Earth Systems and Climate Change Hub

National Environmental Science Programme

Understanding coastal erosion on beaches

A guide for managers, policy makers and citizen scientists

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Understanding coastal erosion on beaches:
A guide for managers, policy makers and citizen scientists

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Front cover image: Shore protection works on the northern Bellarine Peninsula, Port Philip Bay.

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EXECUTIVE SUMMARY

Beaches are dynamic landform systems which are in a constant state of flux as they interact with waves breaking on the shore. It is their ability to respond to each wave event that allows beaches to survive in high energy environments.

Erosion on a beach occurs when sand is moved from one location to another. It is a natural process. Sand is not lost from the beach it is simply moved to another location to balance the energy that impacts the coast.

The active part of the beach, termed the beach envelope, extends from the upper limit of waves during storms to wave base. The subaerial beach (that part above low tide) and backing dunes are part of the beach envelope and are the principal store of sand for storm events.

Beaches operate over annual to decadal cycles. Natural movement of tens of meters laterally and over 5 m vertically is commonly expected annually.

Understanding the size and dynamics of the beach envelope is critical for sustainable environmental management on the coast. Erosion only becomes a problem when human populations occupy the active part of the beach. Increasing population at the coast, coupled with climate change, will put increasing amounts of infrastructure into the existing coastal hazard zone. This coastal hazard zone already overlaps with many communities.

Wave and sea level dynamics around Australia can be classified into three distinct zones:

(1) Tropical North dominated by tropical cyclones

(2) Temperate Lows dominated by ex-tropical cyclones in Western Australia and East Coast Lows in NSW and Victoria

(3) Ex-tropical cyclones and eastward traveling fronts which dominate the Southern mainland coast and Tasmania

Climate change projections show an expansion of the tropics southwards with impacts on Southern Ocean storm systems. Tropical cyclones will be less common, but those which occur will be more intense and have the potential to travel further south than at present. El Niño–Southern Oscillation variation will also intensify.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Erosion is a primary concern for all coastal managers. Around the world infrastructure is threatened by inundation by the sea which is predicted to increase as a result of climate change. Managing this threat often leads to conflict between the natural and human systems, even in areas where nature offers inbuilt resilience to changing environments. The impact of erosion is particularly compounded by the exponential rise in human activity on the coast.

Erosion is defined as the removal of material from one location to another. It is a natural process – the product of the coast constantly adjusting to waves and tides at any given moment in time. When a beach experiences erosion, sand is not lost, it is simply shifted to another location, either alongshore or offshore.

Assessment of erosion risk therefore must account for the nature of shoreline change and the impact of that change. For example, a 20 m shoreline recession in a remote national park may have low risk, but the same recession on a beach with urban development (e.g. Melbourne or Sydney) will be a major risk.

Risk is therefore framed as:

Risk = Hazard x Vulnerability x Elements at Risk

Where Hazard is the natural system (e.g. rate of erosion, height of storm surge), vulnerability can include people living on the coast and their ability to adapt (e.g. socioeconomic status), and elements at risk are the number of people or assets exposed to the hazard.

(from Crozier and Glade, 2004)

The major issue for the modern coast is the growth of coastal towns and associated infrastructure has increased the elements at risk in the current hazard zone. Even without a change in hazard (e.g. climate change) the risk would exponentially increase in line with population growth.

2.0 BEACHES ARE DYNAMIC

Beaches are fundamentally dynamic systems. They are loose piles of sand which occur in a very high energy environment. It is their ability to adjust to the wave and tidal conditions at any given moment that allows them to exist. The relationship between beach shape and energy is conceptualised in the theory of *morphodynamics* (Wright and Thom, 1977) (Figure 1).

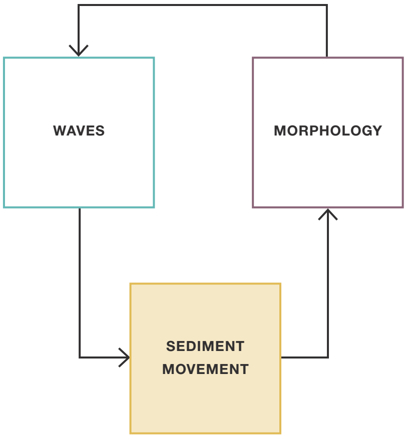

FIGURE 1: The morphodynamic feedback loop. Beaches are in a constant state of movement as sand is shifted when each wave breaks on the shore.

Wooden groyne on Torquay Beach, Victoria.

Beaches adjust to wave energy through transferring sand from the upper to lower parts of the profile. Rip currents are a major mechanism for this seaward transfer of sand and surf zone bars act as moveable obstructions to waves. For example, in low energy environments bars are close to the shore, but as energy increases the bars move further offshore and rips become larger (Figure 2).

FIGURE 2: Kurnell Peninsula, Sydney.

In the morphodynamic system (Figure 1), fluid motion (e.g. a wave) causes sand movement (sediment transport) which leads to a bar being formed in the surf zone (morphology). This bar then causes waves to break further offshore which reduces the energy (wave height) at the beach face and in turn slows the rate of sand movement.

The process by which the system keeps itself in balance is known as a *negative feedback* (or self adjusting system). Any adjustment to beach morphology acts to reduce the amount of wave energy that the beachface experiences. A *positive feedback* (or self destroying) loop occurs when sand movement leads to an increase in energy. This most commonly occurs in front of a seawall. Waves reflect off the wall and cause sand to be eroded and thereby increase water depth. As water depth increases more wave energy can impact the wall leading to more erosion.

Beaches are the buffer between the waves and land.

3.0 SPATIAL TIMESCALES OF CHANGE

Sediment movement on beaches occurs in the zone of wave agitation. This ranges from as far offshore that waves can stir the bottom (termed *wave base*), to the furthest inland limit of wave run-up. On the Victorian open-ocean coast wave base is at around 50 m water depth which means the active part of the beach may extend many kilometres offshore. At the upper limit of waves, the active beach also includes the dune systems, specifically the front dunes (foredune and incipient foredune). During storm periods sand is transferred from the upper part of the beach to the surf zone, and during calm periods the reverse occurs.

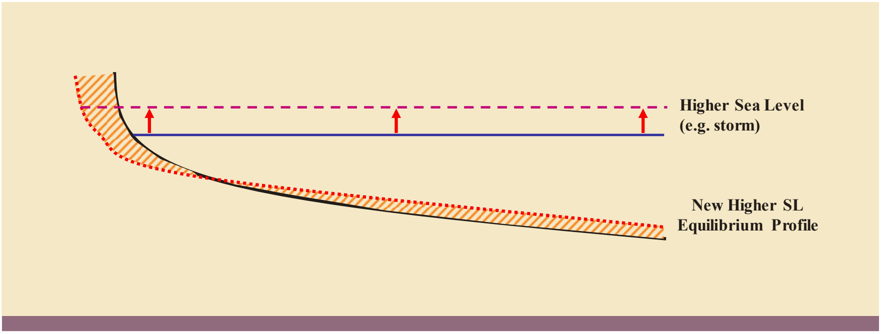

FIGURE 3: A typical equilibrium conceptualisation of long term beach movement (often called the Bruun Rule). A beach adjusts during higher energy events by shifting sand from above to below sea level and as a result the profile gradient decreases.

As sand is moved into the surf zone and offshore, a key factor in the recovery of a beach is the amount of transfer that occurs between beach embayments (Figure 4). In areas where the sand is contained within a single embayment the overall volume of the beach may remain stable through time. In many instances however, material is transferred around headlands and to adjoining beach systems. Such situations are termed leaky embayments. This means many beaches may be reliant on the movement of sand from adjacent beach systems for their post-storm recovery. Management interventions on one beach therefore may impact beaches in adjacent embayments.

The subaerial portion of the beach (above low tide) and the front dunes are part of the active beach. This zone is the store of sand for beach adjustment during storms. The primary question for coastal management is therefore the spatial and temporal movement of the active storm-store zone.

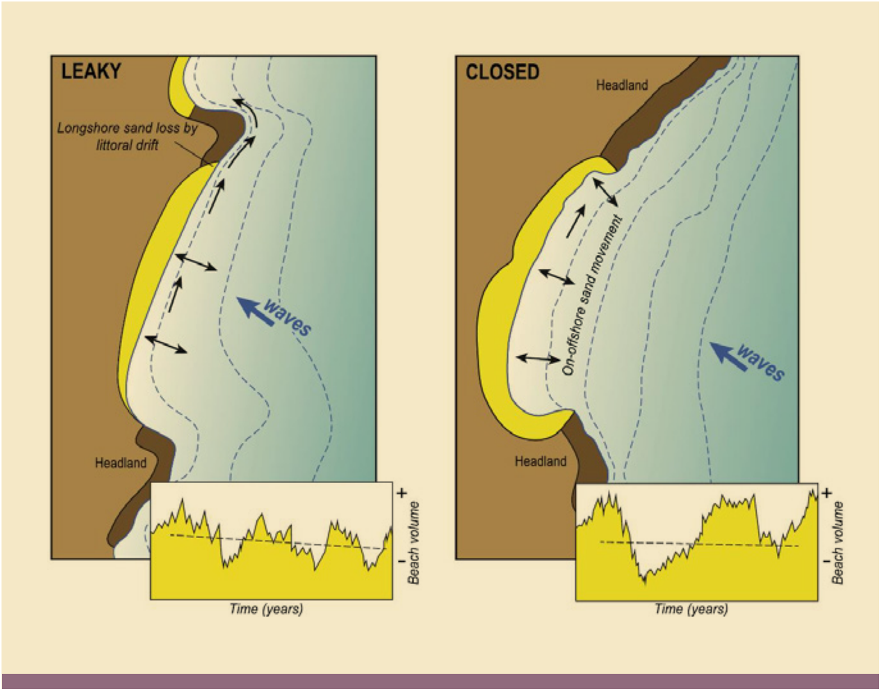

FIGURE 4: Two types of sediment compartments. (a) A leaky compartment where sand can move from one beach to another along the coast. (b) A closed compartment where sand stays within the one embayment during storm events. (SOURCE: THOM ET AL., 2018)

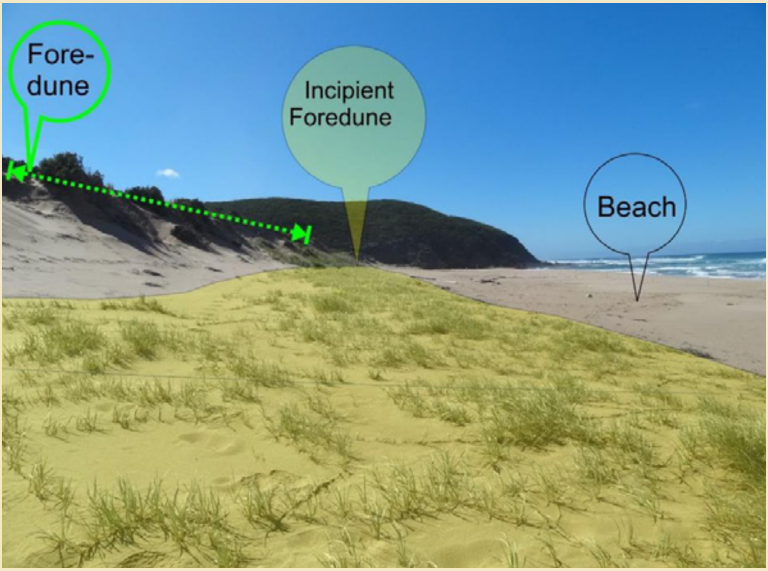

FIGURE 5: Dunes are the store of sand for storm events. Generally, the incipient foredune can be expected to be eroded by storms every 1-10 years.

KEY MESSAGE

The dunes and beach are the store of sand for storm events

3.1 TEMPORAL STABILITY

Individual storm events can cause significant change to the beach profile, on the order of 10+ m (Figure 6). Such change is commonly associated with winter storms. For example, regular storms in Warrnambool, Victoria (between 6/3/14 & 2/7/14) led to over 10 m of lateral and almost 4 m of vertical profile movement. This is seen in the field in the loss of several meters of dune crest. The maximum material removed from the subaerial beachface was almost 30m^3/m (Ierodiaconou et al., 2016).

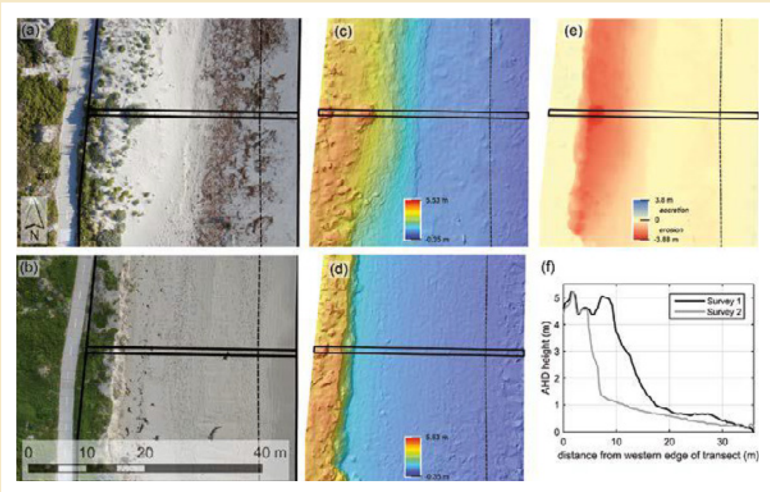

FIGURE 6: Aerial photos (a, b) and digital elevation models (c, d) of the autumn and mid winter beach at Warrnambool. The total change between the images is shown in (e) with the before and after beach profile (f) showing the landward retreat. (SOURCE: IERODIACONOU ET AL., 2016)

Erosion along a beach is most commonly not uniform. Areas of erosion “hot spots” occur, often formed in relation to rip currents. The erosion observed in Warrnambool shows this pattern well (Figure 7). Erosion was lowest at the ends of the beach and highest at 150 - 200 m from the southern end. The sand that was removed from the beachface was redistributed into the offshore embayment (Schimel et al., 2015) and later returned to the beach during summer.

Even though one area experiences greater erosion than another during the two times periods, it is the total volume of sand moved that is important. Any attempt to stop erosion at a hot spot will cause greater erosion elsewhere on the beach. This is because a specific volume of sand is required to be moved along the entire beach so as the system can naturally adjust to storms. If this sand is not available (due to works such as sea walls) more material will be eroded from other sections of the beach. This acts to transfer and enhance shoreward retreat.

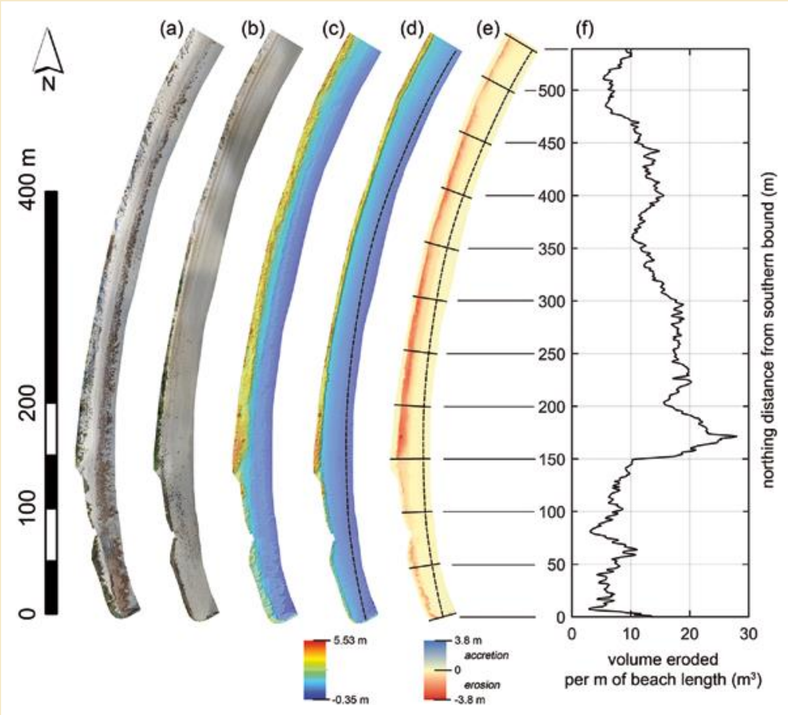

FIGURE 7: Aerial images and digital surface models of the Warrnambool embayment showing the volume of sand removed from the beachface and dunes during the early winter storms. (SOURCE: IERODIACONOU ET AL., 2016)

In some situations, sand movement during a storm may shift predominantly in a longshore direction. That is, be redistributed by waves along the coast in addition to moving offshore. This is well observed in the recent changes at Inverloch Surf Beach. On this beach over the past 6 years, waves have been shifting sand from the open ocean coast (in front of the surf club) alongshore and into the mouth of Anderson Inlet (Figure 8). The result has been 44 m of recession on the Surf Beach and 450 m of progradation on the inlet beach. This has meant erosion issues near the centre of town no longer occur and significant habitat for endangered beach nesting birds has been created. On the other hand, infrastructure is now threatened along a small stretch of the same road further along the coast and at the Surf Club.

The volume of change measured represents the *beach envelope*. Understanding the dynamics of the beach envelope and its overlap with human infrastructure is fundamental for coastal management.

FIGURE 8: The beach at Inverloch showing the eroded dune and area of new beach. (PHOTOS: A, B: DAVID KENNEDY, AERIAL: VCMP INVERLOCH CITIZEN SCIENCE DRONE GROUP. BLACK CIRCLES SHOW PHOTO LOCATION AND DIRECTION OF VIEW.)

3.2 DECADAL TIMESCALES

Beach erosion during winter storms and accretion during milder summers is a commonly recognised phenomenon. Ocean climate however often operates over longer decadal cycles as seen in the El Niño -Southern Oscillation (5-7 years) and the Pacific Decadal Oscillation (10-20 years). This means a 'normal' storm event may be of different magnitude during different climate phases. For this reason, estimating the size of the beach envelope over decadal timeframes is very important.

Little data exists globally on beach volume change over 20+ years. The best record comes from Moruya Beach in southern New South Wales which has been continually surveyed since 1972 (Figure 9). This surveying has provided an unprecedented dataset of beach change (McLean and Shen, 2006; Thom and Hall, 1991) and is notable for its length of record as well as the fact the system is in a completely natural state – all changes observed are free of human influence.

At this location the beach has moved by over 100 m laterally and over 6 m vertically since 1972 (Figure 10). The largest single change occurred during the storm of 1974, which saw most of the subaerial beach, and the incipient foredunes, moved into the surf zone. The profile surveyed on 1976 shows the beach as much shorter than today and lacking a well-developed dune. By 1980 the profile had rebuilt to its former position, but no dune had developed. By 1984 a small dune started forming which continued to build for the rest of the surveying period.

Cackile sp. growing at the back of the beach.

Dune erosion at Inverloch Surf Beach.

FIGURE 9: The beach at Moruya showing a well developed foredune sequence. The scarp from the 1974 storm appears at the right hand edge of the photo with the incipient foredune in the centre being developed after 1984.

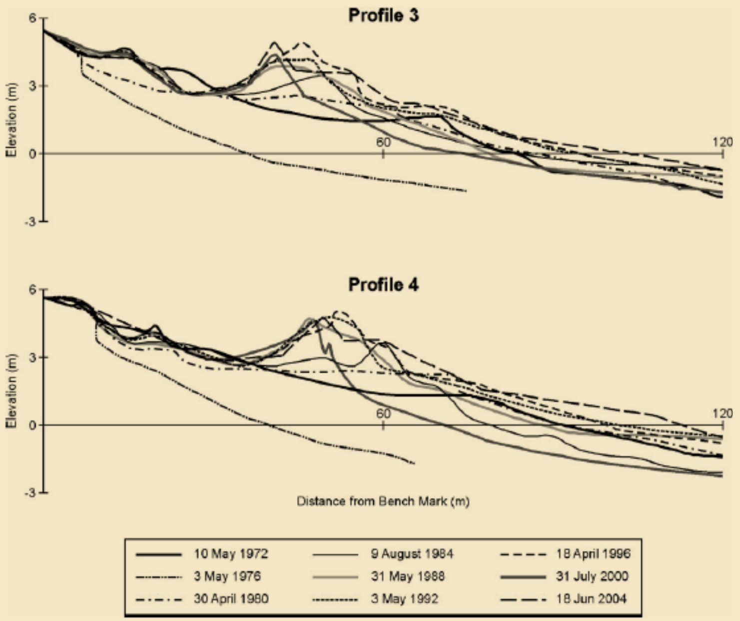

FIGURE 10: Examples of cross sectional beach profiles surveyed along Moruya Beach. (SOURCE: MCLEAN AND SHEN, 2006)

The change in the beach is best observed when considering sand volume (Figure 11). The erosion of the beachface in 1974 is very marked. It then took around nine years for the beach volume to return to its pre-1974 beach state. From 1983 the beach appears to undergo a decadal pattern of volume change which is superimposed on the annual and monthly storm events.

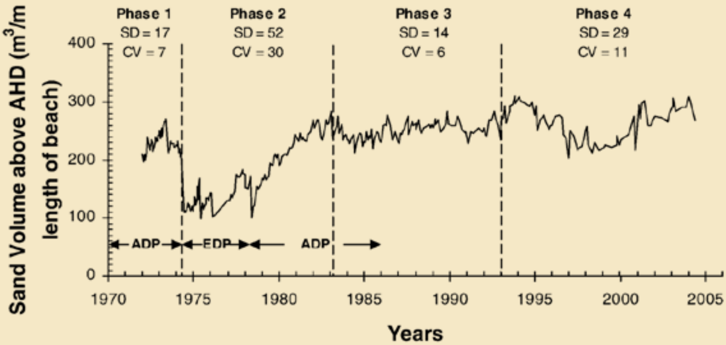

FIGURE 11: Volume change of the subaerial portion of Moruya beach since 1972. The 1974 storm reduced the subaerial beach by almost 50% in size and it took the system almost a decade to return to the pre-storm condition. (SOURCE: MCLEAN AND SHEN, 2006)

At Collaroy-North Narrabeen Beach in Sydney extensive development has occurred on the foredunes, yet on the beachface a broadly similar trend of beach variation is observed, although the dataset here was started after the 1974 storms (Figure 12). On this beach about 60% of sand movement is offshore, with 26% being in an alongshore direction. This means the beach rotates seasonally with sand moving north in winter and south in summer (Turner et al., 2016).

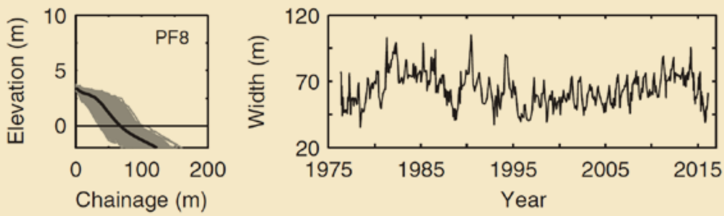

FIGURE 12: Changes in beach dimensions at Collaroy Beach, Sydney. The beach envelope (gray shading on left figure) is around 100 m wide and 5 m high. The change in beach width (right hand graph) shows both seasonal erosion as well as decadal oscillations, similar to observed at Moruya Beach. (SOURCE: TURNER ET AL., 2016)

The impact of building on the active beach profile is well observed in the storm of 6th June 2016, where houses built on the foredune fell into the sea (Figure 13). An exacerbating reason for this erosion was the infrastructure built to protect the surrounding houses. The seawalls on adjacent properties led to what is known as an “end effect”. Essentially, the dune sand was required for the profile to adjust during the storm and as the sea could not access this due to seawall construction the end was outflanked and houses undercut. Further north on the same beach, where there is no housing, only the dune was scarped and there was no loss of infrastructure (Figure 14).

FIGURE 13: Erosion and house damage immediately after the storm. (PHOTO: WATER RESEARCH LABORATORY, UNSW.)

FIGURE 14: Dune recovery north of the developed areas on the 23/7/16. (PHOTO: JUDITH KENNEDY)

KEY MESSAGE

Beaches are dynamic over yearly to decadal timeframes. Erosion during storms is a natural phenomenon and it may take months to years for the beach to return to its pre-storm state.

Seawalls and other structures will impact this natural process and can inhibit natural recovery.

4.0 WEATHER AND CLIMATE IN AUSTRALIA

The drivers of sediment transport

Weather and climate determine how much wave energy impacts the beach. Seasonal to decadal changes in shorelines are determined by changes in weather and climate patterns on these time scales that in turn alter storms, prevailing winds, ocean waves and sea levels. In addition, long term changes due to anthropogenic climate change may lead to permanent changes in coastlines through sea level rise and changes in weather and wave patterns.

Climate-driven variations in average wave directions can cause erosion on the down-drift side and comparable accretion on the up-drift side of embayed beaches. Changes in the frequency or intensity of storm systems can cause significant changes in the size of the beach envelope.

Along Australia's coastline, a range of weather and climate features (see Figure 15) influence the wave and sea level conditions (McInnes et al., 2016).

Tropical Northern Australia: Storm surges generated by tropical cyclones affect mainly the northern coastline of Australia from *Queensland to the northwest coast of Western Australia* although tropical cyclones can track further south to affect the subtropical east and west. Within the *Gulf of Carpentaria* an annual cycle of sea level, with a range of approximately 0.8 m, driven mainly by the seasonal reversal of the prevailing winds, produces the largest seasonal variation in sea levels in the world.

Westerly wind bursts associated with the Madden-Julian Oscillation during the monsoon (November to March) contribute to intra-seasonal sea level variations along the *Gulf of Carpentaria and Indian Ocean coastlines*. Strong sustained south-easterly trade winds during the dry season (April to October) can elevate sea levels in the *Torres Strait Islands*.

SW Western Australia: Easterly or northeasterly travelling Extra Tropical Cyclones (also called mid-latitude cyclones) or tropical cyclones cause elevated sea levels along the *southwest WA* coastline, which may be further enhanced by a sea level annual cycle of 0.2–0.3 m due to variations in the strength of the southward flowing Leeuwin current. During May to June, weak southerly winds allow for a stronger flowing southward current and higher coastal sea

levels due to Coriolis deflection (deflection of currents to the left in the southern hemisphere as a result of the rotation of the earth), whereas during October to November, the opposing southerly winds are strongest and this weakens the Leeuwin current.

NSW, Victoria and Tasmania: Eastward travelling Extra Tropical Cyclones and fronts, most frequent during the winter months, are the main cause of elevated sea levels along the *southern coastline and Tasmania*. Along Australia's east coast, *from New South Wales (NSW) to southeast Queensland (QLD)*, a major cause of elevated sea levels is from East Coast Lows.

Modes of climate variability also influence weather systems that cause extreme sea levels. In addition to its influence on sea levels ENSO affects tropical cyclone frequency, with more tropical cyclones likely during La Nina events, and less cyclones likely during El Niño events (Kuleshov et al. 2008). The Madden-Julian Oscillation also affects tropical cyclone occurrence. The Southern Annular Mode, which in its positive phase amounts to a strengthening and poleward shift of storm tracks, affects the latitudinal position of the Subtropical Ridge. This ridge separates easterly trade winds to the north and the westerlies to the south (Kent et al., 2013) and, hence, extreme sea levels on the southern coastline with potential effects on the longshore sediment transport (O'Grady et al., 2015). The Indian Ocean Dipole also affects regional sea levels to the northwest of Australia with the Dipole Mode Index weakly negatively correlated with coastal sea levels along the WA coast (Charitha Pattiaratchi, pers. Comm. September 2015).

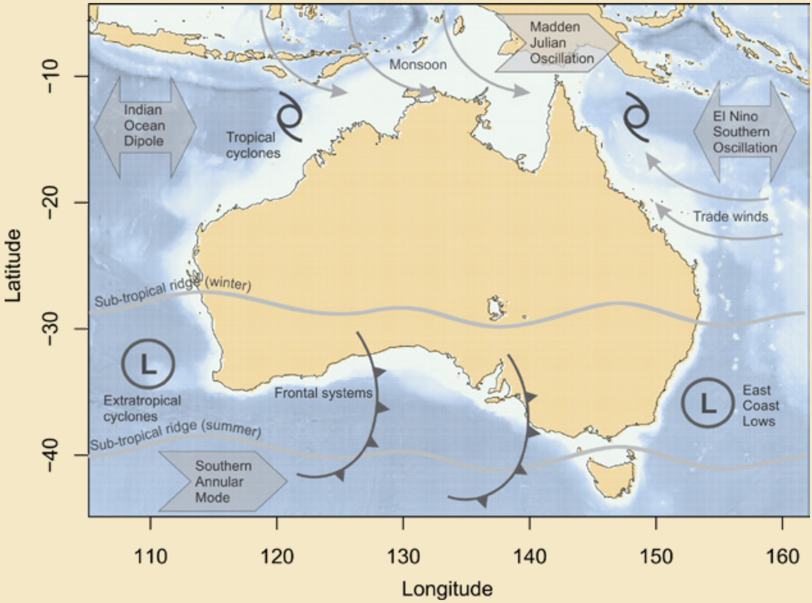

FIGURE 15: The main weather and climate drivers affecting extreme coastal sea levels in Australia. Light-to-dark shading over ocean indicates shallow-to-deep bathymetric depths. (SOURCE: MCINNES ET AL., 2016)

4.1 TRENDS AND FUTURE CHANGES

Future changes to climate and weather drivers due to anthropogenic climate change can influence their impacts on coastlines. *The tropics have widened about 0.5° of latitude per decade since 1979* (Staten et al., 2018) with associated poleward movement of climate features such as the sub-tropical ridge. Associated with this is a poleward expansion of the latitudes of maximum tropical cyclone intensity in recent decades (Kossin et al., 2014). Similarly, there has been a trend in the Southern Annular Mode towards its negative phase in recent decades (Arblaster and Meehl, 2006), which is associated with a poleward migration of the subtropical ridge and the mid-latitude storm tracks to the south of the continent.

Under future conditions the El Niño Southern Oscillation is projected to become more extreme meaning that swings between extreme El Niño to extreme La Niña (the opposite phase of El Niño) will occur more frequently under greenhouse warming (Cai et al., 2015). The global tropical cyclone frequency is expected to decrease or remain essentially unchanged, while the maximum wind speed and precipitation rates will likely increase (Christensen et al., 2013). This means that the proportion of tropical cyclones that reach the most extreme categories of 4 and 5 will likely also increase. Sea level rise will continue to rise and will exhibit regional patterns of rise (Church et al., 2013). For example, eastern Australia is projected to experience a higher than global average rate of rise due to the influence of the warming and southward expansion of the East Australian Current (McInnes et al., 2015; Zhang et al., 2017). The southward contraction of storm tracks to the south of the continent is also projected to continue under global warming. Associated with this is a strengthening of the Southern Ocean storm track, a projected increase of the mean significant wave height across the Southern Ocean and an increase in the mean period of waves reaching the southern coastline of Australia reflecting the greater contribution of these more distantly generated waves (Morim et al., 2018). On the contrary, locally-generated wind waves and storm surges are projected to undergo a small decrease along the southern coastline due to the southward contraction of weather systems (e.g. Colberg and McInnes, 2012; Colberg et al., 2019; Hemer et al., 2013).

5.0 USING PAST CHANGES TO UNDERSTAND FUTURE CHANGES

Future work under the Earth Systems and Climate Change Hub will combine geomorphic understanding of past coastal change in the context of future coastal climate projections to understand how the coastal climate will change. It is anticipated that this will provide a more comprehensive and confident understanding of how the projected changes to climate will manifest at the coastline to aid decision makers and planners to manage these changes.

6.0 CONCLUSION

Coasts are increasingly at risk due to continued human encroachment into the active hazard zone. Understanding the sediment dynamics is key for managing erosion. Erosion is a natural process whereby a beach adjusts its shape in harmony within the incoming waves. Naturally a beach can be expected to move over 100 m laterally and include the dunes at its rear. This movement provides resilience to storms and coastal inundation. Avoidance of this area is ideal, but in situations where infrastructure is present, a balance needs to be made between the protection of built-structures and the maintenance of the natural system. In some locations both will not be possible which requires managers to prioritise the artificial and natural assets present on the coast.

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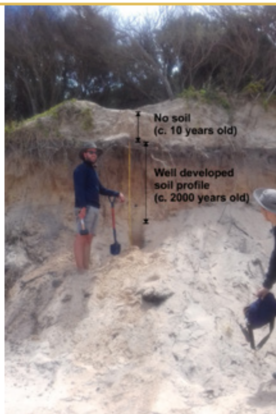
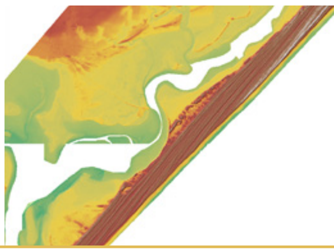
APPENDIX 1

FIELD INTERPRETATION OF TIMESCALES OF CHANGE

Interpretation of the timescales of beach and dune erosion requires a multi-proxy approach. In many instances the detailed data that is required to precisely quantify the beach envelope is not available. The table below highlights some of the common methods used in field interpretation of beach erosion.

Proxy	Detail	Timescales
Soil Profiles	Soils develop through accumulation of organic material on the ground. The thicker the soil the older the landform. Exposure of soils suggests erosion is causing long term change to the coast. The deeper the soil profile the older the surface being eroded. No soil indicates younger surfaces and therefore an active system. 	10–100 years (up to 1000 years)
Hinterland morphology	The wider the coastal plain the more resilient the system. A series of ridges indicates that the coast has been building out, while a single narrow dune indicates a more stable (or even eroding) shoreline. Where the older ridges are aligned differently to the modern coast it indicates a previous climate has influenced dune development. 	100–1000 years

Proxy	Detail	Timescales
Vegetation	Vegetation on dunes follows a standard succession. Grasses grow within years, trees take longer. Some tree species (eg Coastal Wattle and Tea Tree) grow within 10 years while Banksia and Eucalyptus take longer. The more 'mature' the vegetation the older the surface.  	10–100 years
Dating	Dating techniques (eg C14 & Luminescence) provide precise ages of dune sand within a few years accuracy and precision. These allow the exact age of a dune (and beach) to be established and therefore the activity and resilience of the system. 	0–40,000 years (C14) 0–500,000 years (luminescence)

APPENDIX 2

DATA AND METHODS FOR UNDERSTANDING COASTAL CHANGE

Technique	Detail	Cost	Average timeframe of analysis
Aerial LiDAR	Aerial laser surveying with instruments mounted on a light aircraft	>$100,000	months
Drones	Small consumer grade drones which can be operated by citizen-scientists or specialists	$1000/hr up to $60,000 for fully operational citizen science group for 3 years	weeks – months
Shoreline numerical modelling	State of the art numerical models or shoreline dynamics (eg Delft3D, XBeach, Mike21)	c. $50,000 per site (requires specialised knowledge and existing licensing)	weeks – months
On ground profile survey	Range of methods from drones to levels	c. $500/hr	weeks
Geomorphic Assessment	Specialist interpretation using expert opinion	c. $500/hr	weeks
Dating	Radiocarbon Luminescence	$800/sample $1700/sample	8 weeks 12–20 weeks