Climate Change Impacts on Australian Beaches and Surf Spots

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1.Climate changes affecting the Australian coast in general

1.1 Sea Level Rise

Sea level rise (SLR) is one of two projected anthropogenic-induced climate changes identified to have impacts along the entire coastline of Australia. Globally, the latest IPCC sixth assessment SLR projections for 2100 have been revised upwards once again. The IPCC sixth assessment now has an additional high-risk analysis, with findings that a global rise up to 2 m by 2100 under a very high greenhouse gas emissions scenario cannot be ruled out due to deep uncertainty in future ice sheet thermodynamic processes**.** Figure 1 (Kopp et al., 2016; IPCC AR6) below shows that since 1900 the global SLR shows large acceleration in comparison to previous years since 500 BCE. For the 2006-2018 period, it's been rising at a rate of 3.7 mm/year – nearly three times as fast as during 1901-1971 (1.3 mm/year). The confidence level for the 20th century global mean SLR is high - this high confidence level is also found in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) which was published in 2019.

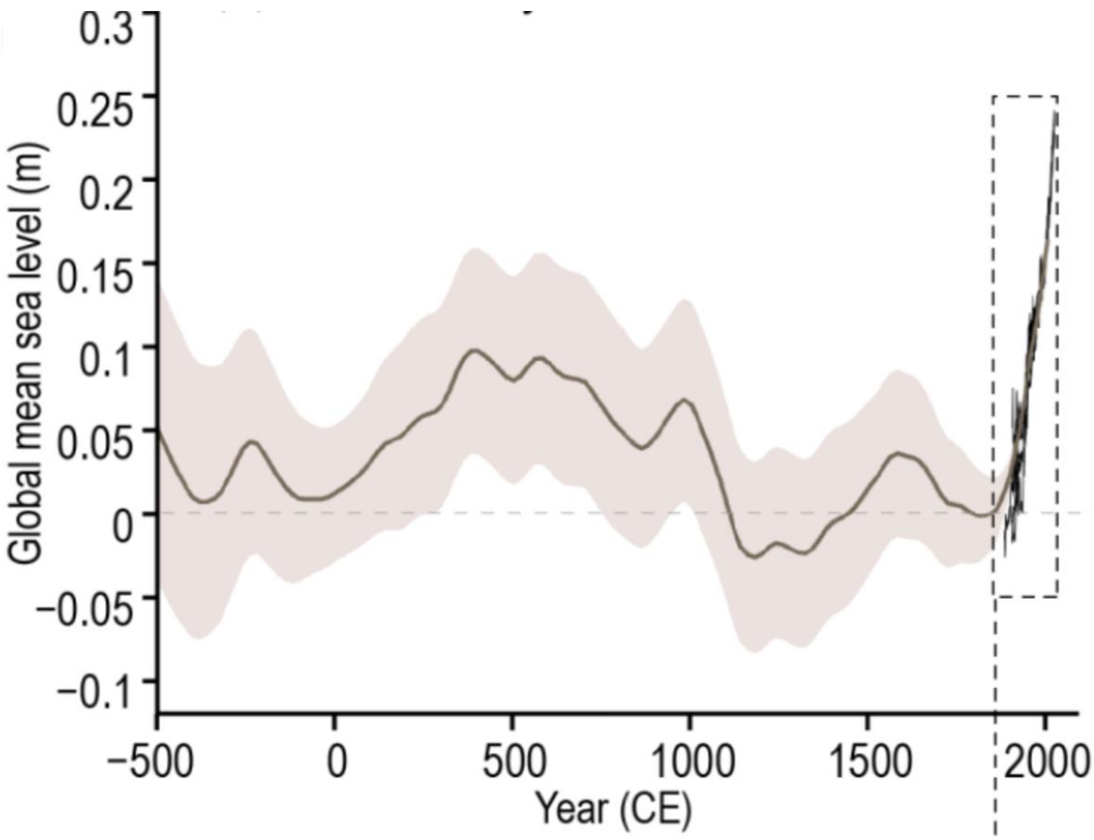


Figure 1 Global mean sea level over the last 2500 years with high confidence band in pink and dashed line showing increase in sea level since 1900. Source: IPCC AR6 Fig 2.28b; Courtesy Realclimate.org

The high-resolution sea level projection for Australia, used by the IPCC sixth assessment chapter 11, is based on the technique of dynamical downscaling and could therefore also be assessed as having high confidence. The largest uncertainty remains in the contribution of the Antarctic Ice Sheet to future SLR and the possibility of higher rates of SLR cannot be excluded ("Australasia", 2023; Lewis et al., 2011). In order to place the SLR projections in the context of the uncertainty of greenhouse gases and aerosols used to create them, the greenhouse gas Representative Concentration Pathways (RCPs) are summarised below:

IPCC 6 emissions scenarios:

- RCP2.6 represents low emissions – indicating a 2.6 watts per metre squared (W/m2) forcing increase relative to pre-industrial conditions.
- RCP4.5 medium emissions - indicating a 4.5 W/m2 forcing increase relative to pre-industrial conditions.
- RCP8.5 high emissions - - indicating a 8.5 W/m2 forcing increase relative to pre-industrial conditions. This is often referred to as the “business-as usual scenario”.

From 1993 to 2009, the average rate of rise for Australia was 4.5 ± 1.3 mm yr-1 - this reduces to 3.1 mm yr-1 after the signal correlated with the Southern Oscillation Index is removed. For a business-as-usual scenario (RCP 8.5), the rate consistently increases during the 21st century, reaching almost 12 mm yr-1 by 2100 along the entire coast ("Australasia", 2023; McInnes et al., 2015; Zhang et al., 2017). Figure 2 below is a global representation of mean relative sea level change from ensemble CMIP5 models under an RCP 8.5 scenario, comparing 2090 with 2005.

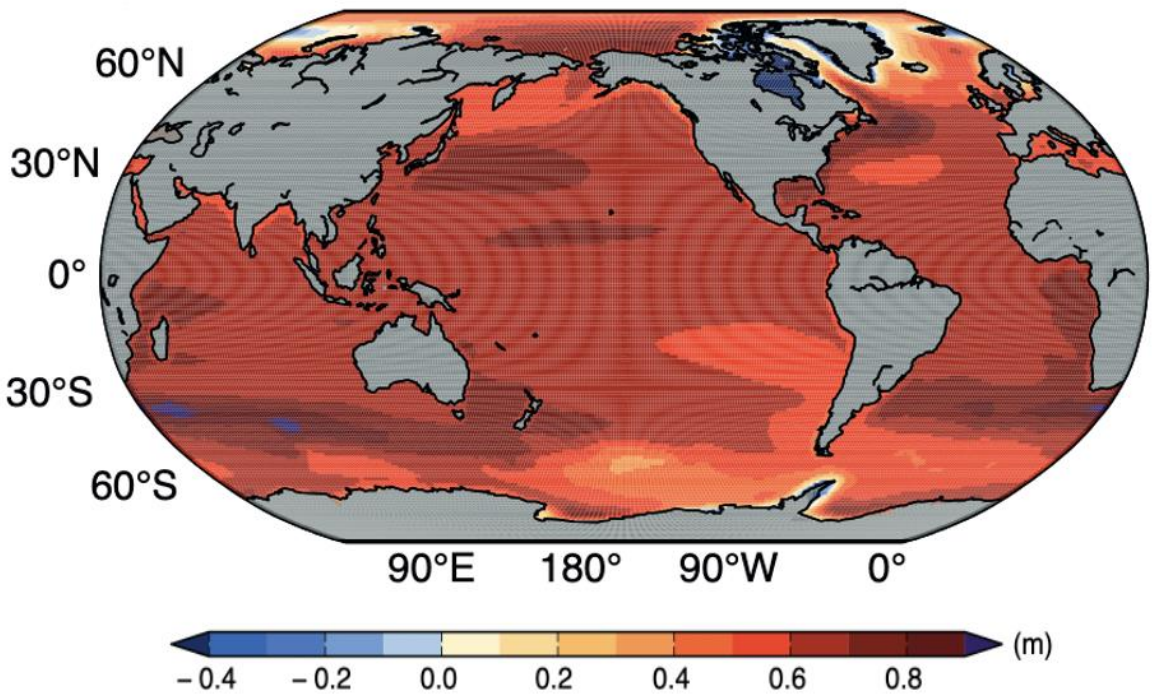


Figure 2 A global representation of mean relative sea level change from 21 CMIP5 models for RCP 8.5, comparing 2090 with 2005. Source IPCC 5 chapter 13

Table 1 below shows the projected sea level rise for the year 2090 (in meters) under an RCP 8.5 scenario, for selected measurement stations along the Australian coast (McInnes et al., 2015).

Table 1 Projected sea level rise at the surf breaks using McInnes et. al (2015) model data. Median values shown with 5 -95% range in brackets. Values are for the years 2050 and 2090 relative to 2005.

Nearest measurement station	**Projected sea level rise (m) for 2050**	**Projected sea level rise (m) for 2090**
Mackay	0.26 (0.18 - 0.35)	0.64 (0.44 - 0.87)
Newcastle	0.27 (0.19 - 0.36)	0.66 (0.46 - 0.87)
Sydney	0.27 (0.19 - 0.36)	0.66 (0.45 - 0.88
Stony Point	0.24 (0.15 - 0.32)	0.59 (0.38 - 0.81)
Bunbury	0.25 (0.16 - 0.34)	0.62 (0.40 - 0.85)

Note that due to accelerating ice sheet melt, sea level rise for the region may exceed these values and reach 2m (Kopp et al., 2017).

1.1.1 Beach erosion from sea level rise

Sea level rise is one of a few changes discussed in this report that can cause beach erosion. The primary response of a beach to SLR is a landward and upward shift of the profile, with encroachment and sediment transported seaward, as shown in fig. 3c (Cowell et al., 1995). Geological evidence, however, shows other responses which are dependent on the shoreface slope – A gently sloping beach may show a net landward movement of sand through wave action, resulting in fill and shoreline recession, as shown in fig. 3a. Alternatively, an intermediate response may occur, with sediment losses both landward and seaward as shown in fig. 3b

This modelling however does not consider sediment sources and sinks outside of modelling boundaries and sand compensation that can occur as a result. There is a threshold in sand movement, though, above which the sand is not replenished after successive storms and SLR and the beach will recede. This has been shown to occur in the geological record (Goodwin et al., 2006).

Changes to beach morphology are therefore beach compartment/ embayment specific and depend on factors such as sediment budget, sources and sinks and their changes.

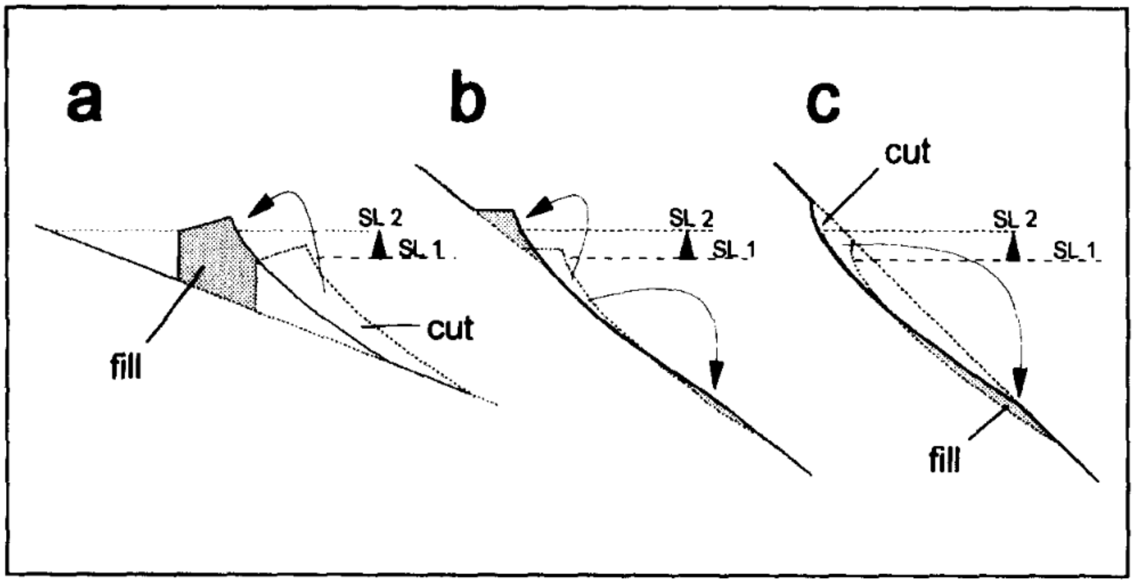


Figure 3 Changes to beach morphology. Reprinted from Marine Geology, Vol 126, issues 1-4, 45-61 Cowell, P. J., Roy, P. S., & Jones, R. A. (1995). Simulation of large-scale coastal change using a morphological behaviour model

The consequences (including economic) of such erosion in connection with beach recreational use in general can be severe (Lazarow, 2007). A recent historical example of beach erosion (although not necessarily related to sea level rise) is the erosion of the dunes of Main and Clarkes Beach, Byron Bay, 2020 to 2021, which caused the exposure of clay and coffee rock and damaged paths and accessways (refer Byron Shire Council website).

Consequences of beach erosion from SLR for surfing specifically are also beach specific and depend on whether sand influences wave breaking quality for surfing. The assessed confidence in this risk is high for beaches constrained with coastal defence structures and/ or coastal infrastructure (and no sediment management infrastructure) (Pilkey & Cooper, 2014). These structures lead to enhanced longshore transport of sediment away from area, hence further erosion (Cooper, O'Connor, et al., 2020). However, for unconstrained sandy beaches erosion effects due to sea level rise may be negligible (Cooper, Masselink, et al., 2020) - 78% of Australian beaches have remained stable between 1988 and 2019 (Short, 2022). In addition, shoreline data from the 1960s has been preserved at a few locations along this coastline and there is no clear correlation with the SLR measured over that time (Short, 2022). A recent study by Xie et al. (2024) found that SLR also creates stronger nearshore currents, which in combination with larger storm waves in some locations (due to climate change) may increase the potential for sand headland bypassing. There is a need for further detailed research to reveal how climate change drivers may impact headlands, and the associated sand headland bypassing (Xie et al., 2024). For sandy unconstrained beaches, this risk due to sea level rise is therefore assessed as low in confidence.

1.1.2 Reduced exposure of swell to sea floor due to increased water level

From a surfing perspective, a primary risk from sea level rise is a reduction in the exposure of an ocean swell to the sea bottom (reef or sandbar bottom) (Toth et al., 2023). A swell requires this exposure to the sea bottom to become a good quality surfing wave. Dissipation of wave energy over reef/sand decreases as water depth increases (Holthuijsen, 2007) leading to reduced quality in the surf break overall and/or reduced tidal conditions for when reef or sand exposure is sufficient for surfing – this would especially affect reef and point breaks where sand movement does not affect depth to a significant degree. In addition, the M2 semi-diurnal (which is the dominant component of the tidal signal) tidal range itself is expected to increase due to SLR (Harker et al., 2019), limiting the reef / sand bottom exposure time for suitable swell energy. A high confidence assessment is assigned for reef-based point and reef breaks that are best at low tide for this risk; however, the confidence assessment would be beach compartment specific for beach (sand sea floor) breaks. This risk is for surf breaks throughout the Australian coast.

1.2 Increased El Niño Southern Oscillation (ENSO) rainfall variability

ENSO refers to the El Niño-Southern Oscillation, a recurring climate pattern involving temperature fluctuations in the central and eastern tropical Pacific Ocean. ENSO has three phases: El Niño, La Niña, and Neutral. These phases affect global weather patterns, influencing rainfall, droughts, storms, and temperatures worldwide. Some effects of climate change on ENSO and the Walker Circulation appear uncertain in the current literature. In the South Pacific, it has often been reported that the ocean is moving towards an El Niño like state (Dowdy et al., 2012). However, it seems from recent historical records that the opposite is occurring - the western tropical Pacific has warmed noticeably, as would be expected from such a move towards El Niño, however, there has been a marginal reduction in average sea surface temperature (SST) over most of the eastern tropical Pacific – due to upwelling of cool subsurface water (Lee et al., 2022). Multiple large ensemble experiments (1960 -2020) of Cai et al. (2023) confirm that the simulated post-1960 ENSO amplitude increase is approximately 10% and is not solely due to internal variability. However, there is no consensus on ENSO SST variability changes across the various CMIP models referenced in the IPCC 6th assessment.

Regardless of the uncertainty in this ENSO variability trend, there is some confidence in an increase in ENSO rainfall event variability - for amplitude. This would lead to more extreme precipitation events and storms (IPCC AR6 WG1 Physical Science Basis report; Cai et al., 2023)

The impact of this projected increase in ENSO rainfall variability on Australian beaches is largely connected with increased erosion from storms and in addition infrastructure and ecosystem damage due to extreme events. As with sea level rise, the consequences of beach erosion due to ENSO variability for surfing specifically are beach specific and depend on whether sand influences wave breaking quality. The assessed confidence in this risk is high for beaches constrained with coastal defence structures and/ or coastal infrastructure (and no sediment management infrastructure) (Pilkey & Cooper, 2014). These structures result in a disruption to sediment supply to an area, hence further erosion (Cooper, O'Connor, et al., 2020). However, for unconstrained sandy beaches erosion effects may negligible (Cooper, Masselink, et al., 2020).

1.3 Coastal ecosystem risks:

Marine environments bring AUD$69 billion per year to the Australian economy. They have many rare and endemic species and provide food production, coastal protection, tourism and carbon sequestration (IPCC AR6, Chap 11). This report describes ecological changes from projected climate change that are likely to affect beaches along the coast of Australia, examining impacts on both general use and surfing specifically.

1.3.1 Increased acute illness from seawater due to increased precipitation events

Extreme precipitation events and storms are likely to increase in frequency due to climate change (refer section 1.2). Rainfall has been shown to increase acute illness such as ear infections when surfing in the ocean (Wade et al., 2010). Faecal bacteria in seawater are strongly associated with illness in ocean users only during wet weather. Coastal seawater exposure increases the incidence rates of many acute illnesses among surfers, with higher incidence rates after rainstorms (Arnold et al., 2017).

1.3.2 Increased geographic range and frequency of harmful algal blooms

The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) in September 2019 was the first IPCC report to link harmful algal blooms (HABs) to climate change. Coastal HABs show range expansion and increased frequency since the 1980s due to both climatic and non-climatic drivers such as increased riverine nutrients run-off. Contributing causes for this include ocean warming, oxygen loss and marine heatwaves (Burford et al., 2020; Gobler, 2020).
These HABs can impact on food security, tourism, local economy, and human health (Gobler, 2020).

2. Climate changes affecting the east Australian coast

2.1 Decreased frequency of extra tropical cyclones/ east coast lows (ECLs)

ECLs are one of six commonly recognised synoptic weather types that impact the South East Australian Shelf (Mortlock & Goodwin, 2015). A reliable study from Dowdy et al. (2014), using 18 different global circulation models (GCM's) provided consistent results showing a 42% reduction in frequency of the top 10% most powerful ECLs by 2100 for a high emissions scenario. This projected reduction in ECls has also been noted in the IPCC sixth assessment, chapter 11.
The primary effect on surfing from this change is a negative change in wave height distribution for RCP4.5 and RCP8.5 (Dowdy et al., 2014), resulting in fewer large (or powerful) waves for surfing.

2.2 Decreased frequency of tropical cyclone (TC) occurrence

This is a commonly reported projected and recent historical trend in the literature for the South West Pacific (SWP) e.g. Chand et al. (2019); Chand et al. (2022). The IPCC sixth assessment, chapter 11 quantifies this change as within the following ranges: −8 to +1% (2050, RCP2.6), −15 to +2% (2050, RCP8.5), −8 to +1% (2090, RCP2.6), −25 to +5% (2090, RCP8.5). Since the upper limits of these ranges are positive in sign, the decrease can be viewed as of medium reliability.

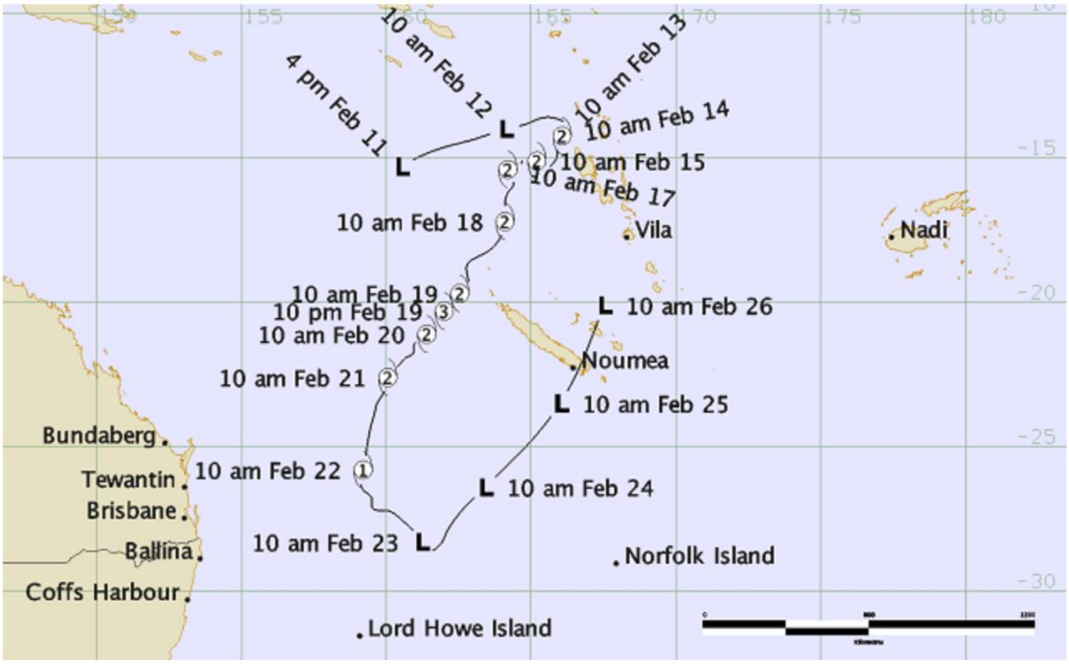
The effect of this for surfing is expected to be a reduced frequency of TC generated swells reaching surf breaks exposed to TC generated swells (those breaks north of Byron Bay) and therefore fewer large (or powerful) waves for surfing.

2.3 Increased power of tropical cyclones

The proportion of intense TCs is projected to increase due to global warming. This is because of the increasing energy available to the TCs from rising SSTs and rising atmospheric temperatures TCs (NESP ESCC, 2020). TCs will be 17% more intense by 2100 under RCP8.5 (Pérez-Alarcón et al., 2023).

This change is expected to cause intermittent extreme beach erosion (Castelle et al., 2007; Splinter et al., 2014). Positive effects on surf conditions due to increased wave power assessed as unreliable since surfing waves from TCs typically do not lack of power and often over- power surf breaks exposed to TC swell (e.g. Gold Coast surfing spots), with large waves that begin shoaling further out to sea and do not break in the same uniform manner as those from less powerful storms. The quality of surfing waves due to TC-generated swell is highly dependent on the tracking direction and speed of an individual TC, and to a lesser degree the maximum windspeeds - the power of the TC (the power of TC-generated swell is fetch-dependant, and this swell fetch is in turn dependent on a number of variables including TC tracking speed, direction and maximum windspeeds (Cagigal et al., 2022; Gramcianinov et al., 2021).

Figure 4 below shows TC Oma, 2012, tracking to a position that was perfect for powerful, high quality surfing conditions in the S.E Queensland region but, as described in the caption (courtesy Australian Bureau of Meteorology (BOM)), caused major beach erosion.



Oma was a long-lived system that existed in the Coral Sea as a tropical cyclone for eleven days. Tropical cyclone Oma caused gale force winds, abnormally high tides and large surf about the southeast Queensland coast, northern New South Wales coast and Lord Howe Island. Significant beach erosion occurred along the southeast Queensland and northern New South Wales coasts and there was one reported drowning fatality off North Stradbroke Island during the event.

Figure 4 TC Oma tracking in the Coral Sea, 11 Feb – 26 Feb 2012.Courtest Australian BOM

Figure 5 Surfing at Snapper Rocks and Kirra, S.E Queensland during TC Oma

2.4 The Subtropical Ridge strengthening and moving polewards

The subtropical ridge (STR) is an elongated area of high pressure in the mid-latitudes. It is part of the atmospheric global circulation and is one of the main factors affecting climate variability and climate change in southeast Australia.

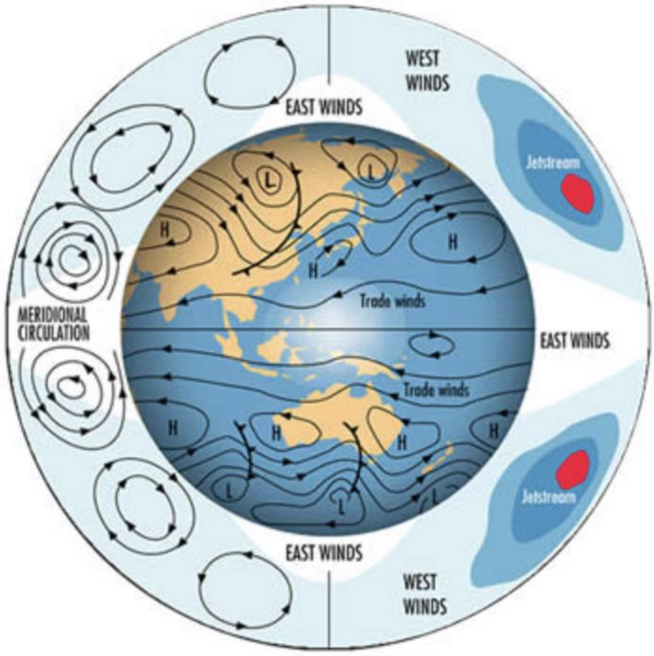


Figure 6 The atmospheric general circulation, showing the location of the STR in the southern hemisphere in relation to Australia. The STR is positioned across the high-pressure systems with trade winds on the northern side of the STR. Courtesy BOM

Multi-model projection used to assess climate change impacts all show positive trends in intensity and pole-ward trends in position (with one model as an exception). However, changes in some models are small. The model results underestimate historical results. The median trend in STR position is -0.21 ° lat. per degree of global warming, which is stronger than that simulated over the recent past (-0.11 ° lat. per degree of global warming). The projections from 23 CMIP3 models showed -0.25° latitude per degree of global warming. The newer models therefore indicate a slightly smaller poleward shift compared to CMIP3 (Grose et al., 2015; Kelly et al., 2019).

Effects of this change in STR position are:

- Reduced wave heights overall because of reduced occurrence of south swells, with more NE directed swells (Hemer et al., 2013). However, Hemer et.al. (2013) recognises this change as small - therefore medium reliability in this prediction. Slightly smaller surfable waves are expected and less favourable to those spots with wave windows exposed to southerly swells. On the other hand, slightly more consistent for surf spots with NE directed swell windows.
- Reduced longshore sediment drift/ headland bypassing. This effect is surf beach specific - some beach compartments (non "leaky" ones) are more stable and resistant to this. Others that are dependent on downstream sand accumulation may reduce in quality (Splinter et al., 2012; Toimil et al., 2020).

2.5 The Southern Annular Mode (SAM) trending positive due to anthropogenic climate change

The SAM (or the Antarctic Oscillation) has influence predominantly in the high to mid latitudes of the Southern Hemisphere (Thompson & Wallace, 2000). It is an index of sea level pressure and is either positive or negative – positive SAM aligns with low air pressure anomalies in the Antarctic and high air pressure anomalies in the mid latitudes, with correspondingly strong westerly winds, shifted poleward. A positive SAM generally results in drier conditions in southern Australia and New Zealand, as storm tracks shift southward. It also brings wetter conditions to eastern Australia as moist tropical air flows into the region, particularly in spring and summer. It is often associated with warmer temperatures in the southern mid-latitudes and cooler temperatures in Antarctica. In negative SAM occurrences, the westerly winds are relatively weaker and move towards the equator. The westerly winds expand northward toward Australia, New Zealand, and South America. This leads to cooler and wetter conditions in southern Australia and New Zealand as more storms reach these regions. It can also result in drier weather in eastern Australia as the airflow becomes less influenced by tropical moisture (Lee et al., 2019). There was a trend toward more positive SAM from 1979 to 2017 of 0.011 index points per year (NOAA, 2017; Thompson & Solomon, 2002). King et al. (2023) finds that the modern positive trend falls outside the 2σ (2 standard deviations) range of the prior 2000 years at multidecadal time scales, supporting the inference that the SAM's positive trend over the last several decades is a response to anthropogenic climate change. However, studies are hindcasts/ recent historical in nature, so confidence is medium to low.

Possible effects of this change in SAM are:

- An anticlockwise rotation of wave direction – resulting in more easterly swells (Hemer et al., 2010). Hence fewer southerly swell events for surfing in winter with smaller wave heights reaching the Australian East coast. Surf breaks that favour southerly swell directions will be less reliable. Once again, it seems breaks with easterly oriented swell windows will survive but others will suffer.
- Reduced longshore sediment drift/ headland bypassing. This effect is surf beach specific - some beach compartments (non "leaky" ones) are more stable and resistant this. Others that are dependent on downstream sand accumulation may reduce in quality (Splinter et al., 2012; Toimil et al., 2020).

3. Climate changes affecting the south and south-west Australian coast

3.1 Increased significant wave height (Hs) and power along southern coast

- Erosion from increased Hs and power along southern coast (Lemos et al., 2019; Morim et al., 2020).
- Most surf spots along this coast do not lack in size and power already so this might make this coast less suitable to general surfing (or more suitable to big-wave surfing).

4. Summary table and key numbers concerning projected climate change effects to Australian surfing beaches

Table 2 below summarise the findings in sections 1 to 3.

Table 2 A summary, using the information in sections 1 to 3 of the projected effect of anthropogenic climate change for the Australian coast for 2050 and beyond.

Coastal range	**Atmospheric or oceanographic metric**	**Projected trend**	**Effects to beach or beach users**
Australian coast from Fraser Island, Queensland in the east to Vlamingh Head, Western Australia in the west.	SLR	↑	• Erosion • Reduced exposure of swell to sea floor due to increased water level which negatively affects surfing wave quality
	ENSO rainfall variability	↑	• Erosion from extreme events • Surfer health impacts from increased precipitation events affecting water quality
	Algal blooms	↑	• Surfer health impacts from increased exposure to harmful algal blooms
East coast	TC	↓ (frequency) ↑ (power)	• Fewer days with TC-generated good surf • Increased erosion at the more northerly located spots from TC events
	Severe ECLs	↓ (frequency) ↓ (power)	• Fewer days with severe ECL-generated good surf
	Subtropical Ridge	Polewards	• Reduced wave heights • Increased erosion from reduced longshore sediment drift/ headland bypassing
	SAM	↑	• More easterly swells. Surf breaks that favour southerly swell directions will be less reliable. • Reduced longshore sediment drift/ headland bypassing. This effect is surf beach specific – beaches that are dependent on downstream sand accumulation may reduce in quality
South and south-west coasts	Wave height (Hs)	↑ (SLR)	• Less suitable and more dangerous surf for the typical surfer • Better quality surf at big wave spots

Key Numbers

Tables 3 to 6 summarise some key numbers relevant to the impacts on these beaches.
Data courtesy IPCC AR6 Chapter 11/ "Australasia" (2023)

- Rainfalls

Table 3 Rainfall extremes: Intensity of daily total rain with 20-year recurrence interval

Year/Scenario	RCP 2.6	RCP 8.5
2050	+4 to +10%	+8 to +20%
2090	+4 to +10%	+15 to +35%

- Sea level rise

Table 4 Sea level rise

Scenario	RCP 2.6		RCP 8.5	
Location\Year	**2050**	**2090**	**2050**	**2090**
South	13-29cm [21cm]	23-55cm [39cm]	16-33cm [25cm]	40-84cm [61cm]
East	14-30cm [22cm	22-54cm [38cm]	19-36cm [27cm]	46-88cm [66cm]
North	13-28cm [21cm]	22-55cm [38cm]	17-33cm [25cm]	41-85cm [62cm]
West	13-28cm [20cm]	22-55cm [38cm]	16-33cm [24cm]	40-84cm [61cm]

*without considering Antarctic dynamic ice sheet factor which increased global sea level projections for RCP8.5 by approx. 10cm

- Surge

Table 5 Sea level extremes

Scenario	RCP 2.6		RCP 8.5	
Location\Year	**2050**	**2090**	**2050**	**2090**
South	21cm	41cm	25cm	66cm
East	24cm	49cm	30cm	86cm
North	21cm	43cm	26cm	70cm
West	21cm	43cm	26cm	70cm

- Tropical cyclones

Table 6 Tropical Cyclones (TC) and East Coasts Lows (ECLs)

	RCP 2.6		RCP 8.5	
Location	**2050**	**2090**	**2050**	**2090**
Eastern TC	-8 to +1%	-8 to +1%	-15 to +2%	-25 to +5%
Western TC	-10 to -2%	-10 to -2 %	-20 to -4%	-30 to -10%
ECLs	-15 to -5%	-15 to -5%	-30 to -10%	-50 to -20%

5. Economic impacts of projected climate change to Australian beaches

- Value of marine environments to the Australian economy, including tourism and coastal protection: 69 billion AUD/year.
- Value of a single Gold Coast beach is estimated to be $19.47 per person (Ware et al., 2020).
- Expected costs of implementing coastal protection between RCP 2.6 and RCP 8.5 are $573,792/km to 1.7 million/km (Ware et al., 2020).
- Estimated global costs from erosion due to sea level rise due if no adaptation measures are implemented are USD$300-1000 billion. These costs include losses and the displacement of affected populations requiring migration.

6. Case studies of seven iconic Australian surf spots

Australia has an abundance of good to world-class surf spots along the entire coast from Vlamingh Head, Western Australia on the west coast to Fraser Island, Queensland on the east coast. Seven iconic surf spots have been selected here to investigate the effects of climate change, as projected to the years 2090 – 2100.

A table of expected sea level rise for each surf spot for the RCP 8.5 emission scenario, as measured at the nearest measurement station, is shown below:

Table 7 Projected sea level rise at the surf breaks using McInnes et. al (2015) model data from the nearest measurement station to the surf break. Median values shown with 5-95% range in brackets. Values are for the years 2050 and 2090 relative to 2005.

	Sea Level Rise, under RCP 8.5 emission scenario		
Surf Break	**Nearest measurement station**	**Sea level rise (m) for 2050**	**Sea level rise (m) for 2090**
Noosa Heads	Mackay	0.26 (0.18 – 0.35)	0.64 (0.44 -0.87)
Burleigh Heads	Newcastle	0.27 (0.19 – 0.36)	0.66 (0.46 – 0.87)
The Pass, Byron Bay	Newcastle	0.27 (0.19 – 0.36)	0.66 (0.46 – 0.87)
Lennox Head	Newcastle	0.27 (0.19 – 0.36)	0.66 (0.46 – 0.87)
Angourie	Newcastle	0.27 (0.19 – 0.36)	0.66 (0.46 – 0.87)
North Narrabeen	Sydney	0.27 (0.19 – 0.36)	0.66 (0.45 – 0.88
Bells (Winki Pop, Rincon and The Bowl)	Stony Point	0.24 (0.15 – 0.32)	0.59 (0.38 – 0.81)
Main Break, Margaret River	Bunbury	0.25 (0.16 – 0.34)	0.62 (0.40 – 0.85)

The projected effects of climate change on the seven surf spots, for the years 2090 – 2100 are described below and thereafter summarised in table 8, along with an associated climate change consequence-to- surfing weighting for each surf spot - the higher the score, the more detrimental to surf quality projected climate change is expected to be. These scores can be used to evaluate each spot relative to the others.

6.1 Noosa Heads, Sunshine Coast, QLD

Figure 7 Noosa Heads, Sunshine Coast, Qld - surf spots are between Noosa Head and Main Beach. Satellite map courtesy TomTom

A series of linking bays with rocky points and some beaches create excellent point break surfing conditions and the area has therefore become increasingly popular both with surfers and tourists. Surf breaks in order from main beach are: First Point, Johnsons, National Park, The Boiling Pot, Tea Tree Bay and Granite. Most have better quality surf on a lower tide but can be surfed at high tide for a less hollow surfable wave (Warren, 1999). Projected SLR is therefore expected to reduce surf quality (or could eliminate one or more of the six surf breaks entirely). In addition, the SLR is expected to increase erosion along the coast in this area (Wishaw et al., 2020), which will affect surf quality. The surf is best in an east to north-east swell direction and so counterclockwise change in swell direction for the region (Wishaw et al., 2021) may not affect the surf quality. This counterclockwise change in direction is however, expected to cause an increase in beach erosion from modal conditions (Wishaw et al., 2020). The best surfable waves are from TCs in the Coral Sea (or occasionally ECLs/ Central and Southern Tasman Lows (CSTLs)). Due to a reduction in the expected frequency of TCs for the region (as described in section 2.2), there is a projected decrease in the number of surfable days. Since TC power is expected to increase, erosion due to extreme events is expected to increase for this climate change projection. Erosion due to extreme events is also expected to increase due to a reduction on long-shore sand transport by tropical expansion (Goodwin et al., 2016). Noosa Heads has a climate change negative consequence ranking of 1, as shown in table 8.

6.2 Burleigh Heads, Gold Coast, QLD

Figure 8 Burleigh Heads, Gold Coast, QLD. Satellite map courtesy TomTom

A world-class right hand point break formed by sand piled against round boulders (Warren, 1999). Better quality surf on a low to medium tide (Surfline.com) but can be surfed at high tide for a less hollow surfable wave. Projected SLR is therefore expected to reduce surf quality. Although the SLR and change in swell direction is expected to increase erosion, this area has a beach nourishment program managed by the Gold Coast council and so the effects here of climate change with regards to erosion are unknown. The surf is best in a south to south-east swell direction and so a counterclockwise change in swell direction for the region will reduce the surf quality. The best surfable waves are from TCs in the Coral Sea, ECLs, CSTLs and high-pressure (HP) systems. As described by (Morim et al., 2019), significant wave height is expected to decrease here under the RCP 8.5 emissions scenario which will decrease surf quality. Burleigh Heads has a climate change negative consequence ranking of 2, as shown in table 8.

6.3 The Pass, Byron Bay, NSW

Figure 9 The Pass Byron Bay, NSW. Satellite map courtesy TomTom

An excellent but surfer-congested sand point in an area that is highly popular both with local surfers and tourists. Better quality surf on a low to medium tide (Surfline.com) but can be surfed at high tide for a less hollow surfable wave. Projected SLR is therefore expected to reduce surf quality. In addition, SLR is expected to increase erosion along the coast in this area. The surf is best in an east to north-east swell direction and so counterclockwise change in swell direction for the region (Wishaw et al., 2021) may not affect the surf quality. This counterclockwise change in direction is however, expected to cause an increase in beach erosion from modal conditions (Wishaw et al., 2020). The best surfable waves are from TCs, ECLs, and CSTLs (Goodwin et al., 2013). Since TC power is expected to increase but severe ECL power is expected to decrease (Dowdy et al., 2014), the effect of climate change on erosion due to extreme events is unknown. The Pass has a climate change negative consequence ranking of 2, as shown in table 8.

6.4 Lennox Head, NSW

Figure 10 Lennox Head, NSW. Satellite map courtesy TomTom

Another classic hand point break breaking over round boulders (Warren, 1999). Surf is good at all tides (Surfline.com). Projected SLR is therefore expected to reduce surf quality when high tide conditions are reached (resulting in extra-high tides relative to current tide levels). SLR and change in swell direction is expected to increase erosion with a detrimental effect to the surf quality due to reduced sand cover over the boulders. The surf is best in a south to south-east swell direction and so a counterclockwise change in swell direction for the region will reduce the surf quality. The best surfable waves are from TCs in the Coral Sea, ECLs, CSTLs and high-pressure (HP) systems. As described by Morim et al. (2019), significant wave height is expected to decrease here under the RCP 8.5 emissions scenario which will decrease surf quality. Since TC power is expected to increase but severe ECL power is expected to decrease (Dowdy et al., 2014), the effect of climate change on erosion due to extreme events is unknown. Lennox Heads has a climate change negative consequence ranking of 1, as shown in table 8.

6.5 Angourie, NSW

Figure 11 Angourie, NSW. Satellite map courtesy TomTom

Angourie, a right-hand point break, is one of the classic waves of the world and is situated in a surfing reserve. It breaks over a rock shelf with minimal sand influence (Warren, 1999). Surf is good at all tides (Surfline.com). Projected SLR is therefore expected to reduce surf quality only for high diurnal tides levels (resulting in extra-high tides relative to current tide levels). The surf is best in an east to north-east swell direction and so a counterclockwise change in swell direction for the region is not expected to reduce the surf quality. The best surfable waves are from TCs in the Coral Sea, ECLs, CSTLs and high-pressure (HP) systems. The change in the number of days with good quality surf is unknown since on the one hand there is a predicted favourable change in swell direction, on the other decreased frequence of severe ECL's and CSTLs.

As described by Morim et al. (2019), significant wave height is expected to decrease here under the RCP 8.5 emissions scenario which will decrease surf quality. Although SLR and change in swell direction is expected to increase erosion and cause beach recession, the effect to the surf quality from erosion is not predictable since surf quality is determined primarily by the rock shelf over which the waves break. Angourie has a climate change negative consequence ranking of 3, as shown in table 8.

6.6 North Narrabeen, NSW

Figure 12 North Narrabeen, NSW. Satellite map courtesy TomTom

North Narrabeen is a left-hand river mouth sand point. Narrabeen lagoon provides a constant flow of sand that forms the banks that make this the most consistent break in the Sydney region (Warren, 1999). Surf is good on a low to mid tide (Surfline.com) and so projected SLR is therefore expected to reduce surf quality. The surf is best in an east to north-east swell direction and so a counterclockwise change in swell direction for the region is not expected to reduce the surf quality. The best surfable waves are from TCs, ECLs, CSTLs, Zonal Anticyclonic Highs (ZALs) and Southern Ocean Lows (SOLs). The change in the number of days with good quality surf is unknown since on the one hand there is a predicted favourable change in swell direction, on the other decreased frequence of severe ECLs and CSTLs.

As described by Morim et al. (2019), significant wave height is expected to decrease here under the RCP 8.5 emissions scenario which will decrease surf quality. SLR and change in swell direction is expected to increase erosion and threaten beach recession (beach erosion is already a problem for this location and has been for years). Since TC power is expected to increase but severe ECL/ CSTL power is expected to decrease (Dowdy et al., 2014), the effect of climate change on erosion due to extreme events is unknown. North Narrabeen has a climate change negative consequence ranking of 2, as shown in table 8.

6.7 Bells Beach, VIC

Figure 13 Bells Beach, Victoria. Satellite map courtesy TomTom

Bells Beach is situated in Australia's first surfing reserve It is one of Australia's renowned big wave spots but can also be surfed smaller waves (Warren, 1999). There are three main breaks, from east to west: Winki Pop, Rincon and The Bowl. The reef at Bells is very much tide effected, and lower tide is best for The Bowl (Warren, 1999). Projected SLR is therefore expected to reduce surf quality. SOLs are the primary source of good surfable waves here. Wave heights for the more southern (and south-western) areas of Australia are projected to increase (Lemos et al., 2019) and so there is no expected reduction in surf quality due to change in wave height. Although SLR is expected to increase erosion and cause beach recession, the effect to the surf quality of erosion is not predictable since surf quality is due to the rock shelf over which the waves break. Bells Beach has a climate change negative consequence ranking of 4, as shown in table 8.

6.8 Main Break, Margaret River, WA

Figure 14 Main Break, Margaret River. Satellite map courtesy TomTom

Main Break, Margaret River is a reef break that can be ridden left or right from the take-off. It is another of Australia's renowned big wave spots. It is good on all tides and so projected SLR may not reduce surf quality. SOLs are the primary source of good surfable waves here. Wave heights for the south-western areas of Australia are projected to increase (Lemos et al., 2019) and so there is no expected reduction in surf quality due to change in wave height. Although SLR is expected to increase erosion and cause beach recession, the effect to the surf quality of erosion is not predictable since surf quality is due to the rock shelf over which the waves break. Main Break, Margaret River therefore has a climate change negative consequence ranking of 5, as shown in table 8.

6.9 Summary table of surf spot findings

Table 8 below summarise the findings in sections 4.1 to 4.8. A ranking in terms of the expected reduction in surf quality is also shown in the final column. This is for comparison between the 8 breaks, with a ranking of 1 having the highest number of negative trends (negative trends are shown in red in the table). The ranking is not, however, a quantitative assessment of climate change consequence or risk, although as mentioned, it does provide for comparison of the various iconic surf breaks along the Australian coast.

Table 8 Evaluation of the effect of RCP emission scenario 8.5 for 2050 onwards at selected surf breaks along the Australian coast. Trends detrimental to surf quality are shown in red and a (negative) consequence score is calculated by summing the number of detrimental trends and expressing as a percentage of total trends evaluated (7). A key to the abbreviations used in the table are shown below the table.

Surf Break Description			**Trends**							**Overall surf quality reduction**
Surf Break	**Weather patterns that produce good quality surf**	**Best swell direction and tide (Warren, Atlas of Australian Surfing and Surfline)**	**Water depth of breaking waves**	**Average significant wave height of surfable waves (Hs)**	**Average wave direction**	**Number of days with good quality surf**	**Beach erosion, modal**	**Beach erosion severity from extreme events**	**Beach erosion event frequency from extreme events**	**Surf spots ranked by total negative consequences in Trends columns**
Noosa Heads	TCs (ECLs, CSTLs Occasionally)	E to NE, low	↑ (SLR)	Unknown	Q	↓ (TCF)	↑ (AWD Wishaw et. al, 2020 and SLR)	↑ (TCP) Long-shore sand transport reduced by tropical expansion also (Goodwin et. al, 2016)	↓ (TCF)	1
Burleigh Heads	TCs ECLs CSTLs HP systems (Allen & Andrews,1997)	S to SE, low to mid	↑ (SLR)	↓ Morim et. al, 2019	Q	Unknown	Unknown due to the fact that GCC beach nourishment program may prevent this	Unknown due to the fact that GCC beach nourishment program may prevent this	↓ (TCF)	2
The Pass, Byron Bay	TC, ECLs, CSTLs (Goodwin et. al, 2013)	E to NE, low to mid	↑ (SLR)	↓ Morim et. al, 2019	Q	Unknown	↑ (AWD Wishaw et. al, 2020 and SLR)	Unknown since TCP ↑ but SECLP ↓ (Dowdy et. al, 2014)	↓ (TCF) ↓ (SECLF)	2

Lennox Head	TCs ECLs CSTLs HP systems (Allen & Andrews,1997)	S to SE, all tides	↑ (SLR)	↓ Morim et. al, 2019	Q	Unknown	↑ (AWD Wishaw et. al, 2020 and SLR)	Unknown since TCP ↑ but SECLP ↓ (Dowdy et. al, 2014)	↓ (TCF)	1
Angourie	TCs ECLs CSTLs HP systems (Allen & Andrews,1997	E to NE, all tides	↑ (SLR)	↓ Morim et. al, 2019	Q	Unknown (on one hand favourable change in swell direction, on the other decreased storminess)	Unknown since the waves break over a rock shelf	Unknown since TCP ↑ but SECLP ↓ (Dowdy et. al, 2014)	↓ (TCF, SECLF)	3
North Narrabeen	TCs, ECLs, CSTLs, ZALs, SOLs (Morlock & Goodwin, 2105; Short and Trenaman, 1992)	E to NE or SE (for the Alley), low to mid	↑ (SLR)	↓ Morim et. al, 2019	Q	Unknown (on one hand favourable change in swell direction, on the other decreased storminess)	↑ (AWD Wishaw et. al, 2020 and SLR)	Unknown since TCP ↑ but SECLP ↓ (Dowdy et. al, 2014)	↓ (TCF, SECLF)	2
Bells (Winki Pop, Rincon and The Bowl)	SOLs	S to SW, low tide for The Bowl	↑ (SLR) (Warren states that the reef at Bells is very much tide affected, and lower tide is best for The Bowl	↑ (Lemos et. al, 2019)	Unknown	↑	Unknown since the waves break over a rock shelf	Unknown	Unknown	4
Main Break, Margaret River	SOLs (Surfline)	SW to W, all tides	Unknown, since good on all tide conditions (Surfline)	↑ (Lemos et. al, 2019)	Unknown	↑	Unknown since the waves break over a rock shelf	Unknown	Unknown	5

Abbreviations:

AWD: Average wave direction
CSTL: Central & Southern Tasman Low
ECL: East Coast Low
SECLF: Severe East Coast Low frequency
SECLP: Severe East Coast Low power
SLR: Sea level Rise
SOL: Southern Ocean Low
TC: Tropical Cyclone
TCF: Tropical cyclone frequency
TCP: Tropical cyclone power
ZAL: Zonal Anticyclonic High

Limitations in the findings of table 4:

Certain beaches, such as the Gold Coast, are maintained through interventions like sand nourishment and sea walls. These measures make them less vulnerable to climate impacts compared to beaches without similar maintenance efforts. Approximate costs of coastal defences against RCP 8.5 threats are in the order of $1.7 million/km, which, using Kirra as an example, would defend private property of value of approximately AUD 50 million (Ware et al., 2020).

7. Conclusions and discussion

SLR, increased sea surface temperatures, changes in wave heights, increased ENSO rainfall variability, changing frequency and power in TCs and ECLs, changes in the STR and the SAM are all projected results of climate change that are expected to have detrimental effects to Australian beaches - for surfing, beach use and for beach health in general.

All the selected surf breaks with the possible exception of Margaret River Main Break are expected to degrade due to climate change but vary in the degree to which they are exposed to the multiple negative consequences of a changing climate. It seems that the more easterly breaks have more climate change related projected negative trends than the westerly (or southerly) located breaks along the coast of Australia. This can be seen by examining the "Overall surf quality reduction" column in table 8. The beach erosion consequences of climate change can be said to be amplified (for example via some sea walls) or in some cases attenuated (for example via beach nourishment) through human interventions or infrastructure. However, the effects of human infrastructure or management activities on the beaches at high RCP 8.5 level climate change conditions is still an area for further research (based on current scientific literature reviews).

Future Solutions to mitigate against climate change induced beach degradation include:

- Nature-based solutions such as using sand dunes, coastal vegetation and beach nourishment to reduce erosion and strengthen the natural defences of beaches.
- The creation of artificial reefs to improve wave quality and provide a barrier against waves and erosion and
- Sustainable coastal management, for example designating key surfing locations as protected areas and limiting shoreline development.

Investment in coastal adaptation strategies such as sand monitoring and advanced beach and coastal modelling (including sand headland bypassing studies) is critical to safeguard our beach health and surfing culture (which has significant wellbeing and economic value). Policies to reduce greenhouse gas emissions and to mitigate against climate change should be supported and implemented.

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