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

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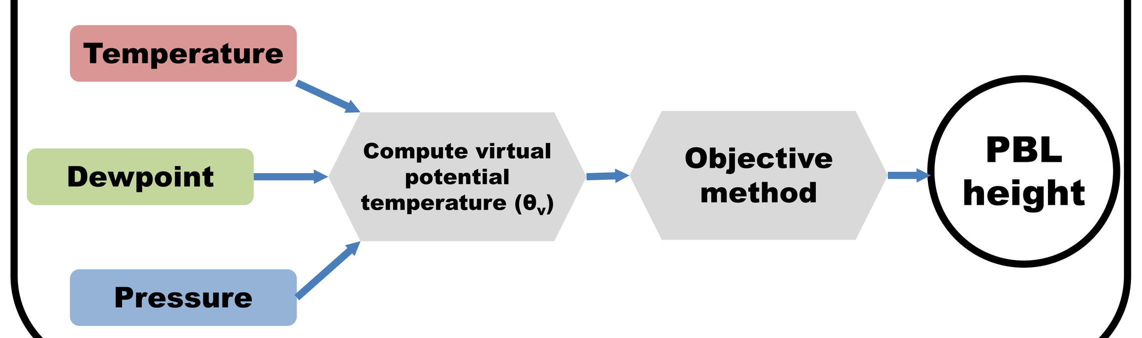
## Method

### Background

The planetary boundary layer (PBL) is the turbulent layer of the atmosphere near the Earth's surface. During the day, it typically comprises about the lowest 10% of the troposphere, but PBL heights of up to 4km have been observed. It is most commonly detected as an inversion in potential temperature and dewpoint, or as a peak in low-level wind speed (Grossman and Gamage, 1995). Determining the PBL height is important because it is where surface moisture, heat, and aerosol constituents are present and exchanged with the free atmosphere above. Subjective observational methods exist to find the PBL height from inspection of a vertical temperature profile or lidar backscatter (Hennemuth and Lammert, 2005), and numerical weather models may use a diagnostic formula using computed turbulence; however, until now, there has not been a consistent observational objective method to diagnose the PBL height.

### Methodology

We used temperature, moisture, and pressure measurements from the ARM SGP radiosondes at 18UTC and 00UTC. This allows the method to be applied to other upper air soundings which do not include wind data.




### Equations

Virtual potential temperature (potential temperature, computed with density equalized for moisture): $\theta_v = T(1 + 0.61q_v)\left(\frac{p_0}{p}\right)^{R_d/c_p}$

The inversion defining the top of the PBL was detected using statistical variance and kurtosis (4th moment about the mean). The variance and kurtosis of a sample **x** (defined as functions) are:

$$\sigma(\mathbf{x}) = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x}) \qquad \kappa(\mathbf{x}) = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left(\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2\right)^2} - 3$$

A test statistic at each height $k$ is computed using these functions over a vertical range of virtual potential temperatures ($n$):
$S_k = |(d_1 - d_2)\cdot\sigma(d_3)\cdot\kappa(d_3)|$
where

$$d_1 = \theta_v[(k-n):k] - T_d[(k-n):k]$$
$$d_2 = \theta_v[k:(k+n)] - T_d[k:(k+n)]$$
$$d_3 = \theta_v[(k-n):(i+n)] - T_d[(i-n):(i+n)]$$

Points exceeding a threshold $S_k > T_1$ were subjected to two other thresholds:

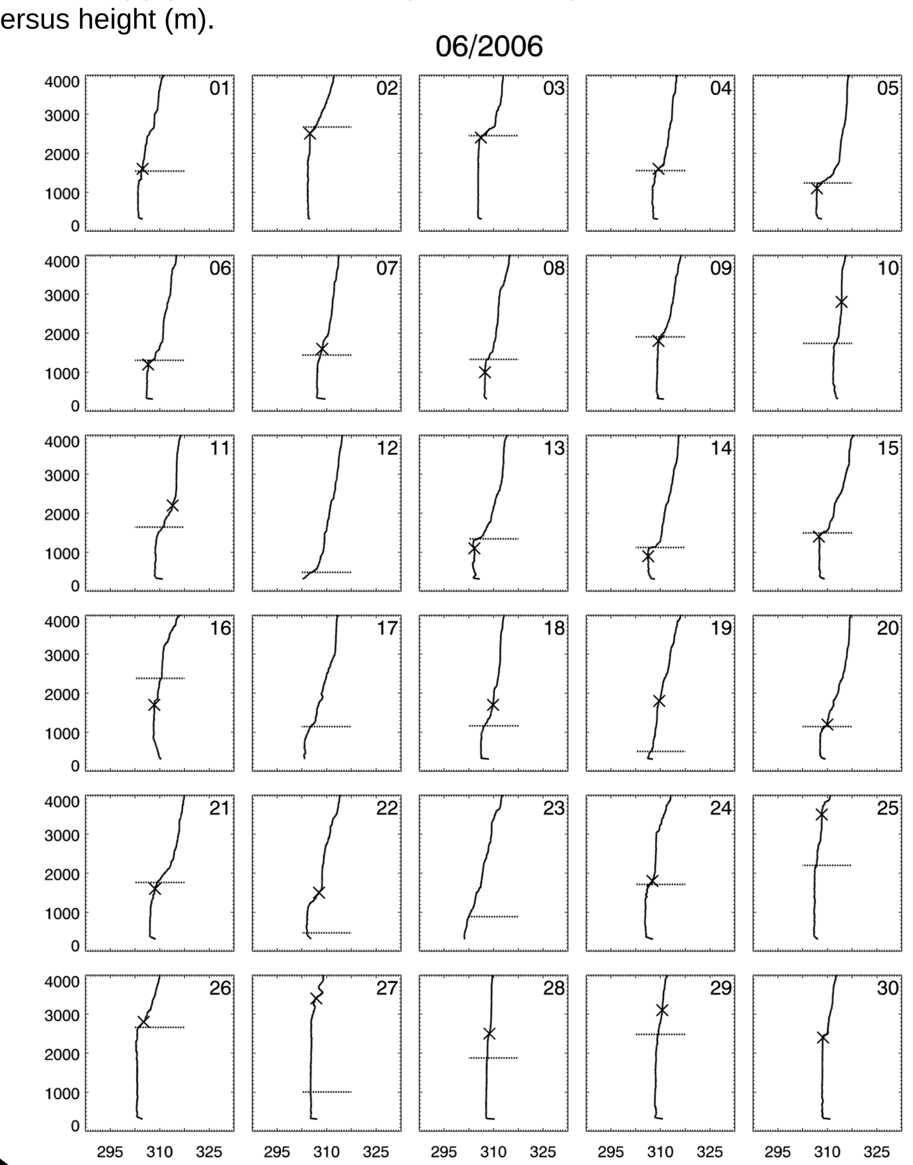
$$|\theta_v(k+1) - \theta_v(k)| > T_2 \qquad \frac{z(k+1) - z(k)}{|S(k+1)/S(k)|} > T_3$$

The first points exceeding all thresholds (in table below) were determined to be the PBL height.

| Value | Time | |
|---|---|---|
| | 1800 UTC | 0000 UTC |
| Number of points ($n$) | 3 | 10 |
| Test Statistic Threshold ($T_1$) | 0.5K | 1K |
| Number of points to check (w) | 3 | 5 |
| Homogeneity Threshold ($T_2$) | 0.5K | 0.5K |
| $\delta z/\delta S_i$ Threshold ($T_3$) | 50.0m | 100.0m |

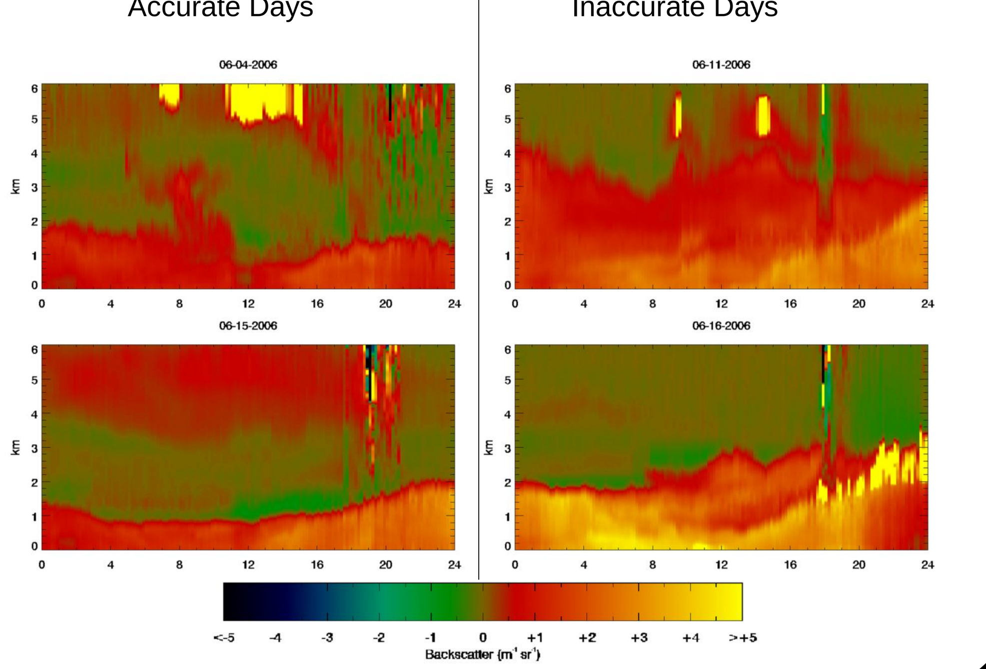
## Comparison

The following shows the comparison between detected PBL heights from the objective method (- - -) with those determined from visual inspection of the ARM lidar (**x**) (Tucker et al., 2009) for each day of June 2006. Plotted is $\theta_v$ (K) versus height (m).



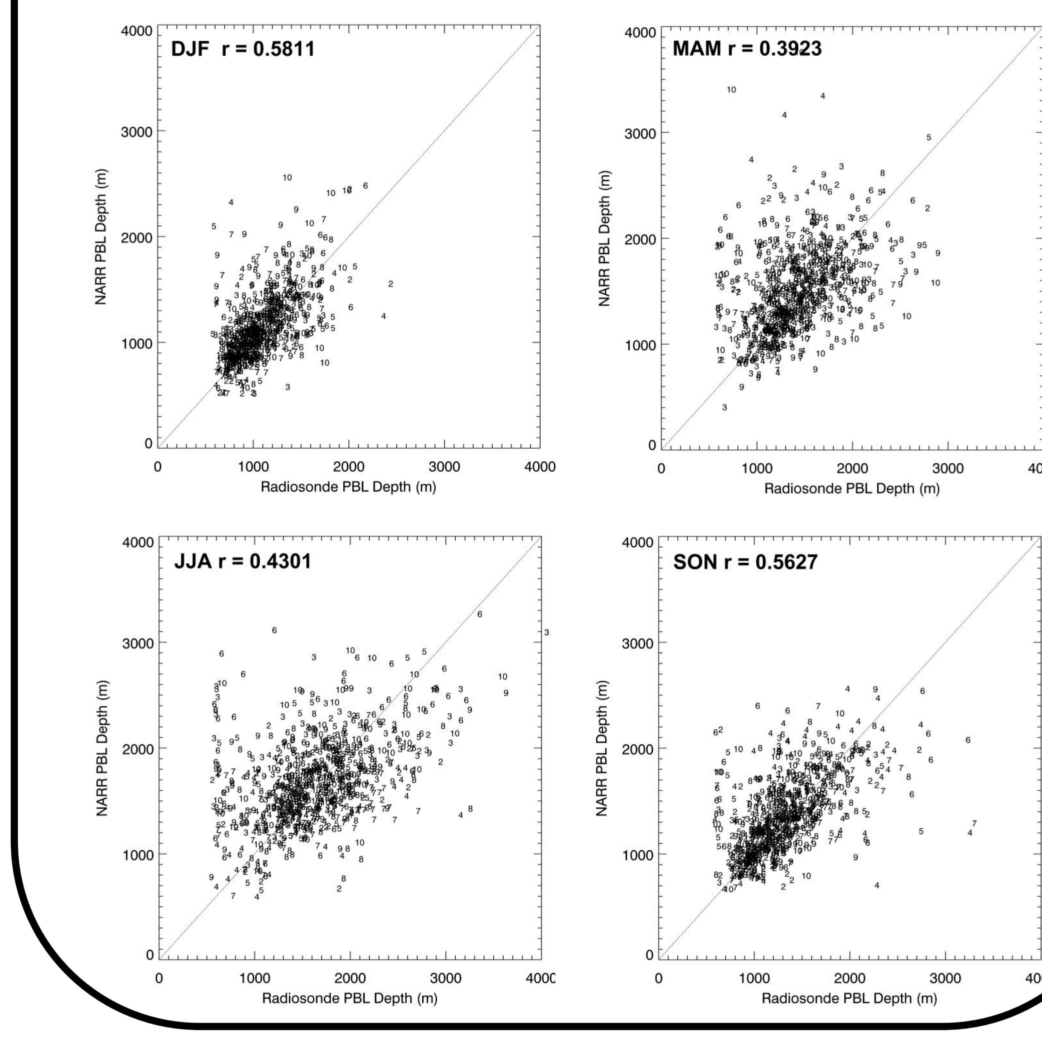

Computed heights were compared with heights identified from examination of the Raman Lidar, at the ARM SGP site, and with heights from the North American Regional Reanalysis (NARR, Mesinger et al., 2006). For the lidar comparison, June 2006 was chosen because a prolonged drought in Oklahoma caused more dust aerosols to be present over the SGP site (Garbrecht et al., 2007), and thus a stronger lidar backscatter. For the both, the analysis should be considered a *comparison* and not a true *verification*. Because different variables (aerosol backscatter for the lidar and turbulent kinetic energy for NARR) are used, a one-to-one verification is not possible.

Lidar backscatter was a useful comparison, but as can be seen below, the lidar does not necessarily provide a more accurate measure of the PBL height than the objective radiosonde measurement. A double maximum in lidar backscatter gradient (associated with the surface layer/mixed layer transition) leads to uncertainty in overall PBL height.



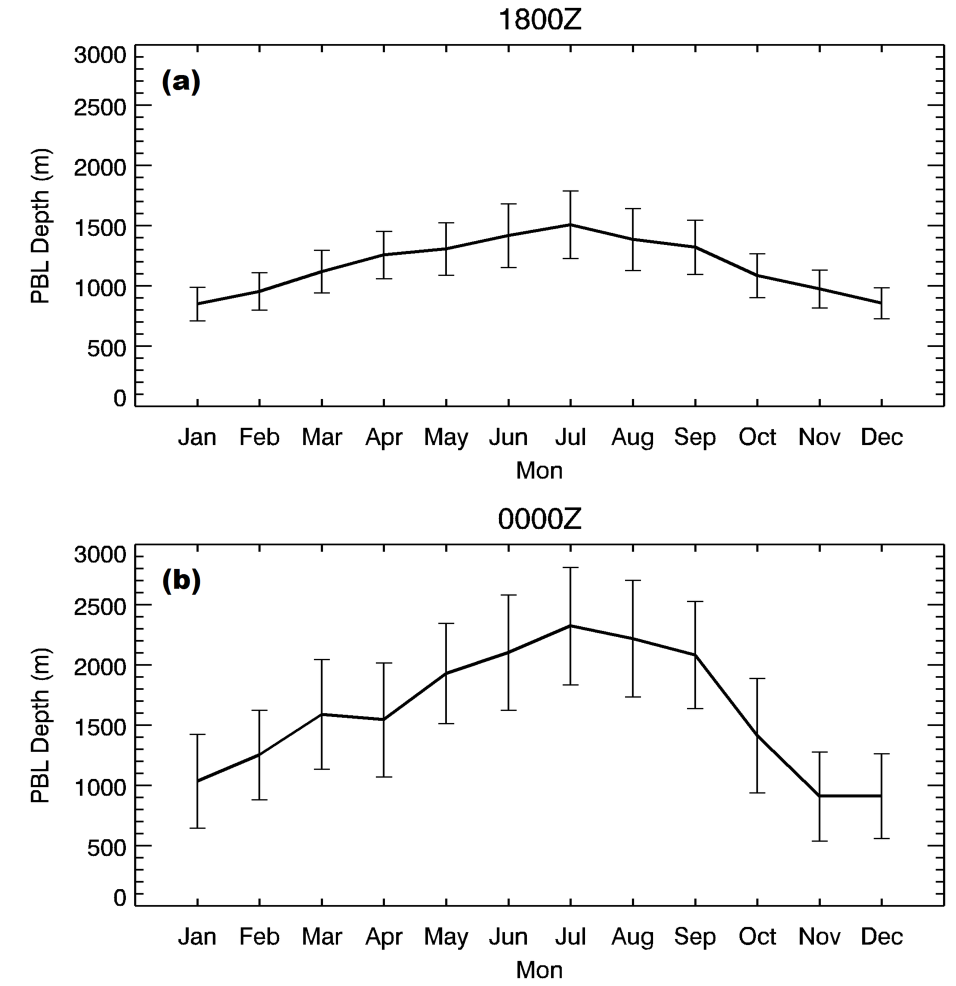

## Results

Shown below is a seasonal comparison of each day by year (2=2002, 3=2003 etc.) of computed PBL heights with NARR PBL heights. A one-to-one fit line is shown for comparison. During the summer months there is a higher spatial variability of NARR PBL heights than during winter months, so the points are more scattered. Therefore despite the relatively lower variability in cooler months, the agreement between NARR and the objective method may not necessarily be better.




### Boundary Layer Climatology

A boundary layer climatology was prepared from eight years of data at the ARM SGP site (2002 – 2010). These years were used because radiosondes were not launched at 18UTC before 2002. The results are comparable with previous studies in the Great Plains. Note in the 00UTC results, a decrease in the mean month PBL heights in April. This is due to afternoon convection (thunderstorms) causing rain to decrease the average late afternoon PBL height from March to April.




## Implications

### Accuracy and Replicability

The objective method is generally as accurate as other objective and subjective methods for determining the PBL height from observations.

- Seidel et al., 2010 surveyed a number of methods and found the typical error in PBL height determination to be ±100m.
- Given we use two variables, the computed error in our objective method is no greater than ±50m.
- Based on a Δz of 5 to 8m depending on balloon height, the error may be as small as ±15m.
- When compared to lidar, we observed 83% accuracy in June 2006.
- Nearly all inaccuracy arises from false detection of the PBL top due to clouds. Eliminating the cloud problem is possible at the SGP site by areas of detected clouds, but may not be replicable at NOAA radiosonde sites.

In applying the method, certain minimum requirements were determined to apply it outside the SPG site.

- The method does not require wind data enabling its use with upper air measurements only reporting temperature and moisture.
- The maximum Δz for an accurate PBL height is thought to be 30-50m. This is well within the range of contemporary and historical radiosondes, but too fine for satellite measurements such as the NASA AIRS sounder.
- The method can only be applied to the daytime boundary layer. At night, different conditions exist at the top of the PBL which preclude detection from a temperature or moisture inversion.

### Future Research

Ongoing research in applying this new method is focused on two projects.

1. Constructing a new observational climatology of PBL heights over the United States. Such a climatology has not been done since Holzworth (1964) and would be useful in diagnosing the surface effects of local and global climate change.
2. Studying the interactions between the surface, sub-surface and free atmosphere using instruments at the ARM SGP site. The ECOR instrument provides high frequency flux measurements and the SWATS instrument provides sub-surface temperature and moisture measurements. By comparing these with observed PBL heights, we can better understanding the surface to free atmosphere energy exchange.

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