Convective Boundary Layer Depth Estimation from S-Band Dual-Polarization Radar

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ABSTRACT

This study investigates Bragg scatter signatures in dual-polarization radar observations, which are defined by low differential reflectivity ($Z_{DR}$) values, as a proxy for convective boundary layer (CBL) depth. Using data from the WSR-88D in Twin Lakes, Oklahoma (KTLX), local minima in quasi-vertical profiles of $Z_{DR}$ are found to provide a reasonable estimate of CBL depth when compared with depth estimates from upper-air soundings from Norman, Oklahoma (KOUN), during 2014. The 243 $Z_{DR}$ Bragg scatter and upper-air sounding CBL depth estimates have a correlation of 0.90 and an RMSE of 254 m. Using Bragg scatter as a proxy for CBL depth was expanded to other seasons and locations—performing well in Wilmington, Ohio; Fairbanks, Alaska; Tucson, Arizona; Minneapolis, Minnesota; Albany, New York; Portland, Oregon; and Tampa, Florida—showing its potential usefulness in monitoring CBL depth throughout the year in a variety of geographic locations and meteorological conditions.

1. Introduction

The depth of the planetary boundary layer (PBL) varies from a few tens of meters at night to several kilometers during the day. This single measurement and its evolution provide useful information on PBL structure. Not surprisingly, PBL depth influences air quality, turbulence, and cloud development. Both wildfire behavior (Clements et al. 2007) and propagation of hazardous materials (Dabberdt et al. 2004) exhibit a strong dependence on PBL depth. Yet, observations of PBL depth come primarily from rawinsonde data collected only twice a day (0000 and 1200 UTC) at 97 locations across the United States. This network offers very poor spatial and temporal resolution; additionally, sounding data can be compromised by thunderstorms or saturated air encountered by the rawinsonde during its ascent. Estimates of PBL depth with better temporal resolution are attainable from 915-MHz vertical profilers (White 1993; Angevine et al. 1994), but these instruments are few in number. Although PBL depth estimates are provided by numerical models, these estimates can be off by a factor of 2, limiting their usefulness (Grimsdell and Angevine 1998; Bright and Mullen 2002; Stensrud and Weiss 2002). The combination of limited in situ measurements in space and time and inaccurate model predictions makes the observation and forecasting of PBL depth problematic.

Weather radar provides a dataset with higher spatiotemporal resolution than other instruments owing to the 159 continuously operating National Weather Service dual-polarization Weather Surveillance Radar-1988 Dopplers (WSR-88Ds). Weather radars, if useful for PBL depth estimation, would significantly improve the density of PBL depth observations and could facilitate routine observations of this important PBL characteristic. Previous studies have used legacy (single polarization) WSR-88D data to investigate PBL depth across a limited number of cases (Rabin and Doviak 1989; Heinselman et al. 2009). The implementation of the WSR-88D dual-polarization upgrade across the country by 2013 provides additional information to address the ambiguities associated with PBL depth signatures. In particular, the ability to differentiate between signatures caused by refractive index perturbations and biological scatterers may facilitate a more reliable technique to estimate PBL depth.

The current study focuses on the daytime PBL, which is often fully turbulent and will be referred to as the convective boundary layer (CBL). We will investigate the use of dual-polarization observations to provide an estimate of CBL depth as compared with CBL depth estimated from rawinsonde observations. Section 2 provides background and motivation for the use of radar data to detect Bragg scatter, which may be associated

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with the CBL top. Section 3 outlines the procedures used to determine CBL depth based on 0000 UTC rawinsonde data, followed by a discussion of how Bragg scatter can be used to determine CBL depth in section 4. To quantify the success of this methodology, a comparison of CBL depth estimation techniques is discussed in section 5 along with eight other example cases taken from dual-polarization WSR-88Ds in a variety of locations and seasons. Section 6 discusses important takeaways from this study and outlines future work.

2. Background

The top of the CBL is characterized by sharp vertical gradients of water vapor mixing ratio and temperature near the boundary between the CBL and the free troposphere. Both water vapor mixing ratio and temperature affect the refractive index of the atmosphere for electromagnetic waves at microwave frequencies. Thus, turbulent mixing of drier free-tropospheric air with moist air in the CBL at the CBL top can induce strong refractive index perturbations at a variety of spatial scales. These refractive index perturbations can scatter radiation. The turbulent perturbations in the refractive index on spatial scales of half the radar wavelength (for 10-cm WSR-88Ds, this corresponds to 5 cm) result in Bragg scattering, wherein the backscattered waves from these perturbations constructively interfere and lead to an enhancement in the received signal. This results in a local enhancement in radar reflectivity factor (reflectivity) at the CBL top (Weiss 1961; Doviak and Zrnić 1993; Melnikov et al. 2013).

Rabin and Doviak (1989) observed a persistent layer of enhanced reflectivity from the 10-cm National Severe Storms Laboratory Doppler radar, which they thought may have represented the CBL top. Later, Heinselman et al. (2009) sought to quantify the relationship between an elevated layer of high reflectivity and the top of the CBL. They assumed that slightly larger reflectivity values would be found at the top of the CBL, where moisture gradients generally are steepest. On 17 days with mainly clear skies and light winds, Heinselman et al. (2009) found that the height of the reflectivity maximum served as a suitable proxy for CBL depth but that the generality of this approach to other environments was unclear. Elmore et al. (2012) added solar insolation measurements in radar reflectivity–derived CBL estimates. This method yielded an improved estimation accuracy, but it was still limited in scope to summertime conditions in central Oklahoma. Using reflectivity alone to identify Bragg scatter at the top of the CBL is prone to contamination by bugs, birds, and other particulates (Heinselman et al. 2009; Melnikov et al. 2011, 2013), which can also produce enhanced reflectivity. Biological scatterers, however, tend to be highly nonspherical, whereas turbulent structures at 5-cm scales leading to Bragg scatter are assumed to be isotropic (Melnikov et al. 2011). Thus, retrieval of information about the shape, size, and distribution of scatterers in the observed region would assist with differentiating Bragg scatter from biological scatterers. Such a distinction would facilitate the use of radar data to detect Bragg scatter in a broader range of meteorological conditions.

With the implementation of dual-polarization capabilities for all NWS WSR-88Ds by 2013, new products and information are available to assist with identification of meteorological and nonmeteorological phenomena. For example, differential reflectivity \( Z_{DR} \) is commonly used to identify the shape or orientation of scatterers in the radar sampling volume (Seliga and Bringi 1976; Kumjian 2013). For clear-air applications, \( Z_{DR} \) has proven useful in differentiating between enhanced reflectivity regions caused by Bragg scatter and those caused by biota in the daytime CBL (Melnikov et al. 2013). Biota tend to produce extremely large \( Z_{DR} \) and low correlation coefficient \((\rho_{hv}) \) values distinct from precipitation and other meteorological echoes owing to their nonspherical, irregular shapes. In contrast, the isotropic turbulent structures causing Bragg scatter lead to \( Z_{DR} \) near 0 dB and \( \rho_{hv} \) near 1.0 (Melnikov et al. 2011). Although reflectivity alone is unable to differentiate between Bragg scatterers and biota, the combination of \( Z_{DR} \) and \( \rho_{hv} \) has proven effective (Melnikov et al. 2013).

3. Rawinsonde estimates of CBL depth

Rawinsondes provide one of the most reliable and best understood in situ observations of the atmosphere. Vertical profiles of sounding data have been used to determine CBL depth. Seidel et al. (2010) defined CBL depth as the height at which the maximum vertical gradient is achieved for the following variables: potential temperature \( \theta \), specific humidity \( q \), and refractivity \( N \). Another technique, commonly referred to as the parcel method, identifies the CBL depth as the height at which a parcel’s virtual potential temperature \( \theta_v \) matches its surface value (Holzworth 1964; Seibert et al. 2000). Alternatively, Coniglio et al. (2013) identified CBL depth as the height at which the parcel reached a virtual potential temperature value equal to the surface \( \theta_v + 0.6 \) K.

The method selected for use in this study combines the aforementioned methods and estimates CBL depth based on maximum vertical gradients in \( \theta_v \), \( \theta \), \( q \), and \( N \). The height at which the maximum vertical gradient for each variable occurs is calculated, and then CBL depth
is defined as the modal height among the four variables. The technique for estimating CBL depth from each variable has errors as discussed in Seidel et al. (2010), but taking a modal approach helps minimize algorithm error. A modal approach is used because it eliminates outliers, whereas a mean approach would incorporate an outlier among the four profiles and skew the CBL depth estimate. An example using this technique is shown in Fig. 1. Sharp vertical gradients in all four variables at a height of 1802 m yield confidence that this layer is associated with the CBL top.

This procedure was applied to all 0000 UTC soundings from Norman, Oklahoma (KOUN), during 2014. Data quality concerns including contamination by precipitation or saturated layers and missing soundings led to the elimination of 64 days. This method worked well for the remaining 301 days, although 49 days had multiple vertical gradient maxima that received careful manual inspection to subjectively determine the most appropriate CBL depth estimate. In most cases with multiple vertical gradient maxima, the lower maximum was closer to the $Z_{DR}$ minimum in quasi-vertical profiles (QVPs) and was used as the CBL depth estimate.

4. Weather radar–based estimates of CBL depth

As described above, a Bragg scatter layer is often present near the top of the CBL, and is characterized by $Z_{DR}$ near 0 dB and $\rho_{hv}$ near 1. In a typical plan position indicator (PPI) scan of $Z_{DR}$, this Bragg scatter layer shows up as a ring of reduced $Z_{DR}$ values encircling the radar (Fig. 2). The ring of locally reduced $Z_{DR}$ expands radially through the afternoon, indicating an increase in the altitude of the Bragg scatter layer. The large
ZDR values indicate the biota-filled CBL. This study uses the 4.5° elevation angle scan, which is the highest elevation angle in clear-air scanning modes [volume coverage pattern (VCP) 31 or 32], in order to minimize the influence of ground clutter (NOAA 2017).

To map the diurnal variation of this Bragg scatter layer, which may be related to CBL depth, the QVP technique is applied (Kumjian et al. 2013; Ryzhkov et al. 2016). In this method, radar data are azimuthally averaged, and plotted with range converted into height. The background ZDR values indicate the biota-filled CBL. The height of the radar beam at each range gate is calculated assuming standard refraction (Doviak and Zrnić 1993, p. 21). QVPs are valid here because the CBL tends to be horizontally homogeneous.

A time series of these QVPs leads to a time–height profile of a given radar variable. Such a presentation maps the behavior of Bragg scatter in the PBL throughout the day. Figure 3 shows a QVP of Z and ZDR for 20–21 May 2014 at the Twin Lakes, Oklahoma (KTLX) radar. The diurnal evolution of Z is dominated by biota (Fig. 3). Around sunset (~0000 UTC), Z values increase and are associated with a biota bloom, which occurs as bats, birds, and other airborne organisms become active. At sunrise (~1200 UTC), a significant decrease in Z is evident as biota retreat. Interestingly, there is an elevated layer of enhanced Z, collocated with enhanced ZDR (at ~1 km AGL), that persists after sunrise, which likely is associated with biota that remain airborne past sunrise. A second, weaker Z enhancement between 0.5 and 1 km AGL is collocated with low ZDR and thus is associated with the top of the growing CBL. After about 1500 UTC, low-level Z and ZDR near the surface increase as insects and biota become more active within the CBL. A second layer of enhanced Z, indicated above the white line in the top panel of Fig. 3, develops and is associated with Bragg scatter at the CBL top. Because Z is highly susceptible to contamination by biota, using it alone to track Bragg scatter can be difficult.

The evolution of ZDR is similar to that of Z, but ZDR can differentiate Bragg scatter from biological scatterers.
more effectively. Around sunrise, two layers of low $Z_{DR}$ values are evident. The layer at about 1.5 km AGL that emerges around sunrise on both days is collocated with a region of low $Z$ and could be associated with Bragg scatter in the residual layer that becomes visible as the higher-$Z$ biota retreat. The second layer closer to the surface is likely Bragg scatter associated with the CBL top. Through the daytime hours, this layer continues to increase in altitude, reaching its peak just before sunset. Starting around sunset, the low values of $Z_{DR}$ develop near the surface and stay near the surface over the nighttime hours. The behavior of this Bragg scatter layer matches the expected PBL diurnal evolution, as described by Stull (1988). For example, in the morning, as surface heating begins, the CBL deepens, ceasing its ascent just before sunset and leaving behind a residual layer. Overnight, a stable and persistent shallow PBL forms, which is indicated by the layer of low $Z_{DR}$ just above the ground. Given the similar evolutions of Bragg scatter layers in $Z_{DR}$ and the CBL, their behavior may be closely related. Theoretically, $Z_{DR}$ of Bragg scatter should be 0 dB; however, when mixed with biota that exhibit high $Z_{DR}$, the total observed $Z_{DR}$ values may be positively biased. Figure 4 shows how different reflectivity contributions of insects (with large intrinsic $Z_{DR}$) and Bragg scatter (with intrinsic $Z_{DR} = 0$ dB) combine to affect the total observed $Z_{DR}$. The contour in each panel shows when the total $Z_{DR}$ is reduced compared to pure insects by 0.5 dB, which we consider detectable with our algorithm. The total observed $Z_{DR}$ will be larger for larger reflectivity contributions from insects compared to the reflectivity contribution from Bragg scatter.
In the absence of insects or biota, \(Z\) and \(Z_{DR}\) QVPs exhibit slightly different characteristics from those shown in Fig. 3. Without insects or biota, which contaminate the \(Z_{DR}\) field, the Bragg scatter region associated with the CBL top exhibits \(Z_{DR}\) values near 0 dB and vertical gradients in \(Z_{DR}\) are less pronounced. There were two such days in 2014 at KTLX without a clear signature of insects in the CBL. For these cases, a low-\(Z_{DR}\) layer exists near the surface and deepens through the daytime hours. This pattern describes days with an insect-laden boundary layer as well; although the presence of insects does influence \(Z_{DR}\) values, the Bragg scatter layer exists irrespective of insects or biota.

Assuming that a Bragg scatter layer is coincident with the top of the CBL during daytime conditions, the CBL depth is the height at which the local minimum of \(Z_{DR}\) occurs in the QVPs at each time. Note that a nonuniform CBL-top height across the radar domain would appear in QVPs as a wider layer of reduced \(Z_{DR}\) because of the azimuthal averaging technique employed. Inspection of many diurnal cycles of \(Z_{DR}\) indicates that there are two predominant patterns of \(Z_{DR}\) that occur throughout the year. The first is characterized by a local vertical minimum of \(Z_{DR}\) aloft corresponding to the height of the CBL top (Fig. 5a). The second is characterized by a sharp decrease in \(Z_{DR}\) aloft (~1.5 km AGL) with no clear subsequent increase in \(Z_{DR}\) at even higher altitudes (Fig. 5b). Identification of CBL height for the second case is more challenging than for the first owing to the much larger vertical extent of low \(Z_{DR}\), suggesting a very deep elevated layer of Bragg scatter.

Despite the azimuthal analysis, the \(Z_{DR}\) QVP is noisy in many cases. Because of this, a simple quality control filter is developed and applied prior to estimating CBL depth. The filter implements the following steps:

1. \(Z_{DR} < -2\) dB (owing to ground clutter contamination from sidelobes) are removed.
2. \(Z > 0\) dBZ and \(\rho_v > 0.8\), which indicate precipitation with larger \(Z\) values than typical of Bragg scatter, are removed (note that we tested the sensitivity of the \(Z\) threshold by making it 10 dBZ; this led to an insignificant increase of 5 m in the RMSE and no change in correlation in the subsequent analysis).
3. At a given time, QVPs with \(Z_{DR} < 2\) dB through the entire column are removed (additional filter for light precipitation).
4. Discontinuities, defined by pixels with a 1-dB difference between adjacent data points, are removed.
5. Isolated pixels, characterized by data points with fewer than two adjacent data points, are removed.

Once the filters are applied, smoothing via application of a running mean over five time and height steps provides further noise reduction to produce a clearer and less noisy evolution of QVP \(Z_{DR}\) during the daytime. The CBL depth can now be estimated by visual inspection, although a simple algorithm is used to find the minimum value of \(Z_{DR}\) in the vertical profile at each time step and records the height at which that minimum occurs. A running mean is applied to the resulting time series of estimated CBL depth to eliminate large jumps and to produce a smoother, and more realistic, behavior. CBL depth is calculated only during the day (1200–0000 UTC); Bragg scatter is often harder to identify overnight, when biological scatterers dominate \(Z\) (and thus \(Z_{DR}\)) and turbulence is often weaker.
To facilitate a comparison between rawinsonde and radar-derived CBL depth estimates, the 2300 UTC Z_{DR} profile is used to compare with the 0000 UTC National Weather Service rawinsonde from Norman (launch time of ~2300 UTC). The KTLX dual-polarization WSR-88D is located 23 km to the northeast of the KOUN rawinsonde site. This separation distance is well within the clear-air sampling volume of KTLX, so the rawinsonde samples the same boundary layer. Precipitation, which contaminates Z_{DR} and makes both radar and rawinsonde CBL depth estimation impossible, occurred on 24 days. An additional 55 days were removed as a result of indiscernible Bragg scatter layers. In cases where the Bragg scatter layer becomes less discernible before 2300 UTC, a visual linear extrapolation of the Bragg scatter layer height was used to estimate CBL depth. Linear extrapolation generally works well an hour or two before sunset, given that the CBL depth changes in a continuous and approximately linear fashion during this time as surface heating persists.

5. Verification of WSR-88D-based estimates of CBL depth

CBL depths were estimated using the absolute maximum vertical gradients for rawinsonde data and the absolute minimum Z_{DR} value for radar data on all days in 2014 at KOUN/KTLX. To evaluate the effectiveness of using radar data to estimate CBL depth, only days with discernible CBL estimates from both rawinsondes and radar were included in this analysis. Manual quality control of both methods led to 243 useful cases for analysis (62 from December, January, and February; 59 from March, April, and May; 62 from June, July, and August; and 60 from September, October, and November). Of the 122 erroneous days, 10% did not have a 0000 UTC sounding; 50% had soundings that experienced a saturated layer (cloud/precipitation) near the surface, indicating that the CBL was indiscernible or absent; and 40% had inconclusive Z_{DR} signatures. For the 243 usable days, the comparison between rawinsonde- and radar-derived CBL depth yielded a correlation of 0.90 and an RMSE of 254 m (Fig. 6).

Bianco et al. (2008) investigated the variability in CBL depth estimation among experts at two locations and found RMSEs of 109 and 135 m. They then used several algorithms to estimate CBL depth with results indicating RMSEs between 152 and 424 m depending on the algorithm employed. Similar values of RMSE were found in Elmore et al. (2012). These values are comparable to the errors associated with the radar-derived CBL depth estimates found in the present study and indicate the feasibility of using Bragg scatter layers to estimate CBL depth.

Although data with which to compare radar-estimated CBL depths are limited during the day, the elevated Bragg scatter layer is observable throughout the daytime. Based on the demonstrated feasibility of using Bragg scatter to estimate CBL depth at one time during the day, and the previously noted similarities between the Bragg scatter layer and CBL depth behavior, it seems plausible that CBL depth estimation could be possible throughout the daytime hours. Though the results shown in this study are limited to central Oklahoma, this technique shows potential applicability to CBL depth estimation at all WSR-88D sites in real time, as suggested by Richardson et al. (2017a,b).

Application to locations outside of Oklahoma

To explore whether an elevated layer of Bragg scatter can be used to estimate CBL depth in different geographic regions representing very different environmental conditions, data from eight other WSR-88D sites are examined: Minneapolis, Minnesota (KMPX), in February; Fairbanks, Alaska (PAPD), in March; Portland, Oregon (KRTX), in May; Albany, New York (KENX), in June; Tucson, Arizona (KEMX), in August; Riverton, Wyoming (KRIW), in September; Wilmington, Ohio (KILN), in October; and Tampa, Florida (KTBW), in December (Fig. 7). The selected locations span meteorologically diverse regions and will test the applicability of techniques discussed herein.

Potential days for an analysis at each location were identified based on 0000 UTC upper-air soundings with a distinct temperature inversion and steep moisture gradient characteristic of the CBL top. In addition, specific days
were selected with an intent to capture extreme weather conditions (e.g., Minneapolis in February and Tucson in August). Care was taken to ensure the selected cases occurred in eight different months to test seasonal applicability as well. The results are shown in Table 1 and indicate that an elevated layer of Bragg scatter is a good estimate of CBL depth across all seasons in a variety of environmental conditions. The results are comparable to those found in central Oklahoma and demonstrate the potential widespread application of this methodology to a variety of locations, times of year, and meteorological conditions. The results indicate good agreement in environments with surface temperatures ranging from $-17^\circ$ to $36^\circ$C and surface water vapor mixing ratio values ranging from 1 to 11 g kg$^{-1}$.

### 6. Operational implications and future work

Elevated layers of Bragg scatter, identified as local minima in $Z_{DR}$, are found to rise from near the ground during the daytime, showing a diurnal evolution that parallels the expected behavior of CBL depth. A comparison of these $Z_{DR}$ estimates of CBL depth to 243 rawinsonde observations yielded an RMSE of 254 m over central Oklahoma. The approach was tested across the country and throughout the year, demonstrating that an elevated layer of Bragg scatter is coincident with the top of the CBL across a variety of observed environmental conditions. Additionally, the use of an azimuthal average to estimate CBL depth provides a more representative measure of...
CBL depth than the point measurement made with a rawinsonde.

Detection of Bragg scatter associated with the top of the CBL is most effective with a higher antenna elevation angle. At a lower elevation angle, the radar beam will take longer to pass through the layer of Bragg scatter, thus making it appear wider on the PPI scan. At higher elevation angles, the Bragg scatter layer will be narrower, as seen by the radar. Though scans at angles >4.5° are not used for clear-air scanning (probably because they take additional time and have not previously been thought of as useful), inclusion of occasional higher elevation scans in a clear-air scanning strategy would allow for more precise detection of the CBL depth based on Bragg scatter. The Radar Operations Center recently announced the implementation of VCP 35, which will incorporate scans at the 5.1° and 6.4° elevation angles. Inclusion of these scans will provide more accurate estimates of CBL depth, and scans at even higher elevation angles would be useful in the future.

Interesting behavior of Bragg scatter was observed in a few cases during 2014 in Oklahoma. On 15 July and 30 November, two layers of Bragg scatter were observable late in the day (Fig. 8). In both cases, rawinsonde

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**Table 1.** Weather conditions and algorithm performance are listed for locations outside of Oklahoma. 0000 UTC rawinsonde surface temperature and mixing ratio are shown next to rawinsonde- and ZDR-estimated CBL depths. Error is defined as the difference between CBL depth estimates.

<table>
<thead>
<tr>
<th>Location</th>
<th>Month</th>
<th>Surface temp (°C)</th>
<th>Water vapor mixing ratio (g kg(^{-1}))</th>
<th>Rawinsonde (m)</th>
<th>ZDR (m)</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis, MN</td>
<td>Feb</td>
<td>−17.3</td>
<td>1</td>
<td>882</td>
<td>900</td>
<td>−18</td>
</tr>
<tr>
<td>Fairbanks, AK</td>
<td>Mar</td>
<td>−13.3</td>
<td>1.37</td>
<td>1077</td>
<td>1009</td>
<td>68</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>May</td>
<td>17.4</td>
<td>4.84</td>
<td>1421</td>
<td>1870</td>
<td>−449</td>
</tr>
<tr>
<td>Albany, NY</td>
<td>Jun</td>
<td>32.2</td>
<td>10.26</td>
<td>2187</td>
<td>2070</td>
<td>117</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>Aug</td>
<td>35.6</td>
<td>4.33</td>
<td>3023</td>
<td>3246</td>
<td>−223</td>
</tr>
<tr>
<td>Riverton, WY</td>
<td>Sep</td>
<td>22.6</td>
<td>5.54</td>
<td>1755</td>
<td>1636</td>
<td>119</td>
</tr>
<tr>
<td>Wilmington, OH</td>
<td>Oct</td>
<td>21.8</td>
<td>7.75</td>
<td>1259</td>
<td>1247</td>
<td>12</td>
</tr>
<tr>
<td>Tampa, FL</td>
<td>Dec</td>
<td>17.4</td>
<td>11</td>
<td>593</td>
<td>813</td>
<td>−204</td>
</tr>
</tbody>
</table>

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**Fig. 8.** (left) The ZDR QVP for 15 Jul and 30 Nov 2014 in central Oklahoma showing a double layer of Bragg scatter. Legend is the same as in Fig. 7, but excluding the daytime CBL depth estimate for clarity. (right) Vertical profiles of refractivity, potential temperature, mixing ratio, and virtual potential temperature demonstrate vertical gradients of moisture/temperature characteristic of Bragg scatter signatures on radar.
profiles also reveal two layers of sharp gradients in moisture and temperature. These examples demonstrate that Bragg scatter regions may also exist outside of the CBL top, as in Melnikov et al. (2013). The case from Wilmington on 2 October 2017 presents an interesting Bragg scatter signature as well (Fig. 7). The temporally constant CBL depth observed based on Bragg scatter seems to deviate from the expected steady daytime deepening of the boundary layer. Further investigation of the 1200 UTC sounding at KILN on 2 October indicates easterly winds at the surface shifting to westerly in the residual layer. The 0000 UTC sounding at KILN on 3 October indicates southerly winds and warmer CBL. Based on these observations, it appears the CBL may have been advected across a boundary. This explanation justifies the presence of a steady-state CBL depth and deviation from the expected surface—heat-flux-driven deepening of the CBL.

In the National Research Council report Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks, the current limitations associated with CBL depth monitoring are highlighted as a major concern (NRC 2009). One recommendation states, “As a high infrastructure priority, federal agencies and their partners should deploy lidars and radio frequency profilers nationally at approximately 400 sites to continually monitor lower tropospheric conditions” (NRC 2009, p. 10). To that end, Demoz et al. (2017) demonstrate the utility of the Automated Surface Observing System (ASOS) network of ceilometers to detect CBL depth across the country. Owing to current Federal Aviation Administration (FAA) restrictions on how the data are used, however, ASOS ceilometers do not currently transmit backscatter in real time, although the information can be collected and used to estimate CBL depth. A change in data procedures for ASOS is feasible, but it requires an extensive review process and may not be possible for several years. The use of dual-polarization radar to detect CBL depth provides readily available information for operational use as well as an extensive archive of >4 years of radar data for use in further exploration and refinement of this method.

The value of real-time monitoring of CBL depth and structure for air quality forecasts, fire weather, model initialization, and convection initiation has been documented by numerous previous studies. Various field campaigns have mapped the CBL depth during the day with increased temporal resolution relative to current methods. Implementation of CBL depth estimation across the country using the WSR-88D network could provide data with greater temporal and spatial resolution compared to current techniques. The use of radar data will result in a denser network of CBL depth estimates, but it could also assist with human forecasting of severe weather, improve forecasts through assimilation into weather models, and equip the public with better preparation for air quality and fire weather concerns.

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