acp-2009-561

Atmospheric diurnal variations observed with GPS radio occultation soundings

F. Xie[1,2], D. L. Wu[1], C. O. Ao[1], and A. J. Mannucci[1]

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
[2] Joint Institute for Regional Earth System Science and Engineering, UCLA, CA

We thank all reviewers for the very insightful and detailed comments. Following the reviewers' suggestions, we made some major changes:

(1) Remove the semi-diurnal variation component from the paper.
   a. New title: "Atmospheric diurnal variations observed with GPS radio occultation soundings"
   b. Remove Fig.2 showing semi-diurnal variations in tropics.
   c. Remove Semi-diurnal amplitude plots in Fig.4

   We agree with the reviewer#1 and review#3 that the phase of the semi-diurnal variations derived from COSMIC RO in the tropics is rather noisy and might not be statistically significant due to weak semidiurnal signal and possibly the lack of sampling. Although, we believe some significant semi-diurnal amplitude over high-latitude stratosphere and the lower troposphere could be realistic, we decide to leave it out, since it could be better supported with model simulations, which is currently not available.

(2) Different colors are added into Fig-1a,c to distinguish different seasons in the diurnal tidal amplitude.

(3) Fig.3 is changed to color version.

(4) Change the title of Section 3 from "*Tropical Tidal Waves*" to "Tropical Diurnal Variations – the Tidal Waves". Also "Section 3.1" title is removed.

(5) Remove the less relevant information in "Discussion" section related to the PBL retrieval in RO observations.

The reviewer's specific comments are addressed as follows.

Replies to Referee #2

Specific comments:

1. My main concern is the interpretation about diurnal and semi-diurnal variations at high latitudes. The authors extensively discuss results at polar latitudes in Sections 4, 5, and 6. The authors note that the average number of profiles in a monthly, 2-hour 5_latitude bin at 75_N amounts to 37. Since this number is the average number of profiles and COSMIC local-time sampling is irregular within one month at high latitudes, I conclude that there are some local-time bins with significantly less profiles available. Furthermore, the number of profiles beyond 75_ latitude further decreases. I think that data sampling is too low to perform reasonable linear harmonic analysis.

We thank the reviewer for raising the important sampling issue. Yes, we did look closely at the sampling rate at different latitudes including the high latitudes, and we believe that the sampling rate at high/polar latitudes should be adequate for diurnal variation study.

Figure-A shows the COSMIC RO samples from both JPL and UCAR retrievals in 2007. Note that the six COSMIC satellites were spread out but not in the final configuration in early 2007. Therefore, the COSMIC RO does show less uniform local time sampling in the polar region 75°N and 75°S. For example, there are fewer profiles around noon in January and 19:00pm LST in April. However, there are still many samples for close-by local time. Noted that the RO sampling shows more uniform local time sampling in year 2008 but results in similar diurnal and semi-diurnal amplitude patterns (not shown), which indicates the *un-even LST sampling* should only play a secondary role in the analysis errors.

On the other hand, we also look into the possible aliasing errors due to the possible *insufficient sampling*. We examined the UCAR retrieval in both 2007 and 2008, which use different calibration technique (e.g., single differencing) and yield approximately twice as many samples as the JPL one at all latitudes. The double sampling of RO profiles from UCAR retrievals suppresses the aliasing errors in the diurnal and semi-diurnal amplitude (< 20%) overall. However, similar amplitude patterns below ~ 35 km (10 hPa) are seen. It is worthy to note that the diurnal amplitude is reduced by about 40% over north polar stratosphere between 100 hPa and 30 hPa around 75°N in January 2007. Another similar reduction of diurnal amplitude is found in south polar stratosphere at around 80°S in April 2008.

This suggests that to first order the diurnal amplitude extracted from the GPSRO (JPL retrieval) is statistically significant and the aliasing from under-sampling is non-negligible in some months but plays a secondary

role. Quantitative evaluation of the aliasing errors due to the un-even and insufficient sampling would require further spectrum analysis (e.g., Wu et al., 1995).

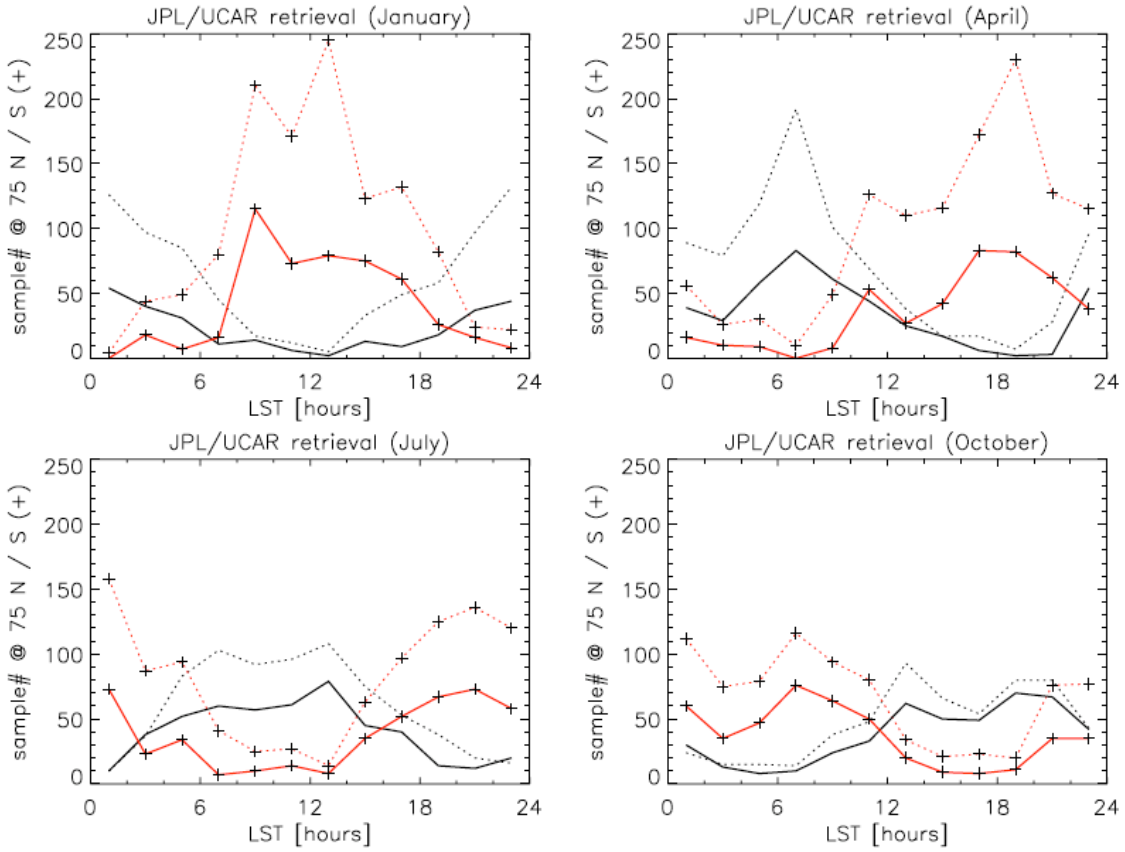

Figure A. COSMIC RO monthly (January, April, July and October) sample numbers within 2-hour LST bin, 5-deg latitude band (at 75°N and 75°S) from JPL (solid) and UCAR (dashed) retrievals in 2007. Note the sample numbers at 75°S are denoted by the plus signs.

2. It would be useful to provide the uncertainty of the derived amplitudes and phases at all latitudes and altitudes, since to my knowledge the highest quality of radio occultation measurements is obtained in the upper troposphere and lower stratosphere region. Furthermore, a discussion of the errors magnitude associated with uneven local time sampling at high latitudes is essential for the interpretation of tidal signals.

The uncertainty of the diurnal amplitudes has been estimated by the SNR, i.e., the ratio of the fitted amplitude over the residual error after the diurnal and semidiurnal fitting. Fig-2 & 4 show the regions with significant diurnal amplitude with SNR > 2 and SNR > 3 with different gray-level shades. Note that the refractivity amplitudes over 0.2% are mostly statistically significant.

Please refer to the answers in Q1 regarding the error due to uneven local time sampling.

The quality of the diurnal amplitude derived from COSMIC/RO is more likely to be limited by the sampling error (e.g., un-even local time sampling and under-sampling) but not the RO measurement precision.

Technical corrections:

All the following comments are corrected in the text. Some with more detailed information ing

1. page 25410, line 4: insert a comma after Meteorology
2. page 25410, line 18: "solar" instead of "solor"
3. page 25410, line 20: "Polar regions show" instead of "Polar regions shows"
4. page 25411, line 4: "satellite radiance measurements"
5. page 25411, line 6: please insert a comma after cloudiness
6. page 25411, line 10: "Chapman and Lindzen" instead of "Chapman and Linzen"
7. page 25412, lines 6/7: Kursinski et al. (1997) specify a vertical resolution of 1.4 km in the middle atmosphere (rather than 1 km)
8. page 25412, line 11: Pirscher et al. (2007) and Zeng et al. (2008) specify that the orbit configuration of CHAMP allows a complete 24 h local time coverage within 130 days. Zeng et al. (2008) further explain that due to the limb sounding measurement principle, the effective repeat period is obtained every 108 days at the equator. These numbers only refer to low latitudes.

All the suggestions above are incorporated. Thanks.

9. page 25413, lines 6/7: As shown by Pirscher et al. (2009) local time sampling at high latitudes is insufficient and irregular within one month. This is because at high latitudes the ascending and descending branch of the orbit move closer together in terms of local time sampling.

We agree with the reviewer that the COSMIC local time sampling at high latitudes is irregular within one month even in the final satellite configuration. However, we argue that it could still be sufficient for resolving the diurnal variations (refer to Q1 and Figure-A).

Text added as: "However, the local time sampling at high latitudes become irregular within one month, because the ascending and descending branch of the orbit move closer together in terms of local time sampling (Pirscher et al., 2009)".

Reference added:

Pirscher, B., Foelsche, U., Borsche, M., and Kirchengast, G.: Sampling of the diurnal tide of temperature using Formosat-3/COSMIC data, in: New Horizons in Occultation Research, (eds. A. Steiner et al.), DOI 10.1007/978-3-642-00321-9 11, Springer-Verlag Berlin Heidelberg, 131-140, 2009.

10. page 25413, line 23: You describe occultation geometry for "setting" events (as the LEO receiver "sets" behind the horizon. . .), but COSMIC is also able to perform "rising" measurements

The sentence is modified as: "As the LEO receiver sets or rises behind the horizon relative to the transmitting GPS satellite … ".

11. page 25414, line 9: "Schreiner" instead of "Shreiner"
12. page 25414, line 13: to be consistent with the units of b1 and b2, you should specify atmospheric pressure in hPa, not in mbar
13. page 25414, line 20: "Kursinski et al., 1997" instead of "Kursinski, et al, 1997"
14. page 25415, line 11: I guess that "Poli and Kursinski 2002" should be "Poli et al., 2002"
15. page 25416, line 8:"Ho et al., 2009" instead of "Ho et al., JGR, 2009"

All the suggestions above are incorporated. Thanks.

16. page 25416, line 8: You write: "A total of 641134 valid profiles over the twoyear span (2007–2008) have been used in this study." But you also write on page 25418, lines 16/17 "2007: a total of 361051 profiles" and page 25418, line 21 "2008: 284227 profiles". 361051 + 284227 = 645278, not 641134. Which numbers are correct?

Thanks for pointing this out. The "645278" is the correct number.

17. page 25418, line 3: "additional errors" instead of "additional error"

Revised as suggested.

18. page 25418, line 16: I do not understand how you derived diurnal variations between 10_S and 10_N: On page 25416, line 25 you write that your data are binned in every 5_ latitude band and on page 25416, line 28, you write that your 5_ latitude bands are centered at, e.g., 5_N. I conclude that your zonal bands reach e.g., from 2.5_N to 7.5_N. Did you average diurnal variations over 5 zonal bands (12.5_S–7.5_S, 7.5_S–2.5_S, 2.5_S–2.5_N, 2.5_N–7.5_N, 7.5_N–12.5_N) or did they average over 4 zonal bands (10_S–5_S, 5_S–0_, 0_–5_N, 5_N–10_N) or did you derive diurnal variations using all data between 10_S and 10_N?

Sorry for the confusion. The 5° latitude band is centered at 2.5N for the

0~5N latitude band. Therefore 10S–10N includes 4 zonal bands, e.g., 10S–5S 5S–0S; 0–5N and 5–10N. The text has been updated as: "For example, in the year 2007, the monthly average numbers of COSMIC soundings at a 2-hr bin is about 54 in a 5°N-latitude band (centered at 2.5°N), 87 at 25°N, …"

19. page 25418, line 20: diurnal variations of refractivity are given in percent—what does the percentage refer to?

The fractional diurnal amplitude of refractivity (Fig.1c) is computed as the ratio between the absolute diurnal amplitude and the mean refractivity at any specific altitude.

20. page 25418, line 23: "vertical structures" instead of "vertical structure"

Revised as suggested.

21. page 25419, line 26: In my opinion, the variability at 140 hPa (14 km) is so small, that it is hardly possible to distinguish between different seasons.

"At and above 140 hPa (~14 km) …" changes to "Above 14 km, the winter and autumn season shows larger diurnal amplitude …". The color is added to distinguish four different seasons.

22. page 25419, line 27: "winter and autumn seasons show larger diurnal amplitudes" instead of "winter and autumn season shows larger diurnal amplitude"
23. page 25420, line 5: "higher altitudes" instead of "higher altitude"
24. page 25420, line 6: "Lindzen" instead of "Linzen"
25. page 25420, line 10: "the temperature tides is"—please use singular or plural form

All the suggestions above are incorporated. Thanks.

26. page 25420, line 24: Equation (2) is specified in Section 2.1.

The sentence related to semi-diurnal discussion is removed.

27. page 25421, line 12: "at all pressure levels" instead of "at all pressures"

Revised as suggested.

28. page 25421, line 13: Does Figure 3 illustrate the time series of the diurnal amplitude at 30 hPa or at 30 km (compare text and figure caption)

It is on 12 hPa (~30 km). Text revised.

29. page 25421, line 23/24: please specify "upper atmosphere".

"upper atmosphere" is changed to "the mesosphere and lower thermosphere"

30. page 25421, line 25: "at pressure levels from" instead of "at pressures from".
31. page 25422, line 12: "to be observed" instead of "to observe".
32. page 25428, line 22: "the COSMIC RO constellation has greatly improved" instead of "the COSMIC RO constellation have greatly improved"

All the suggestions above are incorporated. Thanks.

33. page 25433: Lieberman and Leovy (1995) and Lieberman et al. (2003) have never been cited in the text but are listed in the reference list.

References removed. Thanks.

34. page 25439, caption of Figure 3: please check consistency with the text (30 km/30 hPa)

"30 km" is changed to "12 hPa (~30 km). Text in the draft is also corrected.

35. page 25439, caption of Figure 3: "30°S–30°N" instead of "30S–30N"

Revised as suggested.

36. page 25440, Figure 4: There is too much information for the limited space. Probably, contour intervals of, e.g., 0.25 %, or the use of colors could facilitate the interpretation of the figures.

The new Figure-3 is re-plotted with colors, and the contour levels increased to be 0.25% as suggested. Thanks.

37. generally: you often write, e.g., 12~1.3 hPa. In this case "~" should be replaced by "–" (or more precisely: 12 hPa to 1.3 hPa).

Revised as suggested.