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The morphodynamics of transverse dunes on the coast of South Africa

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Abstract

Transverse sand dunes located within the supratidal zones of beaches are a significant geomorphic feature along sand-dominated coasts worldwide and are generated by strong alongshore winds in areas of high sediment availability. Transverse dunes are present along the South African coast, and these are known to migrate dynamically in response to wind forcing. However, the detailed dynamics of individual dune systems along the same coastal stretch have not been compared to one another, and the relationship of transverse dunes to their hosting beach systems has also not been examined. This study examines the properties and dynamics of transverse supratidal dunes from three systems along the coast of South Africa, using remote sensing methods. Results show that, although the underlying beach system appears to be relatively stable over the time period of analysis, there is a dominant aeolian-driven migration of transverse dunes towards the northeast, following prevailing wind direction, countered by less dominant movement to the southwest. There are also considerable variations in calculated annual dune migration rates between adjacent systems, between summer and winter seasons, and between dunes within a single site. This highlights that, although beach and dune landforms can be conceptually considered as part of the same sediment system, there is not a clear relationship between phases of beach aggradation and phases of dune aggradation. Instead, a primary control appears to be beachface erosion by waves that reduces beach width and influences dune morphodynamics, independent of sediment supply.

Introduction

Globally, broad sandy beaches are commonly backed by sand dunes of different types that act as a buffer to coastal erosion and flooding whilst also providing important ecosystems and records of coastal environmental change (Sherman and Bauer 1993; Regnauld and Louboutin 2002; Walker et al. 2017; Bullard et al. 2019). The sediment system relationships between beaches and dunes, however, are less well studied from the viewpoints of coastal morphodynamics and sediment budgets, compared to studies on the role of external forcing factors such as storms (e.g. Leatherman 1979; Sherman and Bauer 1993; Aagaard et al. 2004; Sabatier et al. 2009; Delgado-Fernandez et al. 2012; Pellón et al. 2020). Despite this, there are important morphodynamic and sediment system linkages between beaches and dunes, especially along coastal stretches with wide supratidal zones or where large beach areas are exposed to aeolian processes at low tide (Houser 2009; Bauer et al. 2012; Yokobori et al. 2020). In such areas, alongshore winds can lead to the development of transverse dunes, so called because they are ridge-like aeolian bedforms located within the supratidal zone of beaches and have a downslope alignment at right angles to the shoreline. As such, transverse dunes can be clearly distinguished from foredunes that are broadly aligned parallel to the shoreline and that are located at the back of the beach. Many studies have examined the nature of wind flow over transverse dunes, from in situ field measurements and numerical modelling (van Dijk et al. 1999; Reffet et al. 2010; Melo et al. 2012; Araújo et al. 2013; Jiang et al. 2014; Jackson et al. 2020), but there are fewer studies of the morphometry and morphodynamics of transverse dunes (Hunter et al. 1983; Miguel and Castro 2018; Knight and Burningham 2019). This includes calculations of dune migration rates, based on field or remote sensing data, which can be linked

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to the development of the dune bedform with respect to wind forcing (Tsoar and Blumberg 2002; Miguel and Castro 2018; Knight and Burningham 2019).

Despite such studies, the relationship of transverse dunes to the surrounding beach environment (e.g. beach size, shape, sediment supply, interdune properties) has not been fully explored. This is a limitation in understanding the nature of integrated beach–dune systems. This study examines the morphodynamics of transverse dunes from three localities along the Indian Ocean coastline of South Africa, using analysis of earth observation imagery for the period 2016–2020. Dune migration rate and direction are examined with respect to regional-scale patterns of wind/wave forcing, and with respect to the nature of beach–dune sediment systems. This analysis enables a better understanding of sediment cells along this under-investigated coast.

Study area

Extensive sandy beaches are found along much of the South African coast, in particular along the western (Atlantic Ocean), southern (Southern Ocean) and eastern (Indian Ocean) sectors (Tinley 1985). These comprise either long, linear sandy beaches with backing sand dunes and incoming microtidal estuaries, or sandy embayments constrained within bedrock headlands. Wind, wave and tide regimes vary between the west (Atlantic) and south/east (Indian Ocean) sectors (Corbella and Stretch 2012; Rautenbach et al. 2019; Veitch et al. 2019). Tides are in the high microtidal/low mesotidal range throughout, and a strong swell wave regime ($H_s > 5$ m) reflects wind forcing from the Southern Ocean (> 5 m) (Wepener and Degger 2019). Several studies have examined sandy beach and dune processes and dynamics in South Africa, and these link their morphodynamics to wind and wave regimes, including episodic storms (La Cock et al. 1992; Olivier and Garland 2003; Mitchell et al. 2005; Corbella and Stretch 2012; Guastella and Smith 2014; Knight and Burningham 2019). However, the dynamics of many sandy coastal areas are not well understood.

Transverse dunes have been identified along several areas of the south and east coasts of South Africa (La Cock et al. 1992; Burkinshaw and Rust 1993; Jackson et al. 2014; Knight and Burningham 2019) but have not been described in detail. The locations in South Africa of sandy beach systems comprising transverse dunes in their supratidal zones are shown in Fig. 1, which is based on systematic survey along the coastline using Google Earth. Transverse dunes within inland dune fields or located on sand flats within river mouths are not included here. This plotted distribution shows that these sites have a specific spatial clustering. This is likely related to accommodation space (within the broader coastal hinterland and with respect to beach width, allowing for the presence of a wide supratidal zone) and sediment supply (either downdrift of river mouths or along straight and unimpeded coastlines). Along much of the west coast, high wave energy and strong onshore winds drive sand inland (Roberts et al. 2009) resulting in transgressive sand sheets and plumes, and where present, sandy beaches are relatively narrow, coarse and steep with a restricted supratidal zone. The south coast is dominated by small and bedrock-bound embayments that are thus geologically controlled and spatially constrained. Where present within embayments, sandy beaches are isolated from each other and have an absence of backing sand dunes and thus represent closed and localised sediment cells. Along the Eastern Cape Province coastline between Port Elizabeth (now called Gqeberha) and East London (Fig. 1), sandy coastal forelands with continuous sandy beaches are common features, and these are backed by a vegetated coastal fringe that marks the approximate boundary between the active and inactive portions of the beach–dune sediment system. Specifically, the sandy foreshore is backed by a transverse dune covered backshore that is then backed by vegetated, established dune ridges that do not play an active role in the beach–backshore system. The dynamics of Eastern Cape beaches are poorly known although asymmetric zeta bays, related to wave-driven longshore processes, have been identified (Dardis and Grindley 1988, pp.157–160). Transverse dunes are only present at a few sites in northeast South Africa (Fig. 1). The geomorphic setting here is that an extensive Quaternary-age coastal plain subject to long-term progradation and stabilisation of the land surface by vegetation growth, and this has resulted in a very narrow active (mobile) beach–dune corridor with low sediment availability (Knight 2021). This coastal sector shows active northward longshore drift associated with active headland bypassing (Meeuwis and van Rensburg 1986; Mitchell et al. 2005).

Methods

Satellite imagery was used to map the transverse dunes in three selected localities along the southeast coast of South Africa (marked on Fig. 1). These sites were chosen because they are relatively close to each other along a 40-km coastal stretch of the southeast-facing Eastern Cape Province coastline where they have similar geomorphic and forcing contexts including (i) wide supratidal zone with transverse dunes, (ii) clearly demarcated zone of inland vegetated dune ridges (which can be considered to act as a barrier to landward aeolian sediment loss), and (iii) linear beach–dune foreshore–backshore system

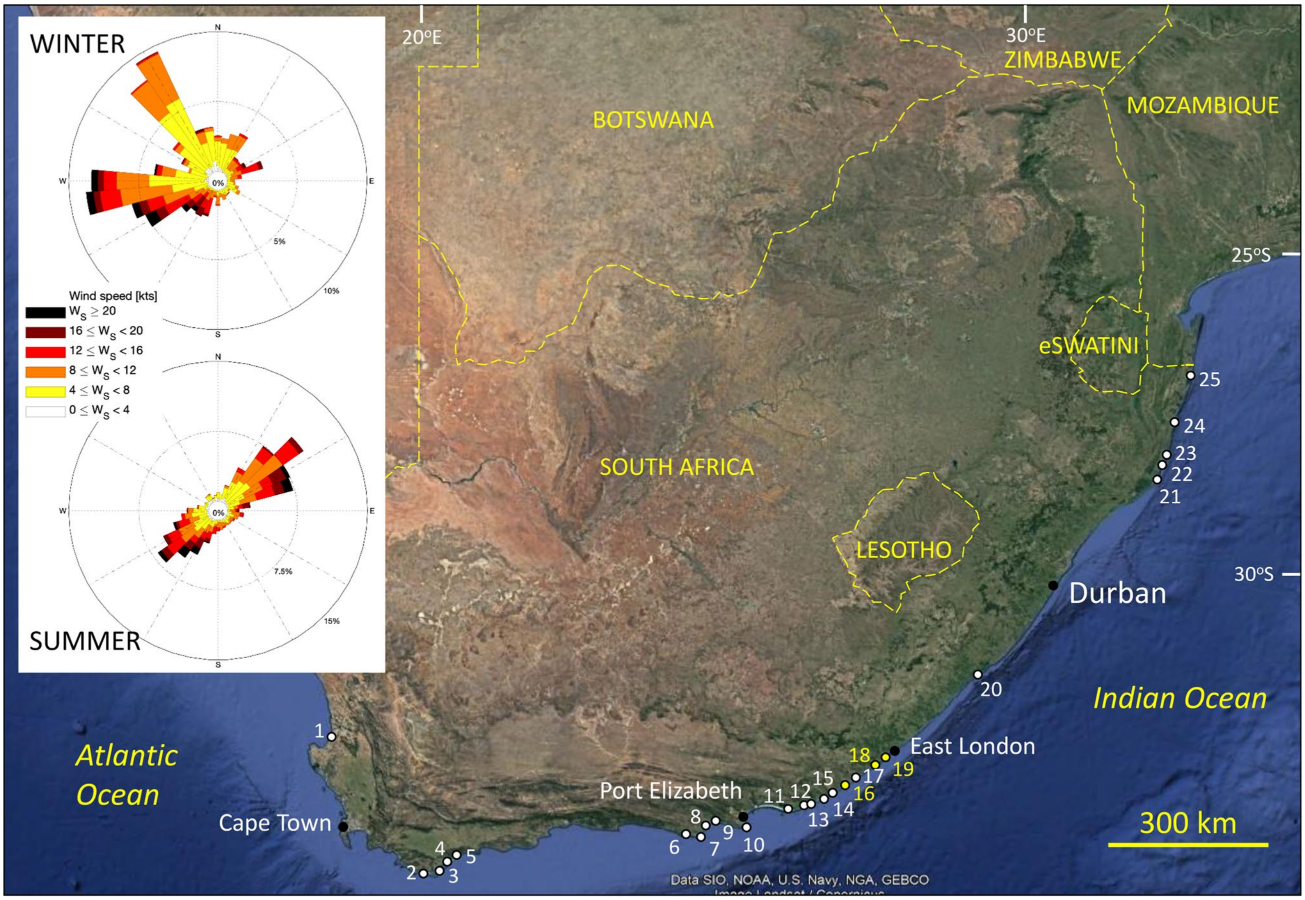


Fig. 1 Map of South Africa (source: Google Earth) showing the locations of sandy beaches where supratidal transverse dunes are observed. (1) Van Riebeeckstrand, (2) Brandfontein, (3) De Mond, (4) Arniston, (5) Overberg, (6) Oyster Bay, (7) Cape St. Francis, (8) Aston Bay, (9) Jeffreys Bay, (10) Cape Recife, (11) Boknes Boesman, (12) Waters Meeting Nature Reserve, (13) Port Alfred, (14) Seafield, (15) Great Fish Point, (16) Hamburg Nature Reserve, (17) Mpekweni, (18) Kaysers Beach, (19) Rockclyffe-on-Sea, (20) Bholani, (21) Gwabalanda Hlawi, (22) Cape Vital, (23) Leven Point, (24) Sodwana Bay, (25) Kosi Lake. The sites examined in this study (16, 18, 19) are highlighted in yellow. Inset shows winter (June–July–August) and summer (December–January–February) wind roses for the period 2016–2020 inclusively from East London, immediately adjacent to the sites of interest

that narrows to the northeast, effectively closing off the supratidal zone where transverse dunes can develop. These can therefore be considered as relatively closed aeolian sediment cells.

For these sites, Sentinel-2 imagery acquired between March 2016 and November 2020 (inclusively) with < 5% cloud cover was acquired (totalling 110 dates for Kaysers Beach, 114 for Hamburg Nature Reserve, 112 for Rockclyffe-on-Sea) using Google Earth Engine. Offsets in positioning were calculated using cross-correlation between each individual image and the most recent (as anthropogenic features in the hinterland provide strong registration), and where necessary, the image was shifted (at most by 1 or 2 pixels in x or y); the positioning of rectified images was then checked manually. Following the method outlined in Knight and Burningham (2019), reflectance was extracted along a single shore-parallel, dune-crossing transect. In this study, the near infrared band 8 (central wavelength 842 nm) proved to be most effective across all sites at differentiating between the northern (highlighted, bright) and southern (shadowed, dark) sides of the dune crests. Peaks in the differential of this reflectance along the transect were then used to identify the location of dune crests. The number of individual dune crests examined at each site is shown in Table 1. Although band 8 of Sentinel-2 imagery is relatively coarse resolution (pixel resolution of 10 m), reducing the certainty achieved in comparing successive images, the high revisit time (5–10 days) and hence the large number of images available over the ~ 5-year period of analysis permit inferences to be made in terms of dune crest movement. Where this movement was greater than ~ 3 m year^{-1}, calculation of statistically significant migration rates was possible.

Table 1 Properties of transverse dunes at selected sites

Site name	Transverse dune properties						
	n	**Length range (m)**	**Mean length (m)**	**Median length (m)**	**Spacing range (m)**	**Mean spacing (m)**	**Median spacing (m)**
Hamburg Nature Reserve (S)	42	65–420	185	155	25–95	55	55
Hamburg Nature Reserve (N)	44	40–315	120	105	30–130	65	60
Kaysers Beach	17	60–200	95	80	45–120	70	70
Rockclyffe-on-Sea	35	55–370	160	140	40–115	75	75

Results

The focus here is on transverse dune properties and dynamics, not on the nature of surrounding beach systems. The reason for this is that the earth observation data used are acquired at different times, capturing different tidal stages. This means that changes in the size, shape, area and geomorphology of the beach system cannot be evaluated with confidence using remote sensing data alone. However, beach systems provide the substrate for dune migration, and there is active building of transverse dunes from blown beach sand, and beach accretion as a result of dune foot erosion by waves. Examples of transverse dunes in the field are shown in Fig. 2. These dunes are commonly wedge-shaped in morphology that are connected at their landward ends to vegetated dune ridges (and less commonly to bedrock) (Burkinshaw and Rust 1993; Hellström and Lubke 1993; Knight and Burningham 2019). Maximum transverse dune height reaches 8–10 m at the landward end of the ridge, and ridge height decreases, and ridge width increases and flattens out in a seaward direction.

Transverse dune morphodynamics

Adjacent to the Fish River mouth, Eastern Cape Province, is the sandy beach–dune system of Hamburg Nature Reserve (#16 in Fig. 1). For ease, this system is divided into northern and southern sectors. The alongshore margins of this combined system are well marked, where the beach and backshore narrow to some 30-m width compared with a maximum width of 650 m in the northern sector of this system. Well-developed transverse dunes with linear crestlines are present throughout the supratidal zone of this system. Properties of these transverse dunes are given in Table 1. Examination of Sentinel-2 imagery over the period 2016–2020 yields relatively consistent averaged transverse dune migration rates of 8.60–11.50 m year^{-1} for individual dune crests, but there is a wide range of values (Fig. 3). Based on multitemporal data, differences in dune migration rates between austral summer (months December–January–February) and winter seasons (months June–July–August) can be identified (Table 2). Summer–winter seasonal differences account for ± 17–33% of annual averaged values, although there is wide variability between individual dunes (dots on Fig. 4a, b), and the fastest migration rates occur during the autumn (May/June). Analysis of the summer and winter migration rates indicates that these seasonal variations in rate have R^2 values of 0.69–0.91 and are all significant at the $p < 0.01$ level (Table 2). The migration rates reported for different dunes within a single year are much greater than averaged interannual rates, highlighting the dynamic nature and short timeframe over which the transverse dunes respond. Tracking of the trajectory of individual dunes ($n = 42$) for the Hamburg Nature Reserve system over the time period of analysis shows a wide range of values with outliers of – 5 m to + 14 m year^{-1} (Fig. 3). Jackson et al. (2020) used a fluid dynamics model based on transverse dunes from a nearby site at Mpekweni. They showed that with dominant seasonal winds from the southwest, significant flow separation takes place over the transverse dune crest, resulting in higher shear stress down the stoss slope which promotes net dune migration towards the northeast. This modelling approach confirms the field observations of this study. The wide range of migration rates (and directions) of individual dunes along the Hamburg Nature Reserve system likely reflects longshore variations in sediment supply and beach width. It is also notable that the southern site generally has transverse dunes that are straight, continuous and lie parallel to each other, whereas the northern site has dunes that are sinuous and with crests that variously divide and merge though Y-shaped intersections. This may suggest that dune migration rates vary significantly along the length of individual crests as well as between dune ridges.

Transverse dunes have been previously noted at Kaysers Beach (#18 in Fig. 1) (Knight and Burningham 2019). Here, the beach system comprises two shore platforms 900 m apart with enhanced wave erosion on the lateral margins of the platform (Fig. 5). At its widest point,

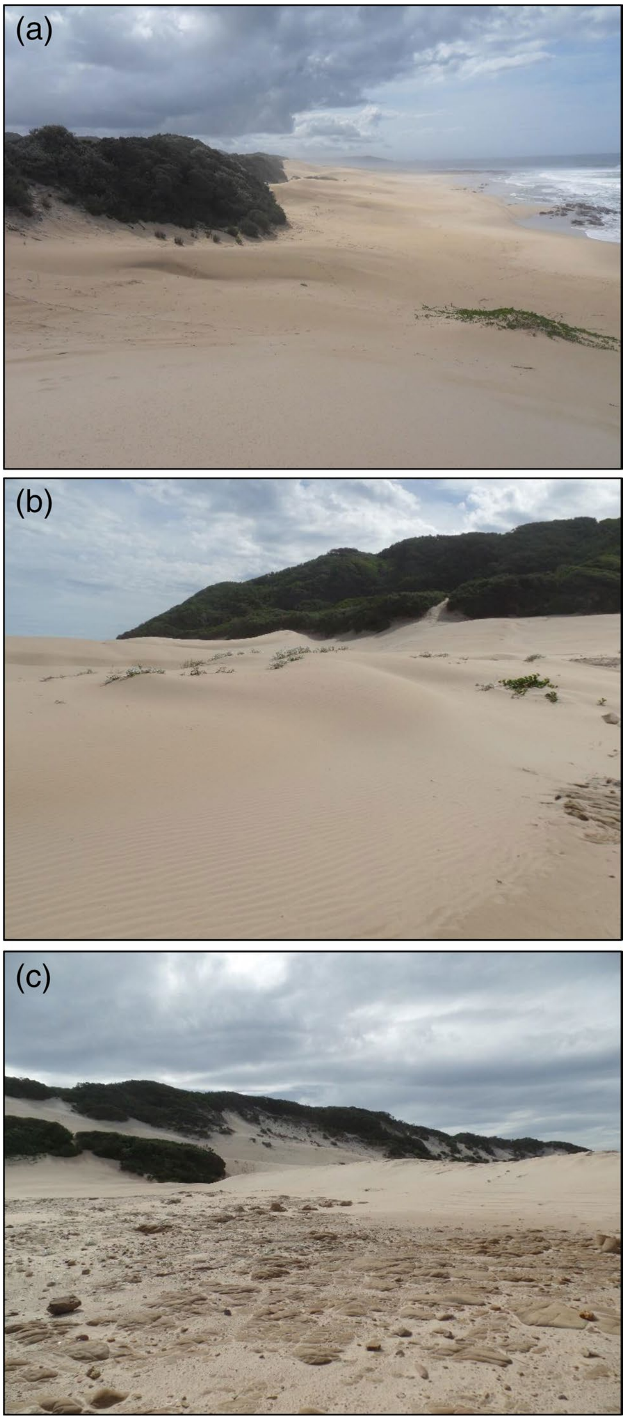


Fig. 2 Examples of transverse dunes on sandy beach substrates in South Africa. (**a**, **b**) Undulating dune ridges at Kidds Beach, (**c**) linear transverse dune at Kaysers Beach overlying an abraded bedrock surface (foreground)

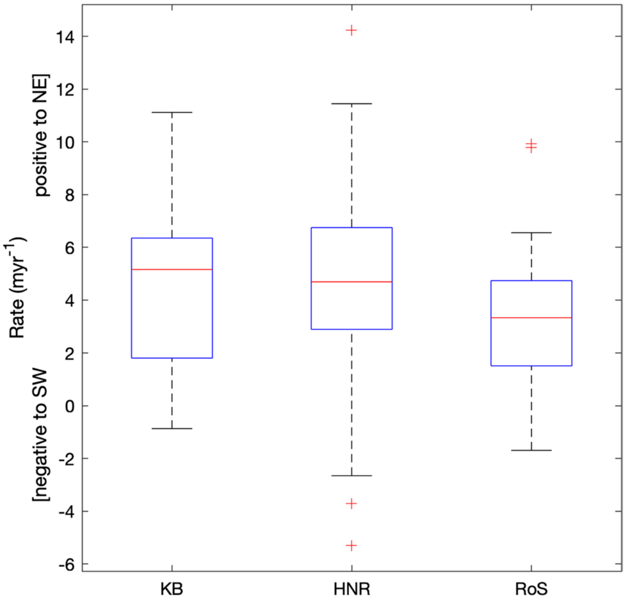


Fig. 3 Box and whisker plots aggregated from migration rates for individual transverse dunes at Kaysers Beach (KB), Hamburg Nature Reserve (HNR) and Rockclyffe-on-Sea (RoS) averaged over the time period 2016–2020. Number of individual dunes examined at these sites is given in Table 1

the dune system is 340-m wide, and the beach pinches out to the northeast and southwest against bedrock outcrops which reduces accommodation space. The rear of the dune–beach system has a well-marked vegetated dune line. Selected transverse dunes show migration rates of 7.60 to 11.12 m year^{-1} with high seasonal variability of ± 1–27% of annual averaged values (Table 2). This yields R^2 values of 0.51–0.73, lower than at other sites, but are all significant at the $p < 0.01$ level (Table 2). Spatial differences in migration rates over time between these dunes may reflect the fact that the dunes are much shorter along the margins of the beach where wave erosion is greater and much longer where the beach is widest (Fig. 5, Table 1). Covariations between beach width and transverse dune length reflect the balance between wave vs wind processes at different places along the beach and have implications for overall sediment availability.

Transverse dunes at Rockclyffe-on-Sea (#19 on Fig. 1) show a similar seasonal pattern of variability (Fig. 6). Here, the beach is anchored on a bedrock outcrop, and the dune–beach system varies from 640-m width at its widest point to 30 m at its northeast and southwest ends that clearly mark the lateral limits of this system. Areas adjacent to the bedrock outcrop show enhanced wave erosion, reducing beach width. Despite this being a smaller system overall than the other examples considered, the transverse dunes are larger (Table 1). Dune spacing also increases towards the widest point and to the northeast of the system (Fig. 6a). The crest mobility data show high seasonal variability, with almost a bimodal seasonal pattern (Fig. 6b, c), and

Table 2 Calculated transverse dune migration rates at the study sites

Foreland	Dune	Time period	Linear mean migration rate (m year^{-1})	R^2 value	Significance level
Hamburg Nature Reserve (S)	Figure 4b	Annual	8.60	0.81	$p < 0.01$
		Winter	7.16	0.77	$p < 0.01$
		Summer	11.51	0.91	$p < 0.01$
Hamburg Nature Reserve (N)	Figure 4c	Annual	11.50	0.81	$p < 0.01$
		Winter	9.94	0.88	$p < 0.01$
		Summer	10.20	0.69	$p < 0.01$
Kaysers Beach	Figure 5b	Annual	7.60	0.72	$p < 0.01$
		Winter	6.65	0.65	$p < 0.01$
		Summer	6.70	0.73	$p < 0.01$
	Figure 5c	Annual	11.12	0.62	$p < 0.01$
		Winter	8.12	0.51	$p < 0.01$
		Summer	11.18	0.70	$p < 0.01$
Rockclyffe-on-Sea	Figure 6b	Annual	4.44	0.29	$p < 0.01$
		Winter	3.55	0.24	$p < 0.01$
		Summer	3.99	0.23	$p = 0.098$
	Figure 6c	Annual	9.78	0.62	$p < 0.01$
		Winter	8.45	0.76	$p < 0.01$
		Summer	9.58	0.57	$p < 0.01$

Winter period is the month June–July–August, summer period is the months December–January–February

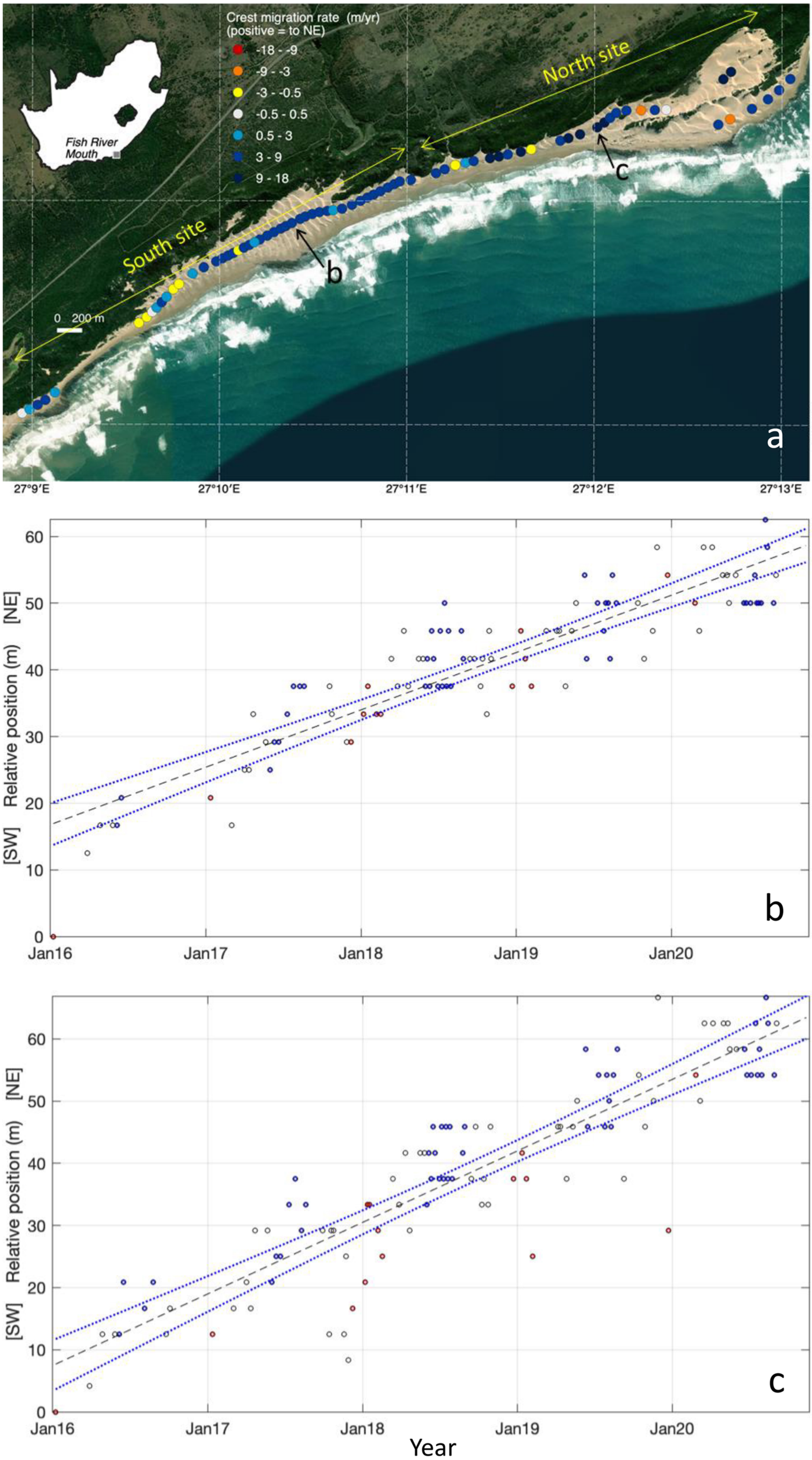
with the west side of the system migrating more slowly (4.44 m year^{-1}) than the east side (9.78 m year^{-1}). High seasonal variability is ± 3–20% of annual averaged values which yields large differences in R^2 values of 0.23–0.76. Considering all the dunes present at Rockclyffe-on-Sea (n = 35), migration rates are generally lower than on the other systems examined here (Fig. 3).

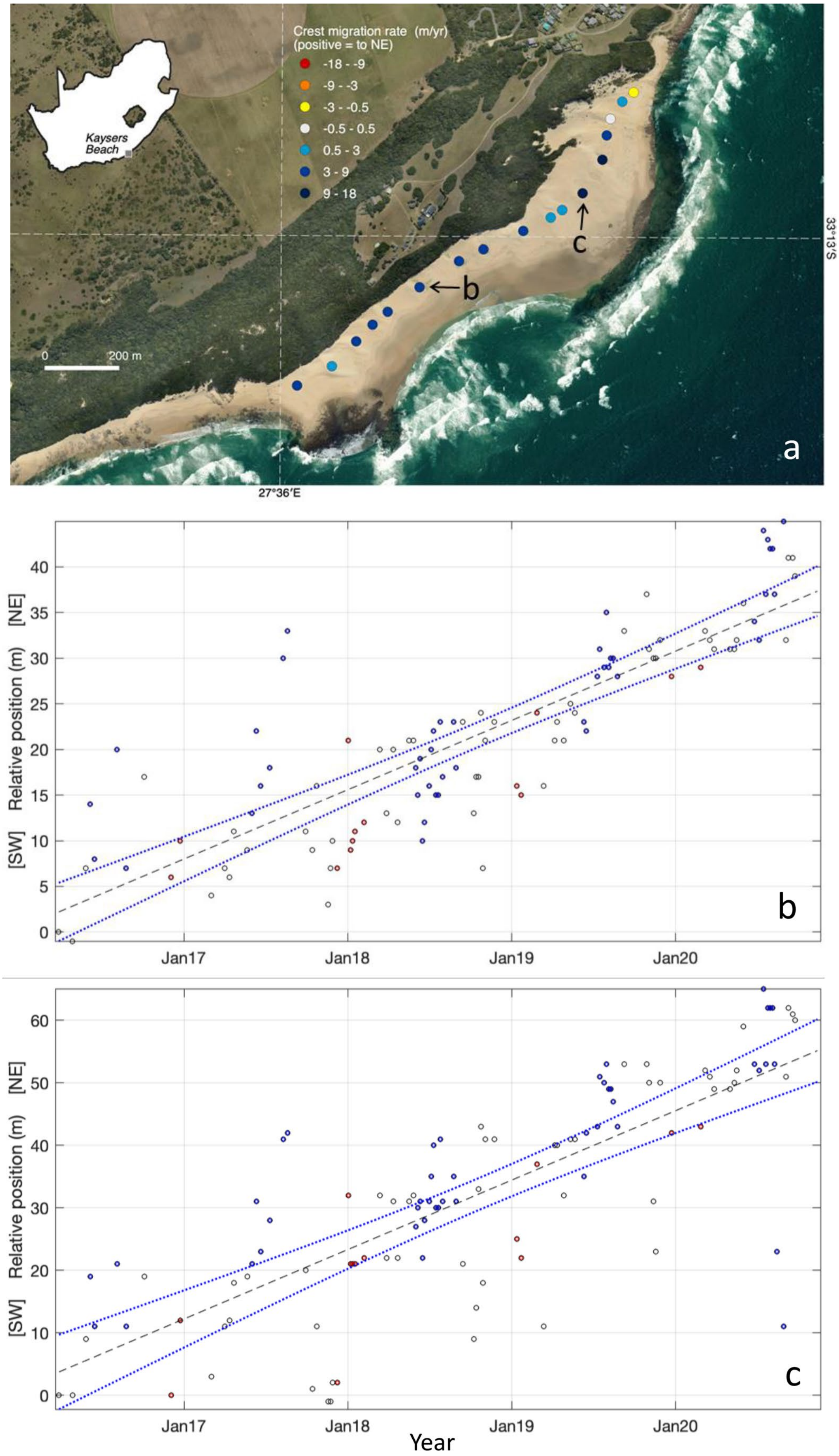
Transverse dune patterns

To illustrate the longevity and spatial persistence of transverse dunes, an example from Rockclyffe-on-Sea is presented. Using Google Earth imagery, a shore-parallel transect through the middle of the dune system (2.7-km long) was constructed and the locations of individual dune crests marked along. This was done along the same transect for 10 different time periods between August 2004 and September 2019 inclusively, and the same dunes were identified and correlated based on visual comparison of dunes between successive time slices. This analysis shows the persistence of individual dune ridges and their positions over time (Fig. 7a). Broadly speaking, most dunes throughout the transverse dune system are present in all time periods, and their relationships to adjacent dunes are consistent and sustained with respect to position and spacing. There is greatest spatial variability around the position of a small river channel outlet (Fig. 7a), which sometimes cuts through the dunes but is sometimes absent, allowing dunes to migrate across the dry beach surface. Dune spacing varies somewhat along the transect with wider spacing at the ends of the beach and with dunes closest together in the middle of the beach (Fig. 7b). This pattern is consistent over time. It is also notable that the dunes are farthest apart and also most discontinuous in the area of the beach where bedrock outcrops in the lower intertidal zone, acting as an anchor for the beach system. It is also in this area where deflated bedrock and boulder surfaces are exposed in the troughs between the dune ridges.

Boundary effects imposed by the landward vegetation and the seaward wave processes are likely to influence the long-term behaviour and dynamics of the dunes. As illustrated at Hamburg Nature Reserve in Fig. 8, the migration rates along the length of individual dune crests (between 2016 and 2020) vary, which is not

Fig. 4 (**a**) Analysis of transverse dune migration rates (colour-coded dots, 2016–2020) from Sentinel imagery at Hamburg Nature Reserve (south and north sites). (**b**, **c**) Analysis of the relative positions of individual dunes (**b**, **c** on panel **a**) from Sentinel images of different dates (note different position scales on the *y*-axis). Blue dots reflect winter migration rates, and red dots summer migration rates. Black dashed line, linear regression over this time period; blue dotted line, 95% confidence limits. Seasonal and annual migration rates are given in Table 2 ▶


Crest migration rate (m/yr)
(positive = to NE)
● -18 - -9
● -9 - -3
● -3 - -0.5
● -0.5 - 0.5
● 0.5 - 3
● 3 - 9
● 9 - 18
Fish River Mouth
North site
South site
0 200 m
b
c
a
33°28′S
33°29′S
27°9′E
27°10′E
27°11′E
27°12′E
27°13′E
[SW] Relative position (m) [NE]
0
10
20
30
40
50
60
Jan16
Jan17
Jan18
Jan19
Jan20
b
c
Year


Crest migration rate (m/yr)
(positive = to NE)
-18 - -9
-9 - -3
-3 - -0.5
-0.5 - 0.5
0.5 - 3
3 - 9
9 - 18
Kaysers Beach
0
200 m
b
c
33°13'S
27°36'E
a
[SW] Relative position (m) [NE]
0
5
10
15
20
25
30
35
40
Jan17
Jan18
Jan19
Jan20
b
[SW] Relative position (m) [NE]
0
10
20
30
40
50
60
Jan17
Jan18
Jan19
Jan20
Year
c

◂**Fig. 5** (**a**) Analysis of transverse dune migration rates (colour-coded dots, 2016–2020) from Sentinel imagery at Kaysers Beach. (**b**, **c**) Analysis of the relative positions of individual dunes (**b**, **c** on panel **a**) from Sentinel images of different dates (note different position scales on the *y*-axis). Blue dots reflect winter migration rates, and red dots summer migration rates. Black dashed line, linear regression over this time period; blue dotted line, 95% confidence limits. Seasonal and annual migration rates are given in Table 2

unexpected when considering the slight sinuosity in dune crest line at this site. The spatial variations in crest migration broadly suggest that the seaward parts of the dune ridges move more quickly than the landward parts. Over the 5-year period analysed here, there is evidence to suggest that the landward vegetation boundary has an anchoring effect on the transverse dunes and offers greater resistance to movement than does the beach boundary. In places, it is also observed that the dune crests can split (bifurcate) and reattach over a period of several years, which might be one mechanism that allows for the continued faster migration of the seaward extents relative to their landward extents. Figure 8 also suggests that crest lines can rotate in response to the quicker migration experienced by the more seaward ends of the dunes.

Discussion

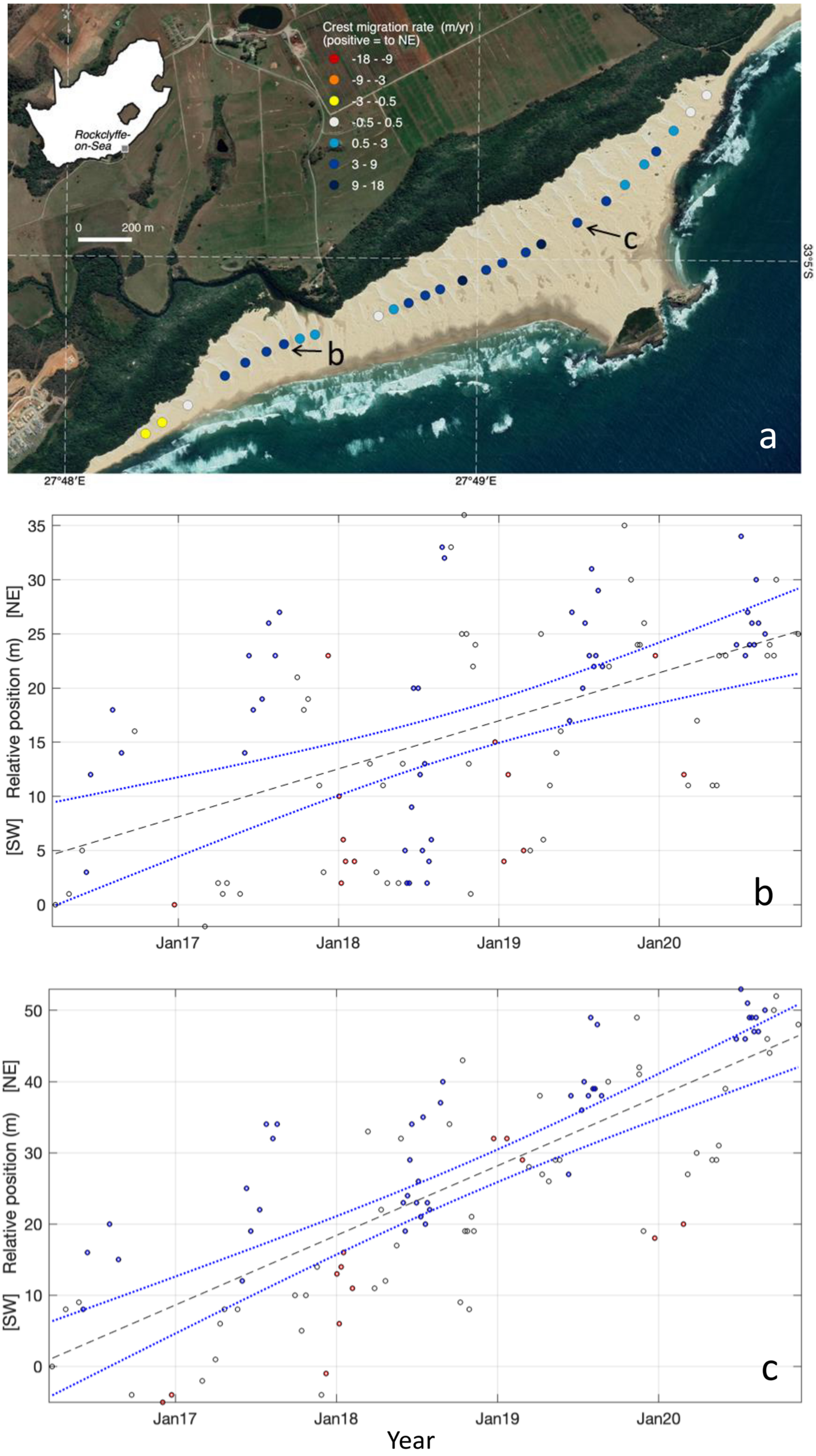
Different elements of dune dynamics such as dune migration rates (Figs. 4–6), dune crest spacing and migration (Fig. 7) and dune crest morphology (Fig. 8) are captured in this study and illustrate consistent patterns of dune dynamics along this coast. Results show that, whilst the underlying beach–backshore systems appear relatively stable, there is a dominant aeolian-driven migration of transverse dunes towards the northeast at all sites, following prevailing wind direction, countered by less dominant movement to the southwest (Figs. 4–6). There are also considerable variations in calculated annual dune migration rates between adjacent systems and between summer and winter seasons (Fig. 3, Table 2). The absence of comparable changes in beach shape and area suggest that, although beach and dune bodies can be conceptually considered as part of the same sediment system, there is not a simple forcing relationship between beach and dune changes. Instead, a primary control appears to be foreshore erosion by waves (e.g. Corbella and Stretch 2012) that reduces the width of the backshore and erodes the seaward ends of transverse dunes, independent of any other changes in sediment supply (Fig. 9).

Transverse dune migration rates

The case studies examined here show relatively consistent interannual transverse dune migration rates (2–6 m year^{-1}) (Fig. 3), which compare well with other studies along the South African coast. For example, Knight and Burningham (2019) showed that transverse dunes at Kaysers Beach have northward interannual migration rates of 3.7–13 m year^{-1}, and annual to decadal rates of 4–12 m year^{-1} (the selected dunes examined at Kaysers Beach in this study (Table 2)) provide a tighter constraint on these values over the equivalent 5-year period to the other case studies. La Cock et al. (1992) reported values of 2.9–9.4 m year^{-1} at the Boknes Strand beach near Kenton-on-Sea (Eastern Cape, #11 on Fig. 1) based on monthly transect values. A notable point is that two ends of the Hamburg Nature Reserve transverse dune system are migrating north at different rates, leading to reduced sediment supply to and therefore thinning of the midsection of the beach system (Fig. 4). Here, the lack of sediment supply to downwind dunes has the result of lowering the backshore surface, making it more vulnerable to wave erosion.

Schumann and Martin (1991) discussed the strong seasonality of dominant wind directions around the South African coast, which are almost parallel to the coastline on the southern and eastern coasts and potentially contributing to the development of transverse dunes. The pronounced seasonal variability in dune migration rates (Table 2) reflects this seasonal wind forcing, and this has been noted in several studies of South African dune systems (Burkinshaw and Rust 1993; Knight and Burningham 2019; Henrico et al. 2020). However, Olivier and Garland (2003) from a beach–dune system adjacent to the Tugela River mouth, 90 km north of Durban, noted that dune activity increases in the winter immediately following sediment transport to the river mouth, brought by high seasonal fluvial discharge the preceding summer. Thus, in this instance, there is a genetic but lagged relationship between fluvial sediment supply to the beach and beach sediment supply to the dunes. This relationship is not observed at Kaysers Beach or Rockclyffe-on-Sea where there are no significant incoming rivers, but the role of other site-scale factors cannot be excluded for other beach–dune systems (e.g. Miguel and Castro 2018).

The dunes are clearly responsive to wind forcing variability at different scales. Short-term shifts in the dominant wind direction force local changes in dune form wherein the crestline can become rounded or flattened, or a reverse slip-face can develop on the crest with the opposite asymmetry of the main dune form.


Crest migration rate (m/yr)
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3 - 9
9 - 18
Rockclyffe-on-Sea
0
200 m
b
c
a
33°5′S
27°48′E
27°49′E
[SW] Relative position (m) [NE]
0
5
10
15
20
25
30
35
Jan17
Jan18
Jan19
Jan20
b
[SW] Relative position (m) [NE]
0
10
20
30
40
50
Jan17
Jan18
Jan19
Jan20
c
Year

◂**Fig. 6** (**a**) Analysis of transverse dune migration rates (colour-coded dots, 2016–2020) from Sentinel imagery at Rockclyffe-on-Sea. (**b**, **c**) Analysis of the relative positions of individual dunes (**b**, **c** on panel **a**) from Sentinel images of different dates (note different position scales on the *y*-axis). Blue dots reflect winter migration rates, and red dots summer migration rates. Black dashed line, linear regression over this time period; blue dotted line, 95% confidence limits. Seasonal and annual migration rates are given in Table 2

These subtle modifications in dune form occur throughout the year, and the reverse migration rates are often simply reflecting the repositioning of the crestline and slip face on what is otherwise a relatively stable dune form. These details are not described in this study. Over the longer term, with persistence of winds from a specific direction, the whole dune form will migrate in an alongshore direction. It may also be the case that smaller transverse dunes, such as those closest to the shore, may appear more dynamic than larger dunes, even under the same net sediment flux, because of their smaller total sand volume.

Dynamics of beach–dune systems

Hitherto, examination of beach–dune systems has focused almost exclusively on foredunes and not transverse dunes (e.g. Sherman and Bauer 1993; Sabatier et al. 2009; Bauer et al. 2012; Walker et al. 2017). However, transverse dunes because they are unvegetated and located in the backshore zone can be considered as a more functionally integrated part of the beach–dune sediment volume when compared to foredunes, which are often functionally dissociated from beach sediment dynamics. Based on the geomorphic patterns identified from the three sites examined in this study, a theoretical model can be proposed that formalises the field relationships between transverse dune and beach systems, linked through concepts of sediment supply, both downstream (by wind transport) and released by wave erosion (Fig. 9). This model starts with the proposition that under constant aeolian sediment availability (assuming a constant beach–backshore width and therefore constant sand flux), it can be anticipated that transverse dunes should have an emergent property of constant spacing and spatially similar patterns of dune crest migration that reflect

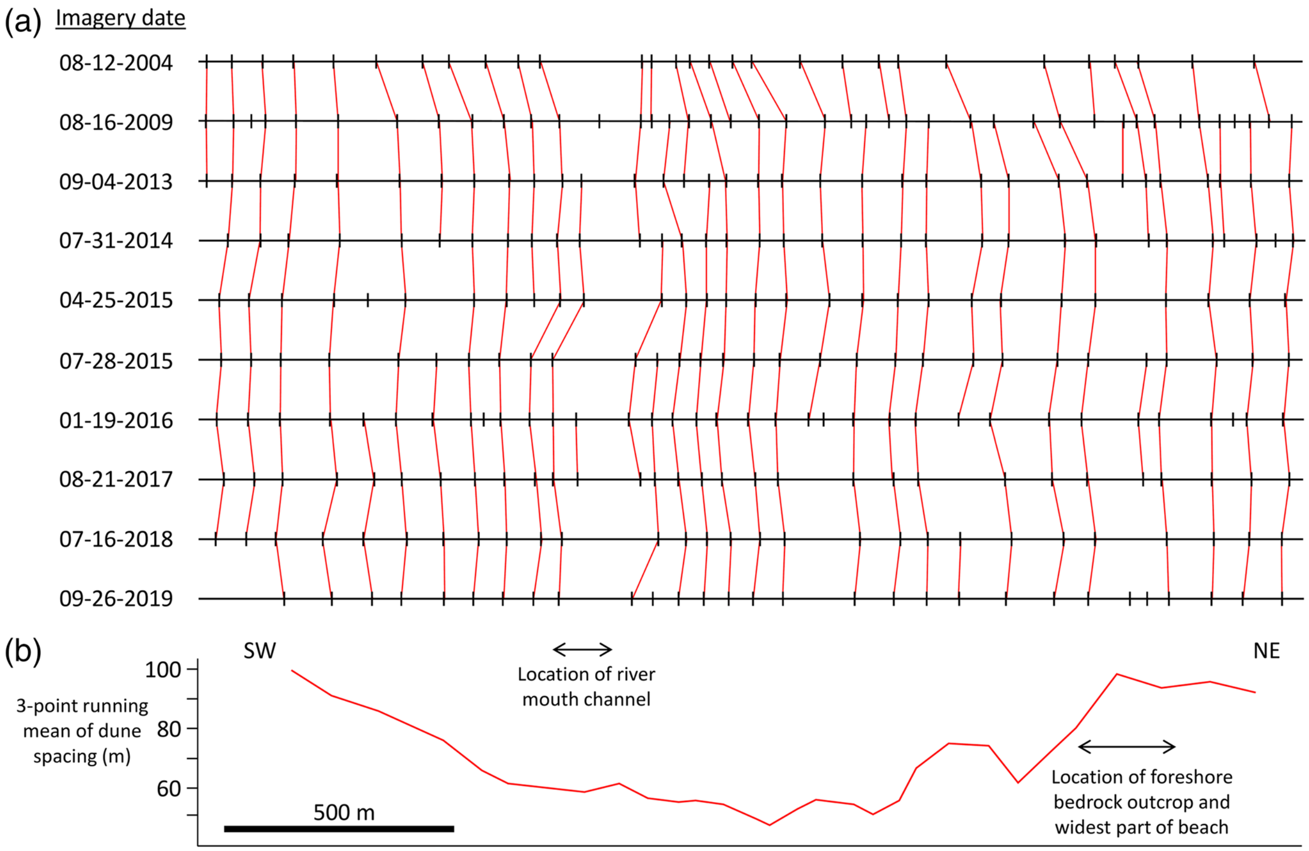

Fig. 7 (**a**) Schematic representation of dune crest migration patterns along a SW to NE transect along the supratidal part of the beach at Rockclyffe-on-Sea. Black ticks mark the positions of ridge crests along the transect observed at each time slice. Individual ridges are traced over time (red lines) based on visual comparison between successive time slices. (**b**) Three-point running mean of dune ridge spacing along the transect (data from 22 September 2020)

Fig. 8 Variation in migration rate along dune crests in the southern sector at Hamburg Nature Reserve, based on the differences in position digitised from Google Earth imagery from August 2016 to July 2020

dynamic steady-state conditions (Pelletier 2009; Yokobori et al. 2020). Irrespective of any changes in wind climate or sediment availability that can give rise to a dune response (e.g. van Dijk et al. 1999; Jiang et al. 2014), changes in supratidal (backshore) beach width result in changes in downflow sediment supply. For example, if the backshore gets narrower downflow, it can be anticipated that this may result in a concentration of sediment flux per unit width, leading to a closer dune spacing that reflects this higher sediment supply (Fig. 9b). (Sediments may also be lost when blown out to sea.) Likewise, the opposite situation, where there is a downflow increase in supratidal width, results in decreasing sediment flux (sediment starvation) and leading to dune ridges becoming farther apart, smaller, with broken or subdued crests, and separated by deflated surfaces of armoured gravel, bedrock or beachrock (e.g. Cooper et al. 2013; Knight and Burningham 2019) (Fig. 9c). Bedrock outcrops of varying sizes are also observed in the lower intertidal zone (e.g. Figures 5, 6). These act as anchors that stabilise the backshore zone (Fig. 9d), the surface of which can rise up towards the outcrop on both sides. Approaching this outcrop from the upflow side results in compression of the boundary layer and enhanced downstream sediment transport (e.g. Jackson et al. 2020); hence, dune ridges become closer together (e.g. Figure 7). Downflow of this position where sediment deposition takes place, dunes become farther apart as a result of sediment starvation, and in many instances, this bedrock outcrop gives rise to enhanced wave attack on each side, also reducing the width of the supratidal zone and thus its accommodation space (e.g. Figure 6).

Within the supratidal zone, transverse dunes may be free dunes, where the entire dune ridge is mobile and unvegetated, or may be partially pinned at their landward ends by a ramp of aeolian sediment (Fig. 2) or by isolated eroded dune hummocks on the supratidal plain (Figs. 2, 4). This yields greater mobility of the dunes at their seaward rather than their landward ends (Fig. 8). In addition, the seaward extent of transverse dunes is determined by high tide position, with waves eroding out its seaward edge. Wave activity focuses in the low elevation troughs between dune ridges (Cooper et al. 2013, their Fig. 4B), giving rise to a scalloped wetted perimeter reminiscent of beach cusps (Fig. 9e). A specific example from Rockclyffe-on-Sea is shown in Fig. 10. Here, winter wave erosion shows how effective wave swash can be in extending far into the troughs between dune ridges, flattening the seaward ends of the dunes, and scarping their leeside slopes. The successive imagery from July to

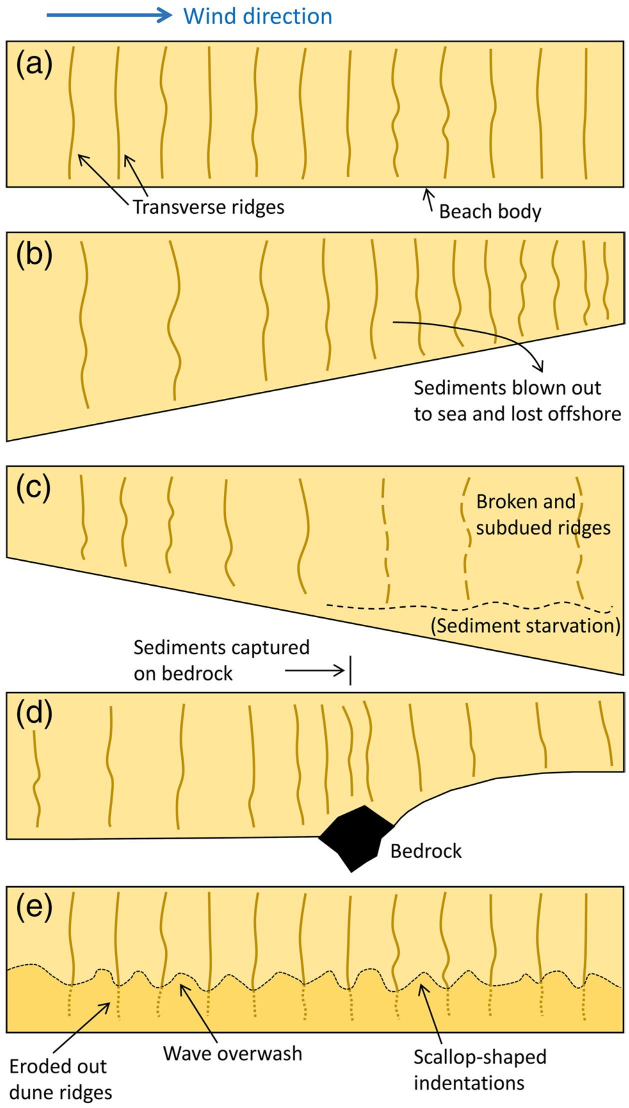

Fig. 9 Schematic model of different geomorphologic relationships between the sandy beach sediment body (yellow-shaded zone) and associated transverse dunes

September 2020 at this site provides evidence of the relative role of waves and wind on dune dynamics at the beach–dune interface. The backshore zone between the active foreshore and permanent dune complex responds rapidly to changes in forcing. Ephemeral, low dunes with wavelengths of the order of 10–15 m form here during periods of enhanced shore-parallel winds, but are efficiently removed by elevated water levels and far-reaching swash during periods of high wave energy. Inundation of the seaward edge of the dune complex allows swash reworking of the lower edges of the dune ridges. As water levels and wave energies diminish, the backshore and seaward parts of the dune troughs become dry, and the low ephemeral aeolian bedforms are quick to reform. This implies that sediment removed by marine processes is efficiently cycled back into the supratidal system through aeolian processes during periods of lower wave energy.

These successive wave and wind events therefore result in dispersal of dune sediments across the fronting beach, removal of dune sediments out to sea with the backwash, and overall reduction in dune length and therefore dune sediment storage. Thus, well-developed transverse dunes that are affected by overwash in the upper intertidal zone can exert an influence on shoreface erosion patterns and in turn longshore sediment supply. This also means that a steeper erosional foreshore is found along midsections of beach–dune margins, with a transitional to net depositional conditions nearer the broadest part of the system (e.g. Xhardé et al. 2011). These considerations therefore illustrate the close genetic link between beach and transverse dune systems through both wind and wave processes that impact on beach–dune sediment dynamics.

Conclusions

Transverse dunes are a key geomorphic element of many sandy beaches worldwide, but their properties and dynamics have not been examined in detail. This study presents evidence for transverse dune morphodynamics from three beach–dune systems in South Africa. The dunes change in orientation, spacing and migration rate as a result of wind-transported sediment fluxes, but also change in length as a result of beach erosion by waves which reworks dune sediments onto the foreshore (and likely out to sea) and also reduces supratidal accommodation space. Transverse dunes are therefore not simply a passive area of aeolian sediment storage in the supratidal zone, but show complex morphodynamic and sediment budget relationships to the wider beach–dune system.

Examination of transverse dunes from the three sites for the period 2016–2020 based on remote sensing data shows averaged migration rates of ~ 3.4–5.2 m year^{-1} for the different dune systems (Fig. 3), but with considerable variability of individual dunes, from – 5 to + 14 m year^{-1}. This highlights the complexity of aeolian dynamics, superimposed on beach–dune systems that are most responsive to wave forcing (Fig. 9). Understanding the co-relationships between dune and beach landforms can yield a better understanding of the sediment dynamics of coastal systems in their entirety, as well as their sensitivity to wind and wave forcing. Future research may include extending the time period of analysis to establish longer-term

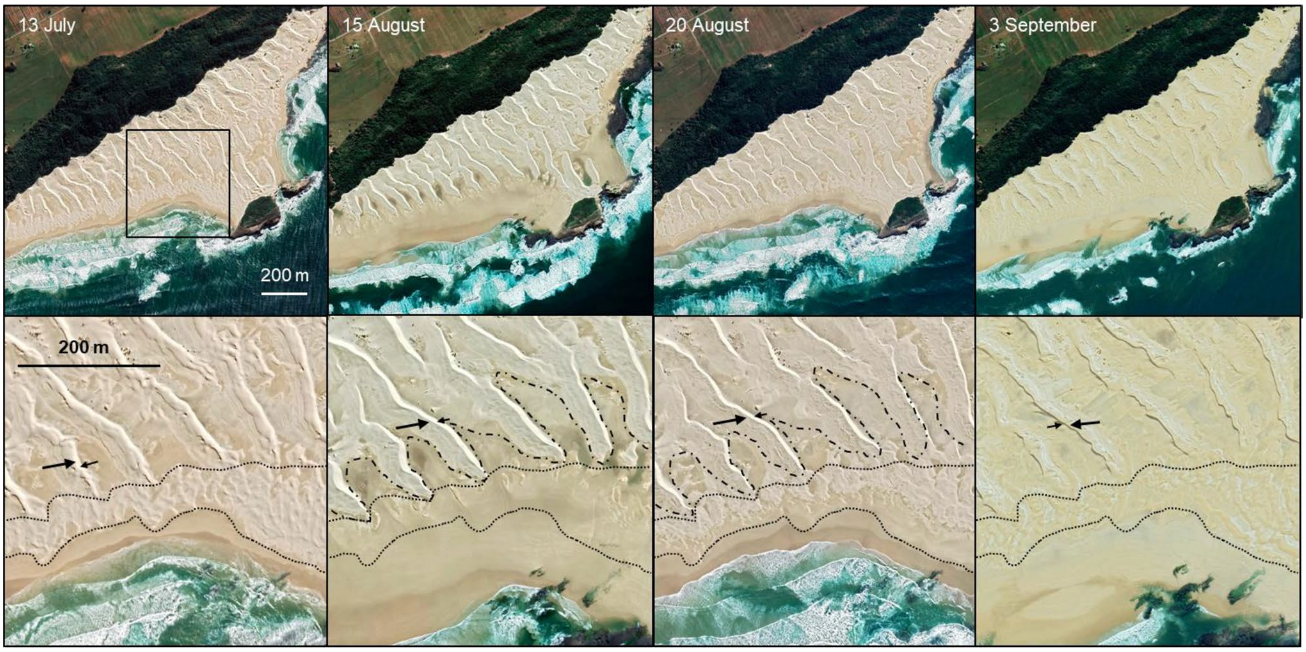

Fig. 10 Changes in the beach–dune interface at Rockclyffe-on-Sea between 13 July and 9 September 2020, derived from Google Earth imagery. Upper panel shows the system-scale, lower panel zooms in on the beach–dune interface and are annotated to show the boundary of the backshore zone that lies between the foreshore and the permanent dune area. Arrow sizes on the dune crests represent the dominant aeolian forcing direction based on asymmetry in the dune form

(decadal) variations in dune–beach systems, including the periodicity of wind and wave climate forcing.

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Declarations

Conflict of interest/Competing interests. The authors declare no competing interests.

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