EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **37**, 1661–1677 (2012)

Published online 31 August 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3306

Wind direction and complex sediment transport response across a beach–dune system

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Received 3 October 2011; Revised 5 April 2012; Accepted 5 July 2012

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Earth Surface Processes and Landforms

ABSTRACT: Evidence from a field study on wind flow and sediment transport across a beach–dune system under onshore and offshore conditions (including oblique approach angles) indicates that sediment transport response on the back-beach and stoss slope of the foredune can be exceedingly complex. The upper-air flow – measured by a sonic anemometer at the top of a 3·5 m tower located on the dune crest – is similar to regional wind records obtained from a nearby meteorological station, but quite different from the near-surface flow field measured locally across the beach–dune profile by sonic anemometers positioned 20 cm above the sand surface. Flow–form interaction at macro and micro scales leads to strong modulation of the near-surface wind vectors, including wind speed reductions (due to surface roughness drag and adverse pressure effects induced by the dune) and wind speed increases (due to flow compression toward the top of the dune) as well as pronounced topographic steering during oblique wind approach angles.

A conceptual model is proposed, building on the ideas of Sweet and Kocurek (*Sedimentology* **37**: 1023–1038, 1990), Walker and Nickling (*Earth Surface Processes and Landforms* **28**: 111–1124, 2002), and Lynch *et al.* (*Earth Surface Processes and Landforms* **33**: 991–1005, 2008, *Geomorphology* **105**: 139–146, 2010), which shows how near-surface wind vectors are altered for four regional wind conditions: (a) onshore, detached; (b) onshore-oblique, attached and deflected; (c) offshore, detached; and (d) offshore-oblique, attached and deflected. High-frequency measurements of sediment transport intensity during these different events demonstrate that predictions of sediment flux using standard equations driven by regional wind statistics would by unreliable and misleading. It is recommended that field studies routinely implement experimental designs that treat the near-surface wind field as comprising true vector quantities (with speed and direction) in order that a more robust linkage between the regional (upper air) wind field and the sediment transport response across the beach–dune profile be established. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: aeolian sand transport; secondary air flow; flow–form interaction; topographic steering; wind and transport vectors

Introduction

Aeolian geomorphologists have traditionally privileged wind speed over other system variables in explaining and predicting the magnitude of aeolian sediment flux, although substantial effort has been devoted to understanding the complicating influences of surface moisture content, binding salts, textural mixtures, topographic slope, and the presence of vegetation or snow/ice cover (e.g. Logie, 1982; Hesp, 1989; Sherman and Hotta, 1990; Namikas and Sherman, 1995; McKenna Neuman and Langston, 2006; Leenders *et al.*, 2007; Wiggs *et al.*, 2004; Nordstrom *et al.*, 2011). The nomenclature within the field of sediment transport mechanics identifies 'transport-limiting' conditions as those for which sediment flux is controlled solely and uniquely by the strength of the fluid flow, in contradistinction to 'supply-limiting' conditions for which flux is reduced to a value below that of its maximum potential because of a host of surface controls that serve to impede the entrainment and transport of sediment. Wind speed (or alternatively, shear velocity, which is derived from the vertical profile of wind speed) is incorporated explicitly into every known predictive model of aeolian transport flux through a variant of the well-known power–function relationship between sand flux, q, and wind speed, U, (i.e. $q = \mathrm{f}(U)^n$ where n is an exponent typically assuming a value of three). This widely accepted formalism highlights the dominance of wind speed as the primary control on sediment flux above all other system-limiting factors, which are usually accommodated by adding correction factors or extra adjustment terms in the basic transport equations (Sherman and Hotta, 1990) while retaining the same basic physics. By extension, wind speed has also assumed primary importance in management-oriented problems such as assessing the sand delivery potential from the beach to the foredune for purposes of maintaining coastal integrity against storm damage (cf. Delgado-Fernandez and Davidson-Arnott, 2011).

Formally, both U and q in the power–function relationship are vector quantities with magnitude and direction components, but practically, U and q are treated as scalar magnitudes only. Implicitly then, the direction of sediment transport is assumed to align generally with wind direction. Onshore flow periods are perceived to be of greatest relevance to beach–dune management, whereas offshore flow periods are typically (sometimes erroneously) considered to be inconsequential (cf. Hesp, 2005; Lynch *et al.*, 2010). Indeed, during most field experiments, instruments are oriented in anticipation of onshore winds, and data-acquisition systems are rarely switched on during offshore flows. Only a handful of studies have investigated and documented sediment transport conditions under offshore wind in coastal systems (see Nordstrom *et al.*, 1996; Lynch *et al.*, 2008, 2009, and references cited therein) despite evidence that directional variability in wind approach angle can be critical to long-term evolution and maintenance of dunes along some coasts (e.g. Hesp, 2005).

Alongshore and obliquely onshore approach angles have been documented more extensively, in part because they occur frequently but also because of the importance of the fetch effect for enhancing the magnitude of sediment flux across narrow beaches (e.g. Nordstrom and Jackson, 1993; Bauer and Davidson-Arnott, 2003; Delgado-Fernandez, 2010). Nevertheless, for most of these studies wind direction is recorded only as a measure of broad directional trends and as a matter of providing situational context. Analytical attention typically reverts back to wind speed as the primary mechanistic variable driving sediment transport, and relatively few studies (e.g. Arens *et al.*, 1995; Walker *et al.*, 2006, 2009) have dealt specifically with the role of wind direction as more than a general state variable that pre-conditions the geomorphic system to behave in certain ways (much like 'wet/dry' or 'vegetated/non-vegetated' states). On rare occasions, wind direction receives theoretical consideration because the formalism of a modeling environment needs to treat wind velocity as a vector quantity requiring specification of both magnitude and direction (e.g. Parsons *et al.*, 2004; Beyers *et al.*, 2010; Liu *et al.*, 2011).

The primary objective of this paper is to present field evidence that demonstrates the complexity inherent to near-surface sediment transport responses on foredunes relative to what might be expected from simple assessments based on regional wind parameters alone. Similar observations were made previously (e.g. Arens *et al.*, 1995; Walker *et al.*, 2006, 2009), but never with the support of high-frequency measurements of wind and sediment transport across the foredune profile. Near-surface wind adjustments due to flow–form interaction are critically important in determining sedimentary response across a beach–dune system, and therefore in influencing potential sediment exchange between the beach and dune. Rather than treating wind direction as a passive state variable within the sediment delivery problem, the evidence recommends that wind direction be considered as a primary controlling variable – as important as wind speed – within the experimental design of future field studies as well as within model parameterization. Aeolian geomorphologists should routinely treat wind velocity as a true vector quantity rather than a simple scalar magnitude in order to yield more nuanced insights into sediment transport response to regional wind variation.

The Importance of Wind Direction

The role of wind direction in the development and maintenance of dune systems has been appreciated and conceptualized for some time. The literature on desert dunes in particular recognizes how important the seasonal shifts in wind direction can be for explaining the morphology of linear (seif) dunes and star dunes as well as the migration patterns of barchan dunes (e.g. Tsoar, 1983; Lancaster, 1995, 2009; Livingstone *et al.*, 2007). Wind direction has also been recognized as an important parameter in explaining the evolution and orientation of various coastal features as small as foredune blowouts (Jungerius *et al.*, 1991; Gares, 1992; Hesp and Hyde, 1996; Hesp and Pringle, 2001), small to large foredunes (Rasmussen, 1989; Arens *et al.*, 1995) and barchan dunes (Bourke, 2010), and as large as stacked parabolic and cliff-climbing dunes (Hesp, 2005) as well as the general character and size of dune fields relative to coastline orientation (Hesp *et al.*, 2007; Miot da Silva and Hesp, 2010). Arguably, then, there is tacit appreciation of the importance of wind direction as a significant control in shaping the nature of dune systems over long time periods (i.e. decades to millennia).

Nevertheless, in attempting to explain the existence and long-term maintenance of specific desert and coastal dune morphologies (and larger dune assemblages such as sand seas), inferential reasoning is drawn upon to support causal explanations. For example certain elements of the dune form (e.g. dip and strike angles of avalanche slopes or internal facies; directional shifts in trailing remnants of migrating parabolics) are argued to be consistent with the general nature of prevailing (and shifting) wind climatologies, which are often derived from proxy climate records averaged over decades or centuries. These types of correlative associations become accepted, not unreasonably, as the basis for causality, and therefore, as the foundation for understanding the evolution of certain geomorphic forms and for process–form interaction. The monumental task of monitoring and modeling the long-term (decades to millennia) evolution of a dune system based on actual sediment transport fluxes driven by hourly or daily wind velocity records across ever-changing terrain has yet to be undertaken by the aeolian community of researchers (cf. Baas, 2002; Nield and Baas, 2008; Parteli *et al.*, 2011). This is perhaps one of the grandest challenges facing aeolian geomorphologists.

At meso-scale (days to seasons), some interesting insights into the importance of wind direction to dune maintenance have been provided by a combination of sound theoretical reasoning supported by empirical evidence derived from short-term field studies (Wiggs, 2001). For example, Sweet and Kocurek (1990) proposed a model of air flow on the lee-side of a dune that has three basic system states:

(a) *attached and undeflected flow*, which occurs when wind approach angle is highly oblique (within about 10° of crest parallel) and the lee slope has an angle less than 20° such that the incident wind moves across the dune form with minimal topographic steering and no flow detachment;
(b) *attached and deflected flow*, which occurs when wind approach angle is oblique (roughly between about 10° to 70° of crest parallel) and the lee slope is not steep such that the incident wind does not become detached in the lee but it is strongly steered so that the flow becomes aligned in a dune parallel orientation; and
(c) *detached (separated) flow*, which occurs when wind approach angle is essentially perpendicular to the dune crest (i.e. > 70° of crest parallel) and when the lee slope is steep (> 20°) or the dune height is large relative to its length, such that flow detachment occurs at the crest region and flow reversals and eddy recirculation currents are generated in the lee.

These types of lee-side flow patterns ostensibly are of importance to sediment transport and dune form maintenance, and several wind-tunnel and field studies (e.g. Arens *et al.*, 1995;

Walker and Nickling, 2002; Wang *et al.*, 2003; Baddock *et al.*, 2011) have already validated elements of the model. Lynch *et al.* (2009) demonstrated that a recirculation eddy develops on the beach side of a large dune system in Northern Ireland during prevailing offshore flow conditions, and recent research at this site indicates that the near-surface, onshore-directed recirculation eddies may be integral in maintaining dune form via landward sediment transport from the point of flow re-attachment toward the dune toe (Delgado-Fernandez *et al.*, 2011; Jackson *et al.*, 2011).

Over very short time periods (i.e. seconds to hours), which are more typical of field-based process studies or wind-tunnel experiments, wind direction may (or may not) be recorded and analyzed as part of the experimental design. Interest is often focused on the mechanics of saltation rather than the spatial distribution of erosion and deposition so the focus is typically on 'at-a-point' conditions (cf. Nield and Wiggs, 2011). If wind direction is indeed measured, it is usually for one of two purposes. The first is purely operational – to demonstrate that the wind field was directionally steady during the measurement interval, ideally with an onshore or obliquely onshore approach angle. Such directional steadiness ensures that wind direction was not a confounding issue during the study period and therefore for the nature of interpretations drawn from the field data (e.g. Bauer, 1991). In short, wind direction is measured to assert its irrelevance. The second purpose (consistent with the theme of this paper) is to develop an improved understanding of how a regional flow field might be modulated locally by the presence of specific topographical forms and to determine whether these are of importance to geomorphic system response. Although such flow–form interactions have been referred to as 'secondary' airflow effects (Walker, 1999; Walker and Nickling, 2002; Lynch *et al.*, 2008; Walker *et al.*, 2009), there is increasing evidence that they may be critical to maintaining dune form by altering the nature of near-surface turbulence and hence, sediment transport magnitude and pathways (e.g. Wiggs *et al.*, 1996; Walker and Nickling, 2003; Walker *et al.*, 2006, 2009; Baddock *et al.*, 2011; Jackson *et al.*, 2011; Weaver and Wiggs, 2011; Chapman *et al.*, 2012).

Rarely have field studies managed to measure the spatial distribution of wind vectors and also coincident sediment transport fluxes across the dune form at high frequency. As a consequence, the linkages between the wind field and the sediment transport regimes that maintain coastal dune systems remain largely a matter of speculation based on extrapolation of at-a-point measurements. Although the capacity to measure and predict the magnitude of sediment flux has become more sophisticated recently with the implementation of laser-based particle counters (e.g. Hugenholtz and Barchyn, 2011), it is not evident that the sediment flux vector (i.e. including both the magnitude and direction of sand transport) can yet be measured with any degree of confidence. The results from a recent field study will serve to demonstrate some of the complexities and challenges.

Study Site and Experimental Design

A field study was undertaken at the Greenwich Dunes, Prince Edward Island, Canada, as a continuation of a long-term, multi-institutional collaboration (Davidson-Arnott *et al.*, 2003, 2008; Walker *et al.*, 2003, 2006, 2009; Hesp *et al.*, 2005, 2009; Bauer *et al.*, 2009; Davidson-Arnott and Bauer, 2009; Delgado-Fernandez and Davidson-Arnott, 2011; Chapman *et al.*, 2012; Davidson-Arnott *et al.*, 2012; Hesp *et al.*, submitted; Ollerhead *et al.*, submitted) with the purpose of collecting high-quality data on beach–dune dynamics to facilitate advanced modeling of aeolian sediment transport and geomorphic adjustments over micro (seconds to hours) and meso scales (days to seasons). Figure 1 shows the site location, which comprises a gently sloping, dissipative sandy beach and linear two-dimensional foredune overlying relatively weak sandstone bedrock. The beach is approximately 30–40 m wide on average, but since this is a micro-tidal coast with a mixed semi-diurnal regime and maximum spring tide range of about 1 m, beach width can vary considerably. During storms, wave set-up and surge effects frequently wet the entire beach surface (Bauer *et al.*, 2009) and storm waves scarp the foredune toe under extreme events (Hesp *et al.*, 2009; Ollerhead *et al.*, submitted). Along this stretch of coast, the foredune is about 8–10 m high with a relatively linear, two-dimensional stoss slope and a crenulated crest line. The stoss slope above the wave-cut scarp has an angle of 22°, and the lee-side slope angle is also about 20° except for a steep section immediately in the lee of the crest where eddy recirculation occurs. Prevailing winds are offshore from the southwest and west-southwest, and under these conditions beach width tends to be enhanced, especially at low tide. Strong northerly and north-westerly winds occur in association with cyclonic storm systems that track through the region.

The stoss slope of the foredune has a nearly continuous cover of marram grass (*Ammophila breviligulata*), which experiences seasonal cycles of growth (April through September) and dormancy (October through March). Hesp *et al.* (2009, submitted) and Davidson-Arnott *et al.* (2012) discuss the implications of vegetation cover on wind flow and sediment transport on this dune system. In past years, a relatively flat, wide, and vegetated embryo dune developed in front of the foredune as the system prograded seaward (Ollerhead *et al.*, submitted). However, prior to the April–May 2010 experiments, the embryo dune had been completely eroded, and the toe of the foredune had a prominent scarp that was being infilled through the creation of an extensive dune ramp. The beach sediments are dominantly quartz sand with a mean diameter of 0·26 mm.

Figure 2 presents a cross-sectional profile of the beach and dune along the instrument line, as well as an oblique ground photograph that shows the main morphologic features. The instrument line was oriented perpendicular to the dune crest, which trends almost exactly along an east–west (magnetic) alignment. Thus, the instrument line and cross-sectional profiles were aligned parallel to magnetic north to within ±1°.

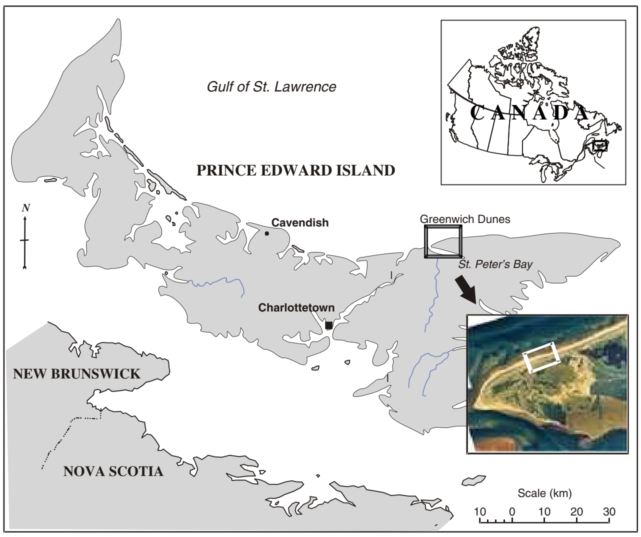
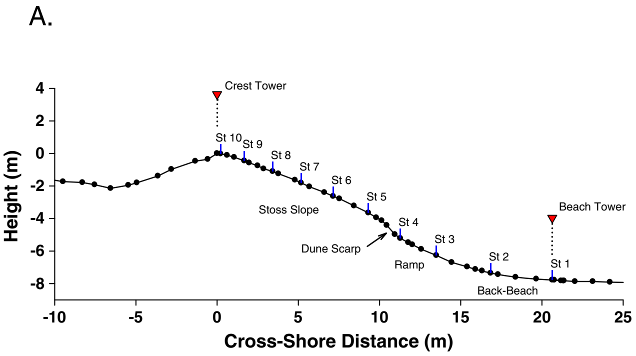


Figure 1. Site location – Greenwich Dunes, Prince Edward Island, Canada. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Instruments were installed using a high-quality compass and clinometer, and therefore anemometer orientation is believed to be level and oriented accurately to within ±1·5° relative to magnetic north. An operational frame of reference was adopted that uses a clockwise azimuth system with 180° signifying onshore (northerly) flow, 90° indicating alongshore (westerly) flow, 270° indicating alongshore (easterly) flow, and 360° indicating offshore (southerly) flow. Zero indicates no flow. The Environment Canada meteorological station at St Peter's Bay (approximately 10 km away) uses a clockwise azimuth system based on True North indicated by 360°. The magnetic declination at the study site during the period of the experiment was 19° 10′ West. Conversion to our site-specific instrument reference frame yields the following equivalents: northerly (180°; 341° true), westerly (90°; 251° true), easterly (270°; 71° true), and southerly (360°; 161° true). When the incident wind was aligned offshore, it became necessary to re-orient the operational reference frame so that averaging across the 0°–360° discontinuity did not produce erroneous mean quantities. Steps were taken to adopt an interim reference frame that minimized the value of directional standard deviation while producing histograms of direction that were unimodal whenever possible. Summary statistics (e.g. mean direction) were then converted back to the original reference frame based on magnetic north for the purposes of developing graphs and statistical tables.

Instrument clusters were located at 10 stations spaced along the profile. Wind flow was measured with R.M. Young cup anemometers and with Gill 2-D Windsonic and 3-D Windmaster sonic anemometers all with analog d.c. voltage outputs sampled at 1 Hz. The wind profile was measured at two towers situated at St 1 on the beach and St 10 on the dune crest using five cup anemometers with nominal heights of 20, 45, 70, 110, and 175 cm above the bed. A 2-D sonic anemometer was placed at the top of each tower at a nominal height of 381·5 cm and 364 cm for the beach and crest towers respectively in order to provide a measure of flow in the upper boundary layer. The crest tower anemometer was sufficiently high in the flow field as to provide an indication of the regional (upper air) wind velocity at the site even though this anemometer may not strictly represent free-stream conditions at all times. Flow conditions close to ground (20 cm) were measured using 3-D sonic anemometers at stations St 1, St 3, St 7 and St 10, covering the beach, dune ramp, mid stoss slope and dune crest. At the remaining stations (St 2, St 4, St 5, St 6, St 8 and St 9), single 2-D sonic anemometers were deployed at a height of 20 cm. To avoid confusion, the seaward slope of the foredune will be referred to as the 'stoss' slope whereas the landward side will be referred to as the 'lee' slope. This follows the convention for onshore wind approach angles. When the wind direction was offshore, the landward side of the foredune will be referred to as the 'windward' slope whereas the seaward side will be referred to as the 'downwind' slope, while continuing to reserve the convention of using 'stoss' and 'lee' to describe sediment transport responses on the seaward and landward slopes of the foredune, respectively.



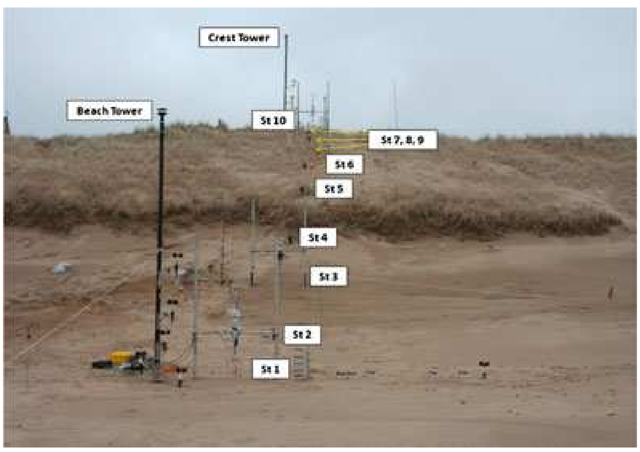


Figure 2. Cross-sectional profile (A) to scale and oblique photograph (B) of the beach–dune system (May 2010) showing instrument locations. Note prominent wave-cut dune scarp below St 5 and dune-ramp deposition at St 3 and St 4. Dune crest elevation was 9·75 m above mean sea level (EGM96 geoid model). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Sand transport intensity was measured using Wenglor Laser Particle fork sensors (Model # YH08PCT8) with 8 cm path lengths coupled to pulse-count modules. The laser beam has a diameter of 0·6 mm and the smallest particle size that can be sensed is approximately 0·04 mm. The sensor has a response time of 50 µs. When the laser beam is broken, an analog voltage spike is sent to the pulse-count module, which treats spikes in excess of a predetermined level as binary events. These events are counted over a 1 s interval, and the total count is downloaded to the data-acquisition system prior to re-setting the count to zero at 1 Hz sampling frequency. The instruments were deployed with the beam in a horizontal orientation at a height of 1·4 cm above the sand surface. Wenglor sensors were deployed at each of the stations across the beach–dune profile (see companion paper by Davidson-Arnott *et al.*, 2012). No cosine adjustments were applied to the count data to adjust for variation in wind angle relative to the path length of the laser beam. Thus, the count data, for the purposes of this paper, should not be interpreted as absolute measures of transport flux but rather only of relative transport intensity.

Preliminary tests in the field (Davidson-Arnott *et al.*, 2009) demonstrated that the Wenglor sensors provide a much more accurate and detailed assessment of sand transport intensity than piezoelectric sensors because grain counts are not related to particle size or impact momentum. The term 'count' is used interchangeably with 'grain count' herein, in reference to events that are registered by the sensor in consequence of the laser beam being broken. A detailed description and evaluation of the instruments in the laboratory and field is given in Hugenholtz and Barchyn (2011), who discuss the possibility of a single count occurring in consequence of one or multiple grains passing through the beam at the same time. There is no easy method to assess when this has occurred, and the likelihood increases during intense saltation activity, which might lead to a slight under-counting of true particle transport. The laser beam can also be broken by small bits of woody debris or plant stalks that waver in the wind, which leads to an over-count. Care was taken to deploy the Wenglors at locations that would not be influenced by wavering plant stalks and close-by stalks were clipped moderately to eliminate this possibility.

All electronic instruments were hardwired to Hobo EnergyPro Data loggers (manufactured by Onset Computer Corporation) housed in water resistant boxes adjacent to the stations. Each data logger had six analog channels for recording output from the anemometers and six digital channels, which were used to record the pulse output from the laser sensors via a Hobo pulse-count module. All data were sampled and recorded at 1 Hz throughout the experiment. Standard data conversion routines were applied following manufacturers' recommended guidelines or according to instrument calibration procedures conducted in the field.

Results

Event 1: Onshore flow – April 30, 2010

Wind conditions

Onshore flow conditions were documented on April 30, 2010, with persistently overcast skies. Meteorological data from the St Peter's Bay station (sensed at 10 m height) showed hourly-average daytime air temperatures between 3–5°C, relative humidity of 85–95%, and wind between 17–19 km h^{-1} (4·7–5·3 m s^{-1}) steady from the north (160°–190° magnetic). Table I reports wind statistics at the experimental site for all instrument stations over a 41-minute period when the flow was onshore, as indicated by the two tower anemometers on the dune crest and beach. The values indicate that there were some micro-topographic steering effects close to the dune surface, even with onshore winds, but they were relatively minor (less than ±10° deviation relative to the highest anemometer located 364 cm above the dune crest). Directional fluctuations, as indicated by the standard deviation in wind direction, were smallest toward the upper stoss slope of the dune (St 7, St 8, St 9, St 10) and largest on the back-beach (St 1 and St 2) and dune ramp (St 3 and St 4) leading up to the dune scarp (just in front of and below St 5, located on the lower stoss).

As expected, the crest tower anemometer recorded both the fastest and steadiest wind because it was positioned highest in the flow field (and most closely approximates the regional wind conditions). Surface anemometers showed a generally increasing trend in wind speed toward the dune crest, due to flow acceleration up the face of the dune, but this trend was disorderly from station to station because of micro-topographic influences and vegetation effects, which become more important in a relative way at these slow, ambient wind speeds. The range in mean wind speed measured across the dune extended from approximately 2·7 m s^{-1} on the back-beach to 6·9 m s^{-1} on the dune crest (with standard deviations of about 1 m s^{-1}). Thus the spatial variance at the site was greater than the temporal variation in mean wind speed measured at the St Peter's Bay station (4·7–5·3 m s^{-1}) for the entire afternoon. This indicates how effective minor topographical elements can be in modulating near-surface flows [as noted by Hesp *et al.* (2005) and Walker *et al.* (2006, 2009)], and it further highlights the importance of using site-specific measurements for the purpose of assessing aeolian sediment flux.

Table I. Summary statistics from 41-minute anemometer time series (15:53.58 to 16:35.00) on April 30, 2010 during onshore (northerly) flow

Location	Height (cm)	Mean speed (SD) (m s^{-1})	Mean direction (SD) (deg)	Deviation from Crest Tower
Crest Tower	364	10·0 (0·99)	181 (5·9)	—
St 10	20	6·9 (0·93)	182 (6·4)	+1
St 9	20	5·2 (0·88)	181 (7·2)	0
St 8	20	5·4 (0·97)	172 (7·2)	−8
St 7	20	6·3 (0·94)	181 (7·5)	0
St 6	20	5·6 (1·04)	187 (9·0)	+6
St 5	20	5·8 (0·92)	188 (12·3)	+7
St 4	20	3·7 (0·67)	190 (20·5)	+9
St 3	20	3·8 (0·70)	186 (17·8)	+5
St 2	20	2·7 (0·70)	190 (19·9)	+9
St 1	20	3·7 (0·77)	184 (12·5)	+3
Beach Tower	381·5	6·4 (0·92)	180 (8·5)	−1

Note: Positive (negative) deviations indicate skew to the east (west) of onshore. Deviations are due to micro-topographical influences rather than instrument orientation errors. See Figure 2 for station locations. SD refers to standard deviation.

Sediment transport conditions

For most of April 30, the sediment transport system was only intermittently active in association with minor wind gusts that temporarily exceeded the threshold of sediment motion. Wenglor sensors at most stations across the beach and dune recorded either no transport whatsoever (e.g. St 3, St 9) or more typically, only sporadic transport amounting to a few grain counts every few minutes. The only exception was St 5, located on the lower stoss slope immediately above the dune scarp, where an instantaneous shift in regime from no transport prior to 16:58 was followed by a burst of transport that gradually declined over a 10-minute interval (Figure 3). There was no apparent increase in wind speed that could have accounted for this difference in transport response while also explaining the subsequent decline in transport. The mean wind speed at St 5 (5·8 m s^{-1}) was close to the threshold of sediment entrainment, while the directional time series (Figure 3) shows that a local veering of about 20°–30° occurred at 16:58, which shifted the wind approach angle from approximately northerly (onshore) to north-easterly (obliquely onshore). Photographs (not shown) indicate that there was relatively dense vegetation immediately upwind of St 5 whereas a wind approach angle slightly toward the east caused the sensor to be fronted by a bare, dry sand surface. Thus, the shift in wind direction introduced a new surface condition upwind of the instrument, which was more susceptible to entrainment and transport of sediment.

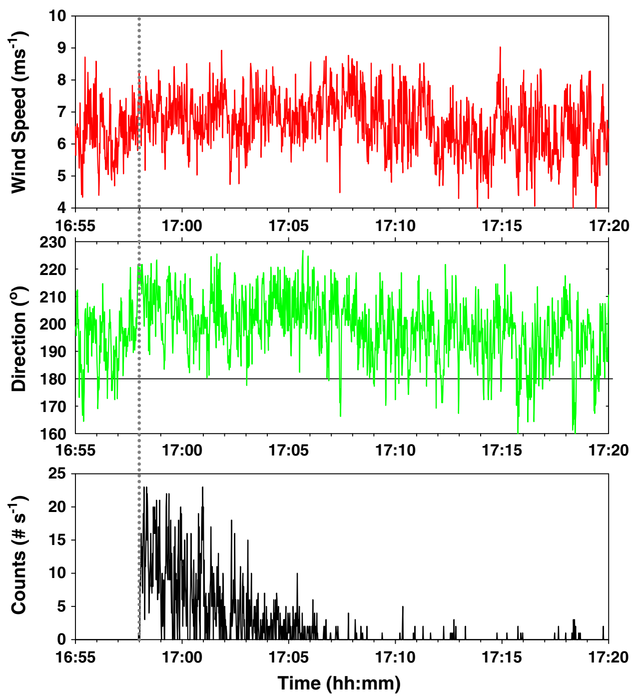


Figure 3. Time series of wind speed, wind direction, and grain counts on April 30, 2010 at St 5. Onshore wind corresponds to 180°. Sediment transport responded to wind directional shift at 16:58. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The transport event at St 5 is a very subtle and inconsequential one, but it sits in stark contrast to the general absence of transport activity at any other site on the beach or stoss slope of the dune, especially on the dune crest where the mean speed was 6·9 m s^{-1}. Such spatial differentiation exemplifies the very localized and complex nature of transport response across a dune profile as controlled by the interaction of wind direction and local surface conditions. Similar effects can be anticipated when the transport system is more active, thereby forcing localized increases and decreases in transport flux relative to a predicted norm based on a flat, dry, unvegetated surface. The following sections provide examples at larger scales.

Event 2: Offshore and obliquely offshore flow – May 2, 2010

Wind conditions

Meteorological conditions on the afternoon of May 2, 2010 were sunny and warm. Hourly-averaged air temperatures at St Peter's Bay station were between 15–20°C, with relative humidity of 38 to 50%, which is ideal for promoting sediment transport because the sand surface was very dry except along the foreshore. Mean wind speed at the meteorological station was between 16–21 km h^{-1} (4·4–5·8 m s^{-1}) and steady from the south (1°–10° magnetic – offshore) veering to south-westerly (50°) later in the afternoon. Given the relatively modest mean wind speeds (similar to those encountered on April 30) and the offshore directionality, the likelihood of experiencing sediment transport on the beach–dune system seemed minimal.

Figure 4 shows trends in wind speed and direction from the uppermost anemometers on the dune crest tower and the beach tower reported as five-minute, block-averaged means with error bars proportional (in both the positive and negative directions) to the standard deviation of each five-minute block. At the dune crest, mean wind speed increased from about 5·8 m s^{-1} at the beginning of the measurement period, to a maximum of about 9·1 m s^{-1} (at around 15:25), followed by a gradual decline to about 4 m s^{-1} at the end of the measurement period (17:30). Mean wind direction across the dune crest was almost exactly offshore (southerly) in the early afternoon with a gradual veering toward the southwest to a maximum of 48° (magnetic), consistent with the St Peter's Bay records. Except for a few brief periods at the beginning of the afternoon, the wind direction was very steady (indicated by five-minute standard deviations of only 10°).

In contrast, mean wind speed at the top of the beach tower was much smaller, with slightly less than 2 m s^{-1} at the beginning of the measurement period increasing to a maximum of only 4·6 m s^{-1}. Wind direction on the beach tower was very erratic with large values of standard deviation around 90° at the beginning of the measurement interval decreasing to about 30° for the balance of the afternoon.

Large standard deviations for wind direction are cues for interpreting the directional mean with extreme caution because it is a singular statistic that averages across a wide range of approach angles. In an extreme case of a directionally bi-modal wind with flow coming from opposite quadrants (i.e. with periodic flow reversals), the mean does not represent either mode faithfully and gives a misleading directional signature. For example, a wind field with two modes centered at 180° and at −180° produces a mean wind direction of approximately 0°, which is mathematically correct but meteorologically nonsensical. Only when a directional mean is associated with a small standard deviation should it be accepted as a robust indicator of average wind direction during the measurement interval. This poses considerable analytical challenges to interpreting lee-side flow domains where flow reversals are common.

Although the mean wind direction at the top of the beach tower was, on average, offshore until about 14:30, there were significant onshore wind gusts (flow reversals) during this early period of the afternoon, likely associated with intermittently occurring eddy recirculation cells downwind of the dune crest. Similar beach-resident recirculation cells have been documented elsewhere for offshore flows over large coastal dunes (e.g. Lynch *et al.*, 2010). After 14:30, wind direction high above the beach veered rapidly to the west with mean values of about 60° (magnetic) sustained for most of the afternoon. Toward the end of the day, wind direction on the beach tower reached a maximum of 73° with relatively small standard deviation

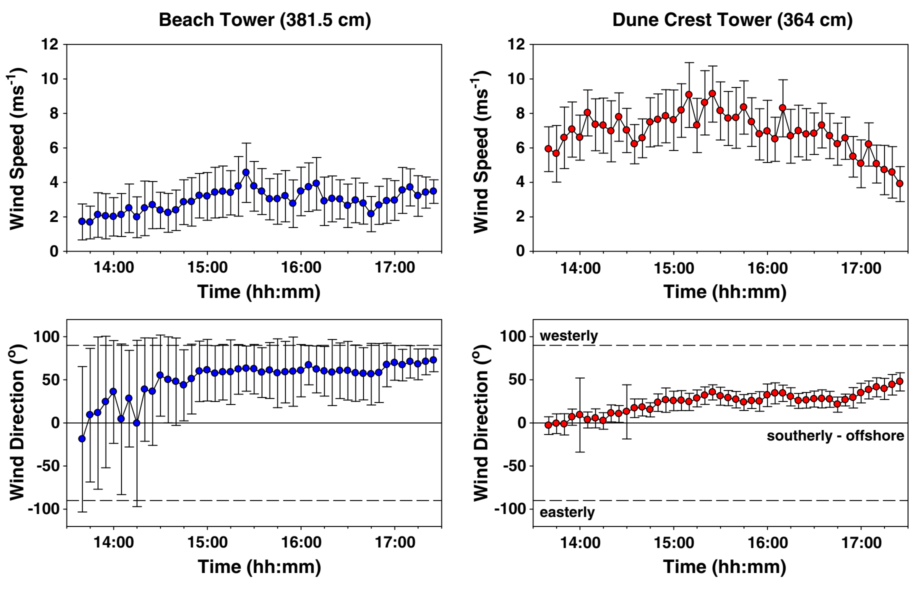


Figure 4. Time series of wind speed and wind direction (May 2, 2010) on top of instrument towers positioned on the beach (left panels) and on the dune crest (right panels). Solid dots represent five-minute, block-averaged mean, and error bars are proportional to one standard deviation both above and below the mean. Westerly (easterly) flow is indicated by 90° (−90°), which is aligned alongshore, whereas southerly (0°) is offshore and northerly (180°) is onshore. Large values of standard deviation for wind direction are indicative of erratic winds and likely flow reversals (bi-modality). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

(about 15°), which indicates that the flow was aligned alongshore (westerly) with only a slight offshore (southerly) component. Coincident with veering, mean wind speed on the beach tower increased slightly, whereas on the dune crest tower the mean wind speed decreased through to the late afternoon (from 16:30 to 17:30).

The near-surface wind conditions (at 20 cm height) on the dune crest (St 10) and on the beach (St 1) are shown in Figure 5. The temporal trends are similar to those measured at the tops of the towers (Figure 4), but there are important spatial differences that have potential ramifications for sediment transport pathways. The difference in five-minute mean wind speed between the top and bottom (St 10) of the 3·6 m crest tower was only about 1·5–2·0 m s^{-1}, with an overall mean wind speed (averaged across the entire afternoon) for the upper crest anemometer of 6·9 m s^{-1} versus 5·2 m s^{-1} for the surface anemometer. These differences are small in relation to a classic velocity profile developed over a flat surface. Flow compression and near-surface acceleration is to be expected up the windward (landward) slope of the dune during offshore winds, and this may explain the speed-up evident in the near-surface anemometers. In contrast, the beach tower anemometer had an overall mean wind speed of 2·9 m s^{-1} relative to a surface value (St 1) of 2·8 m s^{-1}. This indicates that there was virtually no appreciable difference in wind speed between the top and bottom of the beach tower, which stood 3·8 m high. The entire beach tower was in the protected wake zone on the downwind side of the dune. Given that the mean speed at 20 cm height measured on the dune crest was 5·2 m s^{-1} in comparison to 2·8 m s^{-1} on the beach, the potential for sediment transport on the crest should have been much greater than on the beach for these offshore flow conditions.

Examination of the wind direction time series from the dune crest tower (Figure 4, right lower panel) to the dune crest surface (Figure 5, right lower panel) shows that the wind field close to the surface was steered moderately by the dune topography so as to align the near-surface flow vectors toward a crest-perpendicular orientation. The upper anemometer showed a gradual wind veering from southerly (0°) to south-westerly (45°) over the course of the afternoon, whereas the surface anemometer maintained a fairly persistent offshore (southerly) orientation with a slight south-westerly deviation (20°–30°) in the late afternoon. This indicates a counter-clockwise rotation within the near-surface boundary layer (from top to bottom of the crest tower) of approximately 20° when the regional wind was oblique (south-westerly), in contrast to virtually no rotation when the regional wind was directly offshore (southerly) and crest-perpendicular.

On the beach, the effects of topographic steering were equally pronounced but in an opposite direction to that on the dune crest. The upper anemometer on the beach tower (Figure 4, left lower panel) shows that the dune acted as a bluff body that re-oriented the flow on the downwind (seaward) side to a more oblique, alongshore (beach-parallel) direction. The surface anemometer at the base of the beach tower (Figure 5, left lower panel), in contrast, shows that the mean flow was oriented almost directly onshore (approximately 180°) at the beginning of the afternoon with gradual backing to an alongshore westerly orientation (approximately 90°) toward the end of the day. Consistent with the Sweet and Kocurek (1990) model, this indicates a shift from separated flow during offshore regional wind conditions at the start of the measurement period to attached and deflected flow during obliquely offshore regional wind conditions later in the afternoon (cf. Rasmussen, 1989). The values of directional standard deviation on the beach were quite large until about 14:50, which indicates that wind direction during the separated flow phase was erratic and not consistently onshore (except in an averaged sense).

The trends shown in Figures 4 and 5 indicate that a regional offshore wind (oriented perpendicular to the dune crest) can yield highly variable flow conditions with markedly reduced mean wind speed on the downwind side of the dune (e.g. Lynch *et al.*, 2010). The dune acts to block the incident wind (from landward) and causes wake-like turbulent motions on the beach where flow re-attachment occurs. Some degree of eddy recirculation – with onshore-directed wind vectors on the beach surface – can be expected under these conditions, if only for brief periods. As the regional wind begins to veer (or back) to an obliquely offshore orientation (greater than 15° relative to crest perpendicular), the bluff body effect is reduced. The dune presents a more streamlined profile to the regional flow field, which reduces flow separation and enhances topographic steering on the downwind (seaward) slope of the dune (i.e. attached and deflected flow). This interpretation is

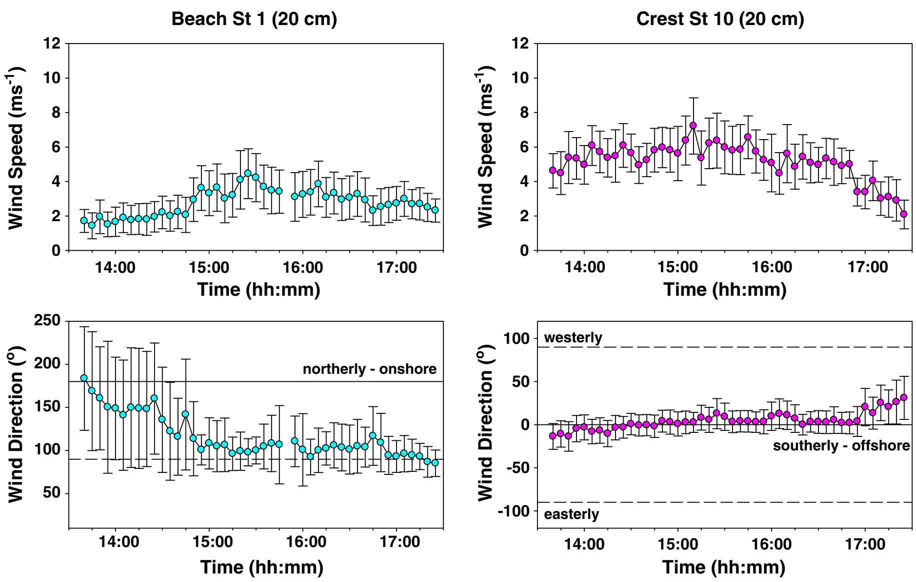


Figure 5. Time series of wind speed and wind direction (May 2, 2010) at the base of instrument towers positioned on the beach (left panels) and on the dune crest (right panels) at a nominal height of 20 cm above the sand surface. See Figure 4 for explanation of symbols. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

consistent with the slight rise in mean wind speed on the beach tower toward the end of the measurement period, during an interval when the crest tower anemometers recorded a consistent decrease in mean wind speed. A greater proportion of the available streamwise momentum in the flow field was carried to the downwind slope of the dune and onto the beach later in the afternoon. Similarly, the observed decrease in standard deviation for both the mean speed and mean direction toward the end of the measurement period suggests a less disrupted flow field when approach angle is oblique to the dune crest. Since greater flow momentum is carried to the beach, there should be ramifications for sediment transport potential on the seaward slope of the dune and on the beach.

Sediment transport conditions

In contrast to the situation on April 30, the transport conditions on May 2 were more active despite similar mean regional wind speeds and offshore flow conditions. Figure 6 shows grain count time series from across the beach–dune profile. In general, transport was highly intermittent throughout the day, with a marked increase in transport from about 14:30 to a peak period at 15:30, followed by a gradual decline in transport intensity until about 17:00. Transport intensity was greatest at the dune crest (St 10) with several gusts exceeding 200 counts per second (maximum of 312 counts per second), as might be expected from the relatively large near-surface wind speed at the crest during the peak period. Nevertheless, the transport system at St 10 was highly intermittent with an overall intermittency value (Stout and Zobeck, 1997) of about 25% (i.e. only 25% of the time series recorded some level of transport activity). During the peak transport period (between 15:00 and 16:00), intermittency at St 10 was still less than 38%. At other stations across the beach–dune profile, intermittency values were much smaller, indicating less active transport conditions, although during the peak transport period the beach stations had intermittency values in the range of about 35–45%, slightly greater than the dune crest for unknown reasons.

At the beginning of the event (prior to about 14:45), when the regional wind was offshore with occasional flow reversals on the beach, only the crest region experienced transport. Some of the mobilized sediment from the crest appears to have been transported down the dune slope to St 9 and St 8, perhaps in a grainfall mode as described by Nickling *et al.* (2002). Other locations on the lower stoss slope experienced very little sediment activity. Between 14:30 and 15:00, the regional wind began to veer to the southwest and the speed increased slightly (see Figures 4 and 5), forcing a modest transport response at most stations. Between 15:00 and 15:30, wind speed achieved its maximum values for the day, and wind direction veered further to the southwest. On the beach, the wind direction at this time was dominantly alongshore with a slight onshore component (due to weak eddy recirculation), indicating an absence of effective fetch restrictions on transport potential. This was the period of most active transport on the beach, and the transport rate at St 1 and St 2 was much larger than most other locations except the dune crest (note different axes scaling in Figure 6). Significant reduction in transport rate was evident at the transition from the back-beach to the dune ramp (St 3) and toward the base of the dune scarp (St 4), consistent with the predominantly alongshore nature of the transport system and an incapacity to move sediment onto the stoss slope.

On the lower stoss slope of the dune (St 5 and St 6), sediment transport amounted to only a few isolated counts (typically fewer than five counts per second), which coincides with the most benign wind conditions found anywhere across the dune during this offshore flow period. Average wind speed at these two stations was less than about 2 m s^{-1} with occasional gusts reaching 5 m s^{-1}, close to the threshold of motion. More importantly, the average wind direction at St 5 and St 6 had a slight offshore component whereas at St 4 and St 3 there was a slight onshore component. Even though these wind vectors suggest that the lower stoss slope was a zone of air mass convergence – and therefore of potential net deposition – it would appear that very little sand accumulated there. Transport from the dune crest was not sufficiently energetic to move all the way down the seaward slope, whereas the large volumes of alongshore transport measured on the beach surface (at St 1 and St 2) were unable to move past the dune ramp (St 4) and scarp. In effect, the transport system on the beach was decoupled from the transport system on the dune slope, and these profile segments operated as independent systems with different sediment

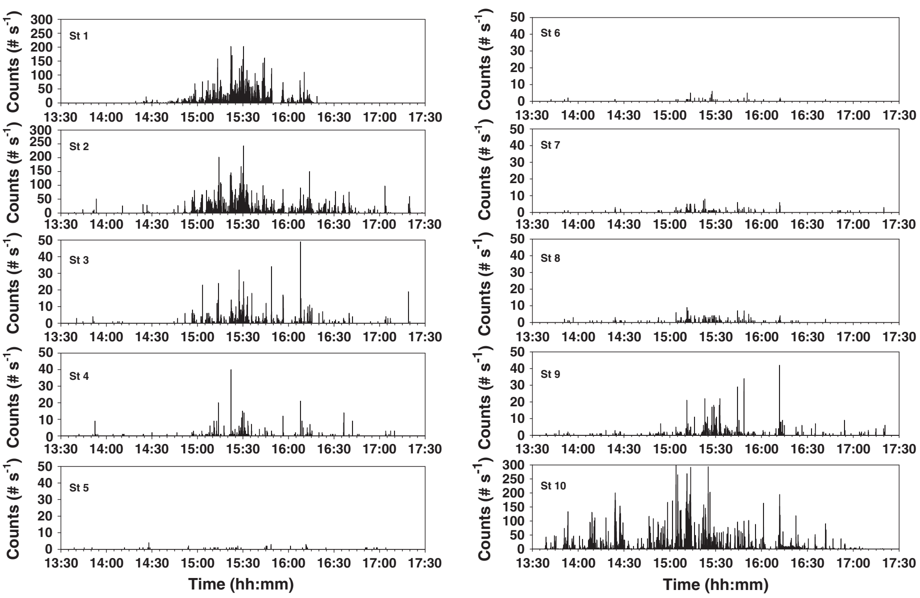


Figure 6. Grain count time series (May 2, 2010) corresponding to Figure 5. Left panels show transport intensity on the back-beach (St 1, St 2, St 3), the dune ramp (St 4), and the lower stoss above the scarp (St 5). Right panels show transport intensity from the mid-lower stoss (St 6) up to the dune crest (St 10). Note six-fold difference in scale of vertical axes for St 1, St 2, and St 10.

sources and sinks. As the event waned (between 16:00 to 17:30), there was a marked reduction in transport intensity everywhere across the beach–dune profile.

Event 3: Alongshore flow – May 3–4, 2010

Wind conditions

A significant storm system was forecast for the late evening of May 3 and early morning of May 4, and the instruments at the site were programmed to initiate data recording automatically at 22:00 on May 3. A total of 4·1 mm of rain was measured by Environment Canada for the hour prior to data recording at the site, and approximately 0·5 mm of rain was measured between about 22:00 and 22:15. The sand surface across the beach–dune profile was therefore moistened at the beginning of on-site data recording. Meteorological statistics from the St Peter's Bay station indicate that an average barometric pressure of 982·4 millibars was recorded for the hour between 23:00 and midnight, followed by the passage of a significant cold front. Hourly mean wind speed at the St Peter's Bay station was 24 km h^{-1} (6·7 m s^{-1}), having increased progressively from the late afternoon with wind veering from south-south-easterly to west-south-westerly by midnight. Cold front passage was accompanied by a marked increase in wind speed with hourly averages in excess of 30 km h^{-1} (8·3 m s^{-1}) and a peak hourly average of 39 km h^{-1} (10.8 m s^{-1}) in the early morning.

Figure 7 shows temporal trends in wind speed and wind direction recorded at the beach tower and the dune crest tower for the four-hour period between 23:00 (May 3) and 03:00 (May 4). The crest tower graphs (right panels) show that the wind approach angle prior to 01:00 was obliquely offshore from the southwest (50°–60°) with five-minute mean wind speeds of about 6–9 m s^{-1}. Standard deviations for wind speed and direction were exceptionally small, indicating the very steady nature of the regional flow for most of the storm event. The same trends were evident in the beach tower record (left panels), except that the speeds were slightly smaller prior to 01:00 (about 5–7 m s^{-1}) and the direction was aligned more alongshore (70°–80°).

At around 00:45, a significant shift in incident wind conditions occurred in association with the cold front. Mean five-minute wind speeds at both towers increased to 12 m s^{-1} by 01:00 and sometimes exceeded 15 m s^{-1} on the crest tower. Standard deviations of only 1·5–2 m s^{-1} persisted throughout the storm, although during the height of the storm, short-term gusts up to and in excess of the anemometer operating settings (30 m s^{-1}) were recorded at most locations across the beach–dune profile. Wind direction was from the west-northwest (95°–120°) with very small standard deviations (approximately 5°). The wind field above the crest tower showed a continuous veering trend spanning approximately 70° over the four-hour period (from 54° to 123°), whereas the beach tower anemometer registered only 40° of veering (73° to 110°). A comparison of the lower panels in Figure 7 indicates that topographic steering by the dune constrained the flow on the beach to a dominantly alongshore (westerly) alignment (90° ± 20°) whereas the regional wind approach angle high above the dune crest had a much wider span of approach angles.

Figure 8 shows graphs for the corresponding near-surface flow field on the beach (left panels) and dune crest (right panels). The temporal trends were similar to the tower positions (Figure 7), but the overall mean wind speeds were smaller for the near-surface flows. Prior to 00:45, when the regional flow was obliquely offshore, the surface anemometers on the beach and crest registered virtually identical speeds (approximately 4 m s^{-1}), whereas after about 01:00 when the wind direction shifted to obliquely onshore, the crest station experienced faster near-surface wind (in excess of 11 m s^{-1}) in comparison to the beach (less than 9 m s^{-1}). This differential response is consistent with slight flow acceleration up the stoss slope of the dune during onshore wind. The shift in wind direction at the beach and crest locations from obliquely offshore to obliquely onshore approach angles occurred simultaneously, but the degree of rotation at the crest and beach positions was different. On the beach surface, there was a muted response to the regional wind veering that amounted to only 25° (84°–109°), whereas on the crest surface the rotation amounted to fully 90° (48°–138°). This indicates that the directional response on the beach surface was much like that on the beach tower – a tendency for strong alongshore alignment of the flow under both obliquely offshore and obliquely onshore regional winds – with more pronounced topographic steering closer to the surface. On the dune crest, topographic steering forced a more crest-perpendicular orientation, such that

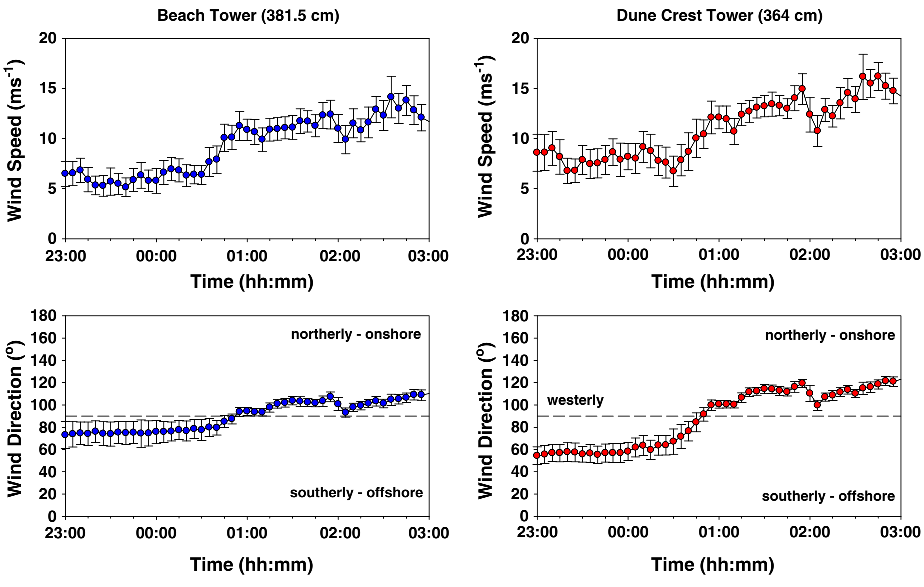


Figure 7. Time series of wind speed and wind direction (May 3–4, 2010) on top of instrument towers positioned on the beach (left panels) and on the dune crest (right panels). See Figure 4 for explanation of symbols. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

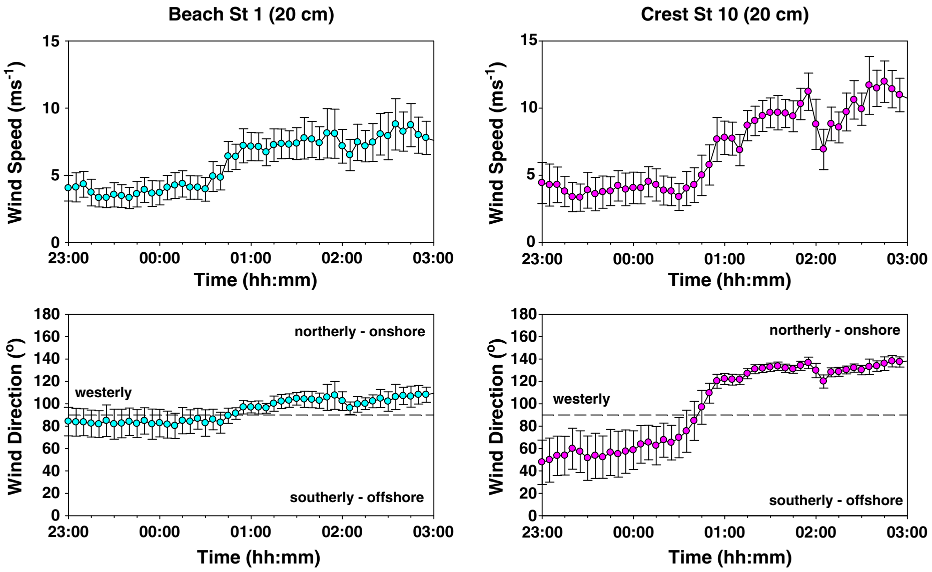


Figure 8. Time series of wind speed and wind direction (May 3–4, 2010) at the base of instrument towers positioned on the beach (left panels) and on the dune crest (right panels) at a nominal height of 20 cm above the sand surface. See Figure 4 for explanation of symbols. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

obliquely offshore regional winds became more offshore oriented whereas obliquely onshore regional wind became more onshore oriented. Once again, this differential response of the near-surface wind conditions on the beach versus the crest should have ramifications for sediment transport intensity and pathways.

Sediment transport conditions

Alongshore flow conditions during the May 3–4 storm provide a unique opportunity to understand the impact of topographic steering on sediment transport response in comparison to the predominantly onshore (April 30) and offshore (May 2) conditions discussed earlier. Figure 9 shows time series of counts registered by Wenglor sensors located across the entire beach–dune profile. The most striking feature is the high degree of spatial variability in transport conditions encountered during this event. The four stations on the beach (St 1 through St 4) registered very large grain counts, in excess of 1000 counts per second after about 01:15, whereas the stations on the dune slope (St 5 through St 9) and dune crest (St 10) registered orders of magnitude less transport during this initial phase of the event (note different axes scales). Moreover, transport at St 1 and St 2 was continuous (intermittency values of 100%) for tens of minutes, which indicates intense saltation.

Unfortunately, the Wenglor sensors on the beach became inoperative after only 10–30 minutes because of moisture seepage into the electronic circuitry. Instrument failure was not instantaneous but led to progressive signal decline in all the beach sensors, as evident in Figure 9, such that no useable information was available after about 01:45. This does not

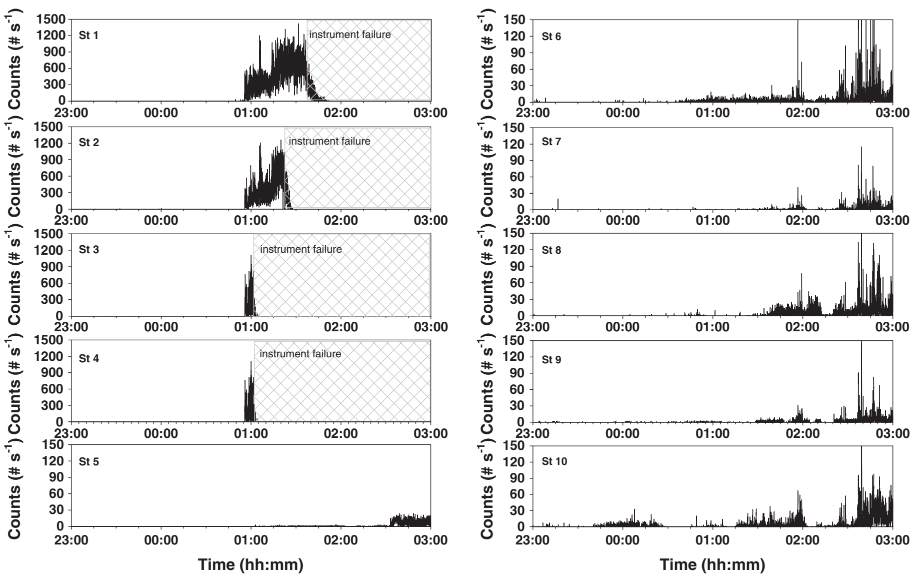


Figure 9. Grain count time series (May 3–4, 2010) corresponding to Figure 8. Left panels show transport intensity on the back-beach (St 1, St 2, St 3), the dune ramp (St 4), and the lower stoss above the scarp (St 5). Right panels show transport intensity from the mid-lower stoss (St 6) up to the dune crest (St 10). Note 10-fold difference in scale of vertical axes for St 1, St 2, St3, and St 4.

imply that sediment transport was not continuously active on the beach after 01:45, but rather that there are no data records to indicate the degree of transport intensity. Fortunately, all the Wenglor sensors deployed on the dune (St 5 through St 10), which were sealed more effectively, operated reliably over the week-long experiment. Functionality of the damaged Wenglor sensors was restored after a period of extensive drying in the laboratory, which suggests that the electronic circuitry was not permanently damaged in a way that would undermine the reliability of the data before 01:45.

The traces in Figure 9 demonstrate that transport intensity on the dune, extending from the lower stoss (St 5) through to the crest (St 10), was much smaller than on the beach, particularly between 01:00 and 01:45 for which there are simultaneous recordings of transport flux from all Wenglor sensors across the entire beach–dune profile. Transport intensity on the lower stoss (St 5) was particularly small, with only a few scattered counts being registered in the time series until about 02:30 when the storm entered the most intense phase and when transport activity increased substantially on the dune. Such differences in transport response on the beach (intense transport) relative to the dune (relatively little transport), separated by a zone of virtually no transport on the lower stoss (St 5), again suggests that the beach and dune slope regions were decoupled and failed to exchange sediment. Sediment mobilized on the beach stayed on the beach, whereas sediment mobilized on the stoss slope stayed on the dune. Unlike on the previous day when there was evidence from the anemometers for air mass convergence on the lower stoss, the wind field on May 4 after 01:00 was obliquely onshore everywhere across the beach–dune system. These wind vectors, therefore, suggest that transport should have been continuous from the beach to the dune crest, although the Wenglor data indicate otherwise. It seems unlikely that sediment mobilized on the beach could have passed over the lower stoss region without registering grain counts at St 5, so the most reasonable explanation is that the lower stoss was a zone of inactive transport, perhaps because of the barrier presented by the dune scarp or the line of vegetation.

At around 02:30, a small number of counts began to register at St 5. Even then, this amounted to fewer than 20 counts per second in comparison to the other sensors higher on the stoss slope (in excess of 50 to 100 counts per second). There is no indication that any of these sensors were working improperly, and despite differences in transport activity from station to station, each of the time series contains intervals when there were no counts followed by large bursts of counts.

The temporal evolution of transport intensity at each of the stations (Figure 9) reveals a great deal of complexity in process–response relationships as the regional wind veered from obliquely offshore to obliquely onshore (Figures 7 and 8). On the beach (St 1 and St 2) and dune ramp (St 3 and St 4), there was no transport at all during the first two hours of record, except for the odd count spaced many seconds apart (barely evident in Figure 9 given the axis scaling). One may be tempted to ascribe this to the moist nature of the sand surface following the early rain. However, at 00:52:30, the first of four brief gusts passed through the instrument array on the beach thereby mobilizing tens of particles across all beach Wenglors simultaneously in a succession of saltation clouds propagating alongshore. It seems exceedingly unlikely that the surface could have dried so uniformly across the entire beach so as to allow a simultaneous transport response. At 00:55.35 a marked increase in transport (several hundreds of counts per second) was initiated, and within a span of a few seconds, all beach Wenglors were registering large counts continuously for tens of minutes (until instrument failure began). The wind speed and wind direction time series from the beach surface anemometer at St 1 (Figure 8) demonstrate that this rapid transition from no transport to continuous transport on the beach occurred in conjunction with a rapid shift in wind direction from obliquely offshore (about 85°) to obliquely onshore (about 95°) as well as a jump in wind speed (five-minute mean) from about $5\,\mathrm{m\,s^{-1}}$ to greater than $6\,\mathrm{m\,s^{-1}}$. Thus, it seems most reasonable to ascribe this sediment transport response on the beach to altered wind conditions rather than surface controls.

The change in wind direction and wind speed at around 00:55 was even more pronounced on the dune crest (Figure 8, right panels), and yet there is little evidence for anything but a very subtle transport response anywhere across the entire stoss slope of the dune. The transport time series at St 9 and St 10 (Figure 9) indicate that there was intermittent transport during the early stages of the event (from 23:00 to 00:30) when the wind was obliquely offshore and while there was no transport on the beach. The difference in transport response on the crest versus the beach cannot be explained by differences in wind intensity because the average wind speeds on the crest and beach were approximately the same up until about 00:45. Sediment surfaces on beaches are typically wetter, flatter, and more compacted than on dune crests, which tend to be hummocky and loosely packed. Sand particles on small mounds and crenulations are more exposed to wind forces and are likely to be preferentially dried and mobilized. Perhaps this explains why, during the early period of the event (prior to 00:45) when the wind was obliquely offshore, sediment was mobilized at the dune crest and transported a short distance downslope to St 9, while very little sediment was mobile anywhere else across the beach–dune profile.

However, once the wind veered to obliquely onshore (at approximately 00:50), a pronounced sediment response occurred on the beach (continuous transport with hundreds of counts per second), whilst very little transport was activated on the dune (intermittent transport with only tens of counts per second or less). Figure 8 shows that the mean wind speed at the crest was, on average, greater than on the beach, and the wind direction was more crest perpendicular. These conditions, along with presumably drier sediments, should have yielded greatest transport intensities at the crest, but this was not the case. Later in the event (02:00 and beyond), five-minute mean wind speed on the crest increased to more than $10\,\mathrm{m\,s^{-1}}$ and this seems to have been critical in initiating widespread transport across the stoss slope of the dune (and overcoming the buffering effect of vegetation). Throughout the later stages of the event, when transport was most intense on the dune slope and (by inference) also active on the beach, the lower stoss region remained relatively inactive with grain counts at St 5 numbering fewer than about 20 counts per second even during the peak transport periods. Once again, the topographical break at the dune scarp and the diverging wind vectors seem to have been critical in decoupling the transport systems on the beach and dune.

Discussion

The data described earlier cover a wide spectrum of incident (regional) wind conditions ranging from onshore (April 30), to obliquely onshore and alongshore (May 3–4), to offshore (May 2) approach angles with mean (five-minute) speeds less than $4\,\mathrm{m\,s^{-1}}$ to greater than $15\,\mathrm{m\,s^{-1}}$ (and gusts exceeding $30\,\mathrm{m\,s^{-1}}$). Two generalizations can be drawn from these field results. The first is that there can be a large degree of topographic steering and modulation of the near-surface wind field in the presence of large coastal foredunes that protrude well into the coastal boundary layer, as was noted by previous studies (e.g. Arens *et al.*, 1995; Walker *et al.*, 2006, 2009). Quantitative knowledge of the near-surface wind vectors, including speed and direction, is critical to understanding the nature and extent of this topographically-forced modulation, and by extension, to predicting sediment transport pathways across the beach–dune system. The second generalization, which follows directly from the first, is that the response of the sediment transport system across a beach–dune profile can be very complex and characterized by extreme spatio-temporal variability even under fairly constant regional wind conditions. Although the nature and degree of wind modulation might be understandable and crudely predictable, the same cannot be claimed for the sediment transport system.

Topographically-modulated, near-surface wind vectors

Local wind vectors at any near-surface position can vary appreciably across a beach–dune system relative to the regional (upper-air) flow conditions. In this regard, our experimental results are generally consistent with many previous studies that have examined secondary airflow effects in the presence of coastal and desert dunes (e.g. Tsoar, 1983; Rasmussen, 1989; Sweet and Kocurek, 1990; Arens *et al.*, 1995; Frank and Kocurek, 1996; Wiggs *et al.*, 1996; Walker, 1999; Hesp, 2002; Walker and Nickling, 2002; Walker *et al.*, 2006; Baddock *et al.*, 2007; Lynch *et al.*, 2008; Walker *et al.*, 2009; Beyers *et al.*, 2010; Baddock *et al.*, 2011; Jackson *et al.*, 2011; Liu *et al.*, 2011; Weaver and Wiggs, 2011; Chapman *et al.*, 2012). Indeed, many common elements are beginning to emerge (see Baddock *et al.*, 2007). Topographic steering and modulation of the regional wind field by classic transverse dune geometries create a characteristic assemblage of flow zones (i.e. stagnation bubble at the dune toe; flow acceleration and streamline compression up the stoss slope; flow separation at the crest; eddy recirculation in the lee; flow re-attachment and downstream development of a new internal boundary layer) each of which has distinctly characteristic fluid signatures.

Lynch *et al.* (2010) demonstrated that the presence of an eddy recirculation cell in the lee of a dune is dependent on several inter-related factors including the size and geometry of the dune relative to the mean wind speed and approach angle. They quantified the conditions for which flow separation and eddy recirculation were encountered at their study site, and loosely these can be summarized as follows: (a) wind approach angle at the crest that is within ±20° of crest perpendicular flow; (b) a relatively high dune (greater than about 7 m) with sharp-crested geometry and windward stoss slope angles greater than about 16° and lee-side slope angles greater than about 23°; and (c) mean wind speed that is sufficient to create flow instabilities in the lee of the dune. Their findings provide strong support for the Sweet and Kocurek (1990) model, especially the transition from separated flow to attached and deflected flow, although the precise details regarding dune size and slope angles require further investigation and verification. At the meso-scale, then, the nature and degree of topographic forcing seems conceptually understandable, and recent advances in computational fluid dynamics support this contention (Parsons *et al.*, 2004; Beyers *et al.*, 2010; Jackson *et al.*, 2011; Liu *et al.*, 2011).

Figure 10 presents polar plots that summarize the range of incident wind conditions and near-surface wind vectors encountered during this study. Each plot is based on 30-minute averages taken during periods when the wind field was relatively steady in terms of direction and speed. Regional mean wind statistics (appearing in parentheses) were derived from the dune crest tower anemometer (identified by the inverted triangle that sits toward the outermost wind-speed circle on each plot). Figure 11 is a graphic rendering of the flow relationships suggested by the data in Figure 10, and this conceptual model builds on earlier work by Sweet and Kocurek (1990), Walker and Nickling (2002), and Lynch *et al.* (2008, 2010).

For onshore flow conditions (Figure 10 upper left; Figure 11A), there was relatively little topographic steering anywhere across the beach–dune profile, with every station showing less than ±10° deviation from the crest tower direction (184°), even with relatively large mean wind speed ($10{\cdot}5\ \mathrm{m\,s^{-1}}$). The main influence of dune topography was to force reductions in wind speed in front of the dune (i.e. at St 1 and St 2 on the beach and at St 3 and St 4 on the dune ramp), as has been observed by others working on transverse dunes (e.g. Wiggs *et al.*, 1996; Walker and Nickling, 2002; Weaver and Wiggs, 2011).

For obliquely onshore wind (north-northwest and northwest), there were two notable effects due to topographic forcing (Figure 10 middle and lower left; Figure 11B). Firstly, the near-surface wind field on the upper stoss slope (St 9) and dune crest (St 10) was turned toward a more crest-perpendicular (cross-shore, northerly) alignment relative to the upper-air flow on top of the crest tower. For example, when the regional incident wind had a north-westerly approach angle of 113° (i.e. 67° deviation from shore normal), the near-surface wind at St 10 had an approach angle of 132° (i.e. 48° deviation from shore normal), which amounts to about 20° of turning of the near-surface wind in the crest-perpendicular direction relative to the upper-air vector. Secondly, the near-surface wind field across the beach (St 1 and St 2) and dune ramp (St 3 and St 4) was steered into a shore-parallel (alongshore, westerly) alignment, contrary to what happened at the crest where the steering was crest-perpendicular. The degree of steering on the beach yielded deviations of about 10° from the regional wind (in a direction opposite to that on the crest), and therefore the total range of topographic steering of near-surface flow across the beach–dune system was approximately 30° for the same obliquely-onshore regional wind.

The divergence or splitting of the near-surface wind explains, in part, how sediment transport pathways on the beach (alongshore directed) begin to decouple from those on the stoss slope (onshore directed). As the regional approach angle becomes highly oblique (more alongshore), the reduction in mean wind speed at the base and lower stoss of the dune (most evident with onshore wind) becomes imperceptible as more flow momentum is carried across the dune profile, which presents less of a flow barrier given the oblique wind approach (cf. Arens *et al.*, 1995). This has the effect of increasing the transport potential along the beach while reducing the opportunity to deliver sediment to the dune. Sediment transport potential on the dune slope may also decrease because an alongshore wind blows across a significantly greater vegetated fetch, thereby inducing a larger disparity in the transport response on the dune versus the beach.

For offshore conditions (Figure 11C), the influence of dune topography in modulating the regional flow field was more pronounced than for onshore conditions. The polar plot showing offshore flow conditions (Figure 10 upper right) indicates that complete reversals of mean flow direction were recorded at all downwind stations (on the stoss slope) except for the dune crest (St 10) and high above the beach on the tower. Mean wind speed at these downwind stations was less than $2\ \mathrm{m\,s^{-1}}$ with large directional standard deviations, as

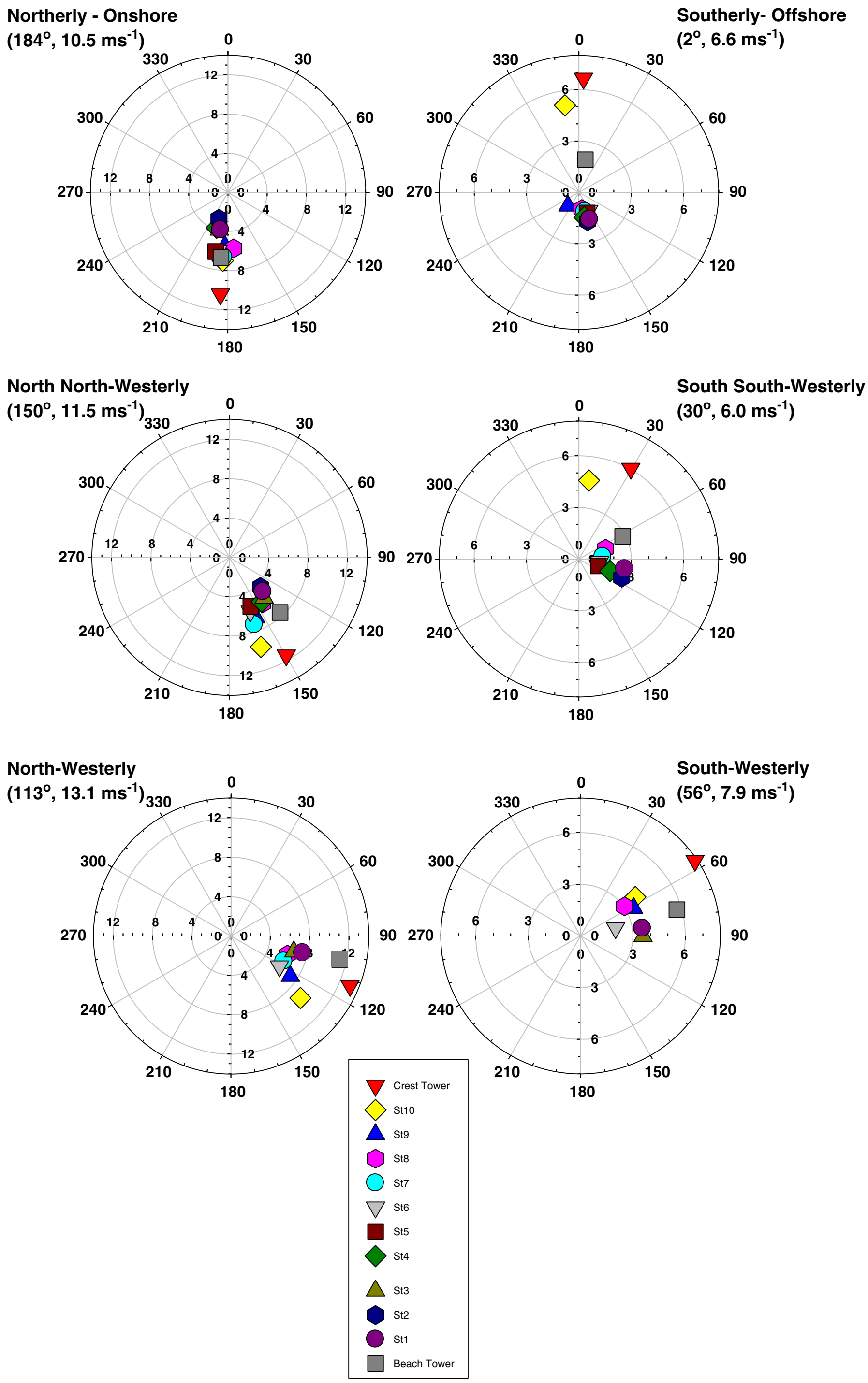


Figure 10. Polar plots showing wind vectors (speed and direction) for stations across the beach–dune profile (refer to Figure 2 for locations) across a range of regional (incident) wind conditions. Data are mean quantities derived from 30-minute blocks of 1 Hz measurements during periods of relative steadiness. Values in parentheses indicate conditions at the top of the crest tower (corresponding to the inverted triangle on each polar plot). Onshore flow is 180°; offshore flow is 360°; and westerly (alongshore) flow is 90°. Wind speed axes for the onshore and obliquely onshore plots (left side) have a larger range than those for the offshore and obliquely offshore plots (right side). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

would be characteristic of lee-side eddy flows in the wake of a bluff body.

When the approach angle is obliquely offshore (south-southwest to southwest), the recirculation eddy on the downwind slope diminishes in size and importance (Figure 10 middle and lower right; Figure 11D). During south-southwest winds (30°) there seems to be evidence of attached and deflected flow at stations St 7, St 8 and St 9 with mean wind angles between 56°–95°, which indicates pronounced steering in the alongshore (westerly) direction. In contrast, the lower stoss (St 5) and beach locations had mean angles of about 110° (i.e. obliquely onshore), which implies that some degree of eddy recirculation still existed on the lowermost sections of the downwind slope of the dune. This is suggestive of a complex, hybrid flow response on the downwind side of this relatively large foredune (> 8 m) during oblique offshore wind. On the dune crest (St 10), there was strong forcing of the flow in the crest-perpendicular direction (as was the case with obliquely onshore conditions; Figures 11B and 11D). When the wind veered to a south-westerly approach angle

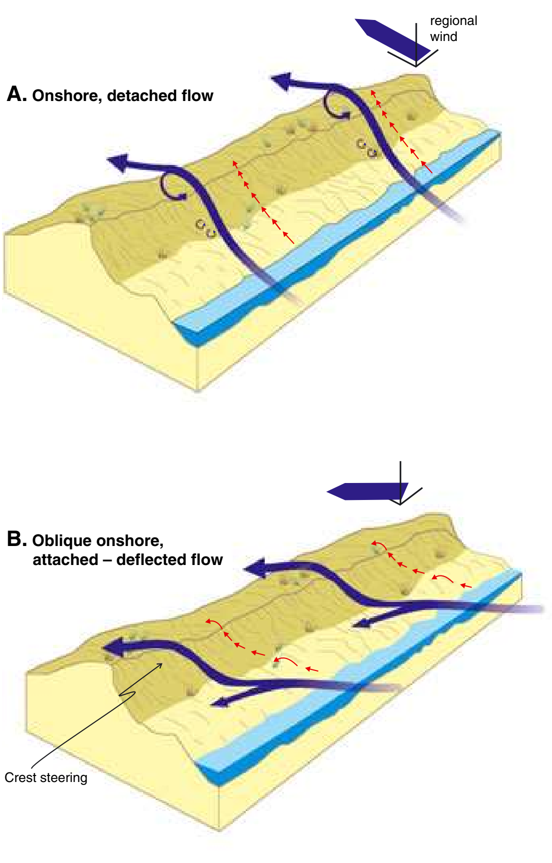


Figure 11. Conceptual model of flow–form interaction over large (> 8 m) foredunes for variable wind approach directions. Large solid arrows correspond to near-surface wind flows, modulated and steered by the local topography. Small arrows show likely sediment transport directions. See text for detailed explanation. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

(56°), there was no evidence for eddy recirculation and the main effect was topographic steering in the alongshore direction, especially on the beach (i.e. attached and deflected flow).

The trends in Figure 10 are generally consistent with the empirical model proposed by Sweet and Kocurek (1990) regarding wind steering in the lee of desert dunes, as well as field evidence provided by Lynch *et al.* (2010) for the transition from separated flow to attached and deflected flow when approach angle becomes more oblique. Nevertheless, there are two significant modifications suggested by the data in our study (and depicted in Fiure 11). The first deals with topographic steering near the dune crest and upper slope when the regional wind has a highly oblique approach angle (up to about ±40° from crest-perpendicular). Our observations indicate that the near-surface wind will be turned to a more crest-perpendicular orientation, as was noted by Arens *et al.* (1995) and Walker *et al.* (2006). Such crest-proximal steering occurs regardless of whether the incident wind is dominantly onshore (Figure 11B) or offshore (Figure 11D). The character and roughness of the topography on the windward side of the dune (whether seaward for onshore wind or landward for offshore wind) will likely impose important controls on the degree of turning as well as the magnitude of flow acceleration up the windward slope. It is not known to what extent, if any, this near-surface flow re-alignment at the crest will affect sediment transport and dune evolution because it is a somewhat localized phenomenon and does not extend down the entire length of the stoss slope (contrary to observations by Walker *et al.*, 2006).

The second modification to the model is that attached and deflected flow can exist not only on the downwind side of the dune (with both onshore and offshore conditions), but also at the base of the stoss (windward) slope of coastal foredunes during onshore conditions (Figure 11B). This is a rather critical effect for beach–dune systems because it implies that there may be strong alongshore flow vectors on the beach when the regional wind is either obliquely offshore (as demonstrated by Lynch *et al.*, 2010) or obliquely onshore (as recorded in this study and in previous studies such as Arens *et al.*, 1995). Such alongshore flows have the potential to drive large amounts of sediment transport along the beach because of unlimited fetch restrictions, and even slight onshore obliquity can yield substantial landward sand flux that may be important to repairing wave-cut scarps and building dune ramps (Ollerhead *et al.*, submitted). Evidently, such dune ramps are critical to enabling sediment transport from the beach to the lower stoss slope of the dune.

Sediment response across beach–dune systems

The sediment transport data collected during this study indicate that the near-surface response to seemingly simple regional wind conditions can be very complex and spatially disjoint. With moderate onshore wind (April 30; Figure 3), only the station on the lower stoss (St 5) immediately above the dune scarp showed transport activity, and even then for a limited time at very low intensity. In contrast, with moderate offshore wind of approximately the same upper-air mean speeds (May 2; Figures 4–6), sediment was mobilized near the crest as well as the beach, but not on the lower and mid-stoss. Sediment transport on the crest is expected because flow acceleration up the windward (landward) slope of the dune should yield near-surface speed-up and large surface shear stress. However, transport on the beach is less easily explained during offshore flow because the beach is in the wake of the dune and wind speed is expected to be reduced. Nevertheless, transport on the beach occurred in this study as soon as the regional wind approach angle became sufficiently oblique to the dune profile to cause significant topographic steering on the downwind (seaward) slope. Under these conditions, the near-surface wind vectors on the beach turned to alongshore and increased in speed. This indicates a strong decoupling of the transport system on the beach from that on the dune even though the timing of wind and transport peaks and lulls across the beach–dune profile were simultaneous.

When the wind was dominantly alongshore (May 3–4; Figures 7–9), sediment transport on the beach was not initiated until both the regional and near-surface wind vectors veered to slightly onshore. This is likely not so much a directional effect as it is a consequence of wind speed increasing significantly on the beach at the same time that the wind veered from obliquely offshore to obliquely onshore. Sediment transport on the stoss slope of the dune did not activate until much later, despite similar increases in wind speed, perhaps because much stronger onshore wind is required to penetrate the vegetation layer. In addition, there may have been confounding issues related to surface moisture effects (and drying processes) during this study.

Summary and Conclusions

The results from this field study demonstrate that regional (upper-air) wind fields can be strongly modulated by the presence of large coastal foredunes in ways that lead to complex, near-surface flow vectors and sediment response. At meso-scale, the nature of these flow–form interactions is increasingly predictable, and many prior field-based and modeling studies have documented features similar to those measured during our study. In particular, our results are consistent with (a) the development of a lee-side, recirculating eddy during onshore (and offshore) flows that are oriented perpendicular to the dune crest to within $\pm 20°$, (b) a transition from flow *detachment* to flow *attachment* and alongshore *deflection* on the downwind slope of the dune as the regional wind veers from perpendicular to oblique approach angles (i.e. greater than 20°), and (c) flow reduction at the dune toe and flow acceleration toward the upper stoss when the regional wind is onshore. In addition, we have documented alongshore deflection of flow on the beach fronting the dune when regional approach angle is obliquely onshore, as well as strong topographic steering at the crest and upper stoss that aligns the near-surface wind in a crest-perpendicular orientation. These combined steering influences lead to a decoupling of the beach and dune regimes. The inability of the beach system to contribute sediment to the dune slope can be exacerbated by the presence of a wave-cut scarp at the base of the dune.

This study is one of only a small number of field-based experiments that have successfully measured sediment transport flux at high frequency (i.e. 1 Hz or greater) alongside detailed wind parameters across an entire beach–dune system (cf. Lynch *et al.*, 2008; Chapman *et al.*, 2012). Although the transport data are not considered to be definitive in regard to identifying generalized sediment pathways across beach–dune systems, the spatial and temporal complexity that is evident from this study seems characteristic of coastal environments in particular and argues against the use of regional wind measurements (obtained from meteorological stations distant from the site) for purposes of sediment transport prediction and coastal zone management. In addition to flow–form interaction at the scale of dunes, various micro-topographic features, such as hummocks, incipient blowouts, and erosional scarps, will further modify inner boundary layer dynamics leading to extreme flow complexity. Add to this the wide range of 'supply-limiting' factors such as differences in textural composition, surface moisture, vegetation, and cohesive binding agents, and it becomes evident why sediment transport response along coasts is notoriously difficult to predict (Bauer *et al.*, 1996; Sherman *et al.*, 1998; Delgado-Fernandez and Davidson-Arnott, 2011).

It is increasingly evident that topographic modulation of the regional wind at meso- and micro-scales will force significant changes in wind speed and wind direction (and perhaps also, turbulent signatures) close to the sand surface, and that a better understanding of these flow–form interactions will be central to understanding transport response. Nevertheless, even such detailed knowledge may prove inadequate for predicting dune evolution and form maintenance. There is little empirical evidence to suggest that sediment flux can be predicted to within an order of magnitude even under fairly ideal field conditions, let alone considering the complexities inherent to a beach–dune system. Moreover, it seems likely that for complex sloping surfaces such as the stoss of a dune, the direction of the sediment flux vector will not align perfectly with the wind vector. Thus, if we are to continue on the path of empirical reductionism, we should be deploying sediment flux sensors that provide information on both flux magnitude as well as flux direction in conjunction with three-dimensional wind sensors. Until such flux sensors are developed, it is advisable to measure detailed patterns of deposition and erosion (using erosion pins or detailed surveying) across the beach–dune profile in order to understand what the geomorphic effectiveness of various wind events has been. Treating wind as a true vector quantity is a first step toward understanding sediment flux as a closely coupled vector quantity, which is critical to understanding patterns of erosion and deposition that are driven by spatial gradients in transport flux ($\nabla \cdot q$).

Acknowledgements—The authors thank Rhiana Bams and Connie Chapman for able assistance and good humor in the field. They also thank the Park staff, especially Allan Doyle (Maintenance Supervisor), Kirby Tulk (Park Ecologist) and Roger Steadman (Park Warden) for help and encouragement. The Mount Allison Coastal Wetlands Institute, funded by the Canada Foundation for Innovation (CFI), provided logistical support. The study was supported financially by grants from Prince Edward Island National Park to RDA *et al.* and by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) to RDA and IJW. PH acknowledges support from NSERC and an LSU faculty research grant. Cheerful graphical assistance was provided by Marie Puddister. Three anonymous reviewers and the special issue editors provided constructive comments that vastly improved the manuscript.

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