NOTES AND CORRESPONDENCE

Local Structure Parameters of Temperature and Humidity in the Entrainment-Drying Convective Boundary Layer: A Large-Eddy Simulation Analysis

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ABSTRACT

Many wave propagation applications depend on the local, instantaneous structure parameters of humidity ($C_{2q}$) and of potential temperature ($C_{2\theta}$). This study uses a large-eddy simulation to explore and compare the variability of $C_{2q}$ and $C_{2\theta}$ in the shearless, entrainment-drying convective boundary layer (CBL). The predicted horizontal mean profiles of these quantities are shown to agree with corresponding observations. The results in the bulk CBL suggest that the largest $C_{2q}$ occur in the entrained tropospheric air whereas the largest $C_{2\theta}$ are within the convective plumes. There are distinct correlations between the vertical velocity and $C_{2q}$ and between the vertical velocity and $C_{2\theta}$. It is shown that these correlations can significantly contribute to the mean vertical velocity biases measured from radars and sodars. A physical interpretation for these contributions is offered in terms of the CBL dynamics.

1. Introduction

The small-scale fluctuations of the absolute temperature $T$ and of the specific humidity $q$ are known to perturb the outdoor propagation of electromagnetic and acoustic waves (Tatarski 1961; Ostashev 1994). To understand these perturbations, it is usually assumed that the relevant atmospheric fluctuations are in an elementary scattering volume of size $r$, on the order of 10 m, in which the turbulence is locally homogeneous and isotropic. This assumption defines the inertial-convective range of turbulence. Under this assumption, the wave perturbations can be shown to depend on the local, instantaneous structure parameters of $T$ and $q$, hereinafter denoted $C_{T,q}$, respectively, and on the local temperature–humidity structure parameter $C_{T,q}$ (Tatarski 1961; Feltier and Wyngaard 1995; Pollard et al. 2000; Cheinet and Siebesma 2009).

As a result, the variability of these local structure parameters in the boundary layer affects a wide range of activities in outdoor optics and acoustics [e.g., see the review by Cheinet and Siebesma (2009)]. This variability can be documented through in situ sensors (Druilhet et al. 1983; Wyngaard and LeMone 1980). Sodars and UHF radars also measure the acoustic and electromagnetic reflectivities, which are proportional to $C_{n,r}$, the local structure parameter of the refractive index $n$ (Thomson et al. 1978; Ottersten 1969). In the monostatic configuration, $C_{n,r}$ depends on $C_{T,q}$, $C_{q,r}$, and $C_{T,q,r}$. The formulas of Ostashev (1994) and Pollard et al. (2000) lead to

\[
\begin{align*}
\text{acoustics: } C_{n,r}^2 &\approx C_{T,q}^2 + 4.11 \times 10^2 C_{T,q,r}^2 + 4.26 \times 10^4 C_{q,r}^2, \\
\text{electromagnetism: } C_{n,r}^2 &\approx C_{q,r}^2 - 2.57 \times 10^{-4} C_{T,q,r}^2 + 1.64 \times 10^{-8} C_{T,q}^2.
\end{align*}
\] (1)

The first rhs terms in Eq. (1) generally have a dominant contribution.

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Peltier and Wyngaard 1995; Muschinski et al. 1999; Pollard et al. 2000; Scipion et al. 2008). The recent LES study by Cheinet and Siebesma (2009, hereinafter CS) investigates the variability of $C_{\theta,r}$ in the dry CBL. (Hereinafter the structure parameters of potential temperature $\theta$ and of $T$ are approximated to be equal.) They find that $C_{\theta,r}$ is larger in the convective plumes and correlates to the vertical velocity. Sodars show the same correlation (Peters et al. 1998; Petenko and Shurygin 1999). None of these LES studies has specifically compared the variability of $C_{\theta,r}^2$ and $C_{\theta,r}^2$ in the same meteorological conditions.

The study presented here investigates the variability of $C_{\theta,r}^2$ and $C_{\theta,r}^2$ in the entraining CBL and the implications of this variability for radar and sodar measurements. It is organized as follows: Section 2 presents the method used to diagnose the local, instantaneous structure parameters in our LES. Section 3 analyzes the variability of the predicted local structure parameters in a prototype entraining CBL. Section 4 discusses the implications of our results for the radar and sodar measurements of the mean vertical velocity. The last section summarizes the results.

2. Structure parameters from LES

We recall our method to derive the local, instantaneous structure parameters from LES fields. Details on this method can be found in CS. For LES-generated structure parameters, the characteristic scale $r$ is the LES grid spacing $\Delta$. Let us denote the dissipation rate of the subgrid variance of a resolved scalar field $s$ as $\varepsilon_{s,\Delta}$ and the dissipation rate of the subgrid turbulent kinetic energy (TKE) as $\varepsilon_{\text{TKE},\Delta}$. Following the methods of Peltier and Wyngaard (1995), Pollard et al. (2000), and CS, we calculate the local, instantaneous structure parameter of $s$ from

$$C_{s,\Delta}^2 = \frac{\beta_{1,\text{loc}}}{0.25} \varepsilon_{s,\Delta}^{-1/3} \varepsilon_{\text{TKE},\Delta}^{-1/3},$$

where $\beta_{1,\text{loc}}$ is the Obukhov–Corrsin constant, set to $\beta_{1,\text{loc}} = 0.4$.

Our LES uses a standard parameterization for $\varepsilon_{\text{TKE},\Delta}$:

$$\varepsilon_{\text{TKE},\Delta} = A_u \frac{\text{TKE}^{3/2}}{\Delta_c},$$

where $\Delta_c$ is the LES truncation size and $A_u$ is a closure coefficient. The parameterization of $\varepsilon_{s,\Delta}$ follows from the local budget equation between the gradient production and dissipation of the subgrid variance:

$$\varepsilon_{s,\Delta} = 2K_s \left( \frac{\delta s}{\delta x_i} \right)^2,$$

where $K_s = N_s \Delta_c (\text{TKE})^{3/2}$ and $\delta$ denotes a grid differencing. Cheinet and Siebesma (2009) derive the closure coefficients $N_s$ and $A_u$. In our LES configuration, which is the same as in CS, $\Delta_c$ is taken as $\Delta_c = 2.5\Delta$ under locally unstable conditions and depends on TKE and on the Brunt–Väisälä frequency under a locally stable stratification (see also CS). Equations (2) and (4) are easily generalized to derive $C_{\theta,r,\Delta}$ which can take either sign. In that case, the associated dissipation rate is parameterized according to

$$\varepsilon_{\theta,r,\Delta} = 2K_s \left( \frac{\delta \theta}{\delta x_i} \right) \left( \frac{\delta q}{\delta x_i} \right).$$

The set of Eqs. (2)–(5) involves two major assumptions. The first is that the small-scale (subgrid) fluctuations, relevant to our diagnostics, are locally homogeneous and isotropic. This assumption makes turbulence studies more tractable and is a cornerstone in many wave-propagation applications as well as in atmospheric LES (Tatarski 1961; CS). It has been verified to some extent in the inertial-convective range, but it is expected to fail outside this range, so that the above structure parameter derivation may not be used directly with coarse-grid atmospheric models (CS). The second assumption is the first-order closure for the parameterization of the dissipation rates [Eqs. (3)–(5)]. It is evaluated by Peltier and Wyngaard (1995) in the context of LES diagnostics of structure parameters (see also Pollard et al. 2000; CS show that this second assumption leads to structure parameters diagnostics that are strictly equivalent to a direct spatial differencing of the resolved LES fields, as used in Muschinski et al. (1999) and Scipion et al. (2008).

Thus, our method shares a strong consensus with the previous studies dedicated to structure parameter diagnostics with LES. Another common aspect of the LES predictions of local structure parameters is their limitation very near the surface and in mean stable conditions, because of unresolved motions (CS). For this reason our analysis spans from above the three first (near surface) LES levels to the upper part of the CBL but does not extend above the inversion.

3. Analysis of LES results

a. Case setup and description

We simulate an idealized fair-weather CBL, under quasi-stationary conditions, with no clouds and no large-scale advections—in particular, no geostrophic wind and no vertical divergence. The mean vertical velocity $\bar{\nabla}$ is zero at all heights. Hereinafter, the overbar indicates horizontal averaging over the LES domain. The initial profiles are inspired from the monthly averaged profiles reported
in Cheinet et al. (2005) from daytime observations in summer over the southern Great Plains of the United States. The initial potential temperature and specific humidity gradients are set to 5 K km$^{-1}$ and 0.002 kg kg$^{-1}$ (Fig. 1). The surface temperature and specific humidity are of 300 K and 0.012 kg kg$^{-1}$. The turbulence is driven by the prescribed surface vertical fluxes of temperature (0.15 K m s$^{-1}$), specific humidity (6.1 $\times$ 10$^{-5}$ m s$^{-1}$), and momentum ($-0.073$ m$^2$ s$^{-2}$). The latter accounts for the local shear stress near the surface.

The LES domain is 6 km $\times$ 6 km $\times$ 2.1 km. The model has 201 $\times$ 201 $\times$ 71 grid points, with an isotropic spatial resolution of $\Delta = 30$ m and a time step of 1 s. This setup is comparable to the ones used in previous LES studies of local structure parameters in the CBL (Peltier and Wyngaard 1995; Pollard et al. 2000; CS). A computational trade-off is needed in such studies, between the model domain (large to account for large-scale fluctuations; see below) and the model resolution (small to resolve well the inertial-convective range). Van Dinther (2010) reports that increasing the spatial resolution does not significantly change the structure parameter diagnostics in our LES.

Figures 1a and 1b show the vertical profiles of $\theta$ and $q$ at $t = 10$ 000 s. At that time, the simulated flow has the expected structure of a well-mixed layer capped by an inversion in potential temperature. The mixed-layer height is $Z_i \approx 1000$ m, and the mixed-layer convective velocity scale is $w_c = 1.71$ m s$^{-1}$. The associated mixed-layer scales for the structure parameters are $(C_\theta)_a = 1.28 \times 10^{-11}$ m$^{-2/3}$, $(C_q)_a = 7.7 \times 10^{-5}$ K$^2$ m$^{-2/3}$, and $(C_{\theta,q})_a = [(C_\theta)_a(C_q)_a]^{1/2}$. The resolved fluxes of sensible and latent heat decrease very near the surface, as the subgrid-flux contributions are nonnegligible. As apparent from the linear flux profiles in the mixed layer (Figs. 1c,d), a quasi-steady state is reached. The ratio between the buoyancy fluxes at the top of the mixed layer and at the surface is $-0.19$, a typical value in convective boundary layers.

The latent heat flux (Fig. 1d) increases with height in the CBL. The humidity at a given level strongly increases as the level is incorporated in the rising CBL (moisture flux convergence). Once in the CBL, the same level experiences a progressive drying (moisture flux divergence). According to Mahrt (1991), this feature is typical of an entrainment-drying CBL, in which dry entrained air penetrates deeply. Mahrt argues that this causes a negative moisture skewness in the lower CBL (see also Couvreux et al. 2007). This result will also be noted in our simulation (see below in Figs. 4c,d). For these reasons, hereinafter our results are compared with observations in the entrainment-drying CBL.

b. Local structure parameters

Figure 2 shows that $C_{\theta\Delta}$ and $C_{q\Delta}$ both decrease with height in the lower boundary layer and increase near the inversion (nota bene: the logarithm is in base 10 in all figures). Our predictions show a satisfactory qualitative and quantitative agreement with the measurements of Druilhet et al. (1983), which also exhibit the features
noted by Mahrt (1991) in the entrainment-drying CBL. Cheinet and Siebesma (2009) report that LES tends to underestimate $C_{q,\Delta}$, which is also apparent in Fig. 2. They attribute this underestimation to the LES spatial filtering of subgrid scales and point that it should not alter the predicted variability of the structure parameters. Wyngaard and LeMone (1980) report that $C_{\theta,\Delta}$ changes from positive to negative in the mid-CBL, a feature that our LES also shows.

The height of minimum $C_{q,\Delta}$ (of $Z = 0.65Z_i$ in our LES) is higher that the height of minimum $C_{q,\Delta}$, which is also apparent in Fig. 2. The observations also show this feature. Fairall (1987) proposes a model of the mean structure parameter $C_{q,\Delta}$ of a scalar $s$, in terms of the ratio $R_s$ of the entrainment flux to the surface flux. With our values of $R_s$ and $R_{\theta}$, his model predicts that the heights of minimum $C_{q,\Delta}$ and $C_{\theta,\Delta}$ are $0.35Z_i$ and $0.65Z_i$, respectively. These estimates are consistent with our predictions.

Figure 3 shows the horizontal variability of $C_{q,\Delta}$ and $C_{\theta,\Delta}$ in the mid-CBL. Appropriate physical thresholds are shown to identify the dry areas (Fig. 3a) and the warm areas (Fig. 3b). The largest $C_{q,\Delta}$ and $C_{\theta,\Delta}$ are correlated with $-q'$ and $\theta'$ (see also CS). Here the prime denotes a local deviation from the horizontal mean. The largest $C_{q,\Delta}$ and $C_{\theta,\Delta}$ occur in distinct air entities.

Well-developed CBLs are expected to feature some mesoscale dynamics of the humidity field (e.g., Jonker et al. 1999; de Roode et al. 2004). In that respect, our simulation does not appear to be affected by the domain size, as it shows about 10 characteristic dry-air structures in the mid-CBL at the time of analysis. To confirm this, we have realized an LES run with the same spatial resolution and a domain of $301 \times 301 \times 71$ grid points, that is, more than 2 times that in our reference run. The structure parameters statistics in this large-domain simulation are very comparable to our reference results. The relatively short period of integration is expected to explain this result; simulations over longer periods may require larger computational domains.

As argued by, for example, Berg and Stull (2004), $q'$ and $\theta'$ are indicative of the air origin, for $q$ and $\theta$ are conserved variables in the CBL. For example, in the $(q', \theta')$ plane, the tropospheric (drier, warmer) air shows in quadrant 4 (Fig. 4c), whereas surface-layer air (moister, warmer) shows in quadrant 1. The variability of the structure parameters is now investigated on this basis.

Figures 4a and 4b show the distribution of $C_{q,\Delta}$ and $C_{\theta,\Delta}$ at $Z = 0.85Z_i$, with the joint probability distribution of $(q', \theta')$ as contours. From the interpretation above, the largest $C_{q,\Delta}$ and $C_{\theta,\Delta}$ are caused by the air parcels of tropospheric origin. At $Z = 0.1Z_i$ (Figs. 4e,f), the parcels of surface-layer origin explain a major part of the largest $C_{q,\Delta}$ and $C_{\theta,\Delta}$. At $Z = 0.5Z_i$, the largest $C_{q,\Delta}$ occur within air parcels of surface-layer origin but the largest $C_{\theta,\Delta}$ occur in parcels of free-tropospheric origin (Figs. 4c,d). These latter parcels approximately follow the zero buoyancy line given by

$$\theta' = -[0.617(1 + 0.617\eta)]q'.$$

The penetration of entrained air, with large $C_{q,\Delta}$, down in the lower CBL is thought to explain the lower height of minimum $C_{q,\Delta}$ relative to $C_{\theta,\Delta}$ (Fig. 2).
These results hint that the variability of the local structure parameters follows the air parcels’ origin, which is driven by the CBL dynamics. Let us denote $w$ as the (resolved) vertical velocity. The joint probability densities of $(w, C_{\theta,\Delta}^2)$ and $(w, C_{u,\Delta}^2)$ at specific vertical levels are shown in Fig. 5. The ascending plumes ($w > 0$) originating from the surface explain the significant probability to find parcels with concomitantly large $w$ and $C_{\theta,\Delta}^2$ (relative to the mean values) at $Z = 0.2Z_i$. Following these parcels with height from their large vertical velocity (Cheinet 2003), we see that they show progressively decreasing excesses in $C_{\theta,\Delta}^2$ with height (Figs. 5d–f). Conversely, the largest excesses in $C_{\theta,\Delta}^2$ are within the entrained subsiding air at the considered heights ($w < 0$; Figs. 5a–c). Note that at $Z = 0.2Z_i$ the plumes also show significant excesses in $C_{\theta,\Delta}^2$ (Fig. 5a). As we will see later (Fig. 6), however, it is only below that the plumes’ excesses are larger than those stemming from the subsiding motions.

Hence, in the bulk CBL of our simulated case, the entrained tropospheric air carries the largest excesses in $C_{\theta,\Delta}^2$ while the surface-rooted plumes explain the largest excesses in $C_{u,\Delta}^2$. In confirmation of this result, Fig. 5 compares well to the joint probability densities of $(w, c_r)$ and $(w, c_b)$ obtained by Wyngaard and Moeng (1992) in the mid-CBL, where $c_r$ is a top-down scalar (i.e., with an entrainment flux at the mixed-layer top and no surface flux) and $c_b$ is a bottom-up scalar (surface flux and no entrainment flux). Thus, in our entrainment-drying CBL, $C_{\theta,\Delta}^2$ and $C_{u,\Delta}^2$ can respectively be thought of as top-down-driven and bottom-up-driven fields in the mid-CBL.

The resulting correlation coefficient between $w$ and $C_{\theta,\Delta}$ is positive below $0.7Z_i$; it becomes negative at the height $Z_q = 0.75Z_i$ in our simulation (Fig. 6a). Conversely, the correlation between $w$ and $C_{u,\Delta}^2$ is positive near the surface and changes sign at the height $Z_q = 0.2–0.25Z_i$. The plumes combine positive $w$, $\theta'$, and $q'$, whereas the descending parcels combine negative $q'$ and positive $\theta'$. Hence, both contribute positively to the correlation between $w$ and $C_{\theta,\Delta}$.

4. Discussion

As argued in the introduction, the variability of $C_{\theta,r}^2$ and $C_{u,r}^2$ can affect many wave-propagation applications. One such impact is illustrated in this section, in the area of boundary layer remote sensing.

The mean vertical velocities obtained by sodars and radars through time averaging of the measured power spectra have been found to show biases in the CBL. The radar biases reported by Angevine (1997) typically reach $-0.25$ m s$^{-1}$ in the bulk CBL (see also below). A comparable negative radar bias is obtained by Lothon et al. (2002). Conversely, the measured sodar biases are positive in the CBL (e.g., Peters et al. 1998). The sodar bias reported by Coulter and Kallistratova (2004) reaches $0.4$ m s$^{-1}$. Lothon et al. (2003) concomitantly document a negative radar bias along with a positive sodar bias in the lower and bulk CBL that changes sign above $Z = 700$ m. The relatively low degree of consensus between the observations on the magnitude of the biases may be caused by differences in the instrumental characteristics, the signal processing, and the meteorological conditions. Still, we note that these observations were made over land in fair-weather summertime conditions.
favorable to the entrainment-drying character. Also, Angevine (1997) reports that a site with wetlands shows a smaller negative radar bias. A number of hypotheses have been suggested, such as the low signal-to-noise ratios of sodars (Coulter and Kallistratova 2004) or the presence of insects for radars (Angevine 1997), to explain these biases. Tatarski and Muschinski (2001) analyze the potential contribution of a correlation between \( w \) and \( n \) at scales that are smaller than the radar sampling volume. Nastrom and VanZandt (1994, 1996) point out that a correlation between \( w \) and the reflectivity or, equivalent, \( C_{n,r}^2 \), contributes to the biases. Peters et al. (1998), Muschinski et al. (1999), and Muschinski (2004) also discuss this hypothesis. An experimental evaluation of these various suggestions is difficult (Muschinski et al. 1999). For example, the correlation between \( w \) and \( C_{n,r}^2 \) is poorly documented. Hence, the radar and sodar biases remain to be explained and interpreted.

After Muschinski [2004, his Eq. (115)], the bias contribution resulting from the above correlation writes as \( w_n \), with the generic definition for any scalar \( s \):

\[
w_s = \frac{\iiint_V w C_{s,r}^2 dV}{\iiint_V C_{s,r}^2 dV},
\]

where \( V \) is the sampling volume. Let us consider that the sampling volume is our LES grid box. Then we can document \( w_n \) directly from our LES predictions of \( w \), \( C_{q,r}^2 \), \( C_{n,r}^2 \), and \( C_{\theta,q,r} \) [see Eq. (1) and Muschinski et al. 1999, their Eq. (40)]. From Fig. 6a, at radar wavelengths, \( w_n \) is positive in the surface layer and negative in the bulk CBL (\(-\)0.5 m s\(^{-1}\)). Our \( w_n \) in sodar acoustics is positive in the bulk CBL (1 m s\(^{-1}\)) and changes sign near the inversion. The characteristic size of the sampling volume of some sodars or radars may differ considerably.

Fig. 4. Distribution of (left) \( \log(C_{q,r}^2) \) and (right) \( \log(C_{n,r}^2) \) in the \((q', \theta')\) plane at (top) \( Z = 0.85Z_i \), (middle) \( Z = 0.5Z_i \), and (bottom) \( Z = 0.1Z_i \). The joint probability distribution of \((q', \theta')\) is also contoured in arbitrary units. The four-quadrants decomposition used in the text is indicated in (c).
from our LES grid box. We have also used Eq. (6) with a sampling volume of $3 \times 3 \times 3 = 27$ LES grid boxes. As shown in Table 1, our results are marginally sensitive to this change.

Comparison with the LES predictions by Muschinski et al. (1999) is difficult, because they derive the reflectivity from the vertical differencing of a strictly passive scalar field over an anisotropic LES grid. On the observational side, our LES predicts the same signs with height as the bias measurements of Angevine (1997), Lothon et al. (2002, 2003), and Coulter and Kallistratova (2004), for example, the positive bias for sodars and the negative bias for radars in the bulk CBL. Our LES also reproduces the observed sensitivity, as a test with a larger surface latent heat flux ($450 \text{ W m}^{-2}$) leads to a smaller radar bias ($0.3 \text{ m s}^{-1}$). To our knowledge, this consistency with observations is unprecedented among the potential causes proposed to explain the biases. In quantitative terms, the nonfiltered radar biases documented by Angevine (1997), averaged over 39 summer days and from 200 to 1000 m above ground level, reach $0.4 \text{ m s}^{-1}$ in the midday (his Fig. 1a). Our LES predictions are in good agreement with these measurements; they are larger than other observed (sodar and radar) biases that are reported above. Further investigations would be necessary to compare rigorously the observed and simulated biases under the same meteorological conditions.

Sodar and radar measurements may not detect very small reflectivities (e.g., Peters et al. 1998). Table 1 shows that a truncation of the lowest 5% simulated reflectivities does not significantly change the magnitude of our predictions. Besides, some filtering algorithms may eliminate the upper radar reflectivities, for example, to avoid contamination (Wilczak et al. 1995). More sensitivity is obtained with respect to the upper detection values, with notably reduced biases (Table 1). The sodar bias reduces to $0.35 \text{ m s}^{-1}$ with an elimination of the largest 15% acoustic reflectivities. These sensitivities point to the fact that the correlation in the numerator of Eq. (6) is mostly held by the strong reflectivities (see Fig. 5 and Peters et al. 1998).

Our results suggest that the correlation between vertical velocity and local structure parameters, at scales...
resolved by LES, can significantly contribute to the measured biases in the CBL. The predictions of Eq. (6) can be interpreted under the simple CBL decomposition between plumes and subsiding motions (e.g., Schumann and Moeng 1991). According to our LES analysis, one of the two populations often has a much larger structure parameter than the other (e.g., Fig. 4). Equation (6) then gives the vertical velocity in the population that has the dominant structure parameter. Figure 6b shows that \( w_n \approx w_p \) in sodar acoustics. In the lower and bulk CBL, \( C_{\theta,\Delta}^2 \) is larger in the plumes, and therefore the acoustic \( w_n \) approximates the plumes’ vertical velocity. Below the inversion, \( C_{\theta,\Delta}^2 \) is larger in the subsiding air, and \( w_n \) approximates the environmental subsidence. In a comparable way, in radar applications, \( w_n \approx w_q \) approximates the plumes’ vertical velocity in the surface layer and the subsiding motions in the bulk and upper CBL.

5. Summary and conclusions

Many wave-propagation applications depend on the local, instantaneous humidity and temperature structure parameters \( C_{\theta,\Delta}^2 \) and \( C_{\theta,\Delta}^2 \) and the temperature–humidity structure parameter \( C_{\theta,\Delta}^2 \). In the last decade, it has appeared that large-eddy simulations could document these local structure parameters. This study uses an LES to investigate the variability of \( C_{\theta,\Delta}^2 \) and \( C_{\theta,\Delta}^2 \). The method used to diagnose these quantities from the LES resolved fields shares a broad consensus with the formulations proposed in previous studies.

The studied case is a shearless, quasi-stationary convective boundary layer of the so-called entrainment-drying type documented by Mahrt (1991). The predicted horizontal mean profiles of \( C_{\theta,\Delta}^2 \) and \( C_{\theta,\Delta}^2 \) are shown to agree with observations and models of that type of CBL. The local nature of our results also offers an original and comprehensive sketch of the mechanisms at play, which generalizes the results of CS.

In a general sense, the largest \( C_{\theta,\Delta}^2 \) and \( C_{\theta,\Delta}^2 \) occur within the parcels that have the largest absolute values of fluctuations \( |q'| \) and \( |\theta'| \). In the surface layer, the largest \( |q'| \) and \( |\theta'| \) are found within the roots of the ascending convective plumes, and \( C_{\theta,\Delta}^2 \) and \( C_{\theta,\Delta}^2 \) are both

| Table 1. Vertical velocity biases (m s\(^{-1}\)) at \( Z = 0.5Z_i \) for acoustic and electromagnetic remote sensing, obtained with various treatments of our LES data. The sampling-volume-size test uses a sampling volume of \( 3 \times 3 \times 3 \) LES grid boxes. The data thresholds indicated are chosen to truncate the 5% extreme reflectivities in each remote sensing application. |
|-----------------|-----------------|------------------|------------------|
| \( w_n \) radar | -0.52 | -0.52 | -0.50 (\( C_{\theta,\Delta}^2 > 8.2 \times 10^{-12} \text{ m}^{-2/3} \)) | -0.38 (\( C_{\theta,\Delta}^2 < 2.3 \times 10^{-9} \text{ m}^{-2/3} \)) |
| \( w_n \) sodar | 0.97 | 0.96 | 0.94 (\( C_{\theta,\Delta}^2 > 1.1 \times 10^{-5} \text{ K}^2 \text{ m}^{-2/3} \)) | 0.60 (\( C_{\theta,\Delta}^2 < 1.3 \times 10^{-3} \text{ K}^2 \text{ m}^{-2/3} \)) |
positively correlated with the vertical velocity. Below the inversion, the largest \(|\theta^\prime|\) and \(|q^\prime|\) relate to the subsiding entrained air, and \(C^2_{\theta,q}\) and \(C^2_{\theta,q}\) are both negatively correlated with the vertical velocity. In the mid-CBL of our simulated case, the entrained tropospheric air still carries the largest excesses in \(C^2_{\theta,q}\) (negative correlation between \(w\) and \(C^2_{\theta,q}\)) while the plumes explain the largest excesses in \(C^2_{\theta,q}\) (positive correlation between \(w\) and \(C^2_{\theta,q}\)). The predicted correlations \((w, C^2_{\theta,q})\) and \((w, C^2_{\theta,q})\) have opposite signs in the bulk of our CBL.

The correlation between the vertical velocity and the local refractive-index structure parameters is known to contribute to the mean vertical velocity diagnosed by radars and sodars [Eq. (6)]. Our LES predictions for these contributions yield the same orders of magnitude and signs (positive for sodars; negative for radars) as the mean vertical velocity biases measured with radars and sodars. Further comparisons between LES and remote sensing observations, over the same meteorological conditions, are necessary to assess quantitatively the ability of LES in reproducing the observed biases. Still, the obtained consistency between our LES and the available observations suggests that the correlation between vertical velocity and local structure parameters in the CBL, at scales resolved by LES, significantly contributes to the measured biases. Our interpretation of these contributions to the biases suggests that they provide information on the large-scale dynamics in the CBL.

Most of the time, the CBL is capped by drier air that is entrained within the well-mixed layer. Our results may still be particular to the entrainment-drying CBL. The existing studies on the horizontal averages of \(C^2_{\theta,q}\), \(C^2_{\theta,q}\), and \(C^2_{\theta,q}\) in the CBL stress the strong sensitivity of the results to the surface and entrainment fluxes, as discussed by Fairall (1991). The presence of wind shear may also modulate the results (Fairall 1984). Further investigations are needed to evaluate the sensitivity of the present findings to these forcings.

Clouds may have a major impact as well. According to Wang and Stevens (2000), the humidity has a pronounced surface-driven behavior in cumulus-topped boundary layers, but it has a notable top-driven component in stratocumulus-topped boundary layers. In our CBL, the entrainment of dry air induces the largest \(C^2_{\theta,q}\) and we find a negative correlation between \(C^2_{\theta,q}\) and \(q\). White et al. (1991) report a positive correlation between \(C^2_{\theta,q}\) and \(q\) in their radar observations of a marine stratocumulus-topped boundary layer (see also Penc 2001). Thus major changes from our results are expected in cloudy convective boundary layers.

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