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8 **Sediment Transport (Dis)Continuity Across a Beach-Dune Profile**
9 **During an Offshore Wind Event**
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ABSTRACT

Flow dynamics and sediment transport responses over a large, vegetated foredune at Prince Edward Island, Canada, during an offshore wind event are examined. Data were collected along an instrumented transect that extended from the dune crest, down the lee-side (seaward) slope of the dune, across a wave-cut scarp, and on to the back-beach. When the wind direction at the dune crest was approximately crest-normal (less than about 15° deviation), mean near-surface flow directions along the dune slope and on the back beach were generally onshore, indicating reversed (onshore) flow relative to the regional (offshore) wind direction. Although flow patterns were consistent with a lee-side recirculation eddy, large excursions in flow direction were also prevalent, suggesting that the eddy was unstable and alternated with highly turbulent wake flow. As wind direction at the crest veered to greater than 20° from crest-normal, lee-side winds shifted toward strongly alongshore flow with minimal directionally variability. On the dune slope, the wind vectors were slightly offshore whereas on the back-beach they were slightly onshore.

Wind speeds and sediment transport were greatest at the foredune crest and declined rapidly downslope due to flow expansion and deceleration in the wake zone as well as to the influence of a sparse vegetation layer. Mean particle counts (averaged over a 15-minute interval) derived from laser sensors positioned at the crest were large (7.76 per second) in comparison to those measured in the immediate lee of the crest (0.52 per second) and farther down the dune slope (< 0.13 per second). In contrast, the values were as large as 25.62 per second on the middle of the back-beach, declining rapidly to a value of only 0.24 per second at the dune toe. Transport intensity was highly variable with the largest Activity Parameter ($AP = 0.5$) values at the dune crest and on the back-beach, and with the smallest values ($AP < 0.1$) on the lee-side dune slope down to the top of the scarp. Calculations of sediment (particle) flux divergence between instrument stations show that deposition was significant

immediately downwind of the dune crest but negligible across most of the lower dune slope.

Deposition was also prevalent on the dune ramp below the scarp.

These results demonstrate that sediment transport across the beach-dune system was spatially discontinuous during this offshore wind event. Rebuilding of the dune ramp at the toe of the scarp occurred quite independently of, and with a different sediment source than, the broadening of the dune crest, which was fed with sediment from the landward side of the foredune. Such process 'decoupling' is an example of the complexity by which foredunes evolve or are maintained, and as with previous research reinforces the importance of offshore and alongshore wind events to beach-dune morphodynamics.

Keywords: foredune change; sediment transport; flux divergence; wind steering; lee-side eddy recirculation

1. Introduction

Considerable effort has been devoted to the understanding of aeolian dunes as equilibrium features that arise intrinsically from the steady state interaction of a moving fluid passing over a deformable bed comprised of non-cohesive sediments (Andreotti et al., 2009; Durán et al., 2010). The characteristics of the fluid (e.g., viscosity, density) and of the flow field (e.g., speed, direction, depth) in combination with the characteristics of the sediment surface (e.g., grain size, mineral density, sorting, roundness, roughness, cohesion) determine the rate of sediment transport and thereby the scale and geometry of the bedform that is likely to exist for a specific set of state parameters. Supporting evidence comes from studies in wind tunnels (e.g., Walker and Nickling, 2002, 2003; Dong et al., 2007) as well as a host of increasingly sophisticated numerical model simulations (e.g., Parsons et al., 2004; Araújo et al., 2013; Durán and Moore, 2013; Furieri et al., 2014) that demonstrate how equilibrium bedforms of varying geometry evolve, migrate, and interact with near-surface flow dynamics. Our conceptual understanding of dune dynamics is heavily pre-conditioned by such a steady state perspective (see comprehensive reviews by Bauer et al., 2013; Walker and Hesp, 2013; Wiggs, 2013), which parallels ideas pertaining to fluvial bedforms (e.g., Venditti, 2013).

In nature, however, the tendency toward equilibrium adjustments between the fluid forcing and morphological response is confounded by a host of inevitable eventualities that disrupt the trajectory toward such idealized states. These include gradual or radical shifts in flow direction and speed, significant alteration of the sediment supply, imposition of new state variables (e.g., vegetation cover, human influence), and loss of climatic stationarity. As a consequence, some geomorphic forms may never be in a state of simplistic equilibrium, but rather in varying states of continuous adjustment that are strongly conditioned by antecedent conditions and the historical sequencing of formative events. Such is the case with coastal foredunes, which are the manifestation of a complex suite of dynamic

interactions among nearshore, terrestrial, hydrologic, biotic, and meteorological processes (Sherman and Bauer, 1993; Bauer and Sherman, 1999; Hesp, 2012; Hesp and Walker, 2013), and in this context, coastal foredunes are very different from their desert counterparts. Coastal foredunes are frequently exposed to radical shifts in wind direction and intensity, subject to basal scarping by waves during storm surge events, and strongly controlled by dynamic interactions with continually changing vegetation assemblages (Hesp, 2002; Hesp et al., 2013).

The wind climatologies of sandy beaches with foredune systems are typically dominated by strong onshore-directed flow events that are critical for directing sand transport toward the dunes, which is important for their evolution and maintenance. Nevertheless, offshore-directed events with substantial sediment transport potential are not unusual and, on many lee-side coasts with prevailing wind patterns, an offshore flow season can dominate the meteorological signal (e.g., Jackson et al., 2011). Nordstrom et al. (1996) noted that the aeolian literature is heavily biased in favour of studies conducted during onshore wind events, and that there was (at that time) a relative dearth of knowledge regarding the importance of offshore flow to coastal dune morphodynamics. Onshore wind events were thought to be the most formative by moving sediment from the foreshore into coastal dune systems, in keeping with our conceptual predisposition for the steady state, equilibrium model. In contrast, offshore flows were perceived to yield relatively minor readjustments to the beach-dune sediment budget by returning sand from the dunes back to the nearshore usually via opportunistic pathways associated with blowouts, pedestrian pathways, and other gaps in the integrity of the foredune crestline (Gares et al., 1996; Nordstrom et al., 1996).

In the past decade, a series of papers describing wind flow over coastal foredunes at Magilligan Strand (Northern Ireland) and the Greenwich Dunes (Prince Edward Island, Canada) have yielded

significant insight into flow steering and topographic forcing (e.g., Walker et al., 2006, 2009; Jackson et al., 2011; Bauer et al., 2012; Delgado-Fernandez et al., 2013; Lynch et al., 2009; 2010; 2013; Hesp et al., 2009, 2015). In particular, these field experiments demonstrated that offshore flow can be substantially modified in the lee of a large coastal foredune, to the extent that shore-parallel steering and eddy recirculation occurs on the beach (Lynch et al., 2008; Bauer et al., 2012) as recognized by Hesp (2005). Using sonic anemometry and electronic sediment traps, Lynch et al. (2009) showed that sand transport can be directed onshore across the back beach, due to lee-side eddy recirculation, leading to accretion at the base of the foredune whilst upper air vectors were persistently offshore. These measurements are consistent with the observations of Hesp (2005) near Castlepoint, New Zealand, regarding the likely origin of climbing dunes along that coast. Subsequent studies by Walker et al. (2006, 2009), Jackson et al. (2011; 2013), Lynch et al. (2013) and Delgado-Fernandez et al. (2013) using 3D ultrasonic anemometry and computational fluid dynamics have reaffirmed the existence and importance of the lee-side recirculation eddy at the base of the foredune during regional offshore wind conditions and have provided detailed insight into the character of turbulence and the nature of corkscrew vortices that occupy the back-beach region. This work complements research on flow deflection and sand transport divergence over transverse desert dunes (e.g., Walker, 1999; Walker and Nickling, 2002; Walker and Shugar, 2013).

The purpose of this paper is to contribute to our expanding knowledge on the potential importance of offshore flow conditions to the long-term maintenance and evolution of coastal foredunes. Specifically, we report on a three-hour period of regional offshore wind during which wind velocity and sediment transport data were collected along an instrument transect that extended from the dune crest, down the lee-side (seaward) slope, and on to the back-beach. The study reveals the changing nature of flow modification and sediment transport intensity at several stations across the

dune slope, which complements earlier studies that focused mainly on the beach below the dune slope. We also demonstrate how sediment (particle) flux divergence contributes to sedimentation patterns that simultaneously build and broaden the crestal region and reconstruct the sand ramp at the base of the foredune as independent (decoupled) processes with different sediment sources. The standard conceptual model of sediment transport across a coastal foredune imagines sediment pathway continuity regardless of wind approach angle whereas our data indicate that pathway discontinuity and process decoupling are also normal modes of system response. The relative importance of (dis)continuous transport pathways is in need of investigation if we are to fully understand foredune evolution and maintenance.

2. Experimental Design

Measurements were taken during a field experiment conducted at Greenwich Dunes, Prince Edward Island National Park, Canada, which comprises a 5 km-long beach and foredune system facing the Gulf of St. Lawrence (Fig. 1A). The morphologically simple foredune is 8-10 m high with a mildly undulating crest and steep seaward (22°) and landward (20°) slopes. The beach is gently sloping (approximately 4°) with an average width of about 30-40 m. Median grain diameter across the beach-dune profile varies from 0.25 mm to 0.35 mm depending on location. Prevailing winds are offshore from the south-west and west-south-west, although cyclonic disturbances produce strong winds from the north. Aeolian sand transport occurs primarily with oblique winds from the north-west or north-east rather than with shore-perpendicular northerly winds because wave set-up and storm surge driven by onshore winds often inundate the back-beach (Bauer et al., 2009; Delgado-Fernandez and Davidson-Arnott, 2011; Hesp et al., 2013).

FIGURES 1A AND 1B HERE

Fig. 1. (A) Study site location; (B) Topographic profile and instrument positions (see text for explanation).
Inverted triangles (squares) indicate 2D (3D) sonic anemometers.

The experimental site was surveyed using a Leica 1200 RTK differential GPS with a base station set up over an established benchmark about 1 km away. Wind flow and sediment transport were measured along a profile line from the beach to the dune crest (Fig. 1B). A wave-cut scarp at the base of the foredune was partially in-filled through the creation of a dune ramp, but it remained unvegetated at the time of the experiment. The scarp crest and entire seaward slope of the foredune to the crest had a continuous cover of marram grass (*Ammophila breviligulata*) of varying density ranging from 12 to 24% with a mean cover of 15% (average height of 0.25 m). Instrument clusters were located at ten stations spaced along the profile (Figure 1B). Wind flow was measured with R.M. Young cup anemometers and Gill 2D Windsonic and 3D Windmaster sonic anemometers all with analogue DC voltage outputs sampled at 1 Hz. Two towers were situated at Station 1 (St 1) on the beach and at Station 10 (St 10) on the dune crest, and each tower supported a 2D sonic anemometer (height of 3.815 m and 3.64 m for the beach and crest, respectively). Flow conditions close to the ground (0.2 m) were measured using 3D sonic anemometers at St 1, St 3, St 7 and St 10, covering the beach, dune ramp, mid stoss slope and dune crest, whereas the remaining stations (St 2, St 4, St 5, St 6, St 8 and St 9) had single 2D sonic anemometers. The instrument line and cross-sectional profiles were aligned parallel to magnetic north to within $\pm 1.5^\circ$. A frame of reference was adopted that has a clockwise azimuth system with 0° indicating offshore (southerly) flow, 90° indicating alongshore flow (from the west) and 180° signifying onshore (northerly) flow (see Bauer et al., 2012 for additional details). A simple arithmetic averaging approach was used for this data set, which was characterized by predominant flows from the south to south-west. For anemometer positions and time periods that had significant onshore flow components, a transformation to a 360° azimuth system was applied in order to handle the discontinuity spanning the onshore direction (i.e., 179° to -179°), which would yield unrealistic averages. The mean azimuth values

were then transformed back to the original reference framework. A mast of 12 Rimco mini-cup anemometers was utilized as a roving mast and occupied all stations at various times throughout the experiment to provide information on the vertical velocity profile. Cups were positioned at 0.08 m, 0.18 m, 0.27 m and then at 0.10 m spacing up the mast. Non-recording, micro wind vanes were installed at select locations across the dune slope to assist in defining the extent of flow separation as well as the overall flow steering patterns. A line of fine (0.8 mm) erosion pins were placed immediately adjacent to the instrument transect at 1-m intervals extending from the foredune crest down to the beach. Changes in surface elevation were measured with a steel ruler and are accurate to 1 mm.

Sand transport intensity was measured using Wenglor (model # YH08PCT8) Laser Particle Counters (LPCs) with 80 mm path lengths and a beam width of 0.6 mm, giving a nominal cylindrical sampling volume of 48 mm³ with the long axis oriented alongshore. This type of sensor was first deployed for aeolian research by Davidson-Arnott et al. (2009), and its performance has been evaluated in detail by many others (see Barchyn et al., 2014 and references therein). An LPC was positioned at each of the ten stations at a nominal height of 1.4×10^{-2} m. The LPC data series are presented as counts per second (# s⁻¹), also referred to as sediment 'particle' flux rather than sediment mass flux (kg s⁻¹) or volume flux (m³ s⁻¹) because of uncertainties associated with conversion algorithms. Barchyn et al. (2014; their Fig. 7) demonstrated that predicted mass flux from LPC (Wenglor) particle counts is strongly correlated with mass flux measurements from integrating traps under carefully controlled conditions in a wind tunnel, but that there can be differences up to a factor of about 3. Thus, we have confidence in our use of LPC data as reliable indicators of general sediment transport dynamics in a relative sense (because sensor performance is stable and repeatable) but not as accurate predictors of mass flux in an absolute sense (because of conversion uncertainties).

3. Results

3.1. Time Series of Wind and Sand Transport

Meteorological conditions for most of May 2, 2010 were sunny and warm, yielding a relatively dry surface conducive to sand transport. Figs. 2 and 3 show trends in wind speed and direction, respectively, between 13:30 and 16:30 at several instrument locations across the beach and dune. The wind speed time series (Fig. 2) indicate that there was a subtle increase in mean speed at around 14:30 toward peak speeds at around 15:30, followed by a gradual decline through late afternoon. The crest tower anemometer recorded five-minute mean speeds of between 6 ms^{-1} to 9 ms^{-1} , although extreme gustiness yielded instantaneous (1 Hz) excursions from 2.5 ms^{-1} to more than 12 ms^{-1} . At the base of the crest tower (St 10), wind speed was reduced to mean values ranging from about 4.5 ms^{-1} to 7 ms^{-1} although some gusts were of similar magnitude as at the top of the crest tower. The mast of mini-cup anemometers indicated that localized jet flow (speed bulge) was present at 0.25 to 0.30 m above the bed. The coincident wind direction time series (Fig. 3) for the crest tower shows that the flow was oriented almost perfectly offshore (southerly) at the start of the measurement interval, veering slightly to the southwest to a maximum of about 35° by 16:15. At the dune crest surface (St 10), wind direction varied from -15° (south southeasterly) to $+15^\circ$ (south southwesterly), essentially crest normal flow for the duration of the period, indicating a localized, topographically-forced steering effect that constrained the near-surface flow to a crest normal orientation (cf., Hesp et al., 2015). Wind gusts forced small deviations from these mean directions with instantaneous excursions less than about $\pm 20^\circ$. Two large spikey periods in the crest tower time series are due to data processing nuances for those brief periods when the wind vector backed across the $0\text{-}360^\circ$ threshold of the anemometer—they are not indicative of complete flow reversals as much as of exceptionally gusty periods.

FIGURES 2 and 3 HERE (aligned side-by-side)

Fig. 2. Wind speed (m s^{-1}) time series for the 3-h measurement interval at selected stations across the beach-dune profile. Black lines show 1 Hz data; white lines show 5-min running mean.

Fig. 3. Wind direction ($^{\circ}$) time series for the 3-h measurement interval at selected stations across the beach-dune profile. Black lines show 1 Hz data; white lines show 5-min running mean.

As would be expected for offshore flow conditions over a large foredune, wind speed in the lee of the crest (seaward slope) was greatly reduced. The micro cup anemometers and wind vanes (not shown) suggested that the thickness of the separation envelope was about at 0.5 m at St 9, 1.0 m at St 7, and 2.7 m at St 5, indicating progressive expansion in the downwind direction to at least the upper back-beach zone. At St 8, on the upper dune slope, the near-surface mean (five-minute) wind speed was consistently below 3 ms^{-1} and rarely did gust excursions yield values greater than 5 ms^{-1} (Fig. 2). Such reduced wind speeds persisted down the lee-side slope to the back-beach (St 4). Note that that this downslope flow deceleration is partly attributable to the drag imposed by the vegetation layer because the anemometers, positioned at 0.2 m above the ground, were at the top of the plant canopy.

At St 1, located on the back-beach, wind speed increased slightly, especially after 14:45, with peak mean wind speed approaching 4.5 ms^{-1} and gusts yielding excursions up to 10 ms^{-1} (Fig. 2). The beach tower anemometer (at 3.815 m) measured values similar to those close to the beach surface (at 0.2 m). This absence of a normal velocity profile structure (i.e., increasing speed higher in the boundary layer) indicates that the top of the beach tower was largely immersed in the lee-side recirculation eddy, consistent with the thickness of the eddy measured at St 5. The wind direction time series shown in Fig. 3 reveal that the stations on the lee-side (seaward) slope of the dune and on the back-beach show two distinctly different response patterns prior to and after about 14:30. When the crest tower wind direction was less than about 15° from crest-normal, large excursions in flow direction characterize the time series for stations downwind of the crest, even at the top of the beach tower. These directional excursions spanned all compass bearings, which is indicative of rapidly reversing, unstable flow regimes

as would be found in a highly turbulent wake zone. Although the 5-minute mean values during these periods cannot be interpreted with great confidence, it is noteworthy that the mean flow direction for the lee-side stations was generally onshore indicating frequent near-surface flow reversals. In contrast, when the wind direction at the crest tower exceeded 20° (after 14:45), the time series at each of the instrument stations on the foredune slope and back-beach became less directionally variable (see Fig. 3). Specifically, the mean values remained steady in the alongshore direction for the duration of the measurement interval despite periodic excursions in instantaneous flow direction.

Fig. 4 presents time series of particle counts from the LPC positioned at St 10 with the mean wind speed time series from the co-located sonic anemometer (from Fig. 2). There was a close correspondence between sediment transport intensity and wind speed, with most of the transport spikes aligning well with peaks in wind speed. The period between 14:30 and 15:30 had the greatest transport overall, associated with stronger sustained wind speeds. Given offshore wind conditions, such a general association was to be expected for the dune crest location. At other locations on the foredune and back-beach (not shown) the transport was very small prior to about 14:45, after which it became quite intense especially at St 1 and St 2.

FIGURE 4 HERE

Fig. 4. Particle count ($\# \text{ s}^{-1}$) time series for the 3-h measurement interval at the dune crest. For reference, the 5-min mean wind speed is included.

3.2. Spatial Trends in Wind and Sand Transport

Spatial trends in wind and sand transport based on 15-minute averages were plotted according to instrument position across the dune. Fig. 5 shows results for the interval between 15:17 and 15:32, which corresponds to a period of large wind speed and intense transport flux, especially on the back-

beach. Other periods (not shown) are similar in the overall spatial pattern with proportionately lesser values of wind speed and transport flux. Mean wind speed was greatest at the dune crest with rapid decreases immediately in the lee of the crest. For most of the seaward slope of the foredune (St 9 to St 5), mean wind speeds of approximately 2 ms^{-1} were recorded whereas below the scarp and seaward (St 2) mean speed increased to about 4 ms^{-1} . As before, there was virtually no difference in mean speed between the beach tower anemometer (at 3.815 m) and the St 1 surface anemometer (at 0.2 m) directly below.

FIGURE 5 HERE

Fig. 5. Spatial trends in mean wind speed (upper panel), mean wind direction (middle panel), and mean particle count (lower panel) across the beach-dune profile for the 15-min interval between 15:17 and 15:32. Dune crest (St 10) is on far left, whereas the back-beach (St 1) is on far right. Filled triangles provide data from anemometers on top of the instrument towers; circles correspond to near-surface anemometers; crosses correspond to LPCs at 14 mm above the sand surface (note logarithmic axis for mean particle count). The dune scarp was located at 10 m from the dune crest, which separates obliquely offshore (dune slope) from obliquely onshore (back-beach) flow regions.

During this 15-minute interval, the crest tower anemometer (at 3.64 m) measured obliquely offshore flow at an angle of 32° whereas the surface flow (at 0.2 m) was 9° (Fig. 5; middle panel). In the lee of the crest, the wind (at 0.2 m) was topographically steered to alongshore from between 60° - 90° along the seaward slope of the foredune, which indicates only a weak offshore flow component directed toward the beach. However, below the scarp on the dune ramp and back-beach (St 4 - St 1) there was a weak onshore component of flow (97° - 109°) close to the sand surface, while the beach tower anemometer registered slightly offshore flow (64°). These spatial trends in wind speed and direction will force corresponding sediment transport responses across the foredune (Fig. 5; lower panel).

At the surface of the dune crest, the mean particle count was 7.76 per second averaged over the 15-minute interval. Fig. 4 showed that peak instantaneous (1 Hz) values approached 300 counts per

second, which is below the saturation threshold described by Barchyn et al. (2014) as a potential confidence-limiting condition on the LPC measurements. Despite a relatively small mean flux, there were periods of energetic saltation creating large transport intermittency. Immediately in the lee of the crest, mean particle counts per second decreased to 0.52 (St 9), 0.13 (St 8), 0.06 (St 7), 0.03 (St 6), and 0.01 (St 5), with total particle counts summed over the 15-minute interval of only 470, 115, 57, 24, and 12 at St 9 through St 5, respectively. In contrast, the total particle count at St 10 was 6,985. The very small particle counts on the lower slope of the foredune (St 7 to St 5), spanning a cross-shore distance of approximately 5 m, indicates that there was very little sand transport locally during this otherwise intense transport period, consistent with the reduced wind speeds on the lower slope (upper panel, Fig. 5). Somewhat larger total particle counts at St 9 and St 8 are likely due to sand grains launched from the crest region at St 10 being deposited in the wake zone immediately to leeward of the crest (e.g., Hunter, 1985; Anderson, 1988; Nickling et al. 2002; Hesp et al., 2013).

At the base of the scarp (St 4), sediment transport was minimal with a mean particle count of 0.24 per second and a total of only 215 counts over the 15-minute interval. Transport intensity increased rapidly with distance from the dune foot toward the foreshore: 0.58 counts per second (522 total) at St 3; 12.52 counts per second (11,265 total) at St 2; and 25.62 counts per second (23,057 total) at St 1. Note that the value for St 1 is the average of six LPCs deployed in a short horizontal array at the same distance from the dune as St 1, and even though there was variation among these six LPCs (ranging from 10–44 counts per second for the 15-minute mean), the 'ensemble' mean of 25.62 counts per second is thought to be the most reliable estimate of true transport intensity at St 1.

Fig. 6 shows values for the Activity Parameter (AP), a variant of transport Intermittency (Stout and Zobeck, 1997) proposed by Davidson-Arnott et al. (2012), for three 15-minute intervals as measured

by LPCs located at each of the instrument stations from the dune crest to the back-beach. A large AP value (close to a maximum of 1) indicates essentially continuous transport in time whereas a small AP value (close to the minimum of 0) indicates only occasional transport interspersed with dominant periods of transport quiescence (Bauer and Davidson-Arnott, 2014). The spatial pattern in AP was similar for the entire 3-hour measurement period, with larger AP values (up to 0.5) at the dune crest and on the back-beach. In contrast, the zone extending from the lee of the crest (St 9) down to the top of the scarp (St 5) displayed minimal transport activity with AP values less than 0.1 and often approaching zero, consistent with the very small particle counts registered at these locations. In combination, these results (Figs. 5, 6) indicate that there were two active transport zones (dune crest; back-beach) separated by a region of minimal transport activity and small particle counts on the dune mid-slope, which suggests that transport processes on the crest and the back-beach were effectively decoupled. Similar process decoupling was documented by Davidson-Arnott et al. (2012) at the same site for a 16-h wind event with dominantly obliquely onshore flow directions, suggesting that spatially segregated transport responses might be a common occurrence on complex beach-dune profiles. This draws into question the continuous nature of sediment transport pathways that are thought to connect the back-beach and foredune during sand-transporting events.

FIGURE 6 HERE

Fig. 6. Spatial trends in sediment transport Activity Parameter across the beach-dune profile for three 15-min intervals beginning at 14:45, 15:00, and 15:17.

3.3. Cross-Shore Sediment Particle Flux

Wind direction data were used to calculate the sediment particle flux in the cross-shore direction (q_c) as follows:

$$q_c = q_T \times \cos\alpha \quad (1)$$

where q_T is the total particle flux ($\# s^{-1}$) measured by an LPC and α is the wind angle relative to shore-normal measured by the sonic anemometer co-located with the LPC. In essence, this transformation assumes that sand particles generally move in the same direction as the wind. Admittedly this is an oversimplification that neglects slope effects, but in such a first-order analysis (in the absence of actual transport vectors), the directional information in the wind vector can be used to decompose the flux vector into the cross-shore ($\cos\alpha$) and alongshore ($\sin\alpha$) components. Cross-multiplication of the q_T and α time series was performed on the instantaneous (1 Hz) data without time lags since the instruments were closely spaced. Invoking time lag schemes of up to several seconds has minimal consequences for the gross patterns of transport because the phase relationship between peak transport events and wind direction is relatively stable during sustained gusts when transport activity is most pronounced (Davidson-Arnott and Bauer, 2009; Bauer and Davidson-Arnott, 2014). As a consequence, slight phase lags may yield slight differences in sediment flux but not in the overall cross-shore transport direction. Note also that the wind speed magnitude (i.e., wind strength) is not used in the calculations explicitly because wind speed is already dynamically embedded in the LPC-based flux measurements. It is the directionality of the transport flux that is estimated by application of Equation 1.

Fig. 7 shows cross-shore particle flux (q_c) time series for the interval between 15:17 and 15:32 at the dune crest (St 10) and in the immediate lee of the crest (St 9 and St 8). The traces are very spiky with short periods of intense flux separated by long periods of no transport. This is especially the case for St 9 and St 8, although there was an evident increase in transport activity (AP values) toward the

crest. At the crest (St 10), the AP value was 0.45 (see Fig. 6) indicating that the transport system was inactive for about 55% of the time. Peak cross-shore flux values at the crest approached 300 counts per second whereas at St 9 they were of the order of 20 counts per second and at St 8 they were down to 3 counts per second. Notably, virtually all sediment transport at each of these stations was directed offshore (downslope toward the beach). At St 10, for example, a summation of cross-shore flux ($\sum q_c$) yields a value of -6,717 counts for the 15-minute interval in comparison to a total particle count ($\sum q_T$) of 6,985 registered by the LPC during that time period. Because negative values indicate offshore-directed transport (positive values indicate onshore-directed transport), the net proportion of the total flux that was offshore-directed at this location was 96%. The ratio $\sum q_c / \sum q_T$ will always be less than 100% unless all transport is exclusively either directly offshore (negative) or onshore (positive). Note that the cosine factor in Equation 1 yields fractional particle counts (rather than integer counts) and therefore $\sum q_c$ is a complex quantity to interpret. Specifically, a small value of $\sum q_c$ close to 0 may indicate either (i) a balance between offshore- and onshore-directed transport events that cancel each other in the summation or (ii) dominantly alongshore transport for which the onshore or offshore component of flux is negligible in relation to the total particle flux. In contrast, a large value for the ratio $\sum q_c / \sum q_T$ implies a significant cross-shore transport tendency, either offshore (negative) or onshore (positive). At St 9, $\sum q_c$ was -326 counts in comparison to a $\sum q_T$ of 470 counts (-69%), whereas at St 8, $\sum q_c = -76$ counts and $\sum q_T = 115$ counts (-66%).

FIGURES 7 and 8 HERE (above and below)

Fig. 7. Cross-shore particle flux time series (1 Hz) for the 15-minute interval beginning at 15:17 at the crest (St 10) and in the immediate lee of the crest (St 9, St 8). Note that virtually all transport is directed offshore (downslope), and that the vertical scale for St 10 is 10 times greater.

Fig. 8. Cross-shore particle flux time series (1 Hz) for the 15-minute interval beginning at 15:17 on the back-beach (St 1), dune ramp (St 2) and base of scarp (St 4). Note that most of the transport is directed landward (toward the dune toe), although there are periods of significant offshore transport.

Fig. 8 shows the cross-shore particle flux at the back-beach stations (St 4, St 2 and St 1). The St 3 anemometer was inoperative at this time, so it was not possible to calculate the cross-shore flux from the LPC data at that location. At St 1, approximately 10 m seaward of the dune scarp, the cross-shore flux varied between onshore- and offshore-directed events with peak magnitudes of approximately 100 and -50 counts per second, respectively. The absolute magnitude of these transport events was smaller than those on the dune crest even though the overall transport intensity was much greater at St 1 ($\sum q_T = 23,057$ counts at St 1 versus $\sum q_T = 6,985$ counts at St 10). At St 1, $\sum q_C = 3,059$ counts, which accounts for only 13.2% of $\sum q_T$ but indicates a preponderance of onshore-directed transport events. At St 2, most of the transport was directed onshore ($\sum q_C = 3,821$ counts; $\sum q_T = 11,265$ counts) with similar peak magnitudes as at St 1, but with fewer events directed offshore ($\sum q_C / \sum q_T = 34\%$). In contrast, at St 4 on the dune ramp leading to the scarp, there was very little transport overall ($\sum q_T = 215$ counts) with the net flux ($\sum q_C = 12.4$ counts) directed onshore (5.8%).

Video imagery taken during the measurement period indicates that sediment moved alongshore over the beach in the form of intermittent clouds of saltating sand grains. The long axes of these clouds were oriented transverse to the wind direction and the general dimensions of these roller-like transport structures were about 0.2 m vertically, 5 m flow-wise, and 25 m span-wise (i.e., extending from the wet upper foreshore to the dry dune ramp at the dune toe). They were not longitudinal streamers as described by Baas and Sherman (2005), which are linear features extended in the stream-wise direction but instead took the form of span-wise wave crests moving along the beach from north to south with a mildly oblique-onshore drift. Surface ripple patterns confirmed the dominantly alongshore, obliquely onshore transport direction of these saltation waves.

3.4. Flux Divergence and Sediment Deposition

The data on cross-shore particle fluxes presented in Figs. 5-8 indicate where sand transport was most active across the beach-dune profile as well as whether the net transport was onshore or offshore. However, if we are to understand foredune profile change, it is more important to know where sediment will be deposited and where it is sourced. The Exner equation is a variant of the sediment continuity relation (Paola and Voller, 2005), and the generalized form is,

$$\frac{\partial h}{\partial t} = - \frac{1}{(1-p)} \nabla \cdot q_s \quad (2)$$

where h is elevation of the bed, t is time, p is sediment porosity, and q_s is sediment (volume) flux. The equation shows that changes in bed elevation through time are proportional to the sediment flux divergence (i.e., spatial gradients in flux rather than the absolute magnitude of flux at one location). From this, it is possible to predict where sediment should have been eroded or deposited depending on the sign and magnitude of the flux divergence term. For our one-dimensional analysis of cross-shore transport using LPC-derived particle fluxes, this requires calculation of dq_c/dx for sets of neighbouring stations, where dq_c is the **difference** in cross-shore particle flux between stations i and j , and dx is the spatial separation distance between i and j . The horizontal distance rather than the slope distance was used because the intent was simply to understand, in relative terms, where sediment erosion and deposition took place rather than to quantify the actual amount of bed elevation change.

Fig. 9 presents time series of particle flux divergence for neighbouring stations extending from the dune crest to the mid-slope location. The upper panel shows flux divergence between the station on the dune crest (St 10) and in the immediate lee of the crest (St 9), separated by a distance of only 1.5 m, and it demonstrates that there should have been significant particle accretion in this zone. The maximum accumulation rate was almost 200 particles per second per meter length of profile (at about

15:25), but more typically the rate was a few dozen particles per second per meter. Immediately downslope between St 9 and St 8, there was also positive flux divergence (i.e., accretion) but with peak values of only 10 particles per second per meter or less, and a few instances of instantaneous erosion (negative flux divergence). In the zone between St 8 and St 7, which is less than 5 m from the dune crest, the flux divergence values were negligible (less than 2 particles per second per meter), although there was still a net tendency for accretion. This trend of negligible flux divergence persisted all the way down the slope to the scarp region (not shown in Fig. 9). The erosion pin data corroborate these predicted trends in surface change. The pin situated 1 m seaward of the crest line measured accretion of about 5 mm over the entire day, and at 2 m seawards there was net erosion of 1 mm (within the error margin), with negligible change on the remaining pins on the lower dune slope.

FIGURES 9 and 10 HERE (above and below)

Fig. 9. Particle flux divergence time series (1 Hz) showing the propensity for sediment deposition or erosion between pairs of instruments in the dune crest region. Note different vertical axis scales.

Fig. 10. Particle flux divergence time series (1 Hz) showing the propensity for sediment deposition or erosion between pairs of instruments on the back-beach and dune ramp region. Note different vertical axis scales.

Fig. 10 shows flux divergence patterns on the back-beach from just above the scarp (St 5) to the most seaward station (St 1). The stations that span the scarp (St 5 and St 4) yielded very little flux divergence and no obvious trends in accretion or erosion. However, the dune ramp between St 4 and St 2 showed a clear tendency for accretion with peak values ranging from 10-20 particles per second per meter of profile. Short periods of instantaneous erosion were few and far between. On the back-beach (St 2 to St 1), values of flux divergence were relatively large but seemingly balanced between accretion and erosion.

In order to determine whether there would have been net deposition or erosion in each of the zones between the instrument stations over the entire 15-minute measurement interval, the instantaneous (1 Hz) cross-shore particle flux divergence time series (Figs. 9, 10) were integrated through time. Fig. 11 shows the spatial trends in predicted net particle accumulation from the dune crest to the back-beach. Immediately in the lee of the dune crest, there was a zone of significant net accumulation with up to 4,260 particles deposited per meter length of cross-shore dune profile. The source for this sediment was from the landward face of the dune, which is normally a deposition zone during onshore wind events. Only a short distance (less than 2 m) from St 10, the tendency for net accumulation decreased to 139 particles per meter (between St 9 and St 8) and then to 29 particles per meter (between St 8 and St 7). Farther downslope, the values were less than 10 particles of accumulation per meter length of dune profile over the 15-minute interval, which reaffirms the general absence of sedimentary response over a large portion of the stoss slope, extending down to the bottom of the scarp. The dune ramp (between St 4 and St 2) was another zone of substantial particle accumulation with 644 particles per meter of profile length. However, this sediment was derived from the back-beach zone between St 2 and St 1, which experienced net erosion (-201 particles per meter). Presumably the lower beach and wet foreshore would have displayed dominantly erosional tendencies in order to provide the sediment supply to the dune ramp, but there are no measurements to verify this assumption. At a distance beyond the reattachment point, the wind and transport direction would begin to align with the offshore regional wind.

FIGURE 11 HERE

Fig. 11. Spatial distribution of net sediment particle accumulation (per m of profile length) across the beach-dune profile.

4. Discussion

Our current understanding of coastal foredune evolution and maintenance derives largely from observations of topographic profile changes measured over periods of weeks to years (e.g., Hesp, 1988, 2013; Ruz and Allard, 1994; Arens, 1996; Davidson-Arnott and Law, 1996; McLean and Shen, 2006; McLean et al., 2010; Mathew et al., 2010; Ruggerio et al., 2011; Ollerhead et al., 2012; De Jong et al., 2014). Supplemental knowledge comes from detailed measurements of wind flow patterns across transverse dunes in wind tunnels and field situations, typically in desert settings, but with a relative dearth of information on precise sediment pathways. Sophisticated numerical models have also been used to simulate dune evolution and migration under steady-state regimes, but rarely in regard to coastal foredune systems (c.f., Durán and Moore, 2013), which are characteristically complex and unwieldy systems to model. Field studies that quantify transport patterns across an entire coastal foredune profile are few in number, and therefore are limited in the insights they provide across the range of meteorological and biophysical conditions that lead to foredune evolution or maintenance. Ours is the first study to assess the spatial patterns of sediment flux divergence across the stoss slope of a vegetated foredune in an attempt to understand where erosion and deposition are most likely to occur during a single transport event.

For the 3-hour measurement interval in this experiment, there was sustained regional offshore flow as indicated by the crest tower anemometer and by the near-surface anemometer at the dune crest. Topographic steering of the near-surface flow field was prevalent. Lynch et al. (2009; 2010), Bauer et al. (2012), Delgado-Fernandez et al. (2013) and Jackson et al. (2013), building on ideas about flow over desert dunes (e.g., Sweet and Kocurek, 1990; Frank and Kocurek, 1996; Walker and Nickling, 2002; Walker and Shugar, 2013), suggest that when offshore flow is crest normal, a persistent recirculation eddy will form in the lee of the dune, with flow reattachment occurring somewhere on the

beach. Near-surface return (onshore) flow should then be found across some portion of the seaward facing slope of the dune. Our data from the seaward side of this coastal foredune are consistent with these ideas, and the character of flow in this recirculation eddy was typically highly turbulent with rapidly reversing flow directions, as noted by Lynch et al. (2010) for their field site. The point of reattachment extended at least to St 1 on the back-beach, at a horizontal distance of about 20 m and a vertical drop of about 7 m. The recirculation eddy was evident through the early part of the measurement interval, until about 14:30, when the wind on the crest tower veered to greater than about 15° to crest normal. After this, the recirculation eddy transitioned toward an unstable helicoidal vortex as envisioned by Walker and Nickling (2002: Fig. 5) and simulated by Jackson et al. (2013), and then to attached-deflected flow (Sweet and Kocurek, 1990; Bauer et al., 2012) as the incident wind angle veered past about 20° at around 15:00. Lynch et al. (2010) describe a similar transition from recirculation to attached-deflected flow, noting that there may be a dependency on the morphology (i.e., slope, aspect, roughness) of the lee-side slope.

Lynch et al. (2009) demonstrated that foredune accretion can occur during offshore regional winds when the dune is of sufficient size and morphology to induce flow separation at the crest, which forces the evolution of the coherent flow structure that includes the recirculation eddy on the lee side (Bauer et al., 2013). Because the near-surface flow vectors will be directed onshore across the beach, from the point of flow reattachment toward the dune crest, there is the potential for sediment accretion on the dune toe and lower slope. This could have been the situation on our beach prior to 14:45 had the near-surface wind speeds been competent to entrain sediment. However, the data indicate that the near-surface recirculation flow was unable to mobilize sediment on the beach and dune slope when the lee-side separation envelope was most persistent. This is contrary to the findings of Lynch et al. (2009) who document strong onshore transport in the recirculation zone. The only portion of the dune that

experienced active transport prior to about 14:45 was St 10 on the dune crest. However, by 15:00 the LPCs on the beach were registering peak particle counts in excess of 100 per second with rapidly declining values toward the dune scarp. This was the period, when the regional flow at the dune crest became slightly more oblique (in excess of 20°), thereby altering the flow and transport regimes across the foredune and beach.

Numerical simulations by Jackson et al. (2013) indicate that when the regional flow is oblique to the dune crest, corkscrew vortices are established in the lee-side wake zone of the dune. The precise form of these vortices depends in part on the nature of undulations on the dune crest, which influence the reattachment length. At their field site (and in their simulations), a complex system of alternating vortices was established in association with an embryo dune located half-way up the main dune slope (see Fig. 6 in Jackson et al., 2013). Nevertheless, the near-surface flow vectors on their back-beach near the dune toe had an evident onshore component to the flow, which persisted up the dune slope toward the embryo dune zone. Our data are consistent with this onshore-directed flow on the back-beach, but differ in regard to what we find on the slope. The section of the dune slope above the scarp had consistently offshore-directed mean flow (Fig. 5), although the dominant direction was strongly alongshore. It is difficult to reconcile these measured flow vectors with a corkscrew vortex, which ought to have persistent onshore flow components all the way up the slope to the zone of flow separation. Rather, the evidence recommends a flow topology that includes topographically steered mean vectors that remain surface-attached, as proposed by Frank and Kocurek (1996), or at least become reattached only a short distance below the crest. These differences may be due to the differing geometries of the Magilligan and Greenwich foredunes (i.e., dune height, windward slope, crest undulations) in combination with faster regional wind conditions used in the model simulations (15 ms^{-1}) relative to our field measurements ($8\text{-}9 \text{ ms}^{-1}$). Araújo et al. (2013) have shown on the basis of numerical (CFD)

modeling that the length of the recirculation zone in the lee of a 2D transverse dune is somewhat insensitive to the incident wind conditions when the upwind shear velocity was below a threshold value of 0.8 ms^{-1} but then the recirculation zone increases linearly with incident shear velocities beyond this threshold. They also found that a value of upwind shear velocity in excess of about 0.49 ms^{-1} was needed to initiate reverse transport in the separation bubble, and that the near-surface shear velocity within the separation bubble increased from zero at the point of reattachment to a maximum value between the reattachment point and the dune toe. At the dune toe, the simulated shear velocities were much smaller and a persistent discontinuity was found there (see their Fig. 7) because of the break in slope. These numerical results are consistent with the patterns of flux divergence that we find on the back-beach (Figs. 10, 11) and reinforce our conclusion that sediment transport pathways across the beach-dune profile are discontinuous and that processes on the back-beach can be effectively decoupled from processes higher on the dune slope under certain incident wind conditions.

Figs. 3 and 5 indicate that flow direction across the dune slope above the scarp (St 10 - St 5) was persistently offshore with a rapid reduction in wind speed in the immediate lee of the crest and a concomitant steering in the alongshore direction. At the scarp (St 5), the flow was truly alongshore and wind speed was the slowest of any station in the cross-shore array. In contrast, the flow directions below the scarp (St 4 - St 1) were persistently onshore even though the dominant direction was alongshore. In response to these flow vectors, sediment transport was most intense at the dune crest and on the back-beach (Fig. 5) separated by an extensive region on the middle dune slope characterized by highly intermittent, low-intensity transport flux (Fig. 6). Calculations of cross-shore sediment flux divergence suggest significant sediment accumulation in the immediate lee of the crest (Fig. 9) and on the dune ramp leading to the dune scarp (Fig. 10) with virtually no sediment accumulation potential in between (Fig. 11). This offshore wind event therefore led to a broadening of the dune crest by

627 transferring sediment from the landward side of the crest back toward the seaward face of the dune.
628 Because the depositional zone in the lee of the crest was very limited in spatial extent, the slope at the
629 top of the foredune has a propensity to become locally over-steepened (approaching the angle of
630 repose) relative to what an equilibrium stoss slope might attain during an onshore wind event. This
631 suggests that the broad-crested nature of many vegetated coastal foredunes might be related to the to-
632 and-fro transfer of sediment associated with periodic shifts in wind direction from onshore to offshore.
633 Whether this is a distinguishing feature of coastal foredunes in contrast to the sharp-crested nature of
634 unvegetated desert dunes dominated by a single prevailing wind direction remains an outstanding issue
635 for future study.

636

637 Perhaps more important to the long-term evolution and maintenance of this foredune is the
638 gradual rebuilding of the dune ramp at the base of the scarp during offshore wind events. A mechanism
639 of sediment delivery from the beach to the dune is critically important to the in-filling of wave-cut scarps
640 as part of post-storm recovery. There is increasing evidence for the critical role of offshore and
641 alongshore wind events in such dune ramp construction (e.g., Hesp et al., 2009; Lynch et al., 2009). In
642 the absence of such smoothly dipping dune ramps, which provide a continuous sediment pathway,
643 sediment from the beach has little prospect of moving up the dune slope and contributing to foredune
644 maintenance, vertical growth, landward translation, or seaward progradation (Christiansen and
645 Davidson-Arnott, 2004; Aagaard et al., 2004; Davidson-Arnott et al., 2012; Ollerhead et al., 2012; Hesp
646 and Walker, 2013). Dune ramps are also important sediment storage reservoirs that mitigate the
647 potential damage from storm surge and wave scarping during extreme events, which typically occur
648 with strong onshore winds (Bauer et al., 2009). Thus, even though offshore flow events may not lead to
649 visibly significant change in the overall foredune morphology, they may be of critical importance in
650 preconditioning the seaward slope of the dune for smoothly continuous transport during obliquely

onshore events that are able to mobilize large amounts of sediment across the beach (Bauer and Davidson-Arnott, 2003). This study has demonstrated that dune crest widening and dune ramp reconstruction can occur during offshore regional wind events as decoupled processes with different sediment sources. The extent to which such processes are truly critical to foredune maintenance and the restoration of sediment pathway continuity requires further investigation.

5. Conclusions

Field studies documenting wind flow patterns across coastal foredunes are increasingly plentiful, and in general the findings are consistent with our understanding of fluid flow over bluff bodies, especially airflow across transverse dunes as found in desert situations. Depending on the steepness of the windward and lee-side slopes, as well as the wind approach angle, there can be significant topographic steering of the flow lines and flow separation at the crest with a recirculation eddy occupying the lee-side slope. Several recent studies have demonstrated that this is also the case with offshore wind events (e.g., Lynch et al., 2009; 2010; Bauer et al., 2012; Delgado-Fernandez et al., 2013; Jackson et al., 2013), with significant ramifications for sediment transport pathways and foredune evolution. The findings of the study described herein are generally consistent with these previous results, but also extend our understanding of dune morphodynamics by providing detailed information on particle flux divergence patterns, and hence on the spatially-explicit coupling of wind and sediment transport responses across the beach-dune system. Specifically, the study findings include the following:

1. When the crest tower incident wind direction was offshore and less than about 15° from crest-normal, large excursions in flow direction were typical at locations downwind (seaward) of the crest, consisting of rapidly reversing flow vectors as found in highly turbulent wake zones. The mean flow direction for the lee-side stations was generally onshore suggesting the time-

676 averaged presence of a recirculating eddy. In contrast, when the wind direction at the crest
677 tower was offshore and exceeded 20° from crest-normal, the mean flow vectors shifted to
678 alongshore and became less directionally chaotic, as might be expected for attached-deflected
679 flow;

- 680 2. The greatest wind speeds occurred at the foredune crest. Wind speeds in the lee of the crest (to
681 seaward) were greatly reduced. Such reduced wind speeds persisted down the lee-side slope to
682 the back-beach (St 4). At mid-beach (St 1), wind speeds increased slightly, particularly once the
683 incident regional wind direction shifted to a crest-oblique approach angle in excess of 20° ;
- 684 3. There was a close correspondence between sediment transport intensity and wind speed at the
685 dune crest. The greatest transport rate was associated with the strongest sustained wind
686 speeds, yielding Activity Parameter (AP) values of around 0.5. At other locations along the dune
687 profile, transport rate was highly intermittent ($AP < 0.1$) and greatly reduced in magnitude. This
688 coincides with the spatial trends in near-surface wind speed. Sediment transport on the back-
689 beach was very active with AP values similar to those on the crest, but transport rate (as
690 indicated by Wenglor LPC measurements) at St 1 was the greatest found anywhere across the
691 beach-dune profile (more than 3 times that on the crest) despite having lesser mean wind
692 speeds. This is a strong indication that supply-limited conditions dominate the beach-dune
693 profile although the specific controls (e.g., moisture, vegetation, fetch distance) are unknown;
- 694 4. Virtually all sediment flux at the dune crest and in the immediate lee of the crest (St 10, St 9,
695 and St 8) was directed offshore toward the lower dune slope. Flux divergence calculations
696 indicate that this crestal region was a zone of significant sediment accumulation, as verified by
697 erosion pin measurements. The sediment source was the landward slope of the dune. The zone
698 downslope of St 8 to the top of the scarp (St 5) had very little transport activity, negligible flux
699 divergence, and unmeasurable sediment accumulation.

5. Virtually all sediment flux on the dune ramp (St 4 to St 2) was directed onshore with decreasing transport rate toward the dune scarp. As a consequence, flux divergence values were positive indicating a propensity for sediment accumulation. Farther down the back-beach toward the foreshore (at St 1), the transport direction was generally balanced between onshore and offshore events with the dominant vector being alongshore and slightly onshore. Flux divergence values between St 2 and St 1 were therefore negative, demonstrating that this zone was being progressively eroded thereby serving as a partial sediment source for the re-building of the dune ramp.

In combination, these results indicate that there were two active transport zones (crest region of the dune; dune ramp on the far back-beach) separated by a region of limited to zero transport activity (dune mid-slope) during this offshore wind event. Such process decoupling in regard to sediment transport (dis)continuity across the beach-dune profile is evidence for complex process-form interaction in geomorphic systems. A characteristic flow pattern that is regionally and synoptically recurring can be substantially modified at near-surface due to topographic steering and flow separation across the dune, and thereby alter sediment pathways and force trends in erosion and accretion that contribute to foredune evolution in ways that may not be easily anticipated on the basis of steady-state models using simplistic assumptions.

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Figure Captions

Fig. 1. (a) Study site location; (b) topographic profile and instrument positions (see text for explanation).

Inverted triangles (squares) indicate 2D (3D) sonic anemometers.

Fig. 2. Wind speed (m s^{-1}) time series for the 3-h measurement interval at selected stations across the beach-dune profile. Black lines show 1 Hz data; white lines show 5-min running mean.

Fig. 3. Wind direction ($^{\circ}$) time series for the 3-h measurement interval at selected stations across the beach-dune profile. Black lines show 1 Hz data; white lines show 5-min running mean.

Fig. 4. Particle count ($\# \text{ s}^{-1}$) time series for the 3-h measurement interval at the dune crest. For reference, the 5-min mean wind speed is included.

Fig. 5. Spatial trends in mean wind speed (upper panel), mean wind direction (middle panel), and mean particle count (lower panel) across the beach-dune profile for the 15-min interval between 15:17 and 15:32. Dune crest (St 10) is on far left, whereas the back-beach (St 1) is on far right. Filled triangles provide data from anemometers on top of the instrument towers; circles correspond to near-surface

anemometers; crosses correspond to LPCs at 14 mm above the sand surface (note logarithmic axis for mean particle count). The dune scarp was located at 10 m from the dune crest, which separates obliquely offshore (dune slope) from obliquely onshore (back-beach) flow regions.

Fig. 6. Spatial trends in sediment transport Activity Parameter across the beach-dune profile for three 15-min intervals beginning at 14:45, 15:00, and 15:17.

Fig. 7. Cross-shore particle flux time series (1 Hz) for the 15-minute interval beginning at 15:17 at the crest (St 10) and in the immediate lee of the crest (St 9, St 8). Note that virtually all transport is directed offshore (downslope), and that the vertical scale for St 10 is 10 times greater.

Fig. 8. Cross-shore particle flux time series (1 Hz) for the 15-minute interval beginning at 15:17 on the back-beach (St 1), dune ramp (St 2) and base of scarp (St 4). Note that most of the transport is directed landward (toward the dune toe), although there are periods of significant offshore transport.

Fig. 9. Particle flux divergence time series (1 Hz) showing the propensity for sediment deposition or erosion between pairs of instruments in the dune crest region. Note different vertical axis scales.

Fig. 10. Particle flux divergence time series (1 Hz) showing the propensity for sediment deposition or erosion between pairs of instruments on the back-beach and dune ramp region. Note different vertical axis scales.

Fig. 11. Spatial distribution of net sediment particle accumulation (per m of profile length) across the beach-dune profile.

Figure 1a

Figure 1b

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11