|-----------------|----------|-----------|
| PH   | 12             | 23               | 15                | 38                  | 15                | 679           | 260               | 146           | 12                | 2.6%            | 0.81     | -0.77     |
| CN   | 13             | 24               | 16                | 50                  | 15                | 148           | 53                | 113           | 17                | 2.4%            | 0.68     | -0.79     |
| GN   | 10             | 24               | 16                | 49                  | 14                | 103           | 34                | 103           | 22                | 1.5%            | 0.85     | -0.81     |
| FM   | 13             | 21               | 15                | 43                  | 13                | 97            | 32                | 95            | 22                | 1.4%            | 0.85     | -0.80     |
| BU   | 8              | 23               | 16                | 40                  | 12                | 96            | 32                | 102           | 23                | 1.5%            | 0.83     | -0.80     |
| AL   | 8              | 20               | 14                | 32                  | 11                | 120           | 40                | 77            | 20                | 1.4%            | 0.83     | -0.79     |
| ES   | 9              | 17               | 12                | 30                  | 11                | 119           | 41                | 98            | 23                | 1.5%            | 0.78     | -0.75     |
Table 2. Relationships between annual ESL properties and long-term (>annual) sources of sea level variability. Correlations are expressed for both the annual maximum sea level and the annual number of extreme events, which are related to the annual-averaged interannual sea level contribution and the annual-averaged state of the tidal envelope, $R_{\text{interannual}}$ and $R_{\text{env}}^\text{tide}$, respectively. Italicized correlations are significant to 95%; bold correlations to 99%.

| Site | $R_{\text{interannual}}$ | $R_{\text{env}}^\text{tide}$ | $R_{\text{interannual}}$ | $R_{\text{env}}^\text{tide}$ |
|------|-----------------|-----------------|-----------------|-----------------|
| PH   | 0.34            | -0.20           | 0.37            | -0.15           |
| CN   | **0.40**        | -0.07           | **0.63**        | 0.02            |
| GN   | **0.50**        | 0.24            | **0.62**        | 0.16            |
| FM   | **0.44**        | -0.01           | **0.65**        | 0.08            |
| BU   | 0.31            | -0.05           | **0.66**        | -0.10           |
| AL   | **0.39**        | 0.17            | **0.44**        | 0.13            |
| ES   | 0.30            | -0.16           | **0.43**        | -0.12           |

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Table 3. Maximum correlation ($R_{IB}$) and corresponding lag time ($Lag_{IB}$) between the storm surge contribution ($\eta_{SS}$) of sea level variability and the sea level estimated from the inverse barometer effect ($\eta_{IB}$). The slope of the linear regression of $\eta_{IB}$ and $\eta_{SS}$ (refer to corresponding Figure S2 in Supporting Information). The correlation ($R_{\text{surge-SOI}}$) between the annual surge variability (standard deviation each year) and SOI. Italicized correlations are significant to 95%; bold correlations to 99%.

| Site | $R_{IB}$ | Lag$_{IB}$ [hr] | $\Delta\eta_{IB} / \Delta\eta_{SS}$ | $R_{\text{surge-SOI}}$ |
|------|--------|----------------|-------------------------------|---------------------|
| PH   | 0.82   | -15            | 0.45                          | 0.35                |
| CN   | 0.84   | -7             | 0.55                          | 0.25                |
| GN   | 0.81   | -2             | 0.40                          | 0.32                |
| FM   | 0.78   | -3             | 0.38                          | 0.22                |
| BU   | 0.70   | -3             | 0.27                          | 0.16                |
| AL   | 0.54   | -4             | 0.22                          | -0.04               |
| ES   | 0.26   | 0              | 0.16                          | 0.08                |
9 Figures

Figure 1. Study region. a) Location of tide gauges along Western Australia within the b) southeast Indian Ocean region of Australia.
Figure 2. Decomposition of coastal sea level variability (example from Fremantle), showing monthly maximum values for visual clarity. a) combined total sea level; b) decomposed interannual (solid line) and mean sea level trend (dashed line) contributions; c) seasonal contribution, d) surge contribution, and e) tide contribution. e) Southern Oscillation Index (SOI) and Multivariate ENSO Index (MEI).
Figure 3. Variance preserving spectra of a) atmospheric pressure ($\sigma^2_p$) and b) the surge contribution to sea level variability ($\sigma^2_{\text{surge}}$) for each site, as a function of logarithmic frequency (in cycles per day).
Figure 4. a) Ensemble-averaged monthly mean sea levels (colours, in meters) for each site. The black lines denote smoothed contour lines of zero water level (referenced to the mean sea level over the full record). b) Average number of ‘extreme’ sea level events (largest 2% of events) each month for each site. The black lines denote smoothed contour lines where there is an average of 1 event in a month.
Figure 5. Seasonally-averaged sea level anomalies derived from satellite altimetry.  
a) Dec-Feb during the austral summer, b) Mar-May during the austral autumn, c) Jun-Aug during the austral winter, d) Sep-Nov during the austral spring.
Figure 6. Timeseries of a) Southern Oscillation Index (SOI) and b) annual mean sea level (detrended with linear trend removed) at PH, FM and AL. c) Regression between the detrended annual mean sea level and SOI for PH, FM, and AL.
Figure 7. Ensemble-averaged sea level anomalies for a) El Niño (SOI < -1) conditions and b) La Niña (SOI > 1) conditions.
**Figure 8.** a) Annual number of extreme events at Fremantle over the 54-year period, where the red line is a 5-year moving average. b) Mean percentage of different contributions to the extreme events that occurred within each year. Note that the sum of all contributions is defined to equal 100%, so individual bars extending above 100% are compensated by negative contributions.
Figure 9. a) Mean percent contribution to an annual maximum sea level event over the 54-year period. b) Percent contribution to the total (overall) maximum sea level event within the record.
Figure 10. Nonstationary extreme sea level analysis for Fremantle. (Top row) Return levels with time as the co-variate. (Bottom row) Return levels with SOI as the co-variate.