HOW CAN WE TELL IF SEA-LEVEL RISE IS YET CAUSING ANY OF THE COASTAL CHANGE WE SEE?

C. Sharples[1]

[1] University of Tasmania, Hobart, Tasmania

Abstract

Global sea-level has risen about 21 cm since the 1880s and will become an increasingly significant driver of coastal erosion. It is reasonable to expect that sea-level rise to date should be driving some noticeable coastal change, however it is also likely that in many cases other coastal processes are counter-acting such change. I ask whether there are some coastal environments where countervailing processes are less significant and change due to sea-level rise to date is already identifiable. The ability to differentiate “early responder” and “late responder” shores will be important in planning adaptive coastal management.

I am looking for shores showing long-term changes in behaviour over the 70-year air photo record period that are consistent with expected responses to sea-level rise, such as changes from stable to persistently receding behaviour. Coastal environments where other potentially confounding processes such as swell-driven beach recovery are minimal are of particular interest. Where possible responses to sea-level rise are identified it is important to test for other local process changes that may alternately be responsible. Moreover, because correlation does not necessarily imply causation, it is also important to test for a plausible mechanism by which sea-level rise may be causing any apparent responses.

Roches Beach in Tasmania is a moderately swell-exposed beach in a littoral drift - dominated embayment distant from the continental shelf. Seventy years of air-photo history show a major change from a mostly stable shoreline (1946-1975) to accelerating progressive recession since the mid-1970s (1977-2011). A plausible mechanism for an early response to sea-level rise is available via an increasing sand budget deficit resulting from increasingly frequent erosion events due to higher mean sea-levels. Observational testing of the sand budget is in progress, as are tests of other variables such as local wind climate changes which might explain the observed changes.

Introduction

There are well-established theoretical and observational reasons to expect that a rise in sea-level relative to erodible shores will generally (albeit not always) result in erosion and recession of those shorelines. After millennia of relative stability, globally averaged (eustatic) sea-level has risen 21cm since circa 1880 (Church & White 2011), and simplistic estimates based on the Bruun Rule of erosion by sea-level rise (Bruun 1962) suggest this could have resulted in about 10 to 20 metres horizontal recession of some shores by now. However a wide variety of other processes also cause shoreline erosion, and there are also processes which may at least temporarily mask or prevent long term recession trends, such as sediment transport processes.

There is a widespread assumption that it will take somewhat more eustatic sea-level rise than has yet occurred before a shoreline recession signal attributable to sea-level rise is clearly identifiable above the ‘noise’ of other processes. Whereas this assumption is probably justified for many open coast swell-exposed sandy beaches which still have considerable capacity to recover from erosion events, recent progressive shoreline recession is widespread in a number of distinctive coastal environments such as swell-sheltered coastal re-entrants and ‘soft-rock’ shores where some of the complicating processes that might mask the recessional effects of sea-level rise are absent. In several Tasmanian cases evidence from historic aerial photograph time series indicates that there has been a significant change in shoreline behaviour within the last 50 years or so that is commensurate with the sort of changes that might be expected in response to sea-level rise (see below). These observations have led me to undertake a Ph.D. research project framed around two research questions, namely:

1: How can a sea-level rise signal be tested for in coastal landform behaviour, and separated out from all the other processes that may cause coastal erosion or other coastal behaviour changes?

2: Are there some distinctive shoreline types and/or coastal process environments which are responding earlier to global eustatic sea-level rise (by changing to a progressive and/or accelerating recession mode) than others?

Addressing these research questions will be of considerable value in planning for and managing coastal hazards in the context of an ongoing rise in global sea-levels, by providing new insights into which erodible shorelines are more resilient or more vulnerable to sea-level rise.

Previous studies

A recent review of research efforts to identify a signal of recent eustatic sea-level rise in coastal landform behaviour (Le Cozannet et al. 2014) concluded that no studies have yet unequivocally demonstrated such a relationship. In several cases (e.g., Romine et al. (2013) in Hawaii and Zhang, Douglas and Leatherman (2004) on the eastern USA coast), a clear relationship was observed between differing rates of regional sea-level rise and shoreline recession, however the variability in regional sea-level rise rates was strongly influenced by differential vertical land movement (due to volcanic and magmatic processes in Hawaii and glacio-isostatic adjustment in eastern USA). These studies did not separate out a response to the eustatic component of regional sea-level rise in the observed coastal behaviour hence have not established any relationship between recent eustatic sea-level rise and coastal behaviour. In other cases (e.g.,Morton (2008), Gratiot et al. (2008)) other local coastal processes such as (respectively) sand budget changes and long-term tidal cycles were too dominant for any sea-level rise signal to be observed.

It is notable however, that one study not cited by Le Cozannet et al. (2014), namely a study of soft-rock cliff retreat along the Holderness coast (UK) by Pye and Blott (2015), did identify a significant acceleration since 1989 in the long-standing rate of shoreline retreat along this tectonically-subsiding coast. Although the authors stop short of suggesting this may be a result of a eustatic sea-level rise signal emerging from the land subsidence component that has long dominated regional sea-level rise along this coast, they note that an increase in cliff retreat rates is to be expected in future in response to ongoing acceleration of eustatic sea-level rise.

Le Cozannet et al. (2014) identified two key limitations on existing studies that need to be addressed in order to improve capacity to identify eustatic sea-level rise signals in coastal behaviour, namely a general lack of good historical data on variability in shoreline behaviour over the last century, and limitations in the data on regional or local sea-level change histories for many potential study sites that lack good nearby tide gauge records. My research project aims to address these two requirements through extensive interpretation of shoreline histories from air photo time series since the 1940s and beach profiling since 2004, and through the use of regional sea-level history reconstructions based on combining the broader spatial coverage of satellite sea surface height data with the longer temporal coverage of the better tide gauge records (Church & White 2011).

Research plan outline

The plan to address the research questions stated above comprises the following three key steps or objectives:

(1) *Endeavour to identify significant changes in the long-term (1940s to present) behaviour of soft (erodible) shorelines, of a sort that would theoretically be expected from first principles to indicate the emergence of sea-level rise signals.*

(2) *As far as is practicable, select study sites from erodible coastal environments where other competing factors or processes ('noise') that might mask or prevent a sea-level rise signal from being expressed are absent or minimal.*

(3) *Where suspected sea-level rise signals are found in shoreline behaviour histories, test this hypothesis by further investigating and confirming whether or not any other processes and process changes are active at each site that might equally well explain the observed behaviour, and if not whether a plausible mechanism exists at each site for sea-level rise to drive the observed changes.*

The following sub-sections provide further details of these three key elements of the research plan.

Identification of long-term changes in coastal behaviour

I assume that any signal of a coastal response to renewed global eustatic sea-level rise would be characterised by significant changes in the long-term (multi-decadal) behaviour of soft (erodible) shorelines, of sorts that would theoretically be expected from first principles to indicate the emergence of sea-level rise signals. Generally this will mean either a switch from a previously stable or equilibrium shoreline position to a progressively receding one, or else a significant increase in the rate of recession of shores that were previously receding for other reasons.

The most important source of data for identifying such changes is ortho-rectified historical air photos, which for most Australian coasts provide the only coastal behaviour data series long enough (since 1946 in many places) to plausibly yield evidence of long-term coastal behaviour changes. A method of characterising shoreline history and change from air photos is to plot changes over time in a robustly identifiable shoreline position indicator (Boak & Turner 2005) which is known to change sensitively with shoreline erosion or accretion. In most cases, the indicator which best satisfies these conditions is the shoreline vegetation limit, which on soft shores recedes landwards in response to erosion, but also colonises back to seawards if shoreline recovery occurs. I use a technique developed during previous projects (similar to the US Geological Survey DSAS tool) to digitise the shoreline indicator features in a GIS, then use regularly-spaced digital transects to both graphically plot shoreline changes over time and to extract a variety of quantitative measures of those changes.

Figure 1 below shows a shoreline behaviour history plot for Roches Beach in south-eastern Tasmania which is characterised by a long-term change of behaviour from a mostly stable shore with only small-amplitude cut-and-fill cycles from 1946 to 1975, followed by increasing erosional recession behaviour with progressively decreasing shoreline recovery from 1977 to 2011. For comparison Figure 2 illustrates shoreline behaviour at a nearby beach which is not showing any obvious long-term change in behaviour over the same time period. The change illustrated in Figure 1 is the sort that would be expected to result from sea-level rise. Work is in progress to determine whether other explanations can plausibly account for this history given the process environment in which Roches Beach is located (see further below), but if not then Roches Beach may be an 'early responder' to sea-level rise which has a more susceptible process environment than most beaches.

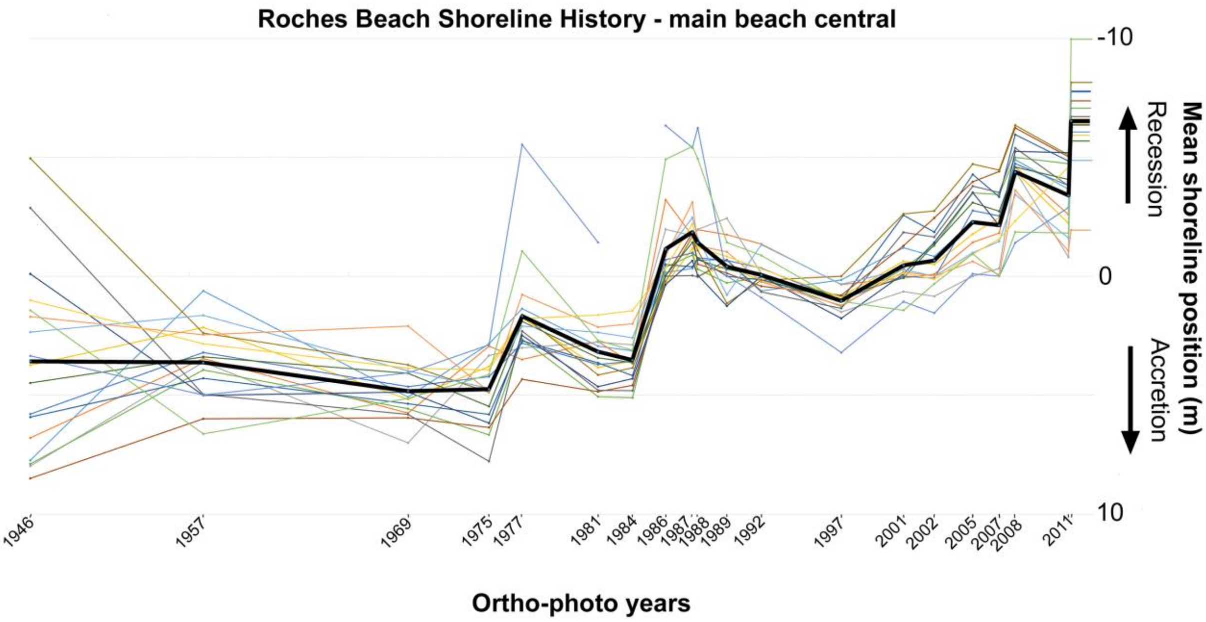

Figure 1: A plot of shoreline change history for an ortho-rectified air photo time series (20 dates) at Roches Beach in south-east Tasmania (from Sharples et al. (2012) plus additional recent work). Each line plots shoreline position changes along one of a number of 100-metre spaced transects in the main part of Roches Beach south of Bambra Reef, and the thick black line represents the mean shoreline position along all transects at each air photo date. This plot demonstrates a significant long-term change in shoreline behaviour from mostly stable from 1946 to 1975, to increasing net recession after 1977.

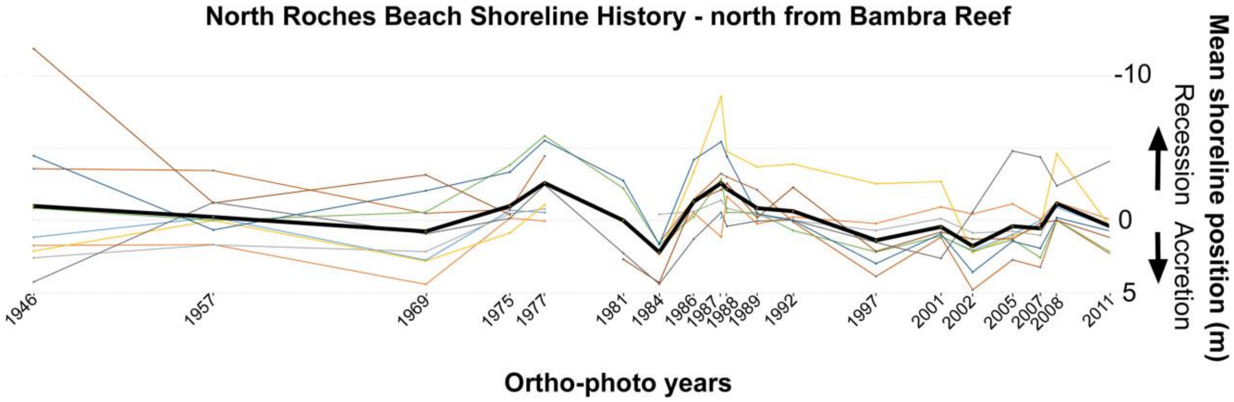

Figure 2: **For comparison with Figure 1, this plot shows a shoreline history for a beach showing episodic erosion and recovery, but no significant long-term change in beach behaviour over the same period as that shown in Figure 1. This plot is derived from the same air photo time series as Figure 1, but shows transects along the northernmost section of Roches Beach (north of a small rocky point at Bambra Reef) which has behaved differently to the main part of the beach shown in Figure 1**.

Because long (multi-decadal) beach profiling and monitoring records are unavailable for most shores, the air photo record is critical in detecting shoreline behaviour changes on usefully-long time scales. However, there are a variety of well-known limitations on using historic air photo records, including not only issues of resolution, camera angle, contrast and availability of accurate reference features for ortho-rectification, but also in particular the irregular temporal separation of most air photos of a given site, which raise the possibility that important beach behaviour events may be 'invisible' in the available record. Attention must therefore be paid to both minimising and quantifying the constraints these issues place on conclusions which can validly be drawn from air photo time series. Some of these limitations can be quantified and allowed for via feature position error measurement. Consideration of the types of shoreline photographed also affects the degree of confidence that can be placed in available shoreline histories (for example, a low scarped cohesive clay shoreline can be assumed to be only receding irrespective of air photo time gaps, whereas time gaps in a sandy swell-exposed beach record could hide episodes of erosion or accretion or both). Where some beach profile survey records are available for sandy shores – which is the case for a number of relevant Tasmanian beaches over the last 10 years via the TASMARC beach profiling project (see www.tasmarc.info) – these higher frequency records will be used to quantify the scale of short-term variability potentially hidden in the longer-term shoreline histories derived from air photos.

It is likely that many shores will not respond noticeably to sea-level rise until a threshold has been passed at which a sea-level response becomes significant compared to the effects of other processes. Thus a fundamental change in shoreline behaviour driven by sea-level rise need not necessarily show a close correlation to sea-level variability on short to medium time scales (interannual to interdecadal). Moreover the effects of beach erosion and recovery in response to large individual storms or other wave climate variations may make it difficult to directly correlate changing shoreline behaviour with sea-level variability on short time scales even where a fundamental change in beach behaviour has been driven by sea-level rise. Nonetheless my project is also examining the possibility that some types of shorelines may respond more rapidly and sensitively to variability in sea-level rise rates than others, so that their shoreline behaviour histories may show a significant response to and thus correlation with sea-level change over relatively short time scales.

One such possibility is that soft rock shores – which may erode easily but cannot recover in the fashion of a swell-exposed sandy beach and thus effectively can only recede – may show relatively sensitive variation in rates of recession in response to variation in rates of sea-level rise. Another very different possibility is that very high energy storm-dominated open coast sandy beaches may show a greater responsiveness to sea-level variability than is the case for most swell-dominated sandy beaches. Work to date suggests this may be the case for the very high-energy Ocean Beach, on the west coast of Tasmania, which has shown a dominantly recessional trend (with some intervals of accretion) since the 1980s. Comparison of an air photo-derived shoreline history of this beach at 13 dates by Walford (2011) with the reconstructed sea-level curve for western Tasmania provided by Church and White (2011) demonstrates a good statistical correlation, particularly when shoreline position is compared to the three-year back-averaged sea-level height at each air photo date (suggestive of a 3-year lag time in beach response to sea-level). See Figure 3. Of particular note is that there is not only a correlation between sea-level rise and beach recession, but also between sea-level stasis or fall and beach accretion which has occurred at times.

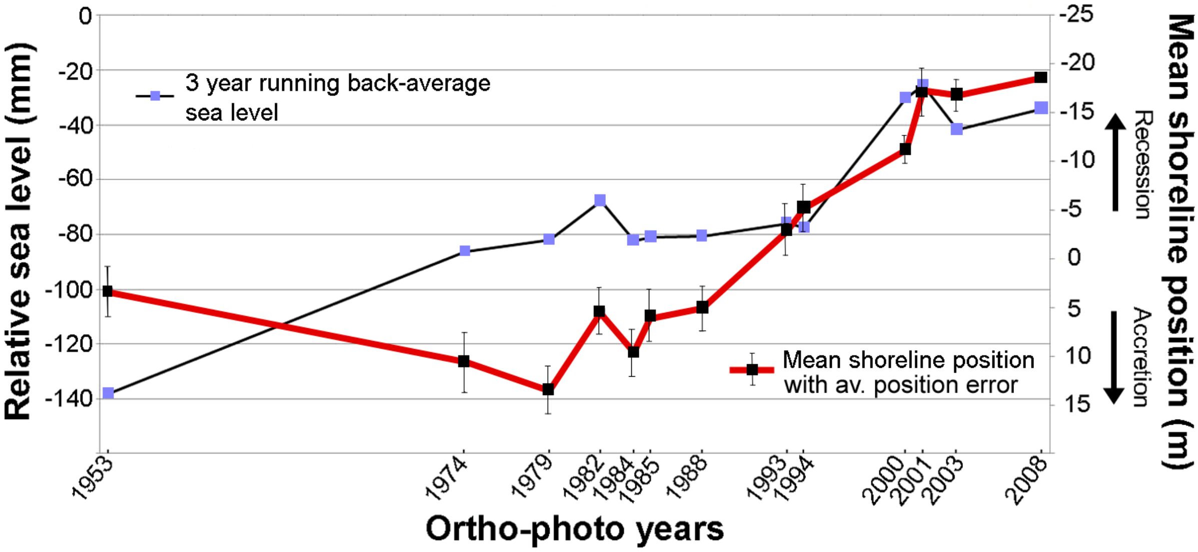

Figure 3: Comparison of averaged shoreline (vegetation line) position at 13 air photo dates for Ocean Beach (western Tasmania) from Walford (2011) with the 3-year back-averaged regional sea-level height at each air photo date for western Tasmania reconstructed by Church and White (2011). With the outlying 1953 date omitted, linear regression gives a good correlation co-efficient of $R^2 = 0.79$ (*p*=<0.0001), suggestive of an explanatory relationship. The shoreline positions at each air photo date are averaged over 100 metre – spaced transects along approximately 15 kilometres length of Ocean Beach.

Selection of study sites to minimise noise

Le Cozannet et al. (2014) identified a number of limitations and constraints on previous efforts to identify a recent eustatic sea-level rise signal in coastal landform behaviour. One such issue is that many previous studies of sea-level rise effects on coasts have focussed mainly on swell-exposed sandy coasts which are not in any case likely to yet be showing a sea-level rise signal because of other confounding processes including swell-driven beach recovery processes and offshore-onshore sand exchanges characteristic of such coastal types. In addition the regional sea-level history itself is in many places significantly modulated by oceanographic processes such as the El Nino Southern Oscillation (ENSO), and/or because of relative (local) sea-level changes due to vertical land movement, both of which mean a signal of eustatic sea-level rise is harder to separate out in both regional sea-level and shoreline behaviour histories.

A key element of my research project is therefore to focus on study sites where such predictable sources of process noise which may mask any sea-level rise response signal are minimised as far as possible. Tasmania is not only an ideal region for my study because it includes a very wide range of coastal process environments, but also because some other elements of oceanographic and tectonic noise are also minimal, as noted below:

Target shoreline types

In respect of the first issue, I have to date identified four distinctive shoreline categories that might show early responses to sea-level rise because they tend not to be influenced by certain types of other confounding coastal process 'noise'. My research project will investigate a number of examples of each of these categories, as follows:

1. *Swell-sheltered 'low energy' sandy shores*

In contrast to the historical focus on swell-exposed open coast beaches, swell-sheltered estuarine and tidal lagoon shores have been comparatively neglected at least in part because they are regarded as 'low energy' and thus 'benign' shores. My own observations of numerous sheltered estuaries and tidal lagoons in south-eastern Australia (particularly Tasmania) that have permanent tidal connections to the ocean and are thus exposed to sea-level variability indicate that recent and active progressive (i.e., non-recovering) shoreline recession – as would be expected from sea-level rise – appears to be widespread on sandy shores in these environments, e.g., see Prahalad et al. (2015). Although there are other possible explanations for the recession of at least some of these shores, the widespread prevalence of recent active erosion on such shores is suggestive that some swell-sheltered sandy shores may be responding earlier and more sensitively to sea-level rise because they are not exposed to constructive swell and large offshore sand supplies capable of moving onshore, which elsewhere counter-act early erosional trends that would otherwise be expected in response to sea-level rise.

2. *Very high-energy swell-exposed sandy beaches*

There is one distinctive class of swell-exposed sandy beaches in Tasmania which in most cases have for some decades now been showing a marked shoreline recession trend. These are the very high-energy beaches of south-west Tasmania which are exposed to the highest swell-wave and storm energies of any sandy beaches in Australia (Hemer et al. 2008) and have in most cases been in a state of persistent erosion and recession with little dune-front recovery for at least three decades now (Cullen 1998). This is in marked contrast to less energetic swell-exposed sandy beaches elsewhere on the Tasmanian coast which mostly are continuing to recover from episodic erosion events. To date the Twentieth Century shoreline change history of the high energy south-west beaches has only been determined for Ocean Beach, however as noted above the behaviour of this beach has shown a strong correlation with the regional sea-level history, suggesting that the dominantly erosive condition of Ocean Beach since the 1980s may be because of the acceleration in sea-level rise over that period.

These very high energy beaches are being studied in collaboration with the geodiversity group within the Tasmanian Department of Primary Industries, Parks Water & Environment (DPIPWE), with whom I surveyed beach and dune profile transects on six SW beaches during December 2014. It is planned to repeat these surveys over at least the next two summers, in addition to compiling shoreline change histories for each beach from air photo time series.

3. *Swell-exposed sandy beaches with unusual process environments*

Whereas most swell-exposed sandy beaches still recover after erosion and this appears to still be masking any obvious response to sea-level rise, there are a few swell-exposed beaches (apart from the very high-energy beaches noted above) in moderate to low energy swell environments which are showing behaviour suggestive of an early response to sea-level rise. This raises the possibility that sandy beaches in certain other relatively unusual coastal process environments may also be more susceptible that most to sea-level rise.

As noted above, one such suspect is Roches Beach in south-eastern Tasmania, which is distinctive in the southeast Tasmanian region in a number of respects, not least of which is the fact that it has since the 1970s become one of the most persistently eroding and receding swell-exposed sandy beaches in the region. Roches Beach is a sandy beach which is relatively distant (up Frederick Henry Bay) from the open ocean and from offshore shelf sand supplies but receives a highly refracted swell. It is a 'zeta-form' beach thought to be experiencing significant longshore transport of sand into, through and out of its shallow embayment. A good air photo time series (from Sharples (2010) and Sharples et al. (2012); see Figure 1) shows that the beach was stable (with minor cut and fill cycles) from 1946 to 1975; however it thereafter had several major erosion events in the 1970s and 1980s, from each of which it only partly recovered, and less so from the later events. Subsequently since 1997 the beach has shown no shoreline recovery from erosion events at all (I have been personally inspecting the beach at intervals since 2001), but was instead slowly but persistently receding without any significant recovery up until a large 2011 storm event which receded the shore a further 5 metres in one event (artificial interventions have dominated subsequent beach behaviour).

I hypothesise that Roches Beach has a coastal geomorphic process environment which makes it a more sensitive 'early responder' to sea-level rise than most swell-exposed sandy beaches. I intend to test this possibility by undertaking further investigation of coastal processes at Roches Beach as noted below, in addition to seeking other swell-exposed beach sites showing unusual changes in behaviour. In the course of doing so I am also acquiring beach history and process data for a range of sandy swell-exposed beaches which are not yet showing any long term changes of behaviour. This will be of value in attempting to identify characteristics that distinguish 'early responder' beaches from those that are 'late-responders' to sea-level rise.

4. *'Soft-rock' (semi-lithified) coastlines*

A fourth category of potential 'early-responder' shores is 'soft-rock' erodible coasts of various compositions, which are common in but not limited to swell-sheltered re-entrant environments. In Tasmania such shores are most commonly semi-lithified claystones, sandstones and conglomerates of Tertiary age, which have high proportions of cohesive clay matrix. In other parts of Australia 'soft-rock' shores include soft limestone cliffs (e.g., Port Campbell, Victoria), lateritic soil shores (northern Australia) and other semi-lithified sandstones and mudstones (e.g., south-east Western Port). An important characteristic of 'soft-rock' shores is that they are readily prone to erosion, but unlike sandy shores have little if any capacity to naturally recover after erosion events (although care is necessary in air photo interpretation to avoid confusing scarp slumping with shoreline 'recovery'). These shores have typically been eroding and receding sporadically over much of the late Holocene in response to stable sea-levels with occasional storm events, but can be expected to recede more rapidly as rising seas increase the frequency with which erosive storm waves attack the shore profile higher up than previously. Trenhaile (2011) and others have provided studies and modelling of erosional processes in soft-rock shores which form a basis for analysis of their response to sea-level rise.

Tasmania's advantages as a study site

As noted above, some previous studies have found a sea-level rise signal in coastal behaviour but have not separated out a eustatic component in the regional sea-level rise history from a vertical land movement (VLM) component which has been important at those sites. In contrast, geodetic studies indicate that Tasmania is tectonically stable with any vertical land movement likely to be negligible or statistically indistinguishable from zero (Burgette et al. (2013), White et al. (2014), Santamaria-Gomez et al. (2012), Argus et al. (2014), Peltier, Argus and Drummond (2015) and King et al. (2012)).

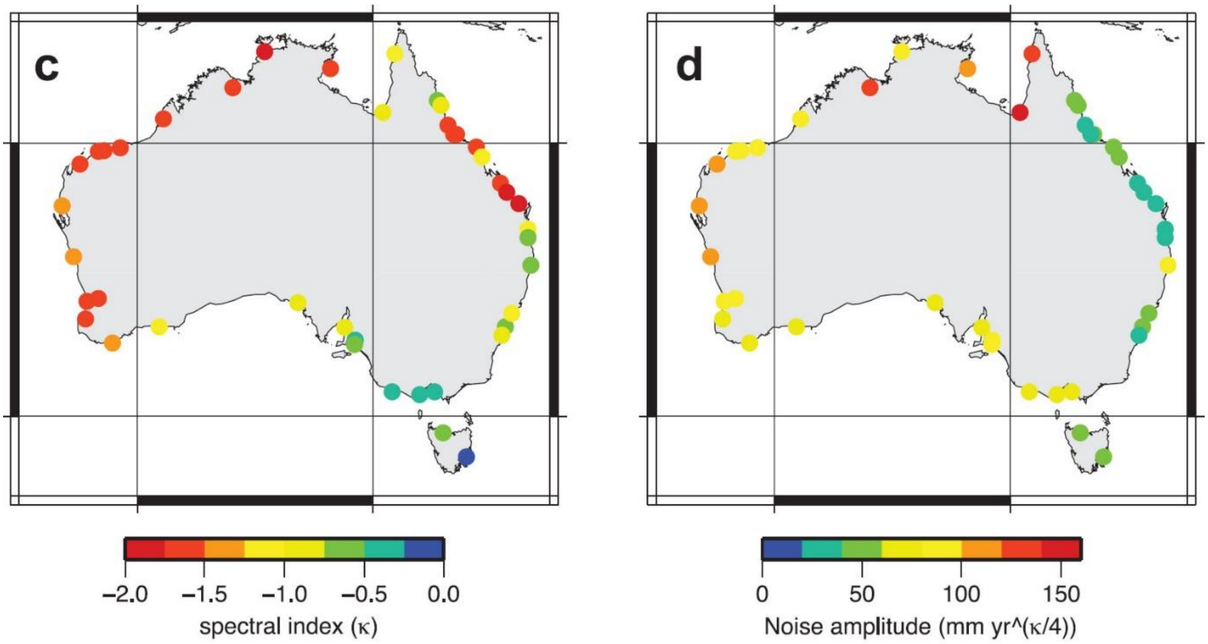

Figure 4: Sea-level 'noise' in tide gauge records around the Australian coast. The spectral index (LHS) indicates the variation between white noise (smaller (negative) or zero values = random variability) and time-correlated noise (larger (negative) values = cyclic oceanographic processes such as ENSO); the noise amplitude (RHS) refers to the strength of the noise. Thus, Tasmania's sea-level record exhibits mainly white noise (random variability) of relatively low amplitude, whereas many northern and western Australian sites exhibit time-correlated noise (i.e., the effects of cyclic oceanographic processes) of large amplitude, which are therefore obscuring the global eustatic sea-level rise signal to a greater extent than is the case in Tasmania. Figure reproduced with permission from (Burgette et al. (2013)).

A further important advantage of Tasmania for the proposed project is that the influence of some key oceanographic processes on regional sea-level variability are lesser around Tasmania as compared to more northerly and westerly parts of Australia. Burgette et al. (2013) and White et al. (2014) analysed sea-level 'noise' (sea-level variability unrelated to global sea-level rise as represented by a linear model) in tide gauge records around Australia, and found that seasonal sea-level variability (related to seasonal climatic and oceanographic processes) is greatest in northern Australia, whilst sea-level noise correlated with interannual and decadal processes including in particular ENSO is greater in northern and western Australia; although such noise also affects Tasmanian sea-level records, in each case Tasmania is by contrast at the lower end of the noise scale (see Figure 4), implying a greater potential for a global eustatic sea-level rise signal in coastal behaviour to be discerned.

Testing for explanations of changed behaviour

Where suspected sea-level rise signals are found in shoreline behaviour histories, it is firstly necessary to test this hypothesis by investigating whether or not any other processes and process changes might equally well explain the observed behaviour. Secondly, because correlation does not necessarily imply causation, it is also ideal to test for a plausible mechanism by which the particular geomorphic processes active at each candidate study site may be interacting with sea-level rise to produce the apparent responses.

In the first case, this will involve both qualitative and statistical comparison of observed trends in shoreline behaviour with other identifiable processes and process changes that might have caused the observed signal instead of or additional to eustatic sea-level rise. Examples may include long-term changes in wave climate or in wind climate (which may significantly influence shoreline erosion by local wind-waves), changes in local sediment transport patterns and budgets due to natural or artificial influences, and processes such as VLM or ENSO.

For example, in the case of the apparent good correlation of shoreline behaviour with regional sea-level history at Ocean Beach noted above (Figure 3), it is clear from observational data that one alternative possibility, namely an increased frequency of swell-driven erosive storms, does not explain the observed beach behaviour in this case. Tasmania's only long-term wave rider buoy is located directly offshore from Ocean Beach and an analysis of data from this buoy by Hemer (2010) showed no increase in (the already high) measured storm wave event frequency over a 23 year period to 2010. Thus, although storm-driven waves are obviously the proximal mechanism of erosion events, there is no evidence that the dominance of progressive shoreline recession over this period can be attributed to any increase in swell-wave storminess (as opposed to the hypothesis of the same storminess causing more recession because of a raised sea-level).

An further possibility still to be tested for Ocean Beach is that the increased recession over the last few decades might be attributable to increased average or extreme wind speeds driving an increased frequency of erosion events due to locally-generated wind waves. This will be tested through analysis of two available local wind records. An increase in local wind speed averages or extremes could also provide a potential alternative explanation of changed shoreline behaviour at Roches Beach (Figure 1). Prahalad, Kirkpatrick and Mount (2011) note that wind speeds recorded at Hobart Airport (near Roches Beach) were higher in the decade before 2009 than prior to 1975, however further analysis is needed to determine whether the magnitude and timing of such changes can plausibly explain (in whole or part) the marked change in beach behaviour that began at Roches Beach in the 1970s. In this case it is noteworthy that comparable recession is not observed on adjacent beaches exposed to the same wind climate (see Figure 2), suggesting that some other process distinctive to the main Roches Beach embayment must be primarily responsible.

This latter point highlights that as well as looking for alternative explanations for apparent sea-level responses in shoreline behaviour, it is also important to ask why and how some shores might be responding earlier to sea-level rise than others. In the case of Roches Beach a possible mechanism was identified by Sharples (2010) but requires testing. Roches Beach is a zeta-form beach between rocky points but with a relatively open and shallow embayment that sand appears to move into, through and out of under the influence of strongly refracted swell a considerable distance up the large coastal embayment of Frederick Henry Bay. Given that sea-level rise can be expected to cause an increased frequency and magnitude of shoreline erosion events without any change in frequency or magnitude of storms being required (because even small storms are becoming more able to reach progressively higher on the shore profile more frequently than previously), it is likely that increased amounts of sand are being eroded and lost from the embayment, while input of sand into the embayment is likely to be little changed, resulting in an increasing sand budget deficit as a direct response to sea-level rise. Measurement of sand transport rates through the embayment, together with other studies of the local process environment including littoral drift measurements and studies of subtidal bed forms are planned as a means of testing this explanatory hypothesis.

Early responders vs. late Responders

A central assumption under-pinning this research project is that some shoreline types in some coastal process environments may show – and may be already showing – an earlier physical response to global sea-level rise than others. To date, arguably the lion’s share of coastal research both globally and in Australia has been focussed on open coast swell-exposed sandy beaches, yet in the majority of cases these are likely to be relatively ‘late responders’ to sea-level rise. If there are indeed other types of shores in other coastal environments that are or will be responding earlier to sea-level rise – in particular through the onset or acceleration of shoreline erosion and recession processes – then it will be of particular value to future coastal planning and management to know what and where these are.

References

Argus, DF, Peltier, WR, Drummond, R & Moore, AW 2014, 'The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories', *Geophysical Journal International*, vol. 198, no. 1, pp. 537-563.

Boak, EH & Turner, IL 2005, 'Shoreline Definition and Detection: A Review', *Journal of Coastal Research*, vol. 21, no. 4, pp. 688-703.

Bruun, P 1962, 'Sea-Level Rise as a Cause of Shore Erosion', *Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers*, vol. 88, pp. 117-130.

Burgette, RJ, Watson, CW, Church, JA, White, NJ, Tregoning, P & Coleman, R 2013, 'Characterizing and minimizing the effects of noise in tide gauge time series: relative and geocentric sea level rise around Australia', *Geophysical Journal International*, vol. 194, no. 2, pp. 719-736.

Church, JA & White, NJ 2011, 'Sea-Level rise from the Late 19th to the Early 21st Century', *Surveys in Geophysics*, vol. 32, no. 4-5, pp. 585-602.

Cullen, P 1998, *Coastal Dune Systems of South-Western Tasmania: Their Morphology, Genesis, and Conservation*, Nature Conservation Report No. 98/1, Parks and Wildlife Service, Tasmania.

Gratiot, N, Anthony, EJ, Gardel, A, Gaucherel, C, Proisy, C & Wells, JT 2008, 'Significant contribution of the 18.6 year tidal cycle to regional coastal changes', *Nature Geoscience*, vol. 1, no. 3, pp. 169-172.

Hemer, MA 2010, 'Historical trends in Southern Ocean storminess: Long-term variability of extreme wave heights at Cape Sorell, Tasmania', *Geophysical Research Letters*, vol. 37, no. L18601, p. 5.

Hemer, MA, McInnes, K, Church, JA, O'Grady, J & Hunter, JR 2008, *Variability and Trends in the Australian Wave Climate and Consequent Coastal Vulnerability*, CSIRO, Bureau of Meteorology and ACE-CRC, Hobart.

King, MA, Keshin, M, Whitehouse, PL, Thomas, ID, Milne, G & Riva, REM 2012, 'Regional biases in absolute sea-level estimates from tide gauge data due to residual unmodeled vertical land movement', *Geophysical Research Letters*, vol. 39, no. L14604, p. 5.

Le Cozannet, G, Garcin, M, Yates, M, Idier, D & Meyssignac, B 2014, 'Approaches to evaluate the recent impacts of sea-level rise on shoreline changes', *Earth-Science Reviews*, vol. 138, pp. 47-60.

Morton, RA 2008, 'Historical Changes in the Mississippi-Alabama Barrier-Island Chain and the Roles of Extreme Storms, Sea Level, and Human Activities', *Journal of Coastal Research*, vol. 24, no. 6, pp. 1587-1600.

Peltier, WR, Argus, DF & Drummond, R 2015, 'Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model', *Journal of Geophysical Research-Solid Earth*, vol. 120, no. 1, pp. 450-487.

Prahalad, V, Kirkpatrick, JB & Mount, RE 2011, 'Tasmanian coastal saltmarsh community transitions associated with climate change and relative sea level rise 1975-2009', *Australian Journal of Botany*, vol. 59, pp. 741-748.

Prahalad, V, Sharples, C, Kirkpatrick, J & Mount, R 2015, 'Is wind-wave fetch exposure related to soft shoreline change in swell-sheltered situations with low terrestrial sediment input?', *Journal of Coastal Conservation*, vol. 19, no. 23-33, p. .

Pye, K & Blott, SJ 2015, 'Spatial and temporal variations in soft-cliff erosion along the Holderness Coast, East Riding of Yorkshire, UK', *Journal of Coastal Conservation*.

Romine, BM, Fletcher, CH, Barbee, MM, Anderson, TR & Frazer, LN 2013, 'Are beach erosion rates and sea-level rise related in Hawaii?', *Global and Planetary Change*, vol. 108, pp. 149-167.

Santamaria-Gomez, A, Gravelle, M, Collilieux, X, Guichard, M, Miguez, BM, Tiphaneau, P & Woppelmann, G 2012, 'Mitigating the effects of vertical land motion in tide gauge records using a state-of-the-art GPS velocity field', *Global and Planetary Change*, vol. 98-99, pp. 6-17.

Sharples, C 2010, *Shoreline Change at Roches Beach, South-Eastern Tasmania, 1957-2010*, Antarctic Climate and Ecosystems co-operative Research Centre, University of Tasmania, Hobart.

Sharples, C, Mount, R, Hemer, MA, Puotinen, M, Dell, M, Lacey, M, Harries, S, Otera, K, Benjamin, J & Zheng, X 2012, *The ShoreWave Project: Development of a methodology for coastal erosion risk analysis under climate change, integrating geomorphic and wave climate data sets*, University of Tasmania, Hobart, Tasmania.

Trenhaile, AS 2011, 'Predicting the response of hard and soft rock coasts to changes in sea level and wave height', *Climatic Change*, vol. 109, pp. 599-615.

Walford, H 2011, 'Assessment of coastal erosion at Ocean Beach, Western Tasmania', Bachelor of Science (Honours) thesis, University of Tasmania.

White, NJ, Haigh, ID, Church, JA, Koen, T, Watson, CS, Pritchard, TR, Watson, PJ, Burgette, RJ, McInnes, KL, You, Z-J, Zhang, X & Tregoning, P 2014, 'Australian sea-levels - Trends, regional variability and influencing factors', *Earth Science Reviews*, vol. 136, pp. 155-174.

Zhang, K, Douglas, BC & Leatherman, SP 2004, 'Global Warming and Coastal Erosion', *Climatic Change*, vol. 64, pp. 41-58.