Inter-comparison of retrieved wind fields from large-eddy simulations and radar measurements in the convective boundary layer

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Abstract. Estimates of the wind retrieved from boundary layer radars are inherently averaged in space and time. Using large eddy simulation (LES) results, we are able to examine to what extent these measurements are representative of the underlying parameters of the convective boundary layer (CBL) and how they are impacted by various averaging methodologies. Comparisons between an LES with real forcing and Boundary Layer Radar (BLR) wind retrievals have been analyzed. Good agreement between the LES winds and those estimated using the BLR is observed. After removing an instrumental bias, an estimate of the probability density function (PDF) and skewness of the radar and LES vertical velocity estimates was calculated as a function of height. The PDFs of vertical velocity and the height profiles of the skewness of vertical velocity exhibit good agreement for both the LES and BLR calculations and have the expected canonical structure.

1. Introduction

Three-dimensional virtual radar wind retrievals based on numerical large-eddy simulations (LES) have been previously obtained in a Multi-Radar Experiment (MRE) described in [1]. Five virtual boundary layer radars (BLRs) were equidistantly spaced within the LES domain (see Section 3). These radars were directed at sampling volumes located at different heights. The retrievals at each height were then estimated every minute and were further used to evaluate turbulence parameters. Although the obtained wind estimates provided satisfactory agreement with those from the LES, they were obtained for an idealized five-radar configuration. A more realistic setup discussed in this study is realized by using a single radar pointing in three non-coplanar directions. The three wind components are obtained employing the Doppler beam swinging (DBS) technique [2]. Two convective boundary layer (CBL) cases are considered. The first is an idealized case of sheared CBL [1; 3–5], for which spaced averaged radial velocity estimates from a virtual BLR are obtained every second. These estimates are compared with radial velocities from the LES. Because estimates of radial velocity every second are not common, a study of different time-averaging intervals is conducted to determine the minimum average time required

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for spaced and time averages estimates from radar and time averages from LES to converge. The second case is a CBL with realistic environmental forcing [6], simulated over 12-hr interval. Realistic forcing is simulated through the incorporation into LES of environmental soundings, observed surface flux data, and geostrophic wind forcing. Numerical data for this case are compared with actual radar estimates of the CBL wind fields.

2. Large Eddy Simulation (LES)

The LES code employed in our study is described in [3] and [4]. This code was extensively tested in comparison with several other representative LES codes and with experimental data for clear CBLs with and without wind shear. The code was found to confidently reproduce turbulence structure for a broad variety of flow regimes observed in the clear CBL. The LES setup used for the idealized CBL case is described in [1; 5]. In addition, a more realistic CBL case observed at the Southern Great Plains Atmospheric Radiation Measurement Climate Research Facility (SGP ACRF) in Lamont, OK, beginning 11:29 UTC on 8 June 2007 is considered. The LES setup for this case, described in [6], uses SGP ACRF soundings along with external data retrieved from a large scale atmospheric model. Examples of instantaneous LES fields for realistic CBL case are presented in Figure 1.

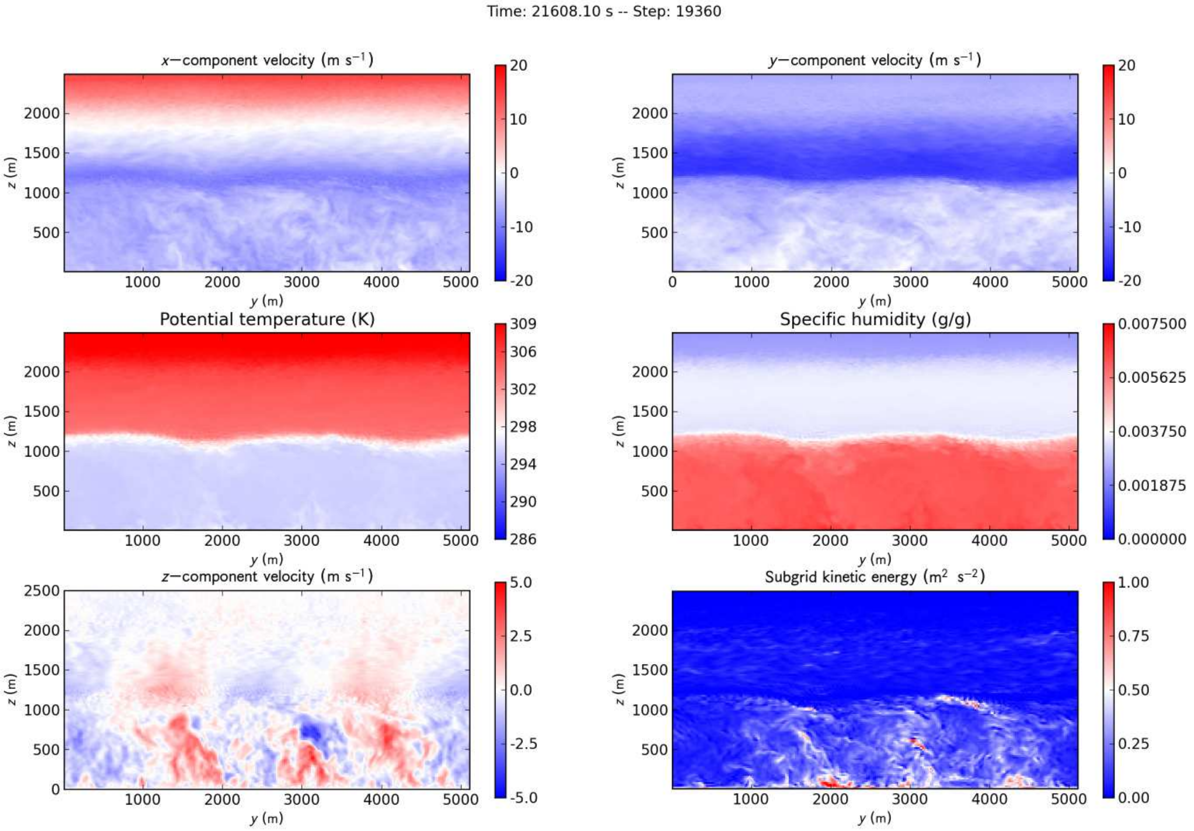

Figure 1. Examples of LES fields in the sub-domain of the radar simulator. Top-left: zonal wind. Top-right: meridional wind. Middle-left: potential temperature. Middle-right: specific humidity. Bottom-left: vertical wind. Bottom-right: sub-grid kinetic energy. All data presented refer to the same single realization in time (one LES time step).

3. LES-Based Radar Simulation

The method to create the simulated radar signals within the LES fields is described in [5] and is based on the work of [7]. The time-series data for the virtual BLR are compiled by summing the contribution from each LES point within the radar resolution volume. This is determined by the radar pulse width and beam width. The virtual radar is patterned after a Vaisala UHF BLR-LAP3000 and operates at a central frequency of 915 MHz, with a half-power beam width of 9°. It is possible to direct the radar beam vertically or electronically steered 15.5° off-vertical along 4 different azimuth angles: 0°, 90°, 180°, 270°. In the present study, a range resolution of 50 m is used. Additive white Gaussian noise was added to the time-series data with an SNR of 10 dB to produce realistic signals. The three moments are estimated after conventional spectral analysis of the time-series data. The maximum time processed for the idealized case is ∼4.3 hr. The radial velocity retrieved from the first moment of the radar was compared with the radial velocity calculated along a similar radial component within the LES domain (an LES "pencil thin" beam). A comparison of both quantities is presented in Figure 2 where good agreement was found between the two estimates. The time interval of each estimate is 1 s.

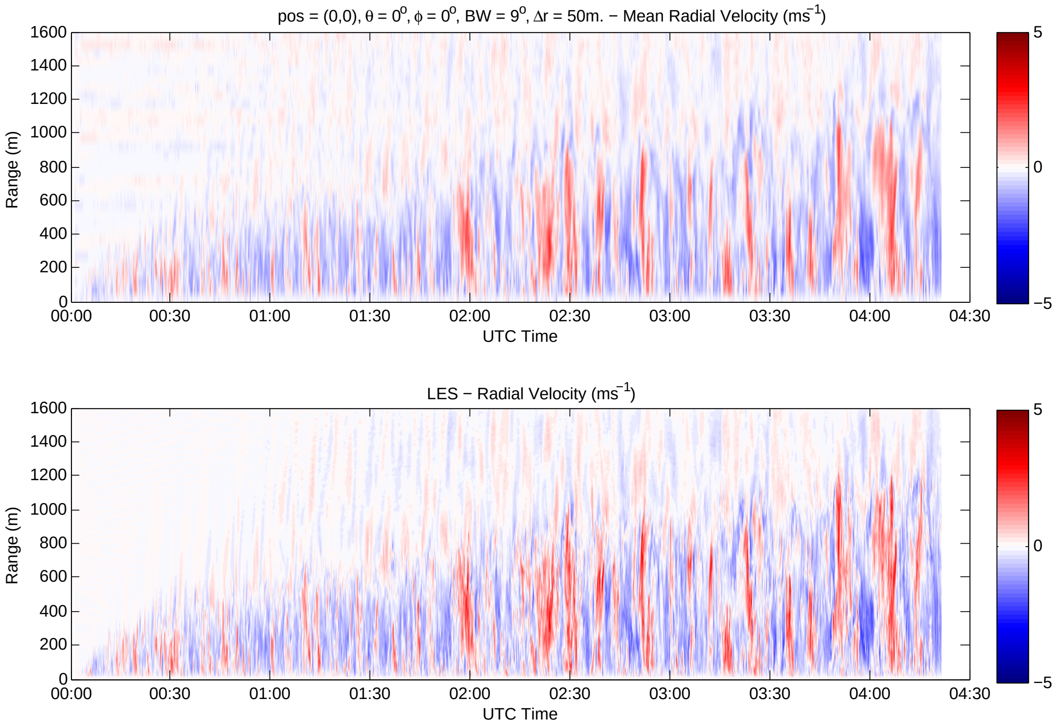

Figure 2. Comparison of the radial velocity retrieved from the virtual BLR (top) and the LES (bottom). The time spacing between subsequent velocity estimates is 1 s.

3.1. Time and Spatial Averaging

Several analyses were made in order to assess the agreement between radial velocities from the radar and LES. As we know, radar estimates are obtained from a time and spatial average within the resolution volume defined by the antenna beamwidth and radar pulse width. The focus of this section is to study the *spatial ergodicity* of the signal and to determine the minimum time average required for both estimates to converge. This averaging time is dependent on the mean wind velocity during the analysis period. The LES radial velocities are obtained at every time step (1 s). However, it is not realistic to obtain radar estimates every second; in the present study, wind velocity estimates are obtained every 12 min or more. Averaged radial velocity estimates from the radar are obtained by first averaging a number of spectra and then calculating the moments. LES profiles are obtained by temporal averaging of the velocity fields directly over a corresponding interval of time. Different time averaging periods have been employed during this study (see Figure 3). As can be observed the correlation coefficient (ρ) increases as the averaging period increases, reaching its maxima at 30 s ($\rho = 0.93$). After 120 s ($\rho = 0.92$) the correlation coefficient begins to decrease indicating a lack of statistical stationary. The peak in the correlation curve corresponds to the time required for atmospheric parcels to be advected through the radar sampling volume at a height of 1000 m and for the prescribed wind speed of 5 m s^{-1} [1; 5]. As in all averaging schemes of real data, a trade-off exists between temporal averaging and stationarity.

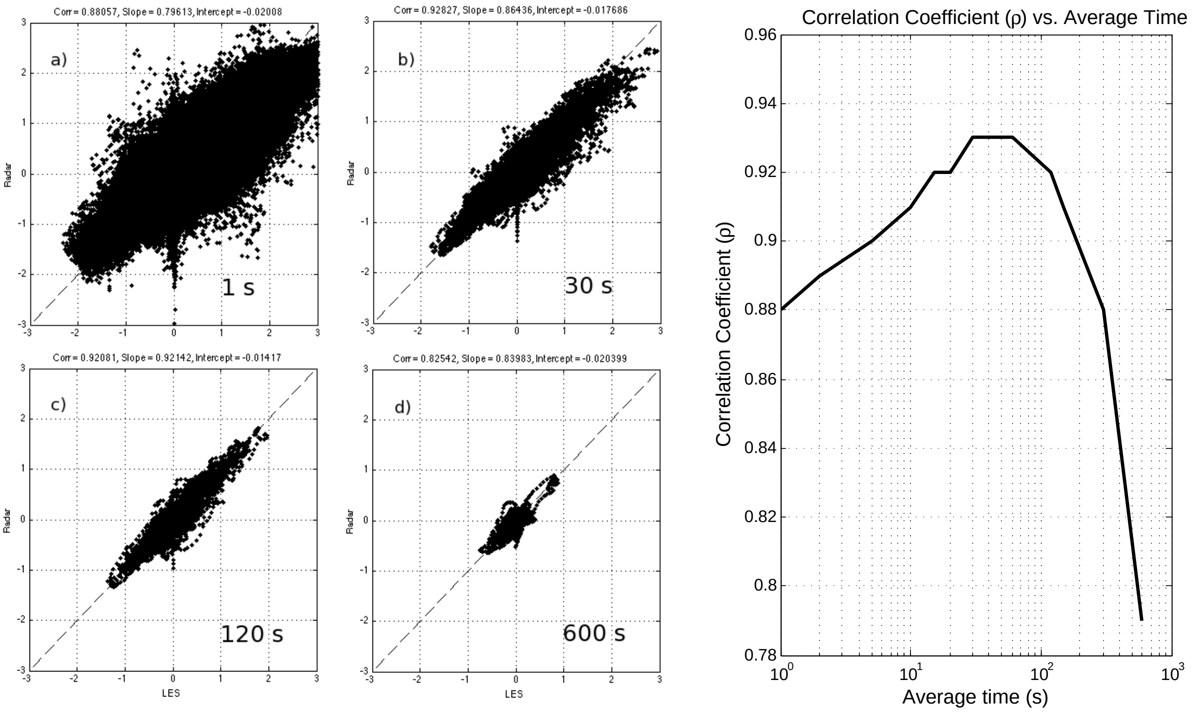

Figure 3. Left: scatter diagrams comparing radial velocity estimates from the virtual BLR with radial velocity profiles obtained from the LES at different averaging times: a) 1 s, b) 30 s, c) 120 s, and d) 600 s. Right: logarithmic plot of correlation coefficient (ρ) vs. averaged time. After 120 s, the correlation coefficient ρ has a value of 0.92, which indicates that the time required for the signal to be *spatially ergodic* has been reached

4. Data Analysis

Data in the following sections are from the realistic LES case, simulating CBL growth on 8 June 2007 at the SGP ACRF [6]. Approximately 11 hr of this 12-hr simulation are used in the analysis. In this case, data were output in slices through the center of the LES domain in the zonal and meridional directions. Radial velocities were then calculated from the LES slices pointing vertically and at 15.5° zenith angle in the four orthogonal directions. These data were used later to estimate the wind components using DBS.

In order to obtain fair comparisons with the 915 MHz radar located at the SGP ACRF site, the averaging time for the LES data was chosen to be 12 min. The mean wind components were estimated from these 12-min averages. For each of the wind components, four quantities were analyzed: DBS values of the radial velocities from the LES (LES$_{DBS}$), output velocities along a vertical profile at the center the LES domain (LES$_{point}$), averaged LES value over beam directions (LES$_{avg}$), DBS estimates from the SGP ACRF radar (Radar$_{ARM}$). Results for the three wind components are presented in Figures 4 (zonal), 5 (meridional), and 6 (vertical).

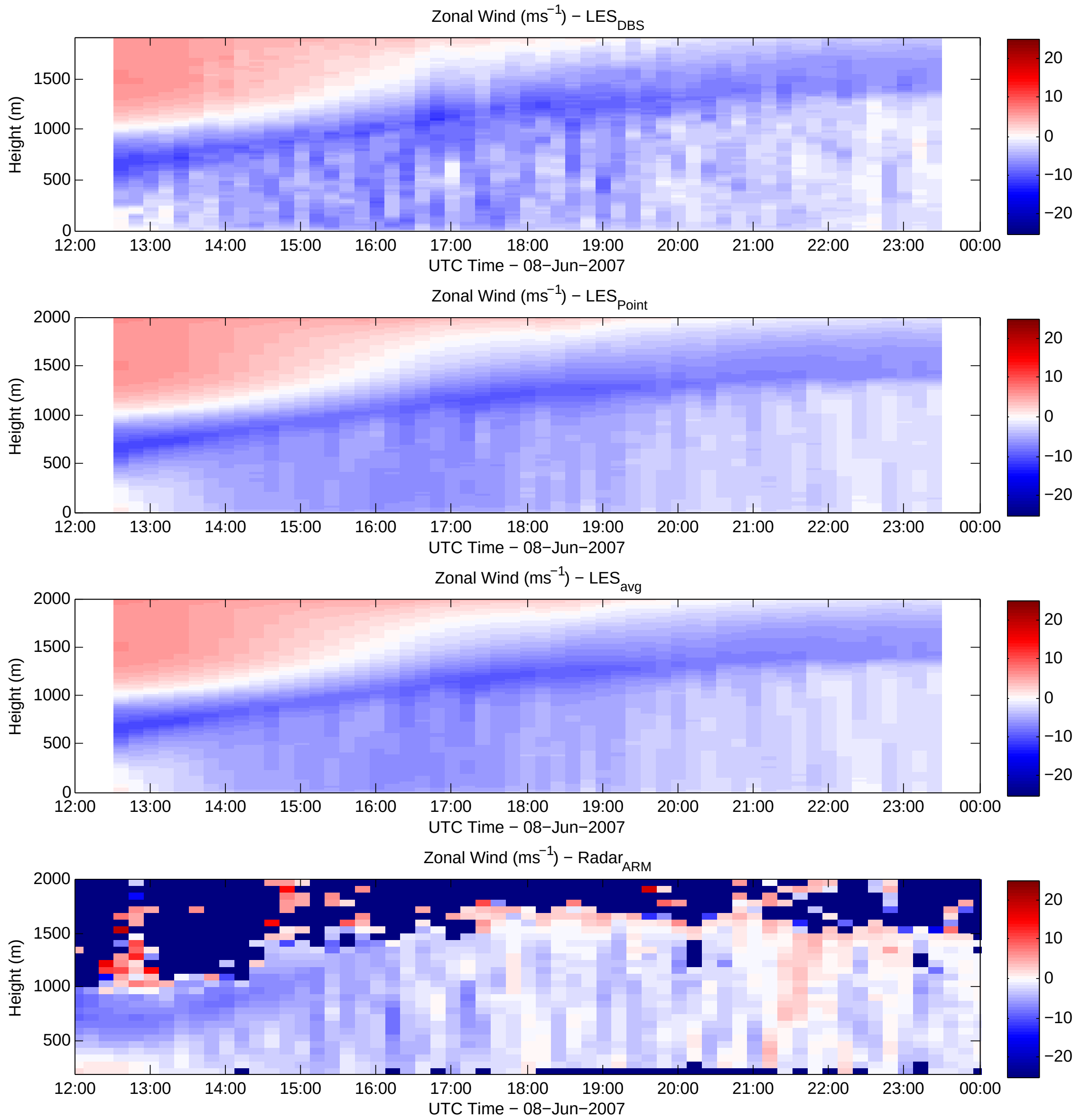

Figure 4. Zonal Wind retrievals averaged every 12 min. Top: LES-DBS. Middle-top: LES-Profile at center of domain. Middle-bottom: spatially averaged profile including the five LES-DBS beams. Bottom: DBS estimates from the SGP ACRF radar.

To obtain the LES$_{DBS}$ values, the following procedure was used. First, the radial velocities from the LES were averaged every 20 s to emulate the dwell time from the radar. Second, velocity samples were taken every 6 min, corresponding to the time required for the radar to return to the same beam position within one DBS cycle. Third, the velocities were averaged

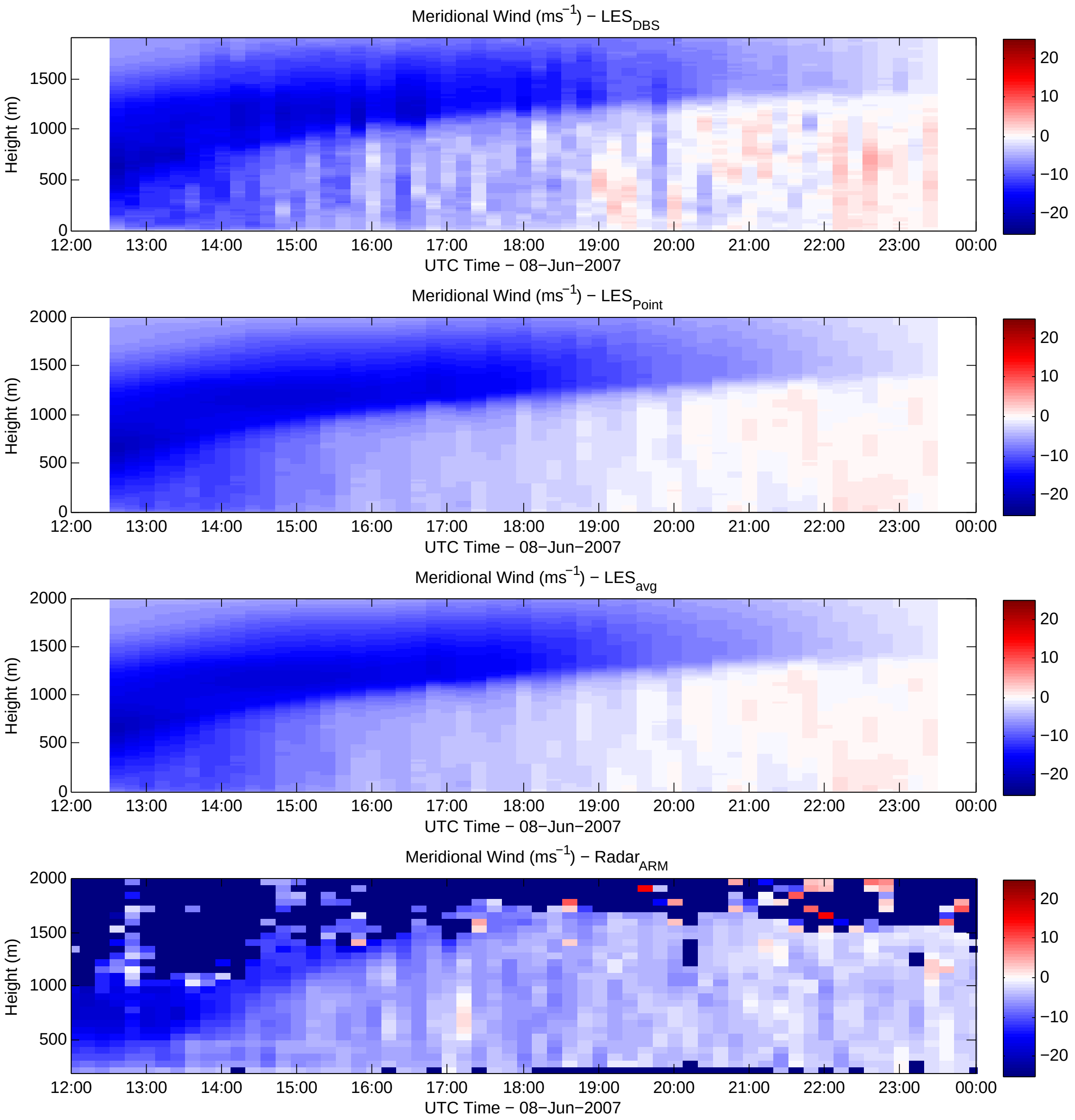

Figure 5. Meridional Wind retrievals averaged every 12 min. Top: LES-DBS. Middle-top: LES-Profile at center of domain. Middle-bottom: spatially averaged profile including the five LES-DBS beams. Bottom: DBS estimates from the SGP ACRF radar.

over 12-min periods representing the DBS sampling time. Finally, DBS was used to retrieve all three wind components. For LES$_{point}$ and LES$_{avg}$, LES data with 10 s increments were averaged in time to obtain 12 min estimates used in the comparisons. Radial velocities from the radar were averaged over the same time period.

Time-averaged wind profiles obtained by LES$_{point}$ and LES$_{avg}$ methods, qualitatively appear similar. This suggests that our earlier assumption of ergodicity is appropriate for this case. Therefore, in further comparisons, only the winds from LES$_{point}$ are used. The estimates from LES$_{DBS}$ in this realistic case do not appear as smooth as those from the idealized case. In general, the simulated wind fields from the LES realistic case [6] agree rather well with the

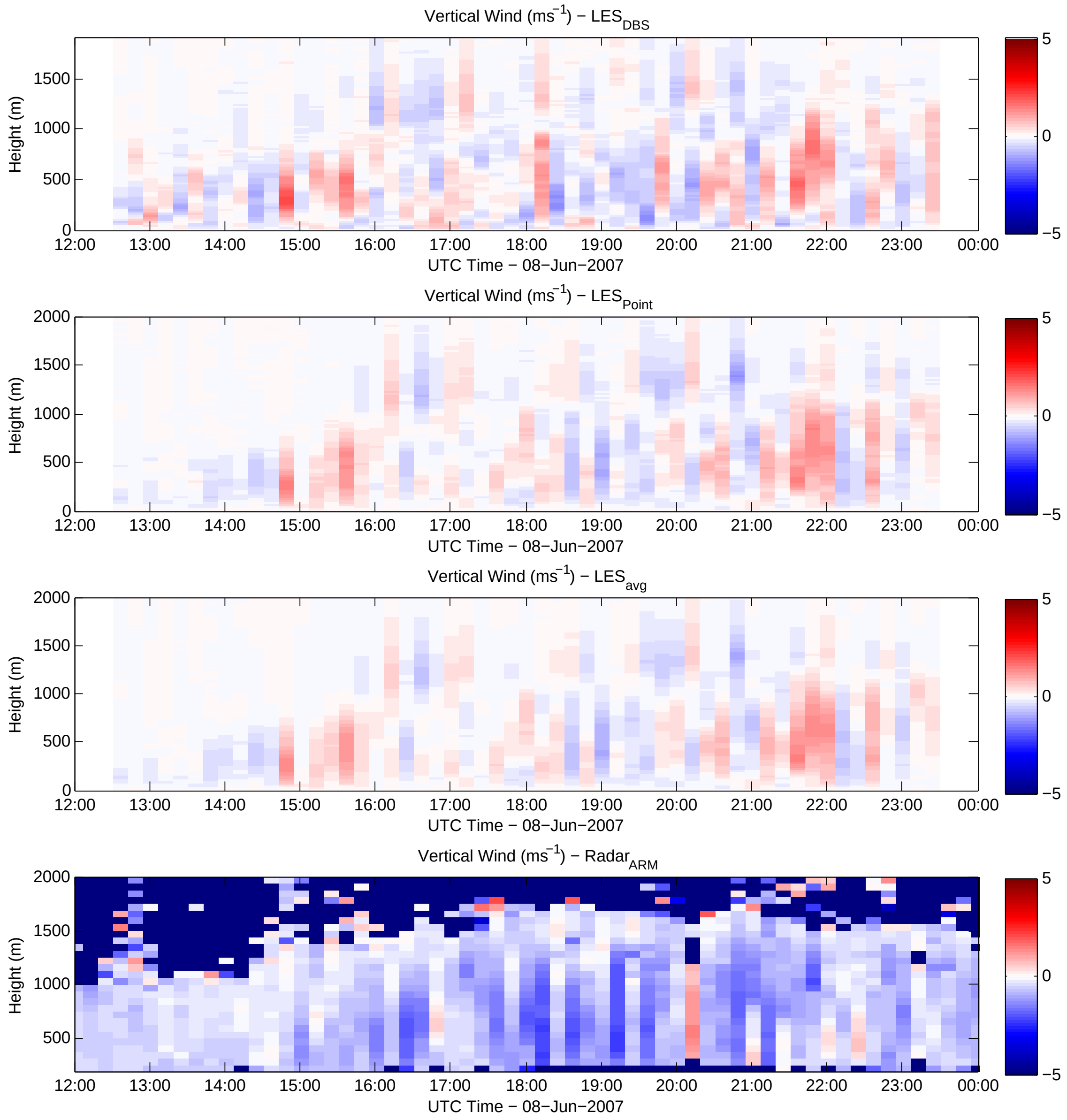

Figure 6. Vertical Wind retrievals averaged every 12 min. Top: LES-DBS. Middle-top: LES-Profile at center of domain. Middle-bottom: spatially averaged profile including the five LES-DBS beams. Bottom: DBS estimates from the SGP ACRF radar.

radar estimates. The same agreement can also be observed in the zonal and meridional winds at $\sim$530 m (see Figure 7). In addition to the LES comparisons, sounding data for 12z, 18z, and 0z are also presented in the same figure. These results complement the comparison of the structure parameter of refractivity (C_n^2) presented in [6].

As can be observed in Figures 6 and 7, radar estimates of vertical velocity do not compare well with the estimates obtained from the LES. A negative bias in vertical velocity can be observed in the lower panel of Figure 7. The bias has a maximum of approximately -1 m s^{-1} and varies over the observation time; suggesting it is not the result of a constant offset error. Presently, the cause of this bias has not been determined; however, the bias is likely due to a slight error in

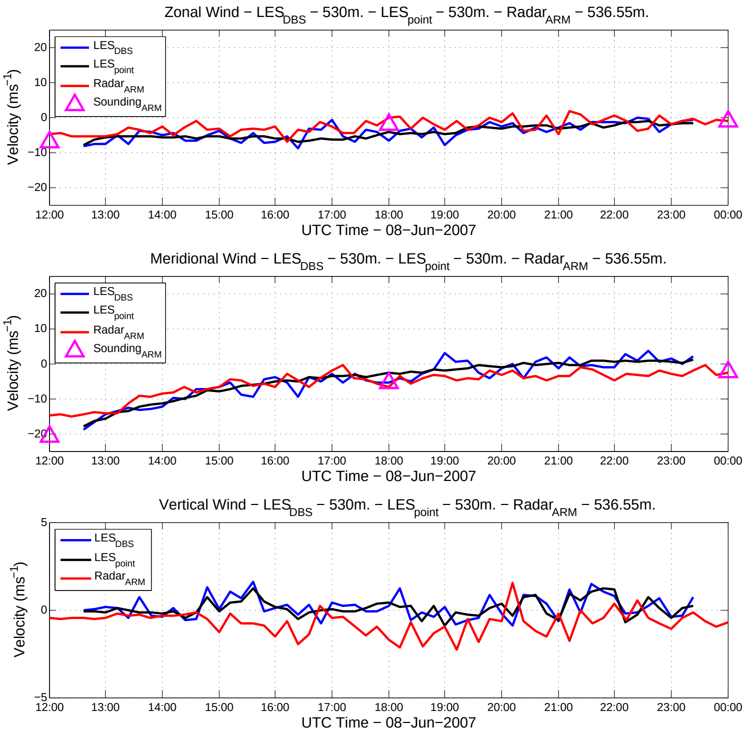

Figure 7. Wind Comparison from the LES$_{DBS}$, LES$_{point}$, Radar$_{ARM}$, and a sounding (launched at three different times: 12z, 18z, and 0z) at ∼530 m. Top: zonal wind. Middle: meridional wind. Bottom: vertical velocity. Vertical velocity from the radar show a negative bias which is not constant over the observation time.

the zenith pointing angle. The zonal and meridional components of the winds are on the order of tens of m s^{-1}, so they would not be significantly affected by the proposed zenith angle error. Furthermore, the radar retrieved horizontal wind estimates are consistent with the sounding data. However, a pointing error could cause a component of the horizontal wind to erroneously be reflected in the vertical velocity estimates and the effects would be expected to vary in time and altitude. This is being further investigated.

The probability density function (PDF) of all the vertical velocities of the LES$_{DBS}$, LES$_{point}$, and Radar$_{ARM}$ are compared in Figure 8. The mean vertical velocity sampled over a sufficiently long period of time is expected to approach zero. However, the mean vertical velocity from the radar has a bias of ∼-0.65 m s^{-1}. As a first order approximation at correcting for the bias, we have at this point simply removed the bias before performing the PDF calculations. It should be noted that the LES$_{point}$ PDF was calculated without any time averaging scheme, which means the time resolution of ∼10 s was used. This explains the smoothness of the curve as well as the wider velocity range. The floor around $5{\times}10^{-3}$ in the radar data can be attributed to the measurement noise inherently present within the estimates. The PDFs from the three signals agree well. Furthermore, each exhibits a positive skewness. The skewness is indicative of overall structure of the observed velocity patterns [8]: when the skewness is positive, updrafts are narrower and more intense than the surrounding downdrafts.

The height dependence of the vertical velocity skewness in the CBL has been previously analyzed using LES and observations [8] and LES and wind tunnel experiments [9; 10]. Here, we calculate vertical profiles of skewness using vertical velocity data from LES and radar for the actual CBL case of 8 June 2007 applying averaging time of three hours (from 20:00 to 23:00). The

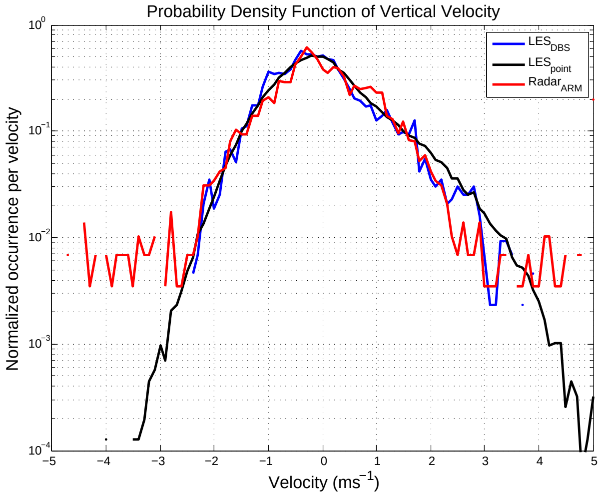

Figure 8. Probability density function of vertical velocity from LES$_{DBS}$, LES$_{point}$, and Radar$_{ARM}$. The bias in the vertical velocity estimates from the radar was removed, which simply shifted the PDF and did not affect the shape. A good agreement is observed among the three quantities. The floor around $5{\times}10^{-3}$ in the radar data can be attributed to the noise inherently present within the estimates.

comparison results are presented in Figure 9. In the main portion of CBL, large scale turbulence structures are represented by narrow, fast updrafts and broader, slower downdrafts, so skewness of the vertical velocity in the mixed-layer is positive. Its grows with height indicates the increase in magnitude and range of vertical positive values towards the CBL top. The Skewness reaches the maximum around the base of the inversion, and then drops to zero in the interior of the inversion layer where the upward component of turbulent motion is in approximate equilibrium with the downward component [10]. The radar estimates of skewness agree reasonable well with the LES estimates and are similar to those presented in [9; 10].

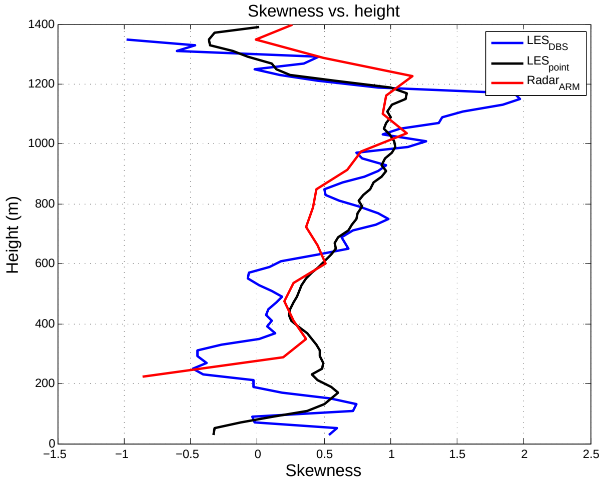

Figure 9. Skewness as a function of height for the vertical velocity between the 20:00 and 23:00 for the case of 8 June 2007. The skewness of the vertical velocity in the mixed-layer is mainly positive and grow with height.

5. Conclusions

Comparisons of the virtual BLR's radial velocities with LES velocity estimates were presented. The minimum averaging time required for the signal to approximate *spatial ergodicity* was estimated to be approximately between 30 s and 120 s for the idealized CBL case. Longer averaging produced decorrelation from the breakdown of statistical stationarity in the signal. Realistic comparisons between LES simulated velocities and actual radar data were also shown for the case of 8 June 2007. Good qualitative agreement was found in the zonal and meridional wind fields retrieved from the radar and estimated with LES. The vertical wind comparisons were studied in more detail after noticing an initial disagreement between LES and radar data. This disagreement between estimates may be attributed to an instrument error; although, further study is necessary to confirm this. After removing the bias, the PDFs from the radar and realistic LES cases were in agreement. The skewness of the vertical velocity has been analyzed as a function of height. In the well-mixed portion of the CBL is mainly positive and grows with height. The promising agreement between wind retrievals from LES and the radar encourages us to continue our research to further characterize the CBL wind and turbulent fields through a combination of both techniques.

Acknowledgments

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