Planetary Boundary Layer Heights from GPS Radio Occultation Refractivity and Humidity Profiles

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Abstract. The height of the planetary boundary layer (PBL) is an important parameter that relates to the various processes associated with the PBL. In this paper, we use Global Positioning System radio occultation (GPSRO) measurements to derive a global climatology of PBL heights. Utilizing the strength of GPSRO in capturing fine vertical structures, the top of the PBL is defined to be the height at which the vertical gradient of the refractivity or water vapor partial pressure is minimum, corresponding to the height where the refractivity or water vapor pressure changes most rapidly. A “sharpness parameter” is defined that quantifies the applicability of these definitions. The sharpness parameter is largest over the subtropical regions characterized by strong subsidence. When the sharpness parameter is large, the refractivity- and moisture-based heights are shown to converge. We derived global PBL height climatology using three years (Dec. 2006–Nov. 2009) of COSMIC/FORMOSAT-3 measurements and compared with values calculated from ECMWF Reanalysis Interim (ERA-Int). We found that the mean PBL heights from GPSRO shared similar spatial and seasonal variations with ERA-Int; however, GPSRO heights were higher by 500 m. The standard deviation was also higher from GPSRO, especially in the tropics. We present detailed comparisons between GPSRO and ERA-Int over the Pacific Ocean and the Sahara desert and examine the PBL height distributions as well as its their annual and diurnal variabilities. These results suggest that the underlying causes of the bias between GPSRO and ERA-Int likely vary from region to region.
1. Introduction

The planetary boundary layer (PBL) or atmospheric boundary layer (ABL) is the part of the atmosphere closest to the Earth’s surface where turbulent processes often dominate the vertical redistribution of sensible heat, moisture, momentum, and aerosols/pollution [Stull, 1988]. The characteristics of the PBL, including its exchange of heat, moisture, and momentum with the free atmosphere and the surface, strongly influence the amount, type, and evolution of the overlying clouds as well as the large-to meso-scale circulations. This in turn impacts the global energy and water cycles through cloud and circulation influences on albedo and precipitation [Ramanathan et al., 1989; Klein and Hartmann, 1993; Lappen and Randall, 2001]. The PBL height is a crucial parameter that can be used to describe much of the diurnal, synoptic, and climatological processes associated with the PBL in a given region, including its cloud characterization and connections between the surface and free troposphere. However, a global climatology of the PBL height has not been established because the PBL height has been mainly derived based on a combination of theory and a few field experiments that were localized in space and time (e.g., ASTEX, FIRE, ATEX, BOMEX, and DYCOMS) [Albrecht et al., 1995].

General circulation models (GCMs) exhibit shortcomings in representing the PBL top in a physically consistent manner and there is also little consistency among different models in their PBL representations [Lenderink and Holtslag, 2000; Hannay et al., 2009]. Overcoming these challenges has been greatly hindered by the lack of adequate validation data, particularly over the oceans where there are very limited in-situ profiling measurements. Adding to the challenge and complexity of this issue, both from a modeling and observation context, is the fact that the PBL top is often so finely defined (i.e., order of 10 meters) that it is difficult to resolve by the limited vertical resolutions in most models [Suarez et al., 1983] and observing systems.

Global satellite observations are starting to yield some methods for characterizing
aspects of the global PBL. For example, the Atmospheric Infrared Sounder (AIRS) provides near daily and global temperature and water vapor profiles but can only give coarse estimates of PBL height since the vertical resolutions are still relatively low ($\sim 1$ km for temperature and $\sim 2$ km for water vapor) to fully resolve the PBL top [Fetzer et al., 2004]. The MODIS (Moderate Resolution Imaging Spectroradiometer) cloud-top temperature and TRMM Microwave Imager (TMI) SST are also useful to retrieve the PBL height but only in limited regions [Wood and Bretherton, 2004]. Spaceborne lidars such as LITE (Lidar In-Space Technology Experiment) [Winker et al., 1996], GLAS (Geoscience Laser Altimeter System) onboard ICESat [Palm et al., 2005], and more recently CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) [Jordan et al., 2010] have been shown to be valuable tools in observing the PBL top through aerosol backscattering. The Multi-angle Imaging SpectroRadiometer (MISR) [Moroney et al., 2002] and CloudSat [Stephens et al., 2008] also offer opportunities for characterization of PBL height, but these observations are based on cloud-only regions on sun-synchronous orbits; thus cloud versus clear-sky and diurnally unbiased estimates are not feasible.

Global Positioning System radio occultation (GPSRO; hereafter GPS in short) measurements provide a new opportunity for developing a global PBL height dataset. First, the GPS signals are in the L-band microwave frequencies, which allow them to pass through clouds and precipitation essentially unaffected. Second, by virtue of their active limb viewing geometry, GPS profiles have fairly high vertical resolution ($\sim 200$ m), making it possible to delineate the fine vertical structure associated with the top of the PBL. Third, with a sufficient number of receivers in orbit, GPS could provide excellent global coverage as well as full diurnal cycle sampling. These facts were recognized early [Melbourne et al., 1994; Kursinski et al., 1997]; however, progress on PBL applications had been hampered due to several issues affecting the accuracy of the retrieved profiles in the lowest few kilometers (e.g., Ao et al. [2003]).
With advances in GPS retrieval techniques [Gorbunov, 2002; Jensen et al., 2003] and instrumentation [Sokolovskiy, 2001; Sokolovskiy et al., 2006b; Ao et al., 2009], a number of studies exploring the possibility of detecting PBL tops from GPS data have appeared [von Engeln et al., 2005; Sokolovskiy et al., 2006a, 2007; Ao et al., 2008; Basha and Ratnam, 2009; Ratnam and Basha, 2010; Guo et al., 2011; Xie et al., 2012].

A standard universal definition of global PBL height does not exist. Depending on the context of the application and the type of measurements available, a number of different methods can be used to estimate the PBL height (or mixing height) [Seibert et al., 2000]. The unique characteristics of the GPS data suggest that non-traditional definitions are needed here. A recent study by Seidel et al. [2010] presented a comparative study of different methods for defining the PBL heights, including the Holzworth parcel method as well as methods that can be utilized for GPS profiles. The study showed that in general different methods can give statistically very different results and need to be interpreted accordingly. In this paper, we focus on two possible definitions for GPS-derived PBL heights: one based on the variation of the refractivity profile and the other based on the variation of the water vapor pressure profile. Both definitions are simple to apply with other measurements as well as climate and weather models. It can be argued that refractivity is the most natural variable to use for GPS because it can be retrieved with minimal assumption and requires no external information. The water vapor pressure is closely related to specific humidity and relative humidity, which are the more common meteorological variables. Thus, the moisture-based definition is simpler to interpret, although it is limited to the tropics and mid-latitudes. It is useful to compare these two definitions to understand their similarities and differences.

Our study is similar in scope to the papers by Ratnam and Basha [2010] and Guo et al. [2011], in that global characterization of PBL heights was made using COSMIC measurements. However, the algorithms used for estimating the PBL heights are
different here. Instead of rejecting profiles based on certain threshold criteria, we choose to include all available profiles in generating the global climatology but provide a metric that helps quantify the physical and statistical significance of the derived PBL heights. In addition, we present a more detailed analysis of the comparison between GPS and ECMWF Reanalysis Interim (ERA-Int) based on a longer dataset over both land and oceans that gives some insight on their differences.

The rest of the paper proceeds as follows. In Sec. 2, we describe the dataset and the methodology used to derive PBL heights. The limitation of the methodology as well as measurement uncertainties are discussed. In Sec. 3, we present mean global PBL height results from three years of COSMIC data and compare them with ERA-Int. Regional comparisons in the Pacific Ocean as well as the Sahara desert will be highlighted. Sec. 4 contains the summary and conclusions.

2. Data and Methodology

For this study, we use three years of GPS data from the six-spacecraft COSMIC/FORMOSAT-3 constellation (hereafter COSMIC in short) [Anthes et al., 2008] from December 2006 to November 2009. Launched in April 2006, the COSMIC constellation has yielded approximately 2000 soundings per day, which represents an order-of-magnitude increase from the CHAMP data that were available before 2006. Furthermore, COSMIC was designed to acquire GPS data with the open-loop (OL) tracking technology that was developed and tested on SAC-C [Ao et al., 2009]. In addition to enabling rising occultations, OL tracking is crucial for PBL studies because it gives much more accurate measurements deeper into the lower troposphere and the PBL. With OL tracking, over 80% of the retrieved profiles reach below 2 km altitude in the tropics, compared to only $\sim 50\%$ achievable under closed-loop tracking.

Each GPS sounding consists of a time series of amplitude and phase measurements along the receiver trajectory as the GPS satellite sets or rises behind the Earth. Using
the canonical transform method [Gorbunov, 2002], the measurements are converted to a ray representation of bending angle profile ($\alpha(a)$, where $\alpha$ is the bending angle and $a$ is the impact parameter). The bending angle profile can be inverted with the Abel integral transform to yield a vertical profile of the refractive index $n(z)$ or equivalently the refractivity $N(z) = (n - 1) \times 10^6$ at the ray tangent points. We note that as a limb sounding technique, GPS has high vertical resolution ($\sim$ 200 m) but relatively coarse along-track horizontal resolution ($\sim$ 200 km). The coarse horizontal resolution will introduce some uncertainty in PBL height estimation especially over coastal regions as well as land with strong elevation variations and changes in surface characteristics (forests, urbanization, etc.); however, we expect its effect will be reduced when looking at climate averages.

The microwave refractivity $N$ is related to the thermodynamic properties of the atmosphere through the relationship [Smith and Weintraub, 1953]:

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2}$$

(1)

where $T$ is the temperature (K), $P$ is the total pressure (mb), and $P_w$ is the water vapor partial pressure (mb), with constants $a_1 = 77.6$ K/mb, $a_2 = 3.73 \times 10^5$ K$^2$/mb. In the upper troposphere and above, the second term (the so-called “wet term”) in the refractivity can be neglected. In this case, the refractivity is directly proportional to the air density. Assuming that hydrostatic equilibrium holds, the temperature and pressure can be uniquely derived from the refractivity. In the lower troposphere and the PBL, the contribution of water vapor to the refractivity becomes important. Here, the refractivity alone cannot be used to retrieve both the temperature and water vapor independently. Since temperature is generally better known than water vapor, our methodology is to assume temperature from an ancillary source (NCEP final analysis here [http://dss.ucar.edu/datasets/ds083.2/]) and retrieve water vapor when the tropospheric temperature is above $\sim$ 250 K [Hajj et al., 2002]. While the assumed
temperature error will affect the accuracy of the water vapor retrieval, its impact on the derived PBL height is expected to be small in the tropics and sub-tropics [Kursinski et al., 2000] (see also Sec. 2.2).

2.1. Definition for PBL Height

The GPS measurements are sensitive to the vertical gradient of the refractivity through ray bending and diffraction effects. Since the transition from the PBL to the free troposphere is often marked by a significant change in temperature and water vapor, the simplest approach for deriving the PBL height is to identify where the greatest change occurs in the retrieved vertical profile. Some possible choices, representing different stages of the retrieval process, are: (i) the bending angle profile, (ii) the refractivity profile, or (iii) the water vapor profile (e.g., specific humidity or water vapor pressure). These quantities all tend to decrease with height across the PBL top; therefore, a useful definition is to consider the PBL top to be where the minimum vertical gradient (or maximum lapse rate) occurs [Ao et al., 2008; Basha and Ratnam, 2009; Seidel et al., 2010; Xie et al., 2012]. A similar but slightly different definition is to find the point where the lapse rate changes the most (the “breakpoint”) [Sokolovskiy et al., 2006a, 2007; Guo et al., 2011].

The bending angle profile is in principle the least-biased observable and offers potentially higher vertical resolution, but it is less straightforward to compare this observable to other measurements or atmospheric models. Therefore, we consider definitions based on the refractivity and water vapor profiles only. For water vapor, we have several options. We can use the water vapor partial pressure $P_w$, specific humidity $q$, or relative humidity. In our earlier work [Ao et al., 2008], specific humidity profiles were used to define the PBL heights. However, the water vapor pressure ($P_w \approx 1.6Pq$) is arguably a better moisture variable to use when dealing with profiles with high vertical resolution because the pressure $P$ automatically provides a heavier weighting towards
moisture layers close to the surface. Thus the minimum vertical gradient of $P_w$ is less susceptible to free tropospheric moisture layers aloft than using $q$.

The refractivity gradient depends on the pressure gradient, temperature gradient, and water vapor pressure gradient. From Eq. (1), the vertical refractivity gradient can be written as:

$$N' = a_1 \frac{1}{T} P' - \left( a_1 \frac{P}{T^2} + 2 a_2 \frac{P_w}{T^3} \right) T' + a_2 \frac{P'_w}{T^2} \equiv N'_P + N'_T + N'_w$$

(2)

where $N' \equiv dN/dz$, etc. For typical atmospheric conditions, the first term due to the pressure gradient is approximately $-30$ N-units/km close to the surface and decreases in magnitude roughly exponentially with increasing height. In the absence of any sharp temperature and moisture layers, this term will dominate, and $N'_{\min}$ will be at the lowest profile height. For the pressure term $N'_P$ to exceed $N'_T$, the temperature gradient must be $T' \gtrsim 40$ K/km. For the humidity term $N'_w$ to exceed $N'_P$, the water vapor pressure gradient must be $P'_w \ll -7$ mb/km (corresponding approximately to $q' \ll -5$ g/kg/km). In the presence of a strong temperature inversion layer capping the PBL, the $N'_T$ and $N'_w$ terms are both negative across the PBL and contribute constructively to the negative gradient in the refractivity. In this scenario, the minimum refractivity gradient and the minimum water vapor pressure gradient will occur at the same height, and both of these PBL height definitions will be consistent. These estimates suggest that a change of 1 g/kg in $q$ (or 1.5 mb in $P_w$) is approximately equivalent to a change in temperature of 10 K across a thin layer in contributing to $N'$. Thus under typical conditions, $N'_w \gg N'_T$. Figure 1 illustrates an example. The temperature and water vapor profiles come from a radiosonde sounding at Lihue, Hawaii (21.98°N,159.35°E) that shows a strong tradewind inversion near 1.5 km altitude. The minimum refractivity and water vapor gradients both occur at the same height that coincides with the base of the temperature inversion layer.

The minimum-gradient based PBL definitions are most meaningful when the profile
is dominated by a single layer with large change in refractivity or moisture. For this to happen, it is necessary that the minimum gradient is large in magnitude relative to the average gradient. To quantify this condition, we introduce the relative minimum gradient or sharpness parameter as

$$\tilde{X}' \equiv -\frac{X'_{\text{min}}}{X'_{\text{RMS}}}$$ (3)

where $X$ is either $q$ or $N$ and $X'_{\text{RMS}}$ is the root-mean-square (RMS) value of $X'$ averaged over the altitude range being considered (0–6 km here). We favor this sharpness definition over another used in our earlier work [Ao et al., 2008] since the new definition utilizes a simpler normalization factor, resulting in numerical values that are easier to interpret. Fig. 2 illustrates three occultations with various values of relative minimum gradients. When $\tilde{N}'$ is large, the refractivity profile is sharply varying within the layer where the minimum refractivity gradient occurs (Fig. 2 top panels). As $\tilde{N}'$ decreases, the minimum gradient layer becomes less distinct (middle panels) and finally appears virtually indistinguishable from other “layers” in the profile (bottom panels). The conclusions are similar when considering $P'_w$ or $q$, except that $\tilde{P}'_w$ and $\tilde{q}'$ tend to have larger values than $\tilde{N}'$ owing to the smaller RMS gradients (i.e., smaller denominator on the right hand side of Eq. 3).

2.2. Measurement Uncertainty

There are several issues that affect the accuracy of GPS retrievals in the lowest 2 km or so. It is important to address them and evaluate their impact on the estimation of PBL heights.

First, it is well known that GPS refractivity retrievals are negatively biased when compared with NCEP and ECMWF analyses in the lowest 2 km altitude (e.g., Rocken et al. [1997]; Ao et al. [2003]; Beyerle et al. [2004]). The negative bias is concentrated over the Eastern subtropical oceans and is believed to be primarily caused by the
presence of critical refraction layers [Xie et al., 2010]. In addition, a negative bending and refractivity bias could result from insufficient tracking depth since data corresponding to the largest bending angles would not be recorded by the receiver [Sokolovskiy et al., 2010]. Both factors only affect profiles with the strongest vertical refractivity gradients and result in the reduction of their magnitudes. However, the reduced vertical gradients (on the order of $-80$ N-units/km or less) are still expected to be much stronger than the average vertical gradient away from these critical refraction layers (on the order of $-40$ N-units/km). Thus the minimum gradient method would be able to identify the height correctly, even if the actual strength of the gradient were underestimated.

The second, more serious, issue has to do with the fact that not all the profiles are retrieved all the way down to the surface. For the JPL retrieval system, the minimum profile height is determined by fitting a step function to the canonical transform (CT) amplitude and truncating the data below the step function boundary. While this procedure has been useful in detecting significant dropoff in signal amplitude due to receiver tracking errors, it is not a very precise method, especially considering the strong fluctuations in CT amplitudes that are present for tropical occultations resulting from small-scale irregularities and horizontal inhomogeneities. Fig. 3 shows the fraction of profiles that are retrieved down to within 0.5 km (top panel) and 1 km (bottom panel) of the surface. The lack of penetration is worst over the tropics and appears to be correlated with water vapor abundance. Presently, the reason behind the distribution of minimum profile heights is not well understood. In this study (as in [Basha and Ratnam, 2009; Guo et al., 2011]), only profiles that are retrieved down to within 500 m of the surface are used to derive the PBL heights. This choice retains a sufficient sample of data for analysis (about 50% of the COSMIC profiles globally but only 10% in some tropical regions), but it should be recognized that current GPS data are not very well-suited in inferring the depths of the shallower PBLs.

The third issue affects the water vapor based method only and arises from the
uncertainty in the temperature that is used in deriving the water vapor pressure or specific humidity. Given that the gradient method relies on changes of water vapor over fine vertical scale, a smoothly varying temperature error will have minimum effect on the derived PBL heights. What is of concern is that the assumed temperature misses or mislocates a strong temperature inversion layer. The error in specific humidity can be related to the error in temperature as follows [Kursinski and Hajj, 2001]

\[ \delta q \sim \left( \frac{a_1 m_w}{a_2 m_d} + \frac{2q}{T} \right) \delta T = \left[ 1.3 \times 10^{-4} + \frac{2q}{T} \right] \delta T \]  

(4)

where \( T \) and \( \delta T \) are in K. For typical values of \( q \) and \( T \), the first term on the right-hand side dominates. For simplicity, we approximate \( \delta q / \delta T \sim 0.15 \) g/kg/K. Consider the scenario illustrated in Fig. 1 and the worst case scenario where the assumed temperature from the weather analysis misses completely a 10 K inversion layer. In this case, \( \delta q \sim 1.5 \) g/kg across the layer, which is only 15% of the actual change in \( q \) across the layer. Thus even in this extreme case, the impact of assumed temperature error is not significant enough to affect the determination of PBL heights. At higher latitudes, however, the change in \( q \) would be small enough that the effect of temperature error is not negligible. For this reason, the water vapor based PBL definition should be used only for low to middle latitudes when uncertainties in the assumed temperature exist. The approximate criterion we have chosen is \( q > 1 \) g/kg below 2 km altitude, which occurs at about 60–65° latitudes.

3. Results

In this section, we present a global climatology of PBL heights computed using the refractivity and water vapor pressure definitions and compare these results with ERA-Int. The GPS results are obtained from three years of COSMIC data (Dec. 2006–Nov. 2009). As discussed in Sec. 2, not all profiles were retrieved to the surface. As a compromise between having more profiles and having deeper profiles, only the
refractivity and moisture profiles that reach within 500 m of the surface are used. Since the PBL heights do not extend beyond 4–5 km altitude, the profiles are capped at 6 km. Both the GPS and ERA-Int profiles are vertically interpolated to a regular 10-m height grid before the PBL height is calculated, with the vertical gradient of variable $X$ at each height $z_i$ computed as a centered finite difference $(X_{i+1} - X_{i-1})/(z_{i+1} - z_{i-1})$.

### 3.1. Global Climatology

Fig. 4 shows the mean and standard deviation of the PBL heights from COSMIC on $5^\circ \times 5^\circ$ grid using the refractivity definition. Outside of the polar regions, the refractivity based PBL heights ($z_N$) are lowest in the subtropical Eastern Pacific Ocean at approximately 1–1.5 km. They are highest over the subtropical deserts over Northern Africa and Australia at 2.5–3 km. The standard deviation is largest over subtropical land (especially Northern Africa and the Middle East) and over much of the tropical oceans. The lowest standard deviation can be found in the subtropical Eastern Pacific Ocean. The standard deviation provides a measure of the temporal (diurnal and seasonal) variability of the PBL heights as well as the sensitivity of the PBL height definitions to varying meteorological conditions.

Fig. 5 shows the corresponding results using the water vapor pressure definition with latitudes restricted to $65^\circ$S–$65^\circ$N. In general the water vapor pressure based PBL heights ($z_w$) are quite similar to $z_N$ in both the mean and standard deviation, indicating that the strongest refractivity gradient is dominated by the water vapor gradient. However, it can be noted that the mean of $z_w$ agrees better with $z_N$ in the subtropics and the mid-latitudes. Over the tropics, and particularly near the Central Pacific Ocean, $z_w$ is slightly smaller than $z_N$.

As discussed in Sec. 2, the PBL heights as defined from the minimum vertical gradients are most meaningful when the absolute minimum vertical gradient is distinctly smaller than the average vertical gradient. For this reason, we have introduced the
relative minimum gradients (or sharpness parameters) $\tilde{N}'$ and $\tilde{P}'_w$. As expected, $\tilde{N}'$ and $\tilde{P}'_w$ are highly correlated with each other, with linear correlation coefficient of about 0.8 for latitudes between 60°S–60°N. Profiles with large $\tilde{N}'$ or $\tilde{P}'_w$ correspond physically to sharp PBL tops. Fig. 6 shows the map of relative minimum refractivity gradient $\tilde{N}'$ (the map for $\tilde{P}'_w$ looks similar). Superimposed on this map are contours corresponding to the 500 hPa vertical velocity $\omega$ from ERA-Int, indicating that regions of large-scale subsidence in the subtropics correlate very well with regions of sharp PBLs while deep convecting regions in the Inter Tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) coincide with regions where the transition from PBL to the free troposphere is poorly defined.

The PBL heights $z_N$ and $z_w$ agree best when the relative minimum gradients are large. Fig. 7 shows the mean and standard deviation of their differences as a function of $\tilde{N}'$ for tropical profiles (30°S–30°N) and mid-latitude profiles (30–60°S, 30–60°N) based on data from 2008. In both latitude bands, the standard deviation increases greatly as $\tilde{N}'$ decreases. However, in the mid-latitude band, the difference averages to zero, while in the tropics, $z_N$ has a positive bias relative to $z_w$ for low values of $\tilde{N}'$. The bias is a result of tropical $P_w$ profiles being more strongly varying close to the surface. Thus in the absence of sharp PBL tops, the minimum gradients tend to occur closer to the surface on average if the $P_w$ profiles are used.

Fig. 8 shows $z_N$ obtained from ERA-Int over the same period (Dec. 2006–Nov. 2009). The ERA-Int data are available four times daily in 1.5° × 1.5° grids at pressure levels of 25 mb apart in the PBL and lower troposphere. The surface level data are not used in the calculations of refractivity or water vapor gradients. This is done deliberately since large water vapor gradients sometimes exist within the lowest 10 m of the surface and the inclusion of the surface level data could lower the derived PBL heights quite significantly over some regions. These shallow surface-based layers are not the focus of the present study; furthermore, they are difficult if not impossible to
be probed with GPS (or any other limb viewing remote sensing) measurements that average over large horizontal distances of $\sim 200$ km.

Comparing with Fig. 4, there is broad qualitative agreement between $z_N$ from GPS and ECMWF. For the mean, the locations of the deepest and shallowest PBL heights match up quite well. However, the $z_N$ from GPS is larger than ECMWF almost everywhere that range from a few hundred meters to over 1 km. The finding that ECMWF is biased low relative to GPS is qualitatively consistent with the marine boundary layer results shown in Guo et al. [2011], which used a different PBL algorithm and collocated ECMWF operational analysis (instead of the full reanalysis that is being used here). For the standard deviation, there is once again general consistency between GPS and ECMWF, with largest variability over Northern Africa and the Middle East and low variability over the Eastern subtropical oceans. In general, the GPS heights have larger standard deviation, especially over the tropical oceans and much of Asia.

Fig. 9 shows the seasonal climatology of $z_N$ from both GPS and ERA-Int. The three-year means from GPS and ERA-Int have been subtracted from the respective seasonal means to highlight the seasonal variations. This subtraction removes the prevalent bias that exists between GPS and ERA-Int, suggesting that the bias does not vary significantly in time. As expected, the largest seasonal variations are found over land. There is fairly good agreement between GPS and ERA-Int, but there are interesting and notable differences. For example, over the India Subcontinent, the GPS-derived PBL grows higher by nearly 2 km going from DJF to MAM (before the monsoon), a fact that was previously noted in Basha and Ratnam [2009]. ERA-Int captures the same deepening of the PBL, but the effect is much reduced.

3.2. Regional Comparisons

To better analyze the differences between GPS and ERA-Int as well as the differences between humidity and refractivity based definitions, we present more detailed
results over the Eastern Pacific Ocean as well as the Sahara desert. The subtropical Eastern Pacific Ocean and the Sahara desert regions have some of the largest relative minimum gradients (Fig. 6) and represent regions where the minimum gradient method is most applicable.

We first consider the PBL heights over the Pacific Ocean region that approximately corresponds to the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) Pacific Cross-Section Intercomparison (GPCI) transect [Karlsson et al., 2010; Teixeira et al., 2011]. The transect is defined here to be 5° × 5° latitude-longitude boxes that extends from the subtropical Eastern Pacific (30–35°N, 125–130°W) to equatorial Central Pacific (0–5°N, 175–180°W) (Fig. 4a). Along this transect, the PBL heights are expected to increase westward towards the equator as sea surface warms and subsidence weakens and correspond to the transition from the stratus/stratocumulus to the cumulus cloudy regimes.

Fig. 10 shows the average PBL heights $z_N$ and $z_w$ from GPS and ERA-Int for the winter (DJF) and summer (JJA) seasons. From these results, two distinct regimes can be observed: the Eastern Pacific (subtropical) regime from ∼15°N to 30°N and the Central Pacific (tropical regime) from 0°N to 10°N. In the subtropical regime, the PBL heights increase by about 500 m as latitude decreases (away from the California coast). $z_N$ and $z_q$ agree very well with each other, which is not surprising since the relative minimum gradients $\tilde{N}'$ and $\tilde{P}'_w$ are quite large. The GPS PBL heights are about 500 m higher than ERA-Int. In addition, the transition from the subtropical regime to the tropical regime occurs a few degrees higher in latitude. In the tropical regime, the GPS results become noisier as the relative minimum gradients weaken. While $z_N$ and $z_w$ remain close for ERA-Int, their difference gets larger for GPS due to the drop of $z_w$. This is consistent with Fig. 7 and reflects the stronger weighting of $P_w$ over $N$ close to the surface.

Fig. 10.

Focusing on the Northeast Pacific region (27°N to 32°N, 130°W to 135°W), Fig. 11
shows the distributions of PBL heights from GPS and ERA-Int. It can be seen that the $z_N$ and $z_w$ distributions are quite similar. However, the GPS distributions are different from the ERA-Int distributions, with the GPS distributions being broader with longer tails. This is especially true for the summer months, when the ERA-Int distributions become more sharply peaked while the GPS distributions become somewhat more spread out and appear to develop into a bimodal structure with peaks at 1 and 1.5 km. Part of this could be related to sampling, as the total number of profiles in this region for JJA is only 40 compared to 72 for DJF. We note also that the longer tails of the GPS distributions, with heights greater than $\sim$ 3 km, were found to correspond to profiles with a smaller minimum gradients. However, even with these profiles excluded, the GPS heights still average higher than ERA-Int. The observed mean difference between GPS and ERA-Int in this region ($\sim$ 300 m) is comparable to the difference between GPS and ECMWF shown in Xie et al. [2012] over the Southeast Pacific. The observed difference is consistent with a low PBL height bias in ECMWF over the marine stratocumulus regions that has been verified in a number of studies through direct comparison with radiosonde soundings [von Engeln and Teixeira, 2004; Hannay et al., 2009; Xie et al., 2012].

Another region where the gradient methods should work well is for the dry convective boundary layers that develop over the subtropical deserts during daytime. Fig. 12 shows the monthly averages of PBL heights in the Northern Africa (Sahara) region (20–30° N, 0–15°E). Strong seasonal cycles can be found in both GPS and ERA-Int PBL heights, with the summer PBL heights being 2 km higher. In this region, $z_w$ and $z_N$ from GPS are much closer to each other than the corresponding results from ERA-Int. In addition, $z_w$ from GPS and ERA-Int agree better with each other than $z_N$. Over land, one expects a large diurnal variation in the PBL height in response to the strong solar heating during daytime and strong radiative cooling during nighttime. Fig. 13 shows the diurnal variations of the PBL heights during the summer months.
The GPS results are averaged in two-hour bins, whereas ERA-Int results are available every 6 hours at 0, 6, 12, 18 hr UT (UT is the same as local time here). A pronounced diurnal cycle can be seen in all the curves, with maximum height in the late afternoon and minimum height in the early morning. With the exception of $z_N$ from ERA-Int, which exhibits the largest peak-to-peak variation, the PBL heights remain very high throughout most of the night, when the PBLs are no longer convectively unstable. We believe that this is due to the residual layers that persist after sunset [Stull, 1988] and maintain large vertical gradients of moisture and refractivity.

The distributions of PBL heights are shown in Fig. 14 for the winter (DJF) and summer (JJA) seasons, with the colors indicating different times of the day. The GPS and ERA-Int distributions are similar, with the primary difference coming from the “nighttime” PBL heights (21–24, 3–9 hr for GPS, and 0 and 6 hr for ERA-Int). This is particularly true for $z_N$ during summer, which for ERA-Int is dominated by shallow depths of 500 m or less. The shallow PBLs are indicative of a lack of sharp structures in the ERA-Int refractivity profiles, in which case the refractivity gradient is lowest at the surface (Sec 2.1). On the other hand, many of the ERA-Int water vapor pressure profiles show vertical variations sufficiently large to overcome the surface values. This explains why the shallow layers are present more in $z_N$ than $z_w$. Note that the low “nighttime” $z_N$ from ERA-Int is responsible for the distinct diurnal variation shown in Fig. 13.

To examine whether the lack of the shallow PBLs might have been affected by insufficient penetration of the GPS profiles, we subsample the ERA-Int dataset at the GPS locations and times, similar to what was done by Guo et al. [2011]. The resulting refractivity-based PBL height distributions for the DJF and JJA seasons are shown in Fig. 15 in cyan color. These subsampled distributions are similar to those shown in Fig. 14 that are based on the full ERA-Int dataset. Next, we truncate each profile from below at the minimum altitude of the corresponding GPS profile. The resulting distributions are shown in Fig. 15 in magenta color. It can be seen that the primary
difference between the two distributions occurs below 200 m. During the JJA seasons, this leads to a $\sim 200$ m difference in the mean PBL height. This shows that insufficient depth penetration only accounts for a fraction of the observed difference between GPS and ERA-Int.

4. Discussion and Summary

GPS RO measurements contain vertically resolved, cloud-penetrating, moist thermodynamics information about the PBL and lower troposphere in the form of the microwave refractivity, which is a function of temperature, pressure, and specific humidity. It offers new opportunities in inferring global PBL heights; however, the unique nature of the GPS measurements required non-traditional approaches in identifying PBL heights. In this paper, we studied two different but closely related approaches that are based on the vertical gradients of the retrieved refractivity and water vapor pressure profiles. Namely, we defined the top of the PBL to be the height where the vertical gradient is minimum (most negative). These definitions are simple to apply and are motivated by the sharp changes in moisture and temperature that sometimes occur in the transition from the PBL to the free troposphere. Similar definitions were exploited in the published literature to some extent, but a detailed examination of the applicability and compatibility of these definitions had not been made.

To characterize the change of water vapor and temperature across the top of the PBL, we make use of the “sharpness parameter,” which is defined as the minimum refractivity gradient relative to the RMS value of the gradient averaged over the profile. We find that the sharpness parameter is largest over the subtropics and coincides with the strong subsidence regions, with maximum value of about 3 in the Southeastern Pacific Ocean. Conversely, the smallest sharpness parameter occurs over the ITCZ and SPCZ where the PBL is not well defined. Over the high latitudes, the sharpness parameter is also small due to the fact that the water vapor contribution to the
refractivity becomes insignificant in these drier and colder regions. We show that when the sharpness parameter is large ($> 2$), the refractivity based PBL height ($z_N$) agrees very well with the water vapor pressure PBL height ($z_w$), indicating that large refractivity gradient arises from water vapor rather than temperature. For sharpness less than 2, $z_N$ and $z_w$ differ but are still within $\sim 500$ m of each other on average.

We applied the minimum gradient definitions to calculate the mean and standard deviation of the global PBL heights from three years of COSMIC data. We found that $z_N$ and $z_w$ were close to each other with gross geographical variations that are qualitatively consistent with known characteristics of the PBL. For example, shallow PBLs were observed in the subtropical Eastern Pacific Ocean and deep PBLs were observed over the Sahara and Australian deserts. These features compare well with ECMWF Reanalysis Interim; however, the ERA-Int PBL heights were found to be lower than GPS almost everywhere (by about 500 m). This was true for both $z_N$ and $z_w$, even in regions where the relative minimum gradients were strong. Despite the ubiquity of the bias, we believe that its causes could well be different in different regions, as evidenced from the regional comparisons over the Eastern Pacific Ocean and the Sahara desert. The bias might reflect an actual low PBL height bias in ERA-Int. It could also be a consequence of the broader distribution of PBL heights inferred from GPS (perhaps arising from free tropospheric variability) that leads to a higher mean PBL. Whatever the reasons might be, it is interesting to note that this bias is substantially reduced when we look at the seasonal anomalies, thus indicating that the bias is largely time-independent. Without the overall bias, the maps of seasonal variabilities look much more similar between GPS and ERA-Int.

In summary, the results of this paper demonstrate that GPS profiles indeed provide useful information about the PBL heights over both land and ocean. The minimum gradient definitions for PBL heights are most useful and unambiguous over the subtropical regions, where the refractivity and water vapor based heights give essentially
the same results. It should be emphasized that these definitions do not necessarily correspond precisely to more traditional definitions of the PBL or mixing heights [Seidel et al., 2001]. For example, over land at night, the minimum gradients might identify the residual layer left from the daytime PBL even though the layer is no longer convectively unstable. Thus when comparing the PBL heights derived from other measurements or models, it is imperative that the same PBL height definitions be applied whenever feasible. Of the two definitions considered in this paper, the refractivity based definition is perhaps preferable since it can be applied to all regions of the globe. On the other hand, if the focus is over the tropics and subtropics, the water vapor based definition is more appealing because the results are easier to interpret.

The bias that exists between GPS and ERA-Int warrants additional analysis, and validation studies involving multiple sensors and models are much needed to establish the accuracy of the GPS-derived heights. Data quality issues affecting the depth penetration of the GPS profiles in the lowest 500 m or so need to be understood and addressed. Finally, it should be pointed out that the minimum gradient definitions used here are somewhat simplistic, and more refined and complex algorithms could be developed that are more robust against measurement noise or atmospheric variability in the free troposphere (see, e.g., [Ratnam and Basha, 2010] for an alternative approach utilizing wavelet covariance transform). In addition, even though the emphasis of this and related works is entirely on the height of the PBL top, it is worth noting that GPS profiles actually contain vertically resolved information above and within the PBL — information which can be difficult to obtain through any other satellite measurement.
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Figure Captions

Figure 1. Refractivity $N$, temperature $T$, water vapor pressure $P_w$, and specific humidity $q$ profiles (left) and their vertical gradients (right) from high-resolution (30-meter) radiosonde sounding launched from Lihue, Hawaii showing a well-mixed PBL capped by a strong inversion layer. The minimum gradients of the refractivity and specific humidity profiles occur at the base of the inversion layer.

Figure 2. Examples of profiles with different relative minimum gradients (“sharpness parameters”). For the “strong” case (top), $\tilde{N}' = 3.1$, $\tilde{P}_w' = 4.5$, $\tilde{q}' = 4.4$. For the “medium” case (middle), $\tilde{N}' = 2.0$, $\tilde{P}_w' = 2.9$, $\tilde{q}' = 2.7$. For the “weak” case (bottom), $\tilde{N}' = 1.37$, $\tilde{P}_w' = 2.1$, $\tilde{q}' = 2.9$. Notice that the bottom case is weak only in terms of $N$ and $P_w$; the sharpness parameter for $q$ is actually larger than the middle case.

Figure 3. Fraction of COSMIC profiles from Sept. 2007 to Aug. 2008 that are retrieved down to within 500 m (top) and 1 km (bottom) of the surface.

Figure 4. Mean (a) and standard deviation (b) of global $N$-based PBL heights obtained from three years of COSMIC data on $5^\circ \times 5^\circ$ grid. A 3-point smoothing has been applied to smooth the data. The $5^\circ \times 5^\circ$ black boxes in (a) correspond to the Pacific cross section used in Sec. 3.2.

Figure 5. Mean (a) and standard deviation (b) of global $P_w$-based PBL heights obtained from three years of COSMIC data on $5^\circ \times 5^\circ$ grid. A 3-point smoothing has been applied to smooth the data.
**Figure 6.** Relative minimum refractivity gradient (sharpness parameter) from three years of COSMIC data on $5^\circ \times 5^\circ$ grid. A 3-point smoothing has been applied to smooth the data. Contours represent 500 hPa vertical velocity from ERA-Int, with black contours denoting sinking air (0.015 and 0.03 Pa/s) and white contours denoting rising air ($-0.015$ and $-0.03$ Pa/s).

**Figure 7.** Difference between $z_N$ and $z_w$ as a function of the relative minimum refractivity gradient (sharpness parameter) over the tropics ($30^\circ$S–$30^\circ$N) and mid-latitudes ($30^\circ$S–$60^\circ$S, $30^\circ$N–$60^\circ$N). The means (represented by the circles) and standard deviations (represented by the error bars) were computed from every 0.5 step bins in sharpness parameter, with the tropical and mid-latitude results being offset horizontally for improved visibility.

**Figure 8.** Mean (a) and standard deviation (b) of global $N$-based PBL heights obtained from ERA-Int on $1.5^\circ \times 1.5^\circ$ grid.

**Figure 9.** Seasonal averages of PBL heights from the minimum refractivity gradient method obtained from COSMIC (left) vs ERA-Int (right). The 3-year annual means have been subtracted from the respective dataset. A 3-point smoothing has been applied to smooth the COSMIC data.

**Figure 10.** PBL heights along the GCSS Pacific Cross-Section Intercomparison transect (see Fig. 4a). The latitude in the x-axis of the plots refers to the Southern boundary of each $5^\circ \times 5^\circ$ latitude-longitude box along the transect.

**Figure 11.** Distributions of refractivity and humidity based PBL heights from GPS and ERA-Int off the coast of southern California over the Northeast Pacific ($27^\circ$N to $32^\circ$N, $130^\circ$W to $135^\circ$W) for the winter (DJF) and summer (JJA) seasons. Dashed line indicates the mean of each distribution.

**Figure 12.** Monthly averages of PBL heights in the Sahara region.
**Figure 13.** Diurnal variation of PBL heights in the Sahara region in the summer months (JJA).

**Figure 14.** Distribution of PBL heights in the Sahara region for DJF (left) and JJA (right) seasons. Dashed line indicates the mean of each distribution. Colors indicate local times in hours (same as UT times in this longitude zone). For GPS, the local times are grouped in 6-hr intervals (21–24 & 0–3, 3–9, 9–15, 15–21), while for ECMWF, they are at 0, 6, 12, 18 hours.

**Figure 15.** Distribution of refractivity-based PBL heights in the Sahara regions from ERA-Int subsampled at the GPS locations and times for DJF (left) and JJA (right) seasons. In one case (cyan), the entire profile is used. In another case (magenta), each profile is truncated at the bottom in accordance with the minimum profile height from the corresponding GPS profile. Dashed lines indicate the means of the distributions.