Evaluation of the Planetary Boundary Layer Heights Derived From GPS Radio Occultation Soundings Over the VOCALS-REx Area

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ABSTRACT

Earth’s planetary boundary layer (PBL) plays an important role in water vapor and heat exchange between the surface and atmosphere through turbulent processes. Using data from the COSMIC/ FORMOSAT-3 global positioning system (GPS) radio occultation (RO) soundings and high-resolution radiosondes launched during the VOCALS-REx (the VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment), PBL heights of collocated points between RO soundings and radiosondes launched onboard the NOAA R/ V Ron Brown ship were compared. Four definitions of PBL height (H) based on RO profiles were considered, two based on refractivity (N), one based on bending angle and the other based on partial water vapor pressure ($P_w$). One of the two methods based on refractivity defined H as maximum vertical gradient of N; the other defined H as the “break point” in the N profile, which is essentially the maximum second derivative of N in the vertical. Results showed that, on the average, PBLH from GPS RO soundings using the “break point” definition were slightly higher than those from radiosondes, while the H estimates from the other three methods were somewhat lower. The RO refractivities showed a negative bias compared to radiosondes below the PBL top. The likely reason for the negative N bias is due to super-refraction that occurs when the vertical gradient of refractivity exceeds the critical refraction value of ~157 N-unit km$^{-1}$. Therefore, the reduced refractivity and its vertical gradient would then affect the N-based and $P_w$-based PBLH defined from GPS RO soundings. The comparison of the four methods for estimating PBLH from the RO observations indicated that those based on bending angle profiles were more consistent with estimations from radiosondes in this study.

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1. Introduction

The planetary boundary layer (PBL) is the lowest layer in the troposphere and the closest layer to Earth’s surface. The surface characteristics and forcing, such as topography, land cover, solar heating and longwave radiative cooling affect the temperature, water vapor, momentum and turbulence in the PBL. Compared with the free atmosphere above the PBL, turbulence and vertical mixing are stronger in the PBL. Therefore, momentum, moisture, sensible and latent heat, aerosols, and pollutants are transported from and to the surface by turbulence. In addition to the energy exchanges between the atmosphere and Earth’s surface, turbulence affects the development and destruction of large-scale circulations and therefore influences weather and climate systems (Stull 1988). The PBL top is often characterized by a temperature inversion layer and by a sudden decrease of humidity.

There is lack of good in situ observations of the PBL over the ocean. However, the six-satellite Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)/ Formosa Satellite 3 (FORMOSAT-3), which was launched in April 2006, provides a large amount of high-resolution Global Positioning System (GPS) radio occultation (RO) soundings over the globe. The GPS satellites emit radio signals that are refracted by the atmosphere of the planet before they are received by a GPS receiver onboard a low earth-orbiting (LEO) satellite (Kursinski et al. 1997). The slowing and bending of the radio waves are measured by the receiver and used to compute the atmospheric refractivity, N, which is related to pressure P, temperature T, and partial pressure of water vapor $P_w$ through the relation (Smith and Weintraub 1953)

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^8 \frac{P_w}{T^2},$$

where P and $P_w$ are in mb and T is in K. Guo et al. (2011) and Ao et al. (2012) defined the PBL height based on refractivity or $P_w$ profiles from GPS RO soundings. Ao et al. (2012) found that refractivity-based and moisture-based PBL heights are consistent if the sharpness parameter is large.

The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx) was conducted over the Southeast Pacific during October and November 2008, and a large number of high-resolution radiosonde soundings were obtained (VOCALS, 2013). Over this region, wide spread persistent stratocumulus clouds occur due to the cold sea surface temperature (SST) below and warm and dry air aloft. Therefore, the PBL can be clearly defined in this area (Richter and Mechoso, 2006). Xie et al. (2012) analyzed data from COSMIC GPS RO soundings from Jet Propulsion Laboratory (JPL), radiosondes and ECMWF analysis over the VOCALS-REx area. They found a negative refractivity bias within the PBL and a smaller vertical gradient of refractivity than radiosonde observations at PBL top, due to the existence of super-refraction layer at the PBL top. In this study I confirm and extend this work using GPS RO soundings from the University Corporation for Atmospheric Research (UCAR) COSMIC Data Analysis and Archive Center (CDAAC, available at http://cdaac-www.cosmic.ucar.edu/cdaac/products.html).

In this study, the objective is to use independent in situ radiosondes observations from the VOCALS-REx to quantify COSMIC detected PBL heights and identify the causes of the difference. Section 2 describes the data and methods used in this study. Comparisons
between two parameters to estimate the PBL height (H) are discussed in section 3. Conclusions and future work are presented in section 4.

2. Data and Method
To evaluate PBL heights derived from COSMIC GPS RO soundings, we used the radiosonde observations collected by the VOCALS-REx during October and November 2008 over the Southeast Pacific Ocean. The VOCALS-REx region is defined between -15°~ -25°S and -87.5°~72.5°W (Figure 1), where many observations were collected (Wood et al. 2007, Rahn and Gareaud 2010). Therefore, two datasets are chosen from the VOCALS-REx and COSMIC GPS RO soundings based on the temporal and spatial requirements mentioned above.

a. The COSMIC/ FORMOSAT-3 GPS RO Sounding
Global Positioning System (GPS) radio occultation (RO) soundings from the University Corporation for Atmospheric Research (UCAR) COSMIC Data Analysis and Archive Center (CDAAC) are used. Retrieved refractivity vertical profile is used to compute the PBL height. Vertical profiles of T and P_w are retrieved by 1D-VAR (one-dimensional variational analysis) using refractivity from COSMIC GPS RO soundings and (1) above (Poli et al. 2002). In addition, the height of “break point” in the refractivity profile and bending angle (BA) profile from RO soundings were used to estimate PBL heights. The “break point” is defined as the height of maximum lapse rate of slope of linear regression in 300-m window (Z_bp) of refractivity profile (Guo et al. 2011; Ao et al. 2012). Then, the height where maximum lapse rate of N, P_w or bending angle occurs is defined as the PBL height, while maximum lapse rate is derived from the following formula

\[ A'(z_i) = \frac{A(z_i) - A(z_{i-1})}{z_i - z_{i-1}}, \]

where A is N, P_w or bending angle, A'(z_i) is lapse rate of A at level i and z is the altitude in kilometer.

b. NOAA R/V Ron Brown Radiosonde
This dataset contains 215 high vertical resolution (~1 second) soundings (Vaisala RS92 sondes) collected onboard the NOAA R/V Ronald H. Brown during October 7 to December 1 2008. Most of the soundings were launched every four hours between -18°~ -22°S and -85°~72.5°W. To define the PBL heights from these soundings, moisture data are used because the PBL top is characterized by a sudden decrease of water vapor. Further, Ao et al. (2012) find that the partial pressure of water vapor P_w is an effective moisture variable to define the PBL heights when using high vertical resolution data.

Since the radiosonde sounding doesn’t measure partial pressure of water vapor, the saturation water vapor pressure, P_{ws}, is derived from dew point temperature T_d by the relation

\[ P_{ws} = \frac{e^{(77.345 + 0.0057T_d - 72.35T_d^{0.2})}}{T_d^{0.2}}, \]
where $P_{ws}$ is in Pascals and $T_d$ is in Kelvins. Partial water vapor pressure, $P_w$, of each level from radiosondes data is equal to $P_{ws}$. Then, refractivity is also computed from radiosonde data by using (1). Finally, the PBL height is defined as the height where the minimum $N'(z_i)$ or $P_w'(z_i)$ (derived from (2)) occurs. Moreover, since the PBL height is not likely to be larger than 5 km in this maritime region, only heights below 5 km are searched.

3. Results and Discussions

a. PBL Top Detection Method

To effectively evaluate PBL heights from GPS RO soundings, we searched for closely located (called collocated in this study) points between COSMIC and Ron Brown radiosondes, defined as two points being within 300-km horizontal distance and 3-hour time difference. Over the VOCALS-REx area and during this time period, 15 collocated points are found. Figure 2 shows refractivity ($N$) based, partial water vapor pressure ($P_w$) based and bending angle based PBL heights and $Z_{bp}$ from COSMIC compared to the $N$-based PBL heights from the Ron Brown radiosondes. (The $N$-based and $P_w$-based PBL heights are nearly the same in Ron Brown radiosonde data.) The COSMIC PBL heights based on $N$, $P_w$ and bending angle are slightly lower than those of Ron Brown radiosondes with mean biases ranging between -0.05 and -0.15 km and standard deviations of biases ranging between 0.15 and 0.16 km in confidence interval of 99.5%. But, PBL heights based on $Z_{bp}$ are higher than PBL heights from Ron Brown with mean bias of 0.2 km and standard deviation of bias of 0.14 km. All methods show significant accuracy in determining the PBL heights. The PBL heights based on bending angles are more accurate than the other three methods in this study. This implies that difference PBL top detection methods is one cause of the difference between COSMIC and radiosondes PBL heights.

b. Accuracy of Refractivity

Another cause of the differences in determining the height of the PBL using the RO refractivity is the accuracy of refractivity. The COSMIC refractivity profiles at all 15 collocated points show a negative bias compared to the radiosonde refractivities below the PBL top. This negative $N$ bias is likely caused by a super-refraction layer ($N' < -157$ N-unit km$^{-1}$) that exists at the PBL top (Sokolovskiy 2003). Over the VOCALS-REx region, all the radiosonde refractivity profiles from the 15 points show that there is a persistent super-refraction layer at the PBL top, even with 100-m smoothing. Figure 3 shows profiles of one collocated point between two datasets. The critical value of $N$ and hence the super-refraction layer cannot be detected from the smooth refractivity profiles of COSMIC observations (Fig. 3b and 3d). The negative $N$ bias in the RO profiles result in a reduced sharp gradient of refractivity at the PBL top and may shift the heights of sharp gradient estimated from COSMIC to lower altitudes. Because the 1D-VAR retrieval process uses $N$ as input to retrieve temperature ($T$) and partial water vapor pressure ($P_w$), the negative $N$ bias also leads to a bias in retrieved $T$ and $P_w$ from 1D-VAR. Then, the bias in retrieved $P_w$ may cause the bias in $P_w$-based PBL heights. However, the errors in retrieved $T$ and $P_w$ may also arise from errors in the first guess and the 1D-VAR retrieval process. The next section will discuss these different sources of error.
c. **Accuracy of 1D-VAR**

The 1D-VAR process uses refractivity from the COSMIC GPS RO soundings and first-guess T and P\textsubscript{w} from ERA-Interim reanalysis to retrieve statistically optimal estimates of T and P\textsubscript{w}. The first guess, the 1D-VAR algorithm, and the COSMIC refractivity all affect the retrieved variables. To understand how much error comes from 1D-VAR and the first guess and how much comes from the negatively biased COSMIC refractivities, the refractivity from the Ron Brown radiosondes (which are assumed to be perfect) and the first-guess T and P\textsubscript{w} from the ERA-Interim reanalysis were used in 1D-VAR to retrieve a set of T and P\textsubscript{w} to compare with the estimates using COSMIC RO refractivity. As seen in figure 4, the retrieved T and P\textsubscript{w} using the Ron Brown refractivity are biased much less than those from COSMIC refractivity. This implies that the negatively biased refractivities from COSMIC contribute most of the errors in retrieved T and P\textsubscript{w}.

In another test I used the observed refractivity from COSMIC and the first-guess T from ERA-Interim reanalysis to calculate P\textsubscript{w} (“P\textsubscript{w}\_calculate” in figure 3) using (1). In this case, the P\textsubscript{w} bias within the PBL is larger than the retrieved P\textsubscript{w} from 1D-VAR. This means that 1D-VAR adjusts P\textsubscript{w} profiles even more when a reasonably good first-guess temperature profile is used, because all of the adjustment to the erroneous N must occur in the P\textsubscript{w} profile. Thus, 1D-VAR using is a better approach to retrieve P\textsubscript{w} and improvement is needed in refractivity from COSMIC GPS RO soundings.

4. **Conclusions**

Over the VOCALS-REx area, a persistent temperature inversion and wide-spread stratocumulus cloud deck exist. The PBL top is clearly detected by high-resolution radiosondes and GPS RO soundings, although the heights determined from the RO soundings vary depending on the parameter used to estimate the height. Maximum lapse rate of refractivity and partial water vapor pressure were used to define the PBL heights in both RO soundings and radiosondes. The N-based and P\textsubscript{w}-based PBL heights estimated from RO soundings are biased lower than PBL heights from Ron Brown radiosondes, which are considered “truth” in these comparisons.

Another two methods were used to estimate the PBL heights from the RO observations. PBL heights from “break point” in refractivity profiles and from bending angle profiles were computed to compare with the PBL heights from Ron Brown radiosondes. The PBL heights estimated from the bending angle profiles were biased less than the other methods.

Another uncertainty is the accuracy of the RO refractivity soundings. From the radiosonde refractivity profiles of all collocated points, a super-refraction layer exists at the PBL top, which leads to a negative bias in refractivity within PBL. This negative bias causes large errors in the 1D-VAR retrieved temperature and partial water vapor pressure profiles from COSMIC refractivity. The bias in refractivity and partial water vapor pressure from COSMIC also results in lower PBL heights than those from Ron Brown radiosondes.

The errors in the 1D-VAR retrieved temperature and partial water vapor pressure are caused partly from errors in the COSMIC refractivity soundings and partly from errors in the 1D-
VAR retrieval process. So, refractivity from the Ron Brown radiosondes, which were assumed to be perfect, was used in 1D-VAR to generate one set of retrieved variables. The results showed that the refractivity errors contribute more to the errors in retrieved temperature and partial water vapor pressure than the 1D-VAR process.

In spite of a negative refractivity bias in the RO soundings caused by a super-refraction layer at the PBL top, the RO soundings provide reasonably good estimation of PBL heights, with errors typically less than 150 m.

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Fig 1. Distribution of COSMIC GPS RO soundings (black stars) and Ron Brown radiosondes (red stars) launched onboard NOAA R/V Ron Brown ship over the VOCALS-REx region during October and November 2008.
Fig 2. a. Comparison of N-based PBL heights of 15 collocated points between COSMIC GPS RO soundings and Ron Brown radiosondes. Pair numbers 3 and 12 and 1 and 13 overlap on this plot. b. Comparison between $P_w$-based PBL heights from COSMIC and N-based PBL height from Ron Brown radiosondes. Pair numbers 3 and 12, 1 and 13 and 10 and 11 overlap on this plot. Mean and standard deviation of PBL heights and the mean and standard deviation of bias between two datasets are shown. The number next to each red dot means the number of collocated points. c. Comparison between PBL heights based on maximum lapse rate of bending angle from COSMIC soundings and N-based PBL heights from Ron Brown radiosondes. Pair numbers 3 and 12 and 1 and 13 overlap on this plot. d. Comparison between $Z_{bp}$ from COSMIC and N-based PBL heights from Ron Brown radiosondes. Pair numbers 3 and 12 overlap on this plot. Pair number 6 and the value of mean of $zbpn_{max}$ (1.60 km) overlap on this plot. Mean and standard deviation of PBL heights and the mean and standard deviation of bias between two datasets are shown.
Fig 3. a. Temperature from Ron Brown radiosonde (blue), the ERA Interim (red) and COSMIC GPS RO (black) obtained from RO refractivity and the 1D-VAR retrieval using the ERA temperature and $P_w$ as first guess. b. Refractivity from COSMIC (black), ERA (red), Ron Brown (blue), and 100-m smoothed Ron Brown data (green). c. Partial water vapor pressure from Ron Brown (blue), ERA (green), $P_w$ obtained from RO refractivity and the 1D-VAR retrieval using the ERA temperature and $P_w$ as first guess (black), and $P_w$ calculated from the relation (Smith and Weintraub 1953) using RO refractivity and ERA temperature (red). d. Vertical gradient of refractivity profile from COSMIC GPS RO soundings. e. Vertical gradient of refractivity profile from Ron Brown with 100-m smoothing. These profiles are from collocated point 11. The vertical red dashed line in d. and e. indicates the critical refraction value of -157 N-unit km$^{-1}$. 
Fig 4. a. Temperature from Ron Brown radiosonde (green), ERA Interim (red), 1D-VAR using RO refractivity and ERA temperature and P\textsubscript{w} as first guess (black) and 1D-VAR using Ron Brown radiosonde refractivity and ERA temperature and P\textsubscript{w} as first guess (blue). b. Refractivity from COSMIC GPS RO (black), ERA (red), the relation from Smith and Weintraub (1953) using retrieved T and P\textsubscript{w} from Ron Brown N (blue) and Ron Brown (green). c. Partial water vapor pressure from Ron Brown (green), ERA (red), 1D-VAR using RO refractivity and ERA temperature and P\textsubscript{w} as first guess (black) and 1D-VAR using Ron Brown radiosonde refractivity and ERA temperature and P\textsubscript{w} as first guess (blue). d. Temperature bias between retrieved T from RO refractivity and Ron Brown (black), between ERA and Ron Brown (red) and between retrieved T from Ron Brown refractivity and Ron Brown (blue). e. Refractivity bias between RO and Ron Brown (black), ERA and Ron Brown (red), and calculated N and Ron Brown (blue). f. Partial water vapor pressure bias between retrieved P\textsubscript{w} from RO refractivity and Ron Brown (black), ERA and Ron Brown (red), and retrieved P\textsubscript{w} from Ron Brown refractivity and Ron Brown (blue). These profiles are from collocated point 11. Black dash line in d., e., and f. indicates zero bias.