Coastal waves, water levels, beach dynamics and climate change

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Wave generation in the ocean

The waves most readily observed at the coast are those generated by the wind. Wind waves observed at a particular location are either sea or swell.

- Sea is generated by local winds at the time of observation. It is characterised by short, discontinuous crest lengths that are closely spaced and often associated with whitecapping.
- Swell has travelled to the coast after being generated by winds at a distant location. It is characterised by long, continuous crest lengths (Figure 1).

At times, particularly during storms, there may be a coincidence of both sea and swell.

Figure 1: Photographs showing examples of sea (left) and swell (right). Photos: © M.G. Hughes.

The distinction between sea and swell is usually made on the basis of average **wave period**, i.e. the average time taken for the passage of two successive wave crests to pass a fixed point. Sea has wave periods less than 8-10 s, and swell has periods equal to that or greater. Wave period is directly related to the average **wavelength**, which is the average distance between two successive wave crests (Figure 2). **Wave height** is the vertical difference in elevation between the wave crest and the adjacent wave trough.

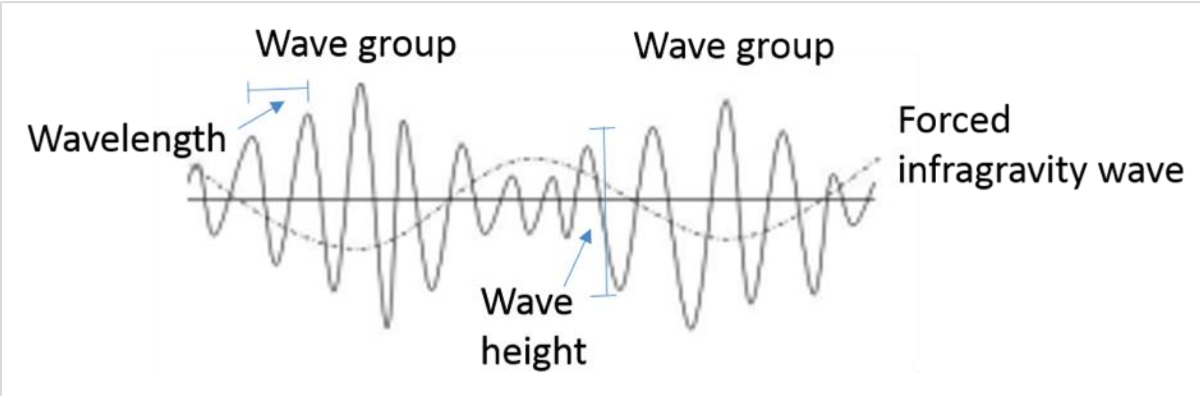

Figure 2: Wave record showing wave groups and the associated forced group-bound infragravity wave. Wavelength and wave height are also defined. Source: © M.G. Hughes.

Swell waves commonly occur in **wave groups**, where a group of larger wave heights are preceded and followed by a group of smaller wave heights. Because the energy associated with waves is proportional to the wave height squared, and therefore the wave groups are of particular significance, the significant wave height is often used to describe wave conditions. The **significant wave height** is the average of the largest one-third of the waves in a record. A further wave type is forced by the wave group—an infragravity wave—which is discussed further below.

The formation of wind waves includes an initial slow growth phase associated with the formation of new waves on a calm water surface. This is followed by a rapid growth phase where the increasing roughness of the sea surface makes the energy transfer from wind to ocean waves more efficient. As a wave field develops there is an increase in the wave height and wave period. Wave growth is not continuous, however, it is limited by whitecapping which dissipates energy. When additional wind energy is offset by whitecapping, so that the waves are no longer growing, **a fully arisen sea** has been achieved.

The wind parameters that determine the size of waves are the distance (area) over which the wind blows (**fetch**), the duration that the wind blows, and the wind speed. The first two determine, for a given wind speed, whether a fully arisen sea is achieved.

As sea waves radiate away from the location where they were generated, the waves with the greatest wavelength (or period) travel fastest and those with the shortest travel slowest; this causes them to become dispersed, according to their wavelength, into organised swell (Figure 1).

Ocean wave measurements for Australia are obtained from waverider buoys, which are usually deployed in 70–100 m water depth on the mid continental shelf. Regional coverage is reasonable for the New South Wales coast, but coverage is patchy or non-existent for the remainder of the Australian coast. Record lengths also vary significantly, which can limit the ability to assess extreme waves. Also available are satellite observations of wave conditions and numerical models that hindcast waves from modelled wind data. These provide a more complete coverage of Australia's ocean territory, and some hindcast records exceed 40 years, which is useful for evaluating extreme waves. Hemer et al. (2007a) provide a description and assess the relative merits of the available sources of ocean wave information.

Wave transformation approaching the shore

In deep water, waves travel without influence from nearshore bathymetry. The wave speed is almost entirely controlled by the wavelength. A wave with a 10 s period, for example, has a speed of approximately 16 m s^{-1}. In intermediate water depths, waves become increasingly influenced by the water depth as they approach the coast. Close to the shore, in shallow water depths, wave speed is almost entirely controlled by the water depth. A wave in 1 m of water, for example, has a speed of approximately 3 m s^{-1}.

As waves approach the shore, from intermediate into progressively shallower water depths, the wave period remains approximately constant, but the wave speed decreases as just described. This means that the wavelength must also decrease. The following sections describe other transformations to waves as they travel towards the shore into progressively shallower water depths.

Wave refraction

When waves approach the coast with their crests at an angle to the seafloor contours, the section of crest in deeper water travels faster than the section in shallower water. This results in the wave crests bending towards becoming parallel with the seafloor contours and ultimately the shoreline (Figure 3). This takes time, however, so waves do not always arrive aligned exactly parallel to the shoreline. Swell with the largest wavelength will undergo the greatest amount of refraction, because wave speed becomes influenced by water depth in deeper water and therefore waves have more time to bend around to the seafloor contours.

Wave refraction also results in the redistribution of wave energy such that the wave height varies along the wave crest. As waves bend around headlands and into embayments, for example, the wave height becomes greater on the headland and reduced in the embayment.

Wave diffraction

Wave diffraction frequently occurs in association with wave refraction. Wave diffraction is when the wave energy is transferred laterally along a wave crest as the wave passes an obstruction such as a headland, island or breakwater. It is a mechanism for wave energy entering into the shadow zone behind the obstruction.

The combined effect of wave refraction and diffraction is responsible for the arcuate shaped shoreline that is characteristically present in the lee of headlands (Figure 3). It is also the reason why swell waves can still penetrate into harbours and other protected settings.

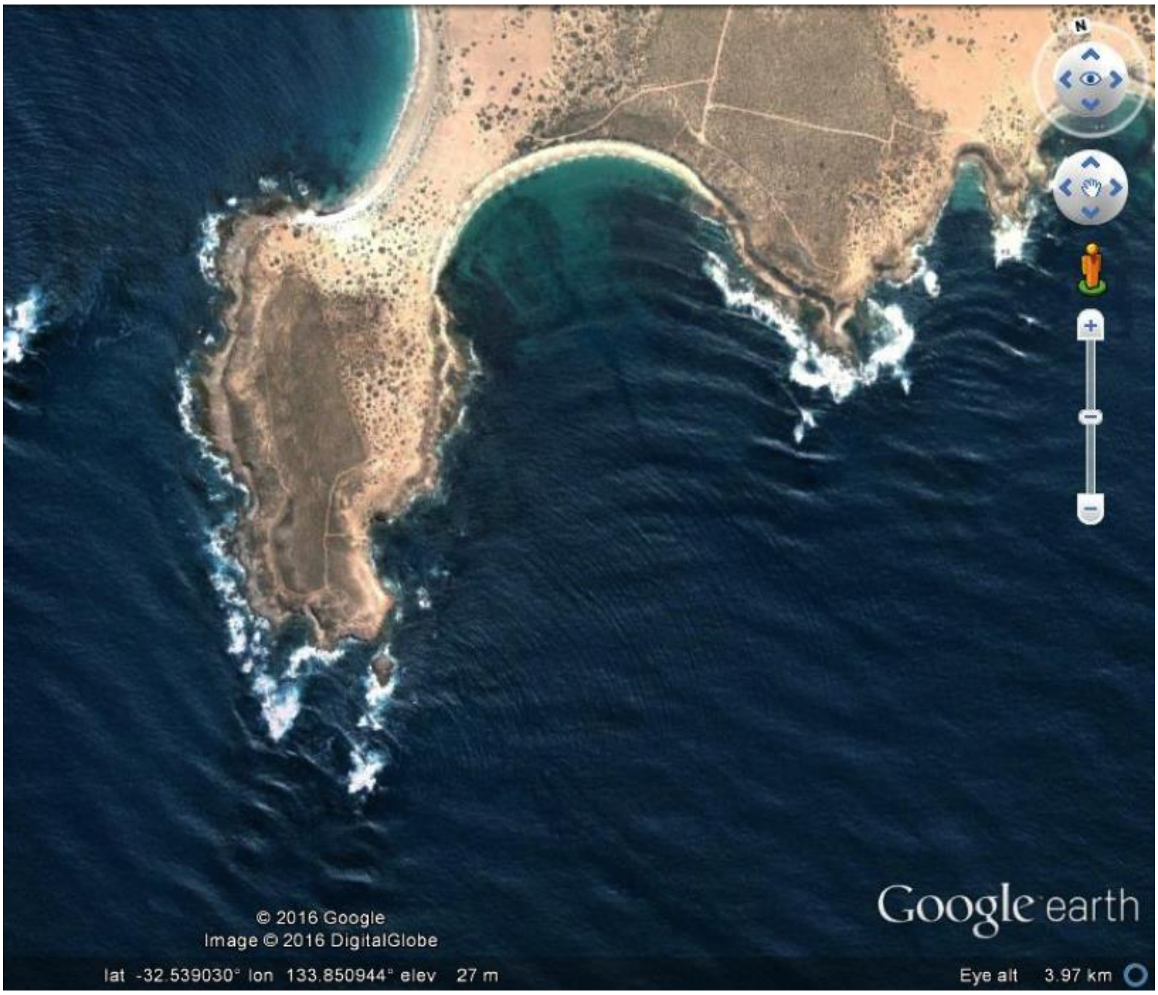

Figure 3: Photograph of the Eyre Peninsula coast, South Australia, to show wave refraction and diffraction. Note the increased wave height focussed on the headlands and reduced wave heights in the embayments. Photo: © Google Earth

Wave shoaling

Wave shoaling refers to an increase in wave height as a consequence of waves entering progressively shallower water depths. As the wave slows down, and thus the wavelength decreases, in order to convey the same amount of energy, the wave height must increase. Wave shoaling, and the increase in wave height, is particularly pronounced in the very shallow water depths just prior to breaking at the seaward edge of the surf zone.

At some point during wave shoaling, the water depth becomes too shallow for the wave to be stable and the wave breaks. This initiates surf zone processes.

Wave breaking and surf zone processes

Wave breaking at the seaward edge of the surf zone occurs because the water in the crest of the wave starts to travel faster than the wave form itself; the wave form becomes unstable and the water falls under gravity and generates bubbles and foam. As a rule of thumb, initial wave breaking occurs when the wave is in a water depth that is 1.3 times the wave height.

The styles of wave breaking include spilling, plunging and surging breakers (Figure 4). **Spilling breakers** are associated with gentle beach slopes and steep waves. **Plunging breakers** are associated with steeper beach slopes, than for spilling breakers, and moderately steep waves. **Surging breakers** occur on the steepest beach slopes and with waves of low steepness. Occasionally there can be over-steepened sections at the bottom of a surging wave causing it to become a **collapsing breaker**. An important consequence of wave breaking in the surf zone is sloping water surfaces in the cross-shore and longshore direction, which drive surf zone currents.

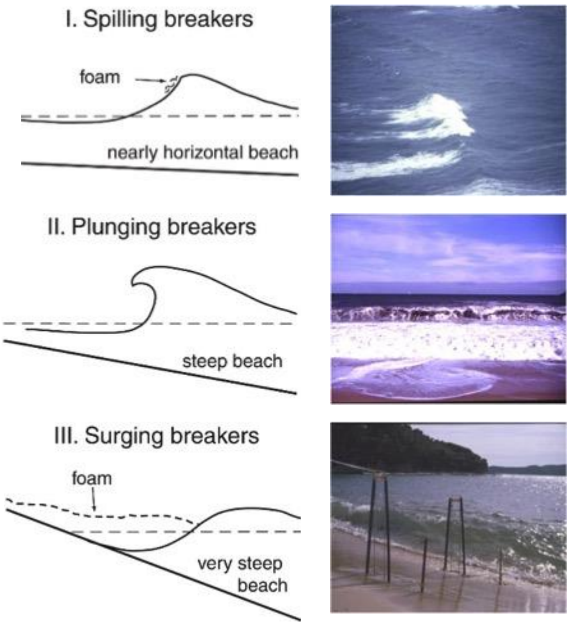

Figure 4: Examples of breaker types. Line sketch (left): Komar 1998, and photos (right): M.G. Hughes.

The dissipation of wave energy inside the surf zone due to breaking results in a transport of momentum in the shoreward direction. To balance that momentum transport, the average water surface (after averaging out the wave oscillations) inside the surf zone slopes up above the still water level and intersects the beach at a level that is higher than the shoreline would be in the absence of waves. This **wave setup** is an important component of coastal water levels during storms (see following section). It also drives a seaward-directed current called undertow or bed return flow (Figure 5). If there are along shore variations in the wave setup level against the beach, then there will be slopes in the average water surface also in the along shore direction. These can drive alongshore currents, which can eventually turn seaward and feed rip currents (Figure 5).

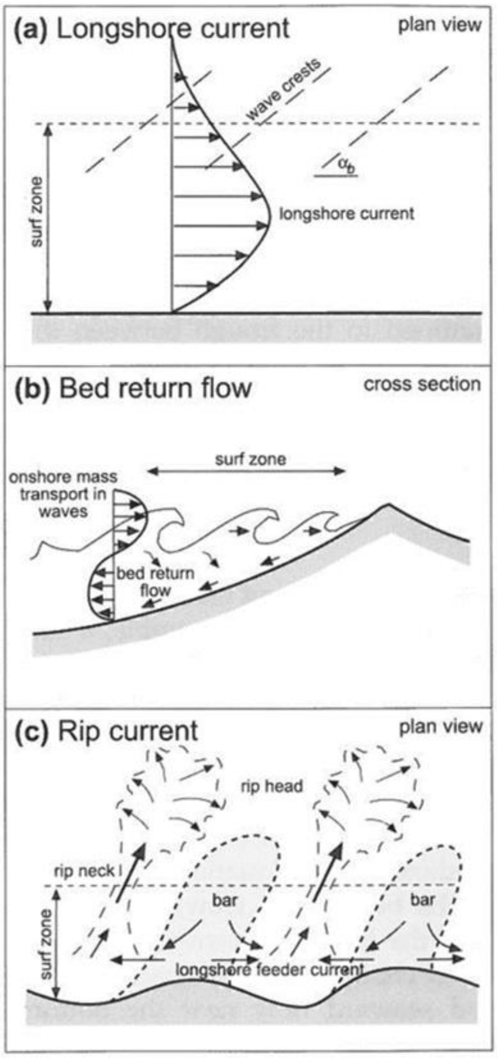

Figure 5: Different types of currents that occur in the surf zone. (a) Plan view of a longshore current due to wave crests arriving at an angle to the beach. The largest current speeds occur at about the mid surf zone or in the trough between the bar and the beach. (b) Cross section of undertow (bed return flow) due to wave setup inside the surf zone. The largest current speeds generally occur where the seabed is steepest. (c) Plan view of rip currents consisting of relatively short longshore feeder currents close to shore turning seaward into the rip channel. The largest rip current speed is usually at the rip neck. Source: Masselink and Hughes 2003.

On some beach types, particularly gently sloping beaches, another type of wave can be important in the surf zone known as an **infragravity wave**. It has a longer wavelength than sea or swell waves with up to a kilometre between the wave crests. While the large wavelength makes these difficult to observe, the presence of infragravity waves can be experienced by an observer standing at the landward edge of the surf zone as a change in the average water level between say their ankles and their thighs approximately every 100 s or so. One source of infragravity waves is the wave groups characteristic of swell waves (Figure 2). The infragravity wave travels with the wave group and is released when the swell waves break at the seaward edge of the surf zone.

Factors affecting coastal water levels

The impact of waves on the coastline during storms depends a great deal on the coastal water level. Elevated water levels can allow storm waves to penetrate higher up the beach for example. The coastal water level at any one time is determined by a range of processes. Some of the most important are represented conceptually in Figure 6 and discussed in the following paragraphs.

Water levels associated with the **astronomical tide** are highly predictable. Storms coinciding with high tide, and in particular spring high tide, cause the greatest hazards on the coast.

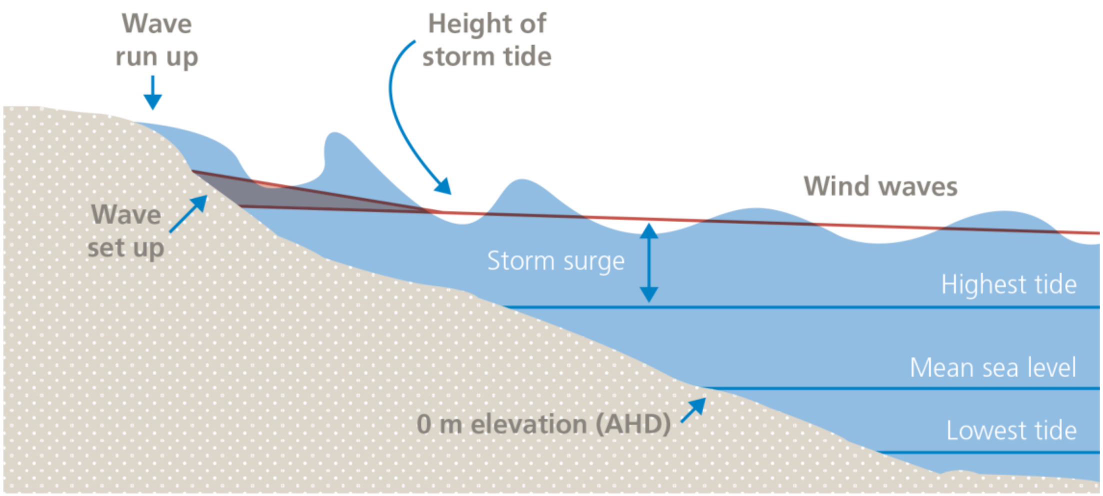

Figure 6: Schematic of the surf zone showing principal contributors to the coastal water level and shoreline elevation. Source: DSE 2012 © The State of Victoria, Department of Sustainability and Environment 2012.

Barometric setup refers to the change in coastal water level as a consequence of the overlying air pressure. Storms are generally associated with low pressure systems, and for each hPa (hectopascal) drop in air pressure there can be up to a 1 cm increase in the coastal water level. Barometric setup of the coastal water level during storms is commonly in the range of 0.1 to 0.4 m.

Wind setup is due to the stress of the wind blowing over the ocean surface and piling water up against the coast. As the wind transfers its momentum to the ocean surface, the surface begins to move and eventually the top few centimetres of the ocean can move toward the coast at up to 1% of the wind speed. Wind setup on exposed open coast beaches can reach 0.5 m or more, but is commonly 0.1 to 0.2 m in height (Couriel et al. 2014). As a general rule, for a given wind speed and duration, the wind setup is greater on broad gently sloping continental shelves than on narrow steep ones.

Barometric setup and wind setup are sometimes jointly referred to as **storm surge** or **storm tide**. Wave setup has already been described in the previous section. **Wave setup** levels are typically around 20% of the offshore significant wave height, and so are commonly in the range of 0.5 to 1.5 m on exposed open coast beaches during storms (NSW Government 1990).

All of the above listed contributors to coastal water level vary with variations in the tide, wind or waves, that is slowly over several hours or more. **Wave runup** refers to the wave setup combined with the oscillation in shoreline elevation (swash) with the passage of each wave arriving at the beach. It includes runup from sea and swell as well as from infragravity waves, and varies on a time scale of seconds to minutes. On gently sloping beaches, the infragravity wave runup can be more important than the runup from sea and swell. The wave runup height on exposed open coast beaches during storms can be 3 to 6 m on top of the other components (NSW Government 1990).

There are a variety of other factors that can influence ocean water levels over longer time periods, and can ultimately influence the highest coastal water level achieved during storms. These include:

- Seasonal water temperature variations that change the density of the ocean and result in seasonal variations in sea level of 0.3 m or more (Couriel et al. 2014). A similar effect can arise on a shorter time scale associated with warm boundary currents such as the Leeuwin Current and East Australian Current impinging onto the shelf.
- Coastal-trapped shelf waves that are caused by meteorological disturbances (atmospheric fronts) being transferred to the ocean through the inverse barometric effect, resulting in a wave (wavelength of several hundred kilometres) traveling along the continental shelf parallel to the coast, which can cause sea level variations of around 0.2 m over several days (Couriel et al. 2014).
- El Niño – Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and other global scale climate oscillations, which cause inter-decadal fluctuations in atmospheric pressure, ocean circulation, temperature, wind patterns and strength. These can result in sea level variations of 0.2 m or so (Couriel et al. 2014).

Dynamics of Australian beaches

Coastal classification models, such as the Australian Beach-State model, are useful tools for aggregating and organising large amounts of research output. They also allow inferences to be made on the nature and variability of a section of coastline without the research necessarily having been carried out at that location. They are useful for first-pass coastal hazard assessments, because the likelihood of particular processes and their related consequences vary consistently between beach types.

Beach state model – wave dominated beaches

There are three main beach states recognised on wave-dominated coasts; dissipative, intermediate and reflective (Wright and Short 1984; Figure 7). The morphology of dissipative (D) and reflective (R) beach states is largely uniform alongshore, whereas the intermediate state is divided into four sub-types based on the alongshore and cross-shore rhythmicity of surf zone bars and troughs. These are longshore bar-trough (LBT), rhythmic bar and beach (RBB), transverse bar and rip (TBR) and low tide terrace (LTT).

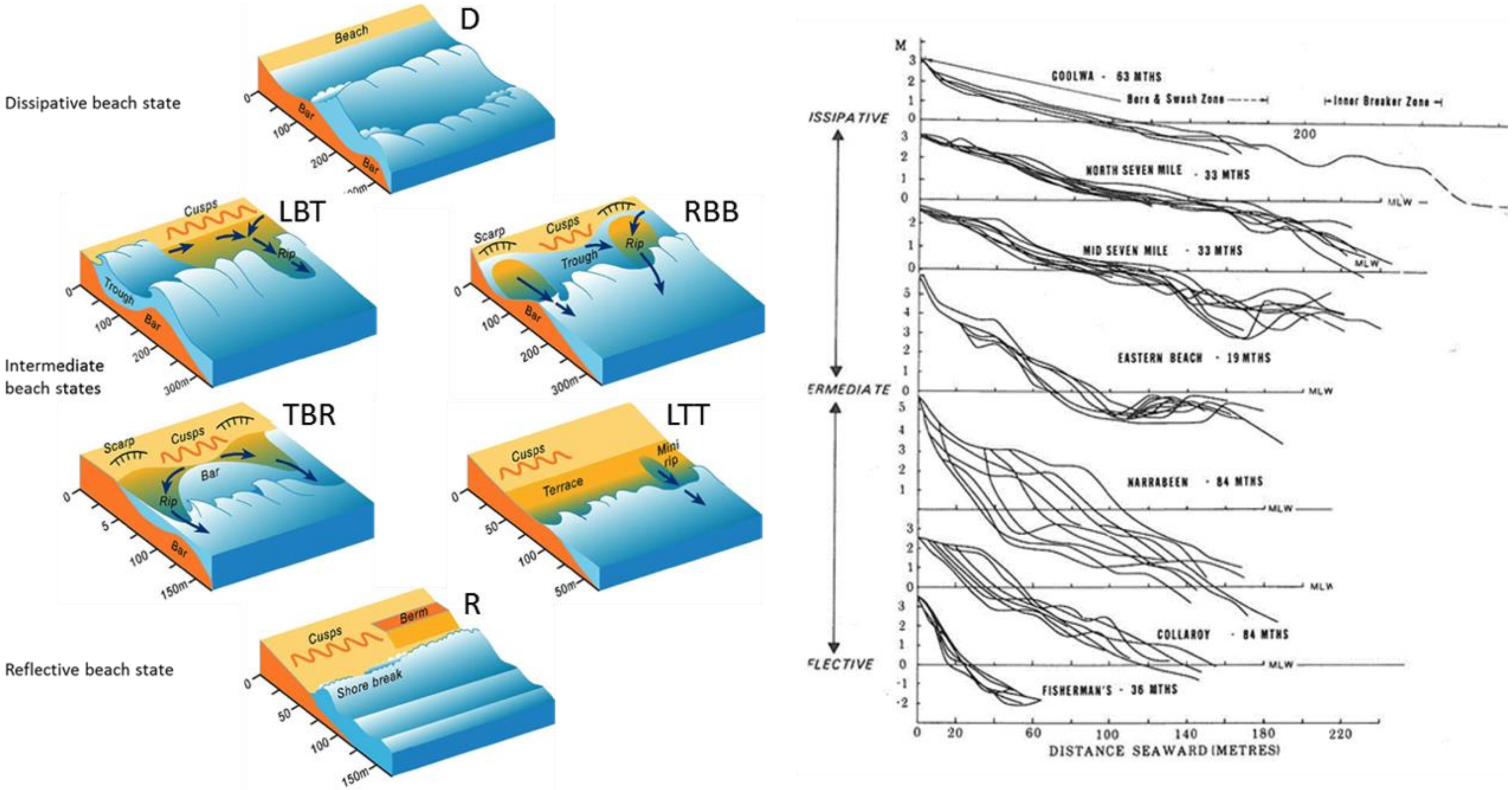

Figure 7: (a) Wave-dominated beach types typically occurring along the central and southern Australian coastline. Dissipative and reflective are the high and low energy end-member types. Intermediate types are distinguished by the arrangement of bars, troughs and rip channels. Source: © OzCoasts (Geoscience Australia) 2016. (b) Beach profile envelopes indicating the range of variability in beach volume and shoreline position are also shown. Source: Wright and Short 1984

Dissipative beaches are characterised by wide surf zones with spilling breakers (Figure 4), and the dominant surf zone currents are alongshore currents that are persistent for long distances and/or undertow (Figure 5). Intermediate beaches typically involve plunging breakers on the bar and the beach, and the dominant surf zone currents are feeder currents that travel alongshore for relatively short distances before turning and flowing offshore as rip currents. Reflective beaches are characterised by breakers collapsing or surging onto the beach and a general lack of surf zone currents (Wright and Short 1984).

The most common morphology that a particular beach displays (i.e. the modal beach state) depends on the most commonly occurring wave conditions (wave height and period) and sediment size. Dissipative beaches are generally associated with high wave energy and/or fine sand whereas reflective beaches are generally associated with low wave energy and/or coarse sand and gravel. Intermediate beaches are generally associated with the most variable wave energy conditions and medium-sized sand (Wright and Short 1984). Thus beach type varies along the coast with relative exposure to the open ocean wave energy and changes in sediment size.

A particular beach can vary from its modal beach state in response to synoptic variations in wave conditions in an ordered sequence: R–LTT–TBR–RBB–LBT–D (Wright and Short 1984; Figure 7). As a storm acts on a beach it may evolve through the full sequence of beach states (if the beach is initially reflective and the storm persists for long enough). More commonly, the beach will only evolve through a partial sequence due to the time required for beaches to respond to the wave conditions. In the recovery period after a storm, the beach will cycle back through the sequence of beach states in reverse order.

Beaches that are dissipative most of the time generally don't vary greatly, because they are in approximate equilibrium with large waves. Similarly, beaches that are reflective most of the time generally don't vary greatly because they are typically located in deeply embayed settings, which places upper limits on the wave conditions reaching the shoreline. The most dynamic beaches are the intermediate beach types; where bars, troughs and rip channels are highly mobile in response to variable wave conditions (Wright and Short 1984; Figure 7).

Beach state model – tide dominated beaches

On coasts where the spring tidal range is approximately three or more times larger than the most commonly occurring wave breaker height, the tide strongly modifies the wave-formed beach (Short 2006; Figure 8). On tide-dominated coasts with low wave energy, and or coarser beach sand, reflective/low-tide terrace beaches occur. If the wave energy is greater, or the beach sediment is finer, then the resulting tide-dominated beach type will be a reflective/low-tide bar-rip or an ultra-dissipative beach type (Short 2006).

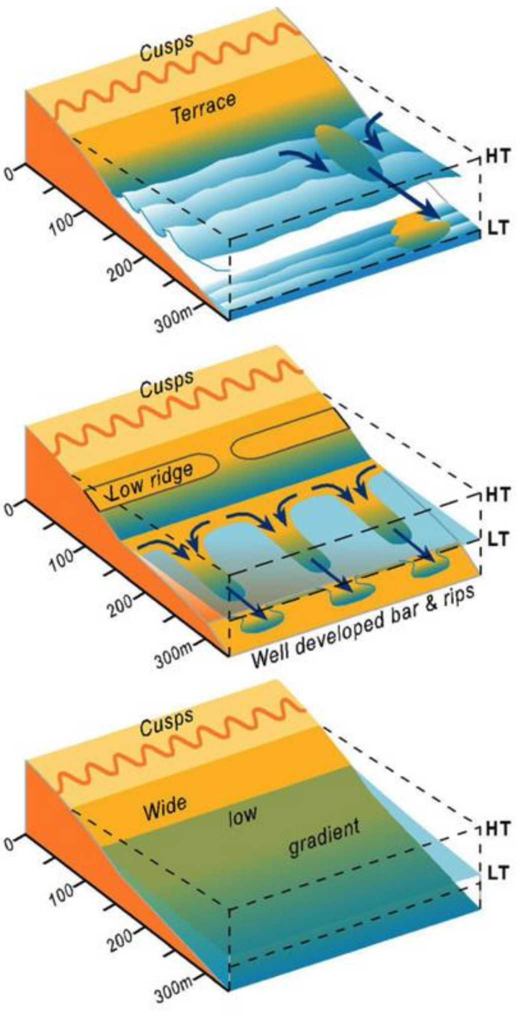

Figure 8: Tide-dominated beach types typically occurring along the northern Australian coastline. Moving from top (reflective/low tide terrace) through the middle (reflective/low tide rip) to bottom (ultra-dissipative) the relative wave energy increases and/or the beach sediment size decreases (after Short 2006). Source: © OzCoasts (Geoscience Australia) 2016.

Geographical variation in primary processes drivers – waves and tides

Based on the beach state model described above, the geographical variation in beach types around the Australian coast should reflect the local exposure to wave and tide energy.

The coastline along the southern half of Australia is exposed to larger waves more often throughout the year (Figure 9). These are generated by the semi-regular west-to-east passage of sub-tropical and temperate low pressure systems. In particular, the southern and southwestern coastlines are exposed to large waves generated by temperate low-pressure systems blowing over the near-infinite fetch of the Southern Ocean. On the southeast coast, less frequent large wave conditions are associated with low pressure systems stalled in the Tasman Sea for extended periods of time (East Coast Lows). The northern half of Australia is mostly influenced by less energetic equatorial and tropical weather systems. The pattern of seasonal variation in wave height in northern Australia is related to the SE Trade Winds (May-November) and the Monsoon (December-April). While the northern half of Australia generally has small waves, the summer months can be punctuated by infrequent tropical lows and tropical cyclones that can result in larger waves (Hemer et al. 2007a).

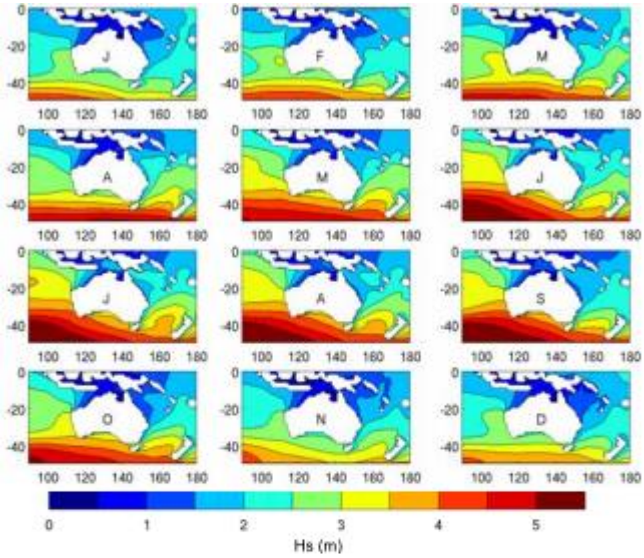

Figure 9: Maps showing monthly means of significant wave height (Hs) determined from model hindcast data covering the period February 1997 to January 2002. Source: Hemer et al. 2007b

Tides are amplified in long gulfs and over broad continental shelves. The coastline along most of the northern half of Australia is meso-tidal (spring tide range 2-6 m) or macro tidal (spring tide range >6 m), with the exception of parts of the Gulf of Carpentaria (Figure 10). The largest tide ranges occur on the central Queensland coast and the Kimberley coast of Western Australia. The southern half of Australia is predominantly micro-tidal; except on the shallow shelf of Bass Strait and in the Spencer Gulf and St Vincent Gulf where the coast is meso-tidal.

As a consequence of the predominance of large tide ranges in northern Australia and large waves in southern Australia, the tide-dominated beach types are most common along the northern coastline and the wave-dominated beach types are most common along the southern coastline (Table 1; Short 2006). The few tide-dominated beaches that occur in Victoria, Tasmania and South Australia are generally situated at the back of deep embayments with very limited exposure to open coast wave energy. The wave-dominated beaches that occur in Western Australia, Northern Territory and Queensland generally occur on the micro-tidal and meso-tidal sections of the coastline in those states (Figure 10).

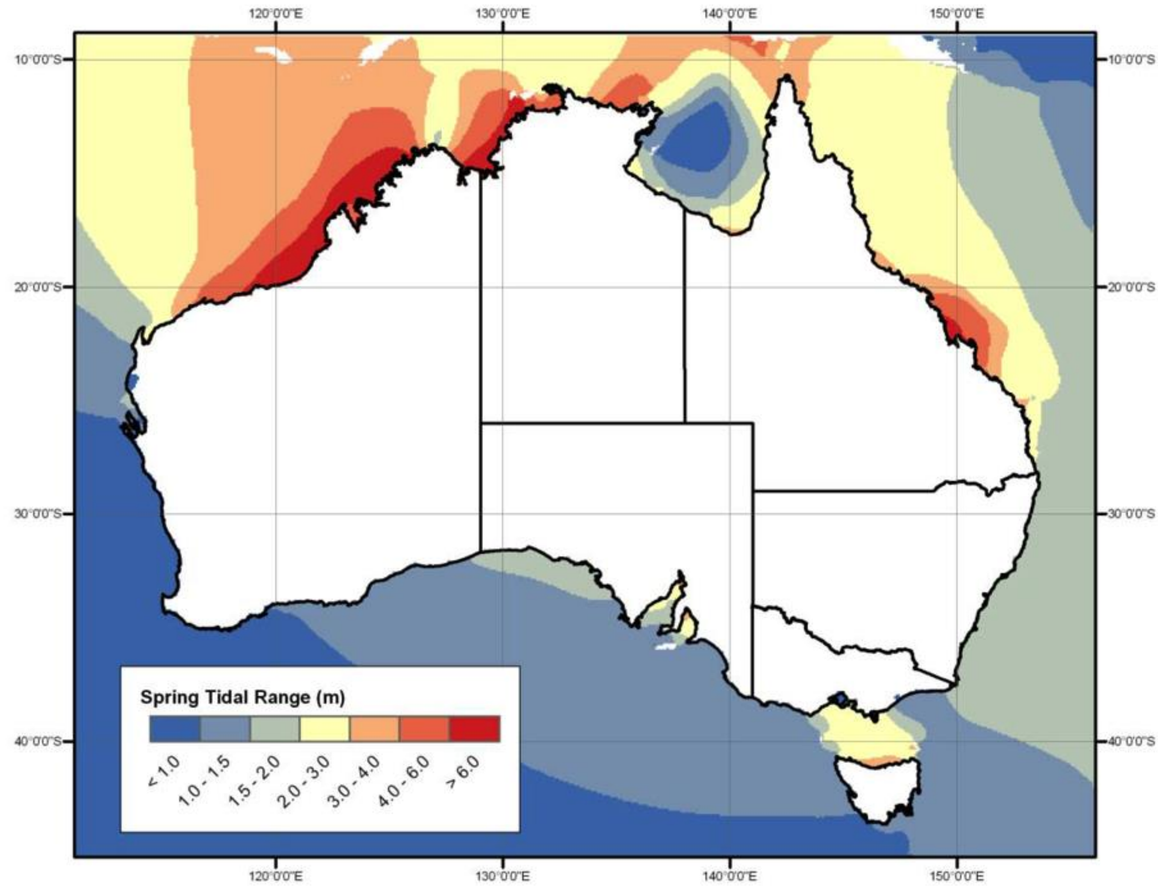

Figure 10: Map of spring tidal range around the Australian coast. Source: © Commonwealth of Australia 2016, Bureau of Meteorology.

Beach hazards and climate change

Present-day extreme waves and water levels

Storm-related hazards on Australia's open coast beaches are usually associated with both extreme waves and water levels. Present day extreme conditions are shown in Figure 11 in terms of the 100-year **average recurrence interval** (ARI) significant wave height and storm tide water level. That is the significant wave height or storm tide level that is exceeded on average once every 100 years.

The largest 100-year ARI wave heights, up to 13 m, occur along the exposed western and southern coasts of Tasmania. Large sections of the southwestern, southern and southeastern coastlines have 100-year ARI significant wave heights exceeding 8 m. So too does the northwestern and sections of the northern coastline, due to tropical cyclones. The northeastern coastline has more modest 100-year ARI significant wave heights, reaching only 6-7 m, due to the protection from tropical cyclone waves offered by the Great Barrier Reef and very shallow shelf waters through the Gulf of Carpentaria. The largest 100-year ARI storm tide levels occur on the coastlines adjacent to the broad flat continental shelf regions of northern Australia and the large, shallow tapered gulfs in South Australia (Mariani et al. 2012).

Storm erosion and inundation hazard

Beach erosion refers to the removal of material from the shoreline and adjacent areas: it results in a landward displacement of the shoreline, either temporarily or semi-permanently. Beach erosion can be measured in terms of either landward shoreline movement or reduction in beach volume. Beach erosion can directly expose built assets to the impact of waves, or it can be sufficiently close to reduce the foundation capacity of coastal land which may lead to undermining and collapse of built assets.

Once storm waves reach a critical steepness, usually due to an increased wave height relative to wave length, wave runup on the foreshore begins to erode the beach. Seaward flowing currents, bed undertow and/or rip currents, transport the sediment from the beach and deposit it as a surf zone bar. Following storms, when the wave steepness decreases below the critical level, waves act to transport the surf zone bar back towards the beach.

If sufficient time passes before the next storm then all of the sand lost from the beach may be returned. If the next storm arrives before the sediment has returned, erosion from the second storm compounds the erosion from the first storm, leading to significant beach cut. Sometimes, however, the amount of erosion associated with subsequent storms will not be as large as the first, even if they were similar in magnitude. The explanation for this is that prior to the second storm the beach may already be close to equilibrium with storm wave conditions. Nevertheless, the greatest hazard is generally associated with clusters of storms that compound the erosion losses.

On some beaches, over a sufficient time period (a decade or more), cycles of storm erosion and recovery result in the shoreline position oscillating around the same location and so the system is said to be in equilibrium. On other beaches, these storm/recovery cycles in shoreline position occur on an underlying trend of landward shoreline movement, which reflects disequilibrium in the system. This arises due to other factors working in addition to storm erosion, which results in insufficient sediment recovery after each storm. An underlying landward trend in shoreline position is referred to as **recession** and is discussed further in the next section.

Coastal inundation results from a combination of marine and atmospheric processes causing the sea level at the coast to be raised above its normal elevation (Figure 6), resulting in the flooding of normally 'dry' land.

The flooding of coastal land behind open coast beaches can occur through overtopping of natural shoreline topography (e.g. dunes) or built shoreline infrastructure (e.g. seawalls). If stormwater drainage infrastructure is open to the coast, then inundation can also occur through a hydraulic gradient driving seawater back up through the storm drainage network to inundate low lying land without actually overtopping dunes or structures.

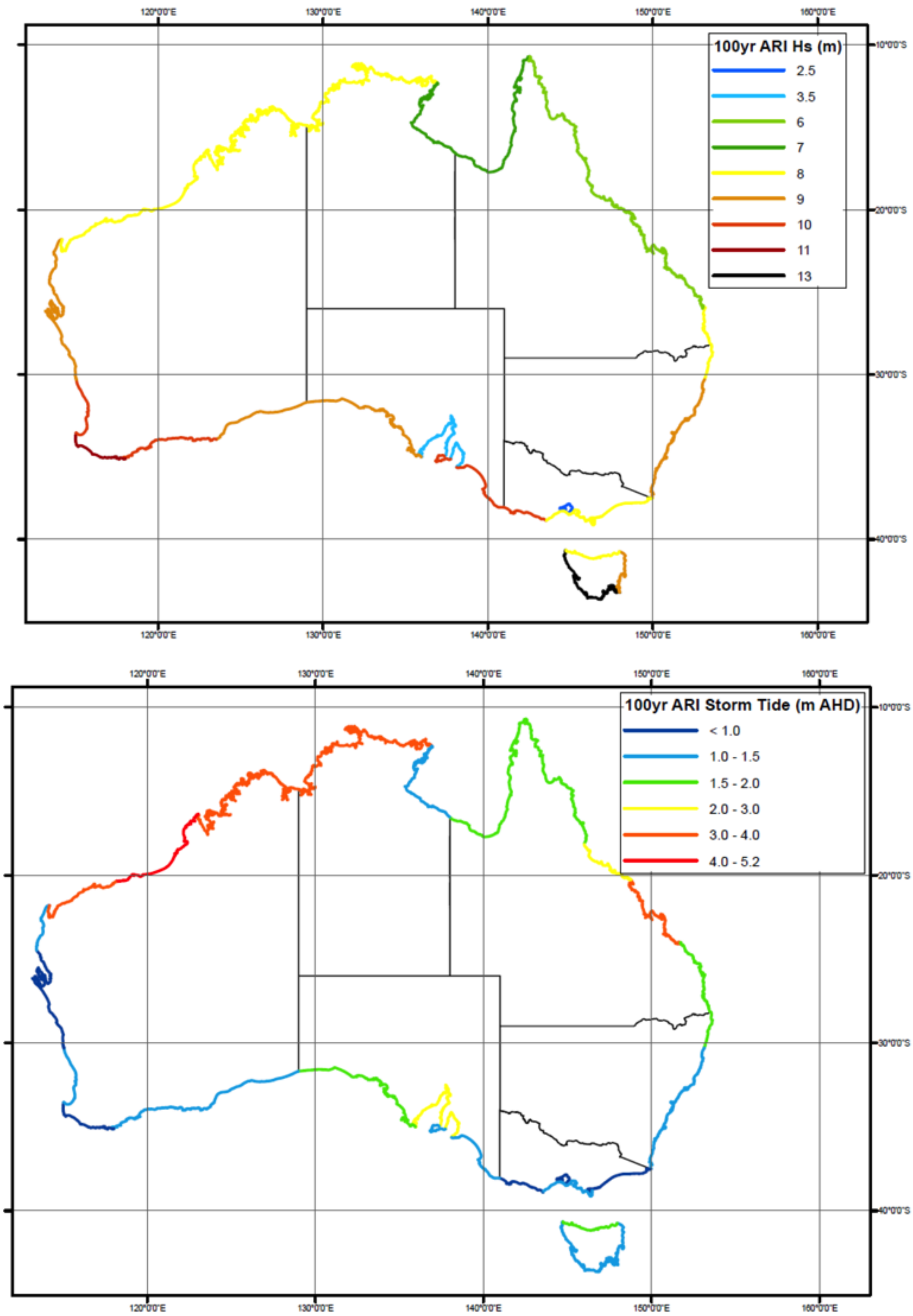

Figure 11: Present day 100-year average recurrence interval significant wave heights in 20 m water depth (top) and storm surge elevations along the Australian coast (bottom). Source: Mariani et al. 2012 © Antarctic Climate & Ecosystems Cooperative Research Centre 2012.

Overtopping of dunes or built shoreline structures can also pose hazards through large volumes of high velocity water impacting built assets and causing safety issues for pedestrians. If a dune or hard structure is breached, then the flooding and other impacts will be greater, as the barrier is lowered.

The actual amount of beach erosion and/or inundation that occurs during a storm is difficult to predict, due to the complex interaction of many factors including the:

1. beach state – this controls the natural rate that a beach tends to respond to storms;
2. dune height and beach width - determines the amount of sand available to initially buffer the erosion impact on the dunes and the amount of freeboard that might exist as the storm water level rises and reaches its peak;
3. storm wave height, period and duration – determines the rate at which erosion occurs and how long the erosion proceeds, and therefore the total volume of material removed from the beach;
4. storm tide level – determines the height that waves can reach to overtop natural and built structures, and the depth of inundation behind the shoreline;
5. time since the previous storm – determines whether the current storm will be compounding the sediment losses of a previous storm or sequence of storms;
6. localised processes – this includes processes like rip currents that can locally enhance the storm erosion.

Beach recession and rotation hazard

Thus far discussion has focussed on sediment exchange in the cross-shore direction due to storms. This direction of sediment movement dominates on swash-aligned beaches and embayed (pocket) beaches (Figure 12a). For swash-aligned beaches, the offshore wave direction is such that the wave crests arrive perfectly parallel to the shoreline. For embayed beaches, the same occurs, but wave diffraction and refraction about a headland are also involved and result in an arcuate shape to the shoreline. Longshore currents on swash aligned and pocket beaches are minimal. When offshore conditions are such that refraction and diffraction processes are not entirely effective in reducing the wave angle at the shoreline to zero, then it is referred to as a drift-aligned shoreline. Longshore currents (Figure 5) are persistent and sediment transport in the longshore direction is dominant on drift-aligned beaches. That is not to say that cross shore storm erosion does not occur on these beaches.

A common cause of erosion and recession on drift-aligned beaches is an insufficient sediment supply at the updrift end of the embayment to match losses at the downdrift end. The impact of a sediment deficit in an embayment is best understood through the sediment budget concept. A sediment budgeting exercise involves the identification and (relative) quantification of sediment sources and sinks (Figure 12b). Sediment sources potentially include rivers, cliff erosion, biogenic production, onshore transport from the shelf and longshore transport from the adjacent embayment. Sediment sinks potentially include losses to dunes, tidal inlets, the shelf and adjacent embayments.

A sediment deficit on a drift-aligned coast may arise because sediment delivery from the up-drift embayment is exceeded by loss to the down-drift embayment. This might be due to the shoreline orientation not yet having achieved equilibrium with the wave conditions, or there is insufficient sediment in the embayment overall to achieve the equilibrium shoreline orientation. Sediment deficits may also arise due to continuing losses to dunes, tidal inlets or offshore. If the magnitude and variability in sediment inputs and losses to a coastal embayment are not balanced at the timescale of interest, then there may be a sustained sediment deficit that will result in shoreline recession superimposed on the storm erosion and recovery cycles.

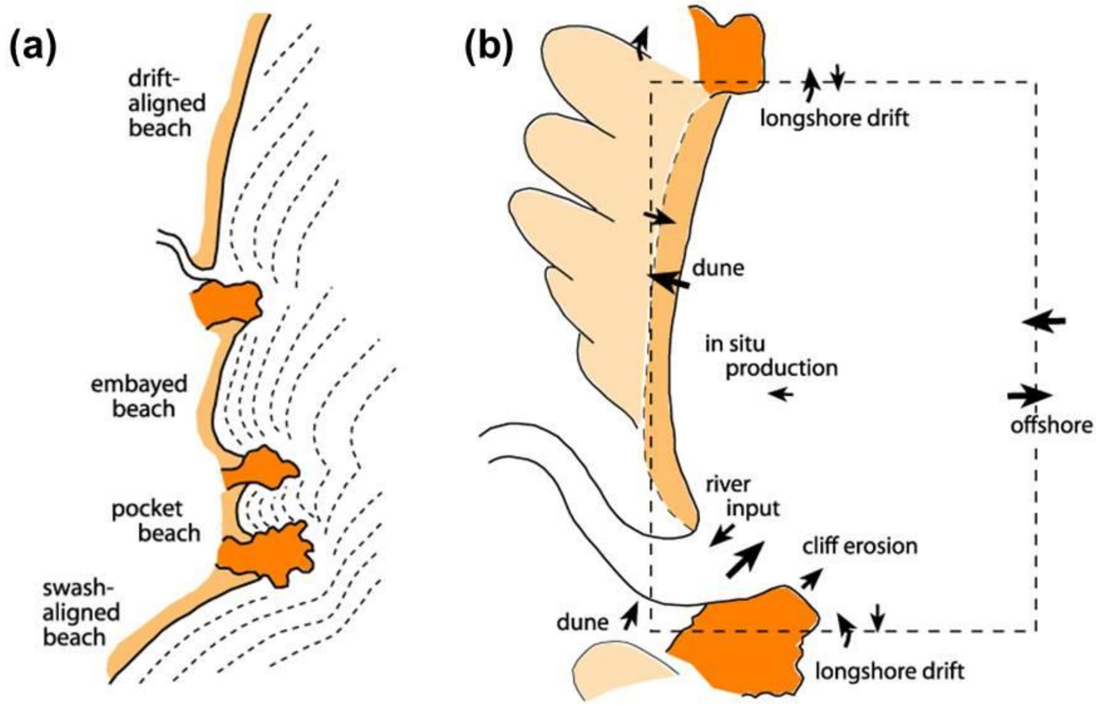

Figure 12: (A) Wave patterns arriving at the shoreline for different embayment types. On swash-aligned, pocket and embayed beaches, wave crests arrive parallel to the shoreline and longshore currents are minimal. On drift-aligned beaches, waves arrive at an angle to the shoreline and longshore currents are well developed. (B) An embayment showing potential sediment sources, sinks and transport pathways used to determine the sediment budget for the embayment. Source: adapted from Woodroffe 2003.

Sediment inputs and losses can operate over very different time scales. For example, on an annualised basis, sediment input from a river or adjacent embayment will generally be larger than the input from cliff erosion or offshore sources. Sediment budgets are therefore assessed in order to represent the relevant management timeframe.

The fact that sediment sources and sinks are characterised by a high degree of variability at both short and medium time scales means that it can be difficult to determine whether landward retreat of the shoreline is the result of a sediment budget deficit, or some other reason.

A process that occurs on embayed beaches and causes a response similar to beach recession is shoreline rotation; which results from either opposing directions of shoreline movement at opposite ends of an embayment or differences in the relative magnitude of shoreline movements at opposite ends of an embayment. In either case, the shoreline rotation generally reverses after a few years. The driver for shoreline rotation can be inter-annual to decadal variations in wave climate (Harley et al. 2011). While shoreline rotation can be incorrectly interpreted as shoreline recession, rotation can cause similar problems in any case.

Climate change impacts

Projected climate change impacts on storm frequency, intensity and distribution over the oceans are associated with considerable regional variability and uncertainty. Therefore, wave climate and storm surge occurring at the coast are also associated with similar variability and uncertainty. Some scenarios predict that there will be more frequent El Niño events in the Pacific, for example, which may influence both wave height and direction along the eastern coast of Australia. Other predictions include increased extreme wind speeds associated with tropical cyclones and temperate low pressure systems, resulting in increased wave height and storm surge in northern Australia. Other forecasts, however, predict that there may be a reduction in waves along the southern and western coastline due to reduced wind speed associated with temperate low pressure systems (Hemer et al. 2013).

Whatever the trends in wind and the resulting change in wave climate turn out to be over the coming decades, they will have knock-on effects for coastal process drivers (waves and water levels) through barometric setup, wind setup, wave setup and wave runup.

Changes to coastal wave energy into the future are likely to change the levels of storm erosion experienced, and potentially even change the modal beach state so that its range of response to storms is altered. Changes in the wave direction due to shifting wind patterns may cause beaches to change from being swash-aligned to drift-aligned, or vice-versa. This would change the predominant surf zone current type and alter the most significant components of the sediment budget. Changes in wave direction will also result in new wave refraction and diffraction patterns, which can shift the focus of wave energy and beach erosion to new locations. A climate-induced increase in wave energy or shift in wave direction may also result in a permanent rotation of the shoreline of an embayment.

Underlying the responses to coastal waves and water levels due to changing climate conditions will be the increase in mean sea level due to global warming. By 2090, sea level is predicted to be between 0.4 m and 0.7 m higher than mean sea level at the start of this century (CSIRO and BOM 2015).

A simplistic assessment of a beach's response to sea level rise suggests that there will be a landward and upward shift of the profile caused by erosion of the beach and dunes by waves and deposition offshore by currents operating during the storms occurring at the higher sea level. This is the encroached mode of response shown in Figure 13 (Cowell et al. 1995). Geological evidence of coastal response to sea level rise in the past, however, suggests alternative responses are possible depending on the underlying shoreface slope. On a gently sloping shoreface, as the coastline is inundated by rising sea level, net sediment transport landward by constructive wave conditions may be predominant, as is the case in the transgressive barrier mode (Figure 13). Note that this still involves shoreline recession. An intermediate response mode may occur, resulting in sediment lost to both the lower shoreface and dunes during sea level rise.

Only considering the cross-shore dimension of a beach ignores potential sediment sources and sinks elsewhere in the system, and how these might respond to changing climate and rising sea level. Some beaches might initially maintain an equilibrium shoreline position under rising sea level, because adjustments elsewhere in the embayment compensate. After a threshold is reached, however, and the successive post storm recovery of sand to the beach continually falls short of balancing the amount eroded by storms, the beach will recede. This type of embayment scale threshold response to adjustments in source and sink terms has been recognised in the geological record, and can guide assessments of large scale coastal response to future sea level rise (Goodwin et al. 2006).

Profile behaviour models like those in Figure 13 can incorporate consideration of sediment sources and sinks elsewhere in the system in order to make predictions of beach response to sea level rise (Cowell et al. 2003). Large-scale coastal behaviour is complex, however, and thus it is difficult to generalise results to a universal prediction of beach response to rising sea level. Site specific assessments will need to rely heavily on quantitative sediment budgets and projections of the magnitude of sediment sources and sinks into the future.

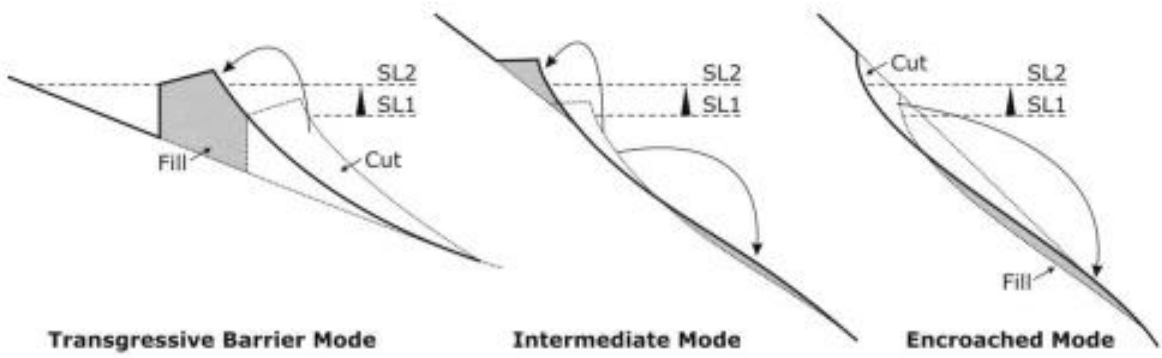

Figure 13: Potential styles of shoreline response to sea level rise, with increasing substrate slope from left to right. The transgressive barrier mode involves sediment losses from the present-day coastline transported landward to the dunes. The encroached mode involves sediment losses transported seaward to the lower shoreface (equivalent to the Bruun Rule). The intermediate mode involves sand losses both landward and seaward. All modes involve shoreline recession. Source: Cowell et al. 1995.

Summary

Treatment of the topic in this paper is not exhaustive. It briefly highlights some of the reasons why understanding wave-related processes is important when managing the coastal zone. Furthermore, it demonstrates that climate change and sea level rise over the next century will have direct and indirect impacts on coastal waves and water levels.

Waves approaching the coastline undergo a variety of transformation processes including wave refraction, diffraction, shoaling and breaking. Wave breakers inside the surf zone produce currents including undertow, rip currents and longshore currents. During storms wave runup and surf zone currents erode the beach. Extreme coastal water levels are due to the astronomical tide, barometric setup, wind setup, wave setup and runup, and these can assist this erosion as well as being the cause of inundation of low lying coastal land. Wave overtopping of shoreline structures and dunes can also result in waves directly impacting on built assets in the coastal zone.

The impacts of climate change on regional wave climates and mean sea level around Australia will be varied and are the subject of ongoing investigation. Possible knock-on effects include changes in beach state, beach rotation and changes to the recurrence interval of coastal inundation levels, to list a few.

Effective coastal management will include due consideration of wave related processes and the likely impacts of climate change. These impacts are difficult to generalise, because regional and site specific factors have a strong influence. Management of a particular coastal system should include site-specific investigation of waves, water levels and sediment budgets to a level commensurate with the risk level required to be managed.

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