6.17 DIURNAL VARIATIONS IN THE 2-DIMENSIONAL NATURE OF WIND SHEAR IN THE PLANETARY BOUNDARY LAYER

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1. INTRODUCTION

Wind shear plays an extremely important role in the dispersion of plumes and puffs of atmospheric pollutants. However, only recently have we acquired the ability to accurately measure shear in the lowest layers of the atmosphere. In the planetary boundary layer (PBL), small-scale turbulent fluctuations are indistinguishable from mean motions when winds are measured using aircraft or balloon-borne platforms, while tower-based wind measurements are limited to a relatively low altitude.

Recently, remote sensing radar profilers are routinely monitoring mean motions and shear of winds in the PBL (Miller et al., 1994; Barth et al., 1994). In this paper we present an initial analysis of wind shear derived from a NOAA profiler positioned in Schenectady NY during October 2003, which was part of an intensive observation period of the NSF-sponsored Hudson Valley Ambient Meteorological Study (HVAMS). During HVAMS, over 80 hours of flights were carried out using the instrumented University of Wyoming King-Air studying PBL properties.

Wind shear is the derivative of the mean winds with height (∂u/∂z, ∂v/∂z), and is thus a two dimensional quantity. Past discussions of shear have often quantified only the MAGNITUTDE of the shear vector over some layer without characterizing the DIRECTION of the shear. Here the 2-D nature of wind shear is defined relative to the mean wind in the layer where shear is being assessed. Section 2 provides a definition of the shear parameters that are discussed. In section 3, an analysis of hourly values of shear measured for the entire month of October 2003 is presented.

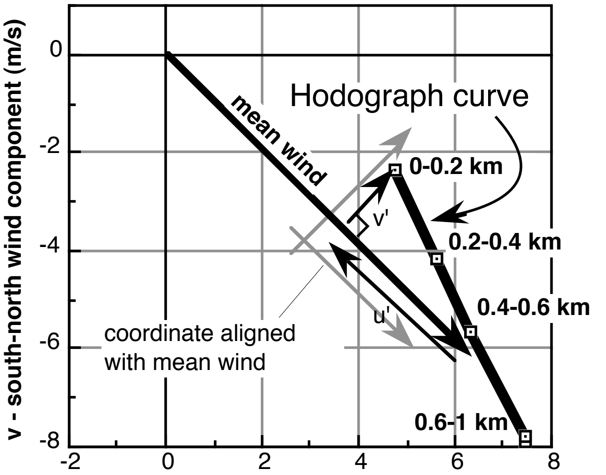

Fig. 1. Hodograph of winds in lowest 1000m above surface measured by a radar profiler over Schenectady, NY at 1PM local time on 23 Oct 2003. Schematic of coordinate system adopted for this derivation to decompose wind deviations from mean into components parallel (u') and perpendicular (v') to the mean wind at all levels is shown.

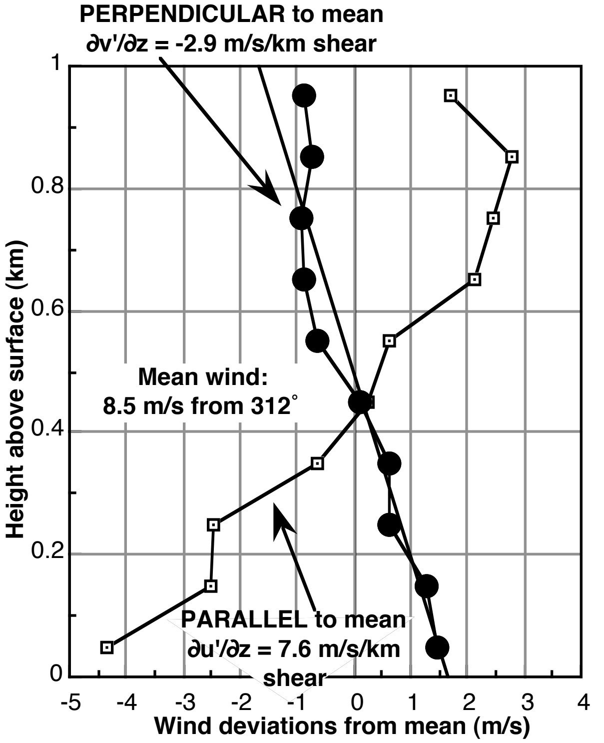

Fig. 2. Variation of wind with height in lowest kilometer above surface for conditions shown in Fig. 1. Winds plotted here are decomposed into deviations parallel to and perpendicular to the mean wind averaged over the lowest 1000m of 8.5 m/s blowing from 312°.

2. 2-DIMENSIONAL SHEAR CALCULATION

Fig. 1 shows a typical wind hodograph measured over Schenectady, NY at 1PM local time on 23 Oct 2003. Individual points on the hodograph curve are winds averaged from a profiler over 200m thick layers, and it is evident that at this time winds are veering in a clockwise direction and becoming stronger with height.

The mean wind is defined for this layer by mass-weighting the winds throughout this layer, and a coordinate system relative to this mean wind can be defined. In Fig. 1, the average winds are blowing at 8.5 m s^{-1} from 312° from the northwest. One can define wind deviations along this profile that are parallel (u') and perpendicular (v') to the mean wind. On Fig. 1 it is evident that in the lower levels of this wind profile, winds deviate to the left (positive v') and are weaker (negative u') than the mean motions throughout the entire

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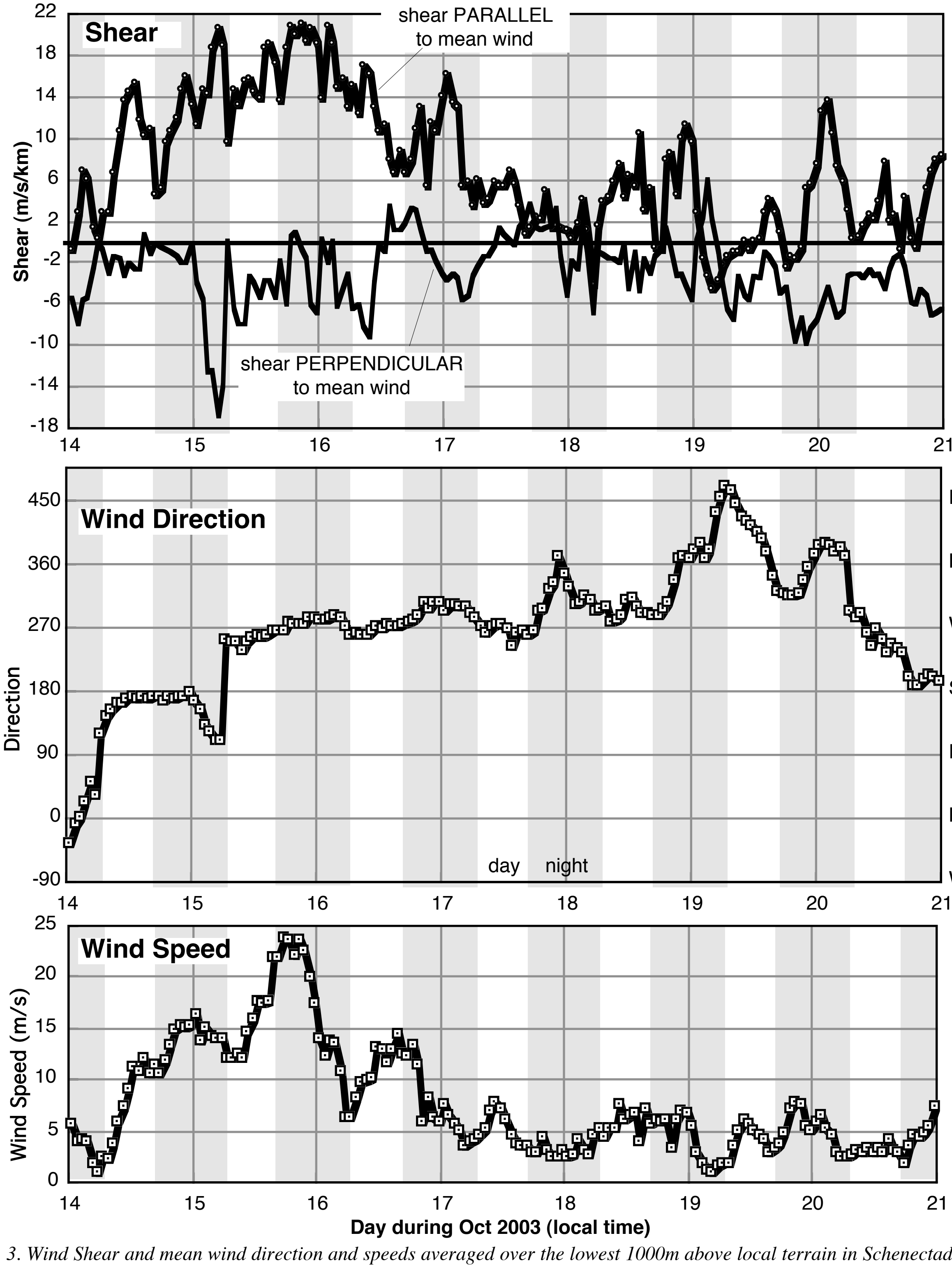

Fig. 3. Wind Shear and mean wind direction and speeds averaged over the lowest 1000m above local terrain in Schenectady, NY during 14-21 Oct 2003. Top panel shows wind shear parallel and perpendicular to mean wind. Middle and bottom panels show the direction and speed of winds averaged over lowest km. Night periods are shaded grey.

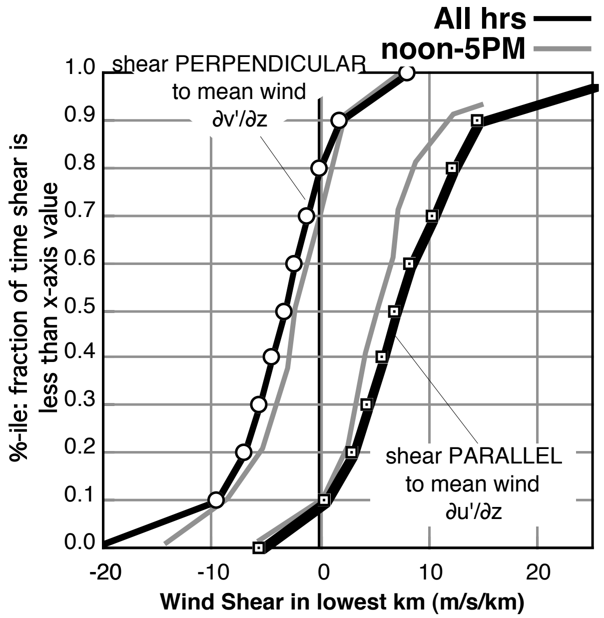

Fig. 4. Frequency distribution of hourly-averaged shear parallel and perpendicular to the mean winds in the lowest 1000m above local surface in Schenectady during Oct. 2003. Black denotes all hours, grey lines denote winds during noon-5PM local time only.

kilometer thick layer. In contrast, winds deviate to the right and are stronger than the mean in the upper portions of this 1000m layer.

Fig. 2 shows the same information as the hodograph Fig 1, but wind deviations are defined parallel to and perpendicular to the mean winds. Generally it is found that wind deviations parallel to and perpendicular to the mean wind follow an approximately linear trend with altitude, as shown in Fig. 2. The nature of the deviations of wind with altitude shown in Fig. 1-2 can be summarized and quantified using the best-fitting linear regression to the measured deviations plotted in Fig. 2. The slopes of these two linear fits define the average nature of the wind shear in the layer. These two slopes therefore quantify the 2-D nature of the shear in the layer: ∂v'/∂z quantifies the "veering" or changing direction of wind with height; while ∂u'/∂z measures the strengthening of the wind with height along the mean direction.

For the remaining analysis described here, wind shear is decomposed into these two components, parallel and perpendicular to the mean wind in the lowest 1000 m above the surface. The choice of 1000 m is arbitrary, but it generally encompasses a large fraction of the afternoon PBL, and is within the viewing range of the NOAA profilers.

3. TYPICAL 2-D SHEAR IN PBL

Fig. 3 shows hourly variations of the two components of wind shear (∂v'/∂z & ∂u'/∂z) in the lower atmosphere during 14-21 Oct 2003. The mean wind direction and speed are also shown on the middle and bottom panels of this figure. Night periods are shaded grey. Shear and wind speeds and directions are vector-averaged over the lowest 1000m above the local terrain. During this one-week period, strong winds out of the south and west associated with a passing low pressure center were replaced by slower winds with weaker shear out of the north, east then northerly directions. It is evident from this figure that wind shear ALONG the direction of the mean winds correlates somewhat with the mean wind speeds. In contrast, wind shear PERPENDICULAR to the mean flow is only weakly correlated with wind speed.

Fig. 4 shows a cumulative frequency distribution of the two components of wind shear during the entire month of Oct 2003. Winds at this site "veer" with height (∂v'/∂z < 0, rotating clockwise with height) 80% of the time, meaning that in the lowest few hundred meters, winds are directed to the left of the mean winds, while in the upper portions winds veer to the right. Veering winds are consistent with a northern hemisphere Ekman spiral. However there are exceptions to this pattern and about 20% of the time, winds "back" with height and rotate counterclockwise with altitude.

During the daytime, surface heating induces turbulence and a well-mixed planetary boundary layer grows. Typically, the PBL reaches a maximum depth in the late afternoon of 1200-1400 m (Holzworth 1972). Therefore in mid to late afternoons, one would expect that the winds shown here are within the turbulent mixed layer of the PBL, and shear and gradients of other scalar quantities should smoothed out by intense turbulent mixing. The grey lines on Fig. 4 show the frequency distribution of winds from noon-5PM local time. It is evident that shear ALONG the mean wind direction is slightly lower during the midafternoon. In contrast, shear PERPENDICULAR to the mean wind direction remains the same whether the layer contains appreciable turbulence or not. Furthermore, the lowest 1000m does not become "well mixed", and appreciable gradients of momentum exist at all times throughout the day.

4. DUIRNAL PATTERN OF SHEAR

Fig. 5 shows the diurnal trend of the two components of wind shear in the lowest 1000m above the surface during the entire month of Oct 2003. Wind shear parallel to the mean wind direction decreases throughout the daytime period as turbulent mixing smears out gradients. The lowest along-wind shear occurs in the late afternoon, and has a magnitude of about 5 m s^{-1} km^{-1}. Maximum wind shear along the mean wind direction occurs in the early morning hours and has a magnitude of 8-9 m s^{-1} km^{-1}.

Fig. 5 shows that shear PERPENDICULAR to the mean wind direction shows a slightly different diurnal pattern. Shear perpendicular to the flow maximizes in the early morning hours 7-9 AM with a peak value of about -6 m s^{-1} km^{-1}. During the remainder of the day, the magnitude of the shear in this direction decreases under the influence of turbulent mixing, reaching a minimum around local sunset time of ~2 m s^{-1} km^{-1}.

The shear values presented in Fig 5 are shear relative to the mean winds averaged over a 1000 m-thick

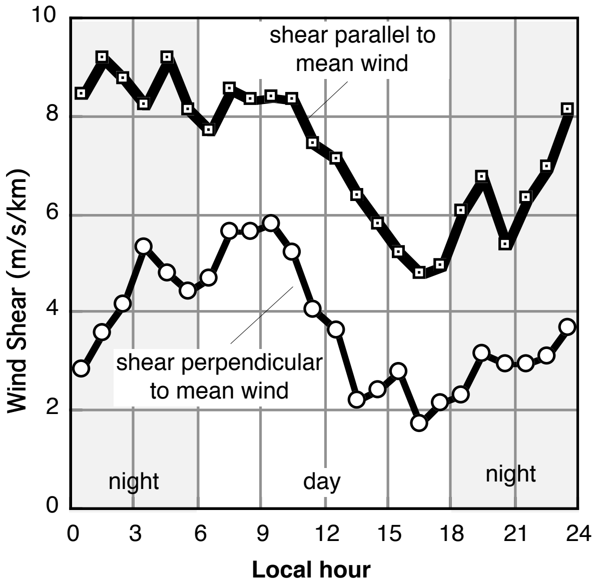

Fig. 5. Diurnal variation of shear in the lowest 1000m over Schenectady NY measured during Oct. 2003. Shear decomposed into vector components parallel and perpendicular to the mean wind over the same layer. For plotting purposes, shear perpendicular to mean wind shown here is the NEGATIVE of this component of the shear, and winds perpendicular to the mean flow nearly always "veer" (rotate clockwise) with altitude.

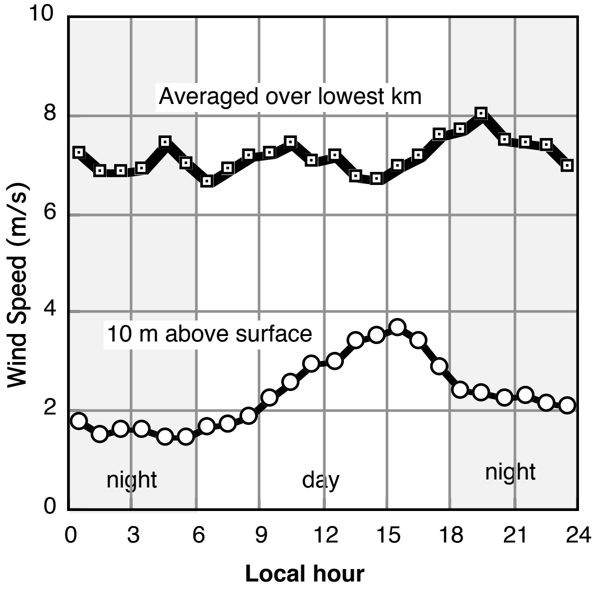

Fig. 6. Diurnal variation of wind speed measured at 10 m and averaged over the lowest 1000m above local surface in Schenectady NY during October 2003.

layer, and the diurnal variation of wind speeds in this layer are shown for informational purposes in Fig. 6. Here the winds are compared with more routinely-available 10-m winds. When averaged over an appreciable depth, wind speeds do not show a pronounced diurnal variation throughout the day, in contrast to surface-measured winds, which show a strong peak in the late afternoon and a minimum in the early morning hours.

5. CONCLUSIONS

Vertical profiles of hourly-averaged wind speeds and directions remotely sensed at Schenectady, NY using the NOAA profiler during the month of Oct 2003 are analyzed. A technique for defining the 2-dimensional nature of wind shear is presented where shear of the wind with height is decomposed into components that are parallel to and perpendicular to the average wind vector in a predefined layer. In the lowest kilometer, wind shear perpendicular to the mean wind in that layer reaches its greatest magnitude of slightly less than -6 m/s/km during about 3-9AM local time, and is lowest near sunset (-2 m/s/km). Generally we see a "veering" of wind with height (wind direction turning clockwise with increasing height above the surface) in the lowest kilometer, although about 20% of the time, winds "back" with height (counterclockwise rotation with height). On average, we see about –3.7 m/s/km wind shear perpendicular to the mean wind in the lowest km, although the 90th and 10th percentile shears are –10 m/s/km and +2 m/s/km. Even during daytime periods when the lowest kilometer is clearly within the "well mixed" planetary boundary layer, we do not observe "well mixed" wind speeds and directions. In fact, some of the time we see evidence for something like an "inverse" of a nocturnal jet during early morning time periods where winds in the layer 500-1000m above the surface are reduced to will below a frictionally-balanced pressure gradient and Coreolis wind, and wind speeds are frequently higher near the surface than in the upper boundary layer during this brief time period due to an oscillatory dynamic response of the air in the upper PBL due to the sudden imposition of frictional drag by the growing boundary layer. Shear magnitudes are considerably greater than calculated thermal wind or Ekman shear would dictate, suggesting that shear in the PBL is not in a balanced dynamic state with respect to the forces acting on air in the lowest kilometer.

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