Investigation of three-dimensional wind flow behaviour over coastal dune morphology under offshore winds using computational fluid dynamics (CFD) and ultrasonic anemometry

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ABSTRACT

The behaviour of offshore-directed winds over coastal dune and beach morphology was examined using a combination of modelling (3-D computational fluid dynamics (CFD)) and field measurement. Both model simulations and field measurements showed reversal of offshore flows at the back beach and creation of an onshore sediment transport potential. The influence of flow reversals on the beach-dune transport system and foredune growth patterns has previously received little attention. Detailed wind flow measurements were made using an extensive array of mast-mounted, 3-D ultrasonic anemometers (50 Hz), arranged parallel to the dominant incident wind direction. Large eddy simulation (LES) of the offshore wind flow over the dune was conducted using the open-source CFD tool openFOAM. The computational domain included a terrain model obtained by airborne LiDAR and
detailed ground DGPS measurements. The computational grid (~22 million cells) included localized mesh refinement near the complex foredune terrain to capture finer details of the dune morphology that might affect wind flows on the adjacent beach.

Measured and simulated wind flow are presented and discussed. The CFD simulations offer new insights into the flow mechanics associated with offshore winds and how the terrain steering of wind flow impacts on the geomorphological behaviour of the dune system. Simulation of 3-D wind flows over complex terrain such as dune systems, presents a valuable new tool for geomorphological research, as it enables new insights into the relationship between the wind field and the underlying topography. The results show that offshore and obliquely offshore winds result in flow reversal and onshore directed winds at distances of up to 20 m from the embryo dune toe. The potential geomorphological significance of the findings are discussed and simple calculations show that incoming offshore and obliquely offshore winds with mean velocities over 13 m s\(^{-1}\) and 7 m s\(^{-1}\), respectively, have the potential to create onshore-directed winds at the back beach with mean velocities above 3.3 m s\(^{-1}\). These are above the threshold of movement for dry sand and support previous conclusions about the significance of offshore winds in dune and beach budget calculations.

**Keywords:**

airflow; coastal foredunes; CFD; aeolian sediment transport; lee-side coasts
Introduction

A principal component of sediment budget analysis in the beach and foredune environment is the identification of wind events capable of aeolian sediment transport from the beach to the adjacent coastal dune field (Anthony et al., 2007; Delgado-Fernandez and Davidson-Arnott, 2010). Sediment budget calculations routinely exclude offshore wind (Fryberger, 1979; Illenberger and Rust, 1988) because the cosine effect implies no sediment input into the dunes for winds approaching at an angle larger than ±90° from onshore perpendicular (Bauer and Davidson-Arnott, 2003). Localized sheltering by foredunes was also thought to lower offshore winds speeds on the back beach and to create sub-threshold conditions for sediment movement regardless of the incoming wind magnitude (Gares et al., 1993).

The existence of extensive aeolian dunes on coasts where the dominant wind direction is offshore (leeside coasts) is therefore difficult to explain within the traditional assumptions of foredune morphodynamics and regional shifts in wind regime are often invoked to explain their evolution (Shennan and Andrews, 2000). Numerous studies reporting on complex interactions between the wind field and underlying topography, and the resulting topographic steering of the wind have contributed to a change in this view. Hesp (2005), for example, suggested that topographic steering of the wind field resulting in a flow reversal, was the dominant mechanism in the development of climbing dunes on a leeside coast in New Zealand. Research in deserts (Frank and Kocurek 1996a, b; Baddock et al., 2007) and wind tunnels (Walker and Nickling, 2003) indicates that airflow across dunes results in a wide range of turbulent processes at the lee side, such as flow separation and reattachment, deflected flow and reversed eddies, or complex roller vortices or roller helixes (Walker and Nickling, 2002). Spatio-temporal variability of
shear stress within turbulent flows helps maintain entrainment of grains (Baas and
Sherman, 2005). Hence, flow velocities below the threshold for dry sand do not
necessarily result in cessation of sediment transport providing turbulent conditions
prevail (Wiggs et al., 1996). The existence of a range of processes resulting in
conditions favourable for transport toward the foredune suggests that the effects of
offshore winds should be included in sediment budget calculations.

For this to happen, the dynamics of airflow and sand transport under offshore winds
need to be better understood. The investigation of flow and transport dynamics
under offshore wind regimes, however, is hampered by fundamental limitations in
technology and methodologies. Recently, however, field experiments (Lynch et
al., 2008, 2009, 2010) measured (rather than simply inferred) landward aeolian
sediment transport associated with local topographic steering of offshore directed
airflow and established the basis to understand the importance of offshore flows on
lee-side coasts. Lynch et al. (2009, 2010) showed that post-storm recovery of wave-
scarped foredunes relied almost exclusively on offshore winds; flow reversals from
these winds transported sand from the beach onto the scarped section and thus
aided reconstruction of a dune ramp. The role of offshore wind events was such that
their omission from sediment budget calculations resulted in large under-estimation
of predicted sediment input to the foredune in the long-term (Lynch et al., 2008).

However, the degree of steering and magnitude of the reversed flow varied
depending on wind direction and foredune morphology (Lynch et al., 2010) which
could explain why reversed flows have been considered inconsequential in sediment
transport dynamics on other coastlines (Nordstrom et al., 1996; Nordstrom et
al., 2006; Walker et al., 2006). It is therefore important to explore the conditions
under which offshore winds play a major role in coastal dune dynamics. This
requires the adoption of methodologies that are able to resolve turbulence in a 3-
dimensional environment, where changes in wind direction and terrain morphology
can be considered.

Computational fluid dynamics (CFD) models have been applied widely to a number
of natural settings using both 2-dimensional (Jackson and Hunt, 1975; Castro, 1991;
Byrne and Holdo, 1998; Abe et al., 1993; Nicholas, 2001; Safarzadeh et al., 2009)
and more recently 3-dimensional numerical simulations (Lane et al., 2002; Nguyen
and Nestmann, 2004; Inkratas, et al., 2009; Shi and Huang, 2010). In particular the
3-D modelling approach can provide detailed patterns of flow behaviour over non-
uniform topography (Lee et al.2002; Lun et al., 2003; Stangroom, 2004), enabling a
more thorough examination of complex environments such as natural dune forms
and their associated airflow fields. Attempts to apply 2-D CFD to the investigation of
aeolian dunes have been promising. Parsons et al. (2002) validated a 2-D numerical
model based on PHOENICS™ 3.5 code using experimental wind tunnel flow
measurements obtained by Walker and Nickling (2003). Measured and predicted
velocities agreed in general but significant disagreement was found in the lower
velocities at the lee separation zone. A 2-D model was used by Parsons et al. (2004)
to simulate wind flow over a single idealized transverse dune of different dimensions
to explore processes such as relations between dune size and re-attachment points.

More recently, Wakes et al.(2010) successfully compared 2-D numerical simulations
against field data collected with cup anemometers and a wind vane at a coastal dune
complex at Manson Bay, New Zealand, showing the potential of CFD tools to
improve modelling of flows over complex surfaces.

Advances in the application of 3-D simulations of wind flow over coastal dunes are
desirable for a number of reasons. CFD allows a much more complete spatial
coverage of the wind field to be assessed than could be achieved from an instrumental approach. Simulations could be used to investigate the role of offshore winds under a wide range of scenarios. The detailed output resolution of the CFD models can also be used to inform field instrument deployments for optimal data gathering. Progress in this area to date has been limited by computing power, a lack of cross-disciplinary collaboration and the operational challenges of collecting the appropriate types of data at suitable spatial and temporal resolution for calibration of CFD simulations. Finally, there is a need to better characterize the wind field in key areas such as the lee separation zone.

This paper reports results of a project that aims to measure and model wind flow and aeolian sediment transport under offshore winds at a beach-dune system on a lee-side coast. The results from a deployment of an array of 3-D sonic anemometers across the beach–dune interface and associated 3-D CFD simulations using a detailed 3-D topographic surface model are presented. Model simulations were compared with field data to obtain a first assessment of the performance of the model at different heights over a given dune profile. Full validation of the 3-D model simulations will be discussed in future articles but examples are presented here to highlight the potential of CFD as a tool in the study of coastal dunes. The aim of this paper therefore is to investigate the existence of significant secondary airflows and the potential of CFD tools to model them correctly. The objectives are (1) to assess whether the onshore-directed flow under both perpendicular and oblique offshore winds is transport-capable; (2) to evaluate the performance of a number of turbulence models and explore the effect of introducing roughness into the simulations; (3) to discuss the potential of 3-D airflow simulations to provide insights into important feedbacks between form (dune shape/size) and processes (wind flow).
The first part of the paper describes field and modelling methods and results. The second part compares field data with model simulations. The final section discusses geomorphological implications of the work and future research, such as measurements of sediment transport at the beach and temporal changes in topography.

Site Location

The field experiment took place at Magilligan Strand, Northern Ireland, where a range of foredune topographies exist. The strand is part of a 6 km-long, north-west to south-east sandy beach system (Jackson et al., 2005) extending from Magilligan Point to Benone Strand (Figure 1). The wind regime is dominated by (offshore) south-westerly winds (see insert in Figure 1). The foredune is largely linear and unbroken and approximates an idealised transverse ridge. Previous research has shown that the foredunes are of sufficient height (up to 11 m) to induce significant secondary airflow effects (Lynch et al., 2008, 2010). Dune vegetation consists of a dense, homogenous cover of marram grass (Ammophila arenaria) with an average height of 0.35 m. The adjacent beach is planar and generally unvegetated with little surface debris. Beach and dune sediments consist of uniform, well-sorted, fine-grained quartz sand (mean diameter 0.17 mm). The experimental site falls within a military area which provided security for the instruments. An established regional meteorological station providing continuous records of wind speed and direction is located at Malin Head, 30 km north-west of the site.

Methods
Field data

Twenty-four ultrasonic anemometers (3-D Gill HS-50 model), were configured into a series of six vertical arrays (masts) to capture vertical and horizontal components of the wind over the foredune and across the beach surface (Figure 2). Sensor height locations (1 to 16.3 m above the local beach/dune surface) were based on a preliminary CFD run. The rig line was positioned in a near perpendicular orientation to the coastline. Each sensor had a measurement elevation angle of +/- 50° from the horizontal and $u$ (horizontal streamwise), $v$ (horizontal spanwise), $w$ (vertical) wind components were sampled at 50 Hz. Data were transferred to the serial communications from the ultrasonic anemometers (UAs) directly back to the control station position where they were time-stamped and buffered before transfer to a desktop PC. The wind speed accuracy of the windsonics is <1% RMS and the wind speed resolution is 0.01 ms$^{-1}$. The directional accuracy is < ± 1° RMS and the directional resolution is 1°.

Monitoring offshore winds covered a period of 11 days, from 23 September to 4 October 2009, and resulted in a total of 137 h with a diversity of wind speeds and directions. This extensive high quality data set contains rich information about turbulence, streamline patterns, and other wind characteristics that are explored in future publications. Only those processing steps leading to variables needed for CFD comparison purposes (magnitude of wind velocity and direction) are explained here. Wind direction (the angle in the horizontal plane between the incoming wind vector and the geographical north) was first calculated by rotating the coordinate system such that the $u$ component of the wind aligned with the geographical north and thus misalignments due to orientations of UAs in the field were corrected. The angle between $u$ and $v$ was then calculated using the $atan2$ function. Note that in field
situations where wind direction is highly variable the `atan2` is preferable to
the arctangent function, which only returns arguments in the half-plane (i.e. if
both u and v are negative, `arctangent` will give an angle measurement less than 90°,
while the angle should be between 180° and 270°). The magnitude of wind velocity
was calculated by considering the three components of the wind field (u, v, w) and
thus this includes horizontal and vertical accelerations. This paper does not deal with
streamline curvature (angle between the horizontal plane and w) or any of the
corrections associated with it (Walker, 2005; van Boxel et al., 2004) as no Reynolds
stresses or quadrant analysis (burst-sweep cycles) are presented.

Synchronized 10 min averaging records of wind velocity and direction were obtained
at each of the sensors, representing a total of 822 runs. Runs were binned according
to wind direction at the reference sensor (6 m height in mast 1 – Figure 2) which
represented the incoming wind direction both for the field data and the CFD
simulations. Wind direction and velocity varied widely during measurement periods
but only those runs in which wind direction at the reference sensor matched two
particular wind directions (cases) were selected for the purpose of this paper. Walker
and Nickling (2003) suggested that offshore incident wind angles above 70° relative
to dune ridge direction resulted in flow separation while angles from 10–70° resulted
in attached and deflected flows. Case 1 contained perpendicular offshore winds
(90 ± 5° relative to dune ridge direction) and resulted in a total of 29 runs. Case 2
contained oblique offshore winds (53 ± 5° relative to dune ridge direction) and
resulted in a total of 35 runs. These corresponded with winds from 217° and 270°
with respect to geographical north (Figure 3) and represent 8% of the total data
collected. Finally, the average velocity at all sensors was normalized by the average
velocity at the reference sensor to obtain a velocity ratio \( (v_r) \) that could be compared with the CFD modelling results.

**Computational fluid dynamics simulations**

**Topographic survey**

A LiDAR survey of the entire Magilligan foreland was completed in June 2008 using a LADS MKII LiDAR producing surface terrain data corrected to Belfast Lough Datum using observed tides at Green Castle and Londonderry Port. The spatial resolution of the spot data was every 4 m using the spheroid ETRF 89 and projection UTM, zone 29N, CM 9°W. A section of coastline measuring approximately 150 m (longshore) × 250 m (cross-shore) was then isolated as the area of interest within which the instrument rig was deployed (see detail on Figure 1). To supplement topographic LiDAR mapping, a detailed DGPS survey of the beach and foredune crest consisting of more than 48 000 points was also undertaken during September to October 2009 using a Trimble 4800 RTK at a point sampling resolution of 1 m × 1 m. This was necessary to measure any topographic changes that may have occurred in the foredune and beach area from sea wave and aeolian activity since the original LiDAR survey. In addition, DGPS data points were gathered along the main frontal foredune ridge crest at a resolution of 0.2 m × 0.2 m to examine topographic detail on the crestal region. For compatibility all data from the DGPS surveys were translated into UTM zone 29 and merged with the LiDAR data to complete a detailed topographic mesh surface (Figure 3). The importance of including the detailed DGPS survey data was highlighted in early investigative CFD work applied to the LiDAR generated terrain only. The lower spatial resolution provided by the LiDAR data at the dune crest, unrealistically smoothed the modelled
terrain crest, which reduced or eliminated the onset of a foredune recirculation zone in the simulations.

Computational fluid dynamics (CFD) methods

Previous CFD studies of wind flows over complex terrain have been performed to evaluate the performance of different modelling strategies, especially the ability of turbulence models to predict the measured behaviour of the accelerating and separating flow in three dimensional terrains. Most notable is the CFD validation work carried out for comprehensive wind measurements at Askervein hill (Salmon et al., 1988) and the earlier comparative computational work performed by Raithby et al. (1987). Using a RNG (renormalization group technique) $k$–$\varepsilon$ turbulence model at Askervein hill, Kim and Patel (2000) observed that predicted and measured mean wind speed and turbulence kinetic energy agreed well at the windward acceleration zone but disagreed in the leeward recirculation zone. This was confirmed by Castro et al. (2003) using the standard $k$–$\varepsilon$ turbulence model, who attributed the discrepancies between measured and simulated results for the leeward flow regions to the non-constant surface roughness, the limitations of the turbulence model to deal with the anisotropic nature of the turbulence and streamline curvature and transient nature of the flow. Predictions of the leeward flow anisotropic turbulence characteristics at Askervein hill were improved later by Bechmann and Sorensen (2010) using hybrid RANS (Reynolds averaged Navier Stokes)/LES (large eddy simulations) simulations. LES can resolve turbulence characteristics far away from terrain surfaces but requires too many grid points near the wall to resolve the near wall turbulence structures. RANS simulation law-of-the-wall turbulence modelling strategies offer a compromise by modelling the near wall turbulence rather than
explicitly resolving the flow scales. A combination of both schemes can reduce computational grid counts and are typically classed as hybrid RANS/LES or alternatively as detached eddy simulation (DES) models with a variety of schemes to determine when to switch from LES to RANS schemes in the solution domain. A more comprehensive overview of the development of the hybrid methods and variations to the theme is given by Spalart (2009) and Fröhlich and Terzi (2008).

Spalart and Allmaras (1994) originally developed a one-equation RANS model (SA-RANS) that solves a single transport equation for the eddy viscosity, described in Fröhlich and Terzi (2008). The SA-RANS eddy viscosity transport equation contains a turbulence destruction term that is a function of the wall distance ($d$). In the subsequent DES approach developed by Spalart et al. (1997), the wall distance was replaced by a length scale dependent on the grid size ($\Delta$) which modifies the SA-RANS model into a LES SGS model. In this SA-DES model the length scale switches between wall distance (RANS) and grid size (LES). The grid length scale used in this model is the maximum of the three dimensional grid spacing instead of the more traditional cube root of the grid volume. One of the disadvantages of earlier DES models was its sensitivity to grid induced separation (GIS) where well-intentioned grid refinement approaches may actually reduce the accuracy of an LES simulation and can produce less accurate results than traditional RANS simulations on coarser grids (Spalart, 2009). One of the strategies to reduce the GIS effect resulted in the delayed DES (DDES) (Spalart et al., 2006), which extends the RANS region by detecting boundary layers, rather than the LES/RANS switching over simply being controlled as a function of the wall distance or grid size alone. The improved delayed detached eddy simulation (IDDES) of Shur et al. (2008) is a further derivative of the DDES which combines the DDES with wall-modelling LES.
(WMLES) and blends the applied RANS and LES length scales. For details on modified length scales formula and blending functions see Fröhlich and Terzi (2008) and Shur et al. (2008).

Simulations were carried out using the open-source CFD software OpenFOAM to solve the system of partial differential equations representing the governing fluid dynamic equations on a three-dimensional computational grid using finite volume discretization strategies. The general flow solver follows standard CFD solution techniques of finite volume discretization and pressure–velocity coupling techniques (Shur et al., 2008). The present work evaluated four turbulence modelling approaches: (1) steady state RANS formulation using the RANSk–ω SST (shear stress transport) turbulence model of Menter (1994); (2) the IDDES model of Shur et al. (2008); (3) the one equation eddy (k) LES; and (4) an approach using the one equation eddy (k) LES-ABL (atmospheric boundary layer) simulations that accounted for terrain roughness by including a constant aerodynamic roughness length (z0) in a law of the wall logarithmic velocity profile that updates the near wall-eddy viscosity (see Boundary conditions section). While a number of assumptions needed to be considered, the aim of the fourth approach was to evaluate the impact of including roughness into the simulations rather than discussing an appropriate method for calculating z0.

Boundary conditions

As in previous studies (Wakes et al., 2010) several simplifications were adopted for the purpose of conducting the simulations. The approaching wind profile was judged to be similar to flow over open natural terrain. A logarithmic wind velocity profile was
used to provide the steady wind speed variation over the height of the domain inlet and also applied as the law of the wall function for the LES-ABL simulations:

\[ U(z) = \frac{u_*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right) \]  

(1)

where \( U(z) \) is the wind speed at elevation \( z \) and \( K \) is the von Karman's constant (≈0.4). The aerodynamic surface roughness length \( (z_0) \) and shear velocity \((u^*)\) for all simulations was 0.1 m and 0.70 m s\(^{-1}\), respectively, and were estimated from mean wind profiles at masts 1–3 (over the dune field) using the method proposed by Namikas et al. (2003). The inlet turbulent kinetic energy \( (k) \), specific turbulence dissipation rate \( (\varepsilon) \), eddy viscosity and turbulence intensity profiles used for the simulations were derived from the turbulence inlet conditions given by Richards and Hoxey (1993):

\[ k = \frac{u_*^2}{\sqrt{C_\mu}} \]  

(2)

\[ \varepsilon = \frac{u_*^2}{\kappa(z + z_0)} \]  

(3)

where \( C_\mu \) is a model constant (=0.09). The inlet specific turbulence kinetic energy, turbulence viscosity and turbulence intensity are subsequently given by:
\begin{align}
\omega &= \frac{\varepsilon}{C_\mu k} \\
\nu_t &= \frac{k}{\omega} \\
I_u &= \frac{\sqrt{\frac{2}{3}} k}{U(z)}
\end{align}

Results

Field data

Figures 4 and 5 display results for Case 1 (29 runs) and Case 2 (35 runs), respectively. Areas of flow steering and reversal have been identified in parts A of both figures and wind roses at each of the sensors are displayed in parts B and C. The length of the arrows depends on the scatter of wind direction and the colour is a function of the velocity ratio. Results confirm ideas by Walker and Nickling (2003) and observations by Lynch et al. (2010) at the same site, and show flow separation and reversal on the lee-side of the foredune for offshore winds (Case 1) and flow deflection for oblique winds (Case 2). The higher density array of this study has allowed insights into the vertical behaviour of the flow. The wind direction for Case 1 and 2 remained constant at sensors deployed over the highest topographic point in the profile (Figures 4A and 5A). Wind steering and/or flow reversal were measured at the lowermost sensor in mast 2 and at heights below the foredune crest seaward for both cases. This suggests the existence of permanent turbulent areas in the lee side of the foredune under different angles of wind approach. Interestingly, the wind
direction presented an onshore component in sensors closer to the beach surface (mast 5–6) not only in Case 1 (as suggested by Lynch et al., 2010) but also in Case 2. This has implications for potential onshore sediment transport (see discussion).

Velocity ratios ($v_r$) decreased closer to the ground (as expected) but surprisingly remained significantly constant independent of wind velocity at the reference sensor. Table 1 shows mean $v_r$ and corresponding standard deviations ($\sigma$) for each sensor. Note that the first row of data contains the maximum and minimum velocity found at the reference sensor to show the range of mean wind velocities for the 29 and 35 runs of Cases 1 and 2, respectively. Despite diversity in wind velocities at the reference sensor the standard deviations are very low, indicating small variability of individual $v_r$ with respect to the mean value given here. This is particularly useful in providing reasonable estimates of wind velocity at any of the sensors location given an incoming wind at the reference sensor but particularly at the unvegetated beach surface where sand grains may be entrained. Figure 6 displays regression curves between wind velocities at the reference sensor and sensors at 1 m high over the ground in masts 5 (dune toe) and 6 (back beach) for Case 1 (Figure 6A) and Case 2 (Figure 6B). Note that the maximum velocity attained during Case 1 winds was around 8 m s$^{-1}$ while the maximum attained during Case 2 was 14.5 m s$^{-1}$. Despite a larger scatter in Case 2 there is a strong correlation in both sensors which could be useful in predicting wind velocity at 1 m over the beach surface given an incoming wind velocity (see Discussion).

Table 1. Mean velocity ratios ($v_r$) and standard deviations ($\sigma$) obtained for each sensor using 29 10-min runs for Case 1 and 35 10-min runs for Case 2. Note that the range of wind velocities at the reference sensor is displayed in the first row.
<table>
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<th>Array</th>
<th>Sensor height (m)</th>
<th>( v_r^1 )</th>
<th>( \sigma^1 )</th>
<th>( v_r^2 )</th>
<th>( \sigma^2 )</th>
<th>( v_r^1/v_r^2 )</th>
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<td>max ( V = 8.03 \text{ m s}^{-1} )</td>
<td>max ( V = 14.45 \text{ m s}^{-1} )</td>
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<td>min ( V = 3.16 \text{ m s}^{-1} )</td>
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<td>0.53</td>
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<td>0.6</td>
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<tr>
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<td>0.03</td>
<td>0.46</td>
<td>0.05</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Finally, the comparison of \( v_r \) in Table 1 indicates a stronger deceleration of the wind in sensors below 4 m at masts 5 and 6 for Case 1, with wind velocities typically 60% of the value of those in Case 2 most likely due to a higher degree of sheltering.

Figure 7 displays examples of wind profiles at each mast corresponding to the runs with the highest mean velocities at the reference sensor for Case 1 (8 m s\(^{-1}\)) and Case 2 (14.5 m s\(^{-1}\)). Only one run per case is presented because the pattern of wind velocity across the dune was similar for a variety of input wind speeds. Wind velocity decreased from mast 1 to mast 2 followed by a speed up close to original levels at mast 3 (foreshore crest). Wind velocities at the upper sections of the wind profiles in
masts 4 to 6 were comparable with velocities at the foredune crest, most likely indicating the free stream zone. As expected, velocities decreased closer to the surface, with the strongest vertical variation in wind velocity being recorded at mast 4, due to larger sheltering by the foredune.

**CFD simulations**

Figures 8 and 9 show results for LES-ABL and RANS $k-\omega$ SST simulations for Case 1 and 2 respectively. LES and IDDES simulations produced results that resemble those of RANS simulations and thus are not presented here. The turbulent models resolved the expected wind recirculation zone leeward of the foredune/beach interface for Case 1 (Figure 8, top images). The LES-ABL simulations predict lower near surface velocities compared with the RANS simulation, owing to the RANS model absence of wall roughness treatment and its inability to capture localized recirculation in depressions and valleys (between masts 1 and 3) along the rig line (Figure 8, bottom images). Both RANS and LES-ABL simulations suggest the recirculation zone reattachment point to be located at the beach surface downwind from the dune crest at approximately 4–5 times the foredune height. This is in line with observations by Frank and Kocurek (1996b) and Walker (2000) in aeolian dunes, and with observations by McLean and Smith (1986) and Nelson and Smith (1989) in fluvial dunes, with reattachment zones from 4–8 times the dune height. The 3-D simulations for Case 1 (bottom images) show no coherent terrain wind steering but instead predict localized recirculation zones along the beach/foredune system that are not two-dimensional. LES-ABL simulations predicted smaller localized recirculation zones along the rig line for Case 2 (Figure 9, top images), including a small recirculation zone at the
foredune/beach location, isolated to the top of the dune. The Case 2 RANS simulation did not predict any recirculation along the rig line. The dune system and its alignment to the prevailing west winds are responsible for localized steering of the wind toward the south-east as can be seen in Figure 5. Both the LES-ABL and RANS simulations capture the near surface wind steering towards the south-east (Figure 9, bottom images). However, the LES simulations predicted lower velocities due to the inclusion of terrain roughness and their likely better resolution of near surfaces eddies.

Discussion

Comparison between measured and simulated CFD wind profiles

Figures 10 and 11 show comparisons between velocity ratios measured in the field and velocity ratios simulated by the four turbulent modelling approaches for Case 1 and Case 2, respectively. As expected, simulations performed without accounting for terrain roughness (IDEES, LES, RANS) did not agree well with the measurements and tended to over-predict the near-surface velocity. The results for the one-equation LES-ABL simulations for Case 1 (Figure 10) agreed favourably with field measurements for all six mast locations, including the recirculation zones captured by masts 5 and 6 (Figure 4). Future simulations will be performed and compared against this set using the IDDES with the terrain roughness modelling. Figure 11 confirms that the LES-ABL simulations agree better with the measured results compared with the simulations performed without aerodynamic roughness but not at all sensors. While the introduction of a roughness parameter is important for better agreement between LES-ABL simulations and field data, some of the wind
profiles in Figure 11 suggest room for further improvement. LES-ABL simulations in Mast 3 and 1, for example, tend to under-estimate near-surface velocity, which may be related to the way in which roughness is modelled. Velocity profiles in Figure 7 suggest that the near surface wind velocities at these locations are less dragged by roughness elements during oblique winds, which could result in an under-estimation of LES-ABL simulations. Assumptions related to the use of the Law of the Wall or a single value for roughness will therefore be explored in future work.

Typical values of $z_0 = 0.1 \text{ m}$ have been used elsewhere (Levin et al., 2008) on a similar terrain and alternative approaches to the calculation of $z_0$ have been suggested by Levin et al. (2008) and Wakes et al. (2010).

**Geomorphological implications**

CFD 3-D simulations presented in Figure 8 (bottom images) indicate the heterogeneity of surface airflow wind velocity and direction when emerging from the foredune crest position. The modelling output shows alongshore patterns which seem to be related to localized undulations in the foredune crest topography. On the other hand, both 3-D simulations and field data indicate that airflow steering and reversal are dependent on incident wind direction at the crest. The agreement between simulated and observed velocity ratios at different heights across the beach-dune profile and the output of 3-D simulations suggest several areas of future research. First, field data needs to be acquired at a spatial grid over the beach surface to validate CFD 3-D simulations. Second, and although previous research has already observed landward sediment transport during offshore winds at this location (Lynch et al., 2008, 2009, 2010), there is a need to measure spatial sediment transport patterns given the heterogeneity of wind velocity observed in 3-D
CFD simulations. Furthermore, there is a need to establish a relationship between potential onshore transport and wind velocity at a known location which could be used for predictive purposes. Although future work will deal with detailed transport dynamics, it is possible to speculate on the potential to perform simplified predictions of sediment input to the foredunes under offshore winds with the results presented here. According to Bagnold (1941), the threshold shear velocity for dry sand can be calculated as:

\[ U_{st} = A \left( \frac{\sigma - \rho}{\rho} gd \right)^{0.5} \]  

\[ (7) \]

where \( A \) is an empirical coefficient = 0.1 for air, \( \sigma \) is the density of grain material (2650 kg m\(^{-3}\) for quartz), \( d \) is the grain diameter (1.7 \times 10^{-4} m), and \( \rho \) is the density of air (1.22 kg m\(^{-3}\)). This produces a \( U_T = 0.19 \text{ m s}^{-1} \) at Magilligan. Equation (1) can be applied to obtain a threshold velocity for dry sand movement \( (U_z) \) at any height \( z \) (assuming a logarithmic profile close to the surface). If the method of Namikas et al. (2003) is used, again with a wind profile obtained from sensors at heights 1 to 4 at mast 6 (bare sand) the roughness length \( z_0 = 10^{-3} \text{ m} \) which in turn results in \( U_{1m} = 3.28 \text{ m s}^{-1} \). Correlations shown in Figure 6 (or velocity ratios displayed in Table 1) may then be used to find the minimum velocity at the reference sensor corresponding to \( U_{1m} = 3.28 \text{ m s}^{-1} \) in mast 6. For example winds over 12.1 m s\(^{-1}\) (Case 1) and 7.1 m s\(^{-1}\) (Case 2) at the reference sensor would result in potential transport at the back beach. Wind direction at this location was steered landward and thus it is reasonable to expect onshore sediment movement (input to the foredune budget).
Finally, for ease of comparison, this paper has focused on 10 min averages of wind velocity. It is acknowledged that transport at the back beach is likely to be strongly influenced by turbulent structures and this will be the subject of future work. Shear stresses at the lee side of the dunes may be greater than those suggested by time-averaged streamwise estimates alone because of the role of turbulent stresses (Walmsley and Howard, 1985; Wiggs et al., 1996). Shear stress generation, and thus the potential for sediment transport, is linked to turbulent fluctuations (i.e. flow unsteadiness) and the destabilizing effects of concave streamline curvature (Bradshaw, 1969; Wiggs et al., 1996; Walker and Nickling, 2003).

Conclusions

The present work describes the first results from field test measurements and comparative CFD simulations carried out to evaluate the off-shore wind flow over complex coastal dune terrain. LES simulations compare well with field measurements when an appropriate value for aerodynamic roughness is included in the model. The agreement obtained using the LES-ABL approach suggests that the CFD method can be used to examine the influences of topographic steering, which is an important element of aeolian sand transport at this and other sites. Furthermore, the LES-ABL results suggest that the method can help identify the recirculation zone location and the localized near-surface wind velocity and turbulence intensity. Such data can help identify the required windward wind characteristics needed to initiate sand transport either within a recirculation zone or along the upper beach during wind steering conditions. Future work will evaluate the performance of the IDDES simulation method with the ABL aerodynamic roughness treatment at the terrain boundary.
If the measured or simulated wind velocity ratios relevant to sand transport are combined with long-term meteorology records from a local reference station, a prediction of the frequency and intensity of foredune sand transport events may be possible. Further examination and comparison between CFD results and field tests is therefore important if sufficient confidence is to be placed in using CFD to simulate flow under other wind directions or different site and terrain conditions. Application of 3-D CFD over dune systems is, however, a valuable new tool that promises new insights into coastal dune geomorphology and dynamics. Finally, the approach may in fact be beneficial for other academic communities, such researchers interested in reconstructing past dune forming conditions for archaeological work or simulating foredune evolution under different climate change scenarios.

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