Re-attachment zone characterisation under offshore winds blowing over complex foredune topography

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ABSTRACT


Studies of the role of secondary airflow effects demonstrate the importance of offshore flows in dune growth and maintenance. Turbulent processes at the lee side of aeolian dunes have previously been only qualitatively described. The recent incorporation of ultrasonic anemometers, capable of measuring the three components of the wind vector, allows quantification of flow patterns in complex areas such as the lee side of dunes. This paper presents measurements taken with an array of ultrasonic anemometers during an offshore wind event at Magilligan Point, Northern Ireland, where flow separation and reversal associated to offshore winds has been previously reported. A simple analysis using the raw $u$ and $w$ components of the wind was conducted to extract quantitative information on the location of turbulent zones along a dune-beach profile. Results indicate sharp differences between the relation of $u$ and $w$ with distance downwind from the dune crest, which in turn can be used to identify turbulent zones. Variations in wind velocity and direction at the dune crest did not result in changes in the location of turbulent zones at the beach surface, suggesting that turbulent structures are significantly constant in time. A quantitative model based on actual field data and using previous conceptual descriptions as a guide is presented to identify turbulent zones at the beach surface under offshore winds.

ADDITIONAL INDEX WORDS: secondary airflows, turbulence, flow reversal, aeolian.

INTRODUCTION

Quantification of sediment supply to the foredunes often excludes the role played by offshore wind events and creates a conundrum when attempting to explain the existence of aeolian dunes on coasts where the dominant wind direction is offshore (lee side coasts). However, recent findings from wind tunnel studies, desert environments and a few coastal sites suggest that airflow separation, lee-side eddies and secondary flows play an essential role in the formation and maintenance of sand dunes. Under offshore winds the surface airflow layer detaches from the ground downstream from the dune crest and generates an area characterised by turbulent eddies on the dune lee slope. At some distance downstream from the dune crest, flow separates into a reversed component directed toward the dune toe and an offshore ‘re-attached’ component (Walker and Nickling, 2002).

The re-attachment length has been observed in other environments. Cooke et al. (1993) for example estimated that the re-attachment distance for broad hills was approximately 5–10 times the hill height. Estimates in fluvial dunes (McLean and Smith, 1986; Nelson and Smith, 1989; Engel, 1981) and aeolian dunes (Frank and Kocurek, 1996a; Walker, 2000) are similar and on average approximately 4-8 dune heights ($h$). Numerical simulations using Computational Fluid Dynamics (CFD) tools performed by Parsons et al. (2004) over an idealised single dune resulted in lengths of the lee side separation zone of 3-15$h$ downwind. Recent CFD simulations over a complex coastal dune terrain by Jackson et al. (submitted) suggest that reattachment at the beach occurs at the lower end of previous estimates, and tends to be approximately 4$h$.

Both the re-attachment length and other turbulent structures at the lee side of aeolian dunes have been included in a number of conceptual models (e.g., Sweet and Kocurek, 1990; Frank and Kocurek, 1996b; Walker and Nickling, 2002). However field methods have primarily focused on flow visualisation and there are few studies presenting quantitative data on the physical properties of the wind at various distances from the dune crest. Walker and Nickling (2002) attribute this to complex flow patterns and irregular velocity profiles that are difficult to study with traditional boundary layer approaches.

This paper presents field data collected over an offshore event at the lee side of a coastal dune using 3D ultrasonic anemometers that are able to solve the three components of the wind vector. The data is used to introduce a quantitative description of secondary airflow patterns. This description is combined with previous
conceptual (qualitative) frameworks to introduce a simple quantitative model that could be used to identify different turbulent zones (such as the location of the re-attachment point) at the beach surface during offshore wind events. The first part of the paper presents the analysis of field data and the quantitative model. The second part presents a preliminary examination of the temporal evolution of the re-attachment zone (RZ) in relation to changing wind velocity and direction. The overall aim of the paper is to supplement the existing qualitative guidelines that describe the position of the RZ using a quantitative approach thus providing a better understanding on the physical characteristics of the flow in the lee of dunes. Implications for beach-dune interaction are discussed in the light of these new findings.

STUDY SITE

Field data was collected during an experiment carried out at Magilligan Strand, Northern Ireland (Figure 1). The strand is oriented NW-SE and is approximately 6 km long. The beach is up to 100 m wide during low tides and displays a dissipative, planar topography due to the effect of high energy Atlantic swell waves. The coast is microtidal with a tidal range of approximately 1.6 m. Beach sediment consists predominantly of very well sorted quartz sand with a mean grain diameter of 0.17 mm (Jackson et al., 2005). Foredune height at the site ranges from 6 to 11 m and is vegetated by Marram grass (Ammophila arenaria) of approximately 0.4 m in height. Prevailing winds in the region (see insert in Figure 1) are from the SW (offshore directed) and dominate the aeolian system. Previous studies have reported significant secondary airflow effects where the foredune is of sufficient height (Lynch et al., 2010). The experimental site (highlighted in Figure 1) was thus located at a section of the beach-dune system where the foredune crest reaches its highest point (11 m). At this location the foredune is largely linear and unbroken and approximates idealised transverse ridges (Lynch et al., 2010).

METHODS

Wind parameters were measured over a profile extending from the dune crest towards the beach, covering a total distance of 55 m cross-shore (Figure 2). Data were collected using an array of six ultrasonic anemometers (3D Gill HS-50 model) deployed in April-May 2010, as part of a larger experiment to characterise airflow and sediment transport under a range of incident wind velocities and offshore wind directions. Each beach station consisted of an ultrasonic anemometer (UA) at 0.5 m over the beach surface coupled with a sand trap and/or a Safire (Baas, 2004). Beach stations were located along the profile (5 m tower spacing) which allowed a detailed examination of the RZ with empirical data. An extra UA was deployed at 6 m over the dune crest, to measure incident wind velocity and direction. All sensor locations (crest station and beach stations located 30 to 50 m from the dune crest) were based on a preliminary CFD run indicating the extent of different turbulent areas. The three-components of the wind vector, \( u \) (streamwise), \( v \) (spanwise), and \( w \) (vertical) were sampled at 25 Hz. Only airflow data is presented in this paper with future publications covering the sedimentary response.

ANALYSIS AND RESULTS

The data presented in this paper corresponds to an offshore storm event recorded on 27-28 April 2010. The storm lasted 23 hours and consisted of relatively constant offshore winds with a variety of wind velocities (Figure 3). Mean wind direction at the dune crest was approximately 210.5° and ranged from 190.5° to 252.7°. Directly offshore winds at this location are at 217°, so effectively the storm contained winds approximately 6° from a directly offshore bearing with a +/- 30° wind direction fluctuation. Mean wind velocity at the dune crest was 9.1 m s\(^{-1}\) and ranged from 3 to 16 m s\(^{-1}\). To examine wind patterns at the lee side associated with incident wind velocity at the crest, 1-minute averaged runs were obtained from the original data high frequency (25 Hz) data, resulting in a total of 1380 runs.
Re-attachment Zone (RZ) Characterisation

Qualitative Description of Lee Airflow Patterns

In the review on secondary airflows, Walker and Nickling (2002) eloquently summarised findings by previous researchers into a qualitative model describing the location and structure of turbulent zones in the lee side of a dune. This work purported that as the fluid flow is compressed up the stoss slope of a dune it may overshoot at the crest, separating from the surface and creating a region of low pressure downwind from the crest characterised by a recirculation of flow back up the lee slope. The near surface reversed flow is confined within the dune toe and the RZ, with the latter located at 4–10$h$ and with a width of approximately 0.5$h$. An inner boundary layer (IBL) begins to redevelop downwind from this point, with rapid development within 6$h$ of reattachment (Walker, 2000) and becoming identifiable by distances of 8–10$h$ (Frank and Kocurek, 1996a). Walker and Nickling (2001) observed a negative wind speed gradient in the lower profile owing to the rapid acceleration of re-attaching flow within 1–2$h$ of flow reattachment. Beyond this, a positive near-surface profile develops, yielding an increase in shear velocity ($u*$). Near-surface wind speed profiles would require a significant distance up to 15$h$ to come into equilibrium which may never be attained in coastal settings or closely spaced desert dunes.

Quantitative Description of Lee side Airflow Patterns

Data presented in this paper corresponds to UAs located at 0.5 m over the beach surface. Although full characterisation of turbulence at the lee side a dune requires examination of the flow at different heights, it is instructive to examine near surface flow patterns, particularly for aeolian transport studies.

To analyse the location of the RZ under strictly offshore winds only those runs where the wind direction at the crest was 0±5° from a perpendicular offshore bearing were initially selected. This resulted in a total of 386 ‘runs’ with wind velocities fluctuating from 3 to 13 m s$^{-1}$. A fixed coordinate system was established for the entire profile which consisted of a right-handed Cartesian system with $u+$ going in the offshore direction and $w+$ going upwards. The relation between these two coordinates at each location should therefore give information about the direction of the flow in these two dimensions. Analyses were conducted to observe which of the four quadrants established by this coordinate system were favoured at each of the zones. Figure 4 displays dispersion graphs of the raw $u,w$ wind components (up), corresponding percentages for each of the quadrants (centre), and estimated resultant directions (bottom). UAs located at the crest and at 30 m showed distinctive trends indicating clear overshoot at the crest and upward flow reversal at the lee of the dune. The flow was reversed at 35 m from the crest but fluctuated between an upward and downward direction. The flow was offshore with a very significant downward direction at 45 m and offshore but with an increasingly significant upward direction at 50 m, probably

![Figure 3. General wind conditions (1-min averages) at the study site over the storm. Wind velocity ranged from ≈ 3 to 16 m s$^{-1}$ and wind direction was predominantly offshore (217°).](image)

![Figure 4. Dispersion analysis between the $u$ and $w$ components of the wind as recorded from UAs located at different distances from the crest (up). Percentages for each UA were calculated for each quadrant (centre) and a resultant flow direction was estimated (bottom). Grey filling indicates offshore (+$u$) directions. The highest percentage has been framed and highlighted in bold. The second highest percentage has been framed only if it was above 25% of the total.](image)
reflecting the initial growth of the IBL. The combination between onshore-directed and offshore-directed flow at the station located at 40 m likely indicates the position of a transitional zone before re-attachment. Interestingly, the quadrant corresponding to \(u-w\) (17\%) is in the third position after \(u+w\) (36\%) and \(u-w\) (18\%) interactions (26\%).

**Evolution of the RZ**

Interactions between \(u\) and \(w\) were expressed as angles calculated using the \(\text{atan2}\) function such as \((u+w+)\): 0 to \(\pi/2\), \((u-w+)\): \(\pi/2\) to \(\pi\), \((u-w-)\): \(\pi\) to \(-\pi/2\) and \((u+w-)\): \(-\pi/2\) to 0. This allowed for simple regression analysis between changes in wind velocity and direction at the dune crest and corresponding changes in the quadrant composition of sensors located at different distances downwind.

**RZ with Wind Velocity**

The 386 runs isolated above were used to analyse the effect of changing wind velocity at the dune crest (3 to 13 m s\(^{-1}\)) with a relatively constant wind direction (0\(^\circ\) to 5\(^\circ\) from directly offshore). Figure 5 (up) shows no relation between increasing wind velocity at 6 m over the foredune crest and changes in the angle between \(u,w\) at stations located at 30, 40, and 50 m. Turbulent zones such as the reversed flow (30 m), transition (40 m) or re-attached flow zone (50 m) were at the same distance downwind from the crest under incident winds of 3 m s\(^{-1}\) and winds of 13 m s\(^{-1}\).

**RZ with Wind Direction**

A total of 516 runs were extracted from the total (1380) with wind velocities between 9 to 10.9 m s\(^{-1}\). This allowed consideration of changes in wind direction only while maintaining a relatively constant wind velocity. Wind direction during these runs varied from -31\(^\circ\) to 25\(^\circ\) from offshore at the dune crest. Figure 5 (bottom) shows no clear relation between changing wind direction and the location of the main turbulent areas at 30, 40, and 50 m from the dune crest.

**Thresholds for Changes**

Figure 5 suggests that the location of turbulent zones at the leeside of the dune is significantly constant under the range of wind velocities and offshore wind directions considered here. In fact, if all runs obtained during the storm (1380; wind direction = 0±25\(^\circ\); wind velocity = 3-16 m s\(^{-1}\)) are considered the percentages for each quadrant are essentially the same than those obtained under strictly offshore winds, suggesting a similar location of turbulent structures (Figure 6). However, one could argue that these structures needed to be formed at some threshold wind velocity or wind direction. Further analyses were performed at stations located at 30 and 35 m distances. These two locations showed clear flow reversal for the majority of time but there were a few runs when the flow was offshore (+\(u\)) and thus it was possible to query the corresponding incident wind at the dune crest during these particular moments. For example, there were 12 runs out of 1380 (0.9\%) with +\(u\) at 30 m. Wind direction at the dune crest during these 12 runs varied from -3 to 18\(^\circ\) and wind velocity from 6.5 to 11 m s\(^{-1}\). There were 365 runs out of 1380 (25.8\%) with +\(u\) at 35 m associated with wind directions from 25 to -15\(^\circ\) and velocities from 4 to 16 ms\(^{-1}\) at the dune crest. Therefore there appears to be no relation between the existence of offshore directed runs at stations located within the reversed flow area and the range of wind directions and velocities at the crest.

**Quantitative Model for Lee Side Airflows**

In Figure 7 the qualitative diagram of Walker and Nickling (2002) has been combined with a summary of the empirical results presented in this paper. The result is a useful model for lee side airflows under offshore incident winds which may be used to identify a range of turbulent zones. By using quadrant analysis and the resulting quantitative description introduced in this paper, identification of particular airflow zones can be achieved more precisely. It should be noted that when there is flow separation and reversal, the distances between the dune crest and different turbulent zones will be variable. The relative significance of \(u\) versus \(w\) components of the wind should however help define whether it is onshore or offshore flow at any particular location.

The range of wind directions and velocities analysed during the storm suggests that leeside turbulent structures are very constant under a wide variety of offshore winds. These results concur with other studies that suggest that the re-attachment length does not depend largely on wind velocity. Research considering a variety of dune forms and velocities indicates that re-attachment distance is essentially independent of Reynolds number in fully turbulent flows (Nelson and Smith, 1989; Frank and Kocurek, 1996a; Walker and Nickling, 2001). According to Walker and Nickling (2002) the magnitude of the Reynolds Stress maximum is variable but the size and extent of the RZ appears to be independent of incident wind speed, and hence, Reynolds number. The distance...
Figure 7. Model to identify turbulent areas at the lee side of a dune based on the work by Walker and Nickling (2003) (up) and quadrant analysis between $u,v$ presented in this paper (bottom). Offshore (+u) and onshore (+v) directions are indicated with grey and white filling circles, respectively.

from the dune crest to the RZ was also similar to simulations conducted with CFD tools at the same study site (Beyers et al., 2010; Jackson et al., submitted) and can be located at approximately 4h.

Future studies should investigate in detail thresholds for wind conditions at the dune crest associated with the development of turbulent structures downwind. The lowest wind velocity measured in this study (≈ 3 m s$^{-1}$) was not enough to obtain a threshold under which offshore flows do not separate at the dune crest. Similarly, there is a need to explore the effect of more oblique offshore wind angles, especially in relation to relative changes in dune shape. Changes in dune height ($h$) and stoss slope basal length ($L$) modify the location and extent of both the separation cell and the turbulent shear zone (Walker, 2000) and thus tradeoffs between wind direction and dune shape will likely have an impact on lee airflow. Relative distances between points 1 to 6 (Figure 7) will only be known in detail after exploring larger data sets with different wind conditions and morphologies.

Finally, the percentages obtained to define turbulent zones at the leeside of the dune need to be investigated at a variety of temporal scales (from 25 Hz to runs of several minutes). Different temporal scales may reveal different patterns as some of the turbulent structures may be superimposed each other.

CONCLUSIONS

Intensive wind measurements collected over the course of a 23 hours storm have been analysed to obtain preliminary results on the location of the re-attachment zone in the lee side of a coastal dune. Data reveals that turbulent structures visible from 1-min averages are significantly constant over time, and are established at wind velocities as low as 3 m s$^{-1}$. At this time scale, there appears to be no relation between significant changes in wind direction (≈ 0±25°) and wind velocity (3-16 m s$^{-1}$). Quantitative results are combined with previous qualitative descriptions to propose a model that allows identification of turbulent areas in the lee side of a coastal dune during offshore wind events.

LITERATURE CITED


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