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Subcontractor Report

Analysis of CASES-99 Lidar and Turbulence Data in Support of Wind Turbine Effects

April 1, 2001 to January 31, 2003

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The nocturnal low-level jet (LLJ) of the Great Plains of the central United States has been identified as a promising source of high-momentum wind flow for wind energy. Wind turbine installation has been proposed near Oxford, Kansas, and Lamar, Colorado. The acceleration of the winds after sunset above the surface produces a jet profile in the wind velocity, as described by Blackadar (1957), with maximum speeds that often exceed 10 m s^{-1} or more at heights near 100 m or more. These high wind speeds are advantageous for wind energy generation. The high speeds aloft, however, also produce a region of high shear between the LLJ and the earth's surface, where the nocturnal flow is often calm or nearly so. This shear zone below the LLJ generates atmospheric waves and turbulence that can cause strong vibration in the turbine rotors. It has been suggested that these vibrations contribute to premature failures in large wind turbines (Kelley et al. 2000), which, of course, would be a considerable disadvantage for wind energy applications. Concerns center around periodic fluctuations or coherent turbulent structures in the flow and wind shears at rotor heights as a cause of premature failure in large wind turbines. The most critical heights are the 50-200 m levels above ground level (AGL).

In October 1999, a field project called the Cooperative Atmosphere-Surface Exchange Study 1999 campaign, or CASES-99, was conducted in southeastern Kansas to study the nocturnal stable boundary layer (SBL) (Poulos et al. 2002). By coincidence, the site of this experiment was near Leon, Kansas, within 30 km of the proposed Oxford location for experimental wind turbine installation. One of the instruments deployed during CASES-99 was the High-Resolution Doppler Lidar (HRDL), a new scanning, remote-sensing, wind-mapping instrument (Grund et al. 2001) developed and deployed by the Environmental Technology Laboratory (ETL) of the National Oceanic and Atmospheric Administration (NOAA). Analyses of data from this instrument have shown that a nocturnal jet in the wind-speed profile is a routine feature of the nighttime SBL at heights of ~100 m AGL, especially during periods of strong surface cooling (Banta et al. 2002). This height is significant because it is below the minimum height of 120-200 m at which data from UHF radar wind profilers are available. Climatological summaries and compilations using profiler data sets thus would miss important maxima in the wind profiles, which are of critical importance to wind turbine operations.

Images from HRDL scan data show waves and relatively large-amplitude turbulence in the shear region below the LLJ. These images indicate that peak-to-peak amplitudes of these fluctuations can reach several meters per second for periods on the order of an hour or more. Thus, HRDL measurements near Leon show that high-amplitude oscillations in the wind exist that have a length scale and height that could have a major adverse impact on the operation of the large numbers of wind turbines being considered for deployment in the regions where the LLJ is frequently observed.

Before undertaking further research and field programs, it makes sense to see what can be learned from the existing CASES-99 data set. The purpose of the present research under Interagency Agreement (IA) No. DE-AI36-01GO11066 has thus been to use HRDL and other data sets from CASES-99 to:

- Determine LLJ characteristics for the month of the CASES-99 project (October 1999)
- Focus analysis on heights of interest for wind energy

- Investigate usefulness of HRDL for studying wind fluctuations as indicators of turbulence activity
- Help plan a future field project involving HRDL
- Convey briefing materials to personnel at the National Renewable Energy Laboratory (NREL), participate in meetings and briefings, and publish results.

LLJ Properties

Funding under this project contributed to completion and publication of a study of LLJ properties using HRDL and other data. In this study, we determined the distribution of LLJ speed, height, and direction during October 1999 in the form of histograms (Fig. 1). Spatial averages were calculated from both vertical-slice scans and conical scans and then further averaged in time and evaluated at 15-min intervals, as described in Banta et al. (2002). The peak in the distribution of the speed is at 9 m s^{-1}; the peak in height is at 80-100 m; and the direction has no strong peak but does have a slight tendency to favor southerly winds. A scatter diagram of jet speed vs. height (Fig. 2) shows that stronger jets tend to be higher. These results have recently been published and can be found in Banta et al. (2002).

For further analysis, we used HRDL velocity data to determine how wind speeds were distributed as a function of height over height intervals that would affect wind turbine operations. Velocity profiles were determined from vertical-slice scan data as in Banta et al. (2002), and wind speed distributions were determined for 20-m height intervals from 20 to 100 m AGL. These distributions (Fig. 3) show the expected increase in wind speed with height, with the mode in the distribution increasing from 4 m s^{-1} in the 20-40-m interval to 8 m s^{-1} at 80-100 m.

We also calculated mean shear values for the layer between 45 and 75 m AGL, based on 15-min mean-wind values (Fig. 4). The distribution for all HRDL nights during CASES-99 (Fig. 4) shows a relatively even distribution between 0 and 0.1m s^{-1} per m [i.e., s^{-1}], probably reflecting the mixture of nights in the sample with strong, medium, and weak winds. The bottom panel shows the value of the power-law exponent α, calculated as shown on the figure, computed from the same data as the shears in the upper panel.

Turbulence Properties

HRDL vertical-slice (or range-height) scan data were also used to calculate the variance of the along-wind component $\langle u'^2 \rangle$ for each scan, and these values were further averaged at 15-min periods as described in Banta et al. (2002). Velocity variance is a measure of turbulence intensity. The variances for 20-m vertical intervals from 20 to 100 m for all days of the CASES-99 project (when HRDL data were available) are given in Fig. 5. It shows that for the entire data set, variance values decreased with height from a mode of 0.6-0.8 m^2 s^{-2} at the lowest level to a mode at less than 0.2 m^2 s^{-2} at the highest level, supporting the notion that the flow tends to be smoother at higher levels of the nocturnal boundary layer. Wind energy interest focuses on nights with stronger winds. Fig. 6 shows two nights with stronger winds. October 21 was a night with a moderately strong LLJ and a period of enhanced turbulence activity for a few hours around midnight (Coordinated Universal Time or UTC) (see Banta et al. 2002, Figs. 3 and 16).

Fig. 6a shows that the variance distribution has a higher percentage of values greater than 0.5 $m^2 s^{-2}$ than the overall sample in Fig. 5. One of the stronger LLJs (reaching nearly 20 m s^{-1}) during CASES-99 occurred on the night of October 25, and Fig. 6b shows that on this night, the variances increased with height from ~0.65 $m^2 s^{-2}$ at the lowest level to ~ 0.85 $m^2 s^{-2}$ at the highest levels. Thus, the idea that the wind flow becomes smoother with height is supported by the mean distribution for the entire data set. Data from individual stronger-wind nights, however, show the opposite: on these nights, which have the greatest impact on wind energy generation. The turbulent kinetic energy (TKE), defined as

$$\mathrm{TKE} = \tfrac{1}{2}\left[\langle u' \rangle^2 + \langle v' \rangle^2 + \langle w' \rangle^2\right]$$

where <u’>, <v’>, and <w’> are the along-wind, crosswind, and vertical turbulent wind components respectively), remains high or often actually increases with height. TKE increasing with height in this way is consistent with turbulence being generated near jet level and being transported downward, in the so-called “upside-down” boundary layer structure (e.g., Mahrt and Vickers 2002).

Turbulence Measures

Turbulence that can produce damaging effects on turbine rotors has been associated with turbulence having high Reynolds’ stress (Kelley et al. 2000), or high values of “coherent TKE” defined as

$$coh\ \mathrm{TKE} = \tfrac{1}{2}\left[\langle u'w' \rangle^2 + \langle v'w' \rangle^2 + \langle u'v' \rangle^2\right]^{1/2}$$

(Kelley, personal communication). Because we are interested in turbulence properties up to 200 m or more above the surface and the CASES main tower was only 60 m high, we wanted to assess the utility of using velocity-variance-profile data from HRDL to determine turbulence that may affect rotor operation. We compared HRDL data with data from the top levels of the 60-m tower. This beginning study concentrated on two issues: (1) Did periods of high HRDL variance correspond to periods of high tower-measured TKE, and (2) Was the ratio of *coh* TKE to total TKE relatively consistent or variable?

(1) Time series of HRDL variance and tower TKE at near-tower-top heights of 50-60 m were plotted for each night. Two examples are given in Figs. 7 and 8. In general, periods of high fluctuations in HRDL data (bottom panel) correspond to high tower TKE (top panel), and low periods also agree. Thus, these semi-quantitative indications are that agreement is good. The next step is to further quantify the correspondence by producing scatter diagrams relating the two quantities. This work is in progress, but several issues remain to be addressed, including further “cleanup” of the HRDL data set—for example, to account for ground intercepts, changes in azimuth angle, periods of weak signal, etc.

(2) The time series of *coh* TKE as measured on the tower is shown in the second panel of Figs. 7-8. As expected, *coh* TKE is high when TKE is high. The third panel in each figure shows the ratio of *coh* TKE to TKE for the various levels. On the stronger-wind night (25 October, Fig. 8), the ratio was mostly between 0.10 and 0.15 at all levels, with some of the

excursions reaching 0.20 or more. On the moderately strong wind night (October 21, Fig. 7), the ratio was more variable, especially during the light-wind period early in the evening and at the lower levels. The magnitude of the ratio does not seem to be very dependent on level, although often the variability of the ratio is greater at the lower levels of the tower (blue).

Reporting of Results

Under this funding, we have provided briefing materials to NREL personnel (Neil Kelley, Mike Robinson) that demonstrate LLJ characteristics and the kind of coherent turbulence structures that can be generated at rotor level (such as those shown in Newsom and Banta 2003). Banta gave a presentation at the 2002 NWTC and Industry R&D Coordination Meeting in Golden, Colorado, entitled "Analysis of CASES-99 Lidar and Turbulence Data in Support of Wind Turbine Effects."

Funding under this project has contributed to the completion and publishing of the CASES-99 LLJ analysis study, "Nocturnal Low-Level Jet Characteristics over Kansas during CASES-99," which appeared recently in the journal *Boundary-Layer Meteorology* (Banta et al. 2002) and a study relating LLJ properties to turbulence measures below the jet (Banta et al. 2003).

We have also engaged in discussions with Neil Kelley and Mike Robinson of NREL regarding a field program in Lamar, Colorado. The purpose of this project would be to:

- Extend the findings of CASES-99, especially regarding the relationship between LLJ characteristics and turbulence
- Use HRDL to specify LLJ characteristics
- Relate these characteristics to tower-measured TKE and *coh* TKE
- Evaluate the ability of HRDL to detect critical turbulence events and explore scanning/staring strategies
- Use HRDL and other available data to study the spatial extent of turbulence events.

Summary

Under this Interagency Agreement, we have:

1. Determined LLJ properties during CASES-99 and published these findings in Banta et al. (2002)
2. Begun to study the relation between LLJ properties and turbulence (Banta et al. 2002, 2003)
3. Performed analyses of the distribution of wind speed and variance as a function of height for height intervals that would affect wind turbines, using HRDL data
4. Investigated the relationship between HRDL-measured variance and TKE measured by the tower, and the relationship between tower TKE and "coherent TKE"
5. Begun a more quantitative assessment of lidar variance vs. tower TKE, to assess the ability of HRDL to measure turbulence-related quantities at heights above the tower

6. Contributed material to the contract manager (Neil Kelley) for briefings on wind energy to the U.S. Department of Energy (DOE) and other agencies, and presented CASES/HRDL-related material at the 2002 meeting in Golden, Colorado
7. Contributed to planning for a possible future field campaign near Lamar, Colorado, involving HRDL (possibly summer 2003).

Finally, we emphasize again that much of the technical progress accomplished under this funding was reported in the two journal articles (Banta et al. 2002, 2003), which should be considered part of this report. This is the final report for DOE Interagency Agreement No. DE-AI36-01GO11066. Copies have been provided to Neil Kelley, the contract manager.

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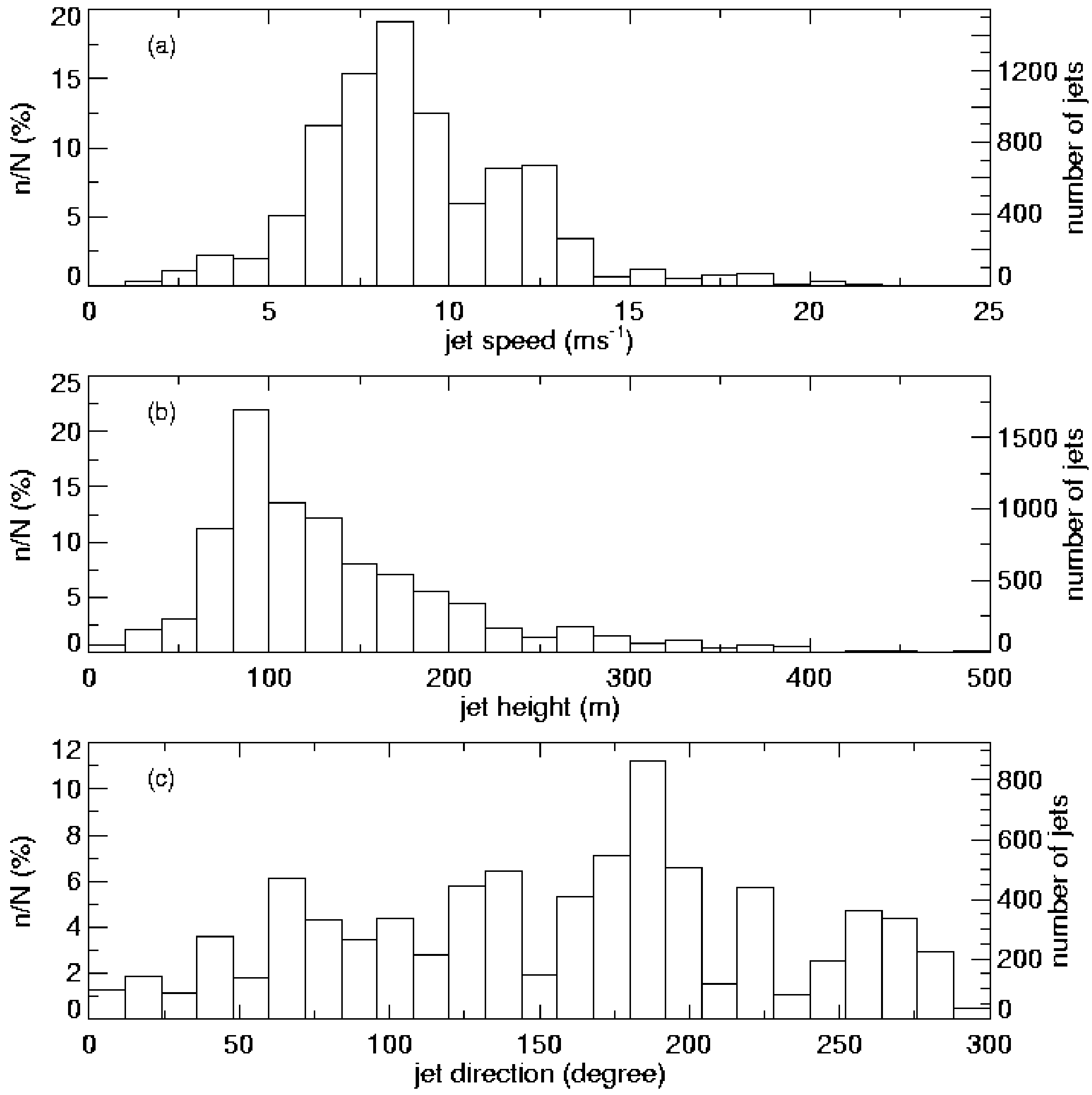

Figure 1. Histograms of jet speed (top panel), height of maximum speed (middle panel), and direction of jet maximum D_X (bottom). Data were compiled from means at 15-min intervals of each quantity, determined from HRDL vertical-slice and VAD-type scans as described in the text. Percentages of occurrences in each bin are shown along the left vertical axis, and total number of occurrences in each bin is indicated along the right vertical axis (from Banta et al. 2002).

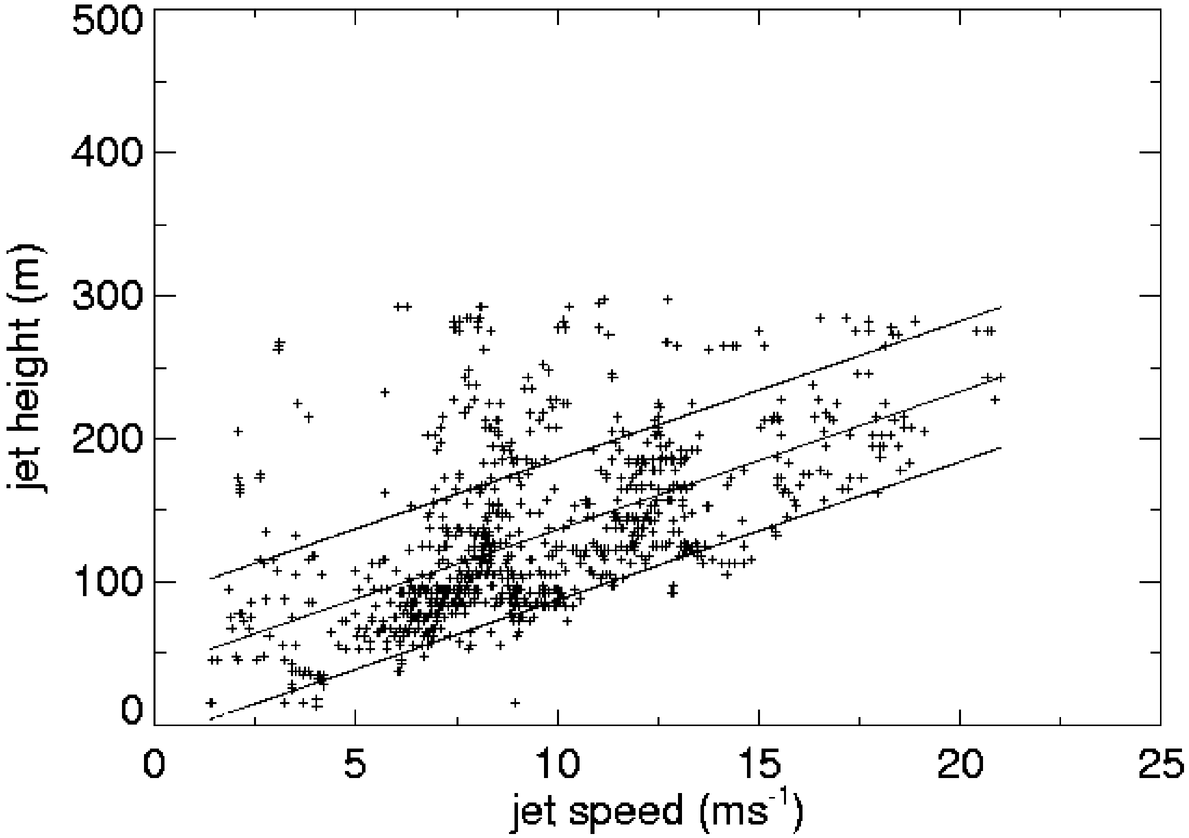

Figure 2. Scatter diagrams of Z_X vs. U_X from the same data as in Fig. 1, taking only those values where $Z_X < 300$ m. Middle line represents best-fit linear regression (R=0.50), and upper and lower lines are for ±1 standard deviation (from Banta et al. 2002).

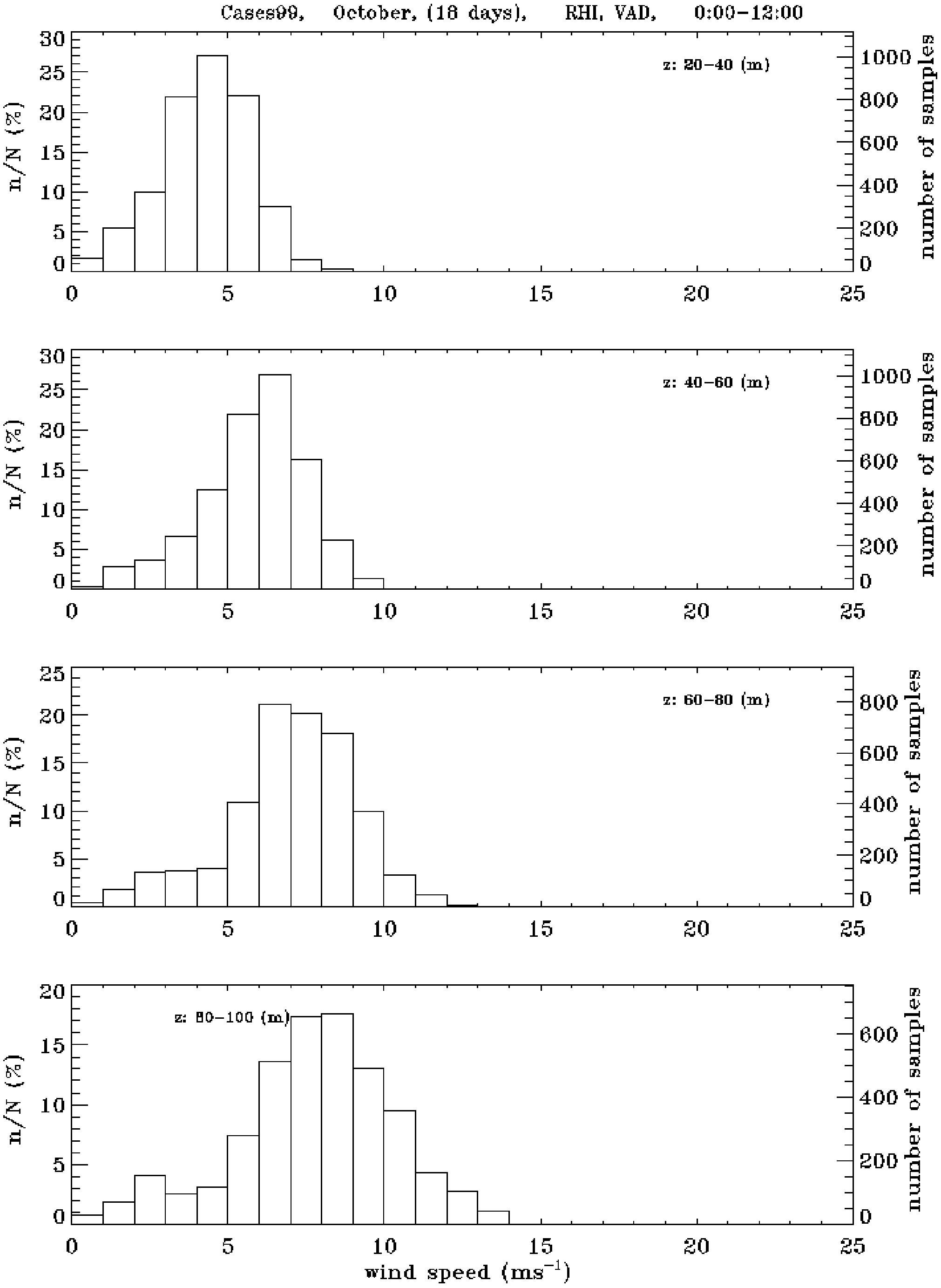

Figure 3. Distributions of wind speed (m s^{-1}) for four 20-m vertical intervals below 100 m AGL. Data are from HRDL-scan data (both vertical-slice and conical) averaged at intervals of 15 min for each night of CASES-99 when HRDL was operating. Vertical axes on left and right are as described for Fig. 1.

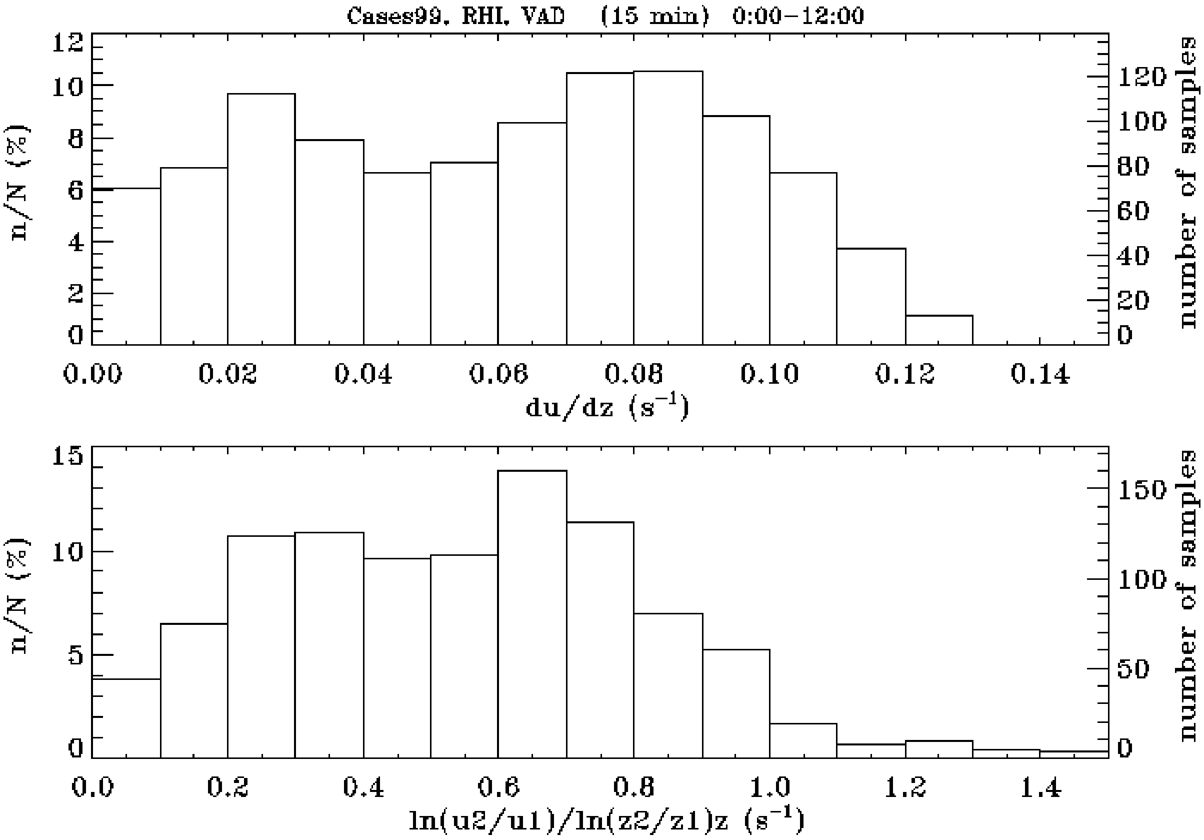

Figure 4. Top panel: Distribution of shear of the streamwise wind component calculated over the interval 47.5 to 77.5 m for vertical-slice scans and over the interval 45 to 75 m for conical (VAD-type) scans. Data are then averaged in time at 15-min intervals. Vertical axes on left and right are as described for Fig.1. Bottom panel: Distribution of the power-law exponent α, computed as shown on the abscissa label.

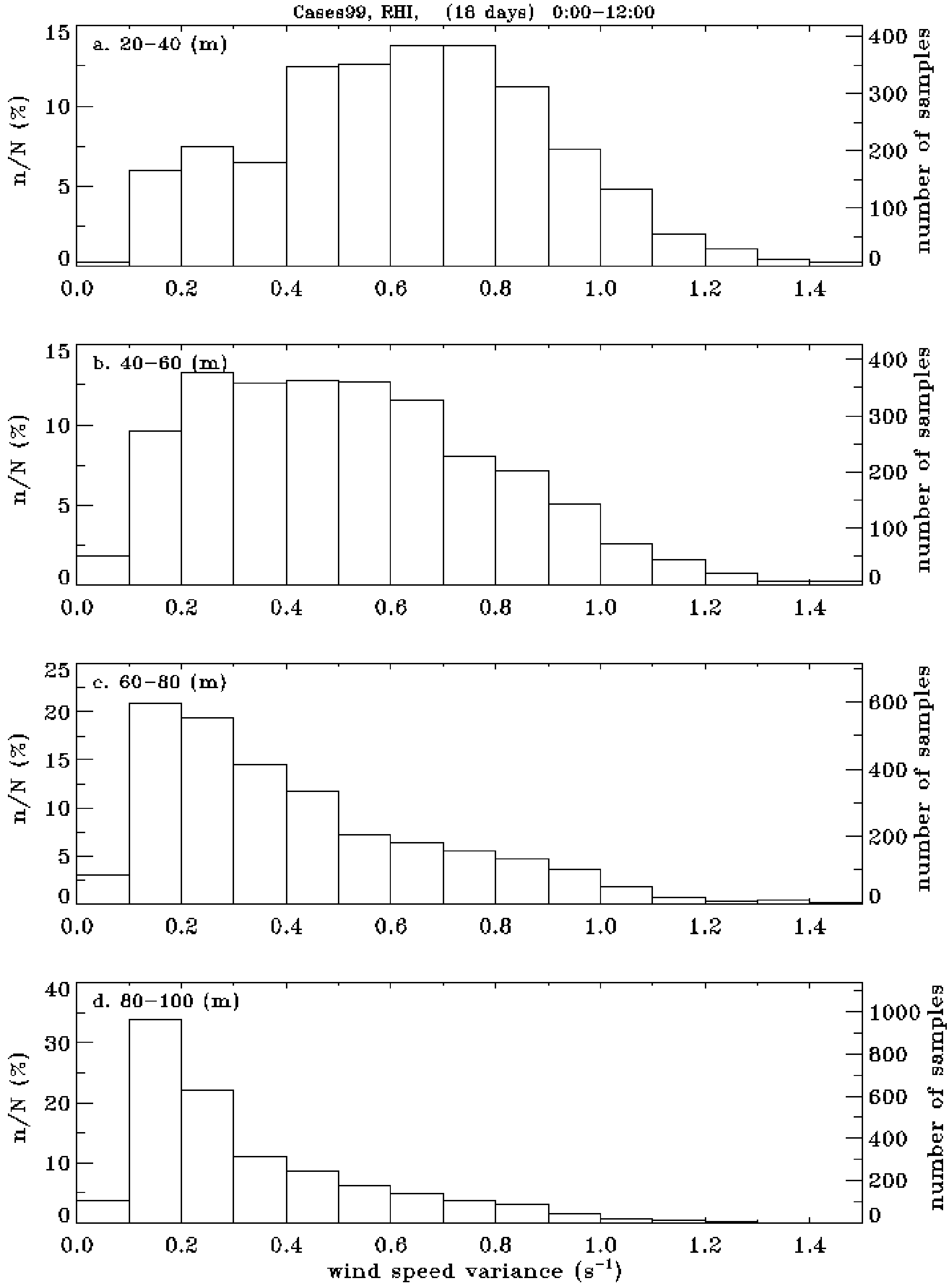

Figure 5. Distributions of streamwise velocity variances ($m^2 s^{-2}$) for four 20-m height intervals below 100 m AGL. Data are from HRDL scan measurements as in Fig. 3, for all HRDL nights. Vertical axes on left and right are as described for Fig. 1.

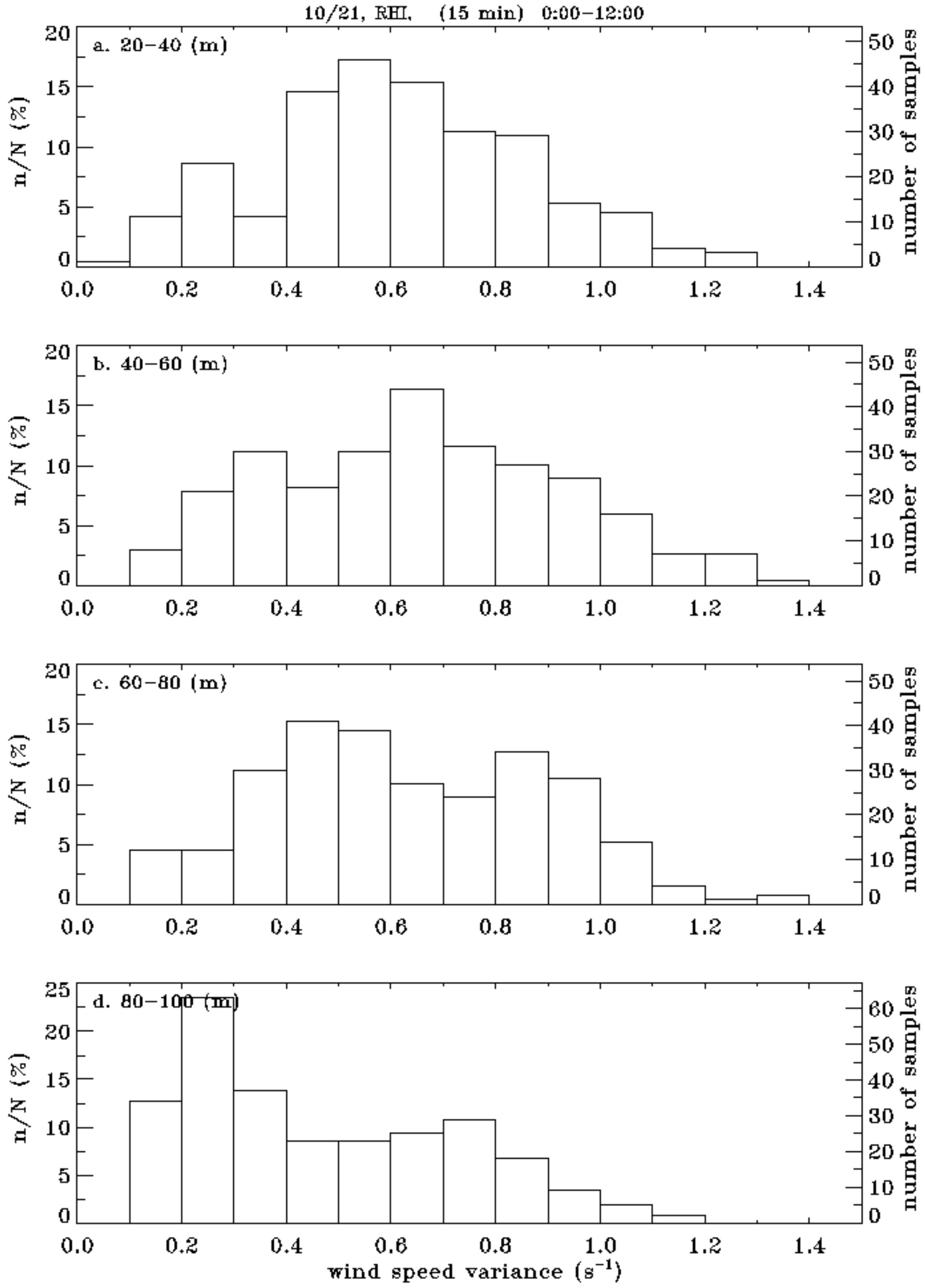

Figure 6a. Distributions of streamwise velocity variances as in Fig. 5 for 21 October 1999.

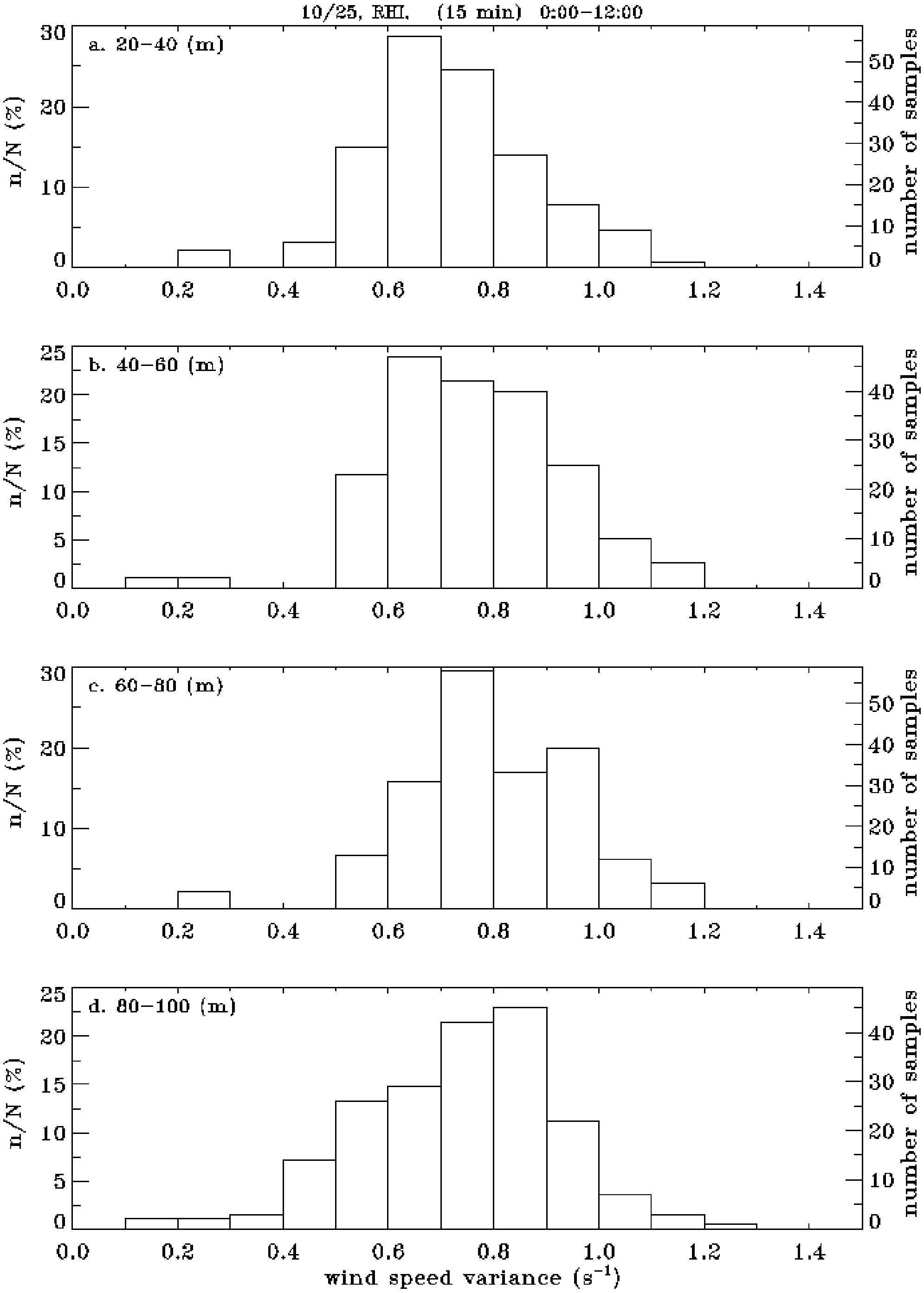

Figure 6b. Distributions of streamwise velocity variances as in Fig. 5 for 25 October 1999.

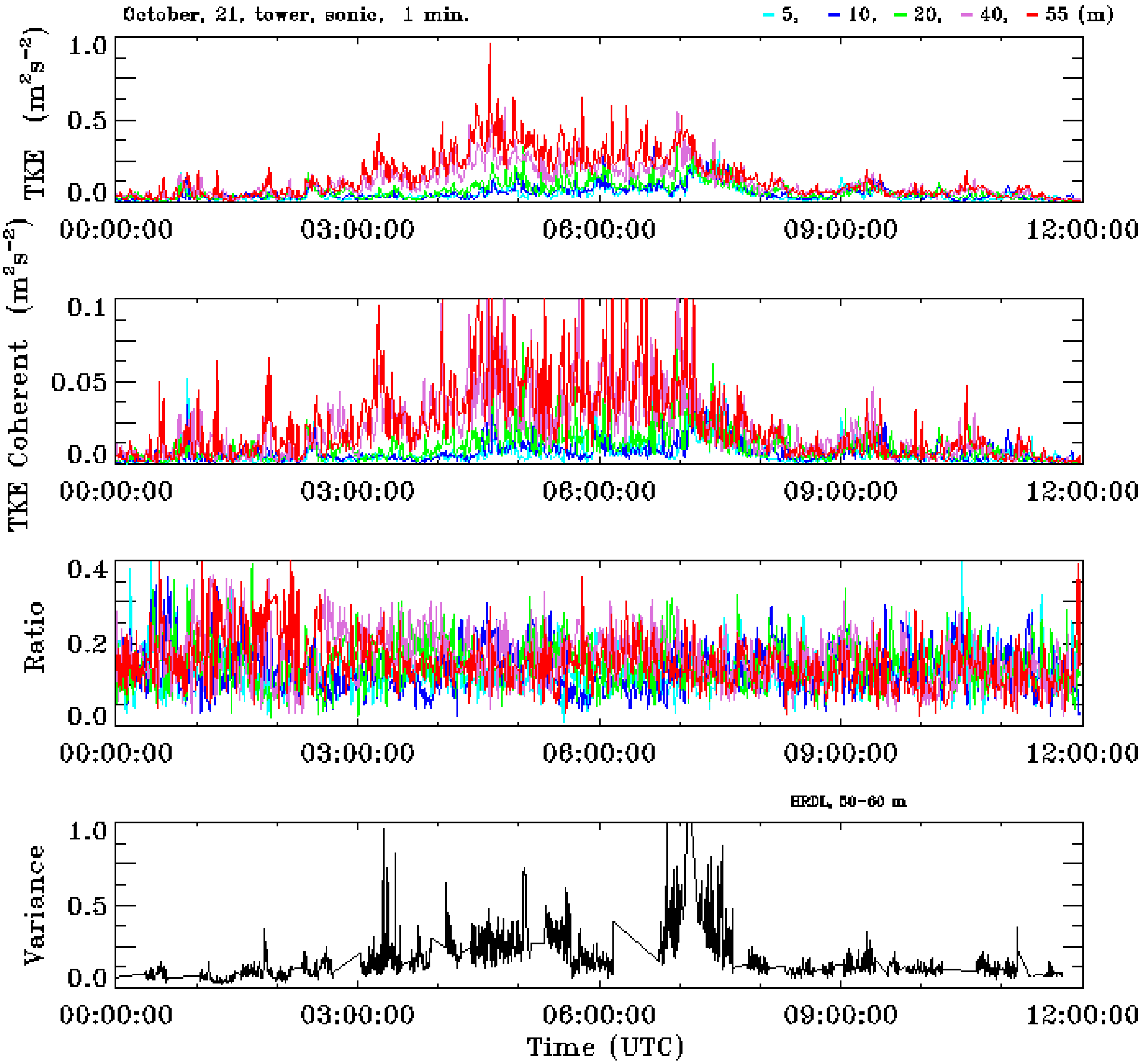

Figure 7. Time series for 21 October 1999 UTC of TKE (top panel), coherent TKE (second panel), and ratio of coherent TKE to TKE (third panel) for five levels for 5 to 55 m on the CASES-99 main tower. Bottom panel shows time series of spatial variance (m^2 s^{-2}) calculated from vertical-slice HRDL scan data, which were repeated at 30-s intervals.

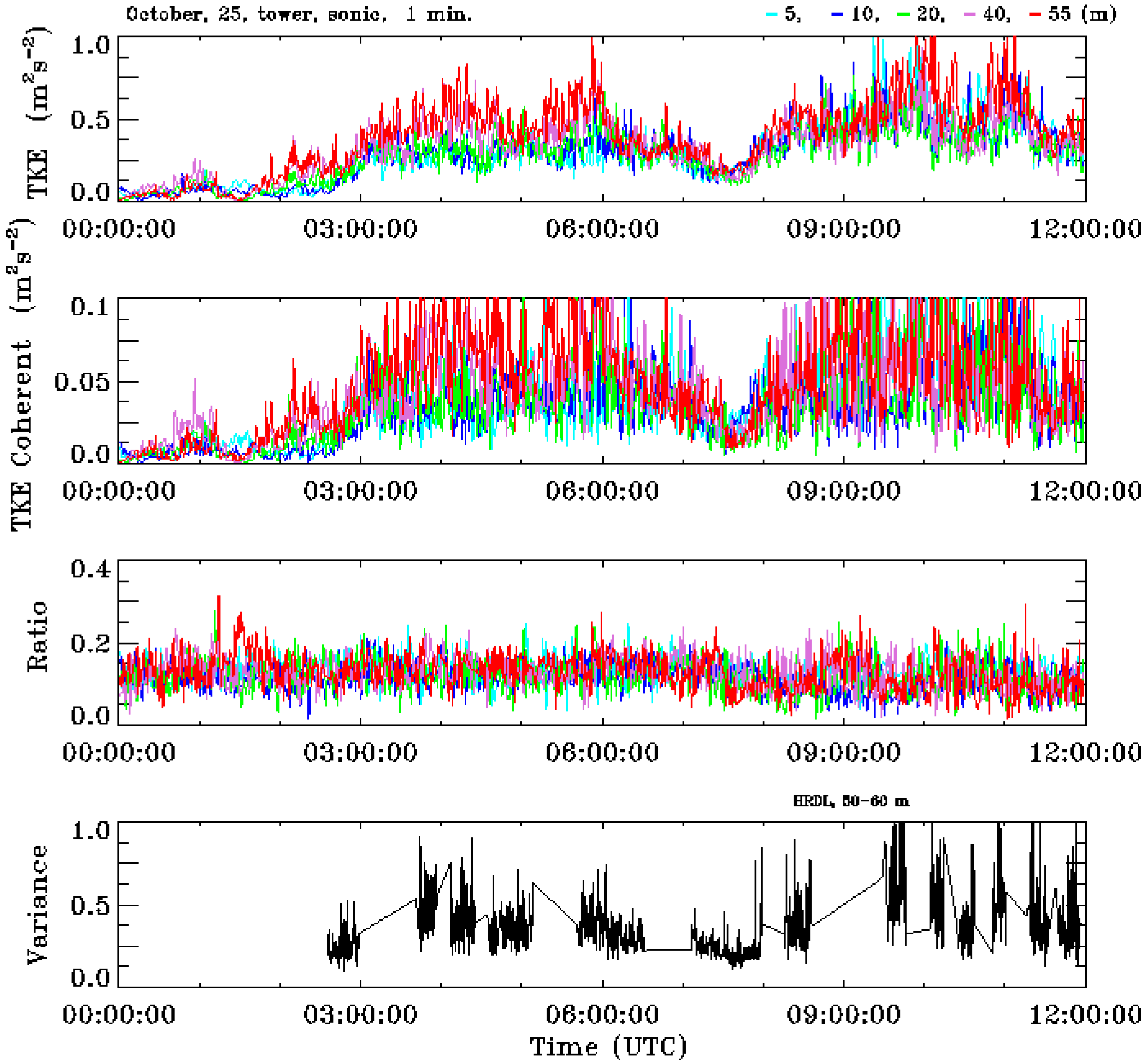

Figure 8. Same as Figure 7 except for 25 October 1999 UTC.

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13. ABSTRACT *(Maximum 200 words)*

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