



[Click here to view linked References](#)

Natural hazards in Australia: sea level and coastal extremes

Kathleen L. McInnes, kathleen.mcinnnes@csiro.au

Christopher J. White, chris.white@utas.edu.au

Ivan D. Haigh, I.D.Haigh@soton.ac.uk

Mark A. Hemer, mark.hemer@csiro.au

Ron K. Hoeke, ron.hoeke@csiro.au

Neil J. Holbrook, Neil.Holbrook@utas.edu.au

Anthony S. Kiem, Anthony.Kiem@newcastle.edu.au

Eric C. J. Oliver, Eric.Oliver@utas.edu.au

Roshanka Ranasinghe, R.Ranasinghe@unesco-ihe.org

Kevin J. E. Walsh, kevin.walsh@unimelb.edu.au

Seth Westra, seth.westra@adelaide.edu.au

Ron Cox, r.cox@wrl.unsw.edu.au

22 **Abstract**

23 The Australian coastal zone encompasses tropical, sub- and extra-tropical climates and
24 accommodates about 80% of Australia's population. Sea level extremes and their physical
25 impacts in the coastal zone arise from a complex set of atmospheric, oceanic and terrestrial
26 processes that interact on a range of spatial and temporal scales and will be modified by a
27 changing climate, including sea level rise. This review details significant progress over recent
28 years in understanding the causes of past and projections of future changes in sea level and
29 coastal extremes, yet a number of research questions, knowledge gaps and challenges
30 remain. These include efforts to improve knowledge on past sea level extremes, integrate a
31 wider range of processes in projections of future changes to sea level extremes, and focus
32 efforts on understanding long-term coastline response from the combination of contributing
33 factors.

34

35

36 **1. Introduction**

37 Australia's coastal zone — defined herein as the region of low-elevation coastal land and
38 adjacent estuarine and marine ecosystems — is bisected by approximately 34,000 km of
39 coastline and encompasses tropical, sub- and extra-tropical climates. The arid nature of much
40 of Australia's interior means that approximately 80% of Australia's population lives in or near
41 the coastal zone together with a diversity of coastal and estuarine ecosystems, making it of
42 critical importance for a range of social, economic and environmental reasons.

43 In this review paper, our region of relevance extends from the continental shelf offshore,
44 where oceanic processes responsible for extreme sea levels occur, through to the low-lying
45 coastal land inshore where physical impacts are felt. Sea level extremes and their coastal
46 impacts arise from a complex set of atmospheric, oceanic and terrestrial processes that
47 interact on a range of spatial and temporal scales. These extremes may be characterized by
48 their frequency, intensity, spatial extent, duration, and timing—all of which can be modified
49 by a changing climate (Seneviratne et al. 2012). Understanding the factors that cause
50 extremes and their trends under present climate conditions is fundamental to determining
51 future impacts. Furthermore, understanding the response of systems (physical, ecological and
52 socioeconomic) to extreme events and projecting their future changes is essential to
53 managing and adapting to those extremes in the face of a changing climate (Leonard et al.
54 2014).

55 This review focuses on sea level and coastal extremes, forming part of this Special Issue
56 describing changes in natural hazards in Australia (Westra et al. this issue). After summarizing
57 our current scientific understanding of sea level and coastal extremes, this review concludes

58 by highlighting key knowledge gaps and providing recommendations of future research
59 priorities. Related hazards are discussed in the companion reviews.

60 **2. Understanding sea level and coastal extremes in Australia**

61 **2.1 Causes of sea level and coastal extremes**

62 Sea level and coastal extremes can arise from singular oceanic phenomena such as storm
63 surges but more commonly arise from a combination of natural phenomena that individually
64 may not be extreme. These phenomena occur on a range of time and space scales (Figure 1)
65 in any given coastal location, and thus the contribution of each phenomenon to extreme sea
66 levels varies. Oceanic and atmospheric variability on timescales of weeks to decades also
67 influences local sea levels. For example, sea level variability is strong over northern Australia
68 where monthly sea-level anomalies are highly correlated with the Southern Oscillation Index
69 (SOI), a measure of El Niño-Southern Oscillation (ENSO; Figure 2a, Holbrook et al. 2011).
70 Positive (negative) perturbations in sea levels during La Niña (El Niño) propagate from the
71 equatorial western Pacific Ocean through the Indonesian Archipelago to northwestern
72 Australia and then anticlockwise around Australia, decreasing in magnitude with distance
73 from Darwin (White et al. 2014).

74 Astronomical tides vary on multiple timescales, including diurnal and semi-diurnal, fortnightly
75 with spring and neap tides, and on seasonal to interannual timescales. Around the coast of
76 Australia, overall highest astronomical tides (HAT, considered over an 18.6 year lunar tidal
77 epoch following common practice) vary between around 0.5 m (e.g. in areas of southwest
78 Australia) to well over 7 m along the northwest coast (Figure 2b); daily mean tidal range
79 patterns are similar to that of HAT. Furthermore tide types range from strongly diurnal, to

1
2
3 80 mixed, through to semi-diurnal along the coastline (Figure 2c); the timing and relative range
4
5
6 81 of (semi-annual) maximum spring tides also vary (Figure 2d).

7
8
9 82 Storm surges, in comparison, are gravity waves arising from the inverse barometer effect and
10
11 83 wind stress. The former elevates sea levels approximately 1 cm for every 1 hPa fall in
12
13 84 atmospheric pressure relative to surrounding conditions, and wind stress induces currents
14
15 85 over shallow water. Wind stress directed onshore (i.e. “wind setup”) leads to an increase in
16
17 86 sea levels, particularly within semi-enclosed embayments or under severe wind forcing such
18
19 87 as produced by tropical cyclones (TCs). In mid-latitudes, wind-induced coast-parallel currents,
20
21 88 which persist for a day or more, undergo Coriolis deflection. In the southern hemisphere this
22
23 89 increases (decreases) coastal sea levels if the currents follow the coast in an anticlockwise
24
25 90 (clockwise) direction and is referred to as “current setup” (“setdown”). Using a hydrodynamic
26
27 91 model forced by tides and atmospheric conditions, Haigh et al. (2014a,b) assessed return
28
29 92 periods of storm surges and tides (i.e. storm tides) around the Australian coast. The highest
30
31 93 storm tides (100-year return period levels >4 m) occur on the northwest coast, while along
32
33 94 the northeast and the mid-southern coastline storm tides are between 2–4 m, and along the
34
35 95 southeast and southwest coasts are typically < 2 m.

36
37
38
39
40
41
42
43 96 Meteo-tsunamis are another source of extreme sea levels that arise from abrupt changes in
44
45 97 pressure or wind during squalls, thunderstorms or frontal passages. Meteo-tsunamis are
46
47 98 shallow-water waves, characterized by wave length much greater than water depth, and a
48
49 99 wave period similar to seismic tsunamis (Pattiaratchi and Wijeratne 2014).

50
51
52
53
54
55 100 Coastally-trapped waves (CTWs) also drive sea level variability along Australia’s extratropical
56
57 101 coastline on timescales between one day and several months. CTW amplitudes are closely
58
59 102 correlated with the continental shelf width and vary from around 0.7 m along the south coast

103 to 0.05–0.10 m along the east coast. In some cases, sea surface height anomalies are a direct
104 response of the ocean surface to the changing wind field from moving weather systems; in
105 other cases, CTWs propagate freely in the absence of wind forcing (Eliot and Pattiaratchi,
106 2010; Woodham et al. 2013).

107 The dissipation of wind and swell waves in the nearshore swash zone also contribute to
108 coastal sea levels. Wave setup is an increase in mean water level due to the cross-shore
109 gradient in momentum flux directed shoreward of the region where wave breaking occurs,
110 whereas runup refers to the uprush of water as an individual waves break. Because wave
111 setup and runup are caused by wave breaking, sheltered coastal areas such as harbours and
112 lagoons—the typical location of tide gauges—generally do not experience these effects
113 (Hoeke et al. 2013).

114 The magnitude of wind-waves is a function of the driving wind speed and the fetch-length
115 over which the wind is blowing. Once generated, wind-waves can travel long distances across
116 the deep ocean with little loss of energy until shoaling near the coast. In Australia, the largest
117 waves occur along the southern margin—from North-West Cape, Western Australia (WA),
118 around the southern coast to the southern tip of Tasmania—where waves, generated by the
119 extra-tropical cyclones (ETCs) of the Southern Ocean, propagate towards and eventually
120 break on the coast. Satellite altimeter-derived estimates of the 20 (100) year return periods
121 of significant wave height (H_s) along Australia’s southern margin have been estimated to be
122 approximately 13 m (16 m) (Izaguirre et al. 2011; Vinoth and Young 2011). In northern
123 Australia, TCs are the predominant driver of extreme waves with 100-year H_s estimated to be
124 10 m (Vinoth and Young 2011).

125 Other coastal attributes, such as continental shelf width, bathymetric depth, coastline
1 orientation in relation to prevailing weather conditions, headlands, estuaries and shoreline
2
3 126 slopes, also influence extreme sea levels. The wider shelf regions along the tropical and much
4
5 127 of the southern Australian coastline (Figure 3) are conducive to larger storm surges and tidal
6
7 128 ranges whereas the narrower shelves along the southeast, southwest and parts of the
8
9 129 southern coastline are exposed to wave-driven coastal extremes. Coral reefs, found along the
10
11 130 northeast (Great Barrier Reef; GBR), north and northwest (e.g. the Ningaloo Reef) of Australia,
12
13 131 also provide coastal protection through wave dissipation offshore (e.g. Gallop et al. 2014).
14
15
16
17
18
19
20
21

22 133 **2.2. Weather and climate drivers**

23
24
25 134 A range of weather conditions cause extreme sea levels around the Australian coastline
26
27 135 (Figure 3). TC-induced storm surges affect mainly the northern coastline of Australia from
28
29 136 Queensland to the northwest coast of Western Australia although TCs can track and hence
30
31 137 influence the east and west coastlines further south (Haigh et al. 2014b). Within the Gulf of
32
33 138 Carpentaria an annual cycle of sea level, with a range of approximately 0.8 m, driven mainly
34
35 139 by the seasonal reversal of the prevailing winds, produces the largest seasonal variation in
36
37 140 sea levels in the world (Forbes and Church 1983; Tregoning et al. 2008; White et al. 2014).
38
39 141 Westerly wind bursts associated with the Madden-Julian Oscillation (MJO) during the
40
41 142 monsoon contribute to intra-seasonal sea level variations along the Gulf of Carpentaria and
42
43 143 Indian Ocean coastlines (Oliver and Thompson 2011). Strong sustained south-easterly trade
44
45 144 winds during the dry season can elevate sea levels in the Torres Strait Islands (Green et al.
46
47 145 2010).
48
49
50
51 146 Easterly or northeasterly travelling ETCs or TCs cause elevated sea levels along the southwest
52
53 147 WA coastline (Haigh et al. 2010; Eliot et al. 2012), which may be further enhanced by a sea
54
55
56
57
58
59
60
61
62
63
64
65

148 level annual cycle of 0.2–0.3 m due to variations in the strength of the southward flowing
149 Leeuwin current. During May to June, weak southerly winds allow for a stronger flowing
150 southward current and higher coastal sea levels due to Coriolis deflection, whereas during
151 October to November, the opposing southerly winds are strongest and this weakens the
152 Leeuwin current (Pattiaratchi and Eliot 2008).

153 Eastward travelling ETCs and fronts, most frequent during the winter months, are the main
154 cause of elevated sea levels along the southern coastline and Tasmania (McInnes and Hubbert
155 2003; McInnes et al. 2012b; Colberg and McInnes 2012). Along Australia’s east coast, from
156 New South Wales (NSW) to southeast Queensland (QLD), a major cause of elevated sea levels
157 is from East Coast Lows (McInnes and Hubbert 2001; Walsh et al. this issue).

158 Modes of climate variability also influence weather systems that cause extreme sea levels
159 (Westra et al. this issue). In addition to its influence on sea levels ENSO affects TC frequency,
160 with more (fewer) TCs likely during La Niña (El Niño) events (Kuleshov et al. 2008). The MJO
161 also affects TC occurrence (Hall et al. 2001). The Southern Annular Mode (SAM), which in its
162 positive phase amounts to a strengthening and poleward shift of storm tracks, affects the
163 latitudinal position of the Subtropical Ridge (STR), which separates easterly trade winds to the
164 north and the westerlies to the south (Kent et al. 2013) and, hence, extreme sea levels on the
165 southern coastline. The Indian Ocean Dipole (IOD) also affects regional sea levels to the
166 northwest of Australia (Feng and Meyers 2003) with the Dipole Mode Index weakly negatively
167 correlated with coastal sea levels along the WA coast (Charitha Pattiaratchi, pers. comm. September
168 2015).

169 **2.3. Terrestrial factors**

170 Extreme sea level impacts at the coast, such as inundation and erosion, are influenced by
171 terrestrial factors including vertical land movement, geomorphology, fluvial contributions and
172 anthropogenic modifications to the coastal landscape. In addition to flooding from sea level
173 extremes, cliff instability and beach erosion may also occur from sea level rise (SLR) and storm
174 and wave-climate changes (Department of Climate Change 2009).

175 As well as long-term vertical land movement from Glacial Isostatic Adjustment (GIA), local
176 vertical movements can occur due to natural processes such as sustained or abrupt tectonic
177 disturbances, and anthropogenic causes such as sediment consolidation, reduced sediment
178 delivery to the coast, and extraction of subsurface resources such as gas and groundwater
179 (Wong et al. 2014). Among Australian tide gauge locations with co-located Global Positioning
180 System (GPS) technology, White et al. (2014) estimated subsidence rates at Hillarys, Perth,
181 Darwin and Adelaide of $-3.1 (\pm 0.7)$, $-2.1 (\pm 0.7)$, $-1.6 (\pm 1.4)$ and $-0.4 (\pm 0.3)$ mm yr⁻¹
182 respectively.

183 In estuarine regions, floods can be caused not only by elevated ocean levels, but also by fluvial
184 contributions arising from heavy rainfall on the catchment. The nature of floods in these
185 regions is complex (Johnson et al. this issue), with flood magnitude dependant on intensity
186 and duration of the extreme rainfall event (Leonard et al. 2008), antecedent catchment
187 conditions (Johnson et al. this issue) and whether the hydrograph peak coincides with the
188 peak in extreme sea levels (Zheng et al. 2015). Because extreme rainfall and storm surges are
189 often produced by similar weather patterns, there is a significant probability that both
190 processes will occur simultaneously (Zheng et al. 2013), with the probability depending on
191 the location along the coastline, the duration and the absolute magnitude of the rainfall and
192 storm surge events (Westra et al. 2015). This means that extreme water levels in estuarine

193 areas can occur even when all of the driving processes are individually non-extreme (Leonard
194 et al. 2014).

195 **3. Historical changes and their causes**

196 **3.1. Historical changes to extreme sea levels**

197 Trends in mean sea level from Australian tide gauges and satellite altimeters are generally in
198 close agreement, although tide gauges are known to be affected by vertical land motions.
199 Variations in mean sea level are strongly related to ENSO—particularly on the northern and
200 western coastlines—as well as the GIA and atmospheric pressure. Correcting for these factors
201 yields Australian trends since 1993 of between $2.1 \pm 0.2 \text{ mm yr}^{-1}$ and $3.1 \pm 0.6 \text{ mm yr}^{-1}$ from
202 tide gauges and altimeters respectively (White et al. 2014), which are similar to respective
203 global mean trends over the past 45 years. Generally changes in extreme sea levels are
204 consistent with mean SLR in global tide gauge data (Menéndez and Woodworth 2010).
205 However, at Australia’s longest tide gauge records (see Figure 3), extreme sea levels were
206 found to be increasing more rapidly than median sea levels (Church et al. 2006).

207 The analysis of trends in waves is challenging because of the limited number of long-term
208 wave buoy observations, the earliest of which commenced in the mid-1970s along
209 Australia’s east coast (Figure 3). Satellite observations provide an alternative record, and
210 although of limited length (e.g. Young et al. 2011), have been found to be strongly positively
211 correlated with the positive trend in SAM (Westra et al. this issue) particularly from March
212 to August (Hemer et al. 2010).

213 Wave models forced by winds from atmospheric reanalyses provide an alternative means to
214 study longer-term trends in waves. The latest generation of models represent waves along

1 215 the Australian coast with high skill, although some regional biases exist due to known
2
3 216 limitations of the wave models – for example, parameterisation of the GBR results in
4
5 217 positive biases along much of the QLD coast, and known issues with Southern Ocean wind
6
7 218 forcing and swell dissipation terms lead to biases along the southern Australian margin, with
8
9
10 219 positive biases in wave height in this region (Hemer et al. 2016). Additionally problems of
11
12
13 220 temporal homogeneity in reanalysis products (Wang et al. 2006) lowers the confidence in
14
15 221 the trends.

16
17
18
19 222 For extreme waves, Young et al. (2011) found mostly significant positive trends of between
20
21 223 0.5% and 1.0% per year in mid-latitude oceans but less clear trends over tropical oceans in
22
23
24 224 99th-percentile satellite-measured wave heights from 1985 to 2008. Young et al. (2011)
25
26 225 suggested that positive trends were evident in the 100-year return period wave heights, but
27
28
29 226 their approach did not resolve the significance. Hemer (2010) also found strong positive
30
31
32 227 trends in the frequency of wave events exceeding the 98th-percentile in reanalysis wave data
33
34
35 228 over 1985 to 2002, but not in data from a wave buoy situated on Tasmania’s west coast over
36
37 229 the same period. Over the southern Indian Ocean, Bosserelle et al. (2012) found a significant
38
39
40 230 positive trend in annual mean wave height in a reanalysis-forced wave hindcast, also
41
42 231 attributed to the positive trend in the SAM, but no significant trends in the 90th percentile
43
44
45 232 wave height or extreme wave frequency ($H_s > 7$ m) impacting Western Australia. Izaguirre et
46
47
48 233 al. (2011) looked at the relationship between interannual variability of altimeter-derived
49
50 234 extreme wave heights and several climate drivers, finding only a statistically significant
51
52
53 235 relationship with the SAM index along the western and southern margins of Australia. Shand
54
55 236 et al. (2011) reviewed the NSW buoy record—one of the world’s longest running wave buoy
56
57
58 237 networks—for trends, and found a positive trend in the number of storms per year over the
59
60
61
62
63
64
65

1
2
3 238 last 22 years. These trends were attributed to a shift in phase in the Interdecadal Pacific
4
5
6 239 Oscillation (IPO) from more El Niño-like to more La Niña-like conditions (Goodwin 2005).

7 8 9 10 240 **3.2. Causes of change in coastal extremes and physical impacts**

11
12 241 Although an increase in extreme sea levels due to mean SLR has been demonstrated
13 242 (Menendez and Woodworth 2010), attribution of increased coastal impacts (i.e. erosion and
14
15 243 inundation) to rising sea levels has not been possible due to lack of long-term observations
16
17 244 and the confounding effect of other anthropogenic influences such as coastal development,
18
19
20 245 changes in catchment land-use and freshwater input to the coastal zone (Wong et al. 2014).

21
22
23 246 Several recent Australian studies have focused on the relationship between shoreline change
24
25
26 247 and natural modes of variability. For example, ENSO has been shown to influence storms and
27
28
29 248 hence wave climate and coastline orientation within embayments in eastern Australia
30
31
32 249 (Ranasinghe et al. 2004; Harley et al. 2011). O'Grady et al. (2015) found that ocean currents
33
34 250 and waves in eastern Bass Strait are generally correlated with the position of the STR location
35
36
37 251 (which in turn is influenced by ENSO and SAM), resulting in anomalous meridional wind- and
38
39 252 wave-driven transport.

40 41 42 253 **4. Future projections**

43 44 45 254 **4.1. Projections of regional SLR and extremes**

46
47
48
49
50 255 Mean SLR will continue to be the major driver of increasing extreme sea levels in the future,
51
52
53 256 with the most recent sea level projections from the Intergovernmental Panel on Climate
54
55
56 257 Change (IPCC) assessment incorporating contributions from oceans, glaciers, ice sheets, land
57
58
59 258 water and large-scale vertical land motion from GIA (Church et al. 2013). For 2090, global

259 mean SLR projections with 5–95% range are 0.47 [0.32 to 0.62] m under a mid-range
260 emissions scenario (RCP 4.5), and 0.62 [0.45 to 0.81] m under a “business-as-usual” emissions
261 scenario (RCP 8.5).

262 Based on the same approach, but using a different model for GIA, sea-level projections have
263 been developed for Australia (CSIRO and BoM 2015; McInnes et al. 2015). Values are larger
264 than global mean SLR projections, especially along the east coast of Australia where the 95th-
265 percentile values for RCP 8.5 in 2090 are up to 0.06 m higher due to the strengthening
266 subtropical gyre circulation of the South Pacific Ocean (Zhang et al. 2013). The GIA
267 readjustment lowers the SLR by several cm along the Australian coastline and up to 0.1 m in
268 the Gulf of Carpentaria, compared to offshore for RCP 8.5 by 2090.

269 Regarding the use of SLR projections in impact studies, Hunter (2012) derived a SLR
270 “allowance”; the height that assets need to be raised to maintain currently accepted
271 exceedance probabilities of coastal inundation (see also Hunter et al. 2013; McInnes et al.
272 2015). The allowance depends on the characteristics of extreme sea levels, projected mean
273 SLR and its range. However, it does not presently account for future changes in the
274 characteristics of extreme sea levels (i.e. frequency and intensity) that may result from
275 climate change. Weather and circulation changes are unlikely to cause large changes in the
276 characteristics of extreme sea levels over much of the coastline compared to the changes
277 brought about by SLR alone (Colberg and McInnes 2012), however it is possible that the future
278 movement of circulation patterns may lead to larger changes in the characteristics of
279 extremes in localized parts of the coastline (e.g. O’Grady et al. 2015).

280 **4.2 Projections of wave climate and storm surge**

1
2
3 282 scale. The NSW coast has received most attention regionally (e.g. Hemer et al. 2013b; Dowdy
4
5 283 et al. 2014; Kinsela et al. 2014). Hemer et al. (2013b) found wave direction to be most
6
7
8 284 susceptible to future climate change, mainly due to its sensitivity to the position of the STR.
9
10 285 They also noted that synoptic drivers of wave events on the NSW coast are poorly represented
11
12
13 286 in both global and regional General Circulation Models (GCMs). Dowdy et al. (2014) utilized
14
15 287 statistical downscaling to provide projections of large waves on the east Australian coast,
16
17
18 288 reporting fewer large waves due to decreasing storminess.
19
20
21 289 Several global wave climate studies provide wave projections for the Australian coast using
22
23
24 290 Coupled Model Intercomparison Project Phase 3 (CMIP3; e.g. Hemer et al. 2013c; Fan et al.
25
26
27 291 2014) and CMIP5 (Hemer and Trenham 2015 and references therein) GCMs. Most studies
28
29
30 292 have focused initially on projections of mean wave climate, although Hemer et al. (2013a)
31
32 293 indicate that the distribution of projected changes of the 99th-percentile and mean is similar
33
34
35 294 but scaled by a factor of approximately two. Future increases in southern ocean wave height
36
37 295 were projected using CMIP3 models and may impact the Tasmanian coast, particularly during
38
39
40 296 winter, while decreases in wave height were projected elsewhere around the Australian coast
41
42 297 (Hemer et al. 2013c). Increase in trade wind-generated waves have been projected along the
43
44
45 298 QLD coast, although this was countered by a projected decrease in wave heights during the
46
47
48 299 monsoon months – a result that is strongly dependent on GCM ability to represent the Coral
49
50 300 Sea cyclone systems. Wave projections based on CMIP5 experiments are largely consistent
51
52
53 301 with those based upon CMIP3 results.
54
55
56 302 Only one published study to date examines the impact of future changes in storm behavior
57
58
59 303 on extreme sea levels in Australia (Colberg and McInnes 2012). Projected changes in 95th-

1
2
3 304 percentile sea surface height in CMIP3-forced GCMs and regional GCMs were mostly small
4
5 305 (within ± 0.1 m) and resembled the changes in wind patterns simulated by the GCMs to some
6
7 306 degree, although inter-model differences were apparent.

8 9 307 **4.3 Projections of coastal impacts**

10
11
12 308 Assessments of how projected SLR will affect coastal inundation and erosion in Australia have
13
14
15 309 been undertaken in several studies. Inundation studies such as the national coastal
16
17
18 310 vulnerability assessment (Department of Climate Change 2009) have used static infill (i.e.
19
20
21 311 bathtub) approaches in which projections of SLR are added to appropriate coastal extreme
22
23 312 sea levels (usually the 100-year storm tide level) and inundation extent calculated. High
24
25
26 313 resolution LiDAR-derived elevations and 100-year storm tides combined with various SLR
27
28 314 projections were used for Victoria (McInnes et al. 2013) and Sydney (McInnes et al. 2012a).
29
30
31 315 These methods, while providing useful guidance for areas most vulnerable, do not capture
32
33 316 processes such as riverine input, or their projected changes due to climate change (see
34
35
36 317 Johnson et al, this issue), frictional attenuation of flows, and obstacles that may either permit
37
38
39 318 or limit flow and hence influence inundation during extreme events (McInnes et al. 2013).

40
41
42 319 While a large-scale assessment of erosion risk was undertaken nationally (Department of
43
44
45 320 Climate Change 2009) using simple Bruun Rule assumptions (Bruun 1962), an emerging
46
47
48 321 approach is to assess coastline response at the coastal compartment scale using physics-
49
50
51 322 based models that account for both ephemeral (storm-based) and chronic (long-term SLR-
52
53 323 induced) erosion (Woodroffe et al. 2012).

54
55
56 324 Using the Probabilistic Coastal Recession (PCR) Model, which accounts for the combined
57
58
59 325 effect of SLR, storm surge and storm waves, Ranasinghe et al. (2012) calculated a 1%

1 326 exceedance probability recession of 45 m at Narrabeen Beach, NSW and noted that Bruun
2
3 327 Rule-based estimates at the same location (for the same SLR) had a less than 8% probability
4
5 328 of being exceeded implying that Bruun rule-derived recession estimates may promote wide,
6
7 329 highly conservative coastal buffer zones. This finding further justifies the increasing concerns
8
9
10 330 about using the Bruun Rule to derive quantitative estimates of SLR-driven coastline recession
11
12
13 331 (e.g. Cooper and Pilkey 2004; Ranasinghe and Stive 2009). Wainwright et al. (2015) used the
14
15 332 PCR model in combination with the Shoreface Translation Model (Cowell et al. 1995) and
16
17
18 333 stochastic selection of SLR to simulate long term coastline trends. They demonstrated for
19
20
21 334 Narrabeen beach that the Economically Optimal coastal Setback Lines (EOSL) could be
22
23 335 determined from such quantitative assessments and that considerable existing infrastructure
24
25
26 336 is located seaward of the EOSL. By combining various modelling techniques including
27
28 337 coastline, coastal profile and 2D hydrodynamic coastal area models, Huxley (2011) showed
29
30
31 338 that coastline recession at Woolli Woolli and Batemens Bay in NSW from both SLR and
32
33
34 339 projected wave changes could be up to 40 m by 2100.

35
36
37 340 At the many inlet-interrupted coasts around Australia (especially NSW and WA), coastline
38
39
40 341 change will likely be affected not only by SLR but also by variations in river flows. Ranasinghe
41
42 342 et al. (2013) applied a physics-based scale-aggregated model to the WA coast near Swan River
43
44
45 343 (Fremantle) and Wilson inlet (Denmark) and predicted worst-case recessions of about 180 m
46
47
48 344 and 150 m respectively. However, application of the Bruun Rule yielded recessions that were
49
50 345 about 50% lower, highlighting its inaccuracy along inlet-interrupted coastlines.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

346 **5. Conclusions, knowledge gaps and recommendations**

1
2
3
4 347 As part of this Special Issue on Australian natural hazards, this review has summarized the
5
6
7 348 most recent scientific advances in both the measurement and understanding of sea level and
8
9 349 coastal extremes, and documented the state of our knowledge on projected future changes.
10
11 350 In this section, we discuss knowledge gaps and future research priorities.

12
13
14
15 351 While significant recent advances have been made in understanding trends in sea level
16
17
18 352 around Australia over the 20th and early part of the 21st Century, understanding of changes in
19
20
21 353 extreme sea levels over the instrumental period is limited, due to the availability of only two
22
23 354 fairly complete digital records of quality-controlled, hourly sea level observations that
24
25
26 355 commence in the late 19th (Fremantle, WA) and early 20th (Fort Denison, NSW) Centuries
27
28 356 (Figure 3). While ongoing updates to global hourly datasets (e.g. Menendez and Woodworth
29
30
31 357 2010; Hunter et al 2013) provide important foundations for such efforts, there is scope to
32
33
34 358 improve the temporal data availability in Australia by digitizing sea level records from the late
35
36 359 19th to early 20th Century – presently available as paper charts – to extend the temporal and
37
38
39 360 coastal coverage of digital tide records (Bill Mitchell, Pers. Comm., Figure 3). Such efforts
40
41 361 would enable more comprehensive studies on variability and trends in Australian extreme sea
42
43
44 362 levels.

45
46
47 363 Observations of waves are also limited, particularly along the more wave-exposed south coast
48
49
50 364 (Figure 3). Improving the coastal coverage of wave observations, including wave direction and
51
52
53 365 height as a function of wave frequency, would enable more detailed calibration of high-
54
55 366 resolution reanalysis datasets. This in turn would allow for a more rigorous understanding of
56
57
58 367 the relationship of extremes to natural modes of climate variability and climate change (i.e.

1
2
3 369 between wave climate and littoral transport processes. There also remains a need to better
4
5 370 understand how sea level and wave extremes during the instrumental period fit within the
6
7
8 371 broader context of paleo-climate reconstructions (e.g. Goodwin et al. 2004; Nott et al. 2013).
9
10 372 Such efforts would help constrain uncertainties around both present day and projected future
11
12
13 373 changes to sea level and coastal extremes.

14
15
16 374 There has been considerable advancement in the projection of SLR with greater
17
18
19 375 understanding of how the contributing processes affect regional SLR projections. However
20
21
22 376 the relatively low resolution of GCMs means that continental shelves are poorly resolved. An
23
24 377 improved understanding of SLR at the regional scale will be facilitated by emerging higher-
25
26
27 378 resolution, horizontal eddy-resolving ocean models (typically 10 km resolution) that are
28
29 379 capable of resolving shelf dynamics. An important limitation on assessing the impacts of SLR
30
31
32 380 in support of adaptation activities is the limited knowledge of local vertical land movements
33
34
35 381 and their projected future changes. This would be improved by increasing the number of
36
37 382 ongoing geodetic observations such as continuous GPS observations.

38
39
40
41 383 The most recent IPCC assessment assigns low confidence to future projections of waves and
42
43 384 in particular, storm surges (Church et al. 2013) due to the limited number of studies, limited
44
45
46 385 regional coverage of storm surge studies and large uncertainties in the ability of GCMs to
47
48
49 386 simulate severe weather events. Higher-resolution GCMs, improved regional climate models
50
51 387 and downscaling approaches will help resolve the relationship between severe weather
52
53
54 388 events and climate including the sequencing of storm events which in turn will improve
55
56 389 simulations of waves and storm surges and resulting coastal impacts. Advancements in
57
58
59 390 computing and hydrodynamic models mean that a greater focus on understanding past and

391 future storm surge changes over larger geographical regions is becoming increasingly possible
392 (e.g. Verlaan et al. 2015), but future efforts also need to consider the combination of storm
393 surge and wave-generated extreme sea levels.

394 How the Australian coastline will respond to SLR and extreme events, such as storm surges
395 and waves through erosion or deposition, remains a major gap in our knowledge. Coastline
396 response is dependent not only on changes to the climatic drivers, but also on coastal
397 geomorphology. A better understanding is needed of how different climatic drivers operating
398 on different spatio-temporal scales manifest in the coastal zone, yet few long-term
399 observational coastal records, such as the Narrabeen record, are available to build this
400 knowledge. Such understanding needs to incorporate coastal hydrodynamic processes that
401 occur both in a cross-shore (vertically non-uniform) and longshore (mostly vertically uniform)
402 sense. The challenge, however, lies in modelling morphological change due to the combined
403 effect of waves and currents at timescales greater than a few years. Scale-aggregated
404 modelling, in which the main physical processes that govern coastline position are
405 parameterised and collectively represented by fully explicit governing equations, may offer
406 an efficient approach to quantify climate change impacts and their uncertainties on coasts
407 (e.g. Stive and Wang 2003; Ranasinghe et al. 2013). However, significant efforts are needed
408 to develop and test such approaches for modelling coastline change.

409 Finally, within estuaries, the number and value of assets that may be impacted by oceanic
410 extremes is at least an order of magnitude higher than those on the open coast. The
411 interactions and dependencies in space and time of tide, surge, wave setup and riverine
412 flooding make the assessment of extreme water levels and inundation within estuaries one
413 of high complexity (Zheng et al. 2013) and in need of further research.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

414 **Acknowledgements**

415 The lead author, MH and RH acknowledge the Australian Climate Change Science Program
416 for funding this research. RR is supported by the AXA Research fund. This paper was a result of
417 collaboration through the 'Trends and Extremes' working group as part of the Australian Water and
418 Energy Exchanges Initiative (OzEWEX).



1 References

- 2 Bosserelle C., Pattiaratchi C., Haigh I. (2012) Inter-annual variability and longer-term changes in the
3 wave climate of Western Australia between 1970 and 2009. *Ocean Dynamics* 62:63-76. DOI:
4 10.1007/s10236-011-0487-3.
- 5 Bruun P. (1962) Sea-level rise as a cause of coastal erosion. *J. Waterw. Harbours Coastal Eng. Div.*
6 *Am. Soc. Civ. Eng* 88:117-130.
- 7 Church J.A., Hunter J.R., McInnes K.L., White N.J. (2006) Sea-level rise around the Australian
8 coastline and the changing frequency of extreme sea-level events. *Australian Meteorological*
9 *Magazine* 55:253-260.
- 10 Church J.A., Clark P.U., Cazenave A., Gregory J.M., Jevrejeva S., Levermann A., Merrifield M.A., Milne
11 G.A., Nerem R.S., Nunn P.D., Payne A.J., Pfeffer W.T., Stammer D., Unnikrishnan A.S. (2013)
12 *Sea Level Change.*, in: T. F. Stocker, et al. (Eds.), In: *Climate Change 2013: The Physical*
13 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
14 *Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United
15 Kingdom and New York, NY, USA.
- 16 Colberg F., McInnes K.L. (2012) The impact of future changes in weather patterns on extreme sea
17 levels over southern Australia. *Journal of Geophysical Research: Oceans* 117:C08001. DOI:
18 10.1029/2012jc007919.
- 19 Cooper J.A.G., Pilkey O.H. (2004) Sea-level rise and shoreline retreat: time to abandon the Bruun
20 Rule. *Global and Planetary Change* 43:157-171.
- 21 Cowell P., Roy P., Jones R. (1995) Simulation of large-scale coastal change using a morphological
22 behaviour model. *Marine Geology* 126:45-61.
- 23 CSIRO, BoM. (2015) *Climate Change in Australia Information for Australia's Natural Resource*
24 *Management Regions*, CSIRO and Bureau of Meteorology. pp. 222 pp.
- 25 Department of Climate Change. (2009) *Climate Change Risks to Australia's Coast. A First Pass*
26 *National Assessment. Report published by the Australian Government's Department of*
27 *Climate Change.*
- 28 Dowdy A.J., Mills G.A., Timbal B., Wang Y. (2014) Fewer large waves projected for eastern Australia
29 due to decreasing storminess. *Nature Clim. Change* 4:283-286. DOI: 10.1038/nclimate2142
- 30 Eliot M. (2012) Sea level variability influencing coastal flooding in the Swan River region, Western
31 Australia. *Continental Shelf Research* 33:14-28. DOI:
32 <http://dx.doi.org/10.1016/j.csr.2011.08.012>.
- 33 Eliot M., Pattiaratchi C. (2010) Remote forcing of water levels by tropical cyclones in southwest
34 Australia. *Continental Shelf Research* 30:1549-1561. DOI:
- 35 Fan Y., Lin S.-J., Griffies S.M., Hemer M.A. (2014) Simulated global swell and wind-sea climate and
36 their responses to anthropogenic climate change at the end of the twenty-first century.
37 *Journal of Climate* 27:3516-3536.
- 38 Feng M., Meyers G. (2003) Interannual variability in the tropical Indian Ocean: a two-year time-scale
39 of Indian Ocean Dipole. *Deep Sea Research Part II: Topical Studies in Oceanography* 50:2263-
40 2284. DOI: [http://dx.doi.org/10.1016/S0967-0645\(03\)00056-0](http://dx.doi.org/10.1016/S0967-0645(03)00056-0).
- 41 Gallop S.L., Young I.R., Ranasinghe R., Durrant T.H., Haigh I.D. (2014) The large-scale influence of the
42 Great Barrier Reef matrix on wave attenuation. *Coral reefs* 33:1167-1178.
- 43 Goodwin I.D. (2005) A mid-shelf, mean wave direction climatology for southeastern Australia, and its
44 relationship to the El Niño—Southern Oscillation since 1878 AD. *International Journal of*
45 *Climatology* 25:1715-1729.
- 46 Green D., Alexander L., McInnes K.L., Church J., Nicholls N., N. W. (2010) An assessment of climate
47 change impacts and adaptation for the Torres Strait Islands. *Climatic Change* 102:405–433
48 DOI: 10.1007/s10584-009-9756-2

- 49 Haigh I., Eliot M., Pattiaratchi C. (2010) Historic changes in storm surges around southwestern
50 Australia, 15th Physics of Estuaries and Coastal Seas Conference, Columbo.
- 51 Haigh I., Wijeratne E.M.S., MacPherson L., Pattiaratchi C., Mason M., Crompton R., George S. (2014a)
52 Estimating present day extreme water level exceedance probabilities around the coastline of
53 Australia: tides, extra-tropical storm surges and mean sea level. *Climate Dynamics* 42:121-
54 138. DOI: 10.1007/s00382-012-1652-1.
- 55 Haigh I., MacPherson L., Mason M., Wijeratne E.M.S., Pattiaratchi C., Crompton R., George S. (2014b)
56 Estimating present day extreme water level exceedance probabilities around the coastline of
57 Australia: tropical cyclone-induced storm surges. *Climate Dynamics* 42:139-147. DOI:
58 10.1007/s00382-012-1653-0.
- 59 Hall J.D., Matthews A.J., Karoly D.J. (2001) The modulation of tropical cyclone activity in the
60 Australian region by the Madden-Julian Oscillation. *Monthly Weather Review* 129:2970-
61 2982.
- 62 Harley M., Turner I., Short A., Ranasinghe R. (2011) A reevaluation of coastal embayment rotation:
63 The dominance of cross-shore versus alongshore sediment transport processes, Collaroy-
64 Narrabeen Beach, southeast Australia. *Journal of Geophysical Research: Earth Surface*
65 (2003–2012) 116.
- 66 Hemer M.A. (2010) Historical trends in Southern Ocean storminess: Long-term variability of extreme
67 wave heights at Cape Sorell, Tasmania. *Geophysical Research Letters* 37.
- 68 Hemer M.A., Trenham C.E. (2015) Evaluation of a CMIP5 derived dynamical global wind wave climate
69 model ensemble. *Ocean Modelling* submitted.
- 70 Hemer M.A., Church J.A., Hunter J.R. (2010) Variability and trends in the directional wave climate of
71 the Southern Hemisphere. *International Journal of Climatology* 30:475-491.
- 72 Hemer M.A., Katzfey J., Trenham C.E. (2013a) Global dynamical projections of surface ocean wave
73 climate for a future high greenhouse gas emission scenario. *Ocean Modelling* 70:221-245.
- 74 Hemer M.A., McInnes K.L., Ranasinghe R. (2013b) Projections of climate change-driven variations in
75 the offshore wave climate off south eastern Australia. *International Journal of Climatology*
76 33:1615-1632. DOI: 10.1002/joc.3537.
- 77 Hemer M.A., Fan Y., Mori N., Semedo A., Wang X.L. (2013c) Projected changes in wave climate from
78 a multi-model ensemble. *Nature Clim. Change* advance online publication. DOI:
79 [http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1791.html#suppleme](http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1791.html#supplementary-information)
80 [ntary-information.](http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1791.html#supplementary-information)
- 81 Hemer, M.A., Zieger, S., Durrant, T., O’Grady, J., Hoeke, R.K., McInnes, K.L. and Rosebrock, U. 2016: A
82 revised assessment of Australia’s national wave energy resource. (in prep)
- 83 Hoeke R.K., McInnes K.L., Kruger J.C., McNaught R.J., Hunter J.R., Smithers S.G. (2013) Widespread
84 inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary*
85 *Change* 108:128-138. DOI: <http://dx.doi.org/10.1016/j.gloplacha.2013.06.006>.
- 86 Hunter J. (2012) A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic*
87 *Change* 113:239-252. DOI: 10.1007/s10584-011-0332-1.
- 88 Hunter J.R., Church J.A., White N.J., Zhang X. (2013) Towards a global regionally varying allowance
89 for sea-level rise. *Ocean Engineering*:1-11. DOI: 10.1016/j.oceaneng.2012.12.041i.
- 90 Izaguirre C., Méndez F.J., Menéndez M., Losada I.J. (2011) Global extreme wave height variability
91 based on satellite data. *Geophysical Research Letters* 38:n/a-n/a. DOI:
92 10.1029/2011gl047302.
- 93 Kent D.M., Kirono D.G.C., Timbal B., Chiew F.H.S. (2013) Representation of the Australian sub-
94 tropical ridge in the CMIP3 models. *International Journal of Climatology* 33:48-57. DOI:
95 10.1002/joc.3406.
- 96 Kinsela M., Taylor D., Treloar D., Dent J., Garber S., Mortlock T., Goodwin I. (2014) NSW coastal
97 ocean wave model: investigating spatial and temporal variability in coastal wave climates,
98 Ulladulla, NSW: NSW Coastal Conference.

99 Kuleshov Y., Qi L., Fawcett R., Jones D. (2008) On tropical cyclone activity in the Southern
100 Hemisphere: trends and the ENSO connection. *Geophysical Research Letters* 35.
101 Leonard M., Metcalfe A., Lambert M. (2008) Frequency analysis of rainfall and streamflow extremes
102 accounting for seasonal and climatic partitions. *Journal of Hydrology* 348:135-147. DOI:
103 <http://dx.doi.org/10.1016/j.jhydrol.2007.09.045>.
104 Leonard M., Westra S., Phatak A., Lambert M., van den Hurk B., McInnes K., Risbey J., Schuster S.,
105 Jakob D., Stafford-Smith M. (2014) A compound event framework for understanding
106 extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change* 5:113-128.
107 McInnes K.L., Hubbert G.D. (2001) The impact of eastern Australian cut-off lows on coastal sea
108 levels. *Meteorological Applications* 8:229-243. DOI: 10.1017/s1350482701002110.
109 McInnes K.L., Hubbert G.D. (2003) A numerical modelling study of storm surges in Bass Strait.
110 *Australian meteorological magazine* 52 143-156
111 McInnes K.L., Lipkin F., O'Grady J.G., Inman M. (2012a) Modelling and Mapping of Coastal Inundation
112 under Future Sea Level., A report for Sydney Coastal Councils Group, . pp. 62 pp.
113 McInnes K.L., Macadam I., Hubbert G., O'Grady J. (2013) An assessment of current and future
114 vulnerability to coastal inundation due to sea-level extremes in Victoria, southeast Australia.
115 *International Journal of Climatology* 33:33-47. DOI: 10.1002/joc.3405.
116 McInnes K.L., Church J.A., Monselesan D., Hunter J.R., O'Grady J.G., Haigh I. D., Zhang X. (2015) Sea-
117 level Rise Projections for Australia: Information for Impact and Adaptation Planning.
118 *Australian Meteorological and Oceanographic Journal* submitted.
119 McInnes K.L., O'Grady J.G., Hemer M.A., Macadam I., Abbs D.J., White C.J., Corney S.P., Grose M.R.,
120 Holz G.K., Gaynor S.M., Bindoff N.L. (2012b) Climate Futures for Tasmania: Extreme tide and
121 sea-level events, Antarctic Climate and Ecosystems CRC. pp. 40 pp.
122 Menéndez M., Woodworth P.L. (2010) Changes in extreme high water levels based on a quasi-global
123 tide-gauge data set. *Journal of Geophysical Research: Oceans* 115:C10011. DOI:
124 10.1029/2009jc005997.
125 Nott J., Green C., Townsend I., Callaghan J. (2013) The World Record Storm Surge and the Most
126 Intense Southern Hemisphere Tropical Cyclone: New Evidence and Modeling. *Bulletin of the*
127 *American Meteorological Society* 95:757-765. DOI: 10.1175/bams-d-12-00233.1.
128 O'Grady J.G., McInnes K.L., Colberg F., Hemer M.A., Babanin A.V. (2015) Longshore wind, waves and
129 currents: climate and climate projections at Ninety Mile Beach, southeastern Australia.
130 *International Journal of Climatology*:n/a-n/a. DOI: 10.1002/joc.4268.
131 Oliver E.C.J., Thompson K.R. (2011) Sea level and circulation variability of the Gulf of Carpentaria:
132 Influence of the Madden-Julian Oscillation and the adjacent deep ocean. *Journal of*
133 *Geophysical Research: Oceans* 116:C02019. DOI: 10.1029/2010jc006596.
134 Pattiaratchi C., Wijeratne E. (2014) Observations of meteorological tsunamis along the south-west
135 Australian coast. *Natural Hazards* 74:281-303.
136 Pattiaratchi C.B., Eliot M. (2008) Sea level variability in southwest Australia: from hours to decades.,
137 *Proceedings of the 31st ASCE international conference on coastal engineering, Hamburg.*
138 Ranasinghe R., Stive M.J. (2009) Rising seas and retreating coastlines. *Climatic Change* 97:465-468.
139 Ranasinghe R., Callaghan D., Stive M.J. (2012) Estimating coastal recession due to sea level rise:
140 beyond the Bruun rule. *Climatic Change* 110:561-574.
141 Ranasinghe R., McLoughlin R., Short A., Symonds G. (2004) The Southern Oscillation Index, wave
142 climate, and beach rotation. *Marine Geology* 204:273-287.
143 Ranasinghe R., Duong T.M., Uhlenbrook S., Roelvink D., Stive M. (2013) Climate-change impact
144 assessment for inlet-interrupted coastlines. *Nature Clim. Change* 3:83-87. DOI:
145 [http://www.nature.com/nclimate/journal/v3/n1/abs/nclimate1664.html#supplementary-](http://www.nature.com/nclimate/journal/v3/n1/abs/nclimate1664.html#supplementary-information)
146 [information.](http://www.nature.com/nclimate/journal/v3/n1/abs/nclimate1664.html#supplementary-information)
147 Seneviratne S., Nicholls N., Easterling D., Goodess C., Kanae S., Kossin J., Luo Y., Marengo J., McInnes
148 K., Rahimi M., Reichstein M., Sorteberg A., Vera C., Zhang X. (2012) Changes in climate
149 extremes and their impacts on the natural physical environment. , In: 'Managing the Risks of

150 Extreme Events and Disasters to Advance Climate Change Adaptation' A Special Report of
151 Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC),
152 Cambridge University Press, Cambridge, UK, and New York, NY, USA. pp. 109-230.

153 Shand T.D., Carley J.T., You Z.J.a., Cox R.J. (2011) Long-term trends in NSW coastal wave climate and
154 derivation of extreme design storms, NSW Coastal Conference Tweed Heads.

155 Tregoning P., Lambeck K., Ramillien G. (2008) GRACE estimates of sea surface height anomalies in
156 the Gulf of Carpentaria, Australia. *Earth and Planetary Science Letters* 271:241-244.

157 Verlaan M., De Kleermaeker S., Buckman L. (2015) GLOSSIS: Global storm surge forecasting and
158 information System, Australasian Coasts and Ports Conference, Auckland, New Zealand.

159 Wainwright D., Ranasinghe R., Callaghan D., Woodroffe C., Jongejan R., Dougherty A., Rogers K.,
160 Cowell P. (2015) Moving from deterministic towards probabilistic coastal hazard and risk
161 assessment: Development of a modelling framework and application to Narrabeen Beach,
162 New South Wales, Australia. *Coastal Engineering* 96:92-99.

163 Wang X.L., Swail V.R., Zwiers F.W. (2006) Climatology and changes of extratropical cyclone activity:
164 Comparison of ERA-40 with NCEP-NCAR reanalysis for 1958-2001. *Journal of Climate*
165 19:3145-3166.

166 Westra S., Leonard M., Zheng F. (2015) Joint Probability Modelling in Estuarine Regions Engineers
167 Australia.

168 White N.J., Haigh I.D., Church J.A., Keon T., Watson C.S., Pritchard T., Watson P.J., Burgette R.J., Eliot
169 M., McInnes K.L., You B., Zhang X., Tregoning P. (2014) Australian Sea Levels - Trends,
170 regional variability and Influencing Factors. *Earth-Science Reviews*. 136:155–174

171 Wong P.-P., Losada I.J., Gattuso J.P., Hinkel J., Khattabi A., McInnes K.L., Saito Y., Sallenger A. (2014)
172 Coastal Systems and Low-Lying Areas, *Climate Change 2014:Impacts, Adaptation, and*
173 *Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the*
174 *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge
175 University Press, Cambridge, United Kingdom and New York, NY, USA, (in press).

176 Woodham R., Brassington G.B., Robertson R., Alves O. (2013) Propagation characteristics of coastally
177 trapped waves on the Australian Continental Shelf. *Journal of Geophysical Research: Oceans*
178 118:4461-4473. DOI: 10.1002/jgrc.20317.

179 Woodroffe C., Cowell P., Callaghan D., Ranasinghe R., Jongejan R, Wainwright D., Barry S., Rogers
180 K., Dougherty A. (2012) Approaches to risk assessment on Australian coasts: a model
181 framework for assessing risk and adaptation to climate change on Australian coasts, National
182 Climate Change Adaptation Research Facility, Gold Coast, 205 pp.

183 Young I.R., Zieger S., Babanin A.V. (2011) Global Trends in Wind Speed and Wave Height. *Science*
184 332:451-455. DOI: 10.1126/science.1197219.

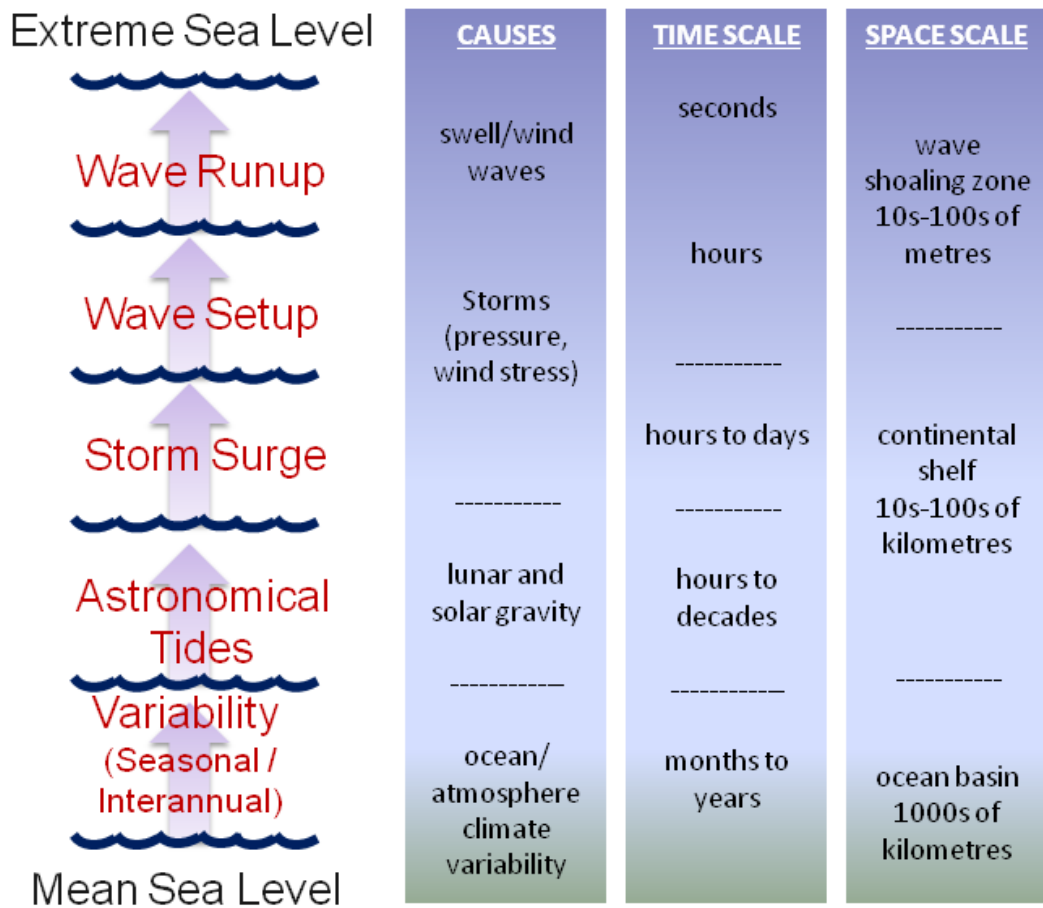
185 Zhang X., Church J.A., Platten S.M., Monselesan D. (2013) Projection of subtropical gyre circulation
186 and associated sea level changes in the Pacific based on CMIP3 climate models. *Climate*
187 *Dynamics*. DOI: 10.1007/s00382-013-1902-x.

188 Zheng F., Westra S., Sisson S.A. (2013) Quantifying the dependence between extreme rainfall and
189 storm surge in the coastal zone. *Journal of Hydrology* 505:172-187.

190 Zheng F., Leonard M., Westra S. (2015) Application of the design variable method to estimate coastal
191 flood risk. *Journal of Flood Risk Management* (in press).

1 **Figures**

2



3

4 **Figure 1:** Oceanic phenomena that contribute to the total water levels at the coast during an
 5 extreme sea level event, their causes and the time and space scales over which they
 6 operate.

7

8

9

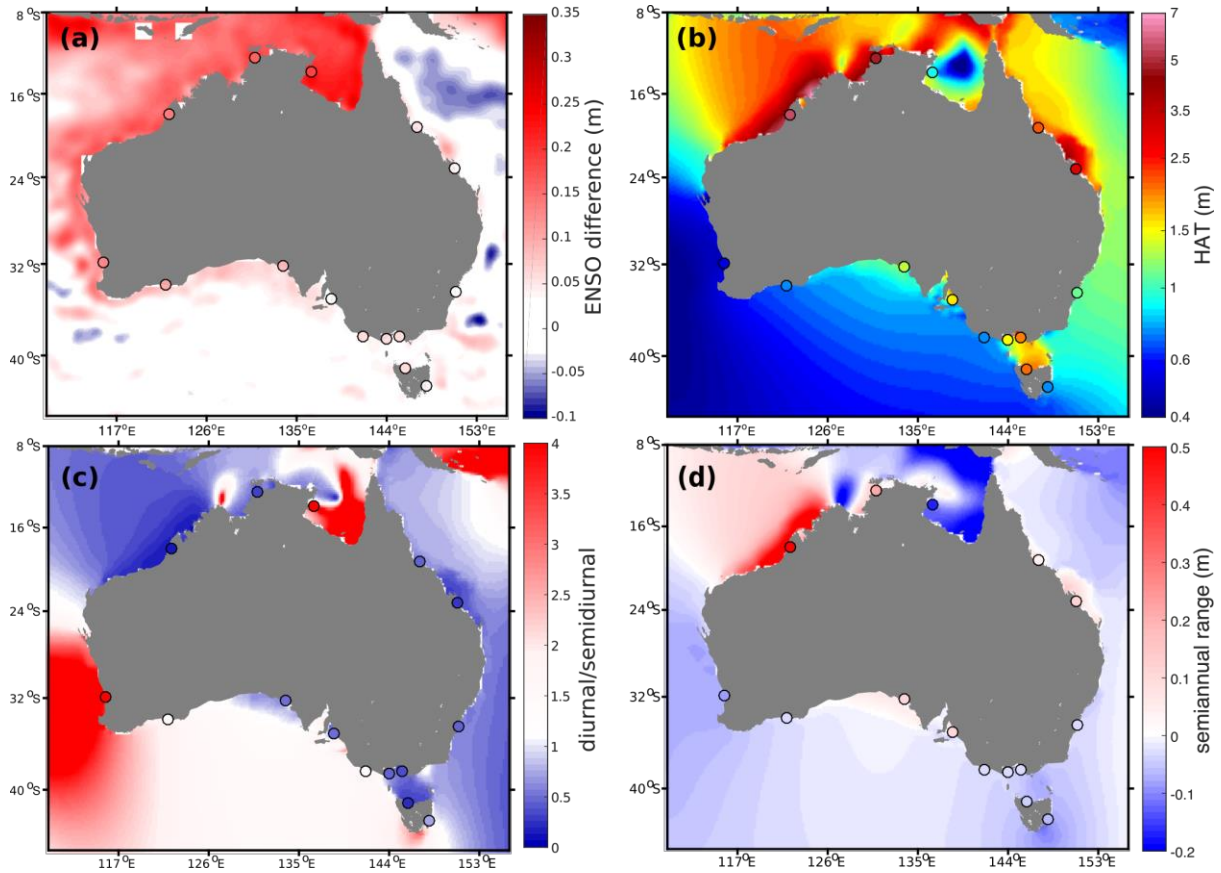
10

11

12

13

14



15

16 **Figure 2:** Tide gauge and satellite altimetry derived ENSO-dependent sea-level differences
 17 and astronomical tidal characteristics around Australia: (a) differences between La Niña and El
 18 Niño sea levels conditions, defined as median monthly sea-level during periods when SOI>1
 19 minus periods when SOI<-1. (b) Highest astronomical tide (HAT) relative to MSL on a
 20 logarithmic scale. (c) Tide type, defined as the ratio of the amplitude of the principle diurnal
 21 constituents (K1, O1) to the semidiurnal constituents (M2, S2); when this ratio is >3 tides are
 22 considered fully diurnal in nature, <3 to >0.25 they are mixed and < 0.25 they are diurnal. (d)
 23 Range in semiannual tidal amplitude (indicated by 2K2 – 2O1 constituents); positive
 24 (negative) values indicate peak astronomical spring tides occur near the equinoxes
 25 (solstices). Black circles indicate tide gauges in the Australian Baseline Sea Level Monitoring
 26 Project network; circle interior colours indicate values derived from hourly sea-level
 27 observations; gridded data values are independently calculated from the following sources:
 28 (a) AVISO DT MSLA "all sat merged" (www.aviso.altimetry.fr); (b-d) TPX07-Atlas
 29 (volkov.oce.orst.edu/tides).

30

31

32

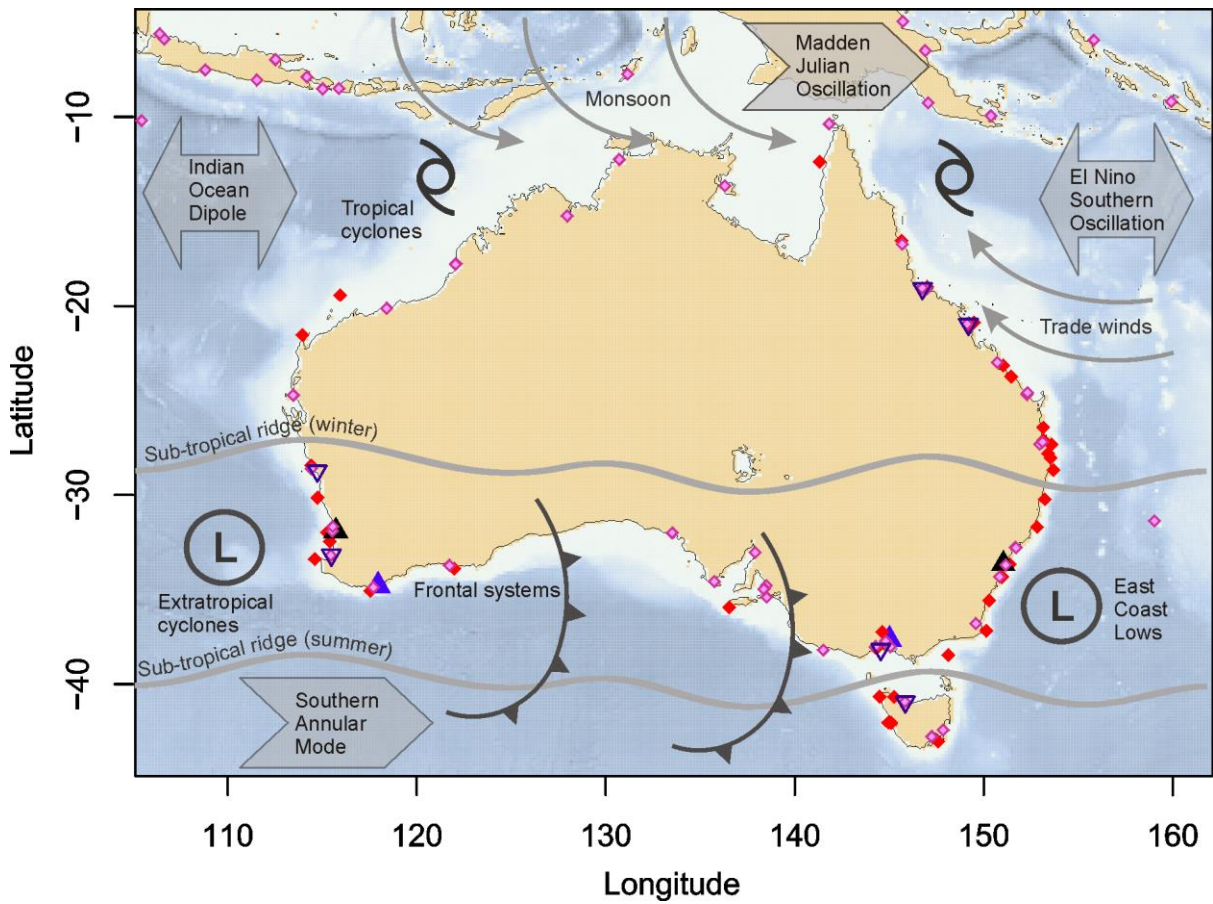
33

34

35

36

37
38



39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56

Figure 3: Australian coastline showing tide gauge locations from the GESLA (Hunter et al 2013) dataset (pink-filled diamonds), locations of Australia’s two longest hourly digital tide gauge data (large black triangles) at Fremantle in the west commencing in 1897 and Fort Denison in the east commencing in 1914, locations where digitization could extend the hourly records to the late 19th century (large solid blue triangles) and locations where digitization could extend the hourly record back at least to 1950 (open blue triangles). Red diamonds indicate locations of wave buoy data. The weather and climate drivers discussed in relation to extreme coastal sea levels are also illustrated. Light-to-dark shading over the ocean indicates shallow-to-deep bathymetry respectively.