Planetary boundary layer evolution over an equatorial Andean valley: A simplified model based on balloon-borne and surface measurements

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Planetary boundary layer (PBL) evolution over a populated Andean valley east of Quito, Ecuador is investigated through an empirical model. Balloon-borne measurements of boundary layer height (PBLh) were found to correlate strongly ($R^2 = 0.871$) as a function of virtual temperature at the surface calculated with 10 min ground station observations. This simplified model captures slow and fast regimes of PBL growth observed from the early morning to midday, which lead to the development of either shallow or deep PBLs. Surface conditions under which different scenarios of PBL develop are discussed in light of a test performed with 2015 station data. The proposed model can be used with the purpose of interpreting air quality measurements.

KEYWORDS
Andes, boundary layer, Ecuador, soundings, surface-based observations

1 | INTRODUCTION

The evolution of the planetary boundary layer (PBL) is critical to air quality for it defines a mixing volume that directly impacts the levels of pollutants in the ambient air. Continuous PBL monitoring requires specialized instrumentation such as lidar or wind profiling techniques, which often involve complex data processing and analysis (Bianco and Wilczak, 2002; Summa et al., 2013). Routine PBL measurements are also effectively obtained from high-resolution radio soundings, but not every station is able to support costs of daily launching operations. In particular, cities in the world located within complex topography, where atmospheric measuring campaigns are scarce, face significant challenges interpreting PBL processes in connection with air quality observations. The tropical Andes, home to millions of people in urban centers that share common air pollution difficulties (Clean Air Institute, 2012), exemplify a geographical area in need of more abundant PBL research. Some modeling work in the region includes the study by Rendon et al. (2014), which investigates scenarios for temperature inversion breakup using simplified geometry to simulate processes over a valley in the Colombian Andes. However, studies of an experimental nature are yet to be developed in a more intensive fashion. In this paper we augment regional efforts by presenting in situ measurements of PBL over a complex Andean valley east of Quito, Ecuador.

We present an empirical approach that uses upper air and surface observations in order to obtain useful knowledge of PBL evolution. A main point of this work is to take advantage of the low seasonal variability in surface conditions (temperature and humidity) over the Ecuadorian Andes to describe PBL growth from station data. For example, during the warmest months (August, September, and sometimes December), 1-hr temperature maximum is 26°C on average. On the other hand, on non-rainy days during the cooler months (e.g., April and November) the range of temperature maxima is 20–22°C. In addition, during fair weather days throughout the year, typical relative humidity at midday is lower than 40% (details in Appendix S1, Supporting Information). Thus,
we investigate a method that uses combined surface data as an indicator to estimate planetary boundary layer height (PBLh). The research questions that we address in this work are the following:

1. How does PBL evolve since the early morning to the early afternoon over the study area?
2. Is it possible to infer PBLh using surface observations easily measured with inexpensive instruments?

In order to address the proposed questions, we present balloon-borne measurements of PBL that include ozone soundings and tethered balloon launches. Through a simplified model we explore surface conditions that lead to the formation of shallow or deep PBLs at midday. In light of this analysis, we estimate the average evolution of PBL using 2015 data.

2 METHODS

Observations were taken at Universidad San Francisco de Quito’s Atmospheric Measurement Station (EMA USFQ, Spanish acronym) at coordinates 0.19°S, 78.4°W, and 2,414 masl (meters above sea level). A map with the geographical location of the station, a topographic view of the valley, and dimensions of the urban surface are included (Figure S1.1). Technical aspects of EMA’s instrumentation and initial PBL measurements can be found elsewhere (Cazorla and Tamayo, 2014; Cazorla, 2016a).

2.1 Balloon-borne observations

The upper air data set was retrieved from 29 flights performed between June 2014 and February 2018. A timeline is presented in Figure 1 with indication of the type of launch (ozone sounding or tethered balloon) and profiles collected during each flight. Ten flights were launched at local time 0700–0800 LST (UTC - 5), 8 between 0900–1035 LST, and 11 between 1200–1400 LST (exact launch times are included in Table S2.1). Pressure, temperature, and humidity measurements were taken with Internet radiosondes model iMet-1-RSB on board of 800-g balloons. Atmospheric ozone was measured with EN-SCI electrochemical concentration cell (ECC) ozonesondes coupled to iMet radiosondes (detailed launching protocols can be found in Cazorla, 2016b). High-resolution vertical profiles of virtual potential temperature ($\Theta_v$), water vapor mixing ratio ($q_v$), and ozone mixing ratio ($O_3$) were successfully retrieved for the majority of the ozone soundings although there was loss of ozone data in two cases (Figure 1, details in Appendix S2).

Tethered launches were performed with a reconditioned radiosonde on board of an 800-g balloon anchored to a fixed reel capable of releasing 550 m of line. Tethered balloons (magenta circles in Figure 1) were launched on May 25, 2015 (one mid-morning flight), May 26 (one early morning flight and two mid-morning flights), and June 29 (one mid-morning flight). In the last launch, the tethered line broke during ascent and the platform was completely released. Only temperature data were successfully transmitted from the reconditioned radiosonde. Thus, only potential temperature profiles ($\Theta$) are available for these soundings.

2.2 PBLh identification

Following previous work (Zhang and Rao, 1999; Stull, 2009; Morris et al., 2010; Seidel et al., 2010), we identified PBLh from ozone soundings by combining information from $\Theta_v$, $q_v$, and $O_3$ vertical profiles. High-resolution data (5-m) was reduced to 20-m profiles. PBL height was identified independently in the $\Theta_v$, $q_v$, and $O_3$ vertical profiles by finding:

1. The level at which there is a strong positive gradient in the $\Theta_v$ vertical profile that indicates a capping inversion and transition into a more stable layer.
2. The level at which there is a sharp decrease in the $q_v$ profile that indicates transition into the drier free troposphere.
3. For morning flights, the level at which there is a sharp increase in the $O_3$ vertical profile that indicates transition through the residual layer and into the free troposphere.
4. For noon and afternoon flights, the level at which there is a sharp decrease in the $O_3$ vertical profile that indicates transition into the cleaner free troposphere.

The three readings were averaged in order to find PBLh for the majority of ozone soundings and the standard deviation (SD) was calculated (Table S2.1). In few cases, PBLh was obtained using two profiles (when there was loss of ozone data or when one of the readings was too different from the other two, Table S2.1). In the case of tethered launches, PBLh was obtained solely from the potential temperature ($\Theta$) profile. PBLh measurements are reported in Figure 1, but readings with each profile are included in Table S2.1. Given differences in the number of profiles used to measure PBLh, we determined the absolute uncertainty in measurements using a propagation of error technique. We discuss absolute uncertainty in the results section and we include details of its calculation in Appendix S3.

2.3 Surface observations and empirical model

PBLh data were correlated with surface observations at the time of every launch. Surface temperature and humidity (10 min data) were chosen for being associated to the formation of thermals that result in PBL growth. Both quantities were combined into virtual temperature ($Tv$). In Figure 1 we include 10 min $Tv$ at the time of every flight. A function that best fits experimental data (PBLh vs. $Tv$) was found through
a normalization method and a statistical regression. The construction of the empirical model and its physical meaning is discussed in the results section.

Ground station observations were also used in order to investigate the monthly variability of PBL evolution over the study area. Year 2015 was chosen because most of the upper air data were collected during that time period. For this analysis, station time series of $T_v$ were calculated using 10 min temperature, humidity, and pressure. PBLh time series were obtained using the empirical model. Monthly curves of PBLh were prepared from 10 min data and exclude rainy days during daytime. These curves were calculated as median diurnal variations (MDV) by overlapping daily data each month and applying a median filter to groups of points every hour. The 2015 PBL evolution is presented for 0700–1400 LST. Supporting Information contains description of weather patterns over the study area and 2015 meteorological data used in this study (Figures S1.2–S1.5).

3 | RESULTS AND DISCUSSION

The compendium of $\Theta_v$, $q$, and $O_3$ profiles from ozone soundings at EMA is depicted in Figure 2, whereas $\Theta_v$ profiles for tethered balloon launches on 25 and May 26, 2015 are presented in Figure 3. For the majority of flights, PBLh was obtained by averaging readings from $\Theta_v$, $q$, and $O_3$ profiles, provided the SD was lower than 63.5 m. This criterion
was set based on the magnitude and distribution of $SD$ (Table S2.1). However, there were cases for which only one or two profiles were used. Hence, we determined the absolute uncertainty in measurements considering two sources of error. First, we accounted for error due to differences in number of profiles, which corresponds to 7.8% (calculation in Appendix S3). Second, we accounted for an 8% error in sonde measurements in the lower troposphere, which has been documented elsewhere (Johnson et al., 2002). Therefore, we obtained an 11.2% $\sigma$ absolute uncertainty in PBLh observations through a propagation of error calculation (details in Appendix S3).

Interpretation of physical mechanisms that lead to the progression of profiles, from early morning to early afternoon, presented in Figure 2 can be done using insight gained from previous work. According to the comprehensive review by De Wekker and Kossmann (2015), PBL evolution is not uniform in all areas of a valley as surface heating and inversion subsidence are influenced by topography and wind flow structure. For areas located near the slope of a valley (as is our case), upslope winds slowly erode the morning inversion after sunrise, while warming of the surface induce the formation of shallow convective layers. Upslope winds recirculate into the valley stably stratified layer and reinforce subsidence over the valley. In the afternoon, the main mechanism for the development of a deep PBL is convective mixing caused by thermals that form at the surface. Often, layered structures form at midday in place of a deep convective layer. When a deep PBL develops, it would usually reach mountain ridge heights. In addition, Rendon et al. (2014) found through modeling over simplified geometry in an urban valley in Colombia that the main mechanism for PBL growth is a combination of subsidence of the inversion layer and simultaneous growth of the convective layer. Rendon’s work finds that in highly urbanized valleys formation of buoyant air masses is a dominant process due to

**FIGURE 2** Vertical profiles of $\Theta$, (a–c), $q$, (d–f), and $O_3$ (g–i) for flights launched at 0700–0800 LST (first column), 0900–1035 LST (second column), and 1200–1400 LST (third column). Panel (b) includes a $\Theta$ profile for the tethered balloon on June 29, 2015, whose platform was ultimately released.
consistent warming of the urban surface. From an observational perspective, the three columns in Figure 2 depict a pattern of PBL evolution that agrees with previous conceptual models. For example, shallow convective layers in Figure 2b can be attributed to air mass removal by upslope winds, while the surface becomes warm through the mid-morning. In addition, deep convective layers in Figure 2c likely develop mainly due to thermals formed at the warm surface. However, important aspects need to be considered in regard to our interpretation. First, we did not have means to investigate wind flow circulation or to measure heat fluxes over the study area. Hence, we only use concepts in previous work as a qualitative reference to understand the evolution of profiles in Figure 2 and hypothesize about mechanisms for PBL growth. Furthermore, the valley where measurements were taken is more complex than idealized geometries. Third, surface conditions in the study area do not vary extremely due to the site’s equatorial latitude and high altitude. In contrast, previous physical models (De Wekker’s review) have been generally developed for the summertime in the mid-latitudes, where weather patterns are substantially different. Given limitations in the extent of our measurements and differences with former research, we followed a purely empirical approach to study regimes of PBL evolution over the study area.

To describe PBL evolution, we built a model (Equation (1)) that fits experimental data pairs PBLh versus $T_v$ depicted in Figure 4. We chose a Sigmoid function to fit the data because it describes observed stages of slow PBL growth when $T_v$ is low (morning), increase in growth rates as $T_v$ increases (mid-morning into midday), fast growth when a deep PBL develops, and a plateau at PBLh maximum. To build the model, we first normalized PBLh data. Second, we found an observed value of virtual temperature ($T_i$) above and below which measurements of PBLh are either deep of shallow (about 25 °C). Third, we plotted normalized PBLh versus the difference $T_v - T_i$ and we statistically found a regression that best fits data using a simple Sigmoid function (normalized function in Appendix S4, Figure S4.1). In the model, $T_i$ is the inflection point at which concavity of the function changes. Finally, we expanded the normalized function to obtain PBLh (magl) directly from $T_v$ (°C), which is more intuitive from an operational standpoint. The $R^2$ correlation coefficient is 0.871 for the model regression presented in Figure 4. The chosen function is similar to the one proposed by Zelaya-Ángel et al. (2010) in their study to estimate PBLh in Mexico City, although their equation adjusts PBLh with the time of the day. In Figure 4, PBLh measurements are presented with $1 − \sigma$ error bars. In addition, $1 − \sigma$ uncertainty in the model (calculation in Appendix S5) was determined for ranges of $T_v$ 13.5–20,
20–25.2, and 25.2–28 °C, which, respectively, corresponds to 94, 307, and ±384 m,

\[ \text{PBLh} = 250 + \frac{2000}{0.75 + e^{-0.5(T_v - 25.2)}}. \]  

Virtual temperature is a robust quantity that combines temperature and humidity, two of the main forcings that induce the formation of thermals resulting in the daytime growth of the PBL. However, virtual temperature itself is not the cause of PBL growth, but rather surface heat fluxes (Stull, 2009). Data in Figures 2 and 4 were collected in different months from morning to midday and reflect the narrow variability of temperature and humidity in the region. We propose that there must be an underlying relationship between the magnitude of surface heat fluxes and the constrained range of variability in conditions, which explains the high experimental correlation between PBLh and \( T_v \). This hypothesis still needs to be investigated through measurements and modeling. However, from a purely observational viewpoint, virtual temperature is a good indicator of surface processes that influence the evolution of the PBL at our measuring site. This experimental finding is of major significance for a simple model with a single predictor can be used to estimate PBL evolution in lieu of more sophisticated methods. The proposed model can be applied to estimate PBLh in non-rainy days between 0700–1400, when observed virtual temperature, temperature, and water vapor mixing ratio, respectively, are 13.5–28 °C, 11–26 °C, and 7–12.5 g/kg.

The monthly variability in PBL evolution in year 2015 is presented in Figure 5. The most frequent occurrences of high and low PBLh maxima happened during the warmest and the coolest months in the year, which correspond to September and December as well as May and July, respectively (Appendix S6, Figure S6.1). In Figure 5, daily variability of PBL evolution is averaged by MDV curves. Thus, monthly curves should be interpreted within the right context of the percentage of data in each month that corresponds to PBLs at midday of 1,000 magl or lower. From our 2015 simulation, such percentages between 1100–1400 LST were
15–20% in January, February, April, and November; 30–37% in March, May, and July; and less than 10% in August–September and December (Figure S6.1).

In the future, additional data points need to be sampled to refine the model and to test its consistency over time. In addition, afternoon profile sampling needs to be done to complete the daytime evolution of the PBL. Moreover, missing parts of information are wind circulation patterns as well as transport of air masses between the valley and the main urban center. In spite of the limitations, this method can be readily used to estimate PBLh over the study area with the purpose of interpreting air quality observations.

4 | CONCLUSIONS

In this work we found that virtual temperature is an effective indicator of surface processes that cause PBL growth in an urban valley east of Quito, Ecuador. We draw this conclusion from a strong correlation found between balloon-borne measurements of boundary layer heights and corresponding T_v at the time of launch. We propose that the cause for such high correlation is the limited variability in surface conditions throughout the year over the study area. The measuring site is located in an Andean valley on the equator (0.19°S) and at high altitude (2,414 masl). At this location, mild temperatures and low humidity only fluctuate within narrow and well-known ranges from morning to early afternoon in non-rainy days. An explanation, which is yet to be tested through additional studies, is that heat fluxes (ultimately responsible for PBL growth) must develop in proportion to thermals of buoyant air masses that form under a restricted range of conditions. As a result, an empirical model that uses a robust quantity such as virtual temperature yields high predictability of PBL evolution in a topographically complex setting. The main implication of this experimental finding is that useful information of PBL evolution can be obtained from inexpensive station measurements as long as the chosen predictor is a strong indicator of surface processes. This method is particularly useful to estimate PBL heights with air quality applications at places where sophisticated techniques for continuous PBL monitoring are unavailable.

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Conflict of interests

The authors declare no potential conflict of interests.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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