Wind characteristics over complex terrain with implications for bushfire risk management

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Draft: 14th July 2008

Abstract

Understanding spatially distributed wind fields over complex terrain is important for a variety of applications including pollutant dispersion modelling, fire spread modelling and bushfire risk management. Directional changes in surface winds are particularly important in the context of fire management. In this paper terrain-modified winds are analysed using joint probability distributions derived from wind speed and direction data collected in rugged terrain to the west and south-west of the Australian Capital Territory. The analyses focus on two landform elements; a steep slope and a moderately steep valley. The joint distributions prove to be useful tools for identifying and characterising the dominant states of the wind-terrain systems. Several processes, including thermally forced winds, lee-slope eddies and dynamic channelling are identified and discussed. The analyses also reveal the stochastic nature of the wind-terrain systems, and thus raise some doubts about the suitability of deterministic approaches to modelling terrain-modified surface winds. Implications of the results relevant to fire behaviour and bushfire risk management are also discussed.

1. Introduction

It is well known that complex or rugged terrain can have a significant effect on micro- and meso-scale atmospheric flows (Blumen, 1990; Barry, 1992; Whiteman, 2000). As a consequence, surface wind fields in rugged terrain can be highly variable, both across space and in time. Understanding these dynamic wind fields is an important part of many environmental problems, for example, the atmospheric dispersion of pollutants, aerial spraying and the prediction of how a wildfire will spread (Kossmann et al., 2001). Terrain-induced flows are also important considerations for light aviation and generally affect the local climatology of mountainous regions. In this paper the focus will be on these dynamic wind fields in the context of wildfire or bushfire risk modelling, which generally includes some form of fire spread modelling (Chandler et al., 1983; Beer, 1991).

Fire spread models permit those concerned with fire management to estimate how a fire will spread under certain conditions, thereby facilitating the better deployment of resources during fire suppression activities, and more targeted fuel reduction treatments as part of longer term fire management practices. Typically fire spread models require
information on the amount and type of combustible fuel, drought conditions, topography and meteorological variables such as wind speed and direction, temperature and relative humidity. Wind is the most critical environmental factor affecting fire behaviour and is one of the main components determining the rate and direction of fire spread (Rothermel, 1972; Catchpole et al., 1998; Gorski and Farnsworth, 2000). Accordingly, fire spread models are highly sensitive to changes in wind direction. Therefore, to accurately simulate fires with these models, it is important to use wind direction data that matches conditions on the fire-ground as closely as possible.

Many approaches to fire spread modelling assume a constant wind speed and direction, as given by the closest source of meteorological information, which can often be tens of kilometres from the fire-ground. While this may be appropriate over flat or slightly undulating terrain, making such an assumption over rugged terrain can lead to serious errors in judgement. More sophisticated fire spread models incorporate methods to make local modifications to the wind field based on topographic considerations. Examples of these include methods that use computational fluid dynamics (CFD) to simulate the terrain-induced wind field (Alm and Nygåard, 1995; Kim and Boysan, 1999; Lopes, 2003; Forthofer et al., 2003; Butler et al., 2006a; Butler et al., 2006b; Forthofer and Butler, 2007; Forthofer, 2007), methods that employ conservation of mass principles to derive terrain-modified flow (Sherman, 1978; Davis et al., 1984; Moussiopoulos and Flassak, 1986; Ross et al., 1988; Forthofer, 2007) and methods like that of McRae (????), which uses a table of correction factors that depend on topographic aspect and ambient wind direction.

A shortcoming of the methods that assume a constant wind direction is that they fail to capture the nonlinear, turbulent and thermal effects that the terrain can have on local winds. Examples include eddy winds, thermally-driven diurnal winds and channelled winds. Mass-conservation methods will also miss these effects. Eddy winds form due to frictional differences or when the inertia of a flow causes it to separate from the surface in the lee of a ridge. Eddy winds are a vortical flow whose axis can be horizontal or vertical. Lee-slope eddies, which form between the lee-slope and the ambient flow passing overhead, would have an approximately horizontal axis running parallel to the ridge line (Byron-Scott, 1990; Whiteman, 2000). Thermally-driven winds arise due to differential heating across a rugged landscape that causes air to flow down-slope after sunset and up-slope after sunrise (Whiteman, 1990; Whiteman, 2000; McCutchan, 1983; McCutchan and Fox, 1986; Sturman, 1987). These thermal winds follow a distinctive diurnal cycle. Channelling of winds along valleys can occur through a number of mechanisms. For example, forced channelling occurs when winds follow the path of least resistance along a valley, while pressure-driven channelling occurs in response to the along-valley component of a broader pressure gradient (Lee et al., 1981; Wippermann and Gross, 1981; Wippermann, 1984; Doran and Whiteman, 1992; Eckman et al., 1992; Whiteman and Doran, 1993; Weber and Kauffmann, 1998; Kossmann et al., 2001; Kossmann and Sturman, 2003).

The processes just described can seriously compromise fire suppression activities and fire-crew safety. In essence, the processes described above all result in directional
changes in the local wind field, which can then differ from the ambient wind direction by up to $90^\circ$, in the case of channelling, or $180^\circ$ in the case of eddy and thermally-driven winds. This means that, on a fire-ground, crews working on suppressing a flank could be suddenly faced with an active head-fire, or if spotting occurs on a lee-slope, fire-crews on the windward ridge would be between two fires spreading towards them. Understanding the intricacies of rugged terrain-wind systems is therefore an important part of understanding the associated fire regime and can improve the safety and effectiveness of fire management strategies.

A natural approach to the problem of quantifying wind-terrain systems is to approximate the atmospheric motion using the fluid equations or mass conservation principles, along with the terrain surface as a boundary for the problem (Forthofer, 2007). Mesoscale numerical weather prediction models have also been used to simulate the terrain-modified flow and have even been coupled with fire spread models (Linn, 1997; Coen, 2005; Winterkamp et al., 2006; Linn et al., 2007). These coupled models have the potential to accurately reproduce actual fires but have the disadvantage of being computationally intensive, requiring resources that are not available to the average fire management agency.

This paper employs an alternative approach for understanding a particular wind-terrain system, based on probabilistic analysis of wind speed and direction data collected by the authors. The approach centres on joint wind direction distributions for a number of different paired locations, and is an extension of an approach used by Whiteman and Doran (1993) to analyse the relationship between synoptic-scale winds and winds in a mesoscale valley. The joint distributions relate the joint probability of the two locations experiencing certain wind directions (not necessarily equal). The data was collected between December 2006 and October 2007 in the Brindabella and Tidbinbilla Ranges to the west and south-west of Canberra, ACT. These regions were selected due to the fact that both contained rugged terrain and both had experienced intense fire behaviour during the January 2003 fires (Nairn, 2003; McRae, 2004; McRae et al., 2006; Mills, 2006). As a consequence of the fires, very little of the forest canopy remained in these areas. This allowed the anemometers to have better access to the wind, without too much disturbance caused by canopy effects. Concentrating on these areas also meant that the wind data being collected could assist in understanding the intense fire behaviour observed in them.

Section 2 outlines the methods employed in the field-data collection and describes the locations and characteristics of the individual sites used in the study. Section 3 discusses the analytical methods used to construct the joint wind direction distributions, before they are analysed in section 4. The results of section 4 are further discussed, in the context of bushfire risk management, in section 5.

## 2. Field-data collection methods

The existing national network of automatic weather stations, maintained by the Bureau of Meteorology, is not dense enough to investigate the micro- and meso-scale phenomena
we are interested in. For this reason additional portable automatic weather stations were deployed in close proximity (with an average spacing of the order of 100-1000 metres) in the area of interest. Augmenting the Bureau’s network in this way enables the capture of finer-scale phenomena in addition to the broader scale meteorology.

Field-data collection concentrated on two regions to the west and south-west of Canberra, ACT. In particular, we deployed portable automatic weather stations in Tidbinbilla Nature Reserve, ACT and Brindabella National Park, NSW, which form part of the mountainous region to the west of the Australian Capital Territory. These particular areas were chosen because they both contained complex topography and had both experienced severe fire behaviour during the January 2003 alpine fires, which had removed a lot of the natural forest canopy. In addition, both areas had reasonable 4WD access, but were still secluded enough so that the risk of people tampering with the deployed instrumentation was minimal.

The instruments used to record weather data were Davis Vantage Pro 2 Plus™ stations, which each consist of an integrated sensor suite connected to a console that logs and displays weather data. Vented and shielded sensors that measure air temperature, relative humidity and dew point temperature, were mounted on an aluminium pole 2 metres above the ground surface. A wind vein and cup anemometer were also mounted on the pole at a height of 5 metres above the ground surface. The standard height at which wind is measured in Australia is 10m. However, experience has shown that wind measurements at a height of 5m, particularly those pertaining to wind direction, do not differ significantly from those at 10m (I. Knight, pers. comm.). Given this, and the logistics of field deployment, it was decided that measurement of wind at 5m would be sufficient. Solar panels to power the device and a console housing box were also fastened to the same aluminium pole at approximately 1 metre above the ground. The pole locked on to a rectangular steel base (approx. 25cm × 15 cm), which was pegged to the ground, and was stabilised by three wire guy ropes. The entire portable automatic weather station described above could be deployed by two people relatively easily in the rugged terrain, with very little or no disturbance to the surrounding environment. The wind veins were aligned with true north using a compass. In total, eleven portable automatic weather stations were deployed in the field.

The stations were deployed on two main landform elements. In Tidbinbilla Nature Reserve, stations were deployed along the ridge and on the east facing slopes of a steep mountain ridge (known as ‘Camel’s Back’) with a relief of approximately 500m. In Brindabella National Park stations were deployed across a mountain valley (Flea Creek) with reasonably steep slopes and a relief of approximately 300-400m. Both the mountain ridge and the valley are aligned roughly in a north-south direction. Where possible the stations were deployed at sites with very little or no canopy so that we could minimise the effects of the canopy on the wind data being recorded. Given the realities of the field setting, however, this was not always entirely possible (see table 1). In total, three transects of portable automatic weather stations were deployed: two in Tidbinbilla Nature reserve, one running northwest to southeast and one running southwest to northeast, and one in Brindabella National Park running roughly west to east. The three transects were
defined by three ridge-top locations and were comprised of an approximately linear array of weather stations. We say ‘approximately linear’ since the difficulties of the terrain prevented us from aligning the stations perfectly. The two transects at Tidbinbilla will be denoted A and B, and the Brindabella transect will be denoted C. Transect A consists of the four locations A1, A2, A3 and A4, transect B consists of the four locations B1, B2, B3 and B4, while transect C consists of the five locations C1, C2, C3, C4 and C5. The positions and descriptions of the thirteen locations referred to above are given in table 1. Note that A4 and B4 both indicate the same location, which has been utilised in both transects A and B. A map showing the locations and the underlying topography can be seen in figure 1. We also use data from two Bureau of Meteorology automatic weather stations not listed in table 1. The two stations are at Canberra Airport (ID=CA, Long.=149.2, Lat.=-35.3, Elev.=578m) and Mt Ginini (ID=MG, Long.=148.77, Lat.=-35.53, Elev.=1760m).

The deployed automatic weather stations were programmed to measure and log air temperature (°C), relative humidity (%), dew point temperature (°C), wind speed (ms⁻¹), wind gust (ms⁻¹) and dominant wind direction for each sampling interval. Wind directions were given in terms of the sixteen standard points of the compass rose: N, NNE, NE, etc. We initially used a sampling interval of 30 minutes, which meant that the data loggers would become full after about 50 days and would require downloading. Accessing the stations, to download the recorded data, became more problematic and dangerous during the winter months, however, due to the presence of ice and snow on the steep slopes. It was therefore decided that a sampling time of 1 hour would be used over the winter months to extend the time between successive visits to download the data.

3. Method of analysis

In the analyses we consider data from selected pairs of stations across the landscape. The first of the two stations will be taken to be indicative of the bulk or ambient wind direction, while the second is indicative of the wind direction patterns at some nearby location within the landscape. In what follows we will take the first station to be a ridge-top station, while the second station will be located on a nearby slope, for example. We denote the wind direction experienced at the first station by \(\theta_1\) and the wind direction at the second station by \(\theta_2\), where \(0° \leq \theta_1, \theta_2 \leq 360°\).

The pair \(p = (\theta_1, \theta_2)\) can be thought of as a state variable for the joint wind direction system for the two station locations. To gain an understanding of the stochastic nature of the joint wind direction system for the two locations in question, it is natural to consider the joint wind direction distribution for the two stations. To construct the joint wind direction distribution we took data from the pair of stations and matched wind direction records according to date and time. For example, at a particular date and time, if the first station has a wind direction \(\theta_1\) and the second station has a wind direction of \(\theta_2\), then we refer to \(p = (\theta_1, \theta_2)\) as a matched pair. We denote the set of matched pairs as \(P\), and suppose that \(P\) contains \(M\) pairs of wind direction data. That is,
Throughout this paper we will use the compass points N, NNE, NE, etc. interchangeably with their corresponding values in degrees 0°, 22.5°, 45°, etc. Hence, the pair (WNW, SE) is the same as (292.5°, 135.0°).

Since the sampled wind direction data is given in terms of the sixteen standard compass points, it is natural to consider the 17×17 grid whose lower left vertices are given by the vectors

\[ x_{jk} = ((j-1)22.5^\circ, (k-1)22.5^\circ), \quad j,k = 1,\ldots,17. \]  

(1)

Note that there are two rows and columns corresponding to north in the grid defined by equation (1). Since 0° and 360° are both identified as north, the natural domain in which \( \theta_1 \) and \( \theta_2 \) reside is the circle \( S^1 \). This means that the pair \( p = (\theta_1, \theta_2) \) actually belongs to the torus \( T^2 = S^1 \times S^1 \), which is the state space of the joint wind direction system for the two station locations. The joint wind direction distribution is simply the distribution of \( p \) over \( T^2 \). To ensure the correct toroidal topology we identify the two sets of opposing edges of the grid in (1), i.e. column 1 is identified with column 17 and row 1 is identified with row 17.

A discrete realisation of the joint wind direction distribution for a pair of stations is then given by the grid-based function

\[ H_{jk} = \sum_{i=1}^{M} \delta^i_{jk}, \quad j,k = 1,\ldots,17 \]  

(2)

where

\[ \delta^i_{jk} = \begin{cases} 1 & \text{if } p^i = x_{jk}, \\ 0 & \text{otherwise}. \end{cases} \]

We will refer to \( H_{jk} \) as the sampled joint wind direction histogram for the relevant pair of stations.

Owing to the nature of the equipment used in the study, the recorded wind direction is only representative of the dominant wind direction during the sampling interval, in our case 30 minutes or 1 hour. Moreover, the canopy at each location can affect the winds in an uncertain manner. Consequently, the sampled histograms provided by equation (2) should not be considered to be without some form of error. We therefore assume that \( H_{jk} \) is a noisy realisation of a continuous joint wind direction distribution function, that is

\[ H_{jk} = g(x_{jk}) + \varepsilon_{jk}, \quad j,k = 1,\ldots,17, \]
where \( g \) is the continuous (actual) joint wind direction distribution function and \( \tilde{e}_{jk} \) is a random error term assumed to be normally distributed with zero mean.

To obtain a more robust estimate of the joint wind direction distribution we use the method of thin-plate smoothing splines (Wahba, 1990). Thin-plate smoothing splines have been used to extract signals from noisy or erroneous climatological data in many instances; see for example Hutchinson and Bischof (1983), Hutchinson (1995a, 1995b, 1998), Sharples and Hutchinson (2003, 2005), Sharples et al. (2005) and Hennessy et al. (2008). The second-order thin-plate smoothing spline estimate of the joint wind direction distribution function \( g \) is obtained by minimising

\[
\frac{1}{n} \sum_{j=1}^{17} \sum_{k=1}^{17} \left[ H_{jk} - f(x_{jk}) \right]^2 + \lambda J_2(f)
\]

over a class of suitably smooth candidate functions \( f \) (Wahba, 1990). Here \( n = 289 \), the number of cells in the grid defined by equation (1).

The first term in equation (3) is the average squared Euclidean distance between the sampled histogram values and the values of the candidate function, while \( J_2(f) \) is the second-order roughness penalty consisting of the integral of squared second-order partial derivatives of \( f \)

\[
J_2(f) = \iiint_{T^2} (f_{xx}^2 + 2f_{xy}^2 + f_{yy}^2) \, dx \, dy.
\]

The smoothing parameter \( \lambda \) in equation (3) determines a balance between fidelity to the sampled histogram values and the smoothness of the fitted spline function. In what follows we will assume a smoothing parameter \( \lambda \approx 0.08 \), which corresponds to a signal of 150 (a little more than half the number of histogram values). For more information on the theory of thin-plate smoothing splines the reader is referred to Wahba (1990).

In practice, the smoothing spline methods described above are implemented using the “ANUSPLIN” package, a collection of FORTRAN routines for fitting and calculating thin-plate smoothing splines (Hutchinson, 2003). The ANUSPLIN package was applied to the various sampled histograms and the resulting thin-plate spline estimates of the joint wind direction distribution surfaces were converted to values located at the centres of cells in a 360×360 1°-grid and displayed using GIS software. In this way we were able to interpolate from a discrete surface, given in terms of a grid defined by the sixteen standard compass points, to a quasi-continuous surface given in terms of the finer grid defined by the 360 standard degrees of a compass. Due to the measures taken previously, to ensure the toroidal topology of the initial grid, the fitted surfaces possess a structure that is approximately toroidal.

As a consequence of the smoothing procedure, some of the values on the 360×360 grid corresponding to the fitted surface were small negative numbers. These arise due to the
smoothness constraint, which causes the surface to overshoot into negative territory. To ensure that the final surfaces were everywhere non-negative (as probability distributions should be), grid cells with negative values were simply assigned a zero value. We also assumed that the final surfaces were scaled so that the total volume contained under each surface was equal to unity. Each surface can then be interpreted as an estimate of the joint probability distribution for the pair \( \mathbf{p} = (\theta_1, \theta_2) \) over the torus \( T^2 \).

To investigate the effect of wind speed on the various wind-terrain systems the procedure described above was repeated using a number of threshold wind speeds. In these analyses, the wind direction pair was only included in the histogram totals if the first station recorded a simultaneous wind speed greater than or equal to the threshold wind speed. The threshold wind speeds used in the analyses were 0, 2, 4, 6, 8, and 10 ms\(^{-1}\).

Station pairings were assigned based on the specific transects to which the stations belong. In what follows we will consider ten station pairings, which are listed in table 2. Also included in table 2 are the additional six pairings of the Bureau of Meteorology’s (BoM) stations CA and MG with the three ridge-top stations. These additional pairings are considered to ascertain how representative the ridge-top wind directions are of the broader-scale wind direction. If there is good agreement between the wind directions experienced at the ridge-top stations with those experienced at CA and MG, then this will justify our use of the ridge-top wind direction as the reference wind direction for each transect.

4. Results

In this section we examine the joint wind direction distributions arising from application of the analytical methods described above. In what follows we will denote the wind speed and direction experienced at \( X \) by \( U_X \) and \( \theta_X \), respectively, where \( X = \text{CA}, \text{MG}, \text{A1}, \text{A2}, \) etc.

4.1 BoM and Ridge Top Stations

We begin by investigating how wind direction experienced at the ridge-top locations compares to that experienced at the BoM automatic weather stations at Canberra Airport (CA) and Mt. Ginini (MG). This will provide information on how representative the ridge-top wind directions are of the larger-scale wind direction. We first consider the pairings (CA, A1), (CA, B1) and (CA, C1) and derive an estimate of the joint wind direction distribution for each, imposing different threshold wind speeds. The results for the pairings (CA, A1) and (CA, C1) can be seen in figure 2. The results for the (CA, B1) pairing were very similar to those for the (CA, A1) pairing, and so will not be discussed.

For the (CA, A1) pairing, all of the joint wind direction distributions are trimodal with modes roughly at (WNW, WNW), (E, E) and (E, W), listing them in order of the most to least dominant. The horizontal bands seen in figure 2a indicate that the (one-dimensional) wind direction distribution for the location A1 is manifestly bimodal, even when very slight winds are considered. Note that the banding becomes more fragmented as the wind
speed increases; discounting the more erratic light winds reveals the true modes of the paired wind direction system. The two-dimensional mode at (WNW, WNW) in figure 2a indicates that when winds at CA satisfy $250^\circ \leq \theta_{CA} \leq 360^\circ$, then the winds experienced at A1 will satisfy $250^\circ \leq \theta_{A1} \leq 315^\circ$ with a high probability. The fact that the horizontal extent of the (WNW, WNW) mode is greater than its vertical extent suggests that the winds at A1 are constrained by the surrounding rugged terrain. This can also be seen, to a lesser extent, in figures 2b and 2c, where only winds at CA that are greater than 4 ms$^{-1}$ and 8 ms$^{-1}$, respectively, were considered. The (WNW, WNW) mode seen in figures 2a, 2b and 2c implies that, modulo the constraining effect of the topography, the wind directions experienced at A1 and CA are consistent. The same can also be said for the (E, E) mode.

The (E, W) mode, on the other hand, implies that at certain times the wind directions at CA and A1 can be diametrically opposed. To explain this mode we note that it is not uncommon for Canberra to experience a sea breeze, particularly during summer afternoons (refs??). Figure 3a shows a plot of the dew point temperature experienced at A1 against the same at CA for all wind direction pairs $(\theta_{CA}, \theta_{A1})$ in the (E, W) mode, i.e. satisfying $45^\circ \leq \theta_{CA} \leq 135^\circ$ and $225^\circ \leq \theta_{A1} \leq 315^\circ$. It is evident that, in the majority, the dew points experienced at CA were significantly higher than those experienced at A1. This implies that for the (E, W) mode the air at CA was moister than that at A1, which is consistent with the sea breeze pushing into Canberra but not further west into the mountainous study region. Furthermore, figure 3b indicates that the wind direction pairs corresponding to the (E, W) mode occur almost exclusively in the afternoon and preferentially in late spring, summer or early autumn which confirms that the (E, W) mode is due to the effects of the sea breeze at CA. Hence, by discounting the (E, W) mode, which arises due to the effects of the local sea breeze, we may conclude that the wind directions at CA and A1 are consistent.

Considering the joint distribution functions arising from the (CA, C1) pairing, which can be seen in figures 2d, 2e and 2f, we find a similar structure to that found in considering the (CA, A1) pairing. Indeed, all of the joint wind direction distributions are trimodal with modes roughly at (WNW, WSW), (E, SSE) and (E, WSW), listing them from most to least dominant. The (one-dimensional) wind direction distribution for C1 is bimodal with easterly and west-south-westerly modes. The apparent preference for WSW winds at C1 is again most likely due to the influence of the terrain on the wind flow. The alignment of the (WNW, WSW) mode suggests that as winds at CA are shifted north from WNW, the winds at C1 also shift north from WSW. The (E, WSW) mode is analogous to the (E, W) mode in the (CA, A1) pairing and is due to the occurrence of a sea breeze that penetrates inland to the Canberra region. Thus discounting the local sea breeze effect, the wind directions experienced at CA and C1 are roughly consistent.

We next consider the pairings (MG, A1), (MG, B1) and (MG, C1). The joint wind direction distributions for the (MG, A1) and (MG, C1) pairings can be seen in figure 4. The joint distributions for the (MG, B1) pairing were almost identical to those for the (MG, A1) pairing and so will not be shown.
For the ( MG, A1) pairing, all of the joint distributions are bimodal, with a dominant mode at ( W, WNW) and a secondary mode at ( E, E). We note the absence of an ( E, W) ‘sea breeze’ mode; MG is further inland and typically beyond the westward extent of the sea breeze infiltration. As can be seen in figures 4a, 4b and 4c, both modes lie very close to the dashed line, indicating equal wind direction, and so we can conclude that the wind directions experienced at MG and A1 are consistent. The same can be said for the ( MG, C1) pairing, which also exhibits bimodal joint distributions with dominant modes at ( W, WSW) and a secondary mode at ( E, SSE). As can be seen in figures 4d, 4e and 4f, both modes again lie very close to the line of equal wind direction and so we can conclude that the wind directions experienced at MG and C1 are roughly consistent.

The above considerations suggest that the wind directions experienced at the ridge-top locations provide a reasonable representation of the broader-scale wind direction. This justifies our use of the ridge-top wind directions as reference wind directions in the analyses of the remaining intra-transect pairings.

4.2 Transect A

The reference wind direction for transect A was provided by the ridge-top station at A1. This station was paired with three other stations at A2, A3 and A4. The details for all these station locations can be found in table 1 and their positions are shown in figure 1.

Figure 5 shows the joint wind direction distributions for the ( A1, A2) pairing for each of the threshold wind speed values. All exhibit a definite modal structure. The joint distribution in figure 5a, corresponding to all matched pairs ( i.e. $U_{A1} \geq 0$ ms$^{-1}$), exhibits four modes located roughly at ( WNW, E), ( ESE, E), ( WNW, WNW) and ( SE, NW) with associated modal probabilities of approximately 0.38, 0.34, 0.21 and 0.04, respectively. The ( ESE, E) and ( WNW, WNW) modes correspond to conditions in which the winds simply flow up and over the ridge line at A1 without any substantial change in the wind direction. The vertically distended shape of the modes indicates that there is greater variance in the wind direction at A2, due to the various local gullies and spur lines.

Increasing the threshold wind speed changes the modal structure of the corresponding joint distributions, as can be seen in figure 5. In particular, the mode at ( SE, NW) has all but disappeared when the threshold wind speed is set at 2-4 ms$^{-1}$ (figures 5b and 5c) and has completely disappeared when the threshold wind speed is 6 ms$^{-1}$ or greater (figures 5d, 5e and 5f). The dates and times corresponding to the ( SE, NW) mode, defined by $80^\circ \leq \theta_{A1} \leq 160^\circ$ and $240^\circ \leq \theta_{A4} \leq 360^\circ$, indicated that such conditions occur preferentially during the night-time. In fact only about 4% of events corresponding to the ( SE, NW) mode occurred between 08:00 and 16:00 hours. Hence the ( SE, NW) mode, and its disappearance as the threshold wind speed is increased, is consistent with the occurrence of a weak nocturnal drainage flow, which is overcome by stronger ambient winds.

Figure 6a illustrates how the modal probabilities respond as the threshold wind speed is varied. As the threshold wind speed is increased the ( WNW, E) mode dominates. The likelihood associated with the ( WNW, WNW) mode drops substantially for $U_{A1} \geq 4$ ms$^{-1}$ with a complementary rise in the likelihood of the ( WNW, E) mode. In fact as the wind
speed threshold rises above 8 ms$^{-1}$ the joint wind direction distribution becomes unimodal at (WNW, E). Note that due to the toroidal structure the (WNW, E) mode ‘wraps around’ from the bottom to the top of the figures. The small probability density seen at the top of figures 5e and 5f is in fact part of the mode centred on (WNW, E). The fact that this mode dominates for high wind speeds across the ridge at A1 is interesting as it indicates that the winds at A1 and A2 are often opposed, despite the fact that they are within a few hundred metres of each other. Considering figures 5e and 5f further, it is apparent that when a WNW wind of 8 ms$^{-1}$ or more is flowing across the ridge at A1, the wind direction at A2 can be anywhere between 0° and 180° with a high likelihood of it falling between NNE and ESE. These conditional probabilities will be quantified further in the next section.

The relationship between $U_{A1}$ and $U_{A2}$ for those data corresponding to the (WNW, E) mode can be seen in figure 7c. On average, $U_{A2}$ is approximately 15% of $U_{A1}$, though the effect that the denser canopy at A2 has on this figure is uncertain. Figure 7d indicates that the dew points at A1 and A2 are approximately equal for those data corresponding to the (WNW, E) mode. This suggests that, in the majority, the same air mass is being sampled at A1 and A2. It is well known that diurnal heating and cooling of rugged landscapes can induce thermal winds that flow downslope just after sunset and upslope at sunrise (Whiteman, 2000). It is therefore possible that the (WNW, E) mode could be due to thermally driven upslope winds. In our study region winds that arise due to this effect would be expected to be slight and occur during daylight hours. Figures 7a and 7b, however, suggest that the data corresponding to the (WNW, E) mode cannot all be due to these diurnal winds. Figures 7a and 7b indicate that the winds at A1 and A2 can be opposed for extended periods of up to 5 or 6 days, as indicated by the unbroken vertical bands in the figures. Moreover, the unbroken vertical bands in figures 7a and 7b mostly occur for higher wind speeds. The wind data represented by these vertical bands are unlikely to be due to thermally driven winds (which would typically occur for only several hours during the day). It is more likely that these data correspond to the occurrence of a lee-slope eddy, which is a mechanical-fluid effect. As stronger winds pass over the ridge their inertia causes them to separate from the surface and recurve back on themselves producing a horizontal vortex between the lee-slope of the ridge and the ambient flow passing above. As a consequence, the winds experienced at the surface on the lee-slope would be opposed to the ridge-top wind direction. The distended shape of the (WNW, E) mode in figure 2 suggest that these thermal and eddy-driven winds can also have an across slope component at times, presumably resulting in an overall helical motion above the slope.

The joint wind direction distributions for the (A1, A3) and (A1, A4) pairings can be seen in figure 8. For brevity, only the distributions corresponding to all matched pairs (figures 8a and 8c) and those satisfying $U_{A1} \geq 6$ ms$^{-1}$ (figures 8b and 8d) are shown. The distributions for the (A1, A3) pairing are quite similar in structure to those for the (A1, A2) pairing. In particular, the distributions for the (A1, A3) pairing also indicate a high likelihood of wind reversal at A3 when it is on the lee side of the ridge. This is not surprising since the locations A2 and A3 are only approximately 60 metres apart. The difference between the distributions for the (A1, A2) and (A1, A3) pairings is the exact
location of the modes. The dominant modes for the (A1, A3) pairing occur at (270°, 270°), (270°, 90°) and (90°, 50°), while the corresponding modes for the (A1, A2) pairing occur at (292.5°, 292.5°), (292.5°, 90°) and (105°, 90°).

Hence, according to the analysis of the (A1, A2) pairing, the univariate wind direction distribution at A1 has modes at 292.5° and 105°, while the analysis of the (A1, A3) pairing suggests that the univariate wind direction distribution at A1 has modes at 270° and 90°. This discrepancy is due to the different sampling periods at A2 and A3. Data at A2 was recorded for approximately nine months over summer, autumn, winter and spring while data at A3 was only recorded for less than two months during summer and early autumn. The difference in the locations of the univariate modes for A1 can therefore be explained by the shift in the synoptic circulation patterns between summer and winter months. This is further confirmed by the joint distributions for the (A1, A4) pairing (figures 8c and 8d). According to this analysis, which was based on data collected during autumn, winter and early spring, the univariate wind direction distribution at A1 has modes at 292.5° and 105°, approximately.

The joint wind direction distributions for the (A1, A4) pairing indicate a more complex wind-terrain interaction, with six identifiable modes when $U_{A1} \geq 0$ ms$^{-1}$ and four when $U_{A1} \geq 6$ ms$^{-1}$ (figures 8c and 8d). The joint distribution for $U_{A1} \geq 0$ ms$^{-1}$ possesses a mode located at (ESE, W) indicating that wind at A4 can flow downslope against the bulk winds. This situation could occur during night-time due to the drainage of cool air into lower areas such as that in which A4 is located. Figure 9a shows the dates and times corresponding to the data pairs in the (ESE, W) mode, i.e. $75^\circ \leq \theta_{A1} \leq 165^\circ$ and $232^\circ \leq \theta_{A4} \leq 352^\circ$. As can be seen, the majority of data pairs in the (ESE, W) mode occur between 16:00 hours and 09:00 hours, which is consistent with them being caused by a nocturnal drainage flow. By contrast, the dates and times corresponding to data pairs in the (WNW, NE) mode follow quite a different pattern. Figure 9b indicates that conditions contributing to the (WNW, NE) mode often occur during daylight hours, but can persist for several days. The pattern in figure 9b is similar to that seen in figures 7a and 7b for the (A1, A2) pairing.

To investigate the similarities further, the dates and times corresponding to the (WNW, E) mode of the $U_{A1} \geq 0$ ms$^{-1}$ joint distribution for the (A1, A2) pairing were compared with those corresponding to the (W, E) mode of the $U_{A1} \geq 0$ ms$^{-1}$ joint distribution for the (A1, A3) pairing and the (WNW, NE) mode of the $U_{A1} \geq 0$ ms$^{-1}$ joint distribution for the (A1, A4) pairing. The results can be seen in figure 10. Figure 10a indicates that the data pairs comprising the (W, E) mode for the (A1, A3) pairing occur simultaneously with those comprising the (WNW, E) mode of the (A1, A2) pairing. Similarly, figure 10b indicates that, in the majority, the data pairs comprising the (WNW, NE) mode for the (A1, A4) pairing also coincide with those comprising the analogous mode for the (A1, A2) pairing, though the coincidence is less complete. This is a strong indication that these analogous modes arise due to the same processes, most likely up-slope thermal winds and lee eddies. If a lee eddy is the active mechanism then figure 10b, which pertains to a location near the bottom of the lee slope, suggests two possibilities - either a single eddy
can encompass the whole slope, or a succession of eddies can form in response to the more prominent sub-features of the main slope.

The additional modes for the (A1, A4) pairing, located at (ESE, S) and (WNW, S), are seen to persist even when strong wind blow across the ridge. They indicate the likelihood of differences in wind direction of approximately 90° at A1 and A4. To facilitate analysis we defined the (ESE, S) mode by 75° ≤ θ_{A1} ≤ 155° and 135° ≤ θ_{A4} ≤ 225°, while the (WNW, S) mode was defined by 252° ≤ θ_{A1} ≤ 332° and 135° ≤ θ_{A4} ≤ 225°. Examination of the dates and times corresponding to the (WNW, S) mode indicated that such conditions occurred preferentially during daylight hours (approx. 10:00-18:00 hours) with only sporadic and fleeting events taking place in the night. The timing of these events suggests the existence of a thermal upslope wind from the south at A4. This is plausible since there is a spur with a steep southerly-facing sidewall just to the north of A4, which could provide the thermal differences required to produce such a flow. The dates and times corresponding to the (ESE, S) mode exhibited a slight preference for daytime occurrence, again consistent with a thermal upslope wind, but also indicated that conditions in this mode can persist for a day or two. This suggests that these persistent conditions are not linked with any diurnal process. Further examination of the dates and times showed that it was mostly these persistent events that were contributing to the (ESE, S) mode for higher threshold wind speeds. Dynamic channelling of the bulk east-south-easterlies could be responsible for these types of persistent events.

4.3 Transect B

The reference wind direction for transect B was provided by the ridge-top station at B1. This station was paired with three other stations at B2, B3 and B4. The details for all these station locations can be found in table 1 and their positions are shown in figure 1.

Several joint wind direction distributions for the (B1, B2) and (B1, B3) pairings can be seen in figure 11. All exhibit a definite modal structure. In figures 11a, 11b and 11c the (B1, B2) pairing exhibits modes at (WNW, E), (WNW, W) and (ESE, ESE). As the threshold wind speed is increased the (ESE, ESE) and (WNW, W) modes deteriorate; the (ESE, ESE) mode vanishes when $U_{B1} ≥ 4$ ms$^{-1}$ (figure 11b) and the (WNW, W) mode vanishes when $U_{B1} ≥ 10$ ms$^{-1}$ (figure 11c). When $U_{B1} ≥ 10$ ms$^{-1}$ a small sub-mode forms at (WNW, SE), but the majority of probability (~ 85%) is connected with the mode at (WNW, ESE). The dates and times corresponding to the (WNW, E) mode, defined by 252° ≤ θ_{B1} ≤ 332° and 5° ≤ θ_{B2} ≤ 165°, were checked against those corresponding to the (WNW, E) mode for the (A1, A2) pairing by means of a plot similar to those in figures 7a and 7b. A strong coincidence was found between the two sets of dates and times, indicating that these corresponding modes in the (A1, A2) and (B1, B2) pairings are due to the same processes, thermally driven upslope winds and lee-slope eddy occurrence.

The modal response curves, showing how the modal probabilities for the (B1, B2) pairing vary as the threshold wind speed is increased, can be seen in figure 6b. It is evident that the (WNW, E) dominates for higher ambient wind speeds, with a complementary fall in the probability associated with the (WNW, W) mode for ambient wind speeds above 4 ms$^{-1}$. This is a very similar response to that of the (WNW, E) and (WNW, WNW) modes
for the (A1, A2) pairing (figure 6a). Figure 6b, however, indicates that winds satisfying $\theta_{A1} \approx \text{WNW}$ are slightly more likely to flow down the slope at B2 than at A2.

The joint wind direct distributions for the (B1, B3) pair can be seen in figures 11d, 11e and 11f. The joint distribution for all matched pairs exhibits definite modes centred near (WNW, SSE), (WNW, WNW) and (ESE, S). Inspection of the dates and times corresponding to the (ESE, S) mode, defined by $75^\circ \leq \theta_{B1} \leq 175^\circ$ and $125^\circ \leq \theta_{B3} \leq 235^\circ$, revealed that conditions contributing to this mode would often persist for several days. This suggests that this mode is not due to diurnal thermal forcing, but is due to a mechanical-fluid effect. It is likely that the ESE bulk winds are channelled by the windward terrain resulting in southerly winds at B3.

The conditions corresponding to the (WNW, SSE) mode, defined by $245^\circ \leq \theta_{B1} \leq 335^\circ$ and $75^\circ \leq \theta_{B3} \leq 215^\circ$, were also seen to persist over several days and exhibited a strong coincidence with the dates and times corresponding to the (WNW, E) mode of the (A1, A2) pairing. Hence, the SSE winds at B3, which occur when winds at B1 are roughly WNW, are most likely due to the combined effects of a lee eddy and a finer scale terrain channelling of the recurved winds blowing back up the slope. It could be argued that the (WNW, SSE) and (WNW, WNW) modes in the joint distribution for all matched pairs ($U_{B1} \geq 0 \text{ ms}^{-1}$) are in fact part of the same mode that extends over $250^\circ \leq \theta_{B3} \leq 560^\circ$. As the wind speed threshold is increased the (WNW, WNW) component of this extended mode retracts towards the north, while the (WNW, SSE) component is stable with respect to wind speed. This suggests that as wind speed increases it is less likely for winds satisfying $\theta_{B1} \approx \text{WNW}$ to flow over the ridge without separating from the surface in the lee near B3.

Not surprisingly, the joint wind direction distributions for the (B1, B4) pairing exhibited a very similar structure to those for the (A1, A4) pairing. For the $U_{B1} \geq 0 \text{ ms}^{-1}$ joint distribution six identifiable modes were present. However, once the threshold wind speed was set greater than $2 \text{ ms}^{-1}$, only three modes remained, all of which satisfied $250^\circ \leq \theta_{B1} \leq 330^\circ$.

4.4 Transect C

The reference wind direction for transect C was provided by the ridge-top station at C1. This station was paired with four other stations at C2, C3, C4 and C5. The details for all these station locations can be found in table 1 and their positions are shown in figure 1. Owing to the thicker vegetation in its vicinity, the maximum wind speed recorded at C1 was only 5.8 ms$^{-1}$.

The joint wind direction distributions for the (C1, C2) pairing can be seen in figures 12a, 12b and 12c, while figures 12d, 12e and 12f show the same for the (C1, C3) pairing. The $U_{C1} \geq 0 \text{ ms}^{-1}$ joint distribution for the (C1, C2) pairing exhibits two prominent modes roughly located at (ESE, E) and (W, ESE), and several more diffuse modes, most notably near (WNW, WNW). As the threshold wind speed is increased beyond 2 ms$^{-1}$ only the two modes near (ESE, E) and (W, ESE) remain with the (W, ESE) registering the highest relative frequency. As the threshold wind speed is increased the mode at (W, ESE) tends
more toward (WSW, ESE) due to changes in the wind characteristics at C1 for higher wind speeds. For the $U_{C1} \geq 0 \text{ ms}^{-1}$ joint distribution the modal probabilities are as follows: the (ESE, E) mode, defined by $15^\circ \leq \theta_{C1} \leq 195^\circ$ and $25^\circ \leq \theta_{C2} \leq 165^\circ$, has an associated probability of 0.3557, the (W, ESE) mode, defined by $207^\circ \leq \theta_{C1} \leq 333^\circ$ and $25^\circ \leq \theta_{C2} \leq 175^\circ$, has a probability of 0.31594 and the (WNW, WNW) mode, defined by $205^\circ \leq \theta_{C1} \leq 345^\circ$ and $227^\circ \leq \theta_{C2} \leq 357^\circ$, has a probability of 0.15562. If we consider $U_{C1} \geq 2 \text{ ms}^{-1}$, the probability associated with the (WNW, WNW) is negligible (~ 1% or less) and the other two modes each occur with a probability of approximately 50%. In particular, if the wind at C1 satisfies $U_{C1} \geq 10 \text{ ms}^{-1}$, then the (W, ESE) mode occurs with a probability of 0.5058 and the (ESE, E) mode occurs with a probability of 0.4938. The (ESE, E) mode corresponds to an approximately easterly ambient wind that flows up and over the slope at C2 and the ridge at C1. The (W, ESE) mode corresponds to the occurrence of a lee eddy or thermally-driven upslope winds at C2 when the ambient winds are from an approximately westerly direction. The fact that the (WNW, WNW) mode vanishes indicates that when the ambient winds are stronger, there is very little net flow passing over the ridge and moving down the slope at C2. Presumably these winds are separating from the surface in the lee of the ridge.

Figure 13 shows that conditions corresponding to the (W, ESE) mode of the $U_{C1} \geq 2 \text{ ms}^{-1}$ joint distribution for the (C1, C2) pairing were mostly coincident with conditions corresponding to the (WNW, E) mode of the $U_{A1} \geq 2 \text{ ms}^{-1}$ joint distribution for the (A1, A2) pairing. This demonstrates that the ambient conditions were producing a consistent effect on similar terrain elements even though they were separated by more than ten kilometres.

Conditions corresponding to the (ESE, E) mode occurred preferentially during the nighttime in summer and early autumn, consistent with a thermally driven nocturnal flow. In winter there were only five events corresponding to the (ESE, E) mode, all of which were associated with conditions that persisted for a day or longer.

The joint wind direction distributions for the (C1, C3) pairing exhibit a different modal structure than those for the (C1, C2) pairing. For the $U_{C1} \geq 0 \text{ ms}^{-1}$ distribution there are four diffuse modes located approximately at (ESE, NE), (WNW, N), (W, SW) and (SSE, SSW). Note that the (ESE, NNE) and (WNW, N) modes wrap around from the bottom to the top in figures 12d and 12e. As the threshold wind speed at C1 is increased there are stable modes approximately at (ESE, NE), (WNW, N) and (SSE, SSW). As the wind speed is increased, however, the modes drift slightly; the (ESE, NE) mode tends more towards (SE, NE), the (WNW, N) mode moves more towards (WSW, NE) and the (SSE, SSW) mode tends more towards (ESE, S). For ambient wind speeds satisfying $U_{C1} \geq 4 \text{ ms}^{-1}$ the (WSW, NE) and (SE, NE) modes dominate with associated probabilities of about 46% and 35%, respectively. The probability associated with the (ESE, S) mode increases slightly from around 6% to 10% as the ambient wind speed measured at C1 is increased from 0 to 4 ms$^{-1}$.

The dates and times corresponding to the (WSW, NE) mode for the (C1, C3) pairing were found to share a high degree of coincidence with those corresponding to the (W,
ESE) mode for the (C1, C2) pairing – only 8 out of 472 dates and times for the (C1, C3) pairing were not included in the dates and times for the (C1, C2) pairing.

Conditions corresponding to the (W, SW) mode for the (C1, C3) pairing occurred preferentially during the day during summer and early to mid-autumn. During the winter months, conditions corresponding to the (W, SW) mode occurred during both day and night, and in some cases persistently over one or two days. Winter events associated with threshold wind speeds satisfying $U_{C1} \geq 2$ ms$^{-1}$ did appear to occur more during daylight hours, however. The dates and times corresponding to data in the (SSE, SSW) mode displayed a less distinctive pattern. During summer and early autumn conditions corresponding to this mode occur fleetingly during both day and night-time hours. From mid-autumn to late winter only three or four events occurred with conditions corresponding to the (SSE, SSW) mode. In all cases the event persisted over a number of days.

The location C3 sits at the lowest point in the cross-valley transect. The down-valley direction is aligned roughly between south and south west (see figure 1c). The results cited above therefore fit with the existence of valley winds driven by thermal differences or frictional effects. Indeed, conditions corresponding to the (W, SW) mode were found to occur preferentially during daylight hours in summer, which is consistent with a thermally driven up-valley wind. During winter, several events corresponding with the (W, SW) mode were seen to persist for several days. This suggests forced channelling of bulk westerly winds around the southern end of Webbs Ridge and up the Flea Creek Valley as a likely explanation for the (W, SW) and (SSE, SSW) modes.

To further test for the existence of valley winds, particular focus was directed at conditions corresponding to $\theta_{C3} \approx N$. We considered two sets of data. The first set contained pairs satisfying $0^\circ \leq \theta_{C1} \leq 212^\circ$ and $280^\circ \leq \theta_{C3} \leq 20^\circ$, while the second contained pairs satisfying $214^\circ \leq \theta_{C1} \leq 354^\circ$ and $315^\circ \leq \theta_{C3} \leq 20^\circ$. The dates and times corresponding to these data sets can be seen in figures 15a and 15b. When the winds at C1 are between $0^\circ$ and $212^\circ$ (roughly north to south-southwest), figure 14a shows that approximately northerly winds will be experienced at C3 predominantly during the night-time. This is consistent with a nocturnal down-valley wind. Figure 14b shows a similar but less distinct pattern when the winds at C1 are between $214^\circ$ and $354^\circ$ (roughly south-southwest to north). A majority of the events occur in the night-time but some events do occur sporadically during daylight hours and are thus unlikely to be a thermally driven down-valley wind. Dynamic channelling of bulk westerlies down the valley to the north of C3 could be candidate mechanisms for these northerly winds at C3.

The joint wind direction distributions for the (C1, C4) pairing can be seen in figures 15a, 15b and 15c. The $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C4) pairing exhibits a prominent mode roughly located at (W, WNW), and several more diffuse modes near (WNW, ENE), (S, ENE), (W, SW) and (E, NW). As the threshold wind speed is increased beyond 2 ms$^{-1}$ the modes near (WNW, ENE) and (S, ENE) vanish and the mode near (E, NW) retracts towards the south. Conditions corresponding to the dominant (W, WNW) mode occurred preferentially during daylight hours during the summer.
months, while in mid-autumn and winter (W, WNW) conditions occurred as persistent events lasting several days at a time. Since C4 is on the west facing valley sidewall, these observations support the occurrence of an upslope wind at C4 that is driven by the combination of thermal effects and the momentum of bulk winds from the west. For wind speeds satisfying $U_{c1} \geq 2 \text{ ms}^{-1}$ the probability associated with the (W, WNW) mode is roughly 50%.

The dates and times corresponding to the (WNW, ENE) mode of the (C1, C4) joint distribution for all matched pairs displayed a distinctly different pattern to that for the (W, WNW) mode. Conditions corresponding to the (WNW, ENE) mode displayed a strong preference for occurrence during night-time hours, with only about 5% of events occurring between 10:00 and 16:00 hours. Given the timing of events corresponding to it, and the fact that it vanishes for wind speeds beyond 2 ms$^{-1}$, the (WNW, ENE) mode is due to the occurrence of a relatively weak nocturnal drainage flow that can move in opposition to the ambient winds when they are slight but whose effect is overcome by stronger ambient winds. This assertion is further supported by the fact that the valley above C4 is aligned in an approximately north-easterly direction (see figure 1c). The mode at (S, ENE) is also due to occurrence of nocturnal drainage flow at C4, with most of the corresponding times falling between 16:00 and 10:00 hours. The only difference between this mode and the one at (WNW, ENE) is the direction of the ambient winds.

Figure 16a shows the times and dates corresponding to the (W, SW) mode of the $U_{c1} \geq 0 \text{ ms}^{-1}$ joint distribution for the (C1, C3) pairing and those corresponding to the (W, SW) mode of the $U_{c1} \geq 0 \text{ ms}^{-1}$ joint distribution for the (C1, C4) pairing. It is evident that the times and dates pertaining to the (W, SW) mode for the (C1, C4) pairing share a similar pattern with those of the (W, SW) mode for the (C1, C3) pairing, which has been discussed previously. The (W, SW) mode for the (C1, C4) pairing is most likely due to the occurrence of up-valley winds and some forced channelling of winds up the Flea Creek valley.

Figure 16b shows the dates and times corresponding to the (E, NW) mode for the (C1, C4) pairing. There is no apparent preference for occurrence during the day or night-time and so the processes responsible for this mode do not seem to be linked to diurnal thermal differences within the valley or slope system. The pattern of dates and times suggests a process, or set of processes, that persists over extended periods of up to 4-5 days. A probable explanation for this mode is forced channelling of bulk easterlies up the Flea Creek valley.

The mode near (E, NW) for the (C1, C4) pairing tended more towards a stable mode near (ESE, SSE) as the threshold wind speed was increased. Focusing on data satisfying $70^\circ \leq \theta_{c1} \leq 170^\circ$ and $100^\circ \leq \theta_{c4} \leq 220^\circ$, a comparison of the dates and times corresponding to these data was made with those corresponding to the (SSE, SSW) mode of the (C1, C3) pairing. The results are shown in figure 16c, which indicates that the patterns displayed by the two sets of dates and times are largely consistent. It is therefore likely that the data in the (C1, C4) pairing, satisfying the inequalities above, arise due to a process similar to
that responsible for the (ESE, SSW) mode of the (C1, C3) pairing. Forced channelling of
bulk easterlies up the Flea Creek valley is a likely candidate.

Figures 15d, 15e and 15f show the joint wind direction distributions for the (C1, C5)
pairing. The $U_{C1} \geq 0$ ms$^{-1}$ joint distribution has three prominent modes near (W, W), (E, NE) and (E, NW). As the threshold wind speed increases the mode near (E, NE) splits into two distinct modes at (E, NE) and (SE, SE), though the (SE, SE) mode accounts for less than 5% of the data, regardless of the threshold wind speed. Considering all data the
(W, W) mode, defined by $200^\circ \leq \theta_{C1} \leq 350^\circ$ and $160^\circ \leq \theta_{C5} \leq 360^\circ$, has an associated probability of 0.50350, the (E, NE) mode, defined by $15^\circ \leq \theta_{C1} \leq 165^\circ$ and $0^\circ \leq \theta_{C5} \leq 100^\circ$, has an associated probability of 0.18776 and the (E, NW) mode, defined by $35^\circ \leq \theta_{C1} \leq 185^\circ$ and $200^\circ \leq \theta_{C5} \leq 360^\circ$, has an associated probability of 0.19360. For threshold wind speeds greater than or equal to 4 ms$^{-1}$, the (W, W) and (E, NW) modes dominate with associated probabilities of 0.54299 and 0.37052, respectively.

The dates and times corresponding to the (W, W) and (E, NE) modes can be seen in figure 17. Figure 17a indicates that conditions pertaining to the (W, W) mode occur preferentially during the day-time or persist for a number of days. Conversely, figure 17b indicates that conditions corresponding to the (E, NE) mode occur most consistently during the night-time, with only sporadic and fleeting events taking place between 10:00 and 16:00 hours. Recalling that C5 is on a west-facing slope, these results are again consistent with a down-slope thermal wind during the night and an upslope thermal wind during the day combining with the ambient flow.

The pattern of dates and times corresponding to the (E, NW) mode was less conclusive but indicated that conditions contributing to this mode occurred in a series of persistent events interspersed with events that lasted several hours at a time. During summer these short-lived events showed a slight preference for night-time occurrence, while during winter these shorter events showed a preference for daylight hours. These day-time events are consistent with a thermally-driven up-slope flow but the night-time ones are not. The persistent events are likely due to the occurrence of a lee-slope eddy at C5 when bulk winds are from the east.

5. Implications for bushfire risk management

Bushfire or wildfire risk management agencies often utilise fire spread simulation models as a key part of their decision making processes. These models allow fire managers to
gauge how a fire will spread under certain meteorological conditions, enabling them to
better prioritise deployment of resources during fire suppression activities. Fire spread
models are also used to conduct hypothetical studies that inform broader risk
management strategies. Typically these models are sensitive to meteorological variables,
particularly wind speed and direction.

Many models combine information on ambient wind speed and direction and terrain characteristics to estimate a terrain modified wind field. The main problem of interest can
be summarised as follows: Given a bulk wind speed and direction, determine the corresponding wind speed and direction at some point in the landscape. The study detailed above directly addresses the directional aspect of this problem. Indeed, the first coordinate in the wind direction pairs treated above was chosen to be indicative of the ambient wind direction, while the second described the directional response of the wind-terrain system at a particular point in the landscape. The study described above therefore provides information of direct relevance to fire managers and fire spread modellers and also provides information that can be used in validating and developing new and existing methods for deriving terrain-modified winds.

As an example of how the results might be employed in bushfire risk management practices, consider the \((A1, A2)\) pairing and suppose that the ambient winds are from the west-northwest. This prompts us to focus on the (univariate) conditional probability distribution defined by taking \(\theta_{A1} = \text{WNW}\) vertical cross-section of the \((A1, A2)\) joint distribution. Figure 18a shows the conditional probability distributions associated with threshold wind speeds of 0, 4 and 10 m\(s^{-1}\). It is apparent that the most likely wind direction at \(A2\) is not WNW, even for \(U_{A1} \geq 0 \text{ m}\(s^{-1}\). The most likely wind direction is in fact closer to E, but as the ambient wind speed increases, winds satisfying \(\text{NNE} \leq \theta_{A2} \leq \text{E}\) occur with almost equal likelihood. This finding implies that fire spread models, which assume a constant wind direction throughout the entire region of interest, could be seriously in error when employed in regions possessing complex terrain. The conditional distributions provide guidance on what the most probable wind direction at \(A2\) would be.

Figure 18b shows the \(\theta_{B1} = \text{WNW}\) conditional probability distributions at \(B2\). A similar trend to that seen in figure 18a is evident with ENE winds the most likely at \(B2\). The similar structure evident in figures 18a and 18b suggests that one could extrapolate the result, with reasonable accuracy, to similar terrain elements in the landscape, e.g. when the wind is from the WNW, it is highly probable that slopes over 25\(^\circ\), which are approximately east-facing, will experience upslope winds. This probability increases as the ambient wind speed increases.

The conditional probability distributions in figure 18a and 18b also indicate that the joint wind direction system is not deterministic; the terrain can cause a WNW wind to respond in different ways depending on the precise conditions of the day or night. For example, figure 18a implies that the wind at \(A2\) can satisfy \(30^\circ \leq \theta_{A2} \leq 50^\circ\) or \(70^\circ \leq \theta_{A2} \leq 90^\circ\) with almost equal probability; 0.18 or 0.17, respectively. Existing deterministic methods for deriving terrain-modified winds would not be able to emulate the type of system behaviour just described.

In many cases the ambient winds can also experience small directional changes due to local terrain forcing or perturbations in the geostrophic forces driving the winds. This means that it is not always possible to define a single ambient wind direction with certainty. In these cases it is perhaps best to specify a mean wind direction and an associated variance. Alternatively, one could use the joint wind direction distributions, or portions of them if appropriate, with a Monte Carlo approach, reselecting from the distribution at each time step, for example. Another approach is to simply assume that the
ambient wind direction occupies some range. For example, suppose that the ambient wind direction satisfies \( W \leq \theta_{A1}, \theta_{B1} \leq NW \). We can then use the joint wind direction distributions to calculate the conditional probability associated with a range of wind direction responses. We adopt the standard notation \( P(A|B) \) to denote the conditional probability of \( A \) given \( B \). Figure 19a shows how the probability of a wind reversal on the east-facing slopes varies with the threshold wind speed measured at \( A1 \) and \( B1 \). Specifically, figure 19a shows the conditional probabilities \( P(NE \leq \theta_{A2} \leq SE| W \leq \theta_{A1} \leq NW) \) and \( P(NE \leq \theta_{B2} \leq SE| W \leq \theta_{B1} \leq NW) \) for different threshold wind speeds. Similarly, figure 19b shows the probability of a wind reversal on either side of the Flea Creek valley for threshold winds speeds of 0, 2 and 4 m\( \text{s}^{-1} \). The conditional probabilities represented here are \( P(ENE \leq \theta_{C2} \leq SSE| SW \leq \theta_{C1} \leq W) \) and \( P(WSW \leq \theta_{C5} \leq NNW| E \leq \theta_{C1} \leq SE) \). In all cases there is an overall increase in the conditional probabilities as the threshold wind speed is increased.

As another example, consider the (C1, C3) pairing, which pertains to a location near the bottom of the Flea Creek transect. If we suppose that the ambient winds satisfy \( SW \leq \theta_{C1} \leq W \), then we can calculate the conditional probabilities \( P(NNE \leq \theta_{C3} \leq ESE| SW \leq \theta_{C1} \leq W) \) and \( P(SSE \leq \theta_{C3} \leq WSW| SW \leq \theta_{C1} \leq W) \), the first of which relates the probability of a wind direction that opposes the ambient winds \( (\theta_{C3} \approx ENE) \), while the second relates to the probability of winds blowing up Flea Creek valley due to channelling or diurnal effects \( (\theta_{C3} \approx SSW) \). Figure 19c shows these conditional probabilities for threshold wind speeds of 0-4 m\( \text{s}^{-1} \). Figure 19c indicates that for lower ambient wind speeds the wind direction at \( C3 \) can satisfy \( \theta_{C3} \approx ENE \) or \( \theta_{C3} \approx SSW \) with almost equal probability. However, for higher ambient wind speeds the wind direction is much more likely to satisfy \( \theta_{C3} \approx ENE \). With this sort of information fire managers can better decide how to deploy fire crews and other resources. For example in this case it would seem unwise to put fire-crews immediately to the north or west of \( C3 \), even in light winds; a spot fire near \( C3 \) could quickly spread up the eastern face of Webbs Ridge or up the Flea Creek valley, with near equal probability of approximately 30-40%.

The increased likelihood of winds opposing the ambient wind direction at \( C3 \), as wind speed increases, is presumably due to the preferential occurrence of a large lee-slope eddy. Indeed this was a probable mechanism for all of the wind reversals observed on lee-slopes (e.g. at \( A2, A3, B2, B3, C2, \) etc.), particularly for high ambient wind speeds and events that persisted for extended periods. In the context of fire management and suppression, lee-slope eddies are a dangerous phenomenon. A theoretical analysis undertaken by Byron-Scott (1990) implied that the rotor motion associated with lee-slope eddies could be accelerated by the presence of a fire. In some cases the effect could produce lee-wind speeds that exceed the ambient wind speed. The turbulence associated with these rotor winds can also lead to increased generation of embers, which due to the accelerated lee-winds can be deposited much further down-wind than would otherwise be expected. Numerical simulations (unpublished) conducted by one of the authors (JJS) support the results of Byron-Scott (1990).

McRae, et al. etc. fire channelling stuff…
The existence of up-valley winds at C3 ($\theta_{C3} \approx$ SSW) can also be dangerous in the context of fire suppression and crew safety. Suppose a fire, driven by westerly winds, is slowly burning down the eastern face of Webbs Ridge toward C3. If the winds were to suddenly swing to the SSW due to channelling up the valley, then the northern flank would become a head-fire and burn up the valley in a direction almost perpendicular to the ambient winds. When the fire burnt up out of the valley it would again experience westerly winds but would now have a much broader fire front due to the lateral spread caused by the up-valley channelling. It is interesting to note that the 1994 South Canyon fire in Colorado, which killed fourteen people, behaved in a way consistent with that just described (Butler et al., 1998 and Check!!!).

6. Discussion and conclusions

A probabilistic analysis of measured data from two wind-terrain systems has been presented. The analysis focused on the structure of joint wind direction distributions for pairs of locations; one relating to the ambient or bulk wind direction and one relating to the terrain-modified wind. A clear majority of the joint distributions exhibited a modal structure, indicating distinct preferences for certain regions of the toroidal state space. Analysis of the timing of conditions corresponding to specific modes provided strong evidence for the existence of several different processes. These processes included thermally driven upslope winds during the day and complementary down-slope winds during the night-time, broader scale diurnal valley winds (up Flea Creek, for example), forced channelling along valleys and lee-slope eddies.

As the threshold wind speeds were increased, different modes responded in different ways. In particular, modes corresponding to processes such as channelling and lee-slope eddies were more dominant for higher wind speeds. This is not surprising since when the winds are strong, mechanical-fluid effects would tend to overpower the weaker thermal effects.

The similarity of the results for transect A and transect B suggest that they could be extrapolated with reasonable accuracy to other steep lee-slopes, particularly in regions that experience a similar bimodal ambient wind direction distribution. At the least, the result should cause fire managers to view lee-slopes, and the regions down-wind, with caution, particularly when the ambient winds are over 8 ms\(^{-1}\) (approx. 30 km h\(^{-1}\)).

The analyses revealed the distinctly stochastic nature of the wind direction data. Given a fixed ambient wind direction it does not seem possible to uniquely specify a corresponding terrain-modified wind direction with complete certainty. This suggests that a more probabilistic approach to the problem is appropriate; rather than specifying a wind direction it should be sampled from the relevant distribution.

The majority of the modes observed in the joint distributions were centred at a specific point on the torus. In the sense of dynamical systems, these points could be interpreted as attractors for the for the local wind direction.
Acknowledgements

This work could not have been undertaken without the efforts of the staff of the Mechanical and Electrical Workshops in the School of Physical, Environmental and Mathematical Sciences, University of New South Wales at the Australian Defence Force Academy. In particular, the authors gratefully acknowledge the contributions of Ray Lawton, Hans Lawatsch and Colin Symons who facilitated the modification of the PAWS units. The authors are also indebted to the staff of NSW National Parks and Wildlife Service and ACT Parks, Conservation and Lands. In particular, we would like to thank Susannah Power, Julie Crawford and Joel Patterson. The authors would also like to thank Stephen Wilkes, Ian Knight, Terese Richardson, Steve Forbes, Alan Walker, Paul McKie, Tom Jovanovic and Peter Scott for their assistance with deploying the weather stations or with other field-work related activities. This work was undertaken as part of the Bushfire CRC’s HighFire Risk project. The support of the Bushfire CRC is gratefully acknowledged.

References


<table>
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<tr>
<th>Location ID</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Elevation</th>
<th>Approx. Slope</th>
<th>Approx. Aspect</th>
<th>Site Description</th>
<th>Sampling Period</th>
</tr>
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<tr>
<td>A1</td>
<td>148.89449</td>
<td>-35.42375</td>
<td>1313m</td>
<td>0°</td>
<td>NA</td>
<td>Ridge-top site. Sparse acacia seedlings to height of 1m within a radius of 5-6m. No canopy overhead.</td>
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<td>A2</td>
<td>148.89675</td>
<td>-35.42162</td>
<td>1250m</td>
<td>30° -35°</td>
<td>93°</td>
<td>E-facing slope. Sparse acacia seedlings and bracken to 1m height. Some larger eucalypts approx. 10m away. Relatively thin canopy.</td>
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<tr>
<td>A3</td>
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<td>-35.42185</td>
<td>1268m</td>
<td>30° -35°</td>
<td>143°</td>
<td>SE-facing slope. Sparse acacia seedlings, bracken and grass up to 1m high. Some larger eucalypts approx 10m away with some overhanging branches within 4m of anemometer. Relatively thin canopy.</td>
<td>16/1/2007 - 9/3/2007</td>
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<td>148.91370</td>
<td>-35.41875</td>
<td>820m</td>
<td>5° -10°</td>
<td>90°</td>
<td>Bottom of main slope, E-facing. Eucalypt regrowth and bracken approx 4-5m away and some larger eucalypts with cambial growth approx 6-7m away. Slightly denser canopy than at A2 and A3.</td>
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<td>NA</td>
<td>Ridge-top site. Sparse acacia seedlings up to 1m high and snow-gum regrowth up to 2m high within a 4m radius of station. Sparse canopy overhead.</td>
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<td>148.90442</td>
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<td>1277m</td>
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<td>148°</td>
<td>SE-facing slope. Sparse bracken and acacia seedlings up to 1.5m in height. Some small eucalypt regrowth approx. 5m from station. Light canopy cover.</td>
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<td>148.90541</td>
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<td>1216m</td>
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<td>100°</td>
<td>E-facing slope on southern face of scree-gully. Very sparse acacia and grass. Very little to no canopy cover.</td>
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<td>B4</td>
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<td>820m</td>
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<td>90°</td>
<td>Bottom of main slope, E-facing. Eucalypt regrowth and bracken approx 4-5m away and some larger eucalypts with cambial growth approx 6-7m away. Slightly denser canopy than at B2 and B3.</td>
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<tr>
<td>C1</td>
<td>148.76619</td>
<td>-35.30373</td>
<td>1026m</td>
<td>0°</td>
<td>NA</td>
<td>Ridge-top site. Relatively dense acacia seedlings and other regrowth outside of 3m. Larger eucalypts with cambial growth approx 4-5m away. Very little canopy immediately overhead but relatively dense canopy over station surrounds.</td>
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<td>148.77113</td>
<td>-35.29196</td>
<td>955m</td>
<td>20° -25°</td>
<td>105°</td>
<td>E-facing slope on western side of Flea Ck. valley. Sparse eucalypt regrowth approx. 3-4m from station. Some taller trees, some with cambial growth, approx. 4-5m from station. Partially intact canopy overhead.</td>
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<td>C3</td>
<td>148.78222</td>
<td>-35.29232</td>
<td>787m</td>
<td>5° -10°</td>
<td>150°</td>
<td>Near bottom of Flea Ck. valley on small knoll. Some burnt trees approx. 3-4m away. Scattered canopy overhead.</td>
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<td>C4</td>
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<td>850m</td>
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<td>300°</td>
<td>W-facing slope near bottom of the eastern sidewall of Flea Ck. valley. Very dense (dead) bracken up to 1.5m high. Some larger trees, some with cambial regrowth approx. 5-6m away. Sparse canopy overhead.</td>
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<td>1000m</td>
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<td>315°</td>
<td>NW-facing slope on eastern sidewall of Flea Ck. valley. Very sparse acacia regrowth and bracken within a radius of 5-6m. Some larger eucalypts 7-8m from station. Relatively sparse canopy overhead.</td>
<td>4/1/2007 - 16/10/2007</td>
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**Table 1.** Descriptions of the thirteen station locations used in the study
<table>
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<tr>
<th>Station pairing</th>
<th>No. of data pairs with $U_1 \geq 0$ ms$^{-1}$</th>
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<th>No. of data pairs with $U_1 \geq 4$ ms$^{-1}$</th>
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**Table 2.** The number of wind direction data pairs for each of the station pairings and for each of the threshold wind speeds analysed. $U_1$ is used to denote the wind speed measured at the first station in each pairing.
Figure 1. Maps showing the locations of the remotely deployed portable automatic weather stations used in the study. Panel A shows southeastern Australia and the A.C.T. region. Panel B shows the two general study areas. Transect C can be seen in panel C and transects A and B can be seen in panel D. The contours in panels C and D represent the local terrain; major contours are spaced at 100 metres, minor contours at 20 metres.
Figure 2. Joint wind direction distributions for CA and A1 (panels a, b and c) and for CA and C1 (panels d, e and f). The first row corresponds to all matched pairs; the second and third rows correspond to matched pairs for which the wind speed at CA was greater than 4 ms$^{-1}$ and 8 ms$^{-1}$, respectively. Highest frequencies are coloured dark blue, intermediate frequencies are coloured green and small or zero frequencies are coloured yellow. The contours are included only to give a better indication of the shape of the surface. The dashed line indicates equal wind direction at the two stations.
Figure 3. (a) Plot of dew point at A1 against simultaneous dew point at CA for all wind direction pairs ($\theta_{CA}$, $\theta_{A1}$) in the (E, W) mode, i.e. satisfying $45^\circ < \theta_{CA} < 135^\circ$ and $225^\circ < \theta_{A1} < 315^\circ$. The different symbols correspond to different threshold wind speeds. (b) Scatter-plot of the times and dates corresponding to the points in panel (a).
Figure 4. Joint wind direction distributions for MG and A1 (panels a, b and c) and for MG and C1 (panels d, e and f). The first row corresponds to all matched pairs; the second and third rows correspond to matched pairs for which the wind speed at MG was greater than 4 m s⁻¹ and 8 m s⁻¹, respectively. Highest frequencies are coloured dark blue, intermediate frequencies are coloured green and small or zero frequencies are coloured yellow. The contours are included only to give a better indication of the shape of the surface. The dashed line indicates equal wind direction at the two stations.
Figure 5. Joint wind direction distributions for A1 and A2 assuming different threshold wind speeds: (a) 0 m s\(^{-1}\) (all matched pairs), (b) 2 m s\(^{-1}\), (c) 4 m s\(^{-1}\), (d) 6 m s\(^{-1}\), (e) 8 m s\(^{-1}\) and (f) 10 m s\(^{-1}\). Highest frequencies are coloured dark blue, intermediate frequencies are coloured green and small or zero frequencies are coloured yellow. The contours are included only to give a better indication of the shape of the surface. The dashed line indicates equal wind direction at A1 and A2.
Figure 6. Plots showing how modal probabilities for the (A1, A2) and (B1, B2) pairings respond to varying threshold wind speed.

(a) For the (A1, A2) pairing the modes are defined by:
- (WNW, E) = \{(\theta_{A1}, \theta_{A2}) \in T^2: 245^\circ \leq \theta_{A1} \leq 335^\circ \text{ and } 0^\circ \leq \theta_{A2} \leq 210^\circ\}
- (ESE, E) = \{(\theta_{A1}, \theta_{A2}) \in T^2: 60^\circ \leq \theta_{A1} \leq 160^\circ \text{ and } 0^\circ \leq \theta_{A2} \leq 160^\circ\}
- (WNW, WNW) = \{(\theta_{A1}, \theta_{A2}) \in T^2: 245^\circ \leq \theta_{A1} \leq 335^\circ \text{ and } 210^\circ \leq \theta_{A2} \leq 360^\circ\}
- (SE, NW) = \{(\theta_{A1}, \theta_{A2}) \in T^2: 80^\circ \leq \theta_{A1} \leq 160^\circ \text{ and } 260^\circ \leq \theta_{A2} \leq 360^\circ\}

(b) For the (B1, B2) pairing the modes are defined by:
- (WNW, E) = \{(\theta_{B1}, \theta_{B2}) \in T^2: 252^\circ \leq \theta_{B1} \leq 332^\circ \text{ and } 0^\circ \leq \theta_{B2} \leq 165^\circ\}
- (ESE, ESE) = \{(\theta_{B1}, \theta_{B2}) \in T^2: 60^\circ \leq \theta_{B1} \leq 190^\circ \text{ and } 57^\circ \leq \theta_{B2} \leq 187^\circ\}
- (WNW, W) = \{(\theta_{B1}, \theta_{B2}) \in T^2: 240^\circ \leq \theta_{B1} \leq 350^\circ \text{ and } 210^\circ \leq \theta_{B2} \leq 360^\circ\}
Figure 7. Diagnostic plots for the (WNW, E) mode of the joint wind direction distribution for the (A1, A2) pairing. The (WNW, E) mode is defined by $245^\circ \leq \theta_{A1} \leq 335^\circ$ and $0^\circ \leq \theta_{A2} \leq 210^\circ$. (a) Plot showing dates (18th Jan – 9th Mar 2007) and times corresponding to the (WNW, E) mode. (b) Plot showing dates (28th Apr – 17th Jun 2007) and times corresponding to the (WNW, E) mode. (c) Plot of wind speed at A2 against wind speed at A1 for data belonging to the (WNW, E) mode. (d) Plot of dew point at A2 against dew point at A1 for data belonging to the (WNW, E) mode.
Figure 8. Joint wind direction distributions for the pairings (A1, A3) and (A1, A4). (a) All matched wind direction pairs in (A1, A3) pairing, (b) All matched wind direction pairs in (A1, A3) pairing satisfying $U_{A1} \geq 6$ ms$^{-1}$, (c) All matched wind direction pairs in (A1, A4) pairing, (d) All matched wind direction pairs in (A1, A4) pairing satisfying $U_{A1} \geq 6$ ms$^{-1}$. 
Figure 9. Diagnostic plots for the (WNW, NE) and (ESE, W) modes of the joint wind direction distribution for the (A1, A4) pairing. All matched pairs (i.e. $U_{A1} \geq 0$ ms$^{-1}$) have been included in the plots: (a) Plot of time of day against date (9th Mar 2007-20th Oct 2007) for data contributing to the (ESE, W) mode, (b) Plot of time of day against date (9th Mar 2007-20th Oct 2007) for data contributing to the (WNW, NE) mode. The (WNW, NE) mode is defined by $252^\circ \leq \theta_{A1} \leq 332^\circ$ and $0^\circ \leq \theta_{A4} \leq 120^\circ$ and the (ESE, W) mode is defined by $75^\circ \leq \theta_{A1} \leq 165^\circ$ and $232^\circ \leq \theta_{A4} \leq 352^\circ$. 

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Figure 10. Diagnostic plots of dates and times corresponding to the analogous (approx. (W, E)) modes of the joint wind direction distributions for the transect A pairings. (a) The (WNW, E) mode of the distribution for the (A1, A2) pairing (black open circles) and the (W, E) mode of the distribution for the (A1, A3) pairing (blue dots), (b) the (WNW, E) mode of the distribution for the (A1, A2) pairing (black open circles) and (WNW, NE) mode of the distribution for the (A1, A4) pairing (red dots). The threshold wind speed was $U_{A1} = 0 \text{ ms}^{-1}$. The various modes are defined by:

(WNW, E) = \{($\theta_{A1}, \theta_{A2}$) \in $T^2$: 245° $\leq \theta_{A1} \leq 335°$ and 0° $\leq \theta_{A2} \leq 210°$\}

(W, E) = \{($\theta_{A1}, \theta_{A3}$) \in $T^2$: 237° $\leq \theta_{A1} \leq 307°$ and 15° $\leq \theta_{A3} \leq 185°$\}

(WNW, NE) = \{($\theta_{A1}, \theta_{A4}$) \in $T^2$: 257° $\leq \theta_{A1} \leq 327°$ and 0° $\leq \theta_{A4} \leq 130°$\}
Figure 11. Joint wind direction distributions for B1 and B2 (panels a, b and c) and for B1 and B3 (panels d, e and f). Panels (a) and (b) correspond to all matched pairs, panels (c) and (d) correspond to matched pairs satisfying $U_{B1} \geq 4 \text{ m/s}$ and panels (e) and (f) correspond to matched pairs satisfying $U_{B1} \geq 10 \text{ m/s}$.
Figure 12. Joint wind direction distributions for C1 and C2 (panels a, b and c) and for C1 and C3 (panels d, e and f). Panels (a) and (d) correspond to all matched pairs, panels (b) and (e) correspond to matched pairs satisfying $U_{C1} \geq 2 \text{ ms}^{-1}$ and panels (c) and (f) correspond to matched pairs satisfying $U_{C1} \geq 4 \text{ ms}^{-1}$.
Figure 13. Diagnostic plots showing dates and times corresponding to data in the (W, ESE) mode of the $U_{C1} \geq 2$ ms$^{-1}$ joint distribution of the (C1, C2) pairing (solid grey circles) and the dates and times corresponding to data in the (WNW, E) mode of the $U_{A1} \geq 2$ ms$^{-1}$ joint distribution of the (A1, A2) pairing (open black circles).
Figure 14. Diagnostic plots showing dates and times corresponding to data in the (C1, C3) pairing satisfying (a) $0^\circ \leq \theta_{C1} \leq 212^\circ$ and $280^\circ \leq \theta_{C3} \leq 20^\circ$, and (b) $214^\circ \leq \theta_{C1} \leq 354^\circ$ and $315^\circ \leq \theta_{C3} \leq 20^\circ$. The open black circles denote that $U_{C1} \geq 0$ ms$^{-1}$ while the closed grey circles indicate $U_{C1} \geq 2$ ms$^{-1}$. 
Figure 15. Joint wind direction distributions for C1 and C4 (panels a, b and c) and for C1 and C5 (panels d, e and f). Panels (a) and (d) correspond to all matched pairs, panels (b) and (e) correspond to matched pairs satisfying \( U_{C1} \geq 2 \text{ ms}^{-1} \) and panels (c) and (f) correspond to matched pairs satisfying \( U_{C1} \geq 4 \text{ ms}^{-1} \).
Figure 16. (a) Diagnostic plot of dates and times corresponding to the (W, SW) mode of the $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C3) pairing (open black circles) and those corresponding to the (W, SW) mode of the $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C4) pairing (solid grey circles). (b) Diagnostic plot of dates and times corresponding to the (E, NW) mode of the $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C4) pairing (open black circles) and those corresponding to the (E, NW) mode of the $U_{C1} \geq 2$ ms$^{-1}$ joint distribution for the (C1, C4) pairing (close grey circles). (c) Diagnostic plot of dates and times corresponding to the (SSE, SSW) mode, defined by $80^\circ \leq \theta_{C1} \leq 200^\circ$ and $155^\circ \leq \theta_{C3} \leq 255^\circ$, of the $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C3) pairing (open black circles) and those in the (C1, C4) pairing corresponding to data satisfying $U_{C1} \geq 0$ ms$^{-1}$, $70^\circ \leq \theta_{C1} \leq 170^\circ$ and $100^\circ \leq \theta_{C4} \leq 220^\circ$ (solid grey circles).
Figure 17. (a) Diagnostic plot of dates and times corresponding to the (W, W) mode of the $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C5) pairing. The (W, W) mode is defined by $200^\circ \leq \theta_{C1} \leq 350^\circ$ and $160^\circ \leq \theta_{C5} \leq 360^\circ$ (b) Diagnostic plot of dates and times corresponding to the (E, NE) mode of the $U_{C1} \geq 0$ ms$^{-1}$ joint distribution for the (C1, C5) pairing. The (E, NE) mode is defined by $15^\circ \leq \theta_{C1} \leq 165^\circ$ and $0^\circ \leq \theta_{C5} \leq 100^\circ$. 
Figure 18. Conditional probability distributions for threshold wind speeds of 0, 4 and 10 ms\(^{-1}\). (a) Wind direction distributions ($\theta_{A2}$) conditioned on $\theta_{A1} = \text{WNW}$, (b) Wind direction distribution ($\theta_{B2}$) conditioned on $\theta_{B1} = \text{WNW}$.
Figure 19. (a) Conditional probabilities $P(\text{NE} \leq \theta_{A2} \leq \text{SE} \mid W \leq \theta_{A1} \leq \text{NW})$ (black) and $P(\text{NE} \leq \theta_{B2} \leq \text{SE} \mid W \leq \theta_{B1} \leq \text{NW})$ (grey) for different threshold wind speeds 0-10 m/s$^{-1}$. (b) Conditional probabilities $P(\text{ENE} \leq \theta_{C2} \leq \text{SSE} \mid \text{SW} \leq \theta_{C1} \leq \text{W})$ (black) and $P(\text{WSW} \leq \theta_{C5} \leq \text{NNW} \mid E \leq \theta_{C1} \leq \text{SE})$ (grey) for different threshold wind speeds 0-4 m/s$^{-1}$. (c) Conditional probabilities $P(\text{NNE} \leq \theta_{C3} \leq \text{ESE} \mid \text{SW} \leq \theta_{C1} \leq \text{W})$ (black) and $P(\text{SSE} \leq \theta_{C3} \leq \text{WSW} \mid \text{SW} \leq \theta_{C1} \leq \text{W})$ (grey) for threshold wind speeds 0-4 m/s$^{-1}$. 