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Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport

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ABSTRACT

Temporal and spatial changes in wind speed, wind direction, and moisture content are ubiquitous across sandy coastal beaches. Often these factors interact in unknown ways to create complexity that confounds our ability to model sediment transport at any point across the beach as well as our capacity to predict sediment delivery into the adjacent foredunes. This study was designed to measure wind flow and sediment transport over a beach and foredune at Greenwich Dunes, Prince Edward Island National Park, with the express purpose of addressing these complex interactions.

Detailed measurements are reported for one stormy day, October 11, 2004, during which meteorological conditions were highly variable. Wind speed ranged from 4 ms^{-1} to over 20 ms^{-1}, wind direction was highly oblique varying between 60° and 85° from shore perpendicular, and moisture content of the sand surface ranged from a minimum of about 3% (by mass) to complete saturation depending on precipitation, tidal excursion, and storm surge that progressively inundated the beach. The data indicate that short-term variations (i.e., minutes to hours) in sediment transport across this beach arise predominantly because of short-term changes in wind speed, as is expected, but also because of variations in wind direction, precipitation intensity, and tide level. Even slight increases in wind speed are capable of driving more intense saltation events, but this relationship is mediated by other factors on this characteristically narrow beach. As the angle of wind approach becomes more oblique, the fetch distance increases and allows greater opportunity for the saltation system to evolve toward an equilibrium transport state before reaching the foredunes. Whether the theoretically-predicted maximum rate of transport is ever achieved depends on the character of the sand surface (e.g., grain size, slope, roughness, vegetation, moisture content) and on various attributes of the wind field (e.g., average wind speed, unsteadiness, approach angle, flow compression, boundary layer development). Moisture content is widely acknowledged as an important factor in controlling release of sediment from the beach surface. All other things being equal, the rate of sediment transport over a wet surface is lesser than over a dry surface. On this beach, the moisture effect has two important influences: (a) in a temporal sense, the rate of sediment transport typically decreases in association with rainfall and increases when surface drying takes place; and (b) in a spatio-temporal sense, shoreline excursions associated with nearshore processes (such as wave run-up, storm surge, and tidal excursions) have the effect of constraining the fetch geometry of the beach—i.e., narrowing the width of the beach. Because saturated sand surfaces, such as found in the swash zone, will only reluctantly yield sediments to aeolian entrainment, the available beach surface across which aeolian transport can occur becomes narrower as the sea progressively inundates the beach. Under these constrained conditions, the transport system begins to shut down unless wind angle becomes highly oblique (thereby increasing fetch distance). In this study, maximum sediment transport was usually measured on the mid-beach rather than the upper beach (i.e., closer to the foredunes). This unusual finding is likely because of internal boundary layer development across the beach, which yields a decrease in near-surface wind speed (and hence, transport capacity) in the landward direction. Although widely recognized in the fluid mechanics literature, this decrease in near-surface shear stress as a by-product of a developing boundary layer in the downwind direction has not been adequately investigated in the context of coastal aeolian geomorphology.

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1. Introduction

Aeolian sediment transport across beaches is characteristically complex, so much so that the ideal conditions for which many 'equilibrium' theories of sediment transport were derived (e.g., Bagnold, 1941; Kawamura, 1951; Zingg, 1953; Belly, 1964; Kadib, 1964; Lettau and Lettau, 1977; White, 1979; Sørenson, 1991) are rarely encountered on natural beaches. Sediment flux at any point across a sandy surface is dependent on wind stress, grain size, and available sand supply, as well as a host of other complicating factors such as moisture content of the sand surface, grain size sorting, bed roughness, beach slope, vegetation cover, and various surface heterogeneities that confound the general utility of the equilibrium models (Sherman and Hotta, 1990). Add to this the unsteady and non-uniform nature of coastal wind systems (Bauer et al., 1998; Davidson-Arnott et al., 2005), and it is not surprising that many researchers have found poor agreement between measured and predicted sand flux on beaches (e.g., Svasek and Terwindt, 1974; Bauer et al., 1996; Davidson-Arnott and Law, 1996; Jackson and Nordstrom, 1998; Sherman et al., 1998).

The complexity of narrow coastal beaches is quite profound because many of the controlling factors on sediment transport interact in unknown and sometimes unanticipated ways (Davidson-Arnott and Law, 1990). For example, Bauer et al. (1990) observed that immediately downwind of the ocean–beach transition, an internal atmospheric boundary layer develops with a steep vertical gradient in horizontal velocity very close to the sand surface. Such steep gradients imply large shearing stresses acting on the foreshore sand surface, which indicates that the wind field has great *potential* to entrain and transport large amounts of sediment locally. Measurements of the wind field alone, when incorporated into a predictive equation for sediment transport, would, therefore, suggest that the greatest rates of transport occur on the foreshore and decrease in the downwind direction. Because the saltation system is not able to respond instantaneously to this large transport capacity at the water–land interface and because no sediment is being introduced from upwind (i.e., from the ocean surface), the rate of aeolian sediment transport on the foreshore is typically much smaller than predicted on the basis of shear stress alone, as verified by measurements using sediment traps (e.g., Bauer et al., 1990). The saltation system must adjust over a downwind distance before the maximum 'equilibrium' (predicted) rate of transport is achieved. The wind-parallel length scale of this zone of adjustment, measured from the leading edge of the sand surface, is referred to as the 'fetch distance' (Bauer and Davidson-Arnott, 2002). Unfortunately, relatively little is known about the 'fetch effect' (Gillette et al., 1996; van der Wal, 1998; Davidson-Arnott and Dawson, 2001) or how it might be controlled by incident wind speed, magnitude of shear velocity, and surface characteristics. Moreover, because the critical fetch distance is measured from the leading edge of the transport surface, all the factors that influence 'equilibrium' sediment transport (e.g., grain size, beach slope, moisture content) must be taken into consideration, as must the feedback of the developing saltation system on the dynamics of the internal boundary layer. Laboratory wind-tunnel experiments are unable to simulate these complex interrelationships (c.f., Dong et al., 2004), which occur over distances of several tens to hundreds of metres in natural environments, and, therefore, the deployment of careful measurement techniques in the field is essential.

This paper reports the results of a field study designed to investigate sediment transport across a beach characterized by highly variable surface conditions (spatially and temporally) with a rapidly changing wind regime. The primary objective was to provide insight into the complex interplay of the range of factors that influence sediment transport across a natural beach with special attention on the fetch effect as a controlling variable that integrates the specific influences of a wide range of physical factors that govern the magnitude of sand delivery into coastal foredune systems.

2. Conceptual background

The 'fetch effect' refers to the progressive increase in sediment transport with downwind distance from a zone of no transport, such as a paved surface, leading edge of a sand sheet, or saturated foreshore (Fig. 1). On a rectangular beach, the maximum available fetch (F_m) is determined by the width of beach (W) and the angle of wind approach (α). The critical fetch distance (F_c) is defined as the wind-parallel distance measured from the leading edge of the transport surface to the point downwind at which maximum sediment transport is achieved, whereas 'F' is simply the downwind distance from the leading edge to any general point of interest on the beach. Sand transported over a nominal width of beach, b, is deposited in the dune over an alongshore distance, l, according to a cosine law. Bauer and Davidson-Arnott (2002) proposed a theoretical framework within which the interaction of beach geometry, wind approach angle, and critical fetch distance can be quantified. The model employs normalized variables and, therefore, the results are general and indicative of expected trends. Their study demonstrated that when the width of beach is small in comparison to the critical fetch distance, the likelihood of achieving the maximum rate of transport anywhere on the beach is greatly reduced. This implies that most equilibrium models of sediment transport will typically over-predict the amount of sand flux at any point on the beach, with poorest agreement occurring across the foreshore where the saltation system is weakly developed (see Davidson-Arnott and Bauer, 2009-this volume, for additional discussion), despite typically large shearing stresses across the foreshore surface (Bauer et al., 1990).

If the beach is sufficiently wide or the wind approach angle is highly oblique, the maximum available fetch may exceed the critical fetch distance. Under such conditions, a zone of maximum 'equilibrium' transport will develop on the back-beach close to the base of the foredune (shaded area in Fig. 1). The maximum rate of transport, however, depends on the mean wind speed, the sediment grain size, and the condition of the sand surface. Most notably on beaches, it is widely appreciated that moisture content can play an important role in controlling the dynamics of sediment transport by increasing the sediment entrainment threshold (via increased inter-particle cohesion) and thereby reducing the overall rate of transport (e.g., Logie, 1982; Hotta et al., 1984; McKenna Neuman and Nickling, 1989; Namikas and Sherman, 1995; Jackson and Nordstrom, 1997, 1998; McKenna Neuman and Maljaars, 1998; Cornelis and Gabriels, 2003; Wiggs et al., 2004a,b; Davidson-Arnott et al., 2005; McKenna Neuman and Langston, 2006). The limited empirical evidence that is available also suggests that the critical fetch distance increases with increasing moisture content of the surface (Davidson-Arnott and Dawson, 2001), so the maximum rate of transport is less on a wet beach, and the

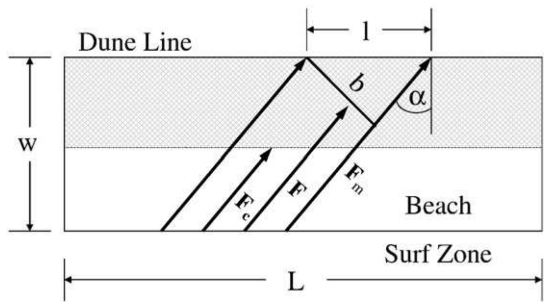

Fig. 1. Definition sketch of the relationship between wind angle (α), beach width (W), and fetch distance (F) on a rectangular beach (after Bauer and Davidson-Arnott, 2002). Shaded area indicates zone of maximum 'equilibrium' transport where actual fetch distance (F) exceeds the critical fetch distance (F_c). Maximum available fetch (F_m) is determined by beach width and angle of wind approach. Sand transported over a nominal width of beach, b, is deposited in the dune over an alongshore distance, l.

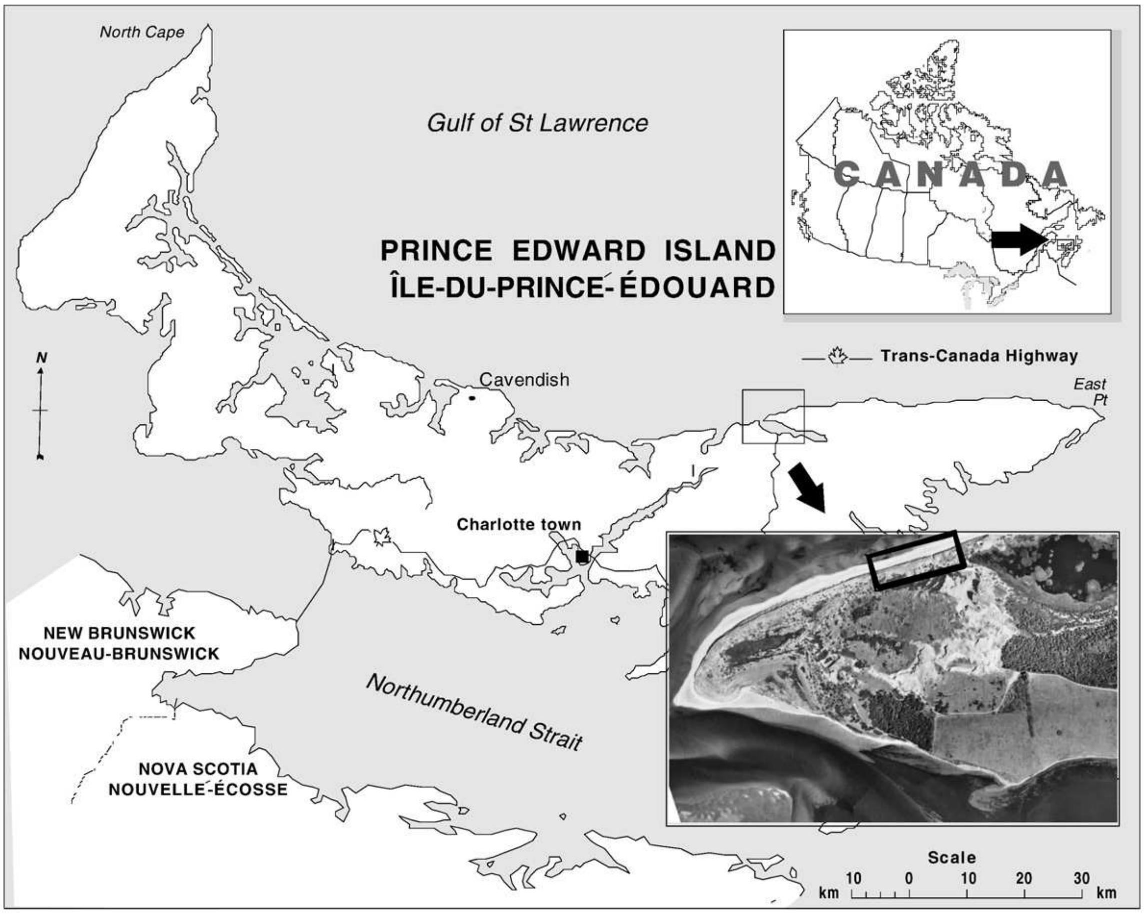

Fig. 2. Location of study area.

distance over which the maximum 'equilibrium' rate of transport develops is longer. This implies that, all other things being equal, coastal dune systems that are fronted by normally wet beaches should grow more slowly than those fronted by dry beaches because sediment delivery from a wet beach is reduced. Over the short-term, the rate of transport at any location on a beach is, therefore, not only dependent on the typical suite of 'local' controlling factors that are thought to govern equilibrium transport at a spot (i.e., wind speed, grain size, grain sorting, moisture content) but also a suite of 'contextual' factors (e.g., beach slope, fetch geometry, boundary layer development, micro-topography, micro-morphology, fluid-sediment interactions) that mediate the local factors by interacting with them in complex ways to produce specific outcomes.

3. Study site and experimental design

This study forms one component of a broader multi-institutional collaboration with the long-term goal of facilitating advanced modeling of aeolian sediment transport across beach and dune systems by collecting high-quality data on beach-dune geometry, wind speed, wind angle, surface conditions, and sediment flux at high frequency over long time periods. The experiments were conducted at Greenwich Dunes, Prince Edward Island National Park, Canada (Fig. 2), which comprise about 4 km of shallow sandy beach and dunes overlying relatively weak sandstone bedrock. The study site was located about 1 km east of the mouth of the St. Peter's Bay estuary where the beach is 30–40 m wide and the foredune is about 8 m high with a relatively straight, simple stoss slope and more complex crest (Davidson-Arnott et al., 2003; Walker et al., 2003; Hesp et al., 2005; Davidson-Arnott et al., 2008). The area is micro-tidal with a mixed semi-diurnal regime and a maximum range at spring tides of about 1 m. Prevailing winds are offshore from the south-west and west. The foredune vegetation is dominated by a nearly continuous cover of marram grass (*Amophila breviligulata*). Over the past two years, a relatively flat embryo dune, about 10 m wide and 0.75 m high, developed in front of the foredune and it is also covered by marram grass with a bare zone about 3 m wide separating the embryo dune from the base of the foredune (Fig. 3). The beach sediments are dominantly quartz sand with a mean diameter of 0.26 mm.

Wind speed was measured with a vertical array of R.M. Young cup anemometers with continuous DC output mounted at heights of 0.25, 0.6, 1.1, 1.9, and 2.6 m on a mast positioned at mid-beach. Incident, free-stream wind speed and wind direction were measured using a Gill 'Windsonic' two-dimensional sonic anemometer mounted at a height of 4.15 m on the same mast. Additional cup anemometers were deployed along the profile and at other strategic locations, with all single anemometers installed at a nominal height of 0.6 m. Measurements of total sediment flux over an interval of 10–12 min were made using vertical traps (Nickling and McKenna Neuman, 1997). The intensity of sediment transport was measured with Sabatech saltation sensors ('safires'). The sensors consist of a tube about 0.3 m in length and 0.02 m in diameter with a 0.02 m wide sensing ring mounted 0.12 m from the base of the tube. Extensive testing of an earlier version of these probes was conducted by Baas (2004), and the details of calibration and deployment are provided by Davidson-Arnott and Bauer (2009-this volume). Output from the anemometers and saltation probes were hardwired to two Instrunet A/D multiplexers at the base of the dune and then by serial cable to a computer data logger housed in a

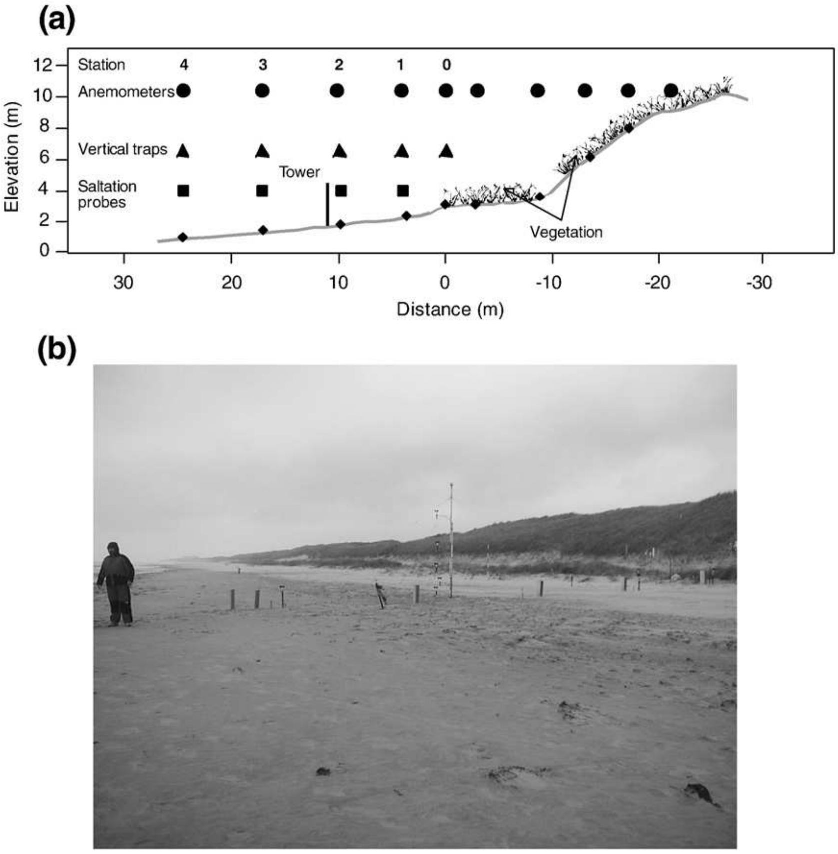

Fig. 3. a) Cross-sectional profile across the beach and foredune showing instrument deployment; b) Photograph looking east along the beach showing instrument deployment on October 11, 2004. The 4 m mast with vertical array of cup anemometers and sonic anemometers is in the centre of the beach. Also shown are some of the instrumentation groups consisting of a cup anemometer, a saltation probe, and a vertical sand trap. Small flags mark the location of temperature and moisture measurements. A cover of marram grass occurs in the embryo dune and bare sand exists on the lower edge of the foredune.

tent beyond the dune crest. Data were recorded at 1 Hz for one- or two-hour runs throughout the day.

The moisture content of the sand surface was measured using a Delta-T Theta probe, type ML2x (Atherton et al., 2001). Following Yang and Davidson-Arnott (2005), the active length of the probe was reduced to 0.02 m by inserting the stainless steel rods through a 0.04 m thick cube of dielectric styro-foam. Measurements were made at points spaced 2.5 m apart along the main profile and also along two other profiles located 20 m on either side of the main profile line. These measurements were carried out at roughly hourly intervals, timed to coincide with measurements of sand flux using the vertical traps. Only single measurements were taken at each location because periodic instrument checks indicated that replicability was not an issue. The calibration of Yang and Davidson-Arnott (2005), which was established at this beach, was used to convert the output of the probe to gravimetric moisture content. Estimates of the temperature of the beach surface were made alongside the moisture measurements using an Omega OS643W — Thermal Probe. This infra-red sensor operates in the 6–14 µm range with a fixed emissivity of 0.95, and it is capable of measuring temperature in the range of −20 °C to 260 °C with a precision of slightly less than 1 °C. The probe was held approximately 15–20 cm from the sand surface, which leads to the measurement of a surface area of less than 3 cm diameter. The probe has internal electronics that produce a stable reading after only a few seconds when held in a stable position relative to the emitting surface. Background air temperature was measured using the K-Type thermocouple function that is integral to the Omega OS643W — Thermal Probe. No site-specific calibrations of the Thermal Probe were conducted because the interest was only with relative differences in temperature to discern spatial and temporal trends rather than accurate and precise measurements of temperature for meteorological purposes, such as quantification of the energy balance.

A reference baseline was established close to the foot of the foredunes for purposes of topographical surveying and precise deployment and referencing of instruments. The baseline was designated as '0 m' in the reference frame with positive distances perpendicular to the baseline in the seaward direction. The position of the shoreline varies depending on tidal stage and storm surge inundation, and, therefore, the maximum width of the beach (and fetch distance) also varies with time. Nevertheless, because fetch distance is a length measure that has its origin at the waterline, calculations of fetch distance require knowledge of the shoreline position, wind angle, and instrument position, and these are not dependent in any way on the location of the arbitrary baseline. Measurements of fetch distance were made periodically throughout the experiment using a tape measure.

4. Results and discussion

4.1. Meteorological conditions

Meteorological measurements at an 8-m weather tower located on the tip of the spit (about 1 km away) show a fairly typical diurnal pattern for temperature and relative humidity prior to the October 11 storm (Fig. 4). Temperatures were typically low overnight (8–12 °C) with minima at dawn and large relative humidity (70%–90%). The air temperature increased during daylight hours to highs of about 20 °C in

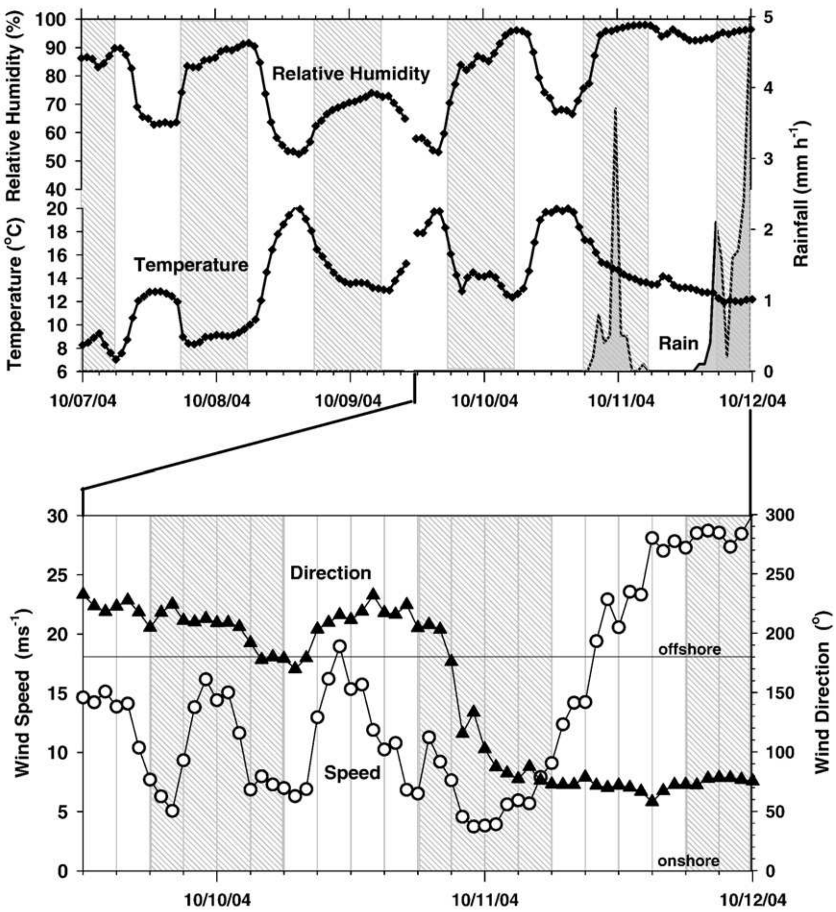

Fig. 4. Meteorological conditions (temperature, relative humidity, rainfall, wind direction, wind speed) for the period October 7–12, 2004 measured at a weather station located about 1 km west of the study site on the tip of the spit. Shaded regions indicate periods of night-time darkness with the date on the label at midnight corresponding to the upcoming day.

the late afternoon (about 1500 h) yielding smaller values of relative humidity of about 55%–65%. Although the beach surface was dry during the days prior to the October 11 storm, very little transport occurred on the beach because the wind was typically below threshold and oriented offshore.

Precipitation in the form of rain occurred during most of the evening hours of October 10–11, ceasing around 0600 h on the morning of October 11. Overnight temperature decreased and continued to decrease slightly (to about 13–15 °C) during the daylight hours, whereas relative humidity stayed well above 90% for all of October 11. Wind direction shifted from directly offshore at night to obliquely offshore (ESE) and then directly alongshore (E) at dawn. By early morning, the wind was obliquely onshore (ENE). Wind speed (measured at 8 m) increased progressively throughout the day from about 7 ms^{-1} at dawn to about 28 ms^{-1} in the late afternoon. The sky was mostly cloud-covered at dawn and became increasingly cloudy through the remainder of the morning. By 1410 h, the sky was completely overcast and periods of light precipitation began.

Fig. 5a shows wind conditions at the study site on October 11. Wind direction (measured at a height of 4.15 m) was essentially alongshore (easterly) at the beginning and end of the day, but backed to obliquely onshore (east-north-easterly) during mid-day to a minimum of about 60° relative to shore-normal in the late afternoon. Wind speed (measured at a height of 0.6 m at several locations along the cross-shore profile) increased from about 6 ms^{-1} in the early morning to about 10–12 ms^{-1} by 1100 h, and then to about 13 ms^{-1} in the late afternoon before dropping radically around 1700 h for a brief period before dusk. Wind direction stayed relatively constant during the active wind period at oblique onshore angles, ranging from about 60–80° relative to shore-normal. Fetch distance was, therefore, quite long despite the general narrowness of this relatively flat beach.

Wind speed, measured at a height of 0.6 m at several different positions across the beach, showed a consistent decrease landward toward the dune (Fig. 5a), which is consistent with a beach-induced internal boundary layer developing with downwind distance from the shoreline. The temptation exists to ascribe this reduction in wind speed to flow stagnation in front of the large dune, and indeed, with directly onshore winds, this may be an issue. The angle of wind approach during this study, however, was highly oblique, and other wind measurements across the dune taken during this study indicate that the stagnation zone was much closer to the dune. The wind profiles measured using five anemometers on the instrument mast located at mid-beach were typically log-linear. Estimates of u_* and z_o were based on four (near-surface) and five anemometer regressions to determine whether profile segmentation was occurring because of the interaction of the marine boundary layer with the near-surface beach-induced boundary layer. Both regressions yielded similar results with R^2 values of 0.95 or better indicating that the profiles were log-linear in a statistical sense. Fig. 5b shows that the temporal trends in u_* were similar to those in wind speed with a rapid increase in the morning followed by a relatively constant period (u_* about 0.6 ms^{-1}) lasting approximately 6 h during the middle of the day, followed by a rapid decline around 1700 h.

Temporal trends in roughness length, derived from the wind speed profiles at the instrument tower, were quite variable. In general, roughness length was greater during the morning, and the maxima in roughness length coincide well with peaks in u_*. After about 1400 h, however, roughness length declined to a value of about 0.0002–

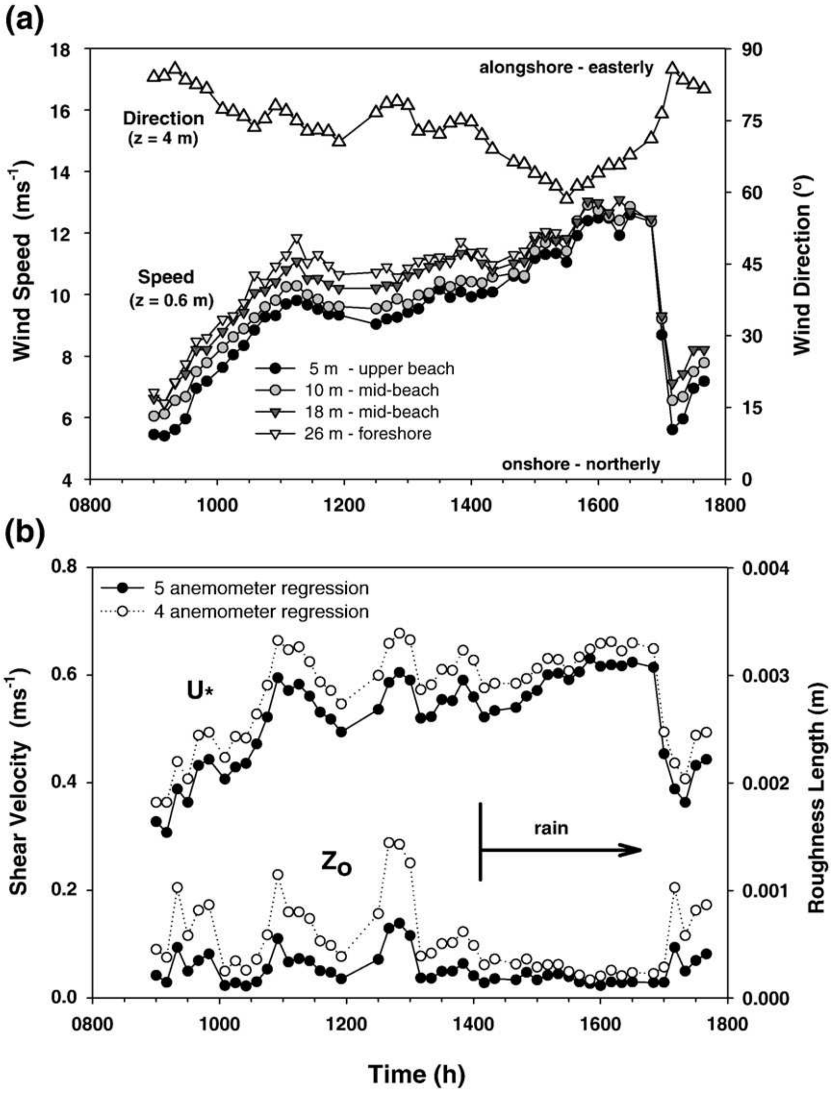

Fig. 5. Wind conditions at the study site on October 11: a) Wind direction recorded at a nominal height of 4 m; wind speed recorded at a nominal height of 0.6 m at four different locations along the cross-shore profile (5 m, 10 m, 18 m, 26 m from baseline at the base of the foredune); b) Estimates of u_* and z_o based on four and five anemometers on the instrument mast for ten-minute intervals during October 11 (see text for explanation).

0.0004 m (i.e., 0.2–0.4 mm) and remained fairly constant thereafter despite consistently large values of u_* throughout this period. As noted above, this corresponds to the time when light precipitation began (about 1410 h), effectively shutting down the sand transport system, which likely explains the reduction in aerodynamic roughness length.

4.2. Moisture conditions on the sand surface

Fig. 6a and b shows the spatial distribution of moisture content across the beach profile on October 7, 8, and 9, measured in the mid- to late-morning of each day. The upper beach was typically dry with moisture content in the range of 3–6% (by mass) whereas the mid-beach was generally wetter with highly variable moisture content. The greatest variability in space and time, however, occurred on the foreshore where moisture content ranged from 10 to 50% (note that values above 25% are far beyond the calibration range of the probe and simply indicate increasing degrees of saturation with uncertain accuracy). Unlike the foreshore, where the temporal changes in moisture content followed a semi-diurnal pattern associated with tidal excursions (and also wave run-up, wave groupiness, and wave set-up), the moisture content of the surface across the upper and mid-beach were relatively constant. Although diurnal variations in surface moisture are typical as a consequence of changes in atmospheric relative humidity, the general trend over the three days was, on average, a progressive drying of the sand surface. In this regard, it is reassuring to note that spatially-localized maxima (e.g., at 12.5 m) and minima (e.g., at 7.5 m) persisted along the profile despite the overall drying trend. These spatial trends are related to micro-morphological zonation associated with differences in grain size or sea weed deposited by extreme high tides (i.e., wrack lines) during prior storms. Fig. 6c shows that the upper and mid-beach regions became significantly wetter on October 11 because of precipitation that occurred the previous evening, and even then, a local minimum at 7.5 m persisted. This indicates that the measurements of surface moisture were quite robust and reliable.

Fig. 6d presents a series of cross-shore profiles of moisture content measured on October 11 from 1000 h through 1646 h. Fig. 7 presents a time series of three-dimensional moisture content surfaces that coincide with the profiles shown in Fig. 6d supplemented by additional data from two cross-shore profiles 20 m on either side of the main profile line. Although the upper beach remained fairly dry throughout the day (3–7%), the foreshore and mid-beach locations became progressively wetter

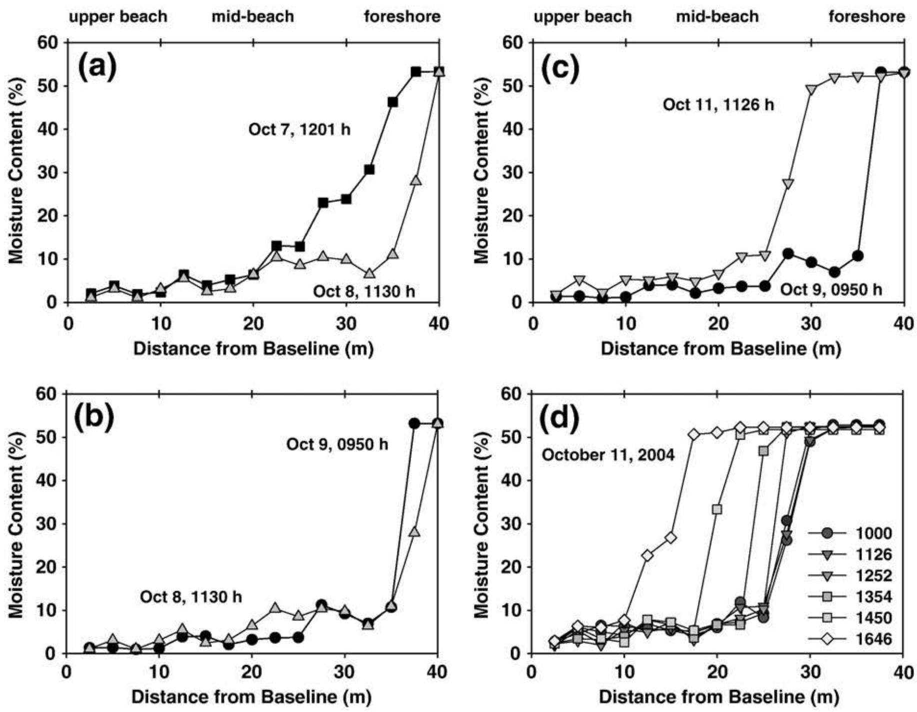

Fig. 6. Cross-shore trends in moisture content of the sand surface between October 7 and October 11. Larger distances indicate closer proximity to the shoreline (farther from the baseline established at the base of the foredune). See text for detailed explanation.

mainly because of storm surge (driven by increasing wind speed). By late afternoon, about 30 m of the 40 m wide beach was completely saturated, and only a narrow 10 m strip of relatively dry sand fronting the foredune was available as a source area to contribute sand to the dunes. The alongshore patterns were quite consistent, reaffirming the two-dimensionality of this particular beach, in terms of morphology and process.

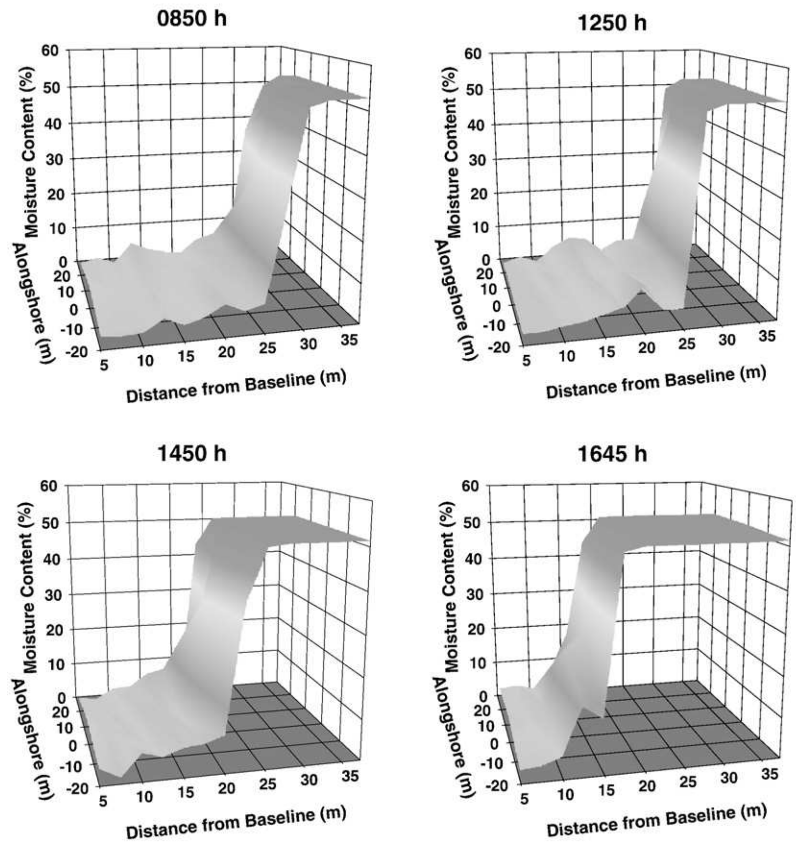

Fig. 7. Three-dimensional representation of the trends in surface moisture on October 11, 2004. Data were collected along three profile lines spaced 20 m apart and at 2.5 m increments from the saturated foreshore to the baseline at the base of the foredune along each profile line.

4.3. Temperature conditions on the sand surface

The temperature of the sand surface is controlled by air temperature, solar radiation, long-wave radiative heat loss, and moisture content, among other factors. Fig. 8 shows a time series of three-dimensional temperature grids that coincide generally with those in Fig. 7 for moisture content. In the early morning (0850 h), the upper and mid-beach sand surface was cold (about 5–6 °C) from overnight (radiative) heat loss. In contrast, the temperature of the sand surface across the lower beach ranged from a low of about 6 °C at 30 m to a high of about 13 °C at 35 m on the foreshore. For reference, the temperature of ocean water was consistent, at about 12.5 °C, whereas the air temperature (Fig. 4) in the morning was about 14 °C dropping to about 12 °C by late afternoon. Throughout the morning, the upper and mid-beach surface experienced heating due to weak solar radiative input and sensible heat transfer from the atmosphere, whereas the foreshore temperature remained fairly constant because of wave run-up. By 1250 h, the entire beach was at an almost constant temperature of 12 °C +/−1 °C, in equilibrium with the air and sea temperatures. At around 1410 h, a period of light precipitation began, and this had the effect of decreasing the temperature of the sand surface on the upper and mid-beach by about 4–5 °C, as shown in the graphic for 1450 h. An anomaly occurred at the base of the foredune, where the surface temperature remained relatively high for unknown reasons (perhaps because of the influence of vegetation or topographic slope). On the lower foreshore, the temperature remained a constant 12 °C because of swash processes and rising storm surge that inundated the sediments with sea water, which was of relatively constant temperature.

4.4. Sand transport

The rates of sand transport measured by the integrating traps, Q, and by the saltation intensity probes, SI, agree remarkably well (Fig. 9). Both spatial series show progressively increasing transport across the beach as a function of fetch distance (measured or calculated separately for each time period based on water level elevation and angle of wind approach). Maximum rate of transport occurred at fetch distances of about 50–150 m, which coincides with the upper portions of the mid-beach rather than farther up the beach at the base of the foredune (i.e., at the baseline). Indeed, the most landward trapping station located on the baseline was next to a vegetated area, which may explain the decreased transport measured at the front of the incipient foredune when the wind angle was highly oblique (i.e., alongshore) and the trap may have been sheltered by vegetation. As overall transport intensity increased (e.g., from 0940 h to 1100 h), the zone of maximum rate of transport shifted seaward to the mid-beach away from the upper beach. Neither of these mid-beach trapping locations was susceptible to confounding influences such as the presence of vegetation, which might explain this trend of a downwind reduction in rate of transport. Indeed, such an across beach trend in the rate of transport seems contrary to what might be expected as a consequence of the fetch effect alone—i.e., a progressive increase in the rate of transport to some maximum value followed by persistence of that maximum in the downwind direction.

Gillette et al. (1996) described three inter-related processes that potentially contribute to the existence of the fetch effect: 1) the ‘avalanche’ process (also commonly referred to as the saltation ‘cascade’) by which a single grain dislodged near the leading edge of a sand sheet will impact the surface downwind and thereby dislodge a large number of grains that will, in turn, dislodge an increasing number of grains farther downwind, and so on until an equilibrium, maximum rate of transport is achieved at some considerable distance from the leading edge; 2) the aerodynamic feedback or “Owen” effect, which refers to the increasing aerodynamic roughness (and hence enhanced shear velocity) experienced within the near-surface boundary layer with downwind distance as more and more sediments

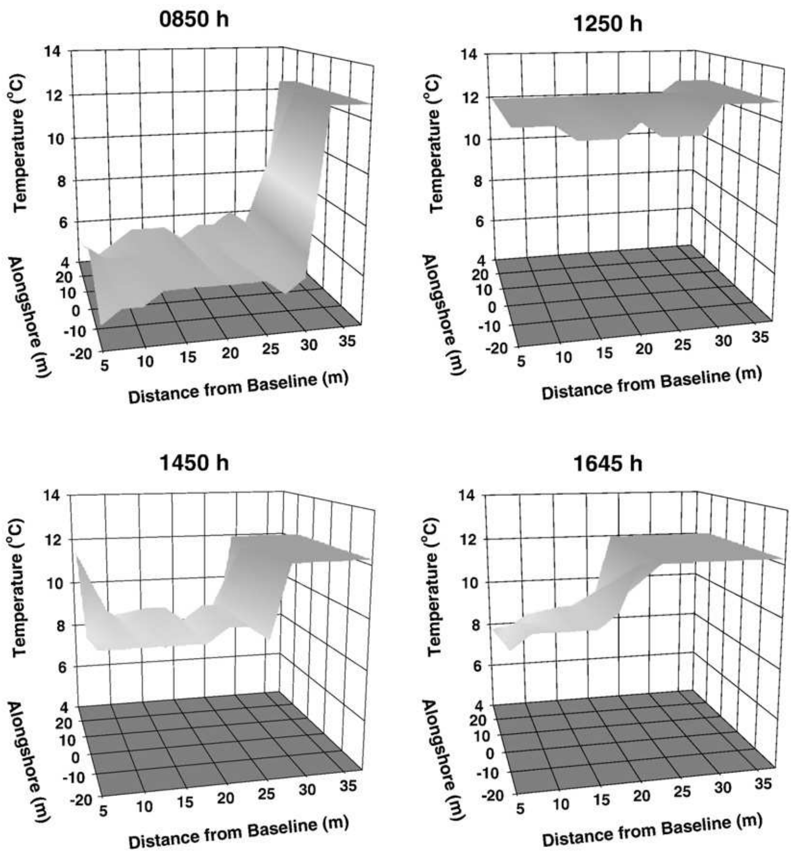

Fig. 8. Three-dimensional representation of the trends in surface temperature on October 11, 2004.

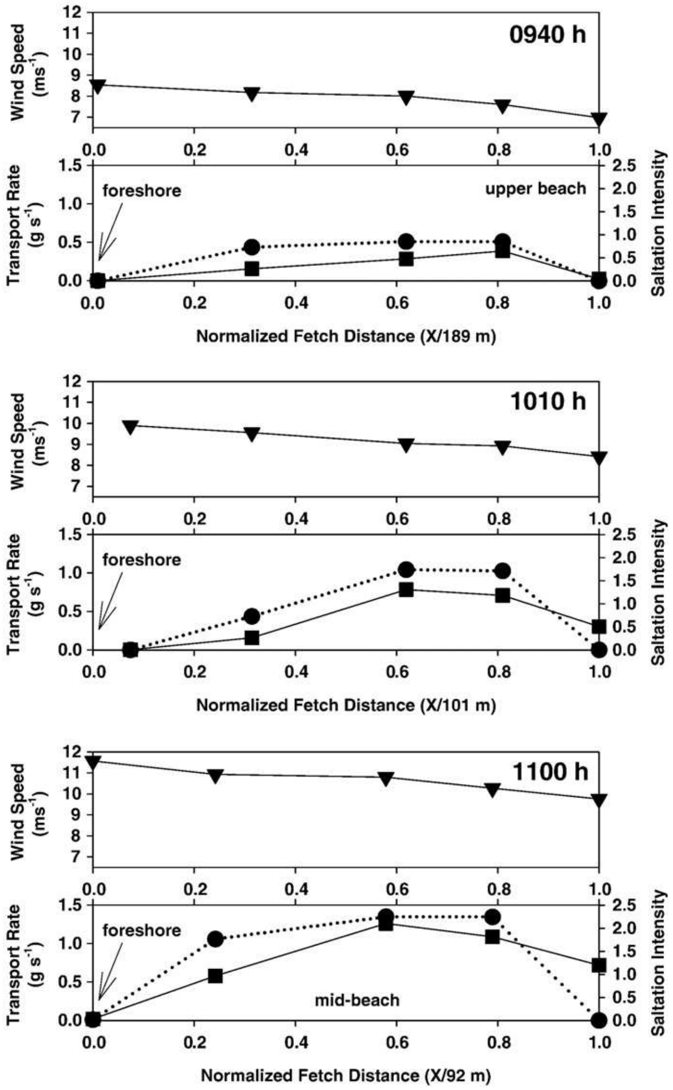

Fig. 9. Fetch-dependent profiles of the rate of sediment transport, *Q* (grams per second) (solid square and solid line), saltation intensity, SI (impacts per second) (solid circle and dotted line), and wind speed (metres per second) for three different times (0940 h, 1010 h, 1100 h) on October 11, 2004. Fetch distance (horizontal axis) depends on angle of wind approach and is normalized by maximum distance between the high water mark on the shoreline and the landward trapping station on the upper beach. This is a period of increasing overall wind speed (c.f., Fig. 5a) and transport intensity (c.f., Fig. 10). The near-surface wind speed (measured at 0.6 m height) decreased consistently with increasing fetch distance (i.e., in the landward direction). The local maximum in the rate of transport (and saltation intensity) shifts from the upper beach to the mid-beach as the overall rate of transport intensifies (i.e., from 0940 h to 1100 h), in contradiction to what is expected on the basis of the fetch effect alone. In this figure, fetch distance is measured from the average high water mark (rather than from the fixed baseline as in other figures), which changes through time because of storm surge and tidal inundation. The trapping locations remained constant on the beach (c.f., Fig. 3a), but the wind angle and high water location changed continuously thereby yielding changes in actual fetch distance leading to each trap.

are introduced into the saltation cloud; and 3) the "soil resistance" mechanism, which is simply an acknowledgement that the threshold entrainment velocity of surface sediments could change with downwind distance depending on the exact nature of the surface (e.g., crusting, grain size, micro-topography, moisture content, etc.). The first two processes involve positive feedback interactions that reinforce the trend of increasing transport in the downwind direction. Wind tunnel studies have demonstrated that such interactions between an evolving saltation cloud and the character of the near-surface boundary layer can be quite complicated (Butterfield, 1999; Spies et al., 2000a,b; Bauer et al., 2004) and may involve an 'overshoot' phenomenon (Shao and Raupauch, 1992). The horizontal length scales for these interactions are of the order of several metres, but typically less than about 15 m. In contrast, the soil resistance mechanism (which might be more generally referred to as a "surface resistance" effect) can involve positive and negative feedback interactions depending on the circumstances, and it is typically influential over distances exceeding 10s to 100s of metres. Gillette et al (1996), for example, measured sediment flux over a distance greater than 1000 m on a crusted dry lake bed, and their data indicate that the most significant adjustments occurred within 150–200 m of the leading edge of the sand sheet.

The results shown in Fig. 9 for this study, however, indicate that the rate of transport first increased with downwind distance to a maximum between 50 and 150 m (as would be expected in consequence of the fetch effect), and then decreased with additional fetch distance. Such decreasing trends in transport across the upper portions of beaches have been noted elsewhere (Derek Jackson, personal communication) but are not easily explained by either the saltation 'cascade' or the 'Owen' effect because both of these processes yield enhanced transport with downwind distance. The 'surface resistance' effect is also not easily invoked in this case because the surface was consistently drier in the upper beach region and, therefore, the sediments should have been characterized by a reduced entrainment threshold in comparison to those on the lower beach (c.f., Davidson-Arnott and Bauer, 2009-this volume). In addition, sediment was being stripped from the foreshore throughout the day and subsequently transported across the mid-beach and deposited on the upper beach. This provides a supply of dry sediment to the upper beach, which could be easily entrained, and such a transition from erosion on the foreshore to deposition on the upper beach further indicates that the transport capacity of the wind field decreased somewhere between the mid-beach and the upper beach—a conclusion that is consistent with the observed decreasing trends in wind speed (measured at 0.6 m height) with downwind distance from the foreshore (see Figs. 5 and 9).

Thus, at least one additional factor is at work that is relevant to the fetch effect—that of the development of an internal beach boundary layer with downwind distance as a function of beach topography (e.g., Bauer et al., 1990; Bauer, 1991). This factor is quite separate from (although interacts with) the influence of the 'Owen' effect. Experiments on flows across flat plates demonstrate that an internal boundary layer develops downwind of the leading edge of the plate. As this internal boundary layer expands vertically with downwind distance, the near-surface wind speed decreases and the total shear is distributed across a thicker layer of the atmosphere, thereby, decreasing the magnitude of the shear stress measured immediately above the surface. When taken in combination, these four processes (three described by Owen and now the internal boundary layer effect) interact on this beach to yield a transport system that was markedly supply-limited on the foreshore, at 'equilibrium' on the mid-beach, and seemingly transport-limited on the upper beach. It is likely that on very narrow beaches with onshore winds, this trend is not usually apparent in trap data because the effects of internal boundary layer development are overwhelmed by the increases in sediment transport because of the classic fetch effect. However, when the wind angle is oblique (as in this study) or if the beach is very wide, ample opportunity exists for the fetch effect to play out fully and for the internal boundary layer effect to initiate a decrease in the rate of transport.

Later in the day, these complex interrelationships became inoperative because storm surge severely reduced the available fetch and because the seaward measuring stations became completely inundated. In addition, a light rain shower, beginning around 1410 h, increased the moisture content of the surface to the point that transport basically ceased. These complexities, inherent to coastal

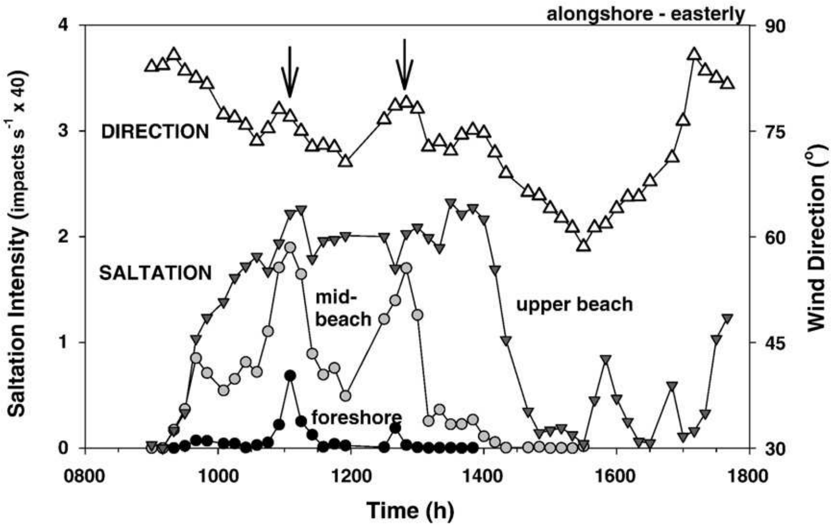

Fig. 10. Temporal trends in wind direction (measured at the top of the instrument mast located on the mid-beach) and saltation intensity, SI (impacts per second) measured on the foreshore, lower mid-beach, mid-beach, and upper beach. Refer to Fig. 5a for wind speed during the same time period. The intensity of saltation is a function of wind speed (increasing wind speed above threshold drives more saltation; see period between 0900 h and 1030 h) but also wind direction even when wind speed is relatively constant (oblique approach angles increase fetch distance and, therefore, sediment transport; note peaks shown by bold arrows at around 1100 h and 1250 h). Rainfall shuts down the transport system; from 1410 h to 1530 h.

aeolian systems, are further illustrated in Fig. 10, which presents time series of wind direction and saltation intensity (SI) at foreshore, mid-beach and upper beach locations. On the lower foreshore, SI increased gradually during the early morning as wind speed increased. Large fluctuations in SI reflect variations, not in wind speed, however, but in wind direction and hence available fetch length. As the wind shifted from onshore to alongshore, the fetch increased temporarily and yielded two spikes in SI around 1110 h and 1250 h. These spikes were evident at all locations, but they were most pronounced at the foreshore and mid-beach location where slight changes in available fetch distance are most critical. Farther inland, the implications of shifting wind direction on SI are less important because the transport system was more intense overall and less susceptible to intermittency issues (Stout and Zobeck, 1997; Davidson-Arnott et al., 2005; Davidson-Arnott and Bauer, 2009-this volume). On the upper beach, the SI was less dependent on short-term fluctuations in wind direction and a closer relationship occurred with wind speed. After about 1300 h, transport ceased virtually everywhere across the beach (except at onshore locations during extreme wind excursions) because of progressive inundation by storm surge as well as light rain that began to fall around 1410 h.

5. Summary and conclusions

Aeolian sand transport across beaches is complex and governed by the interaction of beach geometry, surface conditions, and wind field attributes in the following general ways:

1. Beach geometry is usually thought of as a fixed boundary condition when dealing with time periods of seconds to hours except, perhaps, under extreme storm conditions when strong waves and currents might cause severe foreshore erosion or accretion. Such a 'fixed beach geometry' perspective is implicit to the model of Bauer and Davidson-Arnott (2002), which conceives of the shoreline as a static, linear parameter mostly for the sake of analytical convenience. Nevertheless, tidal excursions and storm surges can exert strong influences on the 'effective' geometry of beaches as it relates to the aeolian transport of sediment, especially in macro- or meso-tidal environments with flat, dissipative beaches (e.g., Nordstrom and Jackson, 1992). Rising (or receding) water levels effectively cause a narrowing (lengthening) of the active aeolian surface, as well as a modulation of near-surface boundary layer processes, even if nearshore processes do not cause net erosion or accretion along the shoreline. To accommodate such natural variation in the time-varying position of the shoreline relative to the foredune line (because of water level fluctuations alone), a generalized version of the Bauer and Davidson-Arnott (2002) model should be developed that is able to deal with non-parallel and non-linear shorelines and foredune lines.
2. Substantial moisture content in the surface sediments reduces transport potential significantly except perhaps when wind speed is particularly intense. Tides and waves influence moisture conditions on the foreshore, whereas atmospheric humidity and precipitation events (and possibly groundwater) are critical to understanding the back-beach environment. Short-term fluctuations in sand transport are, in part, controlled by episodic stripping of dry sand veneers and subsequent exposure of moist, cohesive sand patches, which must then experience prolonged drying before further sand mobilization can be initiated locally. Such spatial patchiness yields temporal variability in transport intensity (i.e., intermittency) even when the wind field is relatively steady.
3. Sand transport is clearly related to wind speed (u) but also to shear velocity (u_*) in ways that are not easy to decipher under field conditions. These attributes of the wind field (u and u_*) are not redundant or interchangeable. On beaches, it is relatively rare to find 'equilibrium' conditions such as those prescribed by the conceptual models of Bagnold, Kawamura, and others because the fetch distances are typically shorter than the critical fetch required to achieve maximum transport. The angle of wind approach is critical to understanding the transport distribution across beaches because highly oblique winds have the potential to yield large fetch distances. Even when the available fetch distance exceeds the critical fetch distance, a constant 'equilibrium' transport with downwind distance is unlikely because the development of an internal boundary layer across the beach surface causes the wind field to adjust with downstream distance. As a consequence, mean wind speed and shear velocity may decrease in the landward direction, as would transport potential (competency), despite increases in fetch distance. Such complex interactions between the wind field and the transport system are relatively easy to

incorporate into the Bauer and Davidson-Arnott (2002) model presuming that analytical expressions can be found that realistically represent the spatial trends in transport mechanics in a robust and general way. The challenge, in this regard, is to first generate a better understanding of the factors that influence sediment transport flux as a function of downwind distance across a beach.

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