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Three dimensional airflow patterns within a coastal trough–bowl blowout during fresh breeze to hurricane force winds

Thomas A.G. Smyth *, Derek W.T. Jackson, J.Andrew G. Cooper

School of the Environment, Flinders University, South Australia 5042, Australia

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ABSTRACT

Wind flow within blowouts is extremely complex as streamline compression, expansion and reversal may occur over and around a single landform. As a result high resolution temporal and spatial measurements are required during a range of incident wind conditions to resolve near surface airflow patterns and turbulent structures. This study examined three-dimensional airflow within a coastal dune trough–bowl blowout using 15 ultrasonic anemometers (UAs) and a high resolution computational fluid dynamics model.

Measured total wind speed and vertical wind speed behaved consistently through 5 Beaufort wind scales ranging from ‘fresh breeze’ to ‘strong gale’, increasing relative to incident wind speed, whilst wind direction at each UA did not alter. Due to the agreement of modelled and measured data, ‘hurricane’ (37 m s^{-1}) incident winds were also simulated and were consistent with modelled and measured wind direction at lower wind speeds. Modelled wind turbulence data was not compared with measured as only average conditions were simulated. However, the standard deviation of measured wind direction remained constant at each anemometer throughout the range of incident wind speeds, whilst the standard deviation of wind speed and turbulent kinetic energy increased relative to incident wind speed.

This paper demonstrates that wind flow behaviour within blowouts throughout this range of wind speeds is governed by topography and is relative to, but does not change structurally with incident wind speed. As a result the extent of streamline compression, expansion, steering and reversal remain constant.

1. Introduction

Blowouts are distinctive erosional landforms, created or sustained by aeolian sediment transport and wind shear at their surfaces. They occur on vegetated pre-existing sediment deposits such as coastal dunes (Jungerius, 1984; Hesp and Hyde, 1996; Fraser et al., 1998; Hesp and Pringle, 2001; Smyth et al., 2011), temperate grasslands (Hugenholtz and Wolfe, 2006; Wang et al., 2007) and semi-arid environments (Hesp, 2002). Formation typically begins where vegetation cover is diminished, permitting deflation of the underlying sediment by wind stress at the sediment surface. Points of initiation can be caused by changes in vegetation species, density or distribution, increased wind speeds and wave erosion in coastal dune systems (Hesp, 2002). As a result blowout activity is a proxy indicator to changes in climate, fauna grazing and anthropogenic activity (Käyhkö, 2007). Once initiated, blowout evolution is dependent on the interactions between wind speed, wind direction, topography and vegetation cover (Gares and Nordstrom, 1995). Due to the complex relationship between deflation variables, blowout morphology differs extensively in shape and size. Most blowouts however can be classified into two broad categories, ‘trough’ and ‘saucer’ (Hesp, 2002). Trough blowouts are deep, elongated, erosional landforms with high steep erosional walls, whilst saucer blowouts are shallow and orbicular in form, with short steep erosional walls. Shallow saucer blowouts can further develop into deeper bowl blowouts which resemble small impact craters (Hesp, 2002; Hesp and Walker, 2012).

Wind speed and direction measured within blowouts is substantially modified compared to ambient wind speed and direction. As wind flows over a blowout’s topography, airflow near the surface becomes manipulated by streamline compression, expansion and separation, resulting in complex patterns of secondary flow (Hesp and Walker, 2012). Furthermore, as airflow within blowouts does not adhere to a logarithmic velocity profile, traditional techniques of calculating shear stress and predicting sediment flux are not applicable (Fraser et al., 1998). As a result the measurement and characterisation of airflow, has been the focus of much research within trough (Hesp, 1996; Hesp and Hyde, 1996; Fraser et al., 1998; Hesp and Pringle, 2001) and saucer type blowouts (Hails and Bennett, 1981; Pluis, 1992; Gares and Nordstrom, 1987; Wang et al., 2007; Hugenholtz and Wolfe,

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* Corresponding author.
E-mail address: thomas.smyth@flinders.edu.au (T.A.G. Smyth).

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2009; Hesp and Walker, 2012; Smyth et al., 2011, 2012). Comparison of airflow data in trough and saucer blowouts, reveal differences in the general characteristics of each. Where wind is parallel with the long axis of a trough blowout, flow becomes accelerated along the narrow deflation basin and steep erosional walls. In saucer type blowouts flow typically separates in lee of the windward erosional wall, expands and decelerates along the deflation basin before accelerating over the erosional wall as it exits. Airflow steering and acceleration within the deflation basin however differs with wind direction in both trough and saucer blowouts (Hesp, 2002). This has implications for potential sediment erosion and deposition patterns, influencing a blowout's morphological evolution.

Whilst near surface airflow within deflation basins has been examined for a range of incident angles, detailed studies investigating near surface three-dimensional airflow patterns for a range of approaching wind speeds are notably absent from the literature. A number of investigations studying airflow dynamics within deflation basins have found that flow is topographically manipulated over blowouts both at low and moderate incident velocities (Fraser et al., 1998; Hugenholtz and Wolfe, 2009; Smyth et al., 2011) and a long-term study measuring surface change in coastal blowouts by Jungerius et al. (1981), found that stronger winds were relatively ineffective at inducing surface change, and at higher wind speeds blowouts were actually filled with sediment. From these results Jungerius et al. (1991) purported that blowouts are formed by the most frequent wind conditions, and that the shape of a blowout is unable to adjust to the aerodynamic characteristics of a high velocity wind event. Comparison of airflow dynamics within a blowout during an extensive range of wind speeds has prevented examination of this hypothesis. Hesp and Walker (2012) have noted that strong winds are capable of transporting sediment beyond the deflation basin, however, the relationship between blowout evolution and storm winds continues to remain unresolved (Hesp, 2002).

This paper aims to:

(1) Measure and examine empirical three-dimensional near surface airflow dynamics and turbulence within a coastal trough–bowl blowout during a range of incident wind speeds using high frequency (50 Hz) ultrasonic anemometers (UA).
(2) Compare measured field data with three-dimensional simulated wind flow conditions from a computational fluid dynamics (CFD) model at a range of wind speeds.
(3) Use modelled data to provide increased spatial resolution of three-dimensional airflow within a bowl blowout during a high wind speed, hurricane event.

2. Study site

The study site for this investigation is located on Carricklahan beach, on the Atlantic coast of the Belmullet Peninsula in western Ireland. Carricklahan is a macro-tidal (>4 m), high energy, dissipative sandy beach constrained by rocky outcrops to the north and south. It is backed by a steep 8–14 m high foredune (>25°), vegetated predominantly with marram grass (*Ammophila arenaria*). Landward of the foredune is relatively flat, species rich machair grassland, which is maintained by intermittent low intensity grazing (Cooper et al., 2005).

Hourly meteorological data has been collected since 1956, 1 km outside the town of Belmullet, 13.5 km north east of the study site (Fig. 1). Data recorded at the meteorological station indicate the area has a temperate oceanic climate, with a mean annual precipitation of 1186 mm and mean annual temperature of 10 °C. Prevailing winds for the study area are from the south west averaging 6.7 m s^{-1} and are associated with easterly moving low pressure systems (Fig. 1).

A range of blowouts, dimensionally and morphologically diverse, exist from the foredune to approximately 1 km inland. Evidence from aerial photography between 1995 and 2005, has shown rapid reduction in bare sand surface in the study area, from 182,119 to 68,568 m^2, a reduction of 62.4% (Jackson and Cooper, 2011).

The blowout selected for investigation in this paper is partially vegetated and located within the lee of the foredune. Geomorphological classification of the blowout is however complex. The largest part of the blowout is located immediately leeward of the foredune and has a large bowl shape structure with a diameter of approximately 50 m. The bowl structure also contains a large ridge within the southern half of the deflation basin which rises approximately 3 m above the deflation basin surface. The bowl does however breach a small section foredune through a trough shaped depression, classified as the blowout throat in previous publications (Smyth et al., 2011, 2012), however it is not connected to active beach surface as it is perched 8 m above it. The trough measures 15 m long by 10 m wide and is orientated to the north east, consistent with the prevailing wind direction. In an effort to acknowledge the multifaceted form of the blowout its shape will be referred to as trough–bowl throughout this paper.

Corresponding to the re-sealing of the local dune system, the trough, deflation basin of the bowl and depositional lobe has become vegetated. However the erosional walls, with the exception of the western wall, remain largely free of vegetation. This unvegetated region was measured during a GPS study of the area and totalled approximately 1500 m^2. Contemporary slump blocks on the erosional walls originating from the blowout rim (Fig. 2) and observed sand avalanching on the steepest erosional walls (>36°) are evidence that continued erosion is occurring at the site.

3. Methods

3.1. Topographic survey

A topographic survey of the blowout was completed on 30th June, 2010. A Trimble 5700 GPS receiver and two Trimble 5000 series GPS rovers were used to collect topographic data points at 1 m × 1 m intervals throughout the foredune, beach, blowout and depositional lobe. Topographic points along the rim of the blowout were collected at 0.25 m × 0.25 m intervals to sufficiently map the abrupt changes in gradient. Topographic data of the vegetated dune surface adjacent and landward of the GPS survey area was provided by 6 m resolution LiDAR data, collected by a survey in June 2008 using an Mk II laser airborne depth sound sounder. Both surveys were combined and interpolated using kriging to generate a 0.5 m × 0.5 m resolution ASCII grid measuring 205 m × 470 m (Fig. 3).

3.2. Field data

In advance of wind flow measurement throughout the blowout by anemometry, preliminary CFD simulations were conducted using the topographic survey data collected in June 2010. These runs predicted extensive secondary flow inside the bowl deflation basin and along the bowl's erosional walls. Subsequently, 15 Gill HS-50 (Gill, 2013) ultrasonic anemometers (UAs) were placed above the surface of the bowl's deflation basin and erosional walls in November 2010, where erosion of sediment was deemed important to blowout morphological development (Figs. 2 and 3). An UA was also placed in the centre of the trough's deflation basin and another located seaward of the blowout to record incident wind