Advances and limitations of atmospheric boundary layer observations with GPS occultation over southeast Pacific Ocean

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We thank the editor and the two reviewers for the very insightful and constructive comments. Some major updates in the revised draft are summarized below:

(1) Following reviewer#1's suggestion, Fig. 3a was updated after including the Stratus cruise radiosonde soundings (~140 soundings in October of 2006 and 2007) in this study. More near-coincident COSMIC RO and radiosonde pairs (a total of 43) were used for the ABL height scatter plot. A better correlation between radiosonde and near-coincident RO was obtained.
(2) Following reviewer#2's suggestion, the two panels plots were added (Fig.7e,f), which compare the ABL height and maximum refractivity gradient along ~20°S transect among COSMIC, ECMWF, and VOCALS radiosondes. Sect. 5.1 is also added to discuss the transect revealed from the tree dataset.
(3) Following reviewer#1's suggestion, Fig.8 was updated and the artificial drop of penetration rate near coast was removed.
(4) One paragraph is added in Sect.1 to reflect the previous studies using satellite observations (e.g., CALIPSO, MISR and MODIS) to infer the ABL heights.

The following references were included and the editor and the two reviewers' comments are addressed in details as follows.

Harshvardhan, Zhao, G., Girolamo, L. Di and Green, R. N.: Satellite-observed location of stratocumulus cloud-top heights in the presence of strong inversions. IEEE Trans. Geosci. Remote Sens., 47, 1421–1428, doi:10.1109/TGRS.2008.2005406, 2009.

Garay, M. J., de Szoeke, S. P., and Moroney, C.M.: Comparison of marine stratocumulus cloud top heights in the southeastern Pacific retrieved from satellites with coincident ship-based observations. J. Geophys. Res., 113, D18204, doi:10.1029/2008JD009975, 2008.

Wu, D., Hu, Y., McCormick, M., Xu, K., Liu, Z., Smith, B., Omar, A., and Chang, F.: Deriving marine-boundary-layer lapse rate from collocated CALIPSO, MODIS, and AMSR-E data to study global low-cloud height statistics, Geosci. Remote Sens. Lett., 5, 649–652, 2008.

Zuidema, P., Painemal, D., de Szoeke, S., and Fairall, C.: Stratocumulus cloud-top height estimates and their climatic implications, J. Climate, 22, 4652–4666, 2009.

Replies to the Editor's Comments:

Editor Initial Decision: Publish as is (03 Aug 2011) by Rene Garreaud

Comments to the Author:

I am very pleased with the prospect of MBL observations using GPS occultation. In my initial review of the paper I saw you compare your MBL Height estimates with VOCALS-radiosondes and ECMWF analysis. Nevertheless, several mesoscale models were run for VOCALS-REx and you can used them to compare MBL Height. Whether or not this issue (more comparisons) is raised by the reviewers, you may consider the results presented in the following papers:

We thank the editor's comments. In Fig. 10 of Wyant et al. (2010), systematically lower ABL heights in various weather/climate models is seen along the 20°S transect when comparing with the in-situ radiosonde and satellite observations over VOCALS campaign regions. The low bias is especially large in models near the coast (Rahn and Garreaud, 2010; Wyant et al., 2010; Wang et al., 2011). These are consistent with the ECMWF analysis results presented in this study.

We have also added the ABL height and the maximum refractivity gradient along the 20°S transect in Fig. 7e,f. The detailed comparison between COSMIC RO, ECMWF and VOCALS radiosondes are discussed in detailed in the new paragraph in Sect. 5.2.

The following suggested references were added into the discussion.

Wyant, M. C., et al.: The PreVOCA experiment: modeling the lower troposphere in the Southeast Pacific, Atmos. Chem. Phys., 10, 4757-4774, doi:10.5194/acp-10-4757-2010, 2010.

Rahn, D. A. and Garreaud, R.: Marine boundary layer over the subtropical southeast Pacific during VOCALS-REx – Part 1: Mean structure and diurnal cycle, Atmos. Chem. Phys., 10, 4491-4506, doi:10.5194/acp-10-4491-2010, 2010.

Wang, S., O'Neill, L. W., Jiang, Q., de Szoeke, S. P., Hong, X., Jin, H., Thompson, W. T., and Zheng, X.: A regional real-time forecast of marine boundary layers during VOCALS-REx, Atmos. Chem. Phys., 11, 421-437, doi:10.5194/acp-11-421-2011, 2011.

In Section 6.4, we added: "*The synoptic and meso-scale processes have known to have significant impact on variations of the ABL height or vertical structures (e.g., Toniazzo et al., 2011).*"

Toniazzo, T., Abel, S. J., Wood, R., Mechoso, C. R., Allen, G., and Shaffrey, L. C.: Large-scale and synoptic meteorology in the south-east Pacific during the observations campaign VOCALS-REx in austral Spring 2008, Atmos. Chem. Phys., 11, 4977-5009, doi:10.5194/acp-11-4977-2011, 2011.

Replies to Referee #1

Specific Comments:

Anonymous Referee #1

This article provides a detailed account of the strengths and weaknesses of using GPS radio occultation (RO) to obtain the depth of the atmospheric boundary layer (ABL) over the subtropical southeast Pacific Ocean. An important contribution of these measurements is an independent measurement of the distribution of ABL height over the southeast pacific with a sufficient sample size to construct a regional climatology, which is shown to be significantly different than that of the ECMWF. The known limitations and areas of uncertainty are an important aspects of this paper that inform potential users of the weaknesses of the method. Overall, it is suitable for publication in ACP, but several issues detailed below should be addressed first.

We thank the reviewer's very constructive comments. Our answers to the specific comments are listed below.

General Comments
An important component of this study is that the distribution of ABL height over the southeast Pacific has substantial differences with the ECMWF. Is the ECMWF climatology constructed using the output at one time of day (e.g., just the 00 UTC analysis) or does it use all analysis times? Also, as a contrast to this study, it might be worthwhile to mention the recent article by Guo et al. (2011) in the Journal of the Atmospheric Sciences. They used a slightly different method to find the ABL height ('break point method') and show the global ABL height distribution. Radiosonde data from the island of St. Helena (16.0_S, 5.7_W) was used as their validation. They claim that the spatial pattern of the ECMWF does indeed agree with the spatial pattern from their ABL retrieval, but the ECMWF still had a low bias. Do the authors have any comments on this?

Yes, our study shows significant difference in ABL height climatology between COSMIC RO and ECMWF analysis over southeast Pacific. We use the 6-hourly (0,6,12,18Z) ECMWF YOTC (Year-of-tropical-convection) analysis, which has spatial resolution of 0.25° with 91 vertical levels. The analysis profiles are down-sampled to 1-deg spatial resolution to generate the ABL height climatology, which is consistent with the result derived from the original 0.25° resolution analysis (not shown).

We have added Guo et al. (2011) into the references. Their ABL height climatology is based on 21 months COSMIC observation (Apr. 2006-Dec. 2007). So for SON (Sep.-Nov.) season, a relative short period (three-month in 2007) data were used to derive the climatology. Our ABL height climatology shows much more details (less noise) of spatial distribution with the usage of 9-month data (2007-2009-SON), which suppress

the sampling errors, especially over low latitudes. The higher ABL in COSMIC comparing with the ECMWF in our study is consistent with Guo et al., 2010. However, they demonstrate the consistence between COSMIC and ECMWF qualitatively without showing the details. Our more detailed regional analysis over SE Pacific actually reveals significant difference between the two.

Guo, P., Y.-H. Kuo, S. V. Sokolovskiy, D. H. Lenschow, 2011: Estimating Atmospheric Boundary Layer Depth Using COSMIC Radio Occultation Data. J. Atmos. Sci., ***68****, 1703–1713.*

Since only 25 of the 190 radiosonde profiles during VOCALS-REx were near-coincident to quality-screened RO soundings, this leads to a small sample size for a comparison, which is already acknowledged by the authors. To increase the sample size of radiosonde observations that are collocated with the RO locations, the authors might want to consider using additional soundings from two cruises to the SE Pacific in 2006 and 2007 when there is also available data from the COSMIC RO. Information and data are available at the Tropical Eastern Pacific Synthesis webpage at the following address: http://people.oregonstate.edu/_deszoeks/synthesis.html

We thank the reviewer for providing the website of the dataset. We have included the high-resolution radiosonde soundings from the cruises over SE Pacific during 2006 and 2007 into our study. A total of 43 radiosonde soundings are found to be near coincident with COSMIC observations within 3 hour and 300 km window. A better correlation between COSMIC RO and radiosonde ABL heights is obtained as shown in the updated Fig. 3a.

In Fig. 8 there is a problem of an artificial decrease near the coast of the percentage of soundings that penetrate below 500 m due to the land eliminating possible soundings. Is there a way to alleviate this problem since we know what fraction of the bin's area is covered by land? Otherwise, the figure is misleading and does not give a good representation of the penetration near the coast.

We applied the 1.25°×1.25° topography data from ECMWF analysis and excluded the grids over the coastal regions contaminated by the topography. The artificial decrease near the coast has been eliminated in the updated Fig. 8. However, it is important to note that there is still a decrease in penetration rate near the coast, which is likely related to the sharp ABL refractivity gradient observed over the stratocumulus region.

Specific Comments

Apart from the science, the general structure and organization is adequate, but there are several places where the writing could be improved or clarified. I offer some editing help in the specific comments, but it is not an exhaustive list of corrections.

*22858, line 26: Do you mean that *despite* the decreasing number of soundings at low latitudes and the lower percentage of soundings that penetrate into the lowest 500 m* *there are small sampling errors in the mean ABL climatology? It reads as if those factors imply small sampling errors, which does not seem to make sense.*

Thanks for the correction. The sentence is revised as the following: ***"At low latitudes, despite the decreasing number of COSMIC RO soundings and the lower percentage of soundings that penetrate into the lowest 500-m above the mean-sea-level, there are small sampling errors in the mean ABL height climatology."***

22859, line 7: Include temperature in "shallow inversion layer."

Corrected as: "a shallow and strong temperature inversion layer"

22860, line 17: I do not know what 'future remarks' means. Do you mean remarks and future studies/work?

Change to: ***"future work"***

22860, line 15: Change present to presents. There are disagreements for other noun/verb pairs in the paper as well (22863 line 24, 22864, line 16, 22873 line 14, etc.). Please double check the grammar.

Corrected. Thanks.

22862, line 21: Remove "less steeper"

Corrected. Thanks.

22868, line 4 and 8: Units missing

Units added. Thanks.

22868, line 5: Typo: radiosndes

Corrected. Thanks.

22869, line 20: What is a 'GO simulation'?

Change to: "*geometric optics simulation*". Thanks.

22870, line 17: 'to detect' should be 'of detecting'

Corrected. Thanks.

Replies to Referee #2

Specific comments:

Anonymous Referee #2

This is an interesting "instrumental" work in which the authors compare several low tropospheric variables derived from GPS radio occultation against radiosonde data over the SE Pacific acquired during VOCALS-REx (October-November 2008) and high resolution ECMWF analysis. The SE Pacific exhibits the typical features of the eastern boundaries subtropical oceans: a nearly-well mixed marine boundary layer (MBL) capped by a strong, sharp temperature inversion and often topped by stratocumulus clouds.

The authors took advantage of the strong temperature and moisture gradient within the temperature inversion, leading to a strong refractivity gradient, to infer the MBL height from GPS-RO data. The discrepancy between the GPS-RO derived MBL height and observations is actually similar or even less than the model (ECMWF) bias. Thus, GPSRO MBL height seems a quite good addition to the list of proxies that can supplement the small number of direct (radiosonde) observations over the SE Pacific and other remote oceanic areas.

The paper is well written and informative, the conclusions are sound and the figures are clear. I consider this manuscript can be accepted for publication subject to addressing the following minor points.

We appreciate the reviewer's encouraging comments. Our answers to the specific comments are as follows.

1. The authors should provide more information of the availability of the GPS-RO data used in this work. For instance, in which period is the data available (beyond the VOCALS period)? What determine the spatial density of these observations? Given a 1_x1_ box over the SE Pacific, what is the average time between one GPS-RO and the next? Is there a seasonal cycle in the data availability?

In Section 1, the availability of COSMIC soundings since April 2006 (~2000 daily profiles) is added into the second paragraph.

The spatial sampling of COSMIC RO over SE Pacific is discussed in details in Section 5. There are ~100 profiles per 500 km×500 km area at ~20°S during the nine-month period (i.e., 2007-2009 SON in Fig. 8a), which correspond to ~10 soundings per month (or ~1 sounding every three days) within a 500 km×500 km grid box. Note that the COSMIC data provided by UCAR COSMIC group have almost double size of the sounding numbers.

The total number of RO soundings has some monthly variations likely due to the satellite orbit configuration. However the spatial distribution of RO samples doesn't show seasonal variations. The sampling errors of COSMIC RO are mainly attributed to the meridional variation of RO sampling (Fig. 8a).

2. The authors discuss that N-bias is quite frequent over the SE Pacific –given the strong gradient in refractivity- but this not affect the estimation of the MBL height. What meteorological information are we missing due to the N-bias?

The *N*-bias leads to systematical underestimation of refractivity gradient at the ABL height. The temperature and water vapor retrieval based on the negatively biased refractivity profile inside the ABL will also biased, i.e., warm bias in temperature and dry bias in humidity retrieval.

3. An important finding in VOCALS-REx was the difference in MBL characteristics between the near-shore (between the coast and about 75_W) and offshore. In the near-shore region, the MBL is thin (1 km) and very stable. Offshore the MBL deepens, sometimes decoupled and become more variable. (Refs: Southeast Pacific atmospheric composition and variability sampled along 20_ S during VOCALS-REx, Atmos. Chem. Phys. Discuss., 11, 2873-2929, 2011; Marine boundary layer over the subtropical southeast Pacific during VOCALS-REx – Part 1: Mean structure and diurnal cycle, Atmos. Chem. Phys. Discuss., 9, 26029-26062, 2009). Most of this longitudinal dependence is readily seen in the different transects along 20_S. I strongly suggest the authors construct such a transect of MBL height (including errors bars) to be compared with the transect in the above mentioned articles. It will be a nice complement to figs. 7-8.

We thank the reviewer for the very constructive suggestion. A transect along ~20°S for the mean and standard-deviation of the ABL height and maximum refractivity gradient from COSMIC, ECMWF and VOCALS radiosondes were added (Fig. 7e,f). We have also included Rahn and Garreaud (2010) into the reference.

4. Connected with the previous points, most numerical weather models severely underestimate the MBL height near the shore at 20_S (observations indicate 1 km but most models calculate 500 m). It seems that, by the contrary, GPS-RO data overestimate this height. Any comments on this?

Based on Fig. 3a and Fig. 7e, COSMIC-RO actually slightly underestimates the ABL height (~140 m) as compared with the near-coincident radiosondes. Rahn and Garreaud (2010) also shows the mean ABL height of VOCALS radiosondes ~1.2 km. The embedded 200-m equivalent vertical smoothing in COSMIC RO retrieval could be the reason of the low bias. Also, the difference between limb sounding geometry of RO and the point measurement in radiosonde, as well as the spatial and temporal difference in the near-coincident pairs (mean: 2-hr and 200 km) all contribute to the

ABL height difference.

5. Some minor typos: Page 2277, line 20: range, not rage. Two lines below, you refer to Fig. 3c but this figure has only two panels.

Corrected. Fig. 3c should be Fig. 4c. Thanks.