A Method for Estimating Planetary Boundary Layer Heights and Its Application over the ARM Southern Great Plains Site

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ABSTRACT

A new objective method to determine the height of the planetary boundary layer (PBL) is presented here. PBL heights are computed using the statistical variance and kurtosis of dewpoint and virtual potential temperature differences measured from radio soundings at the U.S. Department of Energy’s Atmospheric Radiation Measurement (ARM) program at the Southern Great Plains (SGP) site. These heights are compared with those derived from lidar, also on the site, and with gridded model data from the North American Regional Reanalysis (NARR). A climatology of mean heights in the early (1800 UTC) and late (0000 UTC) afternoon from 2002 to 2010 is presented to show the effectiveness of the method. Future work using the new method include producing an observational climatology of PBL heights and understanding the aerosol loading within the PBL as well as a better understanding of the coupling between the surface and free atmosphere.

1. Introduction

The planetary boundary layer (PBL) is the turbulent layer near the earth’s surface. Determining the PBL height is important because it is where any moisture, aerosol, or heat from the surface can be exchanged with the free atmosphere above. It is most commonly observed as an inversion in potential temperature and dewpoint, or as a peak in low-level wind (Holzworth 1964; Grossman and Gamage 1995). The top can also be observed from a strong gradient in lidar backscatter, corresponding to a transition from an aerosol-rich PBL to a cleaner, free atmosphere (Cooper and Eichinger 1994; Gal-Chen et al. 1992).

The work by Seibert et al. (2000) provides a comparison of the benefits and caveats of various observational methods to determine the PBL height. Most previous studies conclude that the most effective way to determine the PBL height from radiosonde measurements is from visual inspection of a temperature profile (Barr and Betts 1997; Shaw et al. 2007). Even using lidar, a common method to delineate the top of the PBL is visual inspection (Hennemuth and Lammert 2006; Tucker et al. 2009) although transform methods, not applicable to radio soundings, do exist to objectively find the PBL top from lidar (Cohn and Angevine 2000). It should be noted that all these methods are most applicable to the daytime or convective boundary layer and not the nighttime or stable boundary layer. At night, surface diagnostic methods are a good proxy for the depth of the stable boundary layer (Steenveld et al. 2007; Vickers and Mahrt 2004).

The Atmospheric Radiation Measurement (ARM) program at the Southern Great Plains (SGP) site conducts regular radio soundings, lidar measurements, and multiple surface and subsurface measurements, which will be used to demonstrate a new method to determine the PBL depth (Ackerman and Stokes 2003; Stokes and Schwartz 1994). Previous studies document the usefulness of these measurements to understanding the structure and evolution of the PBL at the ARM SGP site (e.g., radar and lidar; Chandra et al. 2010). The purpose of this study will be to develop and demonstrate the efficacy of a new method to objectively determine the PBL height. The multifaceted ARM SGP site enables future research into aerosol loading within the PBL and how the height is coupled with measured surface fluxes and soil moisture.

2. Data and methodology

The ARM SGP facility conducts a wide range of meteorological research and is also a significant locale for land-atmosphere coupling studies. The site provides a unique
combination of surface and upper air measurements to demonstrate the new PBL height methodology and compare computed heights to a variety of different land and atmospheric quantities. The primary measurements to demonstrate the PBL height methodology are from radio sounding data. The radiosondes are launched daily, usually within 15 min of 1730 and 2330 UTC.Launches at those particular times began in late 2001 so data before 2002 are not used (Coulter et al. 2009). These data are compared with PBL heights from the North American Regional Reanalysis (NARR) PBL heights (Mesinger et al. 2006). The NARR PBL heights are computed from a diagnostic formula using equilibrium turbulent kinetic energy (Janjić 1996) and are comparable in accuracy to other modeled PBL heights using winds and virtual heat flux (i.e., Holtslag and Boville 1993). While Angevine and Mitchell (2001) showed the model heights to be in good agreement with those measured by a wind profiler, the juxtaposed NARR and computed PBL heights should be considered a comparison, not verification. The 1800 and 0000 UTC model PBL heights are compared with the computed heights. Figure 1 shows the location of the ARM SGP site, with the NARR grid cells averaged for comparison between NARR PBL heights, and the heights are computed from radiosondes.

The PBL height computations are more comparable with PBL heights determined from a visual inspection of lidar images. The onsite instrument is a Raman lidar with a vertical resolution of 15 m and a temporal resolution of 10 min (Newsom 2009). The particular time used for each comparison is the data closest to when the radiosonde passed its detected PBL top. Given that there is no widely accepted objective method to determine PBL height from lidar, only a visual inspection is used for verification. For this study, the lidar verification is performed on a smoothed aerosol extinction coefficient calculated from the extinction-to-backscatter ratio of all pulse wavelengths. The month of June 2006 was chosen for lidar verification because persistent dry conditions in Oklahoma during 2005–06 produced a thicker aerosol profile at the SGP site from dust (Garbrecht et al. 2007). Under normal conditions, the low aerosol loading in the vicinity of the site does not produce a strong enough backscatter to consistently use lidar to detect the PBL top. Welton and Campbell (2002) performed an uncertainty analysis of the ARM lidar. Based on their conclusions, the uncertainty of the lidar verification can be assumed to be negligible for the purpose of our study.

The new objective method used for this study locates the top of the boundary layer by attempting to collocate a change in the slope of virtual potential temperature \( \left( \theta_v \right) \) with a dewpoint \( (T_d) \) inversion. A peak in low-level wind was not consistently present, so it was not considered in this method. To objectively locate these inversions, the statistical variance and kurtosis or peakedness of a sample of \( \theta_v \) and \( T_d \) was computed. Statistical variance \( (\sigma) \) and kurtosis \( (\kappa) \) of a sample \( x \) were computed as

\[
\sigma(x) = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x}),
\]

FIG. 1. Map of the location of the ARM SGP site with NARR grids superimposed. The shaded grid cells are those averaged for comparison between NARR PBL heights, and the heights are computed from radiosondes.

\footnote{For brevity, these soundings will be referred to as 1800 and 0000 UTC, respectively.}
The test statistic treating standard deviation and kurtosis as functions of a sample $d_m$ (where $m$ here ranges from 1 to 3) is

$$k(x) = \frac{1}{N} \sum_{i=1}^{N} (x_i - \overline{x})^4 - 3,$$  

(2)

where $d_1$, $d_2$, and $d_3$ for $n$ sample points above and below a central point $i$ are defined as

$$d_1 = \theta_x[(i - n):i] - T_d[i:(i - n):i],$$  

(3a)

$$d_2 = \theta_x[i:(i + n)] - T_d[i:(i + n)],$$  

(3b)

$$d_3 = \theta_x[(i - n):(i + n)] - T_d[(i - n):(i + n)].$$  

(3c)

A sample of points is taken because the computation of $\theta_x$ from the radiosonde measurements yields nonsmooth values with height. The sample of points must be sufficiently large enough such that every point is not erroneously identified as the PBL top.

The test statistic at each point $i$ is submitted to a threshold test. The maxima of a secondary sample of $w$ test statistic values greater than a threshold $T_1$ are considered potential tops of the PBL. Each point exceeding the threshold is compared to the next point above it ($j$ and $j + 1$, respectively). Two more tests are performed checking for $\theta_x$, heterogeneity ($T_2$) and the strength of the test statistic maximum ($T_3$):

$$|\theta_x(j + 1) - \theta_x(j)| > T_2,$$  

(4a)

$$z(j + 1) - z(j)$$

$$S(j + 1) - S(j)$$

(4b)

If the potential PBL top satisfies both of the secondary thresholds, then it is deemed to be the top of the PBL. If any one of the tests fails for every point, then no PBL can be computed using this method. The parameters discussed here are detailed in Table 1. All thresholds were kept constant for all months for each time. The parameters and thresholds may be adjusted by month or by season in future research.

In general, the error of PBL heights from radiosonde measurements is poorly understood and is highly dependent on the variables used to determine the height (Seidel et al. 2010). The Seidel et al. study found PBL top error to be on the order of $\pm$100 m for each individual variable used (i.e., $\theta_x$, $T_d$, wind) and hypothesized that it would decrease proportionately as the number of variables are increased. Given this method uses two primary variables, the error would be $\pm$50 m. The vertical resolution of the SGP radiosounding is 5 to 8 m depending on balloon height and three or five points are averaged ($w$ in Table 1) to compute it. Based on this, we also may assume the uncertainty to be on the order of the product of $w$ and $dz$, or 15 to 40 m, on the same order of magnitude as the Seidel et al. (2010) approximation.

### 3. Results

The method described above (hereinafter referred to as the objective method) was designed originally to determine the PBL height during summer months. As will be discussed, it performs equally well in cold months. Given the structure of the PBL, it requires a $\theta_x$ and dewpoint discontinuity to delineate the top of the PBL. Therefore, it performs best in the daytime boundary and should not be used to evaluate stable or nighttime cases. If there are deep clouds in the PBL, their base or top may be erroneously identified as the top of the PBL. For any future research in regions prone to such clouds, the thresholds may require modification to accurately determine the PBL top. Noting these potential caveats, this study has used the objective method to produce the following:

- A comparison of objectively determined heights with those determined from visual inspection of lidar backscatter.
- A comparison of objectively determined heights with those computed from the NARR.
- A 2002–10 climatology of mean 1800 and 0000 UTC PBL heights over the ARM SGP site.

Table 1. Parameters used to objectively compute PBL heights at 1800 and 0000 UTC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>1800 UTC</th>
<th>0000 UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of points ($n$)</td>
<td>3</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Test statistic threshold ($T_1$)</td>
<td>0.5 K</td>
<td>1 K</td>
<td></td>
</tr>
<tr>
<td>No. points to check ($w$)</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Homogeneity threshold ($T_2$)</td>
<td>0.5 K</td>
<td>0.5 K</td>
<td></td>
</tr>
<tr>
<td>$\delta z/\delta S$, threshold ($T_3$)</td>
<td>50.0 m</td>
<td>100.0 m</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 details the objectively determined PBL heights (dashed lines) with the heights determined from lidar (crosses) for June 2006 at 1800 UTC. It should be noted that this is not a true verification, as the lidar heights do not necessarily represent a “better” method. There is good agreement on days where there is a single, well-defined PBL top, such as the first few days of June 2006. The
FIG. 2. Plots of $\theta_r$ (K) vs altitude (m above sea level) for each day at approximately 1800 UTC in June 2006. Dashed lines indicate the objectively determined PBL top from the radiosonde measurements. The crosses indicate the subjectively determined PBL top from lidar inspection. Each is plotted only when the height could be determined with the given method.
boundary layer was too clean to clearly delineate a definite PBL top from aerosol backscatter on 12, 17, and 23 June 2006, and on 30 June, the “no threshold” criterion was not met using the objective method. On 10, 11, and 18 June 2006, the objective method outperforms the lidar, and on 22 and 27 June 2006 the lidar detects the PBL top with better accuracy. It is important to note that the real PBL may not have a top defined by a strong $\theta_v$ inversion or aerosol backscatter gradient every day, so on certain days (e.g., 16 and 25 June 2006) the different tops from the objective and lidar methods may be equally valid. On days with a very deep PBL, typically greater than 3000 m, seen on 27, 28, and 29 June 2006, the objective method underestimates the depth. This underestimation is due to lower heights exceeding the threshold $T_1$ and to a deeper entrainment layer causing a weaker delineation at the top of the PBL.

In a subjective visual inspection of the $\theta_v$ profiles combined with lidar, the skill of the objective method can be determined. Note that 12 and 23 June 2006 have an ill-defined PBL top and will not be considered. In the remaining days, we deem the top correctly identified if it is near a change in the slope of the $\theta_v$ profile, whether or not it agrees with the lidar top. Using these criteria, the PBL top is delineated correctly 23 of 28 days, or 82%. The remaining days are underestimated because of a deep PBL. This problem can be eliminated through further adjustment of the thresholds. Correlation coefficients

Fig. 3. Comparison of PBL depth as objectively determined from radiosonde with NARR PBL depths for four seasons: (a) DJF (winter), (b) MAM (spring) (c) JJA (summer), and (d) SON (autumn). The last digit of the year ($2002$, $3 = 2003$, etc.) is each point plotted.
(see Fig. 3) are highest in autumn and winter months because of less PBL height variability. Also, in the warm months there is a high spatial variability of NARR PBL heights, leading to lower correlation.

Figure 3 shows a comparison between the objectively determined PBL heights and those modeled by NARR at 1800 UTC for each day of every year by season: (a) winter [December–February (DJF)], (b) spring [March–May (MAM)], (c) summer [June–August (JJA)], and (d) autumn [September–November (SON)]. As with the lidar measurements, it is important to note these two datasets did not contain the exact same measurements, so it is not a verification. In each panel, a one-to-one fit line is shown for comparison between the two values. During the summer months, there is a far greater spatial variability of NARR PBL heights than during the winter months, so the points are more scattered even with the spatial averaging of the grids shown in Fig. 1. Therefore, despite the relatively lower variability in cooler months, the agreements between NARR and the objective method may not necessarily be better.

Because the objective method is a point measurement, it can be used to determine if there is a bias in the NARR calculations. The summer of 2006 was very dry, following the driest winter on record, while the summer of 2007 was the second wettest on record (Dong et al. 2011). In all panels of Fig. 3, the most common NARR underestimations compared with the objective method occur in 2006 and the most common overestimates are in 2007. This result indicates that the NARR surface model may overestimate the degree to which the surface is coupled with boundary layer depth. The implications of this bias will be explored further in the following section.

Using data from every available year (2002–10), a monthly climatology of mean PBL depths computed from the objective method at 1800 and 0000 UTC is shown in Figs. 4a,b, respectively. The error bars represent the mean of each individual year’s standard deviation of values. The 1800 UTC heights show a larger difference in variability between seasons than the 0000 UTC heights. This is likely due to the fact that winter PBL at the site is not fully expanded by 1800 UTC. The slight decrease in average 0000 UTC depths between March and April is consistent with afternoon rain lowering the detected PBL top. The degree to which atmospheric and soil moisture is coupled with the boundary layer height will be explored in future research.

4. Discussion and conclusions

The results compare well with previous studies of PBL heights near the SGP site (cf. Grimsdell and Angevine 1998). The heights agree with those computed at the site in 1997 (Coulter and Holdridge 1998). The Coulter and Holdridge study also showed a leveling out of maximum daily heights in the spring consistent with afternoon convection. The annual variability of heights, 1300 m at 0000 UTC, compares well with those computed by Holzworth (1964) at nearby sites (Omaha and Dodge City).

This study has demonstrated the effectiveness of a new objective method to determine the height of the PBL. The method is most effective on clear days with a well-defined PBL top as denoted by a change in the slope of $\theta_v$ approximately collocated with a dewpoint inversion. The method was initially developed for summer months but shows the best agreement with heights modeled by NARR in cooler months. As a point measurement, it is the best indicator of the actual top of the PBL when compared to gridded reanalysis. The first implication of the objective method is as a tool to produce historical climatologies of PBL depth. As stated, radio soundings are a more common measurement of boundary layer variables than lidar, radar, or towers. Because the objective method was developed specifically for sounding data, it is suited to produce an observational climatology in future research.

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