9B.2

WIND DIRECTION CHANGES AND PLUME BEHAVIOR IN VERY STABLE CONDITIONS

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1.INTRODUCTION

Wind directions at low wind speeds in very stable conditions are subject to intermittent, rapid, and very large changes. Evidence gathered during the Project Sagebrush Phase 2 field experiments indicates that these wind direction changes occur mainly at wind speeds less than 1.5 m s^{-1} and almost always in association with momentum and sensible heat fluxes approaching zero in low wind shear conditions (Finn et al. 2018a). There is complete vertical decoupling in these conditions allowing for unrestricted meandering. This has consequences for plume mixing and dispersion.

2.EXPERIMENTAL OBSERVATIONS

2.1 *Wind Direction Changes*

An example of the character of wind direction changes in the very stable boundary layer from the field experiments is shown in Fig. 1. Wind directions could remain relatively steady for periods of several minutes up to a half hour or more and then abruptly shift by up to 100 degrees or more in as little as 1 min. The net wind direction changes occurring in 2-min intervals (2-min ΔWD) were calculated for nine extended test periods in very stable conditions during the field study. Figure 2 shows that the large, rapid wind direction changes were largely restricted to wind speeds $U < 1.5$ m s^{-1} for the nine extended very stable test periods examined.

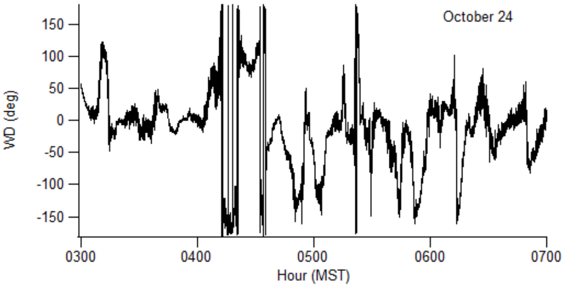

Figure 1. Example 1-s wind direction time series from October 23. The wind directions have been rotated from 0 to 360^{o} coordinates to -180^{o} to +180^{o} to minimize frequent wrapping through true north. Copyright 2018 *J. Appl. Met. Clim.*

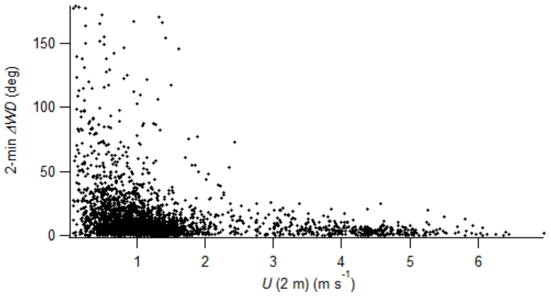

Figure 2. Two-minute ΔWD as a function of U at 2 m AGL for nine very stable test cases. Copyright 2018 *J. Appl. Met. Clim.*

2.2 *Turbulent Fluxes*

Figure 3 shows that the large 2-min ΔWD changes occurred almost exclusively when the turbulent fluxes of sensible heat and momentum were very nearly zero. Figure 4 shows that the large 2-min ΔWD changes were also associated with very low σ_w and turbulent kinetic energy $\overline{e}$. The results for a longer 2-year record with bulk Richardson number $Ri_b > 0.25$ were very similar.

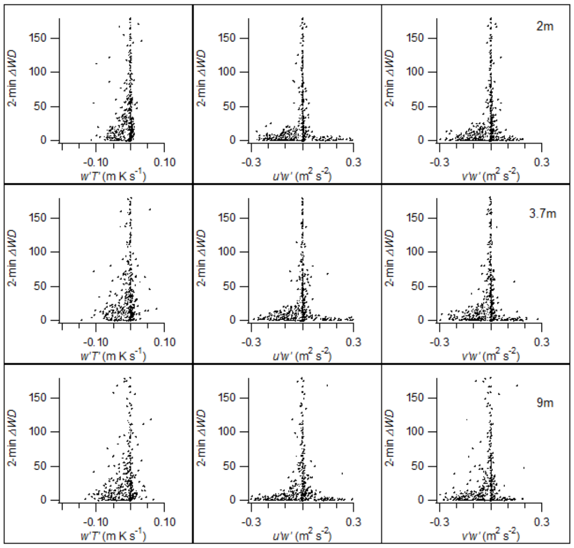

Figure 3. ΔWD results as a function of the sensible heat and momentum fluxes for all the 2-min periods of the nine test periods at three heights on the tower. Copyright 2018 *J. Appl. Met. Clim.*

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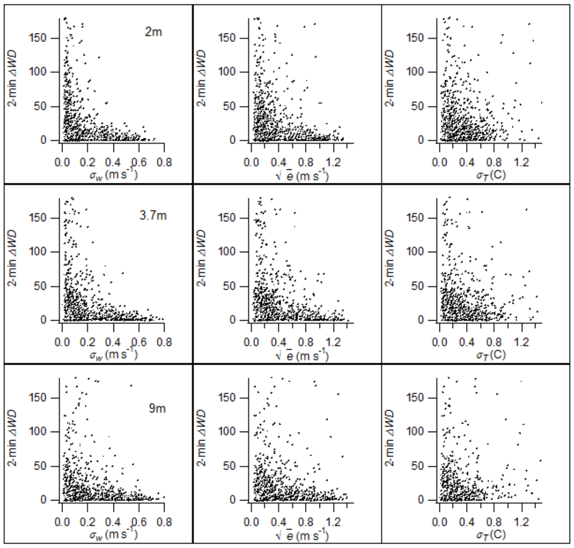

Figure 4. ΔWD results as a function of σ_w, $\sqrt{e}$, and σ_T for the same 2-min periods. Copyright 2018 *J. Appl. Met. Clim.*

2.3 *Effects of Wind Shear*

Increases in wind shear had the effect of suppressing large 2-min ΔWD. Figure 5 shows that the occurrence of large 2-min ΔWD was heavily weighted toward lower values of wind shear (0±0.1 s^{-1}) during very stable conditions. It was also found that the presence of low-level jets (LLJ), with wind speed maxima at heights mostly between 50 to 150 m a.g.l., almost invariably strongly suppressed large wind direction changes.

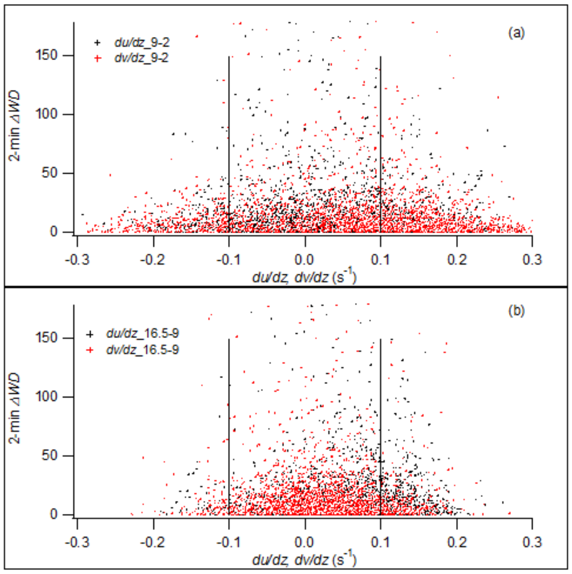

Figure 5. 2-min ΔWD for the aggregated *du/dz* and *dv/dz* wind shears for all time periods included in the test cases for the (a) 2 to 9 and (b) 9 to 16.5 m intervals. Copyright 2018 *J. Appl. Met. Clim.*

2.4 *Example Case Studies*

Some examples of the interrelationship between 2-min ΔWD, low wind speeds, wind shear, and LLJs are shown in Figs. 6 and 7 for two test cases from the field study. It is apparent that larger 2-min ΔWD are associated with low U and the absence of LLJs. The bulk Richardson number Ri_b is a proxy for wind shear with small vertical differences in wind speed in the denominator being the primary contributor to the very large observed values usually associated with the larger ΔWD. There was some evidence that larger ΔWD events were not just linked to low U but sometimes were triggered by wave influences (Finn et al. 2018a).

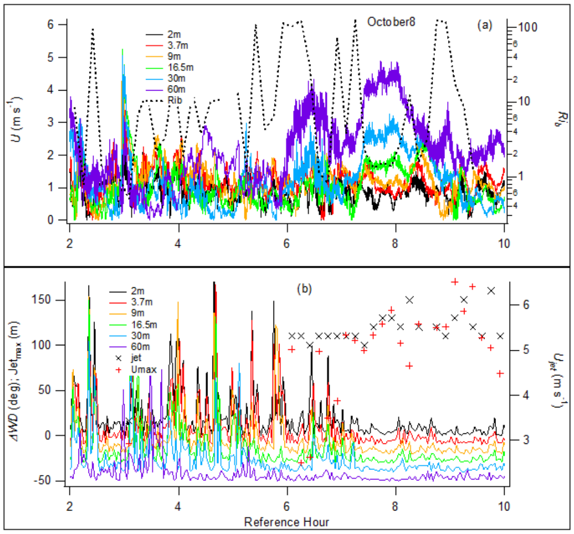

Figure 6. GRI tower October 8: (a) 1-s U and 10-min Ri_b and (b) 2-min ΔWD and 10-min LLJ (height and $U_{\max}$). ΔWD traces for adjacent heights are offset for clarity by 10° beginning at 3.7 m. Hour is time from 1900 MST reference.

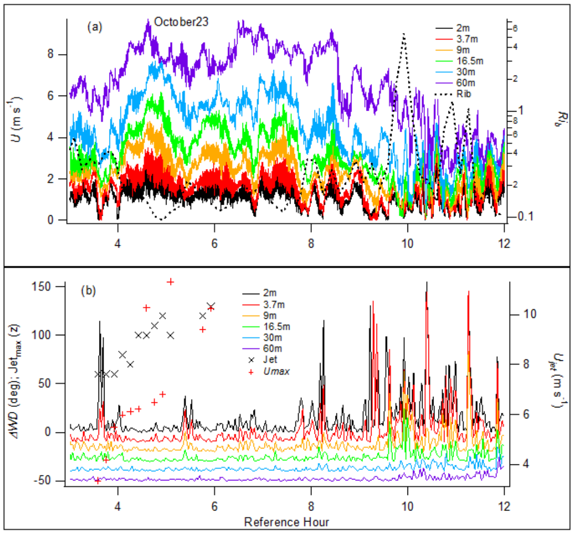

Figure 7. Same as Fig. 6 except now for October 23. Copyright 2018 *J. Appl. Met. Clim.*

3.CONSEQUENCES FOR PLUME DISPERSION

These wind direction change results have consequences for plume dispersion in very stable conditions and the measurement of SF_6 tracer plumes during Project Sagebrush corroborated the meteorological measurements. It was found that wind directions tended to be quasi-steady within a relatively narrow range of arc for up to several tens of minutes at a time and then abruptly shifted by up to 100 degrees or more on time scales of less than 10 min (Finn et al. 2018b). An example of this is shown in Fig. 8. Over the course of the 2-h tracer measurement the plume exhibited two large and abrupt changes in direction. The experiment began with the plume moving steadily toward the north-northeast for the first half hour then abruptly shifted toward the southeast where it was again quasi-steady for the next half hour. The plume then abruptly shifted again toward the northeast within a 10-min sampling period before finally ending the overall 2-h sampling period toward the east-northeast during the final hour. Not shown is the fact that the standard deviation of the wind direction for the individual 10-min tracer sampling periods was small, generally less than 10-20 degrees. That is consistent with results from earlier studies such as Prairie Grass (Barad 1958) and what can be found in current EPA guidance (EPA 2000) for stable conditions. However, the large horizontal plume spreads observed during Project Sagebrush in very stable conditions are wholly inconsistent with the results from Prairie Grass and some current plume modeling practices.

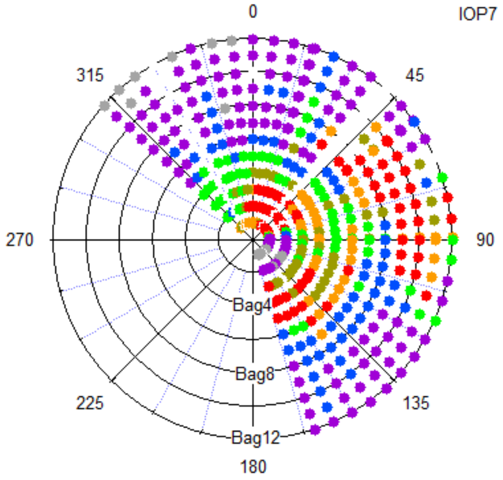

Figure 8. Plume directions as measured on the 100-m arc during the 2-h tracer test 7 for the 10-min averaged bag sampling interval (Bag#). The time (Bag#) increases with radial distance. Concentration color codes (ppt): grey (< 15), purple (15–100), blue (100–500), green (500–2500), olive (2500–5000), orange (5000–10000), red (>10000). Copyright 2018 *Boundary-Layer Meteorol.*

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