Seasonal Variability in the Diurnal Evolution of the Boundary Layer in a Near-Coastal Urban Environment

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ABSTRACT

Boundary layer height is estimated during a 21-month period in Houston, Texas, using continuous ceilometer observations and the minimum-gradient method. A comparison with over 60 radiosondes indicates overall agreement between ceilometer- and radiosonde-estimated PBL and residual layer heights. Additionally, the ceilometer-estimated PBL heights agree well with 31 vertical profiles of ozone. Difficulty detecting the PBL height occurs immediately following a frontal system with precipitation, during periods with high wind speeds, and in the early evening when convection is weakening, a new stable surface layer is forming, and the lofted aerosols detected by the lidar do not represent the PBL. Long-term diurnal observations of the PBL height indicate nocturnal PBL heights range from approximately 100 to 300 m throughout the year, while the convective PBL displays more seasonal and daily variability typically ranging from 1100 m in the winter to 2000 m in the summer.

1. Introduction

The Houston, Texas, region is known for having poor air quality and frequently exceeds the 75 parts per billion by volume (ppbv) 8-h National Ambient Air Quality Standard (NAAQS) for surface ozone. According to the Texas Commission on Environmental Quality (TCEQ), the Houston region (Chambers, Harris, Montgomery, Galveston-Texas City, and Brazoria Counties) exceeded the 8-h ozone standard an average of 92 days yr\(^{-1}\) from 2000 to 2010. Surface ozone is of primary interest to policy makers and the public because of the adverse health effects associated with this pollutant (e.g., Lippmann, 1991; McConnell et al. 2002; Bell et al. 2004).

Efforts to improve air quality forecasting for southeastern Texas and regions of similar coastal and urban characteristics have been hampered by the lack of routine measurements of several key properties, including the planetary boundary layer (PBL) height. Small errors in numerical simulations often lead to erroneous ozone predictions because of the sensitivity of air quality to the details of the PBL structure and evolution (Zhong et al. 2007). The PBL plays an important role in ozone evolution because most nitrous oxide (NO\(_x\) = NO + NO\(_2\)) and volatile organic compound (VOC) sources are found in this layer of the atmosphere, and the PBL height determines the volume available for the dispersion of these pollutants (Seibert et al. 2000).

Most direct convective PBL height observations in Houston are limited to the late summer and fall in support of intense air quality field campaigns and typically range from 1000 to 2000 m (Banta et al. 2005; Rappenglück et al. 2008). Nielsen-Gammon et al. (2008) used an airborne microwave temperature profiler (MTP) and airborne aerosol backscatter lidar (light detection and ranging) to estimate PBL heights in Houston on 1 September 2000. PBL heights were approximately 700 m at 1600 UTC [1100 local time (LT)] and increased to up to 1100 m at 1800 UTC in the Houston area. On two separate days in August 2000, a radar wind profiler estimated PBL heights ranging from approximately 800 to 2000 m between 1500 and 2000 UTC. An airborne lidar also showed PBL heights reaching 2000 m in Houston at
1830 UTC. Rappenglück et al. (2008) used radiosondes to estimate PBL heights at the University of Houston (UH) main campus (approximately 4 km southeast of downtown Houston) during August and September 2000. The average PBL heights were 350, 550, 1300, and 1600 m at 1200, 1500, 1800, and 2100 UTC, respectively. Fifty-six morning soundings were conducted, with 11, 17, and 11 radiosondes were launched at 1500, 1800, and 2100 UTC, respectively.

Knowledge of the nocturnal PBL is very limited in Houston. Day et al. (2009) used a tethersonde system to study the PBL on four nights in August and September 2006 at the UH campus. A weakly stable surface inversion formed typically within 2–3 h after sunset, with an average depth between 145 and 200 m each night. This study also observed a land breeze on three of the nights, which began near the coast and propagated inland with time.

PBL parameterizations used in models often incorrectly simulate the PBL height in Houston. Using radiosondes launched over a 10-day period in July 2004, Zhong et al. (2007) showed the inability of the fifth-generation Pennsylvania State University (PSU)–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) to consistently simulate the evolution of the convective PBL and the early morning inversion during stable conditions. More recently, Lee et al. (2011) found improved agreement between measured and modeled urban boundary layer (UBL) heights in Houston from 12 to 17 August 2006 using the Weather Research and Forecasting (WRF) single-layer urban canopy model (UCM). This study was limited to daytime conditions only, and the authors noted further performance evaluations in predicting the nocturnal UBL still remain.

Zhong et al. (2007) also used radiosonde data from flights at Rice University, located approximately 5 km south of downtown Houston, to compare the performance of the MM5 when different PBL, land surface, and radiation parameterizations were used. The observed PBL heights ranged from 1000 to 2400 m, and there was a general tendency for the different MM5 parameterization configurations to underestimate the PBL heights. In addition, all simulations failed to capture the strength of the observed early morning inversion, and the simulated morning PBL above the surface layer was most often unstable, whereas observations regularly showed near-neutral stratification.

The use of modern ground-based remote sensing techniques capable of continuously measuring the diurnal variations of atmospheric layers has grown substantially. A ceilometer system, or small lidar remote sensing device, is very useful not only because it measures continuously, but because it is also reliable and requires little maintenance. Ceilometers are capable of identifying structures present in the PBL using aerosol backscatter profiles. The use of this instrument for boundary layer height detection, however, is limited to mostly cloud-free days because the light pulse is attenuated as it penetrates dense water vapor.

Several studies have shown overall agreement between lidar and radiosonde estimates of the PBL height during both unstable and stable PBL conditions (e.g., Eresmaa et al. 2006; Emeis and Schäfer 2006; Münkel et al. 2007; Martucci et al. 2007). Martucci et al. (2007) compared 67 noon and 37 midnight radiosonde launches to a backscatter lidar during 2 years in Neuchâtel, Switzerland (47.00°N, 6.97°E). Measurements were performed in different synoptic conditions, but always in a cloud-free environment (excluding high cirrus). A correlation coefficient ($R^2$) of 0.90 was found between the lidar and radiosonde potential temperature gradient estimates of the residual layer height. During unstable conditions, the correlation coefficient was slightly higher, $R^2 = 0.96$. The lower correlation coefficients during nighttime were due to the aerosol multilayer structure present immediately above the residual layer top, which made its height detection more difficult. Münkel et al. (2007) also found overall agreement between radiosonde- and ceilometer-estimated PBL heights during convective ($R^2 = 0.9$) and stable ($R^2 = 0.8$) conditions in Vantaa, Finland (60.30°N, 24.97°E). Approximately 3% and 21% of convective and stable comparisons were removed from the analysis because of low backscattering signal near the surface.

Ceilometers are capable of providing long-term observations of the diurnal evolution of the PBL. Van der Kamp and McKendry (2010) collected 26 months of continuous ceilometer data in Vancouver, British Columbia, Canada (49.28°N, 123.12°W). This study focused on the convective mixed layer (ML) height seasonal variability and excluded all nocturnal observations. After removing periods with either precipitation or low clouds, 250 out of the 710 days were selected for convective ML height estimations. Ceilometer-estimated ML heights agreed well with previous field observations, but the ceilometer-estimated ML heights showed slightly higher values in the morning and evenings compared to the observations. The ML height seasonal cycle peaked from late June to early July for clear days with no cumulus cloud formation. Summer and spring were found to have similar diurnal trends on clear days, and days with boundary layer clouds in the spring had higher ML heights than those in the summer. The site’s coastal location suppressed daily maximum ML heights, which remained mostly below 800 m.

A uniquely comprehensive view of the PBL height evolution and variability on daily and seasonal time scales
is presented for the first time using 21 months of high temporal resolution ceilometer observations over a full diurnal cycle in Houston. Continuous identification of the PBL height will help Houston modelers adjust their PBL parameterizations and unravel the effects of PBL dynamics on surface ozone levels. ceilometer-estimated PBL and residual layer heights are evaluated using radiosondes in this urban and subtropical environment, which offers insights regarding the ceilometer’s ability to estimate the PBL height during intense convective conditions (with PBL heights up to ~3 km) and during the rapid growth of the PBL height in the morning. In addition, estimates of the PBL height using ceilometer and vertical profiles of ozone are compared for the first time. This comparison is important for air quality applications: determining the degree of agreement between the aerosol and ozone defined ML heights.

2. Data and methods

a. Site description and study period

The ceilometer and radiosonde measurements are collected in Houston at the UH main campus located 35 km west of Galveston Bay and 70 km northwest of Galveston, Texas, and the Gulf of Mexico. The ceilometer is mounted approximately 3.5 m above the ground atop a trailer. All radiosonde and ozonesonde launches are conducted outside of the trailer (11 m MSL; 29.72°N, 95.34°W) at the UH campus. The campus is located in a partially wooded and grass-covered land surface approximately 5 km southeast of tall buildings of “downtown” Houston, 1 km southwest of Interstate 45, 3.5 km north of the South Interstate 610 Loop, 80 km from the Gulf of Mexico, and 40 km from Galveston Bay.

Radiosonde and ozonesonde launches from April 2009, when the ceilometer became operational, through November 2010 are used to evaluate the ceilometer. Because the majority of Houston ozone exceedances occur in the spring and late summer, most of the radiosondes and ozonesondes are launched during these two seasons. Monthly and seasonal trends in PBL height are based on ceilometer observations at the UH campus from 1 April 2009 through 31 December 2010 for a total of 640 days.

b. Instrumentation

1) RADIOSONDES

The Vaisala RS80-15N, Vaisala RS92-SGP, and Inter-Met (iMet) 1-AA and 1-BB radiosondes are used in this study. All radiosondes return pressure, temperature, and humidity using a 403-MHz transmitter. The RS92-SGP and iMet radiosondes also measure wind speed and direction using a built-in global positioning system (GPS) unit. The radiosondes weigh between 220 and 265 g and are attached to a Kaymont 100-g balloon. The meteorological sensors are individually factory calibrated.

The three types of radiosondes have a resolution between 0.01 and 0.10 hPa, a response time of 1 s, and an accuracy between 0.5 and 1.8 hPa for pressure measurements. Temperature sensing for the radiosondes includes a resolution ranging from 0.01° to 0.10°C, accuracy ranging from 0.15° to 0.20°C, and a response time of less than 3 s. The humidity sensors for the radiosondes have a resolution of less than 1%, accuracy ranging between 2% and 5%, and a response time from 0.5 to 2 s. The iMet radiosondes have the slower response times and larger uncertainties. Typical ascent rates of the radiosondes range from 4 to 5 m s⁻¹.

2) OZONESONDES

Vertical profiles of ozone are measured using the electrochemical concentration cell (ECC) type (Komhyr 1986) En-Sci 2Z ozonesonde instruments with 0.5% buffered potassium iodide (KI) cathode solution. The Jülich Ozone Sonde Intercomparison Experiment (JOSIE) found biases <5%, a precision of 3%–5%, and an accuracy of 5%–10% up to 30 km for these types of ozonesondes (Smit et al. 2007). The ozone instrument has a response time of approximately 20 s. The ozonesonde package also includes either a Vaisala RS80-15N or iMet 403-MHz radiosonde to measure pressure, temperature, and relative humidity (wind speed and direction with iMet sondes). The sondes were launched either a 350- or 600-g Kaymont balloon. The ozonesonde data from Houston are described in Morris et al. (2006).

3) CEILOMETER

The Vaisala ceilometer CL31 is used in this study and was installed at the UH campus in March 2009. This instrument has a measurement range of 0–7500 m and a vertical resolution of 10 m. The CL31 is an eye-safe ceilometer operating at a wavelength of 905 nm using an indium gallium arsenide (InGaAs) laser diode system. The system uses a single 1.2 μJ per pulse for 110 ns. Eye-safety considerations do not allow larger single pulse energy values. This limitation is overcome by using a high mean pulse repetition rate (8192 Hz), which increases the signal-to-noise ratio (Münk el et al. 2007).

The CL31 uses a single lens design, which allows the instrument to discern structures lower in the atmosphere. The outer part of the lens is used for focusing the back-scattered light on to the receiver, whereas the center of the lens is used for collimating the outgoing laser beam (Münk el et al. 2007). Please see Münk el et al. (2007) for a more in depth description of the instrument.
c. Estimation of the PBL height

Cases for comparison are selected for cloud- (cumulus, stratus, and altostratus) and fog-free conditions (using visual observation); however, cirrus clouds might be present because the ceilometer measurement range extends to 7500 m. No other criteria of selection have been applied.

1) RADIOSONDE-ESTIMATED PBL HEIGHTS

Radiosonde PBL heights are subjectively identified using profiles of temperature and humidity. Different guidelines are used for the unstable (or convective) PBL and stable (or nocturnal) PBL. In a stable environment, the PBL height is found at the height of the first discontinuity, or sharp change in the vertical gradient, in the temperature or humidity profile and/or top of the surface inversion or stable layer using a skew $T$–$\log p$ diagram (Kovalev and Eichinger 2004). Two meteorological methods for determining the PBL height during unstable conditions are used in this study. The first method identifies the PBL height as the base of an elevated inversion or stable layer and/or the height at which moisture sharply decreases using a skew $T$–$\log p$ diagram (Kovalev and Eichinger 2004).

The second method uses potential temperature as a proxy for determining the PBL height during unstable conditions. More specifically, a decrease of potential temperature with increasing altitude indicates an unstable layer and a decrease in the static stability (Stull 1988). The parcel method compares the surface potential temperature to the potential temperature at each level of the sounding to determine the daytime convective PBL height. The intersection of the potential temperature profile with the dry adiabat that starts at the surface temperature (recorded by the radiosonde) is the PBL height (Holzworth 1964, 1967).

2) OZONE PROFILE-ESTIMATED PBL HEIGHTS

The following two different PBL heights are identified using the ozonesonde instrument: 1) using the temperature and dewpoint temperature profiles described above (skew $T$–$\log p$ method) and 2) using the ozone profile described in this section. Both methods are displayed in Figs. 1a,b. The second method is based on the fact that the PBL height represents the top of the layer through which relatively vigorous mixing takes place because of turbulence. Pollutants should be relatively constant in this layer up to the PBL height. The PBL height is determined as that level up to which the ozone mixing ratio had been approximately constant during unstable conditions. In most cases, this is equal to the level at which a sharp change in the vertical ozone gradient is observed. However, mixing under stable conditions is not strong enough to maintain a nearly constant trace gas distribution with height. The stable vertical ozone profile increases linearly with height as a result of the nocturnal inversion inhibiting mixing and dry deposition and chemical destruction serving as a sink across the zone of this linear increase (Güsten et al. 1996). In these cases, the PBL height was therefore determined as the height up to which nearly linear ozone decreases with altitude have been found (Beyrich et al. 1997).

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**Fig. 1.** Three methods for determining the PBL height (horizontal dotted black lines) during unstable conditions: (a) skew $T$–$\log p$ method using temperature $T$ and dewpoint temperature $T_d$, (b) ozone profile method $O_3$, and (c) parcel method using potential temperature $PT$. The surface temperature is shown (vertical dotted black line). Data are from an ozonesonde launched from the UH campus at 1910 UTC 19 May 2009.
It is important to take into account the instrument response time when determining the PBL height using the vertical ozone profiles. This study uses a simple method to determine the altitude correction similar to that of Poberaj et al. (2009): the ozonesonde response time of \( \approx 20 \) s and the average balloon ascent velocity of \( \approx 5 \) m s\(^{-1}\) lead to an altitude correction of \( \approx 100 \) m. This altitude adjustment is applied to all vertical ozone profile data and referred to as “ozone lag.”

It is also necessary to account for sulfur dioxide interference when analyzing launches that did not include sulfur dioxide filters on the ozonesonde instrument. Sulfur dioxide interferes with 1:1 stoichiometry when measuring ozone using the KI method (Bryan et al. 2010). A layer for which the unfiltered ozonesonde reports a sharp negative vertical ozone gradient at the bottom and a sharp positive ozone gradient at the top in the presence of high humidity levels is often indicative of the presence of a sulfur dioxide layer (Rappenglück et al. 2008; Morris et al. 2010). Substantial amounts of sulfur dioxide have been observed after rain events or in early morning profiles with easterly winds when the UH campus is downwind from multiple sulfur dioxide sources and the PBL is shallow. Typical background levels of sulfur dioxide are less than 2 ppbv, and there is usually no significant impact on vertical ozone profiles in polluted areas like Houston.

3) CEILOMETER-ESTIMATED PBL HEIGHTS

The Vaisala PBL height algorithm version 3.5 is used in this study to identify structures present in the ceilometer backscatter retrievals using the gradient method. This method selects the maximum of the negative gradient \( -(d\beta/dx) \) of the backscatter coefficient to be the top of the PBL. This vertical backscatter gradient is a result of atmospheric aerosol concentration, which is largely controlled by changes in PBL stability and the strength of local aerosol emissions sources in the urban environment. The gradient method makes two assumptions about the atmospheric distribution of scattering aerosols: 1) the PBL has a constant concentration of aerosols and 2) there is relatively strong backscatter inside the PBL compared to a lower backscatter level above it (Steyn et al. 1999). During unstable conditions, aerosols are well mixed in the PBL. A sharp decrease in aerosol concentration exists above the capping inversion and thus creates an aerosol gradient between the PBL and free troposphere. During nocturnal or stable conditions, the aerosols are not as well mixed compared to unstable conditions. The weaker or more intermittent turbulence does, however, distribute some aerosols upward within the stable layer, creating a gradient between the stable and residual layers.

The algorithm is capable of determining up to five local maximums. This option allows for other PBL structures to be identified such as the residual layer. A local minima backscatter of \( 200 \times 10^{-9} \) m\(^{-1}\) sr\(^{-1}\) is used, which is the minimum backscatter that is accepted at a local gradient minimum to make it a candidate for the PBL height. The relative gradient determines the threshold for a local gradient minimum to be reported as PBL height. This study uses 15%. The change in the backscatter amount in the vicinity of the possible PBL height has to exceed 15% of the mean backscatter value between 0 and 1000 m. Because of height averaging constraints, the lowest possible identifiable PBL height is 80 m. Please refer to the appendix for a complete summary of the ceilometer settings used in this study.

Certain atmospheric processes, such as precipitation and high wind speeds, act to decrease aerosol concentrations in the atmosphere. Aerosol optical thickness (AOT) observations made at the UH main campus using a CIMEL sun photometer instrument show the accumulation of aerosols before three different rain events followed by relatively lower AOT values after the rain (Fig. 2). AOT is a dimensionless quantity that indicates the amount of depletion that a beam of radiation undergoes as it passes through a layer of the atmosphere. Rain events cleanse the atmosphere. Periods of high wind speeds increase vertical mixing and horizontal advection, which inhibit the formation of distinct aerosol layers within the ML and limit the lifetime of any layers that do form. The CL31 relative gradient percentage may need to be lowered from 15% immediately following rain events and during periods of high wind speeds (especially during nocturnal conditions).

![Fig. 2. Precipitation and AOT at three different wavelengths (1640, 870, and 340 nm) from 7 to 25 Apr 2009 measured at the UH campus.](image-url)
3. Results

a. Evaluation of the ceilometer PBL algorithm

The ceilometer PBL algorithm is evaluated against three sonde benchmarks during unstable conditions (the skew $T$–log $p$ gradient, parcel, and ozone profile methods) and one sonde benchmark during stable conditions (the skew $T$–log $p$ gradient) as described in the previous section. A bias and standard deviation are computed for each comparison similar to Nielsen-Gammon et al. (2008). The bias is defined as the difference between the means of the paired samples, and the standard deviation is the root-mean-square value of the departures of the individual pair sample differences from the mean difference (or bias). A positive bias indicates the mean estimates from the ceilometer are greater than the mean estimates from the given sonde benchmark. A two-tailed, one-sample $t$ test is used to determine the statistical significance of the bias. The null hypothesis (the ceilometer estimate of the PBL is unbiased when compared to the sonde benchmark) was not rejected when the calculated $t$ statistical value was between $6.196$ and the $p$ value was greater than 0.05 (95% confidence).

1) STABLE CONDITIONS

An example of a stable PBL is displayed in the skew $T$–log $p$ diagram using the 19 May 2009 UH campus radiosonde launched at 1200 UTC (Fig. 3). The temperature is approximately 15.5°C at the surface and remains constant until about 125 m, above which temperature begins to increase with height to 18.0°C at 370 m. The low-level inversion limits the vertical dispersion of surface emissions such as aerosols and other particulates and confines these pollutants to the lowest few hundred meters of the PBL, resulting in a strong aerosol gradient at the top of the surface layer. The ceilometer algorithm identifies a gradient at 100 m at the time of the radiosonde launch (1200 UTC), which agrees well with the radiosonde estimation (Fig. 4).

A high pressure system dominated the region during this time, which moved into the area after an intense frontal passage on 17 May. The postfrontal environment includes lower humidity levels, weaker wind speeds, intense radiative cooling, relatively weak mechanical turbulence, and a stable surface layer. The increase in backscatter gradient from approximately 100 to 250 m is a result of increased wind speeds from 0700 to 0915 UTC, which peaked at 6 m s$^{-1}$ at the UH Moody Tower weather station.

Ceilometer- and radiosonde-estimated PBL heights are compared for 26 stable cases (Fig. 5) using radiosondes launched mostly during April and May (Fig. 6). Stable PBL heights range from approximately 100 to 300 m. Overall, the correlation coefficient value of ($R^2$) 0.91 indicates that the ceilometer agrees extremely well with the radiosondes during stable conditions (Fig. 5). Ceilometer-estimated PBL heights have a bias of 2.1 m (~1.2%) and standard deviation of 21.8 m relative to the skew $T$–log $p$ benchmark method, which indicates the ceilometer technique is very accurate in determining the PBL height during stable conditions (Table 1).

It is important to note that 5 of the original 31 stable cases are not included in Fig. 5, suggesting that agreement was good for approximately 84% of the total cases. Aerosol gradients that are insufficient to trigger the default backscatter gradient are present in four of the five cases at about the proper level identified by the radiosondes (at 1100 UTC 25 April 2010, 1100 UTC 26 April 2010, and 0250 and 0605 UTC 27 May 2010). There is no identifiable aerosol gradient in the fifth case (on 5 November 2010).

2) UNSTABLE CONDITIONS

In this study 47 radiosonde launches during unstable conditions are analyzed. The majority of the launches took place at 0000 and 1900 UTC during April and May 2009 in support of the Study of Houston Atmospheric Radical Precursors (SHARP) field campaign (Fig. 6). The
0000 UTC launches are strictly radiosonde flights while the afternoon 1900 UTC launches commonly consisted of a radiosonde attached to an ozonesonde instrument.

PBL height estimation using the skew $T$–$\log p$ method during unstable conditions is displayed for the 0000 UTC radiosonde launch on 20 May 2009 (Fig. 1a). The parcel lapse rate is constant until approximately 1770 m where a temperature inversion begins and the dewpoint temperature begins to decrease rapidly. Weak winds are present near the surface and westerly winds dominate aloft, with a peak wind speed of 12.9 m s$^{-1}$ near 1780 m (now shown). The parcel method is applied to this case, and the estimated PBL height is 1780 m (Fig. 1c) while the ceilometer estimates a PBL height of 1870 m.

Both the skew $T$–$\log p$ and parcel methods are compared to the ceilometer PBL height estimates (Fig. 5) for all launches included in Fig. 6. Correlation coefficients ($R^2$) of 0.96 and 0.92 are computed between the ceilometer and skew $T$–$\log p$ and parcel methods, respectively. Biases of 23.2 (≈1.8%) and −19.4 (≈1.5%) m with standard deviations of 91.6 and 129.4 m indicate the ceilometer estimates are, on average, higher than the skew $T$–$\log p$ technique and lower than the parcel method estimates (Table 1). Neither of these biases is statistically significant. The launches performed later in the day (0000 UTC and later) do not agree as well as those in the afternoon (1900 UTC).

3) PBL HEIGHT ESTIMATION USING OZONE PROFILES

PBL heights estimated using the vertical ozone profiles are compared to the ceilometer estimates (Fig. 5) for 31 ozonesonde flights (Fig. 6). The majority of launches took place in the spring and fall during the afternoon. The ozonesonde launch at 1910 UTC 19 May

![Fig. 4. Log$_{10}$ of the backscatter on 19–20 May 2009 using ceilometer retrievals from the UH campus. Three gradient local minima (Local Min) are indicated. The radiosonde launches at 1200 UTC 19 May and 0000 UTC 20 May 2009 from the UH campus are indicated (white vertical lines).](image1)

![Fig. 5. Comparison of ceilometer-estimated PBL and residual layer heights with five different benchmark technique estimates. The linear regression lines, associated equations, and correlation coefficients $R^2$ are also given for each benchmark technique.](image2)
2009 shows a rapid decrease in ozone at 1690 m using the raw ozone profile or 1590 m when taking into account the ozone instrument “ozone lag” (Fig. 1b). The ceilometer estimates a 1770-m PBL height at this time while PBL heights of 1690 and 1780 m are identified using the skew $T$–$\log p$ technique and parcel method, respectively, on 19 May 2009.

Correlation coefficients ($R^2$) of 0.96 and 0.95 are found between the ceilometer and the raw ozone and ozone lag estimates of the PBL height (Fig. 5) with biases of $-23.0$ and $77.0$ m, respectively (Table 1). The biases are not statistically significant, which indicates overall agreement between the ceilometer algorithm and ozone benchmarks. The 29 June and 17 July 2009 launches are excluded from the analysis (discussed in next section). The ozone PBL height technique is also compared to both meteorological PBL height techniques, skew $T$–$\log p$ and parcel, and overall agreement is found with correlation coefficients ($R^2$) of 0.96 and 0.95, respectively.

4) DIURNAL EVOLUTION

The good agreement between the ceilometer, skew $T$–$\log p$, parcel, and ozone profile gives credibility to the use of the ceilometer in examining the complete diurnal evolution of PBL structures. Ceilometer and four radiosonde-estimated PBL heights are displayed for 19–20 May 2009 (Fig. 7). In addition to identifying the PBL height, the ceilometer algorithm and radiosondes identify a structure around 1250 m from 0900 to 1500 UTC on 19 May 2009. This aloft structure is the residual layer, which can store the previous day’s ozone and ozone precursors, such as nitrogen oxides ($\text{NO} + \text{NO}_2$) and hydrocarbons (e.g., Velasco et al. 2008) both of which influence PBL ozone concentrations later in the day (Morris et al. 2010).

The diurnal evolution of the PBL is very important, but the rapid rise in the morning is of particular interest for air quality purposes because this is when surface ozone also begins to increase. The 27 May 2010 morning sondes extensive shows the ability of the ceilometer in estimating the PBL height during the rapid rise and also displays aerosol and ozone gradients aloft in the residual layer (Fig. 8). In the presence of clear skies and weak mechanical mixing, the residual layer is strongly decoupled from the stable nocturnal PBL (Stull 1988). This isolation of the residual layer from the surface acts to conserve moisture and pollutants from the previous day’s ML and is usually strongest in postfrontal environments in Houston when nonsoutherly flow results in lower moisture levels, weaker winds, and large-scale subsidence. Air is statically neutral in the residual layer, and the top of the residual layer is marked by a capping inversion (Stull 1988). The 19 May 2009 and 27 May 2010 examples also demonstrate the ability of the ceilometer to simultaneously identify the PBL and residual layer heights. Comparisons of 19 radiosonde and ceilometer estimates of the top of the residual layer during strongly stable conditions show overall agreement (Fig. 5) with a bias of less than 1 m and a standard deviation of 126 m (Table 1).

### Table 1. Standard deviation (std dev), bias, and number of data points for comparison of benchmark method with the CL31 algorithm estimates. Each listed bias is defined as the CL31 algorithm estimate minus the corresponding sonde benchmark estimate.

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<th>Sonde benchmark (unstable cases)</th>
<th>Std dev (m)</th>
<th>Bias (m)</th>
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### b. Monthly and seasonal PBL evolution

Ceilometer estimates are used to compute the mean monthly and seasonal diurnal evolution of PBL height using observations from April 2009 to December 2010. Extended time periods with fog, low clouds, or precipitation are manually removed from the dataset in addition to time periods with missing data resulting from the loss of communication between the instrument and the computer responsible for processing and storing the backscatter retrievals. A total of 332 days are used for estimating the PBL height using the ceilometer observations.
Approximately 13 days month\(^{-1}\) (a standard deviation of 4.9 days) are available for analysis in 2009, and the mean daily percentage of coverage of PBL heights for each day is approximately 55\% (i.e., the fraction of day with PBL height observations). As a result of improved communication between the ceilometer and data-logging computer, approximately four more days per month are available for analysis in 2010 compared to 2009 (17 ± 5.3 days month\(^{-1}\)). The number of days missing per month resulting from meteorological factors, however, are similar in 2009 (7.4 ± 4.8 days month\(^{-1}\)) and 2010 (7.3 ± 3.7 days month\(^{-1}\)). The mean daily percent coverage of PBL heights for each available day in 2010 is approximately 60\%.

The ceilometer algorithm output is manually inspected to find the PBL height for every 5-min interval during the 1 April 2009–31 December 2010 study period. If the height of the PBL is not clear, a height is not reported for that particular interval. Each day 20-min bins are created using the ceilometer 5-min-estimated PBL heights, and a mean diurnal evolution of the PBL height is found for each month using the bins from all days within the month (2009 and 2010 are grouped together). The standard deviation for each 20-min bin is determined by

$$\sigma = \sqrt{\sigma_Z^2 + \sigma_S^2},$$

where \(\sigma_Z^2\) is the variance for the measurement errors (using Table 1) and \(\sigma_S^2\) is the variance for each 20-min bin using the 5-min data (Jiang et al. 2007).

Box-and-whisker plots in Fig. 9 summarize the annual and daily variability in maximum convective PBL heights. On average, August has the highest convective PBL height, which peaks at approximately 2030 m, while December has the lowest at just over 1100 m at 2200 UTC. During this afternoon PBL peak, the standard deviations for August and December are very similar (300 and 250 m, respectively). PBL growth begins earlier in August (\(\sim 1300\) UTC) compared to December (\(\sim 1400\) UTC) because of the earlier sunrise in the summer months (not shown). Nocturnal PBL heights are slightly lower in December (\(\sim 130\) m) in comparison to August (\(\sim 160\) m), although this difference is not statistically different. Similar maximum afternoon PBL heights are found in March and April and also in September and October. May and August have the largest upper and lower adjacents (or box whiskers) while June has the smallest compared to the other summertime months.

A seasonal cycle also exists in mean diurnal cycle of the PBL heights, especially for the spring and fall months. Figure 10a shows the mean PBL diurnal cycle for March–May (MAM), with the ML growing earlier in the morning (near 1200 UTC) in May than in April and March. Nocturnal stable PBL heights are very similar.
(∼200 m) whereas the convective PBL heights are approximately 1350 m for March and April and extend to almost 1600 m during May. Similar nocturnal stable PBL heights are found in September–November (SON; Fig. 10b). Growth of the ML is first evident near 1400 UTC for September and is successively later in October and November. September and October have similar peaks in the afternoon (∼1525 m) whereas the November peak is lower at approximately 1200 m. The winter [December–February (DJF)] and summer [June–August (JJA)] have less variability than the spring and fall (not shown).

To more easily distinguish changes in the PBL diurnal cycle during the different seasons, Fig. 11 shows a mean diurnal cycle for each season: DJF, MAM, JJA, and SON. Overall, DJF has the lowest afternoon PBL peak and lowest nocturnal stable PBL while JJA has the highest afternoon peak and highest nocturnal stable PBL. The ML begins to grow the earliest in JJA followed by MAM, SON, and DJF. Although the SON nocturnal stable PBL persists longer than the MAM nocturnal stable PBL, the afternoon PBL height maxima are similar.

Changes in the solar zenith angle also affect the diurnal evolution of the PBL. On the summer solstice (21 June), solar radiation is at a maximum in Houston with a minimum solar zenith angle of ∼6°. The opposite is true on the winter solstice (21 December) when solar radiation is at an annual minimum in Houston, and the minimum solar zenith angle is ∼53°. Months closer to the summer solstice experience an earlier growth of the ML during the morning hours and a longer presence of a convective PBL as a result of more daylight hours (reflected in Figs. 10–11).

4. Discussion

Drawbacks and applications of ceilometer-estimated PBL heights

The previous section showed overall agreement between the ceilometer and sonde benchmark estimates of

FIG. 8. Log$_{10}$ of the negative backscatter gradient on 27 May 2010 using ceilometer retrievals from the UH campus. Three gradient local minima (Local Min) are indicated. The sonde launches (white vertical lines), sonde PBL heights (red circles), and ozone peak heights (brown circles) at 1120, 1340, and 1540 UTC 27 May 2010 observed at the UH campus are indicated.

FIG. 9. Monthly boxplots showing the median, 25th, and 75th percentiles, extreme data points not considered outliers (whiskers), and individual outliers (crosses) of the daily maximum PBL heights. The monthly mean PBL height is indicated (solid black line).
the PBL height. Under certain meteorological conditions or during specific times of the day; however, ceilometer estimates of the PBL height can be erroneous.

1) STABLE CONDITIONS

Heavy precipitation combined with strong winds speeds from 2–4 November 2010 prevented the accumulation of aerosols in the Houston area and thus reduced the aerosol gradient between the PBL and free troposphere. The UH campus rain gauge recorded over 125 mm of precipitation on 2 November in conjunction with a cold front, which passed through the Houston area on the same day. On 3 November 35 mm of rain were recorded followed by a trace amount of rain and wind speeds up to 10 m s\(^{-1}\) on 4 November. These conditions rendered the ceilometer data less useful.

The backscatter relative gradient threshold is lowered on 25–26 April (14% and 10%, respectively) to capture the nocturnal stable layer because a stationary frontal passage decreased the amount of aerosols in the atmosphere. The National Weather Service (NWS) Hydro-meteorological Prediction Center (HPC) surface analysis archive shows the surface front stalled over Houston from 0900 UTC 24 April to 0900 UTC 25 April, and the UH weather station observed wind speeds up to 12 m s\(^{-1}\). The average AOT levels for three different wavelengths (340, 870, and 1640 nm) ranged from 0.034 to 0.121 on 25 April. Average AOT levels for the same wavelengths
during the entire month of April ranged from 0.163 to 0.324.

2) UNSTABLE CONDITIONS

The agreement between the radiosonde- and ceilometer-estimated PBL heights demonstrates the applicability of using the ceilometer algorithm during unstable conditions. One drawback of using a ceilometer, however, during the warm and humid months is the presence of afternoon convection and cumulus clouds. For the purposes of air quality and specifically surface ozone, these days are less interesting because clouds decrease ozone production rates.

The ceilometer algorithm experiences some problems estimating the PBL height in the late afternoon and early evening when the PBL transition from unstable to stable conditions is discontinuous. During this time, the PBL height remains near its daytime maximum until a nighttime stable layer develops, and the previous PBL top becomes the top of the residual layer (as seen in Fig. 7). In other words, convection is weakening, a new stable surface layer is forming, and the lofted aerosols detected by the lidar do not represent the PBL. Few radiosondes were launched during this time period, but the ceilometer often estimates a PBL height of a few kilometers after sunset. This weakness is due to the assumption implicit in the ceilometer method of using aerosols to detect the PBL. The ceilometer does a good job of detecting the formation of a stable gradient a few hours later.

3) ESTIMATION OF THE PBL HEIGHT USING OZONE PROFILES

The small bias between ceilometer and ozone profile estimates of the PBL height indicates collocation of the ozone- and aerosol-defined ML height. This colocation indicates the benefits of using a ceilometer for air quality applications and addresses the lack of ML height observations, which has previously hindered air quality forecasting enhancements in the Houston area. This study provides ML height observations during four ozone seasons in Houston and the required data to improve PBL parameterizations used in air quality models.

It is important to note that two comparisons are removed from the analysis because of instrument error. The 29 June 2009 launch is removed from analysis because of the irregular shape of the ozone profile (not shown). A jump-like decrease in ozone occurs at 1270 m, but the parabolic shape of the ozone layer from 1270 to 2000 m seems artificial and may be the result of sulfur dioxide interference or an instrument malfunction. A change in wind direction or wind speed is not found in this layer (not shown). The National Oceanic and Atmospheric Administration (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model backward trajectories ending at 1900 UTC at 1200, 1400, 1600, 1800, and 2000 m indicate the air mass traveled from the east over Galveston Bay and the Houston Ship Channel before passing over the UH campus (not shown). UH Moody Tower sulfur dioxide measurements are not available on this day. The 1940 UTC 17 July 2009 launch is also removed from analysis because the ceilometer was not operating from 0900 to 1800 UTC. The lack of data before the launch affects the averaging settings used in the algorithm and does not allow for a complete evolution of the convective PBL height. In addition, 24 August and 8 October 2010 are removed from the comparison between the ozone profile and meteorological estimated PBL heights because there is not a clearly defined PBL height using the ozone profile and meteorological estimated PBL heights because there is not a clearly defined PBL height in the late afternoon and early evening when convection is weakening, a new stable surface layer is forming, and the lofted aerosols detected by the lidar do not represent the PBL. Few radiosondes were launched during this time period, but the ceilometer often estimates a PBL height of a few kilometers after sunset. This weakness is due to the assumption implicit in the ceilometer method of using aerosols to detect the PBL. The ceilometer does a good job of detecting the formation of a stable gradient a few hours later.

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5. Summary and conclusions

During both stable and unstable conditions, the commercial aerosol lidar is capable of continuously identifying aerosol gradients in an urban subtropical environment that represent significant atmospheric layers of interest, specifically the height of the planetary boundary and residual layers. A comparison with over 60 radiosondes indicates overall agreement between ceilometer- and radiosonde-estimated PBL heights. In addition, the ceilometer-estimated PBL heights agree well with 31 vertical profiles of ozone. In the polluted boundary layer the aerosol gradient corresponds to the surface ozone layer, which is useful for urban air quality applications because it provides a continuous estimate of the integrated boundary layer ozone column. Long-term diurnal observations of the PBL height in Houston are made for the first time. Nocturnal PBL heights range from approximately 100 to 300 m while the convective PBL displays more seasonal and daily variability typically ranging from 1100 m in the winter to 2000 m in the summer.

Difficulty detecting the PBL height occurs immediately following a frontal system with precipitation or during periods of high wind speeds. The precipitation acts to wash out the aerosols, which decreases the strength of the gradient. The high wind speeds act to disperse the aerosols, inhibiting the formation of aerosol layers. In addition, the ceilometer algorithm experiences some problems estimating the PBL height in the late afternoon and early evening when convection is weakening, a new stable surface layer is forming, and the lofted aerosols detected by the lidar do not represent the PBL. Few radiosondes were launched during this time period, but the ceilometer often estimates a PBL height of a few kilometers after sunset. This weakness is due to the assumption implicit in the ceilometer method of using aerosols to detect the PBL. The ceilometer does a good job of detecting the formation of a stable gradient a few hours later.

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This study also showed the effectiveness of the ceilometer in detecting both PBL and residual layer heights, in the majority of conditions, in an urban subtropical environment. The Houston area often experiences several high ozone days 1–3 days following a frontal passage in the spring and fall. Simultaneous long-term detection of the residual layer and PBL heights will help to better understand the interaction between synoptic and micrometeorological processes resulting in higher surface ozone levels, which is an area of future investigation.

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APPENDIX

Ceilometer Settings

The following CL31 averaging options are used: a 1200-s time average and a 240-m [smaller in near range, as discussed in section 2c(3)] height average with a norm height of 600 m (above this value, increased time and/or height averaging can be initiated). To maximize the performance of the CL31 in aerosol and PBL applications, the following aerosol application settings are used: a message interval of 16 s, angle correction off, profile with 10-m resolution and 770 samples, range gate normalization on, and the necessary algorithm parameters (Vaisala 2009).

REFERENCES


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