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Foredune accretion under offshore winds

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Abstract

Experiments carried out at Magilligan Strand on the north coast of Ireland suggest that topographic steering of offshore winds is an important facet of the aeolian sediment transport system at this location. A five-day study (18-22 June 2005) investigated the pattern of airflow over the foredune while simultaneously collecting data on sediment flux. A simple instrument setup was used to characterise the airflow: a sonic anemometer was placed at the dune crest, with another on the mid-beach. Horizontal traps, electronic and integrating, measured sediment flux on the supra-tidal beach. Results show that offshore wind flow deviated from its original direction in the lee of the dune (seaward of foredune). The change in direction was not a simple steering of flow to a singular new direction, but rather flow separation resulting in turbulent multidirectional flow – including reversal. Traps located at the foot of the dune scarp recorded sediment transport during events forced by offshore winds. Data from sediment traps, wind and observational evidence have been used to argue that sedimentation was occurring in this zone. When budgeting for sediment movement within beach-dune systems it is important to take into account the effect of secondary airflow patterns during offshore winds and their role in constructive processes of foredune formation, particularly in post-storm recovery.

Keywords*:* Aeolian; Topographic steering; Post-storm recovery; Offshore wind; Sediment budget

1. Introduction

The core requirement for quantification of the aeolian component of a sediment budget is to identify winds capable of sand transport. Offshore winds are usually excluded from such calculations because they experience the sheltering effect of the foredune, with the incident wind speed dropping below the threshold necessary for the entrainment of sediment grains (e.g. Sarre, 1989). Indeed, data concerning offshore winds, although recorded, are often deliberately excluded because of assumed unimportance (Nordstrom et al., 1996). At locations where the predominant wind is offshore, such as Magilligan Strand, this may be a considerable methodological miscalculation.

Early research on desert dunes described flow separation at the crest resulting in a shadow zone as ‘filled with swirls and vortices’ and characterised by grain fall (Bagnold, 1941). Further field research into airflow patterns in dune systems (e.g. Arens et al., 1995; Frank and Kocurek, 1996; Hesp, 2002; Kocurek et al., 1992; Tsoar, 1983; Walker, 1999; Walker and Nickling, 2002) as well as wind tunnel studies and numerical modelling (Parsons et al., 2004a,b; Schatz and Herrmann, 2006 ; van Boxel et al., 1999; Walker and Nickling, 2003) has yielded a more detailed understanding of lee-side air flow. The three broad categories--attached and undeflected flow, attached and deflected flow, and separated flow--determined by Sweet and Kocurek (1990) and modified by Walker and Nickling (2002) are dependent primarily on dune topography and the approach angle of the wind. Each type of secondary flow would be assumed to affect the sediment transport system in different ways. Generally speaking, the attached airflows should be capable of entraining sediment in the lee of a dune if competent on the windward side, while a separtated flow should experience a significant reduction in ability to move sediment on the leeward side. Although separated airflow is characterised by an increase in turbulence, Wiggs et al. (1996) have shown that a drop in velocity below an assumed threshold level does not necessarily lead to a cessation of sediment transport if enhanced turbulent conditions prevail. The turbulent flow increases shear stress and thereby continues to entrain grains into the flow field. This ability to move sediment under reverse flow, associated with flow separation, should result in a process capable of moving sediment counter to the primary direction of airflow.

While there is considerable evidence indicating the general absence of a lee eddy in most desert dunes (Sweet and Kocurek, 1990), the topographic shapes required for this type of reversing flow might be more common in coastal environments. The latter are invariably steeper and often sharp-crested – especially scarped foredunes. The morphology of non-vegetated desert dunes is largely adapted to the airflow, tending toward turbulence reduction and formation of an aerodynamic shape; coastal foredunes, however, cannot achieve this aerodynamic shape because of marine erosion and the influence of vegetation on the dune form (Arens, 1996).

Very few studies report coastal aeolian transport under offshore wind conditions. Arens (1996), Gares et al. (1996) and Nordstrom et al. (1996), are examples but none of these studies identified a coherent lee-side eddy. Hesp et al. (2005) and Walker et al. (2006) describe the effects of onshore and alongshore airflows over foredunes and contain detailed descriptions of topographic steering. Hesp (2005) highlighted the potential of offshore airflow as a significant process in sedimentary environments, describing climbing dunes (up to 250 m in height) in the lee of bedrock cliffs that are attributed to flow reversal of offshore winds.

This paper describes the topographic steering (a redirection of incident flow in the lee of, and because of, a topographic feature) of offshore winds over a complex foredune terrain. The modified airflow is shown to have entrained sediment and moved it landward.

2. Regional Setting

The field site was on Magilligan Strand, Co. Derry, Northern Ireland (Fig. 1). The beach is approximately 6 km in length and extends from Magilligan Point at its northwestern extremity to Benone Strand to the southeast. It has a northeastern orientation on the margin of the Atlantic Ocean, and forms the seaward edge of a large Holocene foreland (Carter and Wilson, 1990). The beach has experienced alternating periods of accretion and erosion over the last decades. The tallest seaward dune crest, running nearly the entire length of the beach, appears to be an old erosional escarpment formed during a 1980 storm (Carter and Stone, 1989). (Figure 1)

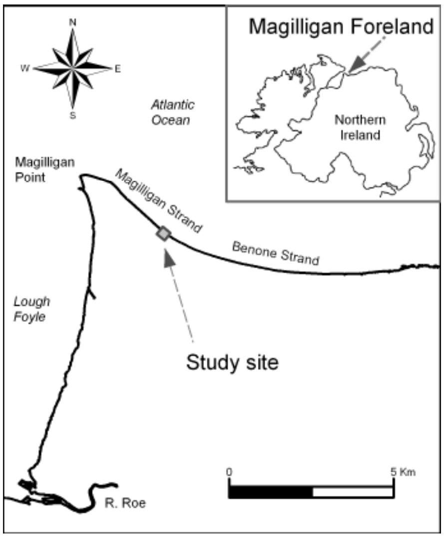

Figure 1. Field site location.

The site itself is at the centre of a ~1 km-long segment that has been accreting since that time. The accretional section, ~ 5 m in width and ranging from 6-7 m in height, has developed against the old scarped dune, which varies in height from 10-12 m along the accreting section. A storm during the winter of 2004-5 eroded the foredune left a scarp of approximately 4 m (vertically) and removed the dune ramp and lowered the beach slope. The beach is wide (up to 100 m at low tide), planar and dissipative, and has a tidal range of ~1.54 m (Jackson et al., 2005). A small sand bar (10 cm height) had welded to the beach at a position just seaward of Trap 1.

Landward of the crest are a series of ridges parallel to the shore. The tallest of these reaches 12 – 14 m in places and is approximately 100 m inland of the crest and separated by a valley floor at 4–5 m Ordnance Datum (OD) Belfast. The landward slope of the foredune crest is 18°, with a 25° slope on the seaward side (Fig. 2). The dunes are densely vegetated with no sediment available for transport landward of the crest, while on the seaward slope, vegetation (*Ammophila arenaria*) is more spatially varied and grows to a height of approximately 1.5 m. (Figure 2)

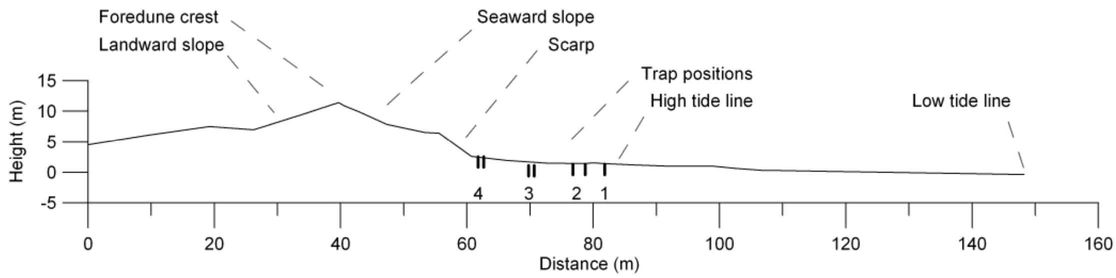

Figure 2. A surveyed cross-section of the site reveals a sharp-crested foredune ridge, with a landward slope of 18° and a seaward slope of 25°, a scarped foredune and a wide planar beach.

3. **Methodology**

Two sonic anemometers (Windsonic by Gill Instruments Ltd.) were deployed to gather velocity and direction data. Each was placed at 0.5 m height, one at the foredune crest and the other 33 m seaward on the sub-aerial beach (Fig. 3). Because the airflow was expected to be of a turbulent nature, the beach anemometer was placed close to the sediment surface to best represent the winds that were moving sediment; the anemometer at the crest matched this height. While topographic variation existed on the beach surface (aeolian ripples 2 – 3 cm height and a sand bar located approximately 10 m seaward of the beach anemometer) the influence of these features on the instrument readings were considered to be minimal in comparison to the larger-scale turbulent structures of the wind pattern in the lee of the foredune. The Windsonic anemometer does not record a vertical component, nevertheless, it has been shown by Sterk et al. (1998) and Leenders et al. (2005) that the horizontal gust structures of turbulent flow are better correlated with sediment entrainment than the vertical component. The instruments were logged simultaneously to a desktop computer on-site. (Figure 3)

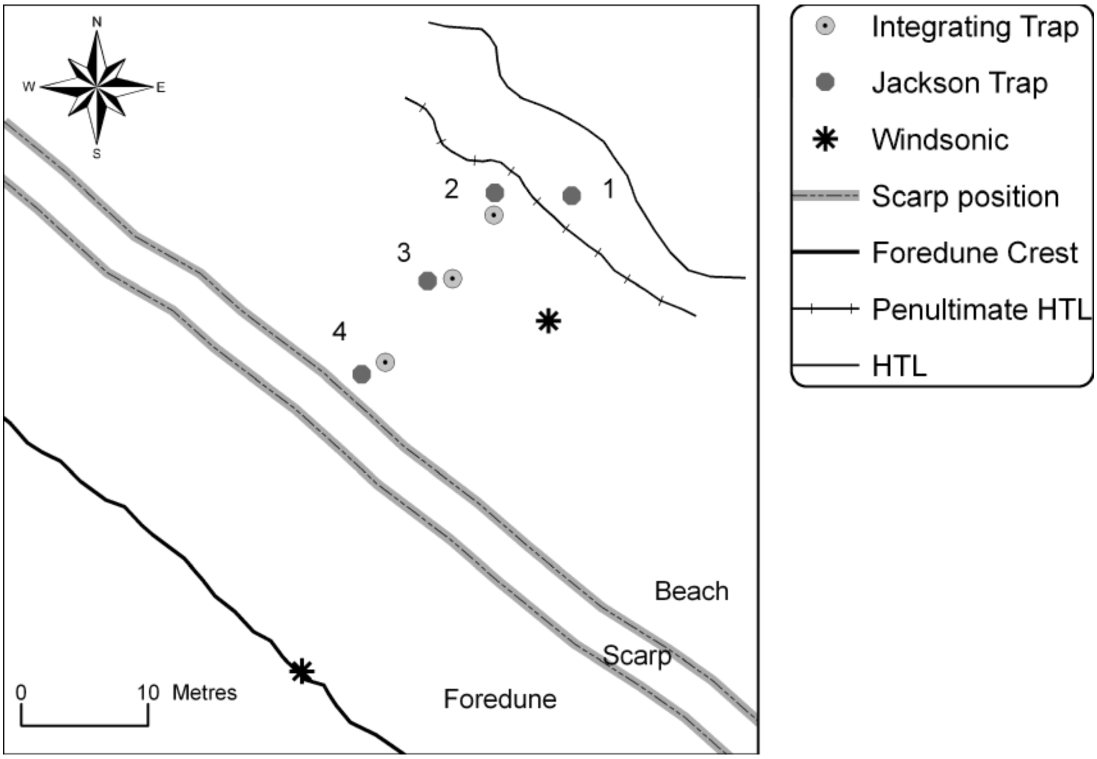

Figure 3. Instrumentation layout.

Sediment transport flux was measured using two types of horizontal traps. Four electronic traps (Jackson, 1996), utilising a tipping bucket mechanism mounted on a load-cell, were placed along a shore-normal transect. Logging frequency was 1Hz and memory capacity allowed 2hr 30minutes of recording before downloading was necessary. In close proximity, also in a shore-normal alignment, were placed three integrating traps (IT). These traps are essentially the outer shell of the electronic traps with the tipping bucket mechanism replaced by a plastic container. This container was replaced once every hour. The content was then weighed on site using a standard balance. While trapping efficiencies have not been quantified for these sand traps, they are assumed to be quite efficient. They are installed flush with the surface and as such have very little impact on the airflow; they are omni-directional and collect sediment moving by reptation and saltation (irrespective of saltation height or hop length). Like all traps, they are liable to sediment bypassing because of limited spatial coverage. Inaccuracies from the loading of the load-cell by the wind alone is not proven , however, if present may be more likely under conditions where the airflow has an enhanced vertical component. The use of the integrating traps helps negate this issue. Instrument positions and profile data were surveyed with a Trimble 4400 Differential Global Positioning System.

Observations of types of sediment transport and indicators of net transport were recorded before and during the transport event. From a vantage point at the top of the dune scarp, sketches of sediment transport types were recorded. The general orientation of aeolian ripples on the beach was recorded to give an indication of the net transport direction at various times throughout the day. Using a ruler, a crude estimation of accretion or deflation was noted at two locations: at an impact sensor, located close to the beach anemometer, the distance from a mark on the sensor to the sediment surface was recorded (the impact data are not presented); on the welded bar the depth of erosional features were measured after the transport event had ended.

4. Results

4.1 Wind Data

The 1Hz wind velocity data were smoothed using a 5-minute moving mode (Fig. 4). Three distinct incident wind directions are clear from these data. Firstly, from 18-19 June an obliquely offshore wind direction is evident at the dune crest. Secondly, the period 19-20 June exhibits an onshore wind while most of the remaining time experienced directly offshore airflow. (Figure 4)

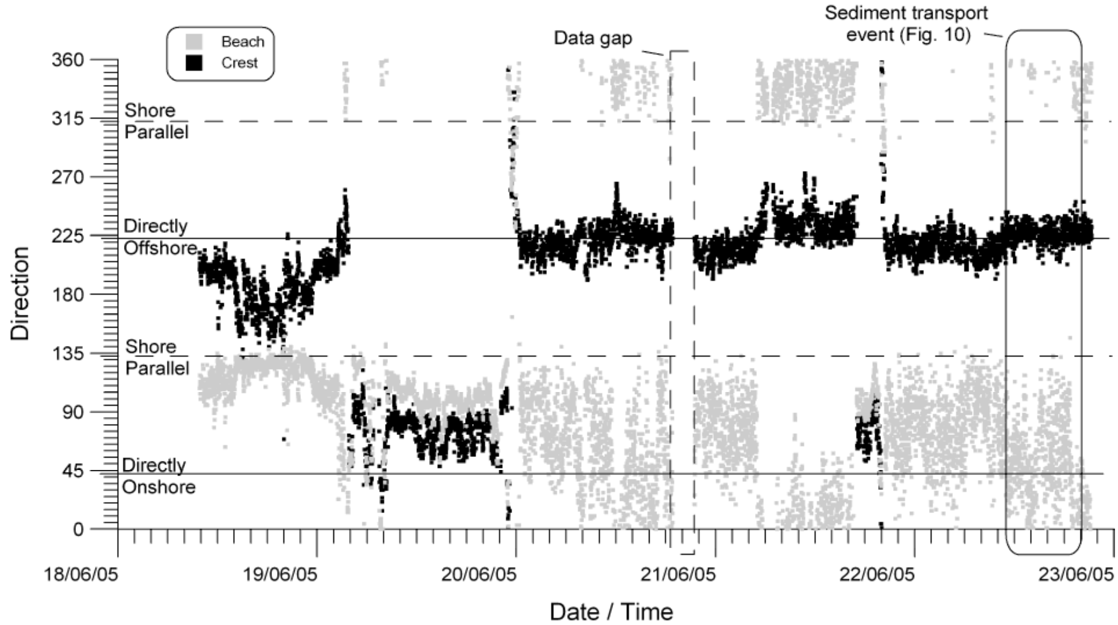

Figure 4. 1Hz Windsonic data smoothed using a 5-minute moving mode. Crestline orientation of 130° -310° results in a directly offshore azimuth of 220° and a directly onshore direction of 40°. Three distinct approach directions are clear from these data: An obliquely offshore wind event [18 June], an onshore wind event [19 June], while the remainder of the period experienced nearly constant directly offshore winds [20, 21, 22 June].

It is clear from Figures 5 and 6 that these offshore winds followed secondary pathways in the lee of the dune crest. During the period 18-19 June (Fig. 5), the leeside flows were steered to a shore-parallel direction. The rose diagrams, grouped at 15° intervals, clearly show that the oblique flows were deflected alongshore. The winds perpendicular to the crest, 20-23 June, had a more varied set of secondary leeside flow directions – including 180° reversal and lacking any offshore component (Fig. 6). (Figure 5)(Figure 6)

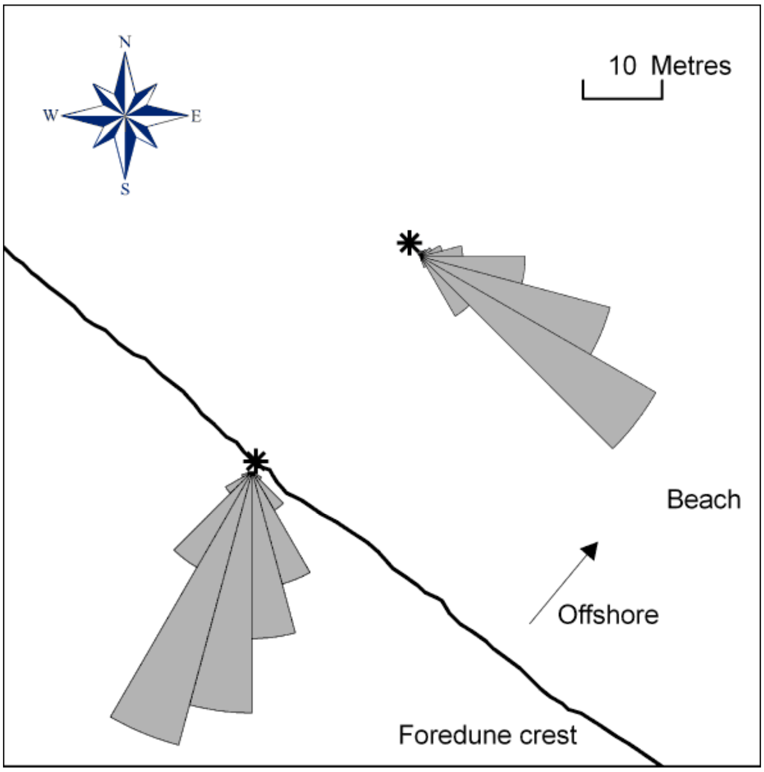

Figure 5. 1° wind direction data, recorded at 1Hz and grouped at 15° intervals, from 18 June 09:45 to 19 June 03:45. Oblique offshore airflow is deflected parallel to the shore in the lee of the dune (Wind roses are not to scale).

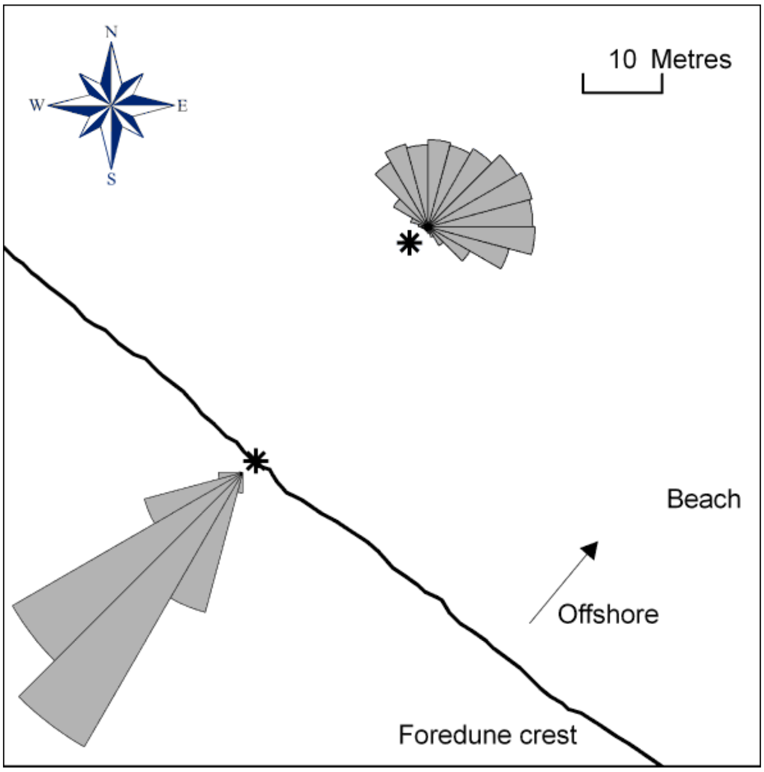

Figure 6. 1° wind direction data, recorded at 1Hz and grouped at 15° intervals, from 20 June 00:00 to 21 June 16:40. Directly offshore airflow exhibits multiple secondary flow directions in the lee of the dune, including 180° reversal (Wind roses are not to scale).

Wind velocity data for the first ten hours and the last six hours of the study period (Fig. 7 and 8) show two separate trends related to wind direction. Figure 7 represents an oblique offshore event and illustrates wind speed at the crest and on the beach to be relatively similar. For a similar crestal velocity, (shown in the latter part of Fig. 8), the directly offshore wind showed a marked reduction in velocity on the beach surface. The Coefficient of Variance (CV:a statistical measure of turbulence) was calculated for these two periods (Table 1) using the formula:

$$CV = (\text{Standard deviation} / \text{Mean}) \times 100 \qquad \text{Equation 1}$$

The CV values at the crest and on the beach are similar for the oblique offshore period. CV values for the directly offshore period display an increase in turbulence in the lee of the dune crest (35% at the crest and 54% on the beach). (Figure 7)(Figure 8)

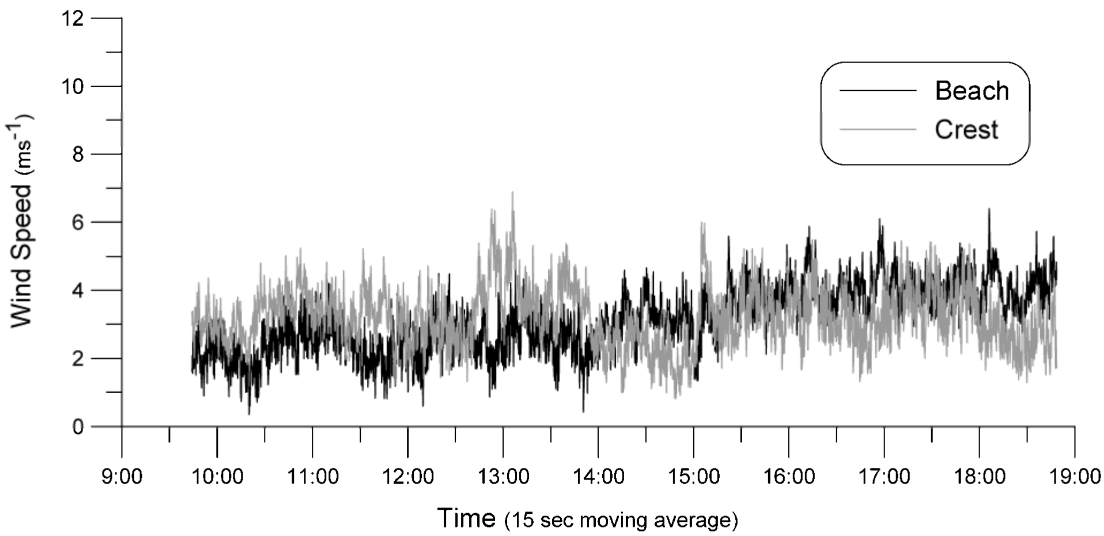

Figure 7. 1 Hz wind velocity data, smoothed using a 15-second moving average, from 09:45 to 18:48 [18 June]. Little difference exists between crestal and beach velocities.

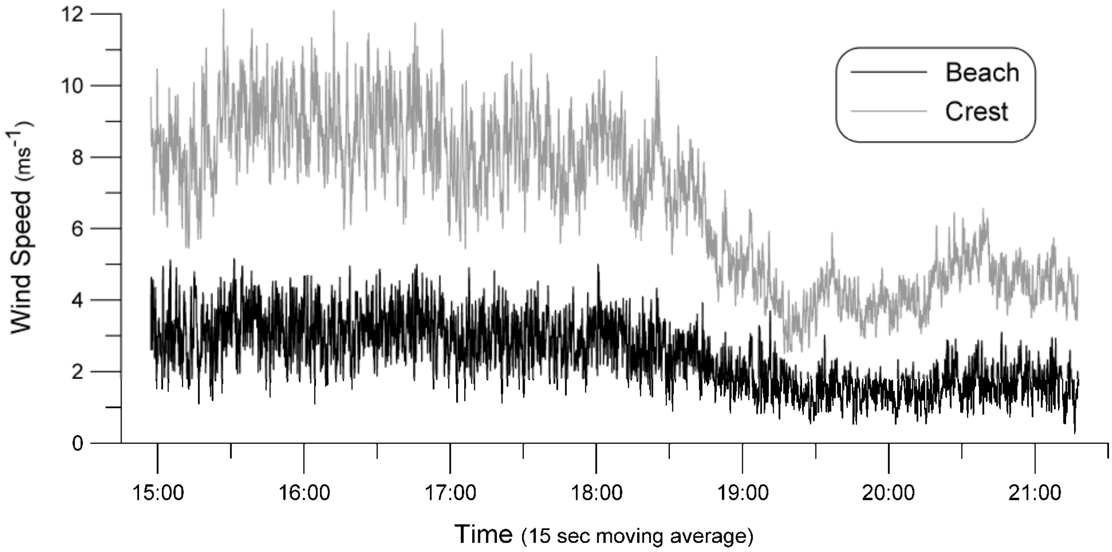

Figure 8. 1 Hz wind velocity data, smoothed using a 15-second moving average, from 14:57 to 21:17 [22 June]. Note the distinctive reduction in velocity between the crestal and beach values, characteristic of flow separation at the crest.

4.2 Sediment Transport:Trap Data

A sediment transport event occurred on 22 June 2005 under primarily offshore winds (Fig 2). This event lasted for approximately nine hours from 11:00 to 20:00. Electronic trap data are presented for the period 16:00 to 18:00. A longer data set was collected for the integrating traps, from 07:00 to 20:00. The electronic trap data reveal little correlation between the rates of transport and wind speed or direction. Comparing flux and wind speed yielded coefficient of determination (r^2) values ranging from 0.00 to 0.39. Averaging times from 5 seconds up to 1 minute were used. The r^2 values for flux compared to wind direction were lower, 0.00 to 0.02. The poor association between sediment flux and wind speed and direction can be seen in a time series plot (Fig. 9). A sample 10-minute period [22 June 16:50-17:00] of electronic trap 3 data is presented in the figure. This period is representative of the entire data set. Linear regression analysis of this subset gave r^2 values of 0.09 for wind speed and 0.01 for direction. (Table 1)(Table 2) (Figure 9)

Table 1. Velocity data statistics for the periods 09:45 - 18:48, 18 June 2005 (Obliquely off shore wind) and 14:57 – 21:17, 22 June 2005 (Directly off shore win). The increase in the Coefficient of Variance between the dune-crest and the beach for directly offshore winds indicates an increase in flow turbulence.

	Obliquely offshore wind		Directly offshore wind	
	Dune crest	Beach	Dune crest	Beach
Mean ($m\ s^{-1}$)	3.19	3.15	6.77	2.47
Standard Deviation ($m\ s^{-1}$)	1.07	1.14	2.35	1.29
Coefficient of Variance	34%	36%	35%	52%

Table 2. A comparison of integrated electronic trap data with data from integrating traps reveal a similar trend: the mid-beach trap (Trap 3) consistently collected more sediment than the other traps.

22-Jun-05	Intertidal beach Trap 1	Lower beach Trap 2	Mid beach Trap 3	Dune foot Trap 4
Jackson Trap (g)				
16:00 - 17:00	402	534	1259	562
17:00 - 18:00	319	156	1484	354
Integrating Trap (g)				
16:00 - 17:00	no trap	384	940	580
17:00 - 18:00	no trap	226	639	456

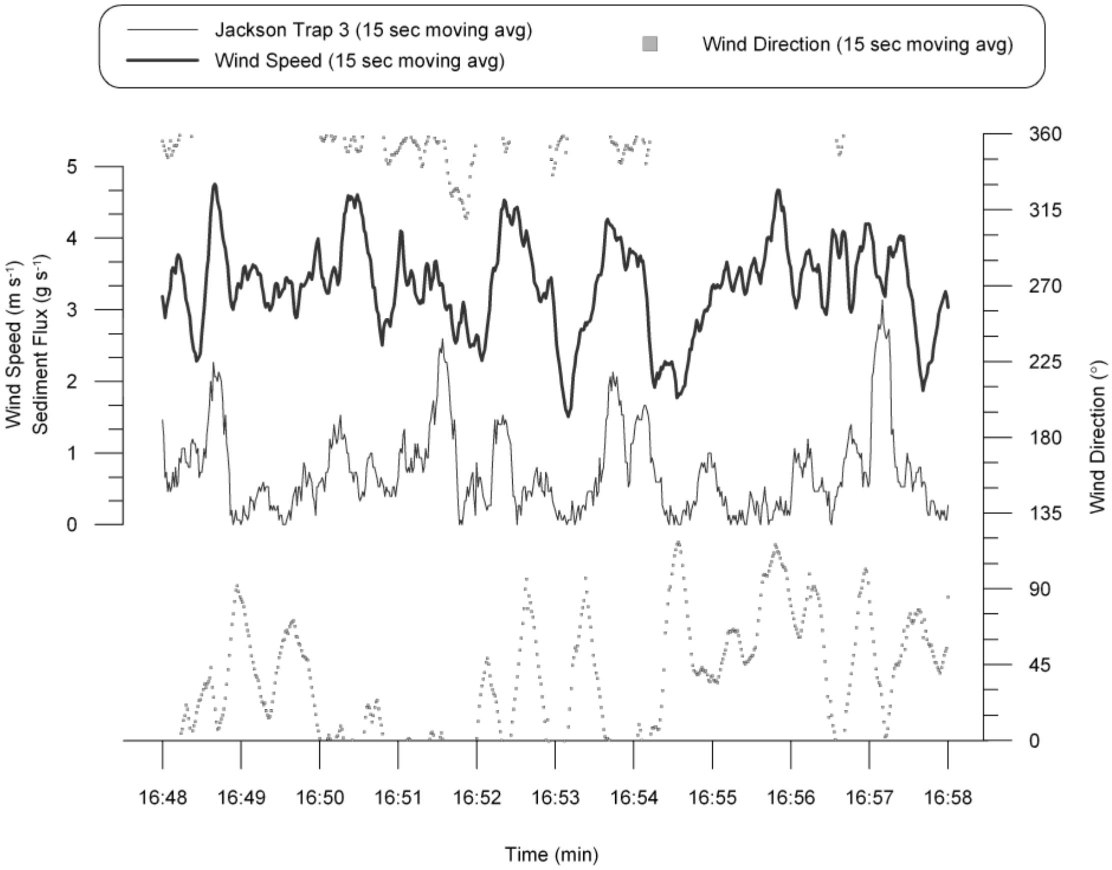

Figure 9. A sample 10-minute period [22 June 16:50-17:00] of 1 Hz electronic trap data showing little relationship between sediment flux and wind speed or direction.

The 1Hz trap data were totalled for each hour and compared to the integrating trap results for the same period (Table 2). Spatially these results show that sediment was moving in all areas across the supra-tidal and intertidal beach. Trapping position 3 (the mid beach) consistently collected more sediment than the other traps. The traps at the dune foot collected similar amounts to those of the lower and intertidal beach traps. The spatial variations evident in the integrated electronic trap data were reflected in the IT data, although some disparity occurs in absolute amounts collected (Table 2).

Over the course of the event, the results from the integrating traps reinforced the view that longer time steps better characterise the relationship between sediment transport and wind data (Fig. 10). Temporal fluctuations in sediment transport were well explained by changes in wind speed (r^2 values ranged from 0.67 to 0.88 for the three traps). The wind direction data bore little relationship to the rates of transport (r^2 ranged from 0.04 to 0.07). The spatial pattern evident in the electronic trap data was consistent throughout the nine-hour event. Higher yield on the lower beach compared to the dune foot was sustained up to 14:00, while after this time the dune foot traps collected slightly more sediment (Figure 10).

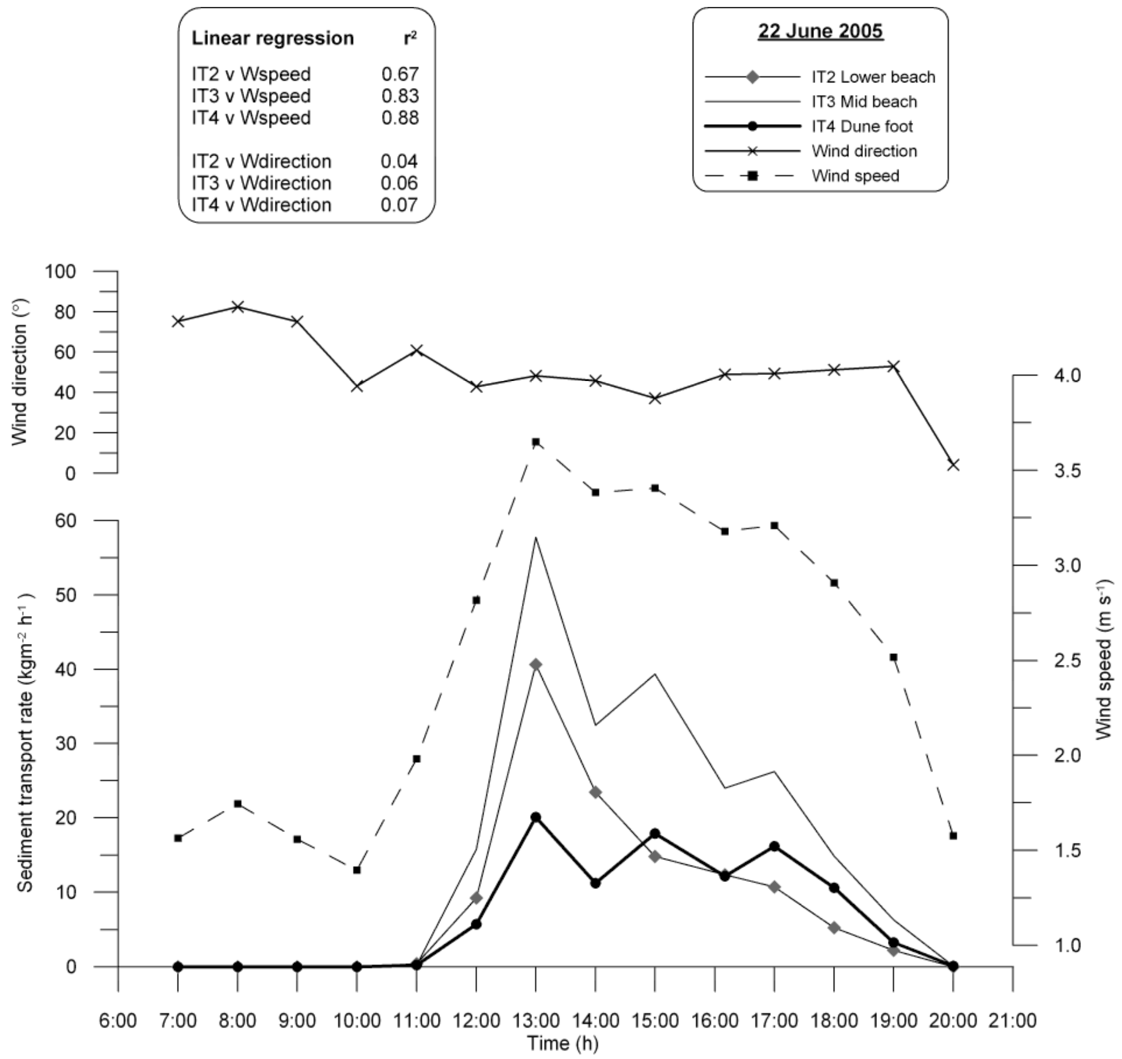

Figure 10. Integrating trap data [22 June 2005] shows a temporal and spatial pattern for the sediment transport event.

4.3 Sediment Transport: Observational Evidence

Figure 11 shows the different types of sediment transport events that were observed during the event. Transport of sediment originating from a central point and spreading out in a relatively uniform pattern in all directions was attributed to discrete pockets of downward wind - vertical bursting. In addition to transport by this distinctly vertical wind motion, rotational forms such as dust devils and streamers also occurred. These types of sediment transport events occurred simultaneously, sporadically and in multiple directions. Observations at the time also noted sediment being blown from the crest of the embryonic dune ramp onto the dune scarp itself.

Ripple-crest orientation was noted - prior to 2:30pm - to be shore-normal (i.e. alongshore transport conditions prevailed) and was then seen to switch to shore parallel (cross-shore transport). Even though highly variable transport conditions occurred during this time, ripple formation and orientation indicate some degree of organisation within the system. (Figure 11)

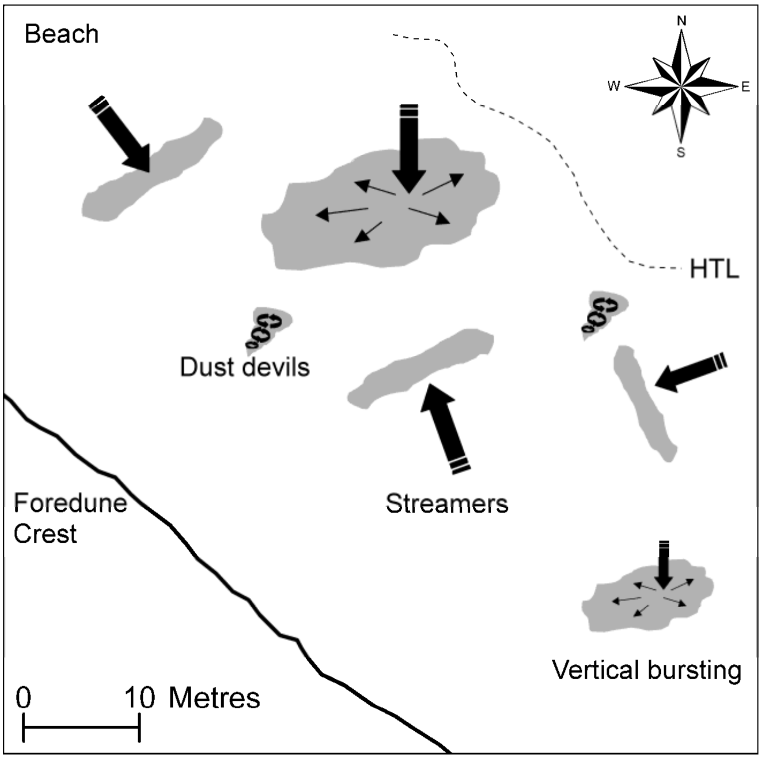

Figure 11. Observational evidence of sediment transport on the beach [recorded 22 June 2005 during directly offshore winds]: Sediment transport by vertical bursting, dust devils and streamers were occurring simultaneously, sporadically and in multiple directions.

Approximately 1 cm of deflation was noted between electronic traps 2 and 3. Deflation was also observed on the surface of a sand bar that had welded to the beach, at a position just seaward of Trap 1. Drying during the day, probably enhanced by the turbulent conditions, was followed by deflation of the dry sediments leaving small erosional features on the bar surface, also in the order of 1 cm vertical relief.

5. Discussion

5.1 Airflow

The salient observation to be made of the wind record over the course of the study is that the offshore winds recorded at the crest (12 m) were not blowing in the same direction as at 33 m (2.75 crest lengths) to the lee of the dune on the beach (Fig. 4). The adjustments of the wind speed and direction in the lee of the dune were analysed to determine what type of flow resulted from the wind-topography interaction, with the flow approach angles separated into two distinct sets - obliquely offshore and directly offshore.

Obliquely offshore winds changed direction in the lee of the crest (Fig. 5). Incident directions in the 150° - 225° envelope were deflected shore parallel to 75° – 150° along the beach surface. The similar distribution of angles (75° arc) between the incident and secondary flows suggests little or no increase in turbulence, as might be expected for attached flows. Also characteristic of flow attachment is the similarity between the crestal and leeside wind speeds exhibited by obliquely offshore winds (Fig. 7). The CV turbulence values for these data differ little, crest (CV=34%) and beach (CV=36%), further supporting a scenario in which the flow has remained attached. Therefore, the secondary airflow patterns resulting from oblique-to-crest incident airflow were inferred to have been attached and deflected.

Turbulence generation and velocity reduction, which are characteristic of flow separation and the formation of a lee eddy, are evident in the data concerning directly offshore winds. An increase in turbulence is inferred from multidirectional winds (195° arc) on the subaerial beach in contrast to the fairly steady winds (60° arc) at the crest (Fig. 6), while a 64% velocity deceleration is evident from the crest to the beach (Fig. 8). The increase in the beach CV turbulence value, (CV=54%), compared to the crestal value (CV=35%), is also consistent with these inferences. The contrast between directly offshore and obliquely offshore flow is clearer when similar crestal speeds are considered (Fig. 7, latter section of Fig. 8). From this evidence it is probable that a recirculation cell develops under directly offshore flows and is possibly in the form of the roller vortex or roller helix model described by Kocurek and Sweet (1996, pp 123).

It is interesting to note that although flow reversal has been observed at the Magilligan site, it was not evident at Arens' (1995) site 2 or site 3, where the dune lee and stoss slopes were quite similar. The very narrow crest line at the Magilligan site compared to the 50 m-wide crest in the Arens (1995) study may have enhanced flow separation in this zone and, thus, caused the reversal of the flow.

5.2 Sediment transport

The most important aspect of the sediment transport results is that sediment was delivered to the foredune foot under offshore winds. While no deposition data have been recorded by this study the evidence points to deposition in this zone. First, the primary airflow direction is offshore with an onshore airflow evident on the mid-beach (Figs. 2 and 10). Second, the electronic and integrating traps recorded transport in this area. Third, observations noted direct sedimentation on the foredune escarpment. Fourth, although sediment transport was highly variable, the net direction of transport was onshore as shown by the orientation of aeolian ripples. The dune foot integrating trap recorded rates of transport of up to 20 kg m^{-2} h^{-1}, and it is probable that the rate of deposition on the growing dune ramp or on the scarp itself were close to this value. This indicates that sediment was available to aid in the post-storm recovery of the beach-dune interface.

At instantaneous time scales, poor correlation between sediment flux and wind speed is widely reported in the literature. The results reported here add to this body of knowledge while reporting on a probable cause - the secondary airflow patterns in the lee of a coastal dune. The high yield for the mid beach trap (Trap 3) might be because it was located within the reattachment zone where highly turbulent conditions contribute to grain entrainment, whereas at the three other trap locations, slightly more organised flow might not be as competent in moving sediment. This is a speculative explanation of the increased rate of transport at the mid-beach location; an improved spatial array of instrumentation would be required to fully quantify and describe the patterns of sediment transport under these complex secondary airflows. If reattachment is occurring on the subaerial beach (the observations of vertical bursting points to this), it has implications for trap type and placement. A simple cross-shore transect will not be adequate to represent multidirectional sediment transport. If, however, the recirculation cell extends into the surfzone (as in Hesp 2005), the return flow may be similar to an onshore wind and be suited to a cross-shore transect trap arrangement. The same can also be said for the influence of fetch distance; in the former case fetch distance is not applicable because no singular leading edge of erodible material exists, while in the latter it should be valid.

The findings of this study have important implications for Magilligan Strand and similar locations on leeside coasts. At Magilligan Strand winds from the southwestern sector dominate and it may now be assumed these are contributing to the maintenance and growth of the foredunes in a more significant way than previously thought. Deflected flows move sediment alongshore in both directions, switching regularly, this redistribution maintains sediment on the subaerial beach that is then available for transport into the dunes when conditions are right with either an onshore wind or a flow reversal of offshore winds.

6. Conclusions

This study has shown that sharp-crested dune topography influences offshore flow to such an extent that secondary flows in the lee of the dune, on the sub-aerial beach, no longer blow offshore. Offshore-directed flow becomes deflected or reversed in the lee of the dune depending on the approach angle of the incident wind. This results in sediment movement alongshore or onshore. This study has recorded sediment transport in the dune foot area under offshore wind conditions. Sediment trap data, wind data and observational evidence have been used to argue that sedimentation was occurring in this zone. This has significant implications for long-term beach-dune evolution and post-storm recovery. Offshore wind, commonly discounted, has the potential to be an important driver in beach-dune evolution and should be taken into account when compiling sediment budgets.

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