Tellus
SERIES A DYNAMIC METEOROLOGY AND OCEANOGRAPHY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Tellus (2008), 60A, 700–705
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TELLUS

Mesoscale wind direction shifts in the stable boundary-layer

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(Manuscript received 18 November 2007; in final form 18 February 2008)

ABSTRACT

The observed mesoscale variability of wind direction near the surface is examined in stable boundary layers. Such direction changes are often perceived as gentle meandering of the wind direction back and forth. However, with weak winds on the order of 1 m s^{-1}, large sudden shifts of wind direction are found to be common, as are a wide variety of more complex variations of wind direction. This study focuses on frequent abrupt changes of wind direction. Various statistics of wind direction variation are interpreted and their dependence on scale is noted. The wind shifts are embedded within a wide variety of complex flow signatures, without emergence of a dominant type of structure. The physics of such variations remain generally unknown.

1. Introduction

With very weak-wind conditions, the wind direction may be quite variable, historically referred to as 'light and variable'. Such variability leads to horizontal dispersion of contaminants and other quantities and modulates the weak turbulence. The mesoscale motions leading to wind direction variability are not predictable and their physical causes are usually unknown. Anfossi et al. (2005) demonstrated that the strength of the mesoscale motions is relatively independent of both wind speed and stability, even though the physics of such motions may change dramatically with stability; for example, internal gravity waves with stably stratified flow in contrast to convectively driven motions with surface heating. This non-stationarity is often perceived as gentle swaying of the wind vector sometimes represented by sine functions (Gifford, 1959; Kristensen et al., 1981; Hanna, 1983; Etling, 1990; Anfossi et al., 2005; Goulart et al., 2007). In addition to gradual rotation of wind direction, Mahrt (2007) found numerous abrupt shifts of wind direction, often exceeding 90° for weak-wind conditions. Such sudden shifts were occasionally associated with mixing events in the presence of significant directional shear, but in general, the cause of such direction shifts remains unknown.

Wind direction changes are closely related to cross-wind velocity fluctuations scaled by the speed of the large-scale flow (e.g. Davies and Thomson, 1999). Although wind direction changes suffer some statistical ambiguities (Section 2), this study focuses on wind direction changes because they have been studied much less than cross-wind velocity fluctuations and are more directly related to certain practical problems. The unpredictability of wind direction changes translates to unpredictable dispersion in weak-wind conditions. This study documents the nature of these wind direction shifts by analysing data sets described in the next section.

2. Data

This study analyses eddy correlation data from a 34-m tower in FLOSSII instrumented from 20 November 2002 to 2 April 2003 (Mahrt and Vickers, 2005). The tower site is located south of Walden, Colorado, USA and characterized by grass, sometimes snow covered. On the main tower, fast-response data was collected at 1, 2, 5, 10, 15, 20 and 30 m with Campbell CSAT3 sonic anemometers. Here, we analyse primarily data at 2 m, but use the other levels for examination of the vertical coherency. The data were quality controlled using a modified version of Vickers and Mahrt (1997). Flow through the tower is not removed since all wind directions are required to capture the wind direction changes and no use will be made of turbulent fluxes in this study. Only data between 1800 local standard time in the evening and 0800 the next morning are included in the analysis in order to remove daytime conditions with surface heating.

Additional data sets (Table 1) will be analysed only in terms of overall statistics. These data sets include CASES99 (Poulos et al., 2001), a burned pine site (Schwarz et al., 2004; Mahrt, 2006), a 15-m ponderosa pine site (Schwarz et al., 2004), a 3-m young ponderosa pine site (Vickers and Mahrt, 2006) and an urban site (Fernando et al., 2001). We also analyse data collected

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DOI: 10.1111/j.1600-0870.2008.00324.x

Table 1. Site name, surface conditions, duration of the measurements in months, % of records with $RV_{meso} > 1$ (eq. 2), % of records with a wind shift of 90° or larger and % of records with wind direction range (R) > 270°

Site	sfc.	mo	$RV > 1$	shift > 90	$R > 270$
FlossII	grass	4	16	23	13
CASES-99	grass	1	07	16	05
Burn	sparse	24	20	18	11
Ponderosa	15-m pine	36	08	14	16
Young	3-m pine	36	32	50	31
Alaska	snow	3	01	02	01
PAFEX	urban	1	07	13	03

from Point Barrow, Alaska, USA from March to May of 2005 with a CSAT3 sonic anemometer at 2 m over flat snow-covered short tundra. Some of this data occur with penetration of sedge shoots with tussocks 10 to 20 cm above the snow surface.

2.1. *Choice of scales*

The statistics and physics of mesoscale motions depend fundamentally on choice of scales. Compared to near neutral and unstable boundary layers, the turbulence in the weak-wind stable boundary layer is weaker and confined to smaller Eulerian time scales, generally less than 30 s. As a result, mesoscale motions extend to smaller scales and are relatively more important compared to near neutral and unstable conditions. Here, we define mesoscale motions for stable conditions to be the deviation of 1-min averages from the 1-h record average. Difficulties with this definition and other definitions are discussed in Mahrt (2007). For example, spectra reveal energy on all scales up to synoptic scales, so that choice of the record length is somewhat arbitrary. The wind direction variability is quantitatively sensitive to choice of record length, although the qualitative conclusions of this study are not sensitive to the choice of record length. For the rest of this study, ‘record length’ will refer to 1 h, unless otherwise noted. The 1-min length for defining mesoscale deviations from the 1-h average is roughly the smallest time scale that excludes turbulence fluctuations for almost all of the stable cases.

The statistics below will be computed after rotating the x-coordinate into the direction of the hour-averaged wind. Wind direction variability is important for a number of different applications. Since wind direction is a circular function, computation of the variability of the wind direction can be problematic for large variations of wind direction (e.g. Fisher, 1987). Here, wind direction variability is computed iteratively as in Mahrt (2007). Wind direction is always computed from averaged components. Wind direction is never directly averaged. In this study, we define the wind direction change across a given 1-min interval as the change of the 1-min wind direction between the previous and subsequent 1-min periods (centred differencing across a 2-min interval). This procedure reduces aliasing problems where the wind shift within a 1-min period is inadvertently captured as two sequential wind shifts of smaller amplitude. Wind direction changes greater than 90° will normally be referred to as large wind direction shifts.

Some of the statistical parameters are sensitive to choice of averaging scales while others are less sensitive. For example, the standard deviation of wind direction (see definition below) is not very sensitive to the choice of the 1-min averaging time scale used to define the mesoscale deviations. However, the standard deviation increases with increase of the record length (nominally 1 h). On the other hand, the range of wind direction decreases with increasing averaging time for computing the deviations (nominally 1 min) due to elimination of the smallest scale mesoscale motions. The range of the wind direction based on 1-min deviations is typically about twice that based on 10-min deviations (Fig. 1). The range increases with record length since greater record length increases the scales included in the calculation of the range. The maximum shift of wind direction is not

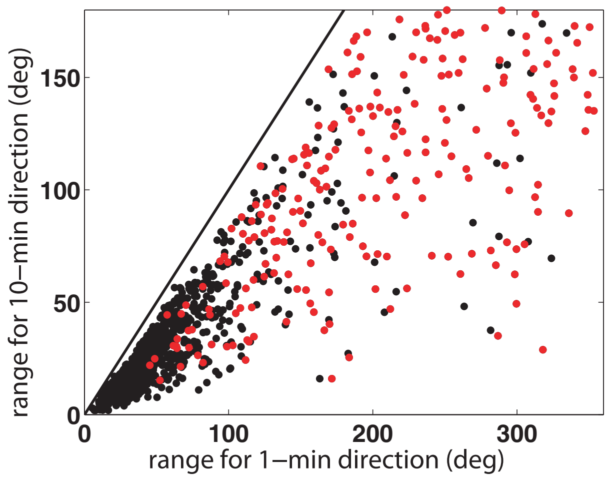

Fig. 1. The range of wind direction within 1-h records for wind direction based on 10-min averages as a function of wind direction based on 1-min averages, for winds $>1.5\,\mathrm{m\,s^{-1}}$ (black) and winds $<1.5\,\mathrm{m\,s^{-1}}$ (red).

sensitive to the choice of the 1-min averaging time used to define the mesoscale deviations. The maximum wind shift for 1-min wind directions is slightly greater than that for 10-min averages.

2.2. *Mesovelocity scale*

A velocity scale representing the strength of the mesoscale flow is defined as

$$V_{\rm meso} \equiv [(\tilde{u}^2 + \tilde{v}^2)^{1/2}]. \tag{1}$$

Here, the tilde indicates deviations of the 1-min averages from the 1-h record average and the square brackets indicate averaging over the 1 h record. This velocity scale is motivated in Mahrt (2007). The wind direction statistics will sometimes be related to the 'relative' strength of the mesoscale flow, defined as

$$RV_{\rm meso} \equiv \frac{V_{\rm meso}}{V}, \tag{2}$$

where V is the speed of the record vector-averaged flow. We will classify data according to either the value of $RV_{\rm meso}$ or the value of the wind speed. The non-dimensional quantity $RV_{\rm meso}$ is a more complete measure for the prediction of wind direction variation, but requires information of the strength of the mesoscale flow. Values of $RV_{\rm meso}$ greater than unity will be used as an indicator of significant influence of the mesoscale modes on the total wind vector. For FLOSSII, this condition occurred 14% of the time at 2 m during nocturnal periods. The wind speed will also be used to classify the records since it is more available in routine applications compared to $RV_{\rm meso}$. Based on Anfossi et al. (2005), weak winds will be defined as speeds less than 1.5 m s^{-1}.

3. Wind direction variability

Although a variety of measures of within-record variability of the wind direction can be constructed, they are all significantly correlated. For example, the range of wind directions over a 1-h period increases systematically with the standard deviation of the wind direction within the 1-h period (Fig. 2). The large number of records with wind speed greater than 1.5 ms^{-1} (black dots) are generally characterized by a wind direction range of less than 70° and wind direction standard deviation less than 20°. For weak wind speeds less than 1.5 ms^{-1} (red dots), the standard deviation of the wind direction is always greater than 45° and the range is often greater than 180°. In the later case, one or more 1-min periods experience winds with a component opposite to the mean wind direction. For weak winds, the range exceeds 270° 43% of the time, in which case the wind comes from all four quadrants at some point during the hour.

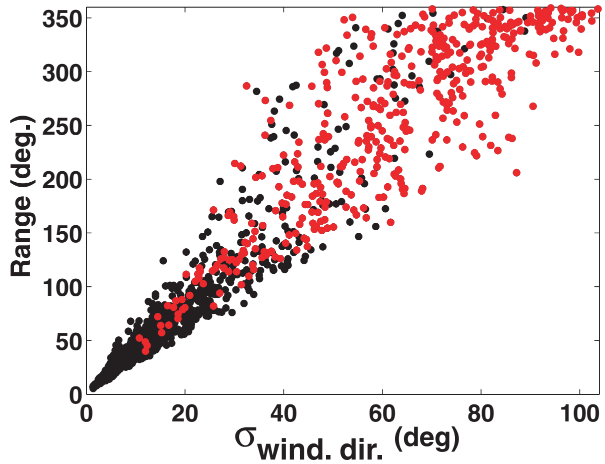

Fig. 2. The within record range of the wind direction as a function of the standard deviation of the wind direction for winds >1.5 m s^{-1} (black) and winds <1.5 m s^{-1} (red). Wind directions are based on 1-min averages.

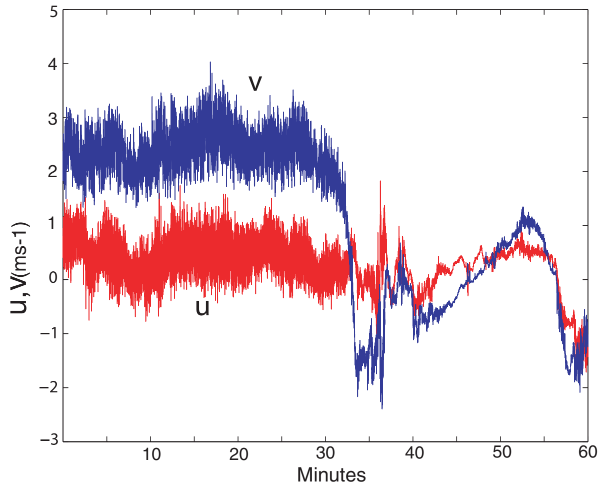

Fig. 3. An example of the wind components with wind direction shifts. For the entire data set, wind direction shifts are embedded within a wide variety of patterns with no typical structure.

3.1. *Wind direction shifts*

Large shifts of wind direction contribute significantly to the overall variation of the wind direction even though they only occupy a small fraction of the record. An arbitrary example of a significant wind direction shift is shown in Fig. 3. For this example, the turbulence decreases dramatically after the wind shift. However, in general, the wind direction shifts are not systematically related to other variables such as turbulence strength. The turbulence energy may increase or decrease with nearly equal probability and often shows little change at all. The wind direction shifts exhibit a slight tendency to occur with onset of cooler sinking air, but this tendency is quite weak with many counter cases and many cases with no significant change of temperature or

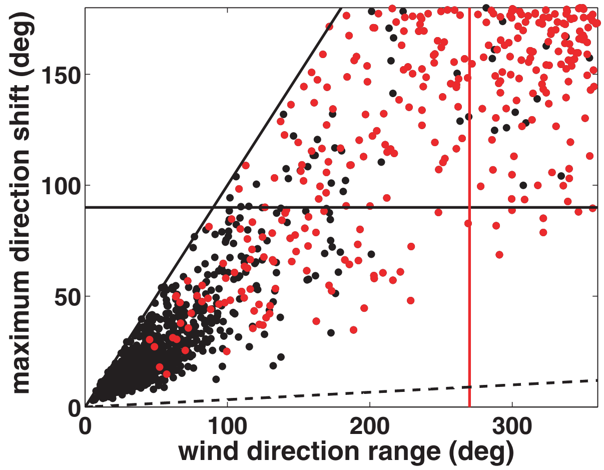

Fig. 4. The maximum wind shift as a function of within record range of the wind direction for winds greater than 1.5 m s^{-1} (black) and winds less than 1.5 m s^{-1} (red). The slanted black line corresponds conditions where the maximum within-record direction shift accounts for the entire wind-direction range, the horizontal thick line corresponds to 90° maximum shift and the lower dashed line corresponds to a maximum wind direction shift of 1/30 of the within record range (linear trend). The vertical red line denotes a range of 270°.

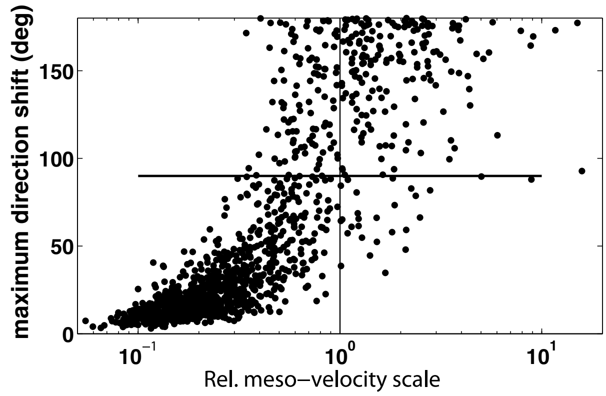

Fig. 5. The increase of the maximum wind direction shift with increasing relative mesovelocity scale. The horizontal line corresponds to maximum direction shift of 90° while the thin vertical line corresponds to $RV_{meso} = 1$ (eq. 2).

vertical motion. However, 66% of the wind direction shifts of 90° or greater occur with an increase of wind speed. The cross-wind component may increase or decrease with equal probability. Allowing for phase shift with height, many of the wind direction shifts are coherent over the entire tower layer while other shifts are limited to tower sublayers, sometimes confined to the lowest 5 m.

The total within-record range of wind direction shows an expected increase with increasing maximum wind shift within the record (Fig. 4). As with all of the indicators of wind direction variability, both the range and maximum direction shift are much larger with weak winds (red points in Fig. 4) compared to moderate and stronger winds (black points). More than half of the weak-wind records contain wind shifts greater than 90°. For weak winds, the wind direction for a large number of records spans all four quadrants (range >270 in Fig. 4).

The maximum wind direction shift is bounded by the value of the range up to 180°. The range cannot be less than the maximum shift. However, the wind direction shift cannot exceed 180°, by definition, while the range can reach 360°. For wind direction ranges less than 180°, the maximum wind shift within the record approaches 180° for a significant number of records (Fig. 4). These cases generally correspond to records where a single directional shift accounts for most of the range of wind direction during the hour. For wind direction ranges less than 180°, the maximum wind direction shift for the record averages 53% of the range. The records with large range, but no significant shifts correspond to gradual wind direction change. With simple linear trend throughout the 1-h record, the directional shift for each 2-min difference would be 1/30 of the maximum range (dashed lower black line in Fig. 4). The maximum shift never approaches this lower limit, indicating that the variation of the wind direction is always more complex than linear trend.

4. Relative mesovelocity scale

The wind direction change is more closely related to the relative mesovelocity velocity scale (RV_{meso}) than wind speed, since RV_{meso} includes information on the strength of the mesoscale activity. The maximum wind direction shift increases with increasing relative mesovelocity scale (Fig. 5). For $RV_{meso} > 1$, more than half of the records have a wind direction shift exceeding 90° and a significant fraction of the records contain a wind direction shift approaching 180°. With large $RV_{meso} > 1$, the wind direction shifts are not only greater compared to cases with small RV_{meso}, but also more numerous.

The frequency distribution of maximum within-record direction shift also show common large shifts for $RV_{meso} > 1$ (Fig. 6). At a given moment, the probability of a wind direction shift of more than 90° within the 2-min centred differencing period is almost 8%. If the wind direction already deviates from the record-average wind direction by more than 90°, the probability of a wind shift more than 90° within the next minute is a little more than 15%. The probability of the wind direction to rotate back towards the mean wind direction is only slightly greater than the probability to rotate even further away from the mean wind direction.

4.1. Regimes

Different statistical regimes can be identified in phase space defined by the frequency of large shifts versus the ratio of the maximum shift to the total wind direction range (Fig. 7). The lower right hand corner of Fig. 7 (region A) corresponds to records with one or two large direction shifts with amplitude near the wind

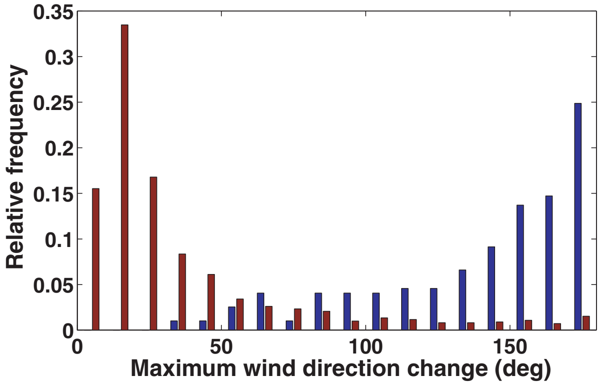

Fig. 6. The relative frequency of the maximum wind direction shift within the hour for $RV_{meso} > 1$ (blue) and $RV_{meso} < 1$ (red) for intervals of direction change 0–10, 10–20 and so forth.

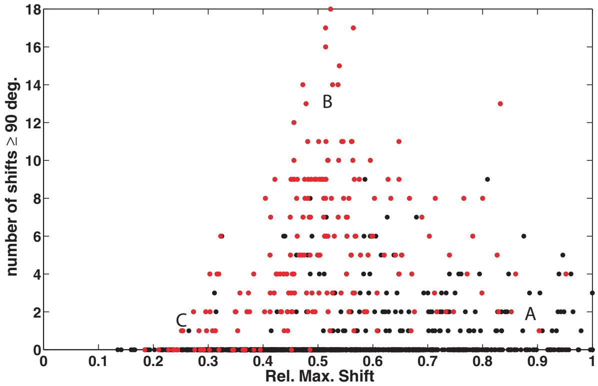

Fig. 7. The number of wind direction shifts ≥90° for a given 1-h record, as a function of the maximum wind direction shift within the hour normalized by the wind direction range for the hour. Results are shown for $RV_{meso} < 1$ (black) and $RV_{meso} > 1$ (red). See text for discussion of regimes A, B and C.

direction range of the record. Some of these records contain a single wind shift with little additional mesoscale activity such that the mesoscale variability averaged over the entire record is only modest and $RV_{meso} < 1$ (black points).

Records with a large number of shifts greater than 90° (upper centre part of figure, region B) correspond to a typical maximum direction shift of about half of the wind direction range of the record. The lower left corner of Fig. 7 (region C) corresponds to one or two large wind direction shifts in concert with considerable other wind direction variability within the record. This wide variety of wind direction signatures probably implies complex underlying physics.

4.2. *Between-site differences*

The overall statistics for stable conditions for 6 additional sites (Table 1) indicate that the probability of large wind variability is related to the probability of $RV_{meso} > 1$. This probability of $RV_{meso} > 1$ varies from 50% at a flat Young Pine Site in central Oregon, USA to only 1% at a flat snow-covered tundra site in winter, near Barrow Alaska, USA. The most notable exception is the Burn site where wind direction variability is less than might be indicated by the relative large percentage of cases of $RV_{meso} > 1$. This site is dominated by drainage flow down a deep narrow valley such that the wind direction range is constrained by the topography. These results indicate that the impact of mesoscale motions on the wind direction varies extensively between sites.

5. Conclusions

The above analysis reveals frequent sudden shifts of wind direction for weak-wind stable conditions in addition to gradual meandering of the wind direction. A large fraction of the 1-h records contains more complex variation in addition to these two simpler states. Within a 1-h record with weak winds ($<1.5\,m\,s^{-1}$), the probability of at least one wind direction shift greater than 90° (Section 2.1) exceeds 50% for the FLOSS data set and the range of wind direction exceeds 270° for 43% of the records. The latter corresponds to subperiods of flow opposite to the mean wind direction.

Large wind direction shifts are associated with a wide variety of phenomena and generally show no systematic relationship to changes of other quantities such as temperature, turbulence strength or mesoscale vertical motion. About 2/3 of the large wind direction shifts are associated with an increase in wind speed.

Various wind direction statistics examined above reveal complex behavior. For example, the relationship between the maximum wind direction shift and the total range of wind directions within the 1-h period (Figs. 4 and 7) show a significant number of records with: (a) one or two large wind direction shifts, which account for most of the wind direction variability (as in Fig. 3), (b) one or two large wind direction shifts with important smaller wind direction variability or (c) maximum direction shift small compared to the range in which case the range is due mainly to frequent smaller variations of wind direction. Both the magnitude of the wind direction shifts and their frequency of occurrence show an expected increase with the ratio of the meso velocity scale to the speed of the large-scale wind (RV_{meso}). The wind direction shifts are sometimes confined to the lowest few metres and sometimes occur over the entire depth of the 30-m tower.

The large wind direction shifts for weak large-scale flow present a serious problem for predicting dispersion. While this study documents the importance and stochastic characteristics of such wind direction shifts for weak-wind stable conditions, the cause of such wind direction shifts remains unknown and unpredictable. The wind shifts observed at a fixed point were generally not associated with propagating wind shifts that could be detected by a surrounding network of stations (not shown in this study). The complex spatial coherence of the parent motions, that contain large wind direction shifts, is currently under investigation.

6. Acknowledgments

I gratefully acknowledge Dean Vickers for processing the various data sets and Danijel Belušić, Branko Grisogono and the reviewers for important comments on the manuscript. I also gratefully acknowledge John Preuger for the SMACEX data, Mathew Sturm for the Alaska data, J Eric Pardyjak for the PAFEX data and the NCAR ATD staff for collection of the FLOSS and CASES-99 data. This material is based upon work supported by ARO Contract W9FN05C0067 and Grants 0607842-ATM and 0354819-ATM from the National Science Foundation.

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