Impact of ENSO on dependence between extreme rainfall and storm surge

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Abstract
Dependence between extreme rainfall and storm surge can have significant implications for coastal floods, which are often caused by joint occurrence of these flood drivers (through pluvial or fluvial processes). The effect of multiple drivers leading to a compound flood event poses higher risk than those caused by a single flood-driving process. There is strong evidence that compound floods caused by joint occurrence of extreme storm surge and heavy rainfall are related to meteorological forcing (e.g. large scale pressure systems and wind) and climate phenomena (e.g. the El Niño Southern Oscillation or ENSO). Therefore, understanding how climate phenomena affect the co-occurrence of coastal flood drivers is an important step towards understanding future coastal flood risk under climate change. Here we examine the impact of one of the most important climate phenomena—ENSO—on dependence between storm surge and rainfall in Australia, using both observed surge and modelled surge from a linked ocean-climate model—the Regional Ocean Modeling System. Our results show that ENSO has a significant impact on the dependence between extreme rainfall and storm surge, thus flood risk resulted from these drivers. The overall dependence is largely driven by La Niña in Australia, with increased dependence observed during La Niña along most of the Australian coastline. However, there can be increased dependence during El Niño in some locations. The results demonstrate dependence is contributed by unequally-weighted mechanisms due to the interaction between climate phenomena and local features, indicating the need for greater understanding of composition of compound flood risk. Where climate phenomena are anticipated to change into the future, it is possible to use integrated process-driven models to establish a better understanding of whether extremes are more likely to co-occur and exacerbate compound flood risk.

1. Introduction
Coastal floods are often a result of compound events (IPCC 2012, Leonard et al 2014, Zscheischler et al 2018), caused by dependent processes such as storm surge and runoff generated from heavy rainfall. Previous research shows that the dependence between extreme rainfall and storm surge can have a significant impact on the risk of coastal floods; and floods caused by these two dependent processes pose higher risk than those caused by a single flood-driving process (Zheng et al 2013). Understanding the collective contribution of processes to compound floods (e.g. the dependence between flood drivers) is important for coastal flood management and mitigation, especially for countries like Australia where the majority of its population live near the coast (ABS 2004). By quantifying the dependence between extreme rainfall and storm surge, a design variable method developed in previous studies can be used to correctly quantify flood risk caused by these drivers (Zheng et al 2013, Zheng et al 2015). Understanding how the dependence between these flood drivers change in the future under climate change will help us to understand and estimate future coastal flood risk.

Coastal flood risk attributed to storm surge and rainfall (through pluvial or fluvial processes) has been reported in many regions around the world, including...
Asia (Lian et al 2013, Ikeuchi et al 2017, Xu et al 2018, Ghosh et al 2019), Europe (Svensson and Jones 2004, Klerk et al 2015, Van den Hurk et al 2015, Bevacqua et al 2017, Ward et al 2018, Hu et al 2019), North America (Wahl et al 2015, Bass and Bedient 2018, Shao et al 2019), North Africa (Zellou and Rahali 2019) and Australia (Zheng et al 2013, Kumbier et al 2018, Wu et al 2018). There is strong evidence that the joint occurrence of extreme storm surge and heavy rainfall is related to large scale weather patterns, such as tropical cyclones, ex-tropical cyclones, frontal systems and East Coast Lows in Australia (McInnes et al 2002, Van den Hurk et al 2015, Wahl et al 2015, Kumbier et al 2018, Wu et al 2018). The weather patterns are a function of incipient climate conditions and are influenced by year-to-year climate variability from large scale climate phenomena (or climate drivers), such as the El Niño Southern Oscillation (ENSO) (Evans and Boyer-Souchet 2012, Santos et al 2017). Understanding how climate phenomena influence the dependence of storm surge and rainfall is therefore important for understanding future compound flood risk in coastal regions.

ENSO is an important climate phenomenon, especially influencing tropical and subtropical regions (Cai et al 2012), with significant impact on much of Australia’s climate (Jarvis et al 2018). ENSO has two distinct phases—La Niña and El Niño, and a neutral phase where there is no La Niña or El Niño due to near-normal sea surface temperatures in the equatorial Pacific (Trenberth 1997). The specific impact of ENSO on weather patterns and climate can be highly variable from ENSO event to ENSO event and location to location. However, for the case of Australia, the stronger-than-normal trade winds in the Pacific Ocean during La Niña typically push warmer water to West Pacific, resulting more rainfall and causing wetter periods in Australia; whereas during El Niño, the weakened trade winds and breakdown of Walker Circulation result in cooler ocean temperatures in the West Pacific, leading to drier periods in Australia (Santoso et al 2019).

The impact of ENSO on rainfall variability has been the topic of many studies (Risbey et al 2009, Vernon-Kidd and Kiem 2009, Cai et al 2012, Evans and Boyer-Souchet 2012, Rauniyar and Walsh 2013, King et al 2014, Raut et al 2014, Forootan et al 2016, Lewis et al 2017, Lim et al 2017, Tozer et al 2017, Hardiman et al 2018), showing differences with respect to extremes, seasonality and local variability. There are also studies investigating the impact of climate drivers on ocean processes, showing significant effect of ENSO on storm surge (Mawdsley and Haigh 2016, Munroe and Curtis 2017, Feng et al 2018) and mean sea level anomalies (Merrifield et al 1999, Becker et al 2012, Miles et al 2014, Barnard et al 2015), thus the resulting sea level extremes (Woodworth and Blackman 2002, Menéndez and Woodworth 2010, Haigh et al 2014b, Marcos et al 2015, McInnes et al 2016, Muis et al 2018). However, there have been no studies on the climatic influence of the dependence between extreme rainfall and surge, which can subsequently influence the risk of compound floods (Wu et al 2018). Therefore, understanding the impact of ENSO on the dependence between storm surge and rainfall is especially important for understanding future coastal flood risk when the occurrence of extreme ENSO events is projected to become more frequent in the future (Power et al 2013, Cai et al 2014, Wittenberg 2015).

This study follows previous work by the authors on the quantification of compound flood risk in coastal regions caused by extreme rainfall and storm surge based on their dependence (Zheng et al 2013, Zheng et al 2015) and the estimation of dependence between the two coastal food drivers around Australia using both observed and simulated surge data (Wu et al 2018). The objectives of this study are therefore (1) to investigate potential impact of ENSO on the dependence between storm surge and rainfall, with Australia as a case study; (2) to demonstrate compound flood risk can be decomposed by mechanisms driving the changes in contributing flood drivers and their interactions; and (3) to examine the suitability of an integrated ocean-climate model for identifying the impact of ENSO on dependence. Together these objectives identify the possibility of using process-driven models (where the physical processes of a system are represented using mathematical equations) to assess compound flood risk under climate change.

2. Methods

The dependence between extreme storm surge and extreme rainfall is assessed under different ENSO phases and in different seasons. Observed cumulative rainfall data, observed storm surge and modelled storm surge were used for many locations around Australia (see section 2.1 on datasets). Relationships between ENSO phases and the magnitude of the two flood drivers (e.g. storm surge and rainfall) were also investigated to demonstrate changes in dependence with respect to ENSO phases.

2.1. Datasets

2.1.1. Rainfall data

Cumulative daily rainfall records in Australia are available at over 17 000 stations from the Australian Bureau of Meteorology. Stations with less than 10 years’ data or more than 10% missing/ erroneous data were removed, which resulted in data from a total of 5300 rain stations across Australia, with record length between 10 years at Dampier Port on the Northwest coast of Australia to 169 years at Port Macquarie on the Southeast coast of Australia. The spatial coverage and the record length of daily rainfall from these 5300 stations are presented in figure 1.
2.1.2. Observed storm surge data

Historical hourly storm surge records from 79 tide gauges around Australia were obtained from the Australian Bureau of Meteorology. Among the 79 tide gauges, 15 gauges are monitored as part of the Australian Baseline Sea Level Monitoring Project (ABSLMP) (http://bom.gov.au/oceanography/projects/abslmp/data/index.shtml) and the remaining 64 gauges are managed by Australian port authorities. The storm surge data were obtained by subtracting the astronomical tide from the observed sea level using harmonic analysis as described in the Australian Tides Manual (Permanent Committee on Tides and Mean Sea Level 2007) using 112 tidal constituents (Westra 2012). Therefore, the storm surge data are the difference between the sea level values and the tide values, referred to as non-tidal residuals. Mean sea level changes were represented using a linear trend term (Wu et al. 2018). ENSO’s influences on the mean sea level (White et al. 2014) could influence the results but are outside the scope of this study. In order to be consistent with previous studies (Zheng et al. 2013, Zheng et al. 2014, Wu et al. 2018), non-tidal residuals were used in preference to the skew surge (Williams et al. 2016).

The surge record length ranges from just under 10 years at Lakes Entrance in Victoria to nearly 120 years at Fremantle in Western Australia. The locations and record length of the tide gauges are also shown in figure 1. The storm surge data are summarised in table S1 of the supplementary material, which is available online at stacks.iop.org/ERL/14/124043/mmmedia. For the dependence analysis, daily maximum surge is used, which results in approximately 3650 data points for sites with 10 years’ overlapping surge and rainfall data.

2.1.3. Modelled storm surge data

Modelled storm surge data were generated using the Rutgers version of the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams 2005), which was extended to cover the entire Australian coastline at 5 km resolution (Colberg and McInnes 2012, Wu et al. 2018). The model was run in barotropic mode with meteorological forcing only (i.e. with pressure and wind input information) to produce ‘true’ storm surge data (rather than non-tidal residuals). The meteorological forcing data, including global pressure and wind at an hourly time step and approximate 38 km spatial resolution, were obtained from the US National Centers for Environmental Prediction Climate Forecast System Reanalyses (Saha et al. 2010). Details of the ROMS model are included in the study by Colberg and McInnes (2012).

The surge outputs from ROMS are available at hourly intervals for 7118 locations along the Australian coastline between 1 January 1980 and 1 May 2013. For this study, 551 locations were sampled from the 7118 locations to provide a reasonable coverage of the Australian coastline at approximately 30 km intervals.

2.1.4. Climate index

Different phases of the ENSO, i.e. El Niño and La Niña, are often monitored by the anomalies in observed sea surface temperatures within a specific region (i.e. [5°S–5°N, 170°W–120°W] of the central and eastern
tropical Pacific Ocean), known as Niño 3.4 (Trenberth 1997). For this study, monthly Niño 3.4 anomaly data, with the mean removed, were obtained from Earth System Research Laboratory at the National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce (https://esrl.noaa.gov/psd/data/climateindices/list/#\#Nina34). The data are available from year 1870 onwards. Monthly Niño 3.4 anomaly data were calculated based on the Hadley Centre sea ice and sea surface temperature data set version 1 (HadISST1) (Rayner et al 2003).

2.2. Identification of ENSO phases and warm and cool seasons

In order to identify different phases of ENSO, i.e. El Niño or La Niña, a five-month running mean of the Niño 3.4 index was used to smooth out variations in the tropical ocean (Trenberth 1997). An ENSO phase is said to be established when the five-month running mean of the Niño 3.4 index exceeds a threshold value for over five consecutive months. Threshold values of ±0.5 °C were used, which are approximately 0.7 times the long-term standard deviation of the index and the threshold value typically used (Manatsa et al 2011).

In this study, ‘cool season’ refers to June to October and ‘warm season’ refers to the period of November to March. April and May are not included in seasonal analysis, as ENSO typically ends by March and is not active during these months (Pepler et al 2014).

2.3. Dependence analysis

2.3.1. Bivariate logistic threshold excess model

Dependence between extreme storm surge and rainfall along the Australian coastline was estimated using the well-known bivariate logistic threshold excess model (Coles 2001) based on daily maximum storm surge and rainfall. The model has been used to estimate the joint occurrence of extreme storm surge and rainfall in Australia (Zheng et al 2013, Wu et al 2018) and is described by the following function (Coles 2001):

\[
g(u, v) = \exp\left[-(\tilde{u}^{-1/\alpha} + \tilde{v}^{-1/\alpha})^\alpha\right],
\]

where, \(u\) and \(v\) represent two random variables, for example storm surge and rainfall. \(G\) is the bivariate distribution function, and \(\tilde{u}\) and \(\tilde{v}\) are the Fréchet-transformed values of the two random variables. The dependence between the two random variables is represented by a single parameter \(\alpha\). An \(\alpha\) value of 1 represents complete independence between the two random variables, implying that the occurrence of extreme events for one variable are uninformative with regards to the other variable. An \(\alpha\) value of 0 represents complete dependence, indicating that when one variable is extreme the other variable will be equally extreme. Since the relationship is nonlinear, even a modest level of dependence can be influential. For example, an \(\alpha\) value of 0.95 corresponds to a sevenfold increase in co-occurring extreme events compared to independence (Zheng et al 2013, Wu et al 2018). The censored threshold likelihood method (Tawn 1988) was used to estimate the value of \(\alpha\). The 99th percentile was used as the threshold value for both storm surge and rainfall, as it has been identified as an appropriate threshold value and concurs with previous studies (Zheng et al 2013, Wu et al 2018).

To investigate how the dependence changes during different ENSO phases and in different seasons, the dependence between storm surge at each coastal location (i.e. 79 tide gauges for observed surge and 551 ROMS locations for modelled surge) and rainfall at each rain gauge was first calculated for all years, then under different ENSO Phases, and for different seasons. The average dependence was calculated between storm surge at a given coastal location and rainfall using all rain gauges within a 100 km radius of the coastal location. The 100 km radius was selected to account for remote locations where there are few rainfall stations, including north and northwest Australia, as shown in figure 1, and concurs with the method of a previous study (Wu et al 2018). To investigate how the dependence changes with distance, the average dependence was also calculated using rain gauges up to 300 km radii from the location at 50 km intervals.

2.3.2. Kendall’s \(\tau\) rank correlation

Relationships between the magnitude of the two respective flood drivers (i.e. storm surge and rainfall) and the strength of different ENSO phases were investigated using the Kendall’s \(\tau\) rank correlation (Kendall 1938). The use of Kendall’s \(\tau\) instead of the bivariate logistic for this analysis is due to the monthly scale of the Niño 3.4 and the significant data reduction at the monthly scale relative to the daily scale. Kendall’s \(\tau\) is less sensitive to outliers and skewed distributions than Pearson’s correlation and can capture nonlinear relationships between variables (Williams et al 2016). Monthly peak storm surge and monthly cumulative rainfall were used with the monthly Niño 3.4 index to analyse relationships between the magnitude of storm surge, overall wetness during a month, and the intensity of ENSO. Statistical significance was determined using a two-tailed test with a \(p\)-value of 0.05 (i.e. only when \(p < 0.05\), the relationship represented by the Kendall’s \(\tau\) rank correlation is considered to be statistically significant).

3. Results and discussion

3.1. Overall dependence

The dependence between extreme storm surge and rainfall estimated during different seasons and ENSO phases are respectively shown based on the observed surge in figure 2 and based on ROMS modelled surge in figure 3. There is strong similarity between the dependence estimated using observed surge data and ROMS modelled surge data, consistent with previous
Significant dependence between extreme surge and rainfall is observed along the majority of the Australian coastline (figures 2(a) and 3(a)). The dependence is the strongest in northwest Australia with $\alpha$ values less than 0.85 obtained for both observed and ROMS modelled surge. Relatively strong dependence is observed in the north, west and northeast of Australia, with $\alpha$ values between 0.85 and 0.95. The dependence is relatively weak in south and southeast Australia, including several insignificant locations ($\alpha > 0.99$). Regarding seasonal variation, stronger dependence is generally observed in the north of Australia during the warm season (figures 2(b) and 3(b)) and in the south of Australia during the cool season (figures 2(c) and 3(c)). Stronger than observed dependence is obtained using ROMS surge along the west of Australia for all scenarios (Wu et al 2018). This is due to a combination of local bathymetry, the resolution of ROMS and its inputs, the weak effect of tropical cyclones in ROMS, and the steric component and high-frequency oscillations of sea level that are not modelled in ROMS (Haigh et al 2014b, Pattiaratchi and Wijeratne 2014, McInnes et al 2016).

### 3.2. Impact of ENSO on dependence

ENSO has a significant impact on the dependence between extreme storm surge and rainfall in Australia. The overall dependence is driven by La Niña along the...
The majority of the coastline (i.e. the overall dependence is similar to the dependence during La Niña). The impact of La Niña is more pronounced in west Australia in the warm season (figure 2(b)) and in east Australia in the cool season (figure 2(i)). On the other hand, El Niño generally results in a reduced dependence between storm surge and rainfall along the majority of the Australian coastline compared to average conditions. This result is supported by the recent finding that the Central Pacific ENSO events (e.g. La Niña events) are more impactful over Australia than the Eastern Pacific events (typically extreme El Niño events) (Santoso et al 2019). However, increased dependence is obtained during El Niño in northern Australia near the Gulf of Carpentaria and the southwest corner of Western Australia from both observed and ROMS modelled surge data (figures 2(d) and 3(d)). This increase during El Niño is more pronounced in the warm season near the Gulf of Carpentaria in the north (figures 2(e) and 3(e)) and in the cool season in southwest Australia (figures 2(f) and 3(f)).

To further investigate the impact of ENSO on the dependence between storm surge and rainfall, two additional analyses were conducted:

1. The average dependence between storm surge and rainfall from rain stations within a radius of 300 km from tide gauges during different ENSO
phases is estimated. Results for all 79 tide gauges are included in figure S1 of the supplementary material. The dependence versus distance results obtained from nine locations representing different climate regions along the Australian coastline are shown in figure 4.

(2) The rank correlation between the strength of ENSO phases represented by the Niño 3.4 index and the magnitude of flood drivers (i.e. storm surge and rainfall) is shown in figure 5. It should be noted that during La Niña, when the Niño 3.4 index is negative, the absolute values of the Niño 3.4 index were used.

Results in figure 4 confirm that ENSO has different impact on dependence between extreme storm surge and rainfall in different regions along the Australian coastline as shown in figures 2 and 3. At most of the locations in the northern half of Australia (e.g. Brisbane, Cairns, Wyndham and Carnarvon in figure 4), dependence between storm surge and rainfall is stronger during La Niña than during El Niño (represented by the lower blue lines with plus signs and the higher red lines with triangles). Near the Gulf of Carpentaria in northern Australia (e.g. Groote Eylandt in figure 4) and the southwest corner of Western Australia (e.g. Albany in figure 4) however, dependence between storm surge and rainfall is stronger during El Niño than during La Niña (represented by the lower red lines with triangles and the higher blue lines with plus signs). ENSO has little impact on the dependence between storm surge and rainfall along the southeast of Australia. As shown in figure 4, dependence does not vary with ENSO phases at Fort Denison in New South Wales, Williamston in Victoria and Adelaide in South Australia. This is because the impact of ENSO on rainfall in this region is mainly via the frequency of daily rainfall rather than rainfall intensity (Pui et al. 2012), which determines the dependence between extreme rainfall and storm surge. In addition, the impact of ENSO on dependence is reasonably consistent with distance for up to 300 km, except for Carnarvon in western Australian and Groote Eylandt in northern Australia where the variation in dependence is likely to be caused by the limited rain gauges within a small radius (e.g. less than 200 km).

Results in figure 5 show that it is the relative relationship between the two coastal flood drivers with respect to ENSO that gives rise to differences in the dependence along the Australian coastline when it is partitioned according to ENSO phases. It should be noted here that the maps for the two different ENSO phases in figure 5 look similar. This is because the absolute values (rather than original values) of the Niño 3.4 index were used to represent the intensity of each ENSO phase (either El Niño or La Niña) for ease of interpretation of results. Although it is well known that La Niña brings more rainfall to northern Australia, it is observed that as La Niña strengthens, not only does the rainfall increase (figure 5(d)), but the storm surge also intensifies in northern Australia (figure 5(b)). It is the positive correlation of both storm surge and rainfall with La Niña that result in stronger dependence between the two flood drivers during La Niña in the northern half of Australia. However, the opposite occurs during El Niño, when the

Figure 4. Impact of ENSO on dependence between extreme storm surge and rainfall at 9 selected tide gauges. (Note: smaller α values indicates stronger dependence).
relationship between ENSO and storm surge reverses in northern Australia (figure 5(a)), while the correlation between ENSO and rainfall stays positive in the region (figure 5(c)). This observation is consistent with existing studies on ENSO impact on Australian climate variables like rainfall (Cai et al 2012, Forootan et al 2016) and storm surge (Muis et al 2018).

Near the Gulf of Carpentaria in northern Australia however, although rainfall is still correlated to ENSO in these regions during La Niña (figure 5(d)), the relationship between ENSO and surge becomes insignificant (figure 5(b)). The breakdown in the relationship between ENSO and surge during La Niña results in weaker dependence between the two flood drivers in these regions. During El Niño on the other hand, the correlation between surge and ENSO becomes negative in northern Australia near Groote Eylandt (figure 5(a)) and the positive correlation between rainfall and ENSO weakens (figure 5(c)). The synchronicity of the change in the relative relationship between the two coastal flood drivers with respect to ENSO increases the dependence between the two flood drivers during El Niño. Near Albany in southwest Australia on the other hand, as El Niño weakens, both storm surge and rainfall intensify (figures 5(a) and (c)), leading to increased dependence during El Niño. This finding is consistent with the known negative relationships between ENSO and the two flood drivers in southwest Australia (King et al 2014, Muis et al 2018).

In southeast Australia, the relative relationship between ENSO and the two flood drivers breaks down during both ENSO phases when either the correlation with rainfall or storm surge becomes insignificant (figures 5(b)–(d)). This could be due to the stronger influence of other oscillations (Cai et al 2012, King et al 2014, Pepler et al 2014, Wu et al 2018), although their influence is yet to be fully identified in some regions of Australia (Tozer et al 2017). There are some departures from the general relationship at various locations (e.g. Port Hedland in Western Australia, Weipa in northern Australia).
Queensland and Bundaberg in east Queensland in figure S1 in the supplementary material, which are most likely resulted from the impact of localised features (e.g. orography, bathymetry, tropical cyclones, etc) on individual flood drivers (Resio and Westerink 2008, Foresti and Seed 2015, Wu et al 2017) or their joint occurrence (Wu et al 2018).

3.3. Comparison of ENSO impact obtained from observed and ROMS modelled surge
To understand how the impact of ENSO on dependence manifests with ROMS modelled surge, the average dependence was examined between ROMS modelled storm surge and rainfall from rain stations within a radius of 300 km from 79 ROMS locations.

Table 1. Category for comparing impact of ENSO on dependence obtained from observed and ROMS modelled surge.

| Category                          | Description                                                                 | Colour representation of solid circles in figure 6 |
|----------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------|
| Similar characterisation         | Reasonable match between dependence results obtained from observed and ROMS modelled surge, i.e. the responses of the dependence estimated using observed and modelled surge to different ENSO phases are similar. | Black                                               |
| Different characterisation       | Different impact of ENSO on dependence observed from results obtained from observed and ROMS modelled surge. For example, different ENSO phases may result in different dependence values estimated using observed surge, but the same dependence values estimated using ROMS modelled surge. | Yellow                                              |
| Significantly different characterisation | Opposite impacts on dependence are observed. For example, one ENSO phase may result in increased dependence estimated using observed surge but reduced dependence estimated using modelled surge. | Red                                                 |
| Insufficient evidence            | There are insufficient data to draw conclusions.                              | Grey                                                |

Figure 6. Comparison of impact of ENSO on dependence between extreme storm surge and rainfall obtained from observed and ROMS modelled surge. (Note: smaller $\alpha$ values indicates stronger dependence.) The large black circles indicate the locations of the three tide gauges marked, i.e. Weipa, Mourilyan Harbour and Victor Harbor.
during different ENSO phases. The 79 ROMS locations were selected to be closest to the 79 tide gauges among the 551 ROMS locations sampled. Results for these 79 ROMS locations are included in figure S2 in the supplementary material. A visual inspection was conducted to compare the impact of ENSO on the dependence obtained from observed surge and ROMS modelled surge and the 79 locations are grouped based on categories listed in table 1. The comparison results are plotted in figure 6.

Similar impact of ENSO on dependence between storm surge and rainfall obtained from observed and ROMS modelled surge data is observed along the majority of the Australian coastline (i.e. represented using solid black circles in figure 6). However, several discrepancies are also observed, especially in northeast and southeast Australia as shown in figure 6. In northeast Australia near Weipa and southeast Australia near Victor Harbor, no significant ENSO impact on dependence is detected based on observed surge (figures 6(a1) and (c1)). However, based on ROMS modelled surges, El Niño results in significantly increased dependence at both locations (lower red lines with triangles in figures 6(a2) and (c2)). In northeast Australia near Mourilyan Harbour on the other hand, significantly increased dependence is observed during El Niño (lower red line with triangles in figure 6(b1)); however, this increase in dependence is not detected when ROMS modelled surge is used (figure 6(b2)).

The different characterisation of ENSO’s impact on dependence from ROMS in northeast Australia is most likely due to the weak effects of tropical cyclones modelled in ROMS. In northeast Australia tropical cyclones are a significant driver of coincident extreme storm surge and rainfall (Haigh et al 2014a, Zheng et al 2014, Wu et al 2018). Tropical cyclones have contributed to the significant seasonal variability in the dependence in this regions (figure 2), trivialising the impact of ENSO (as shown in figure 6(a1)). When ROMS modelled surge data are used to estimate the dependence, the seasonal impact on the dependence becomes less apparent, due to the weak effect of tropical cyclones in the ROMS model (especially considering the rainfall data are observed). This reduced seasonal impact on the dependence estimated using ROMS modelled surge makes the impact of ENSO more prominent (figure 6(a2)).

The different characterisation of ENSO’s impact on dependence from ROMS in southeast Australia, especially near Victor Harbor, however, is more likely due to a combined impact of local bathymetry and the resolution of ROMS model (i.e. 5 km) and its meteorological inputs (i.e. 38 km) (Colberg and McInnes 2012, Wu et al 2018). Another possibility is the strong influence of other oscillations in southeast Australia (Cai et al 2012, King et al 2014, Pepler et al 2014, Wu et al 2018). Since the influence of other oscillations is yet to be fully identified in some regions of Australia, they may not be adequately represented in integrated process models, such as ROMS (Tozer et al 2017). The discrepancies between observed and ROMS modelled impact of ENSO could alternatively be attributed to the difference in the local geometry between tide gauges and the ROMS locations: the tide gauges tend to be located in sheltered locations, while the ROMS locations are in open ocean. It is interesting to note that the reduced performance of ROMS along the western coast of Australia observed in previous studies (Haigh et al 2014b, Pattiaratchi and Wijeratne 2014, McInnes et al 2016) does not have a significant impact on the dependence when portioned by ENSO phases, although it results in different overall dependence in west Australia (Wu et al 2018). This indicates that the relative ranking of surge events modelled in ROMS in these regions in different ENSO phases are similar to those observed.

4. Summary and conclusions

In this study, the impact of ENSO on the dependence between two important coastal flood drivers—extreme rainfall and storm surge, has been investigated. The impact of climate phenomena, such as ENSO, on the dependence is important to understand future coastal flood risk under climate change, as the dependence between flood drivers has a significant impact on the risk of floods arise from them. Given a specific structure and value of dependence between extreme rainfall and storm surge, a design variable method (Zheng et al 2013, Zheng et al 2015) can be used to correctly estimate flood risk resulted from these correlated flood drivers. Thus understanding how ENSO impacts the dependence between these flood drives will improve the understanding and estimation of future coastal flood risk caused by these drivers, especially when the occurrence of extreme ENSO events is projected to become more frequent in the future (Power et al 2013, Cai et al 2014, Wittenberg 2015).

The results show evident impact of ENSO on dependence between storm surge and rainfall, along the majority of the Australian coastline. The La Niña phase showed stronger dependence in general, but El Niño led to stronger dependence in northern Australia near the Gulf of Carpentaria and in the southwest corner of Western Australia. The significant impact on the La Niña phase of ENSO on the dependence is due to the fact that the Central Pacific ENSO events (e.g. La Niña events) are more impactful over Australia than the Eastern Pacific events (typically extreme El Niño events) (Santoso et al 2019), highlighting the importance of ENSO event diversity for evaluating impact of ENSO on coastal flood risk over countries like Australia. The contribution of each phase of ENSO to
dependence was subsequently explained by the synchronicity of correlations for rainfall and storm surge with respect to ENSO. Regardless of which phase gave stronger dependence, this study demonstrates that dependence of extreme events can be decomposed according to different climate mechanisms and that they do not necessarily contribute equally to the overall level of dependence. Given the diversity of the impact of ENSO mentioned above, the analysis can be further stratified for central Pacific El Nino events (given sufficient data) to improve understanding of impact of El Niño. It is also possible to further decompose dependence of extremes according to synoptic weather patterns to gain a better understanding of coastal flood risk.

It was found that the dependence estimated from surge data generated using an integrated ocean-climate model—ROMS, had similar response to ENSO at the majority of the locations along the Australian coastline compared to dependence estimated using observed surge data. However, the performance of this model is impacted by its ability to model certain large scale weather patterns, for example tropical cyclones, and the resolutions of the model and its input data. Given the influence of local features such as orography and bathymetry, it is also important to conduct investigations at a much finer scale using integrated ocean-climate models to link atmospheric and ocean processes. Where climate drivers are anticipated to change into the future, it is possible, using these proposed methods, to establish a better understanding of whether extremes are more likely to co-occur and exacerbate compound flood risk, although the capability of the process-based models of the flood drivers (e.g. the integrated atmosphere-ocean model simulating storm surge) in capturing characteristics of different climate drivers is key to the success of these proposed methods.

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Data availability

The data that support the findings of this study are either openly available or available from the corresponding author upon reasonable request. Details of data availability are given below:

The Niño 3.4 index data used in this study are publicly available from the National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce (https://esrl.noaa.gov/psd/data/climateindices/list/#Nina34). Observed rainfall data are available from the Bureau of Meteorology online database (http://bom.gov.au/climate/data/index.shtml?bookmark=136). Observed storm surge are from the Bureau of Meteorology online database (http://bom.gov.au/oceanography/projects/abslmp/data/index.shtml). These data are held under license from the Bureau of Meteorology (http://bom.gov.au/) and are restricted for research purposes only with approval from the Bureau of Meteorology in Australia. The modelled surge data are provided by Dr Kathleen McInnes from Climate Science Centre, CSIRO Oceans and Atmosphere and are available from CSIRO at the following online repository (https://data.csiro.au/dap/landingpage?execution=e1s2&_eventId=viewDescription) upon reasonable request.

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