J Coast Conserv (2010) 14:153–160
DOI 10.1007/s11852-010-0089-0

Global climate change: an opportunity for coastal dunes??

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Received: 11 July 2009 / Revised: 26 January 2010 / Accepted: 26 January 2010 / Published online: 23 February 2010

Abstract The predictions for coastal change under the scenario of global sea-level rise offer impending disaster for the variety of coastal morphologies, their associated habitats, and the accompanying infrastructure. However, the predictions tend to ignore the role of sediment budget in the maintenance of coastal morphology and the dynamics of sediment transfers in the beach-dune sand-sharing system. Accepting that shoreline displacement may be an outcome of sea-level rise and a negative sediment budget, conditions are presented that could lead to a positive or equilibrium sediment budget in the coastal foredune and the retention of the foredune system even as it is being displaced. Accommodation space is a key requirement for the continued functioning of the foredune morphologies during periods of sea-level rise.

Keywords Foredune · Sea-level rise · Coastal dunes · Coastal geomorphology

Introduction

The recent Fourth Assessment Report released by the Intergovernmental Panel on Climate Change (IPCC) describes a variety of scenarios associated with global climate change and an increase of the world's sea level (Bindoff et al. 2007). The magnitude and rate of the rise has a most probable eustatic increase of about 45 cm during the current century (Fig. 1). One part of the IPCC report focuses on the impacts to the coastal zone and the alterations that are likely in a wide range of environments, including erosion, loss of habitat, increased flooding, salt-water intrusion, and a vast range of socio-economic consequences (Nicholls et al. 2007). There is no doubt that such a relatively rapid increase will affect the shoreline position and lead to increased exposure of the components of the coastal zone to storm surge and inland penetration of the effects of storms. However, there may be situations and locations where part of the response to the new sea-level conditions and the new exposures may be an increased mobilization of sediment and the accumulation of sand in the foredune positions in the coastal system. Indeed, one of the points raised in the discussion of morphological responses in the IPCC report is the consideration of sediment supply and sediment budget (Nicholls et al. 2007). The caveat raised is that the characteristics of the response at the shoreline will be related to the quantity and availability of sediment in the site-specific coastal system. Erosion and displacement may not be the immediate product of a rising sea-level. Further, displacement of the shoreline may not be the product of a negative sediment budget but be related to the changing position of the water level, following the proposition originally espoused by Bruun (1962) wherein cross-shore transfers produce upward and landward displacement of the beach profile even with a balanced sediment budget. Importantly, sediment transfers in the alongshore direction alter the spatial pattern of sediment budget and allow for variation in geomorphological response. Bruun did not consider the alongshore component, but only the cross-shore exchange under a balanced scenario.

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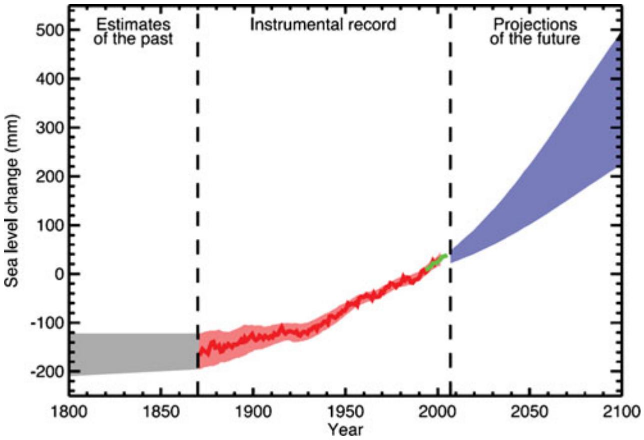

Fig. 1 Range of global mean sea-level position and projection to 2100, relative to 1980–1999 mean sea level. The categories are historical references (*grey* shading), instrumented measurements (*red* shading (*red line*=mean tide gauge; *green line*=mean satellite altimetry)) and projections (*blue* shading) (Bindoff et al. 2007)

Sediment budget as a variable

Whereas an increased sea-level will lead to a displacement of the shoreline and a subsequent migration of the beach-dune profile, the characteristics of the coastal topography are related to the sediment supply and sediment budget, and they will respond to the limitations of those variables under the influence of a changing sea level. The elements of scale are very important in the coastal system because the topographic features are the product of the process-response interaction occurring over the period of years to decades to centuries, the scope of sediment budget as the basis for geomorphological development (Fig. 2). The topographical features will be the product of the net conditions of sediment budget over some period of time. In coastal areas of variable sediment supply, there may be alongshore sequences of erosion and accretion and the existence of a prograding beach-dune system that is composed of traces of the prior shoreline positions in the form of abandoned foredune ridges. Sequences of abandoned foredunes may be related to changes in the episodic input of sediment and may be independent of sea-level trends (Brooke et al. 2008). Conceptually, the beach-dune profile, and especially the foredune in the beach-dune profile, is a product of sediment budget: the amount of sediment delivered or removed over some time period (Psuty 1988, 2004; Sherman and Bauer 1993). Davidson-Arnott (2005) suggests that the sediment budget of the foredune may be maintained under a variety of conditions in which the shoreline is eroding. He especially points to the opportunity for the foredune to exhibit a positive or equilibrium sediment budget under a sea-level rise scenario because of alongshore transport and the alongshore gradient of sediment transfers between the beach and the foredune.

Beach-dune sand-sharing system

Bird (1985) conducted a survey of the world's shorelines and reported that 70% of the sandy shorelines are eroding at this time, or having a negative sediment budget that results in erosion and inland displacement of the shoreline. However, a negative sediment budget need not relate to an attenuation and loss of coastal features. In many of the world's shorelines described as erosional, beaches and dunes continue to exist in the face of inland displacement and a negative sediment budget (Figs. 3 and 4).

The beach-dune system along sandy coasts defines an equilibrium topographic expression that combines the morphological response of processes acting upon available sediment supply that extends from the offshore bar inland to the inland margin of the foredune. The complete system is an accumulation form that is created at the coast where adequate sand is present. However, beaches and foredunes exist at coasts that have negative, equilibrium, or positive sediment budgets, wherein the sediment budget is the measurement of net gain or loss of material for the entire beach-dune sand-sharing system. The differing response to the three conditions of negative, equilibrium, or positive sediment budget is an inland displacement of the beach-dune morphology in areas of negative sediment budget, stability of location with an equilibrium sediment budget, or

Fig. 2 Relationship of sediment budget in time and space scales in the production of the full beach-dune sand-sharing system (modified from Sherman 1995)

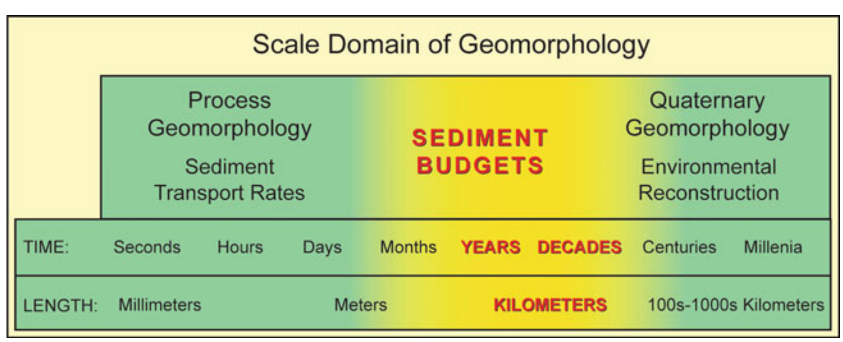

Fig. 3 Variable foredune morphology, Fire Island National Seashore, New York, September 1988. The coastal foredune is actively migrating inland and transgressing older topography in a variety of topographical relationships, including irregular crestline with blow-outs in the nearground, a very linear foredune form in the middle ground, and a curving alignment in the background related to a break in the bar and development of a circulation cell (Allen and Psuty 1987). The foredune remains an area of positive sediment budget (large mass) while the shoreline and the beach-dune system are being displaced inland. (photo by Dr. James R. Allen, National Park Service)

a seaward displacement with a positive budget. Evidence of inland transgression of the beach-dune system in many different environments of the world and the continued presence of viable foredune features leads to the consideration of the foredune as a morphological element that is favored by a mildly-negative sediment budget (Psuty 2004) (Fig. 5). According to this conceptual model, the range of relationships between the beach and the dune systems' sediment budget across time and space serve as the foundation for foredune development and geomorphological evolution across the beach-dune profile. Preservation and retention of the foredune is the persistence of the site of eolian accumulation on the beach-dune profile as it is displaced inland.

Under an accreting condition associated with a positive sediment budget, the foredune site is periodically stranded as the beach widens and pioneer vegetation extends seaward to create a new site for trapping sand, thereby causing a short period of accumulation in any particular foredune. However, as the rate of accretion diminishes, the period of eolian accumulation at a given site is prolonged and the foredune has a greater and greater positive budget. And, in a situation of a minor negative sediment budget, the site of eolian accumulation is slowly displaced inland. In this scenario, the negative sediment budget drives a net inland displacement of the beach-dune system and the topography of the beach retains its dimensions and features while shifting in space, and stored sand is being released to replace that which is being eroded. However, because the foredune's seaward face is being activated often in a negative budget scenario, the pioneer vegetation habitat may be temporarily destroyed. The foredune face then becomes a transportation surface and sediment is mobilized across the dune face, over the crest, and to the inland side (Fig. 6). If the rate of inland mobilization of the foredune is as great or greater than the rate of beach displacement, the foredune may have a balanced or a positive sediment budget as it is displaced inland as noted by Gares et al. (1993) and Vespremeanu-Stroe and Preoteasa (2007). Farther along the continuum, rates of inland transport increase as the foredune form becomes more segmented, leading to the creation of secondary dune forms related to hummocks and parabolic features migrating inland (Fig. 7). Many of the world's shorelines display a large foredune moving inland, noted in Doody (1991) and many chapters in Bird and Schwartz (1985); their widespread occurrence and persistence is an example of a balanced or positive sediment budget in the foredune coincident with an eroding shoreline.

Alongshore morphological continuum

In an alongshore topographical sequence, the morphological continuum may be found in at least three general coastal

Fig. 4 Section through coastal foredune revealing seaward truncation of inland-dipping sedimentary strata indicative of accumulation to the lee of the foredune crest. This feature is a topographic expression of a positive sediment budget in the beach-dune profile as the shoreline is being displaced inland. Fire Island National Seashore, New York, January 1976

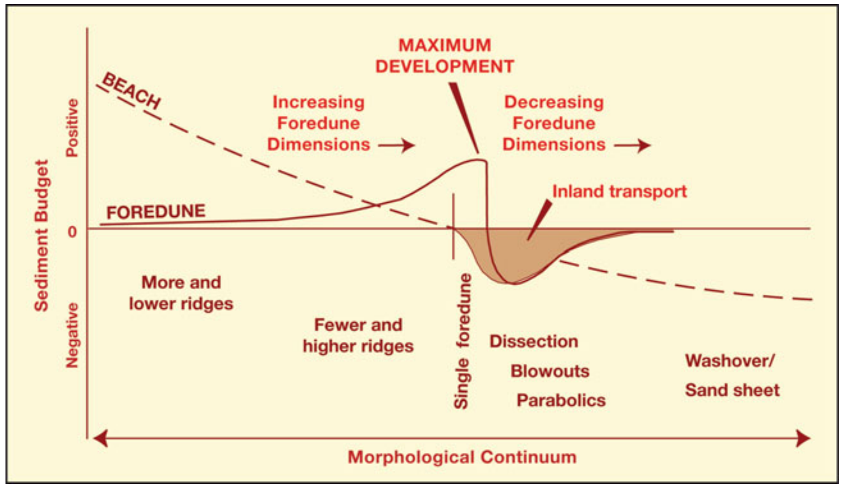

Fig. 5 Conceptual relationship between sediment budget in the beach, the foredune, and the sequence of foredune development. Foredune development is maximized at times of slightly-negative sediment budget. Variable foredune dimension and form are related to position along the morphological continuum (Psuty 2004)

Fig. 6 Inland displacement of the foredune form that retains a balanced or positive sediment budget as it shifts inland. **a** Storm scarping of the dune face has removed much of the stabilizing vegetation and has altered the character of the dune face from an area that trapped eolian-transported sand to that of a transportation surface leading to the accumulation of sediment to the lee of the foredune crestline. Fire Island, USA, March 2008; **b** Scarped toe of a well-vegetated dune, dune form is intermittently transgressing inland over adjacent lowland. St. Fergus, Scotland, United Kingdom, May 2008

situations that are related to the sediment budget association of foredune type: 1) fluvial source of abundant sediment discharge; 2) coastal spit; and 3) barrier island (Fig. 8). In each of these situations, there is an alongshore gradient in sediment supply and accompanying variation in sediment

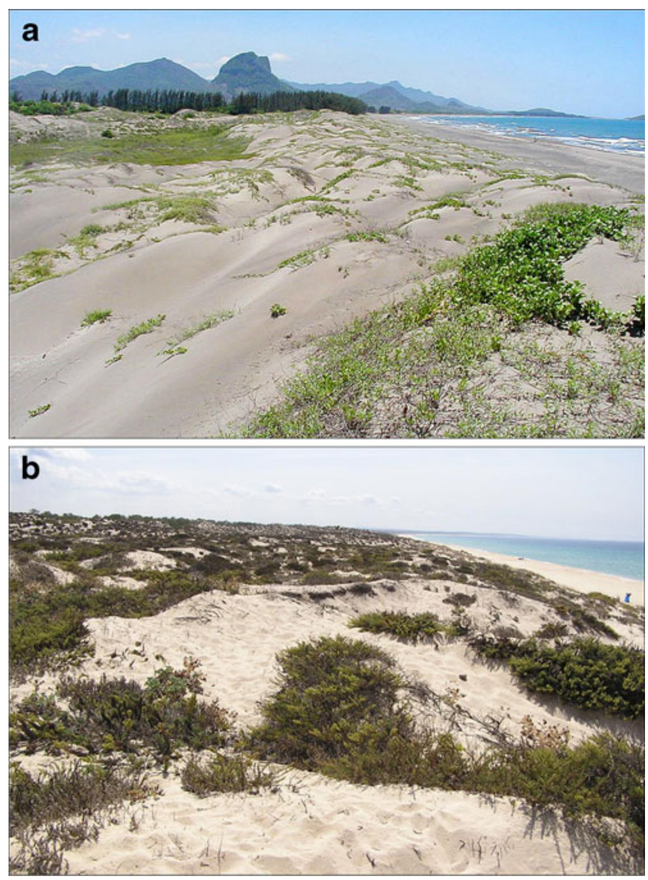

Fig. 7 Segmentation of the foredune crestline leads to inland transport of sand and migrating dune forms. **a** Near San Juan de Villa Rica, Veracruz, Mexico, June 2005; **b** Comporta, Portugal, September 2005

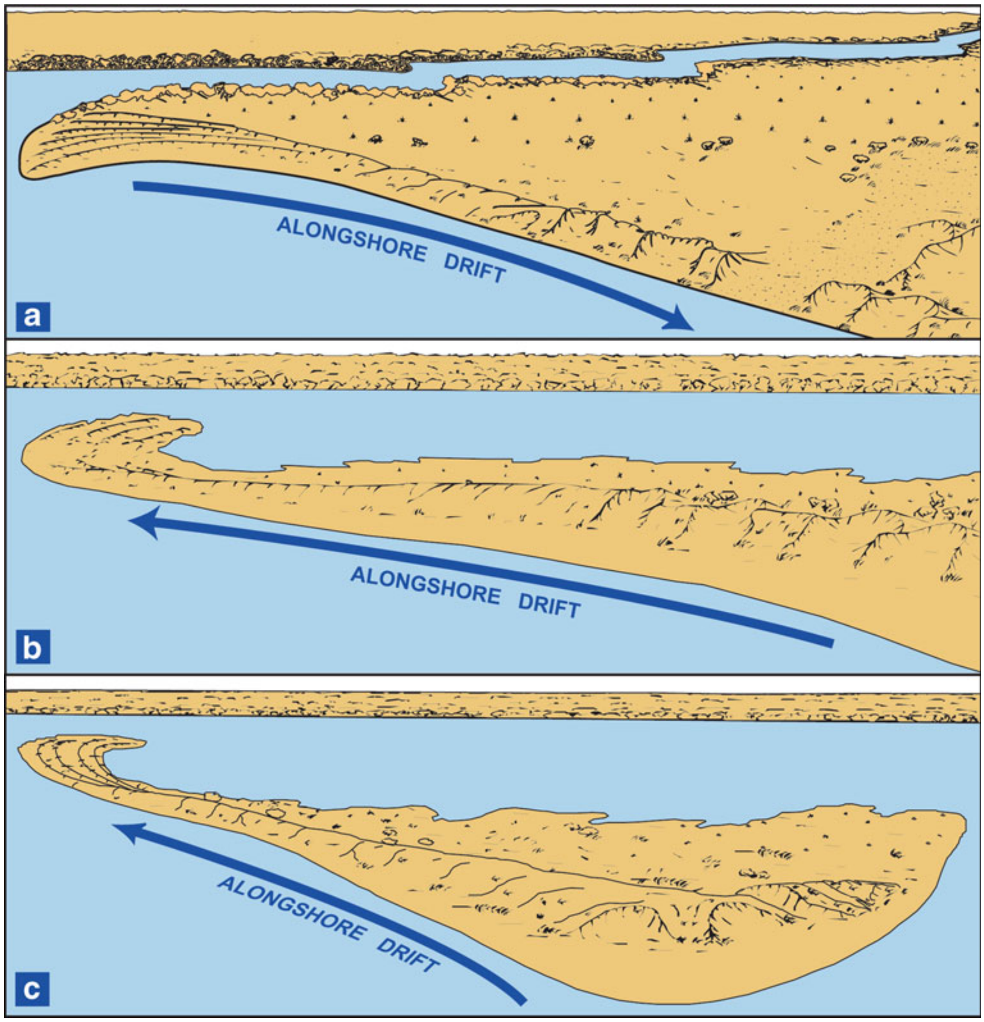

Fig. 8 Conceptual model of coastal foredune features related to the alongshore variation in sediment budget. **a** fluvial source with greatest positive sediment budget near the discharge point and decreasing downdrift; **b** Accreting spit with greatest positive sediment budget at distal end of spit and decreasing toward the base of the spit; **c** Barrier island with erosion of the oldest portion of the barrier releasing sand to be transported to the downdrift terminus; downdrift accretionary ridges develop at area of greatest positive sediment budget. In all cases, there is an alongshore sequence of foredune form and dimension grading from highest positive sediment budget to areas of negative sediment budget

budget. In the area of largest positive sediment budget, the outcome is a prograding shoreline and there is an association of many and low foredune ridges. Moving alongshore toward smaller sediment budget values, the individual foredune ridge increases in dimension but the number of foredune ridges decreases, to the point of a single foredune ridge of maximum dimension in the locale migrating inland over older topography. If the foredune ridge remains coherent, it exists as a single feature being displaced inland. Under conditions of a balanced sediment budget, the

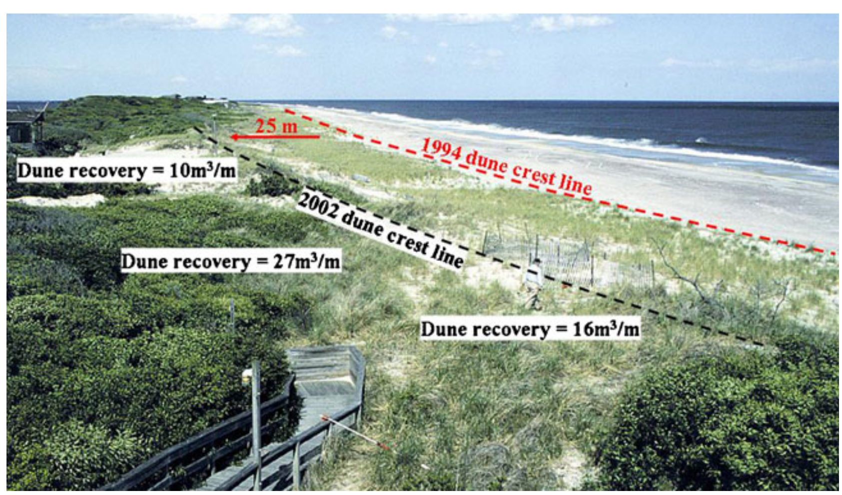

Fig. 9 Erosion and recovery of the foredune crestline, 1994–2002, Talisman, Fire Island National Seashore, New York, June 2002

Fig. 10 Inland displacement of the beach-dune system with accommodation space to allow retention of many of the foredune dimensions and features. This location is eroding slowly under a negative sediment budget, but the beach and dune dimensions have remained consistent. The foredune is scarped and notched. In some locations, the sand is being transported inland to broaden the foredune. In other locations, blowouts are extending through the foredune ridge and causing sand to accumulate inland. Island Beach State Park, New Jersey, August 1997

foredune ridge may continue to be displaced inland while retaining its dimensions. If the foredune's sediment budget becomes negative, eventually the ridge form becomes segmented, various forms of eolian dissection may develop and cause eolian topography inland of the foredune ridge position, most commonly in the form of parabolic dune features. Under this situation, a negative sediment budget in the foredune is accompanied by greater rates of inland transport through gaps and blowouts in the foredune crestline. Carried to its ultimate conclusion, a decreasing sediment budget will ultimately lead to a loss of foredune topography and to wholesale inland transport or, with the lack of any sand, to a complete loss of dunal forms.

Impacts of sea-level rise

Under a scenario of rising sea level, a likely outcome would be an inland displacement of the entire beach-dune profile (Pethick 2001), an activation of the face of the foredune (Feagin et al. 2005), increased inland transport along the entire continuum, and a change in the location of the alongshore sequence of foredune dimensions and features as the equilibrium water/land contact translates up the beach profile (Psuty 2004; Davidson-Arnott 2005). However, from a sediment budget perspective, it is also likely that the sediment budget would slide along the alongshore gradient and the resulting forms would shift towards the location of the more positive sediment budget. Thus, spatially, the site of maximum foredune development would shift toward the direction of greater sediment availability to the foredune. And, the area of dissected foredune crest would also shift and produce a new area of greater inland transport and new development of transgressive parabolic dune forms. Thus, in the three situations presented in Fig. 7, there would be opportunities for foredune dimensional enhancement along part of the alongshore continuum and there would be opportunities for greater inland transport and dune form expansion in another part of the spatial continuum.

Sea level has been rising over the past centuries and many parts of the coast have been responding to the penetration of the water into the coastal landforms. Barrier islands are thought to be particularly vulnerable to the increased water levels, increased storm surge penetration, and limited sediment supply (Pendleton et al. 2004). Along the Fire Island barrier island, recent topographical surveys of the coastal foredune have revealed a means by which some aspects of barrier island topography may persist in the changing environmental system (Psuty et al. 2005). In 1994, a 400 m alongshore length of foredune was removed as an inshore circulation cell eroded much of the beach and the adjacent foredune (causing a displacement similar to the curving inland displacement seen in the distance in Fig. 3). These circulation cells are very common along the Fire Island barrier and have been noted as a mechanism for sediment activation independent of storm conditions (Gravens 1999). Following passage of the circulation cell, the beach dimensions recovered quickly. But the foredune took longer to become re-established. Monitoring of the entire beach-dune system revealed that over a span of eight years the foredune accumulated about as much sand in its cross-sectional area in its new profile as it had prior to the erosional event. But the new foredune crestline was positioned about 25 m inland of its previous site (Fig. 9).

Fig. 11 Erosion of the foredune is leading to the inland transfers of sand in the form of parabolic dunes transgressing into the adjacent wetlands. This is a stage in the continuum that is related to a negative sediment budget in the foredune and an increased expansion of dunal topography inland of the dissected foredune ridge. Southern end of Long Beach Island, New Jersey, August 1997

In portions where the foredune crest was nearly obliterated, eolian sand transport moved into the breach and was soon colonized and stabilized by pioneer plants. In some locations, the net accumulation after eight years was on the order of 27 m^3/m of alongshore length. Over much of the 400 m of dune erosion, the recovery in the foredune was 10–16 m^3/m. The final foredune feature is a bit lower and wider than the previous form, and it is a coherent, stable unit in the beach-dune sand-sharing system.

Throughout Fire Island, the foredune crestline is slowly migrating inland at a rate of about 0.6 m/yr over the past 30 years (Psuty and Silveira 2008). However, the foredune continues as a positive topographical feature in the beach-dune sand-sharing system as sand is episodically transported up the foredune face, across the dune crest, and to the back slope. Traces of circulation-cell incursions into the foredune crestline have created a wavy pattern to the crest (interpreted from aerial photographs) that have alongshore lengths similar to the dimensions of the cells measured in the beach, ca. 300–1,000 m (Allen et al. 2002). Thus, the process of circulation cell penetration to the dune position, eroding the dune mass, and subsequent recovery at an inland position appears to be a mechanism for responding to a negative sediment budget in the beach while retaining the general sediment budget of the foredune as it is displaced inland on an episodic basis. This mechanism could apply in many other locations with a significant alongshore transport system and the creation of circulation cells.

Furthermore, the dynamics of foredune retention of dimension while being displaced inland adds a complication to the consideration of coastal vulnerability under a rising sea-level. In many of the discussions of the impacts of sea-level rise on the coastal system, the dimensions and spatial distribution of the existing foredune are taken as a constant (e.g. Thieler and Hammar-Klose 2001). If the foredune sediment budget is positive, the vulnerability will decrease as the feature shifts inland. If the locations of enhanced foredune development shift alongshore, the vulnerability will also change, increasing in some locations, decreasing in other locations. Any quantification of vulnerability has a temporal constraint and is liable to misrepresent the conditions that will ensue under situations of foredune displacement and alteration of dimension. Therefore, the understanding of foredune sediment budget and the conditions that assist in the creation of a positive budget while displacement takes place is a critical element in the consideration of impacts of sea-level rise.

Conclusion

The general predictions of coastal erosion and change under scenarios of global sea-level rise are probably correct. A displacement of the water-land contact will probably ensue in association with the elevated water level. What is not so certain is the morphological response to the rising sea-level. If there is sufficient sediment, the response may be an inland and alongshore displacement of the sand-sharing system if accommodation space exists (Fig. 10). Amongst the possible opportunities for enhanced foredune development are: 1) general inland migration of the existing foredune as the seaward margin is more frequently scarped and sediment is transported inland over and beyond the foredune crestline; and 2) an alongshore displacement of the zone of maximum foredune dimensions as well as a displacement of the zone of increased inland eolian transport in the form of blowouts and parabolic features (Fig. 11). In a sense, this is similar to the situation described by Clemmensen and Murray (2006) and by Clarke and Renell (2006) that related dune activity or mobilization to the variation in storminess that interacted with sediment supply to cause periods of inland displacement of coastal dunes. Whether driven by increased mobilization associated with a higher sea level or higher penetration of storm surges, or both, there is an opportunity for an alongshore component of dune zone mobility and development at a time when the general shoreline is being eroded.

Acknowledgements Cartography was produced by Michael Siegel, Rutgers, The State University of New Jersey. Appreciation is extended to the many cohorts who have been companions in the field and contributed countless hours of discussion of the significance of coastal dunes in the context of sea-level rise and the development of the foredune continuum model.

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