Airflow reversal and alternating corkscrew vortices in foredune wake zones during perpendicular and oblique offshore winds

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Abstract

On all sandy coastlines fringed by dunes, understanding localised air flow allows us to examine the potential sand transfer between the beach and dunes by wind-blown (Aeolian) action. Traditional thinking into this phenomenon had previously included only onshore winds as effective drivers of this transfer. Recent research by the authors, however, has shown that offshore air-flow too can contribute significantly, through lee-side back eddies, to the overall windblown sediment budget to coastal dunes. Under rising sea levels and increased erosion scenarios, this is an important process in any post-storm recovery of sandy beaches. Until now though, full

visualisation in 3D of this newly recognised mechanism in offshore flows has not been achieved. Here, we show for the first time, this return flow eddy system using 3D *computational fluid dynamics*modelling, and reveal the presence of complex corkscrew vortices and other phenomena. The work highlights the importance of relatively small surface undulations in the dune crest which act to induce the spatial patterns of airflow (and transport) found on the adjacent beach.

Keywords

Computational fluid dynamics; Aeolian; Foredunes; Transport; Airflow modelling; Lee side eddies

1. Introduction

In the calculation of sediment budgets within beach and foredune environments, there is a fundamental requirement to isolate those wind events capable of aeolian sediment transport from the beach (sediment source area) to the adjacent coastal dune field (sink area) (Anthony et al., 2007 and Delgado-Fernandez and Davidson-Arnott, 2011). Until recently, sediment budget calculations (e.g. Fryberger and Dean, 1979 and Illenberger and Rust, 1988) often rejected offshore wind as a contributing component. Extensive aeolian dunes on coasts where the dominant wind direction is offshore (leeside coasts) therefore created a research conundrum within traditional thinking in foredune morphodynamics — why should they exist under low forcing conditions? Conventionally, the evolution of these features has been explained away by concluding that regional shifts in wind regime must have occurred (Shennan and Andrews, 2000). It is recognised however, that even though onshore wind directions may in some cases represent the minority of winds at a site; their influence can be

significant in providing the bulk of the transport-capable winds feeding local foredune sediment budgets. Offshore winds though can still represent an important supplemental part of the total transport system forming foredunes.

Recently, a number of studies on complex interactions between wind and surface topography have provided new insights into important localised steering effects (Lynch et al., 2008, Lynch et al., 2010, Lynch et al., 2013, Delgado-Fernandez et al., 2011,Delgado-Fernandez et al., accepted for publication, Jackson et al., 2011 and Bauer et al., 2012). Research in desert dunes (Frank and Kocurek, 1996a, Frank and Kocurek, 1996b and Baddock et al., 2007) and wind tunnels (Walker and Nickling, 2003) indicates that airflow traversing dunes can result in a large range of turbulent processes in their lee-sides, usually in the form of flow separation and re-attachment, deflected flow and reversed eddies, or complex roller vortices or roller helixes (Walker and Nickling, 2002). A similar set of flow characteristics can also be applied to coastal foredunes (Bauer et al., 2012). Shear stress within turbulent flows in any of these environments has an inherent heterogeneity which, in turn, can help sustain initiation of sand particles from the surface (Baas and Sherman, 2005). In these conditions, winds that are normally predicted to be sub-threshold in the movement of dry sand may not necessarily halt transport (Wiggs et al., 1996). Examining the intricacies of flow behaviour across such environments therefore is paramount in understanding additional transport potential in sediment budget calculations of beach–dune systems (Jackson et al., 2011).

Until recently, field investigations of airflow and sediment transport dynamics during offshore wind conditions, was hampered by shortfalls in technical capabilities of measurement equipment. However, advances in wind modelling and ultrasonic

anemometry have resulted in field experiments where landward aeolian sediment transport from local topographic steering of offshore directed airflow has been quantified (Lynch et al., 2008, Lynch et al., 2010 and Lynch et al., 2013). These mechanisms have been shown to play an important role in post-storm recovery of foredunes scarped by wave action, effectively returning displaced sediment back onto the foredune toe and rebuilding the back beach again. Up until these investigations (e.g. Lynch et al., 2008) significant under-estimation of predicted sediment input to the foredune had likely been commonplace. The recent work of Delgado-Fernandez et al. (2011, 2012) also showed that the behaviour of the reversed flow varied according to wind direction and antecedent foredune morphology (Lynch et al., 2010). These observed heterogeneous flow patterns may have further added to the reasons why they were previously discounted (Nordstrom et al., 1996 and Walker et al., 2006).

Examining the conditions under which offshore winds play a major role in coastal dune dynamics requires adoption of methodologies that are able to resolve airflow in three dimensions to allow changes in wind direction and terrain morphology to be investigated. Indeed, understanding fluid flow behaviour in the lee of dune morphology per se is essential if we are seeking to unravel dune dynamics in general. This applies to dune movement in a range of environments including subaqueous and desert dunes. Complex flow–surface interactions as well as coherent flow structures from antecedent morphology in these environments ultimately require examination and this must be addressed using a number of methodological approaches.

Computational fluid dynamics (CFD) models have been widely used in a number of natural settings using both 2-dimensional (Jackson and Hunt, 1975, Castro,

1991, Abe et al., 1993, Byrne and Holdo, 1998, Nicholas, 2001 and Safarzadeh et al., 2009) and more recently in 3-dimensional numerical simulations (Lane et al., 2002, Nguyen and Nestmann, 2004, Inkratas et al., 2009 and Feng and Ning, 2010). 3-D modelling approaches can give detailed patterns of flow behaviour over non-uniform topography (Lee et al., 2002, Lun et al., 2003 and Stangroom, 2004) and enable a more detailed examination of complex environments such as natural dune forms and associated air-flow over them. To date, mostly 2-D CFD studies have largely been undertaken. Based on PHOENICSTM 3.5 code and using experimental wind tunnel flow measurements obtained by Walker and Nickling (2003), Parsons et al. (2002) validated a 2-D numerical model. General agreement was found between predicted and modelled results, however, significant disagreement in the lower velocities was found at the lee separation zone.Parsons et al. (2004) simulated 2D wind flow over a single idealised transverse dune of different dimensions to examine dune size and re-attachment points. Recently, Wakes et al. (2010) compared basic 2-D numerical simulations alongside cup anemometers data and a wind vane at a coastal dune complex in New Zealand. Jackson et al. (2011) were the first to simulate flow in three dimensions over natural coastal dunes and actually compare model results against 3D anemometer results. Smyth et al. (2012) has also further confirmed the outstanding applicability of using CFD in complex dune blowout environments.

Three-dimensional CFD allows a much more comprehensive spatial coverage of the wind field in natural settings than could ever be accomplished using just an instrumented approach. Simulations may be used to examine the role of offshore winds under a large range of conditions. The variable output resolution of the CFD model can also be used to guide where field instruments should be deployed for

126 selective data measurement. To date, computing power has been a limiting factor
127 combined with a lack of cross-disciplinary efforts and the logistical problem of
128 collecting suitable field validation data.
129 This paper presents the results of a 3-D CFD modelling study over complex coastal
130 foredune topography using the OpenFoam software. Previous field data
131 comparisons with steady state Reynolds-averaged Navier–Stokes (RANS) and
132 Large Eddy Simulations (LES) solutions of the model already show excellent
133 agreement (Jackson et al., 2011) and therefore no detailed comparisons will be
134 presented here. The aim of this paper is to highlight for the first time, the three
135 dimensional nature of secondary airflow within this important interface wake zone
136 between the beach and the dune system. The objectives are: 1) to explore possible
137 causes for the spatial variability found during field measurements of foredune wake
138 zones under offshore wind conditions; 2) to isolate the potential effects of terrain
139 form, roughness and wind directional effects; 3) explore the importance of
140 undulations in the foredune crest in dictating the positioning of the detached flow as
141 it rejoins the beach surface again; and 4) compare against field data to help quality
142 check the model results.
143

144 **2. Methods**

145 **2.1. Computational fluid dynamics (CFD) simulations**

146 For the simulations presented here, the open source CFD software OpenFoam®
147 (version 1.7.1) was used. This model makes use of Reynolds-averaged Navier–
148 Stokes (RANS) equations which are time-averaged equations of motion for fluid flow
149 where an instantaneous quantity is decomposed into its time-averaged and
150 fluctuating quantities (Launder and Spalding, 1974). Through using the RANS

simulation solver it allowed more simulation tests to be performed quickly. Overall, the simulation of airflow in the study is similar to the modelling approach that yielded favourable comparison to earlier field tests measurements by the authors. More extensive details on the CFD simulation methodology followed can be found in Jackson et al. (2011).

2.2. Re-attachment zone characterisations

To evaluate the spatial extent of the simulated re-attachment zone, the resolved U (horizontal) and W (vertical) velocity components obtained from the CFD field solution were combined in an atan2(W/U) function to produce the angle between reversed or re-attached horizontal flow in the wake zone and the vertical flow component. This helps with highlighting and visualising the position of the flow re-attachment position behind the foredune. Function values between zero and π indicate re-attached flow, values between − π and zero indicate the flow reversal zone and the interface between them (the simulated steady state re-attachment position) identified by function values approaching zero. This method is very well suited to CFD simulated three-dimensional wind flow fields as it can provide a clear three-dimensional spatial visualisation of the foredune flow characteristics not possible with field measurements.

2.3. Surface topography of actual terrain

Using a combination of aerial LiDAR data (spot interval distance of 4 m) and dGPS survey points (spot distance of 1 m across the beach and dune and 0.2 m over the crestal ridge of the foredune) a detailed topographical mesh was created measuring 150 m (longshore) × 250 m (cross-shore) incorporating the main foredune ridge (see Fig. 3). Surveyed points were gridded-up using standard interpolation

techniques (kriging) and used as the underlying surface for any wind flow simulations over real terrain.

3. Results

3.1. Artificial dune topography simulations

Prior to performing the simulations for the real terrain where the field wind measurements were conducted, a set of exploratory simulations were carried out for an artificial dune topography, one that mimics the real dune form but where terrain parameters could be altered and tested more readily. The results of these simulations were used to qualitatively isolate the effects of modelled terrain surface roughness; wind direction and dune crest form perturbations. The first simulations were performed to test whether the artificial dune form could qualitatively reproduce a similar spatial extent of the wake zone, as measured and simulated in earlier work. Fig. 1 shows the geometry and results of the first simulation for an offshore wind perpendicular to the dune orientation. Approaching wind flow characteristics included an inlet wind speed of 15 m s^{-1}, surface aerodynamic roughness of 0.01 m and inlet flow profiles and turbulence characteristics as perRichards and Hoxey (1993). The flow reversal zone was visualised with section wind vectors and flow streamlines (shown here) and by plotting the atan2(W/U) function on an terrain following iso-surface of 1 m above the terrain, as shown in Fig. 1. The flow reversal zone and re-attachment position produced here matched earlier results byJackson et al. (2011) and Delgado-Fernandez et al. (2011) well. Further tests were conducted to compare results of modelled and explicitly simulated surface roughness effects. This suggested that the modelled surface roughness approach, which uses a typical surface roughness wall function to address the surface shear (Blocken et al., 2007),

was adequate, although this was not extensively tested or evaluated here. Lastly, the effects of small intermittent dune crest form perturbations were tested by adding small 0.3 m-high crest extensions on the leeside of the crest. Fig. 2 shows the results of this simulation test which highlights the importance of small terrain effects in producing large (5–10 m) differences in the wake-zone extent. It is important to note that the form and positioning of the crest perturbations were done so that the crest height remained uniform throughout, and that the perturbations are only exposed to the leeside flow and not directly to the approaching and accelerating upstream crest wind flows. As shown inFig. 2, the intermittent positioning of the leeside crest undulations alters the position of the re-attachment zone significantly. This suggests that crestal surface undulations may be the dominant parameter for the measured wake-zone local spatial variability compared to effects of surface roughness or wind direction

3.2. Airflow simulations over real terrain: perpendicular offshore-directed winds

Using detailed terrain data obtained from LiDAR and dGPS surveys, a computational domain was created for the OpenFoam simulations that span the area where field measurements were taken. Fig. 3 shows the Magilligan field test site and resultant terrain and computational domain created for the simulations. Simulations were performed with similar approaching wind flow conditions as for the artificial dune simulations.

Magilligan, located in the northern coastline of Northern Ireland, UK was selected because of the numerous studies and datasets accumulated from previous work (e.g.Jackson et al., 2005, Jackson and Cooper, 2010 and Jackson et al., 2011) and not least because of it being located in an exposed windy setting with a predominant

offshore wind regime (see insert of Fig. 3). Previous LiDAR and topographical dGPS surveys added to the reasoning for using this site. At Magilligan, the coastline is oriented in a NW–SE axis and runs for approximately 6 km. The beach is up to 100 m wide during low tide and has a dissipative, planar topography due to the effect of high energy Atlantic swell waves (Jackson et al., 2005). A microtidal tidal range of approximately 1.6 m operates at the site and beach and foredune sediment is made up of predominantly very well sorted quartz sand with a mean grain diameter of 0.17 mm. The foredune ranges in height from 6 to 12 m with dense vegetation dominated by *Ammophila arenaria* of approximately 0.4 m in height. Prevailing winds are from the SW (offshore) and are thought to dominate the aeolian system (Jackson et al., 2011). A section of the beach–dune system was chosen where the foredune crest reaches its highest (10–12 m) and where previous high-frequency wind measurements and CFD modelling have reported airflow separation under offshore winds (Beyers et al., 2010, Delgado-Fernandez et al., 2011 and Jackson et al., 2011).

Fig. 4 shows the simulated steady state wind characteristics through a vertical section through the foredune under examination, for a perpendicular offshore-directed wind. The classic wind reversal, re-attachment point and re-attached flow can be observed. When the atan2 function is applied to the simulated 3D flow field, and visualised on a terrain following iso-surface raised 1 m above the terrain surface, the reversed and re-attached flow regimes can be identified, with the re-attachment location the clear boundary between the two.

The spatial extent of the reattachment position varies between 35 and 40 m which compares well with the measured re-attachment lengths by Delgado-Fernandez et al. (2011). The extent of the reattachment location varies along the length of the

250 foredune to track the lengthwise dune shape characteristics, and in particular the
251 small variation in height and along wind dune crest positions.
252 When compared to the qualitative simulation of the artificially modified dune crest
253 (Fig. 2) presented earlier, it seems that the flow influences of the small alongshore
254 height variations of the crest matches the flow characteristics of the artificial dune
255 well. Hence, small alongwind variations (~ 0.3 m) of crest position, seems to move
256 the along wind position of the reattachment position by approximately 5 m. This is
257 due to a combination of three-dimensional wind flow effects, and specifically
258 interaction between accelerated flows, delayed crest separation positions and
259 associated leeward reversed flow low pressure areas.
260 Also noteworthy, is that the flow recirculation zone contains at least one classic large
261 flow reversal zone, although the form of the reversal zone is influenced by the
262 presence of the embryo dune shoulder located in the leeward zone.
263 **3.3. Real terrain simulations: oblique offshore-directed winds**
264 Fig. 5 shows a similar steady state simulated wind result for an oblique offshore
265 wind. The wind simulated here approached the foredune at an angle of
266 approximately 45° to the foredune crest orientation. From the sectional views of the
267 flow reversal zone, it can be seen that the reversal zone is now much smaller and
268 mostly isolated within the area between the crest and the leeward dune shoulder.
269 The re-attachment location has also moved closer to the toe of the dune. The
270 oblique flow clearly changes the effective height of the dune and reduces the
271 accelerating effect of the crest separation that reduces the recirculation zone extent.
272 In a few locations along the dune, the reversal zone is only present within the zone
273 between the embryo dune shoulder and the crest, with reattached flow already
274 occurring at the embryo dune toe halfway up the dune slope.

Fig. 5 also shows the spatial extent of the flow reversal zones using the atan2 method, highlighting the reduction and spatial variation of the separation zone extent. It also shows the reversal zone being isolated to the area between the crest and embryo dune toe. As expected, the flow in the leeward wake is steered to follow the dune crest which results in a corkscrew type vortex that is small in leeward extent from the crest but is stretched downstream along with the steered wind flows. A more complex characteristic of this corkscrew leeward vortex is shown in Fig. 6, identified with streamlines originating windward of the dune crest. The separating flow re-circulates behind the dune and is steered alongshore. Also, as the flow reattaches downstream near the dune toe, the corkscrew vortex re-circulates up and into the embryo dune shoulder/crest recirculation zone. Thus, the upper smaller recirculation zone that is contained in the crest/embryo shoulder zone, receives steered wind flow from the lower dune toe area further upstream. This is different to the more classical flow reversal zone present for perpendicular offshore wind flows, also shown in Fig. 6.

4. Discussion

Simulations of surface wind flow over complex foredune topography under offshore–oblique offshore events enables us to unravel the distinctive flow behaviour of the wind according to direction and underlying topographical changes. Simple alterations in the crestal undulations provide a clue to their importance in driving changes in the lateral extent of the re-attachment zone. The positioning of the re-attachment zone itself probably promotes back-beach surface drying through enhanced turbulence and downward flow thereby enhancing the aeolian transport potential of the surface sand, regardless of subsequent events. Through even minor (0.3 m in the vertical)

alteration of an artificial 3D foredune crest surface it is clear that this has a significant effect on re-attachment position; significantly shifting the position of this zone. The natural undulations found on a foredune crest therefore give rise to a distinctive heterogeneity in flow re-attachment positioning at the back-beach zone as a result. It might, therefore, be expected that secondary airflow heterogeneity, controlled by small alongshore height variations in crestal topography, would be reflected in sediment transport patterns on the leeside, with the extent of beach where sediment maybe recycled back towards the dune, varying alongshore. Recent results from Lynch et al. (2013) at the site show the distinct variability in transport patterns on the beach during oblique offshore winds and compliment the heterogeneity in air flow found in the modelling in this study. Bauer et al. (2012) also propose a conceptual model for flow–form interaction over large (> 8 m) foredunes under variable wind approach directions. The study of Bauer et al. helps support the modelling results produced here and demonstrates the crucial role played by the crest line in deflecting flow substantially within lee of the foredunes.

The results in this study show that incident approach angle of the wind to foredune topography clearly dictates the resulting flow behaviour inside the wake zone of the foredune ridge. With CFD simulations we can observe two distinct flow patterns according to approach (incident) wind angle. First, directly offshore winds have a relatively more ‘simplistic’ behaviour, with a detached flow at the crest and a return eddy in the lee. Flow then reattaches at the reattachment point on the back beach. Secondly, with oblique offshore winds a clear corkscrew vortex is induced in the wake zone, producing complex flow patterns over the surface. At Magilligan the presence of dune vegetation largely restricts the surface sand in its movement, however, further out from the dune toe and still inside the wake zone, the corkscrew

is likely to still influence surface sediment mobility. If, for example, the downward twist (or trough) of the corkscrew eddy is coincident with the ground then this will push surface sand landward at this contact point. Back along its length, the ‘crest’ of the corkscrew vortex will be elevated above the surface at a height that will be less influential in driving sand transport. This will produce onshore and offshore transport patterns on the back beach and foredune zone, enhancing the heterogeneity of the transport surface during oblique offshore wind events. With changes in incident wind direction, the relative position of the corkscrew will probably change alongshore and therefore add to sediment transport heterogeneity, producing fluctuations in transport activity during offshore flow conditions. It is therefore plausible that oblique wind flows, and its resulting cork-screw vortex that alternates into upper and lower recirculation zones, may present an important mechanism in the evolution of foredune form, somewhat different to the effects of classic perpendicular wind flow reversal geomorphic mechanisms.

Quantification of transport in the wake zone of foredunes at the beach–dune toe area using standard sand-trapping techniques under the above conditions could prove problematic. Fluctuating flow direction and resultant transport pathways from corkscrew activity will probably lead to under-estimation of actual transport rates occurring. Omni-directional trap design based on Jackson (1996) will help avoid this problem. In other dune types such as desert dunes and where upwind topography is not influencing airflow substantially, we can deduce that transport activity is likely to follow the direction of incident airflow on the stoss face whereas in the wake transport patterns will alternate according to corkscrew and other flow behaviour increasing the complexity in transport patterns as a result.

5. Conclusions

The first and rather obvious observation is that small perturbations in the crest position and height can create significant differences in the spatial extent of the leeward recirculation zone attachment position. Within natural foredune ridge topography we generally find a large variability in crest height, undulating according to natural depositional or erosional patterns during its formational history. A second and more interesting observation is that oblique wind flows create more complex three-dimensional corkscrew vortices that are steered alongshore, alternating position between upper crest-to-embryo toe circulation zones and crest-to-lower toe dune positions. These findings have important implications in our attempts at understanding aeolian sediment transport on the back beach and mid-beach zones under variable offshore wind events and highlights the role played by adjacent foredune topography in dictating flow conditions at the back beach. It also emphasises the important role that CFD can play in our understanding of wind flow dynamics over complex geomorphological landforms at a variety of scales, and shows for the first time the presence of corkscrew vortices operating in the wake of foredune morphology. Wake zone airflow (of dunes) is inherently more complex than that of their stoss slopes and the presence of large scale corkscrew vortices will dictate variable aeolian transport conditions in each of these zones as a result. The stoss slope transport will likely follow incident wind direction, whereas wake zone transport will follow complex corkscrew vortex ground contact behaviour and be in tangential directions to stoss transport.

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523 **List of figures**

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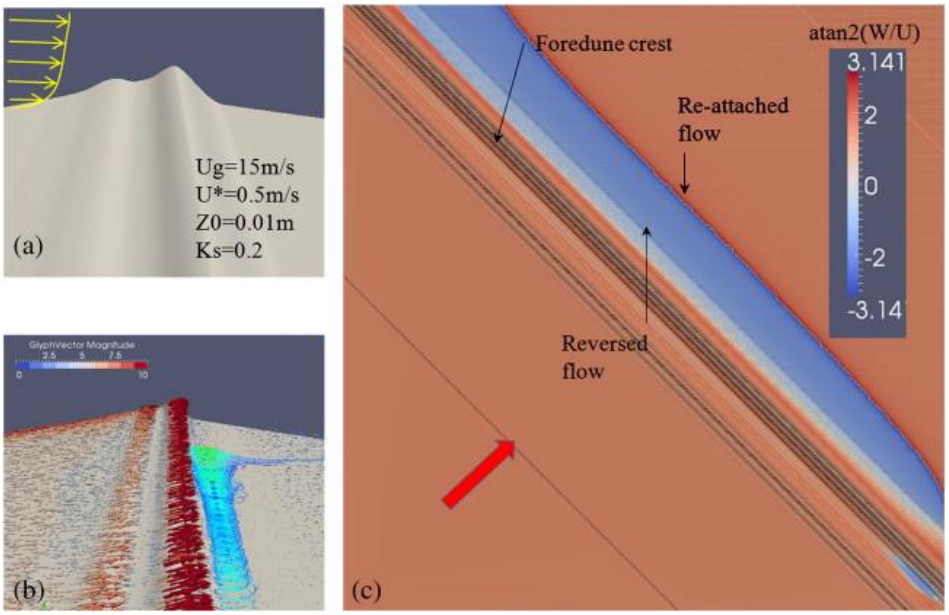

Fig. 1. (a) Artificial dune terrain geometry and approaching flow characteristics to produce a leeward recirculating flow under offshore wind conditions. (b) CFD simulation result of leeward wind flow streamlines and surface velocity vectors 1 m above the terrain. (c) Contour of atan2(W/U) 1 m above the terrain surface to highlight the extent and boundary between the reversed and re-attached wind flow in foredune wake.

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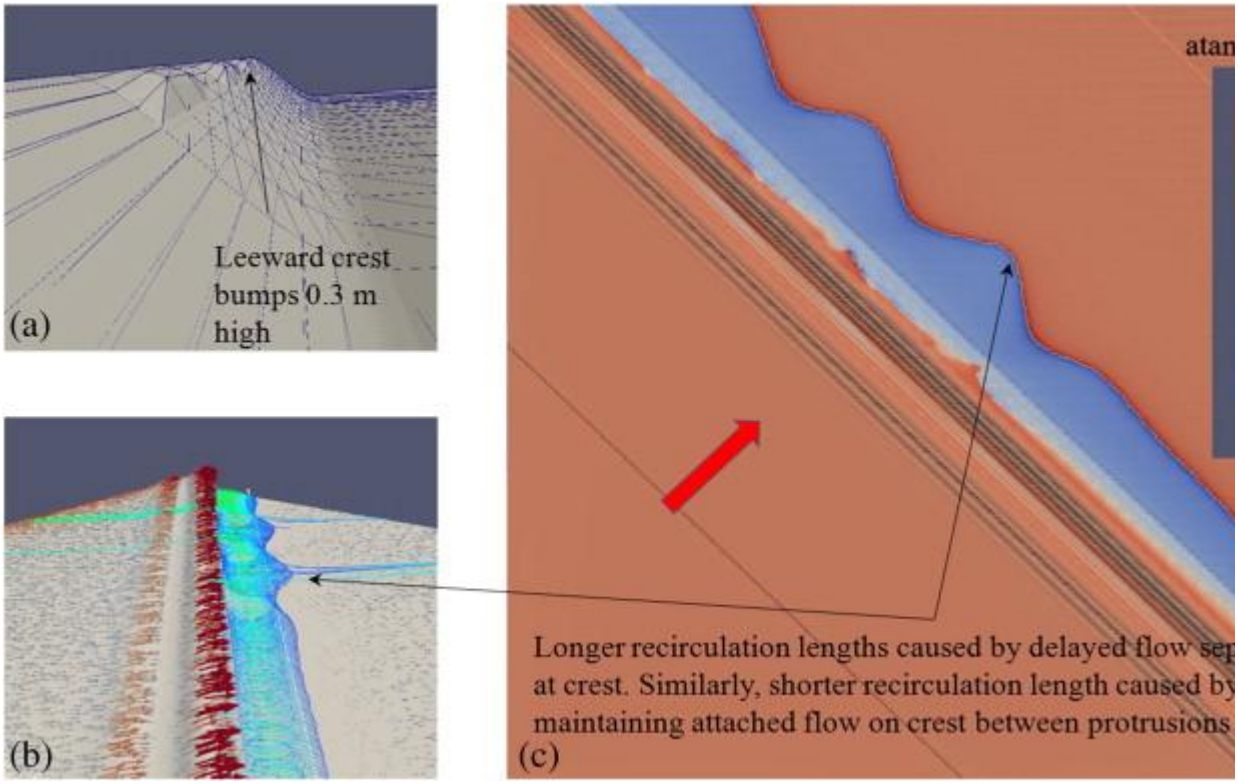

Fig. 2. (a) Close-up of the artificial dune terrain geometry with 0.3 m high leeward dune crest perturbations. (b) CFD simulation result of leeward wind flow streamlines and surface velocity vectors 1 m above the terrain. (c) Contour of atan2(W/U) 1 m above terrain surface to highlight the extent and boundary between the reversed and re-attached wind flow in foredune wake.

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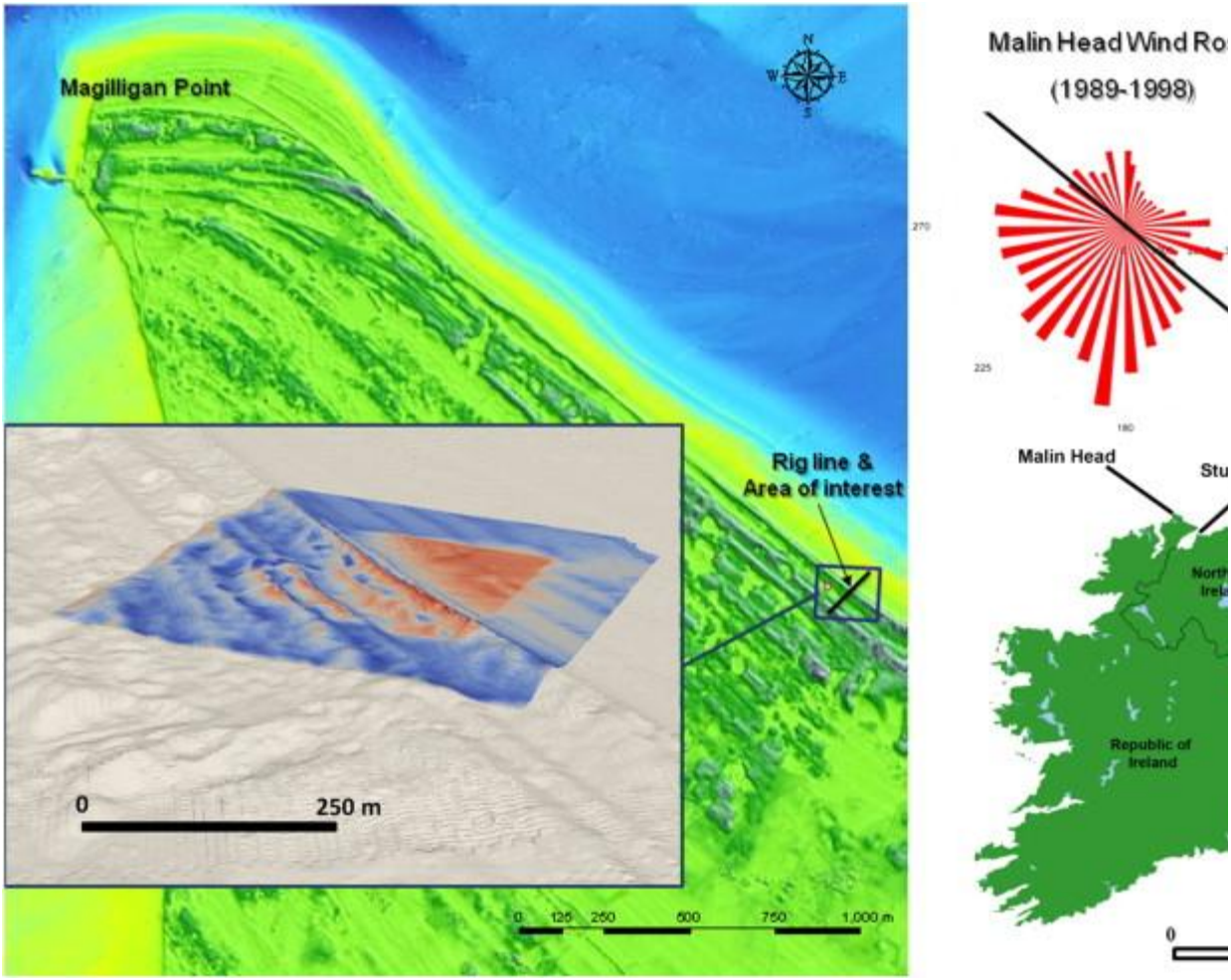

Fig. 3. Location of Magilligan field test site. Insert (left) shows zoomed field test site terrain surface obtained from LiDAR and high resolution dGPS. The colour contour overlay area indicates the horizontal extent of the computational domain created for the CFD simulations. A wind rose for the regional meteorological station at Malin Head is shown (bold black line representing the coastline orientation), demonstrating the dominant offshore winds at Magilligan.

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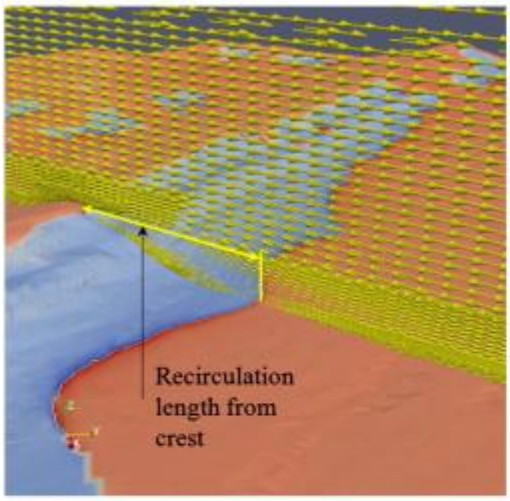

	Field tests	CFD simulation
Recirculation Length	40m - 45m	35m - 40m

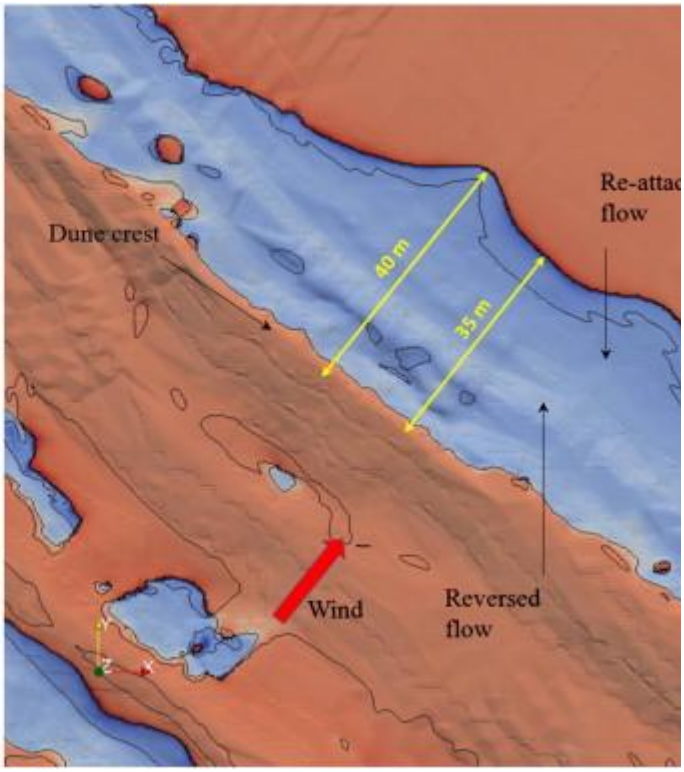

Fig. 4. CFD simulation result for perpendicular offshore wind flow over actual terrain. (Left) Velocity vectors in a vertical plane through the foredune wake zone. (Right) Contours of atan2(W/U) 1 m above the terrain indicating the extent and separation between the reversed flow and re-attached flow in the dune wake zone.

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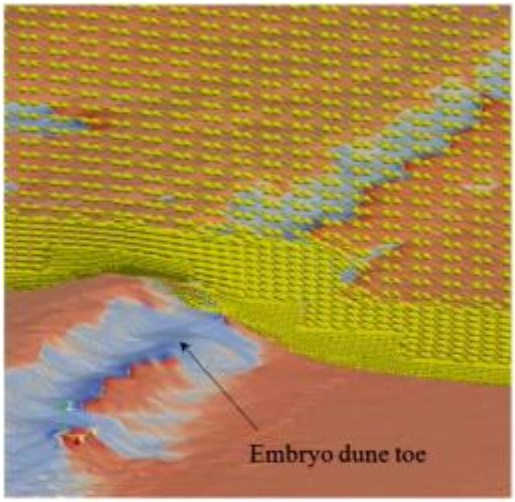

	Field tests	CFD simulation
Recirculation Length	20m - 25m	10m - 20m

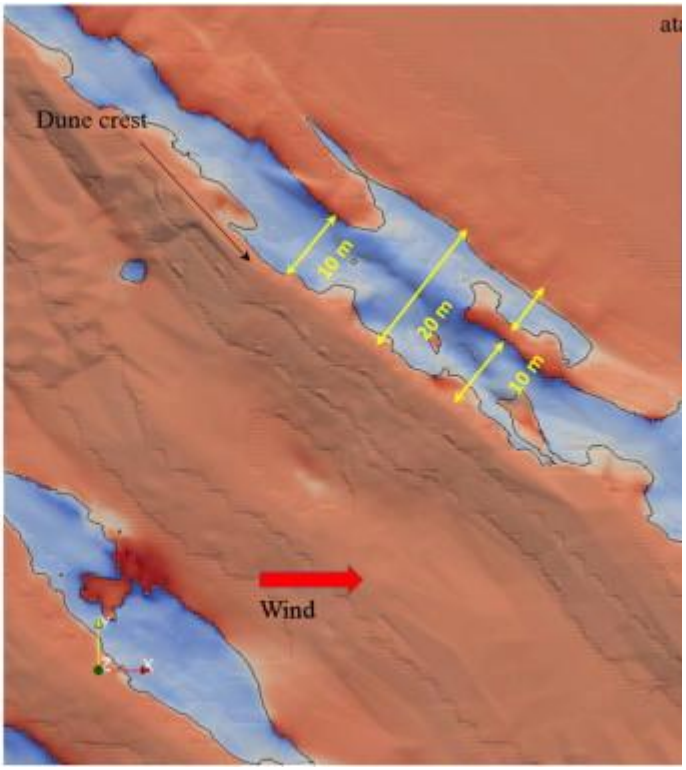

Fig. 5.

CFD simulation result for oblique offshore wind flow over actual terrain. (Left) Velocity vectors in a vertical plane through the foredune wake zone. (Right) Contour of atan2(W/U) 1 m above the terrain indicating the extent and separation between the reversed flow and re-attached flow in the dune wake zone.

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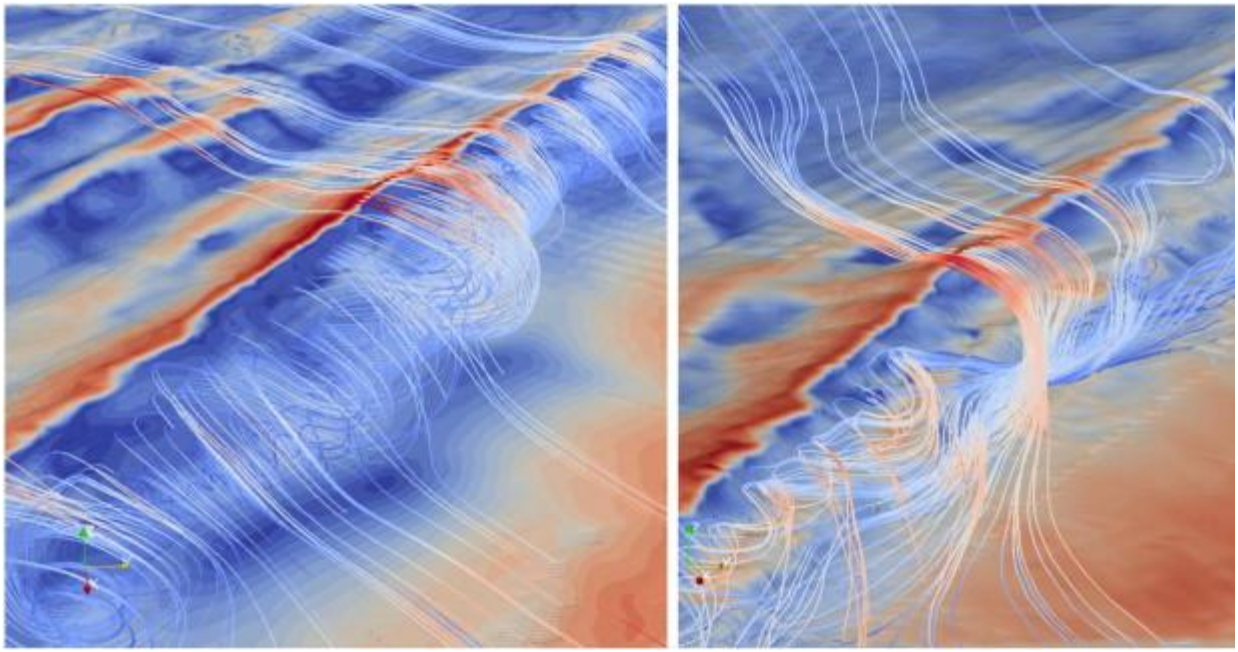

Fig. 6.

Wind flow streamlines in the foredune wake zone under perpendicular offshore winds (left image) and oblique offshore winds (right image) over actual terrain. The wake zone for perpendicular offshore winds shows the classic wake zone characteristics but influenced by the dune crest spatial variations. The oblique offshore wind wake zone shows a corkscrew vortex stretched alongshore by the wind steering. The corkscrew vortex location alternates from the area between the crest to lower dune toe to the area between the crest and embryo dune toe regions.

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