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Effects of Sea Level Rise on Sandy Shores and Coastal Dunes

Abstract For the past half century, consideration and understanding of effects of sea level rise on coastal dunes and sandy shores has been dominated by the Bruun model, which predicts erosion of the foredune and redeposition on the nearshore in the cross-shore profile (Bruun, 1954, 1962; Schwartz, 1967). Recent reevaluation of this model by Davidson-Arnott and others (Davidson-Arnott, 2005; Rosati and Walton, 2013; Cooper, 2004), however, has changed the way scientists are studying the dynamics of beaches and barrier islands and their response to rising sea levels globally. Davidson-Arnott's updated conceptual model describes the landward migration of sand with shoreline recession and increased dune erosion. This new conceptual approach also brings into question past application of the Bruun model to coastal management and engineering, especially in developing countries that are at particular risk of coastline alteration due to anthropogenic climate change (Pilkey and Cooper, 2004). This paper examines mechanisms of coastal alteration due to sea level rise, reviewing current discourse on and predictions of climate change impacts on sandy shores and coastal dunes.

Introduction Analysis of sandy beaches and coastal dunes begins with the sediment budget, a balance of sediment gains and losses in a system unit, or *littoral cell* (Psuty and Silveira, 2010). *Sources* of sediment or sand can come from longshore transport into a cell, erosion of cliffs, transport by a river, beach erosion, relative sea level fall, and even beach nourishment by humans. Sediment *sinks*, can be longshore transport out of the littoral cell, accretion of the beach, dredging of the beach, and relative sea level rise (Rosati, 2005). A *positive sediment budget*, or net gain in a cell, is a result of more sand or sediment availability in a system, and is associated with deposition and accretion on a beach. Such build-up of the beach can result in both seaward expansion of the shoreline and sediment storage in sand dunes. A *negative sediment budget*, or net loss in a cell, is a result of less sand or sediment availability in a system, and is associated with erosion and transport away from the beach. This beach loss can result in landward recession (movement of the shoreline relative to sea level), deconstruction of the dune face, and subsequent aeolian transport of sediment storage across the dune ridge landward (Psuty and Silveira, 2010). The existence of a sandy beach and a dune system is directly dependent upon an area's sediment budget, sea level, and wave action.

In order to focus more clearly on the scale and setting of the processes at play in this paper, a review of the beach-dune system and cross-shore profile is useful (Figures 1 and 2). ***Sandbars*** form where the waves break in the nearshore, lose forward momentum, and a counter-current forms at the bottom of the water column as the wave returns. The counter-current grabs onto sediment when it withdraws from the shoreline, and deposits it just offshore where waves break. The sandbar is thus an erosional and depositional form, and plays a role in both positive and negative sediment budgets as a stopover place for coming and going sand. The beach is divided into the foreshore and backshore. The ***foreshore***, also known as the intertidal zone, is the stretch of beach face between low- and high-water marks. The ***backshore*** extends from the high-water mark to the dunes, and is generally only affected by wave action during exceptional high tides or severe storms. As a result, the backshore is primarily a zone of aeolian processes and transient sediment accumulation. The ***berm*** is a nearly horizontal gently raised portion of the backshore formed by the deposition of sediment by receding waves parallel to the shoreline. ***Coastal dunes*** form where constructive waves and prevailing onshore winds encourage sediment accumulation of sand just beyond the backshore. Dunes require a pre-existing obstacle -wood, vegetation, some other material- to trap sand in order to develop. Over time, dunes will harden just enough to retain their shape. Waves and winds aid in plant germination on the ***dune face***, the seaward side of the dune. Vegetation helps to stabilize the dune with sprawling roots and modified stems called stolons, or runners, typical of sea grasses, and can enable further sand accumulation and storage. The dune **crest** is the apex of the dune formation at the junction of the seaward- and landward-facing slopes. Every dune has a *seaward* or windward slope and a *leeward* slope. The ***foredune*** is the rising dune face on the windward slope.

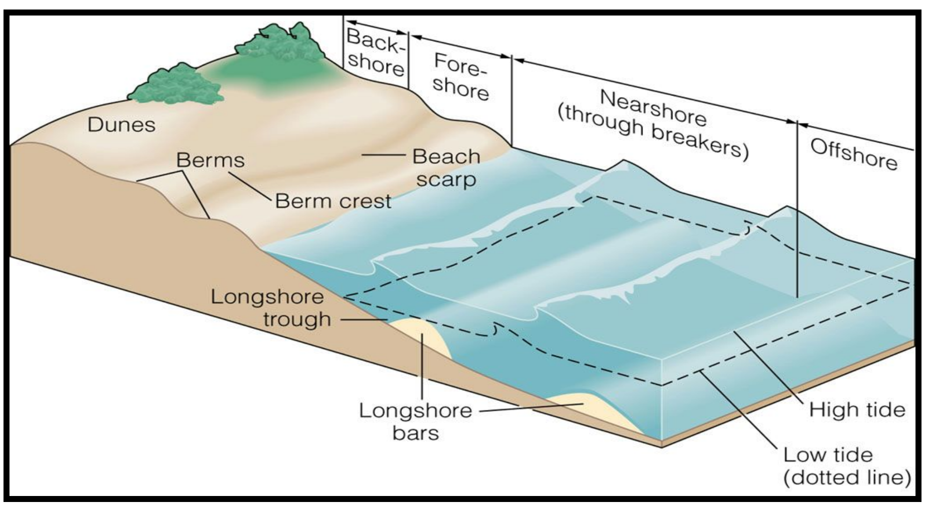

Figure 1. Cross-section of the shoreline from offshore to nearshore to dunes. (Brooks/Cole-Thompson, 2005)

Over the past three decades, concern over the eustatic rise in sea level resulting from anthropogenic climate change, in particular the ice-albedo feedback responsible for melting ice caps, ice sheets, and glaciers, has raised more interest in the actual potential effects of sea level rise (SLR) on the shorelines it threatens to claim. Compounded by isostatic rebound and oceanic thermal expansion, eustatic SLR is certain to affect large coastal populations and economies globally, so it has evoked studies worldwide charged with informing scientists, engineers, and policy makers of potential impacts and mitigation opportunities (Nicholls et al, 2011). The most recent climate change impact reports from the Intergovernmental Panel on Climate Change have estimated SLR to be on the order of 2.5-6mm/yr (Church et al, 2013).

Per Bruun began conceptualizing the processes at work on sandy beaches and their coastal dunes with SLR on at the local level in the 1950s in Denmark, California, and Florida (Bruun, 1954). Bruun's work, and later that of Schwartz in 1965 and 1967, sparked great interest in coastal responses and led to much research on the subject. The Bruun Model, or Bruun's Rule, certainly the first and best known attempt at modeling shoreline retreat with SLR, saw widespread application throughout the second half of the 20th century, and is still being used extensively across the globe for coastal management and engineering purposes. It's fundamental assumptions may not have been far off, but increasing understanding of sediment transport has directly challenged his hypothesis, and led to fuller conceptual models of coastal change (Davidson-Arnott, 2005; Cooper and Pilkey, 2004; Carter, 1991).

THE BRUUN MODEL & BEYOND

The Bruun Model considers a two-dimensional cross-shore profile perpendicular to the shoreline, and does not consider any alongshore transfers nor external inputs and outputs. It states that on the typical concave, upward beach face, rising sea erodes sediment from the upper beach and deposits it in the nearshore to maintain constant water depth. The cross-shore profile is therefore in parabolic equilibrium; the volume of sediment eroded is equal to the volume of sediment deposited (Bruun, 1962; Davidson-Arnott, 2005).

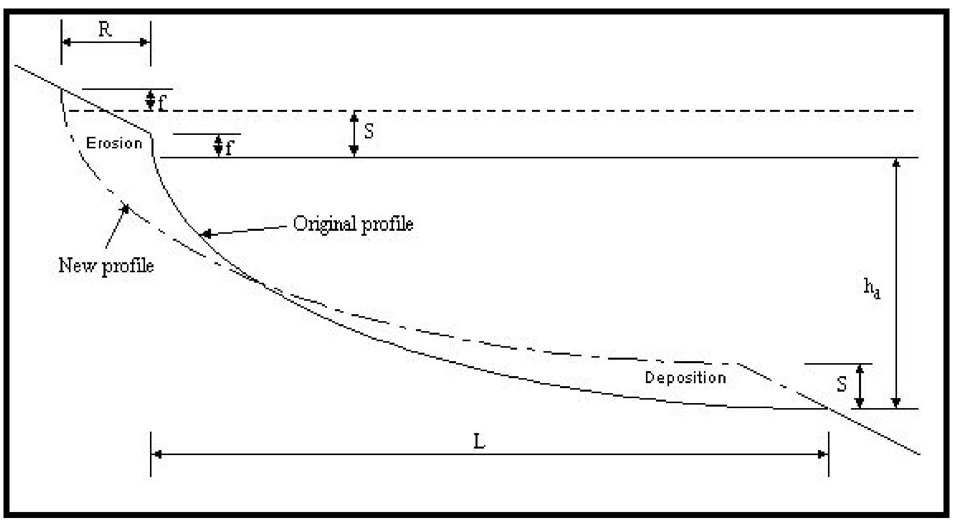

Figure 2. The Bruun Model. (Bruun, 1962)

Davidson-Arnott (2005) concluded that the model is resultingly "elegant in its simplicity", and others have certainly agreed. Cooper and Pilkey (2004) cite numerous reasons for the model's proliferation in the scientific and environmental communities: its simplicity, the difficulty in proving or disproving it, and lack of easy alternatives just to name a few. They find the Bruun model to have been of early benefit in advancing consideration of the processes involved at sandy coasts, but recognize is its invalidity now that more recent research has shed new light on the subject. To Cooper and Pilkey, the Bruun Model "has no power for predicting shoreline behaviour under rising sea level and should be abandoned". The rule's global application can be traced to advocacy by the United Nations, who still assert that Bruun's model applies to small scale local sites (United Nations, 2014). Only recent studies initiated by researchers at the Army Corps of Engineers have attempted to modify the Bruun Rule in consideration of landward transport of sediment following erosion of the upper beachface under rising sea level (Rosati, Dean, and Walton, 2013). As a result, the Bruun Model has infiltrated the practices of coastal scientists and managers across the globe for more than a half-century.

The failure of Bruun's Rule receives particular analysis by Davidson-Arnott in 2005. He notices that if a model is based on the transfer of sediment volumes between the beach and the nearshore, an approach that considers the sediment budget of the locale is required. There are two sediment budgets, the *littoral budget*, affecting the beach and the nearshore, and the *dune budget*, the dune being generally thought of as a sand and sediment storage system. These two zones exchange sediment over time as wave scarping of the foredune releases sediment to the beach, and aeolian processes move sediment from the nearshore and beach to the dunes. Davidson-Arnott further criticizes earlier models for omitting consideration of the dune sediment budget, and argues that this important factor disproves the Bruun Model at its foundation (Davidson-Arnott, 2005).

Davidson-Arnott, in order to improve upon Bruun's long lasting work, produced the "RD-A Model" in his 2005 paper, *Conceptual Model of Sea Level Rise on Sandy Coasts,* that has since personified the shift in conceptualization of impacts of SLR on sandy shores (Houser and Ellis, 2013; Taborda and Ribiero, 2015). Citing extensive documentation of beach-dune sediment interaction (Nickling and Davidson-Arnott, 1990; Psuty, 1988; Sherman and Bauer, 1993), he argues that 1) the beach and the foredune are eroded as a result of SLR, and the junction between beach and dune migrates landward and upward in keeping pace with SLR, 2) a net onshore migration of sediment in the nearshore also keeps pace with SLR- as the outer nearshore is eroded, its deposit in the bar ("point of closure") is moved landward and upward to keep pace with SLR and with landward movement of the shoreline, and 3) all sediment eroded from the dune will be transferred landward resulting in a landward migration of the foredune (or "rolling over"), hence the volume transferred landward is equal to the volume eroded and the dune maintains its overall volume and dimension. Put more simply, under rising sea levels, erosion of the dunes transfers sediment back to the beach and wind action transfers this sediment back to the dunes, the deeper nearshore zone is continually eroded and sediment is transferred landward, net migration of nearshore sediment keeps pace with SLR, and thus the beach and the dune migrate landward over time.

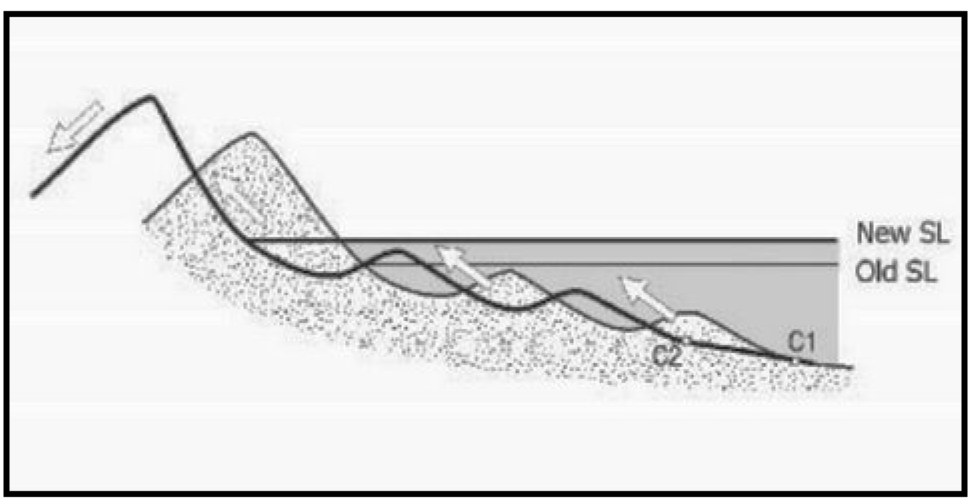

Figure 3. The RD-A Model. (Davidson-Arnott, 2005)

Fundamental differences between the RD-A and Bruun models are that the nearshore is a zone of erosion and landward transport of sediment *rather than* a zone of accumulation, and that dune and backshore erosion lead to net landward migration *rather than* to net loss of dune and backshore sediment to the nearshore. Davidson-Arnott elaborated on the release of sediment from the foredune and backshore with SLR, enunciating the major role aeolian transport plays in landward migration with and coastal response to SLR on sandy shores (Davidson-Arnott, 2005; Bruun, 1962).

By using the RD-A Model to analyze coastal response to global warming and climate change, we conceptualize an environment where rising water and more severe storms produce more scarping of dune systems, thereby releasing sediment to aeolian forces that cause a landward rolling over of the beach and dune profile with shoreline recession. While the basic principles of the improved conceptual framework say little about the implications of migration of sediment and the beach-dune profile landward, and less about what "rolling over" could mean to human, plant, and animal communities, it can be deduced that the effects of beach loss and resulting "coastal squeezing" are numerous and have potentially large socio-economic impacts globally. Replacing the Bruun Model with the RD-A Model will allow coastal scientists, engineers, and managers to more wisely prepare for coastal changes under a local and regional rising sea level scenario. They can also better plan setback lines for development where before they were governed solely by the idea of beach loss.

CONSIDERING THE ALONGSHORE SEDIMENT-SHARING SYSTEM

Psuty and Silveira, in their 2010 paper, *Global Climate Change: An Opportunity for Coastal Dunes??*, take this two-dimensional profile considered by Bruun and improved upon by Davidson-Arnott and apply it to the three-dimensional reality of the dynamic and complex shoreline. Sea level rise will displace the shoreline and deconstruct and activate dune faces, allowing winds to displace the beach-dune profile inland. But, analysis of the beach-dune system, they emphasize, also requires consideration of the alongshore transport in addition to cross-shore sediment budgets.

The topography of a sandy shore/coastal dune area is determined by the sediment budget over time (Psuty and Silveira, 2010). In isolated scenarios, like those that the Bruun and RD-A models depict, a *positive sediment budget* allows for beach widening, vegetation expansion seaward, and foredune growth, while a *negative sediment budget* will drive formations landward primarily due to scarping, destruction, and loss of foredune topography and ensuing onshore prevailing wind. At any given moment in time, a shoreline may also be in an equilibrium state between a positive and negative budget. However, the threatening effects of SLR and climate change, with encroaching tide lines, higher wave action, and more severe storm surges, will ultimately create a *more erosional* environment that leads to increasing landward migration of sand, beach, and dunes.

At the same time, an alongshore topographic sequence, or *morphological continuum*, can be identified on sandy coastlines associated with sediment budgets extending along the beach in three general coastal settings: along beaches near fluvial sediment sources, along coastal spits, and along barrier islands. In each case there is an alongshore gradient of sediment supply and variation in sediment budget (Figure 4).

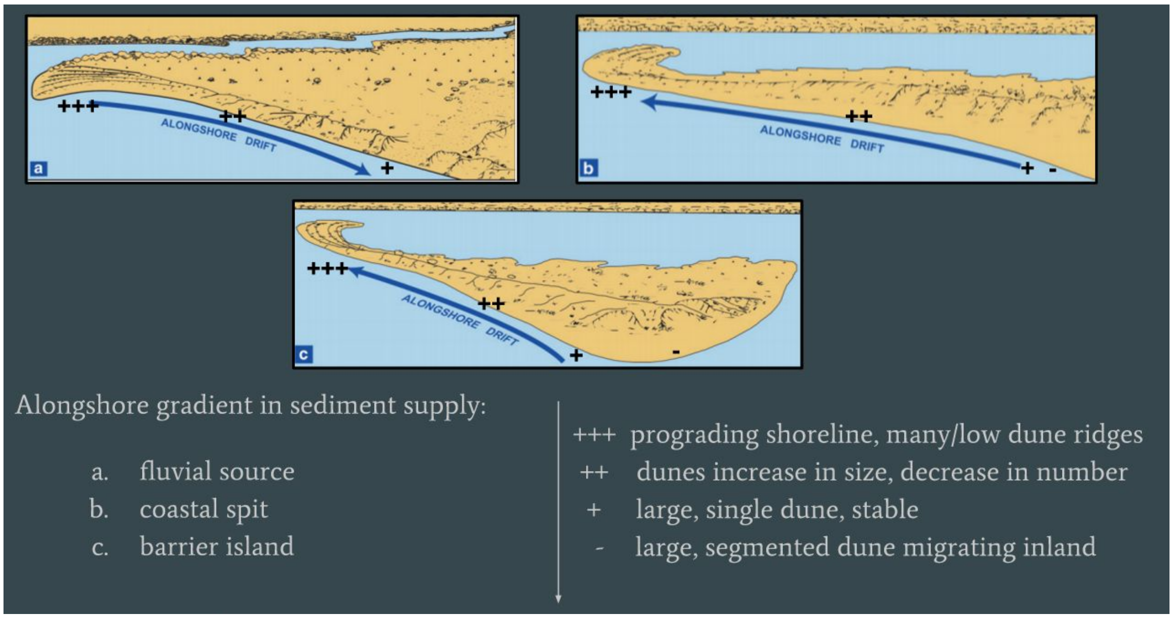

Figure 4. Alongshore sediment gradient and dune growth/transport. (Psuty and Silveira, 2010)

In areas of large positive sediment budget, there is an accreting, prograding shoreline and the formation of many small dune ridges (Figure 4a). The surplus of sand and sediment allows the beach to widen. Along the shoreline toward areas with smaller sediment budgets the ridges begin to increase in size while decreasing in number. Even further down current, dunes decrease even more, resulting in large, stable, singular dunes. From largest to smallest positive budget, and even into a negative budget, the dunes gradually migrate further and further from the shoreline. Where there is no positive sediment budget along the shoreline, the mechanisms of beach-dune migration are most evident. In fact points along the beach may serve as sediment sources for prograding areas down current (Figure 4b and c). These areas of negative sediment budget reveal large, segmented dunes that are rolling over inland as a result of scarping and sediment release to alongshore drift and aeolian forces. Ultimately, if a beach-dune profile has a negative sediment budget, foredune topography will be lost, and the profile will migrate landward. A gradient of inland transport will take place along the entire morphological continuum and the location of new dune formation will translate up the shoreline (Psuty and Silveira, 2010). This creates an opportunity for dune development in areas that have not seen such accumulation before and even a potential for elongation of barrier islands and coastal spits.

CONCLUSION

The majority of the world's shorelines are eroding and being displaced by slowly rising sea (Psuty, 2010; Bird, 1985). In developed nations, particularly, more and more people have flooded to the coasts in the last half-century. In the developing world, rising sea levels associated with human-induced climate change have put all low-lying shorelines, communities, and progress in jeopardy. Given recent advancement in understanding of coastal processes' responses to rising sea level, *new* implications develop for coastal managers, ecologists, and community leaders especially as they consider new ways of responding to changing shores. The needs and desires of opposing parties come into difficult contrast as the sea encroaches and dune formations try to migrate. Ecologists and naturalists recommend allowing coastal dune and beach systems to respond naturally to sediment supplies and sea level forcing. On the other hand, coastal managers and state leaders must consider the defense that dune systems provide for developed areas that may require nourishment, or an external supply, of sand to safeguard livelihoods at the zone between shore and community. Nevertheless, migrating beaches are caught in the "coastal squeeze" where communities are built up to the dune systems, and neither side has any place to go. Once again, the impasse between human needs and anthropogenic climate change is challenged to find balance. Understanding beach dynamics, where natural forces are altering previously acknowledged regimes, and how the fragile coastal environment will respond in the next 50 to 100 years is imperative to preparing for potential destructive impacts associated with global warming. The RD-A Model and Psuty & Silveira's study of alongshore drift and dune system morphology are the needed frameworks for monitoring these dynamics and impelling further research and consideration of the forces at work along sandy coasts today.

REFERENCES

Bird, E.C.F., 1985. Coastline changes. A global review. Wiley, London, p 219.

Bruun, P., 1954. Coast erosion and the development of beach profiles. *US. Army Corps of Engineers Beach Erosion Board Technical Memoir No. 44*.

Bruun, P., 1962. Sea level rise as a cause of shore erosion. *Journal of Waterways and Harbors Division*, ASCE, 88, 117-130.

Carter, R.W.G., 1991. Near-future sea level impacts on coastal dune landscapes. Landscape Ecology, Vol. 6, No. 1/2, pp29-39.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D. and Payne, A.J., 2013. Sea level change. *Climate change 2013*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp.1137-1216.

Cooper, J.A.G., and Pilkey, O.H., 2004. Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. Global and Planetary Change, 43, pp157-171.

Davidson-Arnott, R.G.D., 2005. A conceptual model of the effects of sea level rise on sandy coasts. *Journal of Coastal Research*, 21(6), 1166-1172.

Houser, C. and Ellis, J., 2013. A tribute to the influence of Dr Robin Davidson-Arnott in coastal and aeolian geomorphology. *Earth Surface Processes and Landforms*, *38*(11), pp.1326-1329.

Nicholls, R.J., Hanson, S.E., Lowe, J.A., Warrick, R.A., Lu, X., Long, A.J. and Carter, T.R., 2011. Constructing sea-level scenarios for impact and adaptation assessment of coastal areas: a guidance document. *Supporting*

Material, Intergovernmental Panel on Climate Change (IPCC) Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), Geneva, Switzerland.

Nickling, W.G., and Davidson-Arnott, R.G.D., 1990. Aeolian sediment transport on beaches and coastal dunes. *Proceedings of the Symposium on Coastal Sand Dunes*, National Research Council, pp 1-35.

Pilkey, O.H. and Cooper, J.A.G., 2004. Society and sea level rise. *Science*, 303(5665), p.1781.

Psuty, N.P. and Silveira, T.M., 2010. Global climate change: an opportunity for coastal dunes?? *Journal of Coastal Conservation*, *14*(2), pp.153-160.

Psuty, N.P., 1988. Dune/Beach Interaction. *Journal of Coastal Research* Special Issue No. 3.

Rosati, J.D., Dean, R.G. and Walton, T.L., 2013. The modified Bruun Rule extended for landward transport. *Marine Geology*, *340*, pp.71-81.

Rosati, J.D., 2005. Concepts in sediment budgets. *Journal of Coastal Research*, pp.307-322.

Schwartz, M.L., 1967. The Bruun theory of sea-level rise as a cause of shore erosion. *The journal of Geology*, pp.76-92.

Sherman, D.J., and Bauer, B.O., 1993. Dynamics of beach-dune systems. *Progress in Physical Geography*, Vol. 17 no. 4, pp 413-447.

Taborda, R. and Ribeiro, M.A., 2015. A simple model to estimate the impact of sea-level rise on platform beaches. *Geomorphology*, *234*, pp.204-210.

"The Bruun Rule", Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change. *United Nations Framework Convention on Climate Change*, 2014. Web. http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5315.php