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# OBSERVATIONS OF FLOW OVER COMPLEX TERRAIN WITHIN THE STABLE NOCTURNAL BOUNDARY LAYER

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## 1. INTRODUCTION

While efforts to parameterize neutral to weakly stable nocturnal boundary layers (NBL), where turbulence is quasi-continuous, have been successful, moderate to strongly stable nocturnal boundary layers (hereafter referred to as the stable NBL), where turbulence is intermittent, have remained difficult to characterize due to their delicate yet complex nature.

Breakdown of the stable NBL has been observed as intermittent bursts of heat and momentum near the surface (Nappo, 1991). Theory and observations show that intermittent bursts observed in the stable NBL can produced by both internal and external forcing (McNider et al., 1998). As the stable nocturnal flow decouples from the surface and accelerates, the Richardson Number (Ri) decreases on the underside of the wind maximum. When the critical Richardson Number ($Ri_c$) is reached, a breakdown occurs that mixes heat and momentum, eventually restoring Ri to a value exceeding $Ri_c$. Modeling results have shown that this internal forcing can have a periodic nature (Revelle, 1993, Mahrt, 1999). However, external forcing mechanisms, such as gravity waves and meandering motions, can interact with the natural periodicity of the buildup of Ri, perhaps enhancing Ri and causing a breakdown prior to occurrence resulting from purely internal forcing. Furthermore, complex terrain can introduce streamline deformation, obstacle induced gravity waves, localized circulations and drainage flows that can affect and disrupt the evolution of the stable NBL.

Mahrt (1985) suggested that elevated turbulence resulting from wind shear at the underside of the nocturnal low-level jet can be the primary source of turbulence in the stable NBL. Smedman (1988) observed a two-layered turbulence structure in the stable NBL where the surface-based turbulence was decoupled from elevated turbulence. In the case of elevated turbulence production, it is not likely that surface similarity theory will perform well. It is not well understood how turbulence generated from an elevated source in the stable NBL might affect fluxes of heat and momentum near the surface.

Both Sorbjan (1988) and Mahrt (1985) documented observations of nocturnal drainage flows during the SESAME-1979 experiment over the rolling hills of central Oklahoma, within the large-scale slope of the Great Plains. Flow near the surface was decoupled from and, at times, opposed to the flow above 50 m AGL. For weak southerly flow above the surface layer, Mahrt analyzed a northwesterly current of air existed near the surface with "significant small-scale turbulent activity in the transition zone between the two airflows." He also suggested that, while intermittent bursts of warm air occur from shear instability at the top of the surface layer, bursts of cold air also occur from drainage circulations.

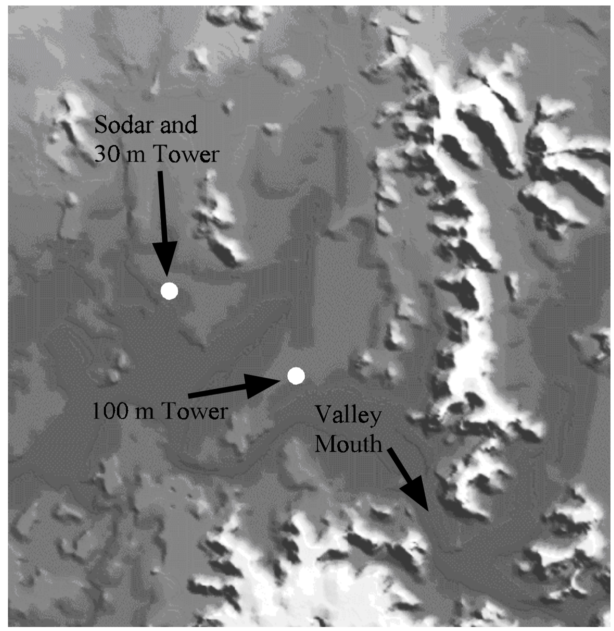


*Figure 1 Topographic map of the study domain.*

The purpose of the present study is to: 1) introduce significant wind and turbulence structure observations from a stable NBL pilot study during November 1999 over the complex terrain in and around Huntsville and Redstone Arsenal in north central Alabama using sodar and instrumented tower data; and 2) to demonstrate the temporal and spatial variability of the stable NBL.

## 2. STABLE NBL PILOT PROGRAM

Five consecutive nights with similar synoptic high pressure conditions (November 5-9) were examined. The NBL was mostly cloud-free and geostrophic winds were weak. The direction of the geostrophic flow varied throughout the five-day period as a result of the center of a synoptic

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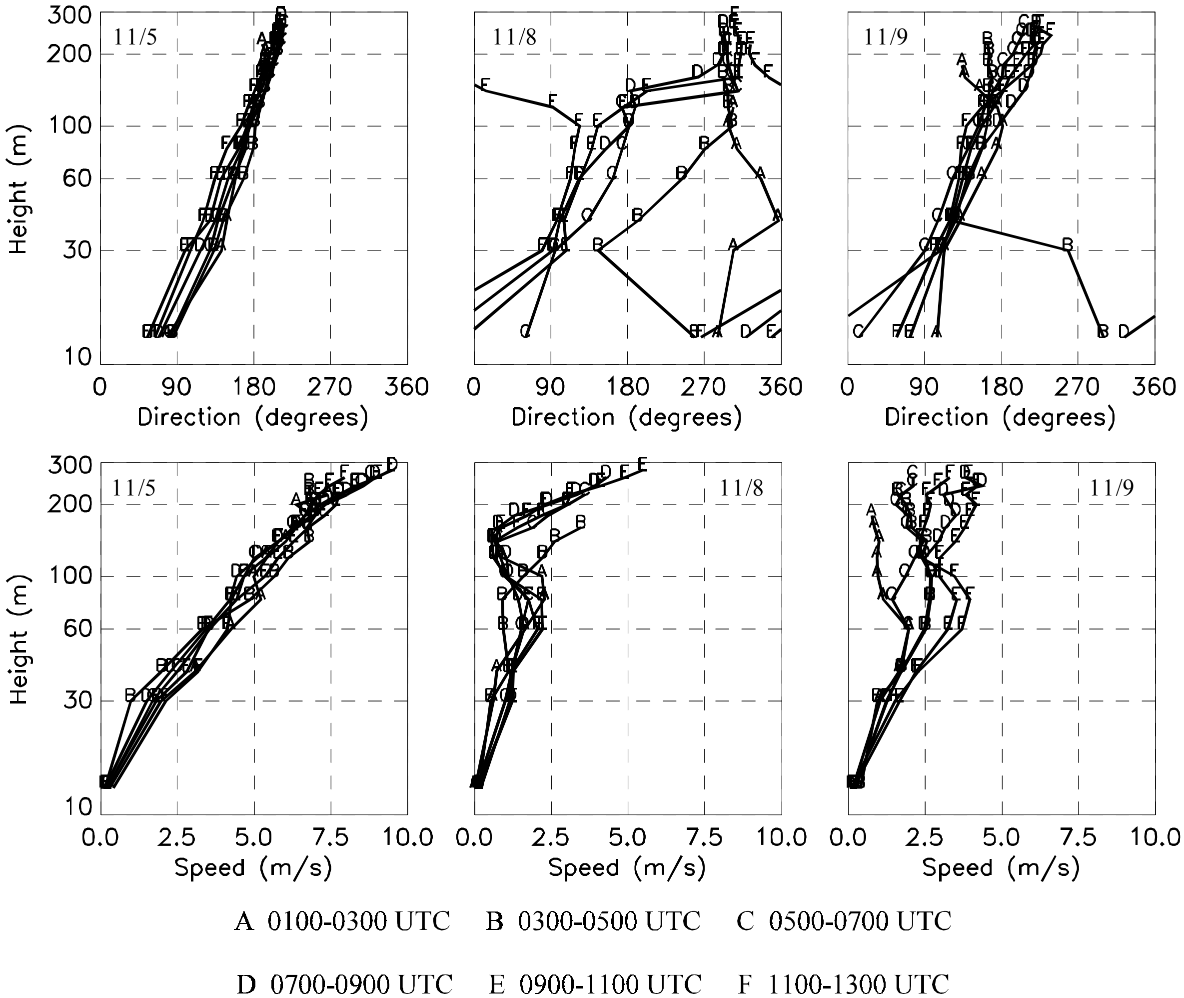


*Figure 2 Two-hour average profiles of wind direction (top row) and wind speed (bottom row) for the nocturnal periods (0100-1300 UTC) of 11/5, 11/8 and 11/9 combined from 30 m tower (13 and 30 m) and sodar data.*

high meandering over the region. Average daily temperatures and dew points increased throughout the study period.

Figure 1 is a digital elevation model map of the local topography of the study area. The city of Huntsville is located to the north-northeast of the experimental site. At the eastern edge of the domain is a north-south ridge protruding 275 m above the plain. There are also ridges to the south-southeast that are more discontinuous, with elevations up to 200 m above the plain. In the southeastern portion of the domain is the mouth of a gently sloped valley of the Tennesse River. The valley is 30 km long with discontinuous ridges lining both sides and extending roughly 200 m above the valley floor. The terrain around the experimental site is comprised of flat plains with undulations on the order of 20 m, with significant isolated orographic features.

For this paper, data are presented from a 100 m tower, a 30 m tower and a 2 kHz Doppler sodar. Wind data from the 100 m tower was averaged for one minute and recorded every fifteen minutes. Wind data from the 30 m tower were collected at 13 and 30 m, and the data was averaged and recorded each minute. The first gate from the sodar wind profiles is at 40 m, with 20 m gate spacing. The sodar data is averaged for 15 minutes. The 30 m tower was collocated with the sodar to provide a continuous wind profile from 13 m to the maximum height coverage of the sodar. Figure 1 shows the relative location of these instruments within the study domain. The 100 m tower is situated 8.6 km from the sodar site at a bearing of 127 degrees.

Times shown on Figures 2-4 are in UTC, which is LST plus 6 hours.

## 3. DATA ANALYSIS

Figure 2 shows profiles of wind speed and direction combined from the 30 m tower and the sodar for the nocturnal periods (0100-1300 UTC) of 11/5, 11/8 and 11/9. The data have been averaged into two-hour intervals. Flow near the top of the sodar coverage (near 300 m) is representative of the synoptic flow. Wind direction on 11/5 and 11/9 is consistently from the southwest near 300 m AGL. There is, however, significant difference in the wind speed profiles for these two nights. The wind speed on 11/5 at 300 m approached 10 m $s^{-1}$ and the profile was log-linear, while wind speeds at 300 m on 11/9 remained less than 5 m $s^{-1}$, and the wind profile exhibited a significantly different shape. A low-level wind maximum occurred at 60 to 80 m AGL on 11/9, which increased in speed throughout the nocturnal period.

The wind speed profile on 11/8 also shows a local wind maximum near 60 to 80 m AGL, however the wind direction profile is quite different than for both 11/5 and 11/9. The magnitude of wind speed near 300 m on 11/8 is greater than 11/9, but the low-level wind maximum is weaker on 11/8. Notice that there was a region of significant directional shear with weak winds on 11/8 between 100 and 180 m. The flow at 60 m was decoupled from the flow above 180 m. One common occurrence on all three nights was that the wind at 60 m was approximately from the southeast. Under the northwesterly flow on 11/8 and the weak synoptic flow of 11/9 a drainage flow developed at that level, while the drainage flow appears obscured by the strong flow on 11/5.

Figure 3 is a time series plot for the 11/8 nocturnal period (0000-1200 UTC) of both fifteen minute average wind direction at 60, 140 and 180 m AGL (top panel) and acoustic backscatter (bottom panel) from the sodar. Sodar backscatter is proportional to the temperature structure function. The backscatter plot clearly shows two layers of turbulence that appeared to couple for brief intervals. The top plot in Figure 4 shows that wind direction at 60 m shifted into a different flow regime from the wind at 180 m. After 0900 UTC, the two flows were counter to each other. The flow at 140 m was near the interface of the westerly to northwesterly flow at 180 m and the southeasterly flow at 60 m. The winds were weak in the region between the decoupled flows. The 140 m wind measurement was near the bottom of the upper flow, and the flow at this level fluctuated between the upper and lower flows. The change in wind direction was greatest just below the elevated turbulence, while wind speed increased in the elevated turbulence region.

Figure 4 is composed of scatter plots relating sodar wind speed and direction measured at 100 m AGL to winds measured by the 100 m tower for the nocturnal periods (0100-1300 UTC) of 11/5-11/8. Gray-shading has been used to show the temporal evolution of winds.

Wind direction on 11/5, the night with strongest south-southeasterly flow, exhibited the tightest grouping with little nocturnal variability. Wind speeds between the two sites related well, also. Winds on 11/6 winds relate well between the two sites, but while winds at the sodar site were primarily from the south to southeast throughout the nocturnal period, winds at the tower site were initially from the northeast and shifted into a southerly flow during the 0700-0900 UTC period. Interestingly, winds weakened throughout most of the nocturnal period on this night. Wind direction on 11/8 showed a bimodal behavior also; however, it was quite different from 11/6. Winds at both sites were initially from the northwest, but sodar winds shifted to south and southeasterly, while the tower winds backed to westerly. Wind speeds at 100 m remain weak at both sites. 11/7 showed the greatest nocturnal variability in wind direction. On this night, the wind minimum above the drainage flow was near 100 m. As a result, wind speeds for both locations at this height remained weak and direction was variable.

## 4. CONCLUSION

The results of this pilot study have shown significant vertical, horizontal and temporal variability in the evolution of the stable NBL over the complex terrain of North Alabama. There is evidence that an extensive drainage flow with a finite vertical and horizontal extent developed during the nocturnal periods of 11/6-11/9. However, on 11/5, the period with strongest flow aloft, a drainage flow did not appear to develop. In the cases when winds aloft were westerly to northeasterly (11/7, 11/8 and late on 11/6), a region of wind shift exceeding 100 degrees (at times reaching 180 degrees) existed above the drainage flow. Sodar backscatter showed weak turbulence near the top of the drainage flow, and then an enhancement of turbulence associated with the acceleration of winds above the wind minimum. Winds exhibited considerable spatial and temporal variability within this interface.

In order to understand the spatial extent and horizontal evolution of the observed drainage flow, more comprehensive observations are needed. It is important to identify the source of the drainage flow, whether it is the ridge to the east of the domain, the valley mouth to the southeast or some other topographic feature. The behavior of this drainage flow is important for civil engineers. Since the flow passes over Redstone Arsenal and Marshall Space Flight Center, pollutants and toxins from military exercises and rocket testing could become trapped within the stable NBL and channeled to nearby residential areas.

## 5. REFERENCES


Mahrt, L., 1985: Vertical structure and turbulence in the very stable boundary layer. *J. Atmos. Sci.*, **42**, 2333-2349.

Mahrt, L., 1999: Stratified atmospheric boundary layers. *Bound.-Lay. Meteor.*, **88**, 375-396.

McNider, R. T., M. P. Singh and S. Gupta, 1998: Turbulence and dispersion in the stable planetary boundary layer—Section B. *Advances in Fluid Mechanics Series: Dynamics of Atmospheric Flow. Atmospheric Transport and Diffusion Processes*, M. P. Singh and S. Raman, Eds, Computational Mechanics Publications, Boston, pp 93-130.

Nappo, C. J., 1991: Sporadic breakdown of stability in the PBL over simple and complex terrain. *Bound.-Lay. Meteor.*, **54**, 69-87.

Revelle, D. O., 1993: Chaos and "bursting" in the planetary boundary layer. *J. Appl. Meteor.*, **32**, 1169-1180.

Smedman, A-S., 1988: Observations of a multi-level turbulence structure in a very stable atmospheric boundary layer. *Bound.-Lay. Meteor.*, **44**, 231-253.

Sorbjan, Z., 1988: Structure of the stably-stratified boundary layer during the SESAME-1979 Experiment. *Bound.-Lay. Meteor.*, **44**, 255-266.

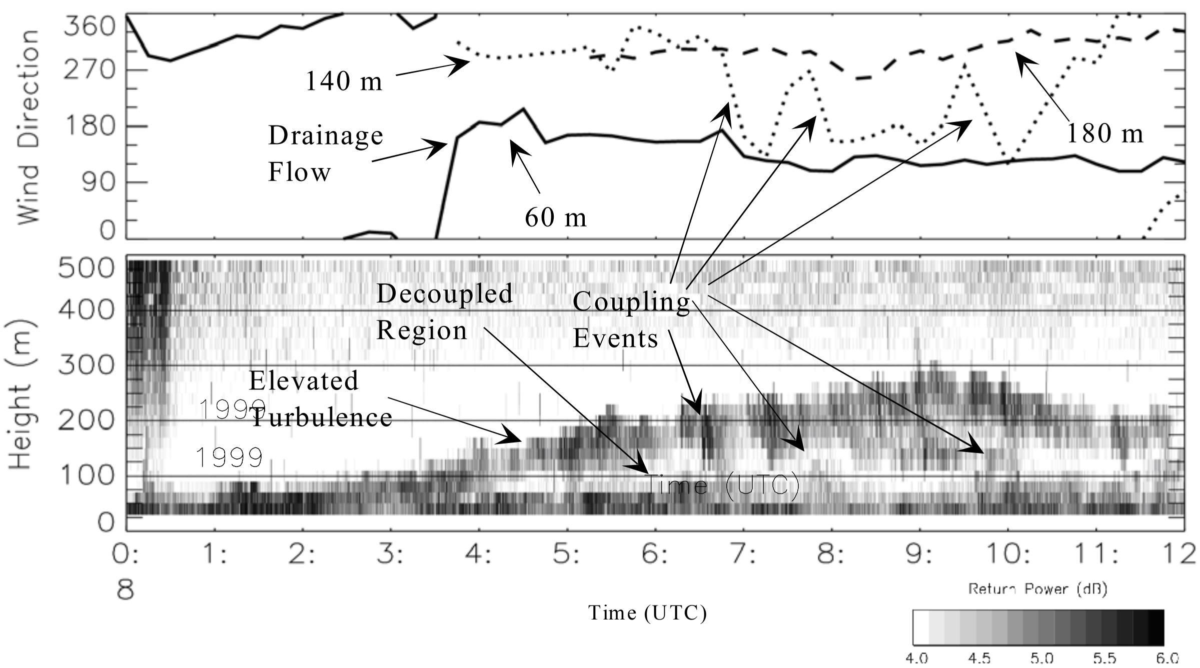


*Figure 3. The top panel is wind direction measured by the sodar at 60 (solid line), 140 (dotted line) and 180 m (dashed line) for the 0000-1200 UTC period on 11/8. The bottom panel is a time-height section of sodar backscatter for the corresponding time period.*

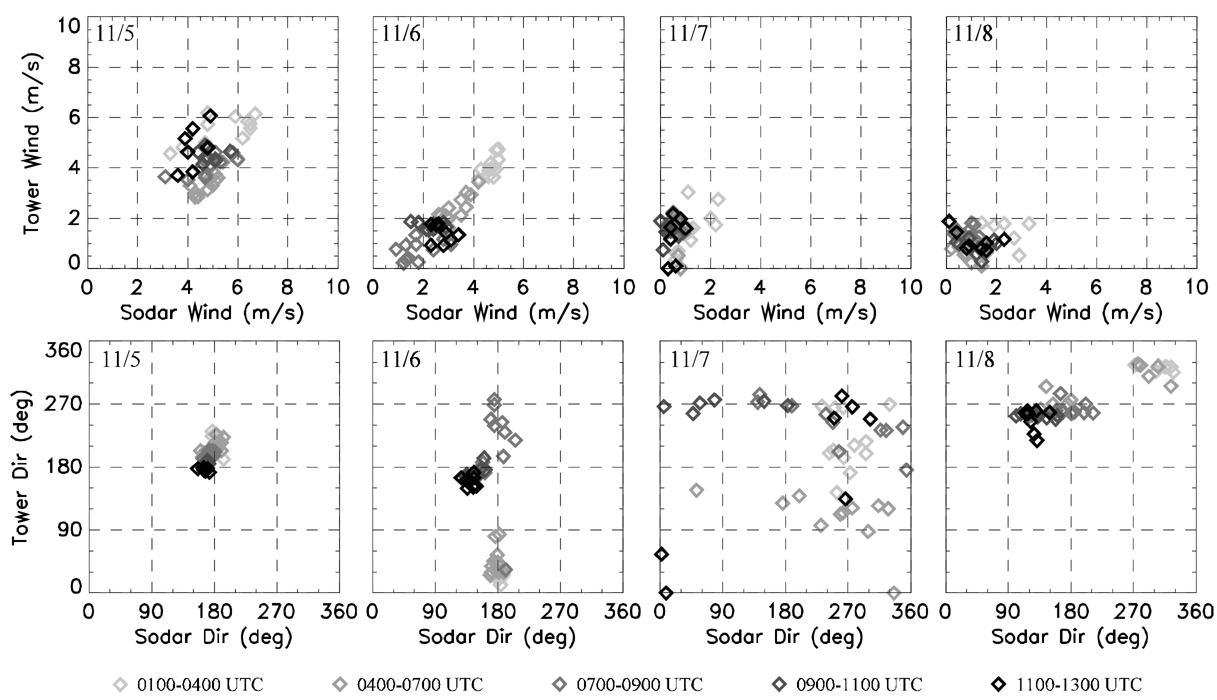


*Figure 4. Scatter plots of wind speed (top) and wind direction (bottom) for the nocturnal periods (0100-1300 UTC) of 11/5-11/9. Data from the 100 m tower are on the ordinate, while data from the 100 m gate of the sodar are on the abscissa.*