Climatic Change
DOI 10.1007/s10584-011-0107-8

Estimating coastal recession due to sea level rise: beyond the Bruun rule

Roshanka Ranasinghe · David Callaghan · Marcel J. F. Stive

Received: 3 September 2009 / Accepted: 5 April 2011

Abstract Accelerated sea level rise (SLR) in the twenty-first century will result in unprecedented coastal recession, threatening billions of dollars worth of coastal developments and infrastructure. Therefore, we cannot continue to depend on the highly uncertain coastal recession estimates obtained via the simple, deterministic method (Bruun rule) that has been widely used over the last 50 years. Furthermore, the emergence of risk management style coastal planning frameworks is now requiring probabilistic (rather than deterministic, single value) estimates of coastal recession. This paper describes the development and application of a process based model (PCR model) which provides probabilistic estimates of SLR driven coastal recession. The PCR model is proposed as a more appropriate and defensible method for determining coastal recession due to SLR for planning purposes in the twenty-first century and beyond.

1 Introduction

Any rise in the mean sea level will result in the retreat of unprotected coastlines (Bruun 1962). Alarmingly, recent research indicates that the global average sea levels may rise at an unprecedented rate during the twenty-first century (Leuliette et al. 2004; Beckley et al. 2007; Rahmstorf 2007; Meehl et al. 2007; Church et al. 2008), which in turn is likely to result in an initiation or acceleration of coastline recession.

R. Ranasinghe (✉)
Department of Water Engineering, UNESCO-IHE, PO Box 3015 DA, Delft, Netherlands
e-mail: r.ranasinghe@unesco-ihe.org

R. Ranasinghe · M. J. F. Stive
Department of Civil Eng and Geoscience, Delft University of Technology,
2628 CN, Delft, Netherlands

D. Callaghan
School of Civil Engineering, University of Queensland, Brisbane, QLD 4072, Australia

Published online: 10 June 2011

The socio-economic impact of such accelerated coastal recession could be massive due to the rapid growth of coastal communities over the last 50 years or so which has led to billions of dollars worth of development and infrastructure within the coastal zone. To ensure the safety of growing coastal communities and to avoid massive economic losses in the future, predictions of coastal recession due to sea level rise (SLR) need to be highly reliable; now more so than ever before.

Although its usefulness as a predictive tool has been a controversial issue for decades (Cooper and Pilkey 2004; Pilkey and Cooper 2004; Nicholls and Stive 2004; Nicholls et al. 2007; Ranasinghe and Stive 2009; Stive et al. 2009), the method most commonly used to estimate coastal recession due to SLR is the simple two dimensional mass conservation principle known as the Bruun Rule (Bruun 1962). Essentially, the Bruun Rule predicts a landward and upward displacement of the cross-shore sea bed profile in response to a rise in the mean sea level (Fig. 1) and is expressed as:

$$R = LS/(B + h) \tag{1}$$

where, $h =$ the maximum depth of exchange of material between nearshore and offshore, $L =$ horizontal distance from the shoreline to depth h, $B =$ berm or dune elevation estimate for the eroded area, $S =$ sea level rise, and $R =$ horizontal extent of coastal recession.

Recent comprehensive and objective reviews of all attempts to verify the Bruun Rule to date have concluded that while it may be suitable for qualitative first-pass regional scale assessments, its relatively low quantitative accuracy and robustness renders the Bruun Rule unsuitable for local scale assessments in which reliable estimates are required (Ranasinghe and Stive 2009; Stive et al. 2009). Furthermore, while the Bruun concept implies that SLR will result in the movement of sand from the berm or dune to the submerged nearshore profile, the actual physical processes by which this dune erosion will occur are not explicitly taken into account. Therefore, by necessity, the Bruun rule requires the specification of several input parameters that are associated with significant uncertainty. One major uncertainly is associated with the estimation of the slope of the active profile, which is governed by 'h' (i.e. depth of closure DoC), using empirical formulations. For example, the application of four widely used DoC formulations at Sydney, Australia resulted in active profile slope estimates ranging from 0.0625 (1 in 16) to 0.011 (1 in 91) (Ranasinghe et al. 2007). This uncertainty range in the active profile slope alone would produce Bruun rule recession estimates that could vary by about 500% (Ranasinghe and Stive 2009).

Despite such ambiguities associated with the Bruun rule, coastal scientists and engineers have been routinely using this approach for almost five decades, mainly

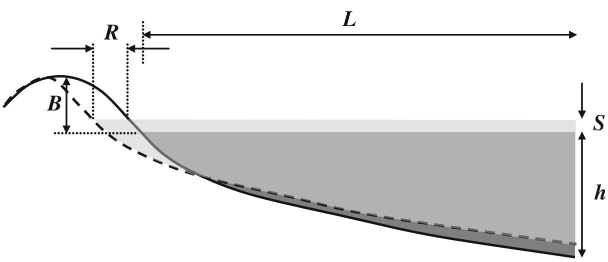

Fig. 1 Schematic diagram showing the Bruun Rule for coastal recession

due to its simplicity and the lack of any other easy-to-use methods. However, can we continue to depend on the Bruun rule for predictions of future coastal recession? This question is now more relevant than ever, particularly in view of the potentially massive socio-economic losses in the twenty-first century and beyond.

Furthermore, the common practice of adopting a single value of coastal recession due to a single SLR estimate is also proving inadequate with the emergence of risk management style coastal planning frameworks which require probabilistic estimates of coastal recession. Although, Cowell et al. (2006) made a significant step forward in developing a method that produces probabilistic estimates of coastal recession due to SLR, this method essentially adopts the Bruun Rule to estimate the quantity of recession and is thus hampered by all the uncertainties and limitations associated with the Bruun concept.

The aim of the present study therefore, is to develop a new approach for estimating coastal recession due to SLR which completely departs from the Bruun concept. The main strengths of the method developed here are: (a) the physical processes governing coastal recession due to SLR (along un-interrupted coastlines) are explicitly taken into account, and (b) robust estimates of coastal recession are provided within a probabilistic framework.

2 Methods

2.1 Study area

Narrabeen Beach, Sydney, Australia is considered as a case study herein. The availability of over 30 years of concurrent wave, water level, and most importantly, monthly beach profile data makes Narrabeen beach an ideal site to test the new modelling approach developed in this study. Located 20 km north of Sydney, Narrabeen beach is a 3.6 km long embayed beach (Fig. 2) which is bounded by Long Reef Point to the south and Narrabeen Headland to the north. The beach experiences a microtidal (spring tidal range = 1.3 m), semi-diurnal tidal regime and is composed of fine to medium (0.3–0.4 mm) quartz and carbonate sands. The deepwater mean significant wave height is 1.6 m and the mean deepwater peak wave period is 10 s (Short and Trenaman 1992). Of the nine survey profiles that were initially established in 1976, profiles 1, 2, 4, 6 and 8 have been surveyed monthly from 1976 to date. The locations of wave and water level measurements and survey profiles 1, 2, 4, 6 and 8 are shown in Fig. 2.

2.2 Processes

Following common practice, the quantity of coastal recession (R) due to SLR is defined as the horizontal displacement of the dune position (toe of the dune) over a long time period. The basic physical philosophy underpinning the method presented herein is that any net long-term recession of the coastal dune is due to the combined effect of storm erosion and SLR. For example, assume that the mean water level (MWL) is zero (compared to a fixed datum) at present and the dune is at $x = 0$ (horizontal axis). Now say a 1 in 10 year storm occurs. The associated storm erosion will then result in a dune retreat of, say, 10 m (dune position $x = -10$). Now assume

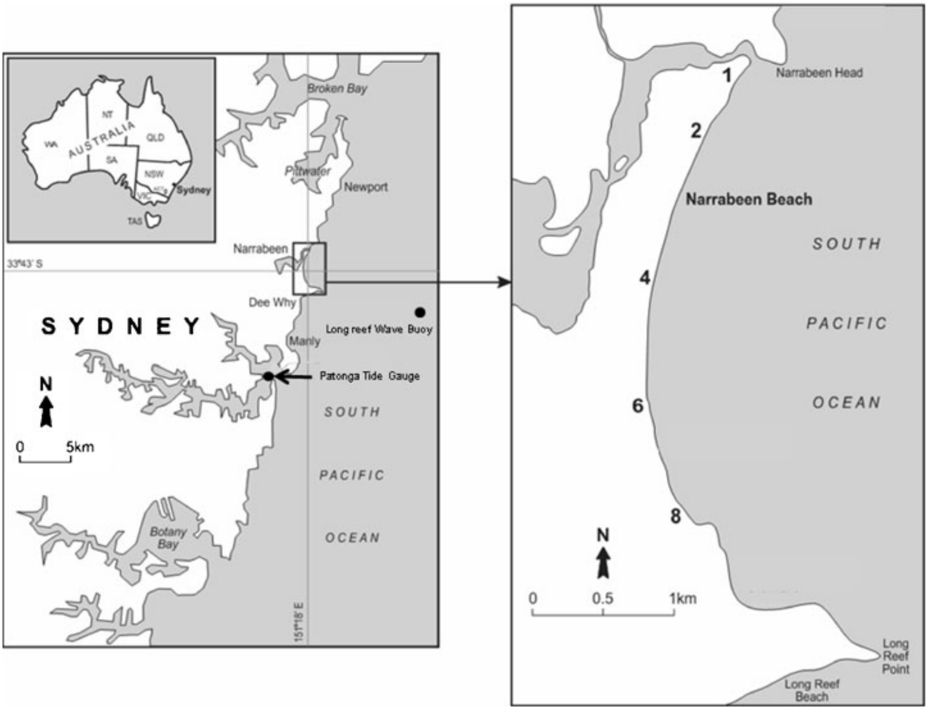

Fig. 2 Location map of Narrabeen beach, Sydney, Australia. The locations of wave and water level measurements, and survey profiles (1, 2, 4, 6, 8) are also shown (modified after Harley et al. 2010)

that the next 1 in 10 year storm occurs in another 10 years when the MWL is elevated to 0 + 10 × (SLR/year). As dune recovery is a slow process relative to storm occurrence frequency, it is very likely that the dune will not completely recover to its original position in the 10 year period that elapses during the two 1 in 10 year storms. Therefore, say in the 10 year elapsed period the dune only advanced 5 m seawards from its eroded position (dune position $x = -5$). However, due to SLR, the MWL at the time the second storm occurs is elevated by 10 × (SLR/year) compared to the MWL 10 years ago. As the elevated MWL will result in the storm waves breaking closer to the coastline (due to the depth limited nature of wave breaking), the second storm will result in more erosion than would have occurred in the absence of SLR. Say the dune retreat associated with the second storm is 15 m (dune position $x = -20$). Thus the net dune retreat due to the combination of these two processes (i.e. hysteresis in dune recovery and enhanced storm erosion due to elevated MWL) over the 10 year period is 20 m (*Note:* even in the unlikely event that the dune does full recover between the two storms (i.e. no hysteresis in dune recovery), the process of enhanced storm erosion due to elevated MWL alone will still result in a net dune retreat of 15 m over the 10 year period). As time progresses and the MWL keeps increasing due to SLR, this combination of processes will recur, resulting in a gradual retreat of the coastline. If climate change results in more intense storms occurring more frequently, this rate of coastal retreat will accelerate further. An example of the possible occurrence of this process at Narrabeen beach, Sydney, Australia over the 1991–2001 decade is shown in Fig. 3.

2.3 Probabilistic coastline recession model (PCR model)

The new probabilistic coastline recession (PCR) model presented here follows the basic procedure outlined below:

1. Generate a 110-year (1990–2100) time series of storms using data derived joint probability distributions of storm characteristics within a Monte Carlo simulation (Callaghan et al. 2008),
2. Using IPCC projections (Meehl et al. 2007; Church et al. 2001), estimate the sea-level rise, S, at the time each storm occurs,
3. For each storm, estimate dune recession using the process based dune impact model presented by Larson et al. (2004) while allowing for dune recovery between storms,
4. Estimate the final dune toe position by temporally averaging the dune toe position in the last 2 years from this simulation,
5. Subtract the initial dune toe position from the final dune toe position to estimate dune recession R between 1990 and 2100,
6. Repeat 1–5 until exceedance probabilities greater than 0.01% converge (i.e. bootstrapping).

On a standard PC, the PCR model application described above takes about 1 h.

2.3.1 Storm time series

The 110 year storm time series is derived using the Joint Probability Method (JPM) model developed by Callaghan et al. (2008). The JPM model essentially fits marginal, dependency and conditional distributions to long time series of forcing parameters (i.e. storm wave height, storm duration, storm wave period, storm wave direction, storm spacing, and tidal anomaly). These distributions are then used within a Monte Carlo simulation to derive a time series of storms and their associated characteristics. The JPM is fully described in (Callaghan et al. 2008) and hence only a brief description is given here.

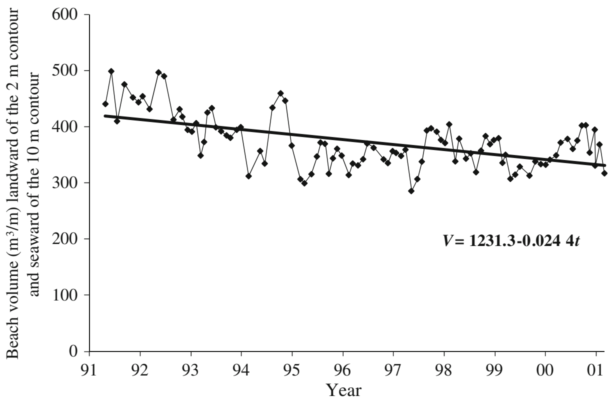

Fig. 3 Net decrease in dune volume over a decade (1991–2001) at Narrabeen beach, Australia

The JPM is implemented as follows:

1. Identify meteorologically independent storm events from measured data
2. Fit extreme value distributions to offshore wave height and storm duration
3. Fit the dependency distributions between offshore wave height and storm duration, and between offshore wave height and storm surge
4. Fit the conditional distribution between offshore wave height and wave period
5. Determine the empirical distribution for offshore wave direction
6. Fit a non-homogenous Poisson distribution to the spacing between storms
7. Simulate the offshore wave climate using the fitted distributions to obtain storm time series.

2.3.2 Sea level rise

The latest SLR projections (by 2100 compared to 1990) given by the IPCC (Meehl et al. 2007) range from 0.18 m to 0.79 m, including an allowance of 0.2 m for uncertainty associated with ice sheet flow. However, IPCC advices that potentially larger values of SLR cannot be excluded (Meehl et al. 2007). Indeed, since 1993, the rate of SLR is estimated to have increased to about 3 mm/year (Leuliette et al. 2004), while Church and White (2006) have shown that rate of SLR continues to accelerate. Significant regional variations in SLR can also occur due to spatial variation in thermal expansion (Meehl et al. 2007; Church et al. 2001).

2.3.3 Dune erosion model

Step 3 of the PCR model procedure requires a structural function capable of simulating storm induced dune erosion. Technically, a detailed process based numerical model such as *Xbeach* (Roelvink et al. 2009) or a semi-process based model such as SBEACH (Larson and Kraus 1989; Wise et al. 1996) could be used here. However, due to the multiple simulations required in the PCR model procedure, the use of such a detailed numerical model as the structural function results in highly inefficient computations. Therefore, the simplified wave impact dune erosion model presented by Larson et al. (2004) is considered as an alternative and efficient structural function to estimate storm induced dune erosion volumes in the PCR model.

The basic premise of Larson et al.'s (2004) wave impact dune erosion model is that any slope approaching vertical and located in the swash zone will act as a barrier to the wave run-up. During large storm events, this vertical face is typically the dune face. A fundamental assumption in this approach is that there is a linear relationship between the wave impact (a force F on the dune due to the change in momentum flux of the wave bores impacting the dune) and the weight of sand eroded from the dune (ΔW) (Fisher and Overton 1984). Thus,

$$\Delta W = C_E F \qquad (2)$$

where C_E is an empirical coefficient, and F is given by:

$$F = \frac{1}{2}\rho \frac{u_0^4}{gC_u^2}\frac{\Delta t}{T} \qquad (3)$$

where u_0 is the bore velocity, t is time, T is the incident wave period, g is gravitational acceleration, ρ is the density of water, and C_u is n empirical coefficient.

A definition sketch is given in Fig. 4.

After some mathematical manipulation, the rate of dune erosion (volume) is expressed as (Larson et al. 2004):

$$q_D = \frac{dV}{dt} = -C_S, \frac{u_0^4}{g^2 T} \tag{4}$$

Where,

$$C_S = \frac{1}{2}\frac{C_E}{C_u^2}\frac{\rho}{\rho_s}\frac{1}{(1-p)} \tag{5}$$

and, $dV =$ volume of sand eroded, $\rho_s =$ density of sediment, $p =$ porosity.

Under a few simplifying assumptions bore speed u_o can be expressed as a function of run-up height (Z_R) and the elevation difference between dune toe and beginning of the swash (z_o) which reduces Eq. 5 to,

$$q_D = \frac{dV}{dt} = -4C_s\frac{(Z_R - z_o)^2}{T} \tag{6}$$

Z_R is defined as a function of offshore wave parameters and beach slope while C_s is a function of H_{rms}/D_{50} (Larson et al. 2004).

As this model relates the wave impact force applied to the dune to the volume of dune erosion, it is more representative of the physics associated with the specific process of dune erosion compared to the simple critical slope based avalanching process that describes dune erosion in both SBEACH and *Xbeach*. Furthermore, replacing the avalanching dune erosion model in SBEACH with Larson et al.'s (2004) wave impact due erosion model did not improve dune erosion predictions, while it did increase computational time (Callaghan 2008). Therefore, to enable fast and physically defensible computations, Larson et al.'s (2004) wave impact dune erosion model is used in stand-alone mode as the structural function in the PCR model.

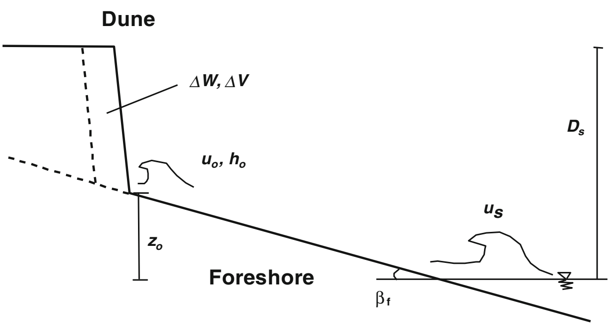

Fig. 4 Dune erosion due to wave impact (after Larson et al. 2004)

3 Model application to Narrabeen beach, Sydney, Australia

3.1 Determination of storm time series using the JPM model

A detailed description of the application of the JPM model to simulate storm erosion statistics at Narrabeen beach (in the absence of SLR) is given in (Callaghan et al. 2008), and hence only a brief summary is provided herein. For the purposes of the present model application, following common practice in the study area (Lord and Kulmar 2000; Kulmar et al. 2005), a storm event is defined as a single meteorological event where the significant wave height exceeds 3 m. Following Kriebel and Dean (1993), a sine-squared function (above the threshold wave height) is assumed to represent the time evolution of storm events. The data employed in this model application included 36 years of non-directional offshore wave data, 14 years of directional offshore wave data, and 90 years of water level data. The generalized Pareto distribution combined with the logistics model is employed to quantify the dependencies among the peak wave height ($H_{s,max}$), storm duration (D), and storm surge (R_s). The wave period which is found to be conditionally dependent on $H_{s,max}$ is modelled using a log-normal distribution. Wave directions (θ_p) are modelled using an empirical distribution fitted to the directional wave data. Storm occurrence is modelled using the spacing between events and assuming a non-homogeneous Poisson process with an annual variation in the occurrence intensity. The most dominant seasonally varying feature of storms in the study area is the occurrence of more storms in winter than in summer. The annual variation in occurrence intensity adopted in the Poisson process sufficiently represents this dominant seasonal signal. Storm grouping is also found to be sufficiently well represented by the Poisson process.

Since the primary interest of this study lies in dune erosion volumes (which ultimately determine dune/coastline recession), the JPM model's ability to produce storm time series' that can result in modelled dune erosion estimates which are statistically similar to measurements should be tested. Unfortunately, the measurements at Narrabeen beach do not always explicitly identify the dune toe and/or top, and therefore the exact amount of storm induced dune erosion cannot always be directly determined from the available data. Therefore, storm erosion volumes above the 2 m contour (thus including part of the beach seaward of the dune) are used as a proxy for dune erosion volumes. However, as Larson et al.'s (2004) wave impact dune erosion model only provides estimates of the erosion of the dune itself and not of the beach seaward of the dune, SBEACH (which simulates the entire cross-shore profile) was used as the structural function in this comparison. As both the standard and modified (with Larson et al.'s (2004) wave impact dune erosion model) of SBEACH have been shown to produce similar results (Callaghan 2008), the above described procedure is expected to provide a defensible validation of the JPM model's ability to simulate realistic dune erosion volume statistics.

Although the sediment budget of the headland bounded Narrabeen beach is relatively well closed, intra-embayment cyclic beach rotation in response to the ENSO phenomenon has been observed at this site (Harley et al. 2010; Ranasinghe et al. 2004). Short and Trembanis (2004) indicated that the fulcrum around which this rotation occurs is located in the vicinity of the central survey profile (Profile 4). Therefore, to minimise the potential impact of alongshore processes on the analysis, the model/data comparison was performed only for Profile 4.

The following procedure was adopted to obtain the time series of storm erosion volumes:

A. Assume first storm event at time t
B. Generate random realizations of $H_{s,max}$, D, T, θ_p, R_s for the storm
C. Transfer the offshore wave climate to nearshore (using the wave model SWAN)
D. Estimate beach erosion using structural function (SBEACH)
E. Determine beach recovery till next storm using the dune recovery model (see Section 3.3)
F. Repeat (B) to (F)

The length of the simulation depends on the desired accuracy at a given return level (Callaghan et al. 2008). In this study a simulation length of 1,000 years was adopted. This is expected to result in reasonably accurate predictions for at least upto 100 year return period events.

The block averaging and consecutive volumes methods were used to convert beach profile measurements to erosion volumes to obtain a qualitative estimate of bias. The block averaging method estimates average beach volume in 1.5 month bins and then determines the maximum change in a 12 month period. The consecutive volumes method estimates beach erosion from successive profile measurements while correcting for the number of effective storms between surveys. Figure 5 shows that the model/data comparisons are acceptable. The model/data mismatch at the 30 year return interval is expected to be due to the availability of only one data point at that return interval rather than due to model inaccuracies.

This result also indicates that the extent of data used in this model application (i.e. 35 years of wave data and 90 years of water level data) is sufficient to obtain reasonable predictions upto return periods that are not negatively affected by field data sampling limitations. It maybe possible to obtain similar predictions with less data, but this is yet to be fully investigated.

3.2 Sea level rise

The upper bound SLR estimated for the Sydney region, accounting for regional variations, is 0.92 m by 2100 compared to 1990 (McInnes et al. 2007). This upper bound of 0.92 m and the shape of the SLR curve from IPCC (2001) (Church et al. 2001) are adopted in the PCR model. The SLR curve is approximated using a fourth order polynomial function.

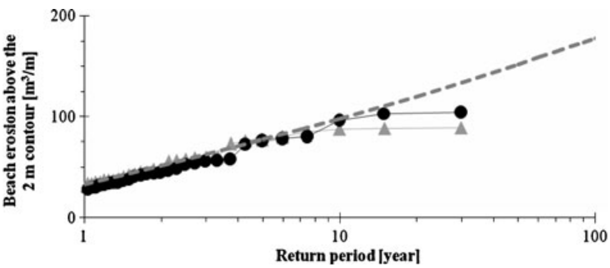

Fig. 5 The eroded sand volume at Narrabeen Beach from; profile measurements (block averaging *triangles* and consecutive volumes *circles*), and the JPM model (*dashed grey line*)

3.3 Dune erosion and recovery

Larson et al.'s (2004) wave impact dune erosion model (see Section 2.3.3) is used to calculate dune erosion volumes. Based on over 30 years of field measurements in the study area, the dune height and C_s were defined as 5 m and 1.5×10^{-3} respectively. The C_s value of 1.5×10^{-3} is within the realistic range of $5 \times 10^{-5} < Cs < 5 \times 10^{-2}$ specified by Larson et al. (2004). The dune recovery rate was calculated based on observations at Narrabeen beach, Sydney, and Gold Coast, Queensland, Australia. Long term observations at both these sites suggest that the long term averaged dune toe position is located at about 2 m above MSL. Therefore, the dune recovery rate that results in an average dune toe position of 2 m above MSL (over a 110 year simulation period) was determined via trial and error application of the PCR model to Narrabeen beach without SLR (i.e. storm forcing only). The 0.1 m^3/m/day dune recovery rate thus determined was adopted in the subsequent SLR inclusive PCR model application to Narrabeen beach described in Section 4 below.

4 Results

The probabilistic estimate of coastal recession at Narrabeen beach when the PCR model was applied with the above described settings is shown in Fig. 6.

When S_{2100} is taken as 0.92 m (McInnes et al. 2007), Fig. 6 indicates, for example, a 50% probability of coastal recession exceeding 20 m ($R/S_{2100} = 22$), and a 1% probability of exceeding 45 m ($R/S_{2100} = 49$).

For comparison, the Bruun rule (Eq. 1) was applied to Narrabeen beach to estimate the coastal recession due to the same 0.92 m SLR by 2100. The main issue regarding the application of the Bruun Rule to any location is the determination of the depth of closure (DoC) and hence active profile slope. Therefore, in this comparison, three commonly adopted methods were used to calculate the DoC; (a) Hallermeier's inner DoC d_l (Hallermeier 1983), (b) Hallermeier's outer DoC d_i (Hallermeier 1983), and (c) Nicholls et al.'s DoC d_c (Nicholls et al. 1996). A dune height of 5 m and a shape factor A (in Dean's (1991) equilibrium profile) of 0.14 were

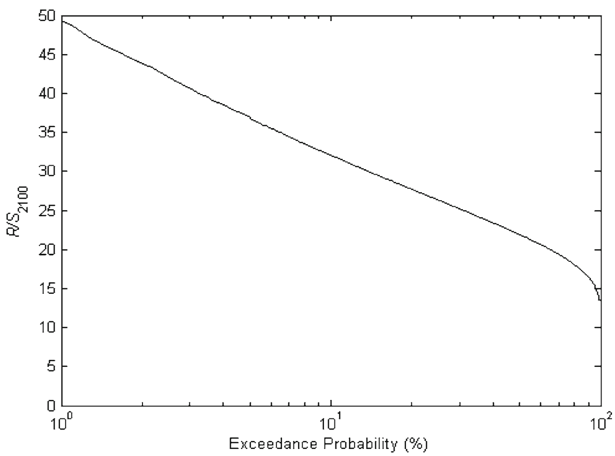

Fig. 6 Model predicted probabilistic estimate of coastal recession at Narrabeen beach, Sydney, Australia by the year 2100 compared to 1990. R = recession (m), S_{2100} = Sea level rise by 2100 (m)

Table 1 Bruun rule estimates of coastal recession (relative to 1990) at Narrabeen beach, Australia

Depth of closure (DoC) method	DoC value relative to MSL (m)	R/S_{2100}	Recession (R) (m)
Hallermeier—inner (d_l)	8.3	34	32
Hallermeier—outer (d_i)	28.0	68	62[a]
Nicholls et al. (d_c)	14.9	55	51

[a]For this case, the DoC value was truncated to 20 m when calculating the recession estimate due the presence of a natural rocky reef at approximately 20 m depth at the site

used in all calculations. The coastal recession estimates thus obtained are shown in Table 1.

Figure 6 and Table 1 indicate that, depending on the DoC formulation used, Bruun rule estimates of coastal recession can lie between 8% and <1% probability of exceedance. This indicates that, at least at this site, Bruun rule estimates appear to be highly conservative. Whether Bruun rule estimates are universally conservative is, however, a matter requiring further investigation. Even if that were the case, an important question that coastal managers and planners need to address is whether such a high degree of conservatism is indeed warranted. The answer to this question would lie in the potential consequences of various degrees of coastal recession and the level of risk managers, planners and communities are willing to take.

5 Advantages and limitations of the PCR model

5.1 Advantages

In contrast to the deterministic, single value estimate of coastal recession provided by a direct application of the Bruun rule, the PCR model provides probabilistic estimates of SLR driven coastal recession that are required by contemporary risk management style coastal planning frameworks.

The uncertainty associated with PCR model estimates is likely to be less than that associated with Bruun rule estimates as the former does not require highly uncertain estimates of the depth of closure. Furthermore, the bootstrapping method employed in the PCR model minimises the uncertainty associated with model predicted probabilistic estimates.

Unlike the traditionally used Bruun rule, which does not describe the physics of coastal recession, The PCR model provides probabilistic estimates of coastal recession based on governing physical processes. The model requires minimal computing effort and requires as input long term water level and wave data which are now available via widespread tide gauges and global wave hind cast models (e.g. WW3, ERA40), and is thus likely to be widely applicable.

5.2 Limitations

In the present application of the JPM model to Narrabeen beach, a storm event is defined as a single meteorological event where the significant wave height exceeded 3 m. While this definition has been tested over time for the study area (Lord and Kulmar 2000; Kulmar et al. 2005), it is unlikely that this definition will be universally applicable. Furthermore, in this application, based on measurements in the study area, it was assumed that the wave direction is independent of wave height. This assumption may also not be universally applicable.

The dune recovery rate adopted for this application is based on measurements at two Australian beaches (Narrabeen and Gold Coast), and hence may not be universally valid. However, sensitivity tests indicate that a doubling or halving of the dune recovery rate (from the 0.1 m^3/m/day adopted for Narrabeen beach) does not result in significantly different recession estimates. An order of magnitude increase in the dune recovery rate ($\sim$1 m^3/m/day, which is, however, at the edge of geophysical reality) can result in upto 500% and 50% increases in the high (>90%) and low (<10%) exceedance probability recession estimates respectively. The purely empirical determination of the dune recovery rate is certainly the weak link in the PCR model, and to remedy this, a devoted 4 year research project is currently being undertaken with the primary aim of developing a process based, yet simple model of dune recovery.

In the present application of the PCR model to Narrabeen beach, the only climate change impact that is considered is SLR. Climate change driven variations in wave climate can be handled by the Poisson approach adopted in the JPM model, at the cost of adding significant complexity to the model. However, McInnes et al. (2007) indicated that climate change driven variations in the wave climate in the study area is likely to be minimal, and hence this phenomenon was justifiably omitted from the model application presented herein. This omission may not be universally justifiable.

Over 30 years of wave and water level measurements were used in the present model application to obtain the various necessary forcing distributions. This does not necessarily mean that such abundant field measurements are a pre-requisite for PCR model applications. It is quite likely that global hindcast data sets would produce not too dissimilar probabilistic predictions of coastal recession. However, this needs to be evaluated by re-simulating the Narrabeen beach case study and other case studies with both measured and hindcast data.

6 Conclusions

A process based, probabilistic model to derive estimates of SLR driven coastal recession has been developed (PCR model). The PCR model completely departs from the traditionally used Bruun rule and provides probabilistic estimates of coastal recession based on governing physical processes. The concurrent application of the PCR model and the Bruun rule to data rich Narrabeen beach, Sydney, Australia for the year 2100 planning horizon shows that Bruun rule estimates for this location appear to be highly conservative (<8% probability of exceedance).

While the sensitivity of model results to the several simplifying assumptions in the PCR model need to be rigorously evaluated, the uncertainty associated with PCR model estimates is likely to be less than that associated with Bruun rule estimates of coastal recession. Furthermore, the PCR model is anticipated to be widely applicable due to the availability long term water level and wave data via widespread tide gauges and global wave hind cast models (e.g. WW3, ERA40). Therefore, the PCR model is suggested as a more appropriate and defensible method for the determination coastal recession due to SLR for planning purposes. The robust and probabilistic estimates of SLR driven coastal recession given by the PCR model, when used in conjunction with socio-economic information, will enable the development of effective risk based coastal planning decisions and adaptation strategies to minimise the impact of climate change in vulnerable coastal areas.

Acknowledgements The authors wish to thank: Prof. Magnus Larson (Lund University, Sweden) for the many discussions regarding the wave impact dune erosion model and SBEACH, Prof. Dano Roelvink (UNESCO-IHE, Netherlands) for the many discussions on Xbeach, Associate Prof. Peter Cowell (University of Sydney, Australia), Associate Prof. Peter Nielsen (University of Queensland), Prof. Hans Hanson (Lund University, Sweden), Dr. John Church and Dr. Kathy McInnes (CSIRO Marine and Atmospheric Research, Australia), and Mr. Phil Watson (DECC-W, Australia) for the numerous discussions and debates regarding climate change, sea level rise, Bruun rule, and the PCR model. Finally, the authors wish to thank the three anonymous Climatic Change reviewers for their excellent and constructive criticism of the original manuscript.

References

Beckley BD, Lemoine FG, Luthcke SB, Ray RD, Zelensky NP (2007) A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. Geophys Res Lett 34:L14608. doi:10.1029/2007GL030002

Bruun P (1962) Sea-level rise as a cause of shore erosion. J Waterways Harbors Division 88:117–130

Callaghan D (2008) Coastal hazard and severe storms in New South Wales, Australia. Report prepared for the NSW Dept of Natural Resources, Civil Engineering, Univ. of Queensland, Australia

Callaghan D, Nielsen P, Short A, Ranasinghe R (2008) Statistical simulation of wave climate and extreme beach erosion. Coast Eng 55(5):375–390

Church JA, White NJ (2006) A 20th century acceleration in global sea level rise. Geophys Res Lett 33:L01602. doi:10.1029/2005GL024826

Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D, Woodworth PL (2001) Changes in sea level. In: Climate Change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Church JA, White NJ, Aarup T, Stanley Wilson W, Woodworth P, Domingues C, Hunter J, Lambeck K (2008) Understanding global sea levels: past, present and future. Sustain Sci 3:9–22

Cooper JAG, Pilkey OH (2004) Sea level rise and shoreline retreat: time to abandon the Bruun Rule. Glob Planet Change 43:157–171

Cowell PJ, Thom BG, Jones RA, Everts CH, Simanovic D (2006) Management uncertainty in predicting climate change impacts on beaches. J Coast Res 22:232–245

Dean RG (1991) Equilibrium beach profiles: characteristics and applications. J Coast Res 7:53–84

Fisher JS, Overton MF (1984) Numerical model for dune erosion due to wave uprush. Proceedings of the 19th International Coastal Engineering Conference. ASCE, pp 1553–1558

Hallermeier RJ (1983) Sand transport limits in coastal structure designs. Proceedings of a Specialty Conference on Design, Construction, Maintenance and Performance of Coastal Structures. ASCE, Arlington, pp 703–716

Harley MD, Turner IL, Short AD, Ranasinghe R (2010) Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring. Coast Eng 58(2):194–205

Kriebel DL, Dean RG (1993) Convolution method for time-dependent beach-profile response. J Waterw Port Coast Ocean Eng 119(2):204–226

Kulmar M, Lord D, Sanderson B (2005) Future directions for wave data collection in New South Wales. Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference and the 10th Australasian Port and Harbour Conference. The Institution of Engineers, Australia, pp 167–172

Larson M, Kraus NC (1989) SBEACH: numerical model for simulating storm-induced beach change. Report 1. Empirical foundation and model development. Technical Report CERC-89–9. Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS

Larson M, Erikson L, Hanson H (2004) An analytical model to predict dune erosion due to wave impact. Coast Eng 51(8–9):675–696

Leuliette EW, Nerem RS, Mitchum GT (2004) Calibration of TOPEX/Poseidon and Jason Altimeter Data to construct a continuous record of mean sea level change. Mar Geodesy 27:79–94

Lord D, Kulmar M (2000) The 1974 storms revisited: 25 years experience in ocean wave measurements along the south-east Australian coast. Proceedings of the 27th International Conference on Coastal Engineering. ASCE, Sydney, pp 559–572

McInnes K, Macadam I, Abbs D, O'Farrell SP, O'Grady J, Ranasinghe R (2007) Projected changes in climatological forcing conditions for coastal erosion in NSW. Proceedings of Coasts and Ports '07, Melbourne, VIC, Australia. On CD Rom produced by Engineers Australia

Meehl GA, Stocker TF, Collins W, Friedlingstein P, Gaye A, Gregory J, Kitoh A, Knutti R et al. (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The physical science basis. Contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 747–846

Nicholls RJ, Stive MJF (2004) Society and sea level rise requires modelling. Science, E-letters

Nicholls RJ, Birkemeier WA, Hallermeier RJ (1996) Application of the depth of closure concept. Proceedings of the 25th International Conf. Coastal Engineering. ASCE, New York, pp 3874–3887

Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. In: Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Pilkey OH, Cooper JAG (2004) Society and sea level rise. Science 303:1781–1782

Rahmstorf S (2007) A semi-empirical approach to projecting future sea level rise. Science 315:368–370

Ranasinghe R, Stive MJF (2009) Rising seas and retreating coastlines. Clim Change (Editorial Commentary) 97:465–468. doi:10.1007/s10584-009-9593-3

Ranasinghe R, McLoughlin R, Short A, Symonds G (2004) The Southern Oscillation Index, wave climate, and beach rotation. Mar Geol 204(3–4):273–287

Ranasinghe R, Watson P, Lord D, Hanslow D, Cowell P (2007) Sea level rise, Coastal recession, and the Bruun Rule. Proceedings of Coasts and Ports '07, Melbourne, VIC, Australia. On CD Rom produced by Engineers Australia

Roelvink R, Reniers A, van Dongeren A, van Thiel de Vries J, McCall R, Lescinski J (2009) Modelling storm impacts on beaches, dunes and barrier islands. Coast Eng 56(11–12):1133–1152

Short AD, Trembanis AC (2004) Decadal scale patterns in beach oscillation and rotation Narrabeen Beach, Australia—time series, PCA and wavelet analysis. J Coast Res 20(2):523–532

Short AD, Trenaman NL (1992) Wave climate of the Sydney region, an energetic and highly variable ocean wave regime. Aust J Mar Freshw Res 43:765–791

Stive MJF, Ranasinghe R, Cowell P (2009) Sea level rise and coastal erosion. In: Kim Y (ed) Handbook of coastal and ocean engineering. World Scientific, pp 1023–1038

Wise RA, Smith SJ, Larson M (1996) SBEACH: Numerical model for simulating storm-induced beach change; Report 4: Cross-shore transport under random waves and model validation with SUPERTANK and field data. Technical Report CERC-89–9, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS