Interactive comment on “A characterization of thermal structure and conditions for overshooting of tropical and extratropical cyclones with GPS radio occultation” by R. Biondi et al.

Anonymous Referee #3

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>>> We thank the reviewer for the thorough review of our paper and for the helpful additional comments. Please find below our point by point response (in italics).

There are 5 issues that I have flagged as requiring major revisions. I do not think any of these issues will be particularly difficult to address, but they should be resolved before this paper is published. The 5 issues are as follows:

1. overshooting is defined by equations 2 and 3, but the variables on the left-hand sides of those equations are not defined. (What is Hcoldest_std? What is Hcoldest_std+1?). After the equation, it says that these variables are "considered to be" some things, but those are not definitions. The best I can do is to interpret this as sloppiness and assume that both should be Hcoldest. Then, when Hcoldest satisfies equation 2, I can "consider it to be indicative of" one thing, and when Hcoldest satisfies equation 3, I can "consider it to be indicative of" another thing.

>>> We corrected this and replaced $H_{coldest\_std}$ *and* $H_{coldest\_std+1}$ *with* $H_{coldest}$ *which is now defined as “the height of the lowest anomaly minimum (*$H_{coldest}$*) between 10 and 22 km”. Equations (2) and (3) and the explaining text now read as follows:*

$$H_{coldest} > H_{mm\_trop} + H_{mstd\_trop} \qquad (2)$$
$$H_{coldest} > H_{mm\_trop} + H_{mstd\_trop} + 1.0\ km \qquad (3)$$

“where 1.0 km is the uncertainty for TC cloud top altitude detection using GPS RO as estimated by Biondi et al. (2013) from analysis with co-located lidar data. If $H_{coldest}$ *satisfies Eq. (2) it is considered to be indicative of possible overshooting when the lowest anomaly minimum (the cloud top) overpasses the tropopause monthly mean altitude plus its standard deviation. Eq. (3) defines an even more robust condition, where* $H_{coldest}$ *is considered to be indicative of possible overshooting when the lowest anomaly minimum (the cloud top) overpasses the tropopause monthly mean altitude plus its standard deviation plus the 1 km uncertainty margin.”*

2. Assuming my interpretation is correct, equation 2 defines an overshooting event as the height of the minimum temperature anomaly being higher than the mean tropopause height plus one s.d. of the tropopause height. (This s.d. is ambiguous in the text, but I assume this is the s.d. of the year-to-year monthly means at that location. This should be clarified.) Defined in this way, we might expect "overshooting" to be detected in 16% of all cases, even without tropical cyclones (if the tropopause heights are normally distributed, then the tail outside 1 s.d. contains 16% of the probability). Equation 3 is perhaps better, but it is difficult for me to quantify the affect of the RO measurement error. (As a side note, the uncertainty of "0.996 km" is silly. Is the uncertainty really

known to 3 significant digits? Even if yes, is that 4 meters so important that we could not call this 1 km?) In the end, though, the precise definition of overshooting might not matter a great deal if the goal is to compare relative overshooting frequencies between basins and different categories of TCs.

>>> We clarified the standard deviation of the monthly mean tropopause altitude, the relevant paragraph in section 3.2 now reads:
"For monitoring possible overshooting conditions during a storm we computed the height of the lowest anomaly minimum ($H_{coldest}$) between 10 and 22 km of altitude for each $T_{anomaly}$ profile (Biondi et al. 2013), the monthly mean tropopause altitude (H_{mm_trop}) of the respective month and area (section 3.1), and the corresponding standard deviation of the monthly mean tropopause altitude (H_{mstd_trop}). We used the multi-annual standard deviation estimate for each month of the year here (e.g., October 2001 to 2012 data for October; sensitivity testing showed that using standard deviation estimates for individual months leads to essentially the same results)."
We agree with the reviewer that the 3 digits are not significant; we reported the value of 0.996 just for being consistent with the cited paper. We have replaced 0.996km with 1.0 km now. We also included an explanation in the text after Eq. (3):
"…where 1 km is the uncertainty for TC cloud top altitude detection using GPS RO as estimated by Biondi et al. (2013) from analysis with co-located lidar data. The uncertainty occurs mainly due to the finite resolution of RO data (see section 2.2), and also due to co-location uncertainty, whereas the RO geopotential height and hence altitude allocation error is only about 10 m in the troposphere and around the tropopause within the 50°S and 50°N latitude band of interest here (Scherllin-Pirscher et al., 2011)."

3. I am encouraged to see events referred to as "possible overshooting", which emphasizes the fact that these may not be true overshooting events. But, I am still left with some unease over the uncertainty as to what these events are. It was Romps and Kuang who noted the possibility that large-scale lifting of the tropopause by TCs – as opposed to convective overshoots – might be responsible for the anomalously cold temperatures. Can RO be used to distinguish between these two possibilities, perhaps when used in concert with some other instrument?

>>> This study is a statistical analysis for understanding the capabilities of GPS RO for the detection of overshooting. Since the reasons of double tropopause can be various (e.g. gravity waves, large scale lifting,…) creating some unknown uncertainties, we plan to deepen the analysis increasing the number of co-location with lidars (satellite and ground based) in the near future. The lidars will be used just for detecting the cloud top altitude and the GPS RO just for detecting the tropopause altitude. The idea is to distinguish (i) cases with one single tropopause and the cloud top is higher than the tropopause level (overshooting), (ii) cases with the cloud top corresponding with the secondary tropopause (overshooting) and (iii) cases with cloud top altitude corresponding to the primary tropopause (tropopause uplift and possible overshooting). The overshooting is present when the tropospheric air is transported by the convection into stratosphere and it remains there due to the stratospheric stability. We do not want to exclude that the tropopause uplift can create an overshooting: with a few hundred cases compared with CALIOP backscatter in the past (Biondi et al., 2012 and Biondi et al., 2013) we have never seen a temperature inversion associated with cloud top altitude higher than local tropopause. Thus we think that one possible explanation could be that the strong convection locally moves the tropopause upward (Fig. 1 below) creating a relatively small bubble where the tropospheric air ascends to stratospheric altitudes (Fig. 2 below). Once the storm is gone, the previous conditions are re-established, the air is trapped at stratospheric levels (Fig. 3 below) and moves

laterally. Of course this depends on the stability and time scales so the process can be either stable or not, but it is a necessary condition for having an overshooting.

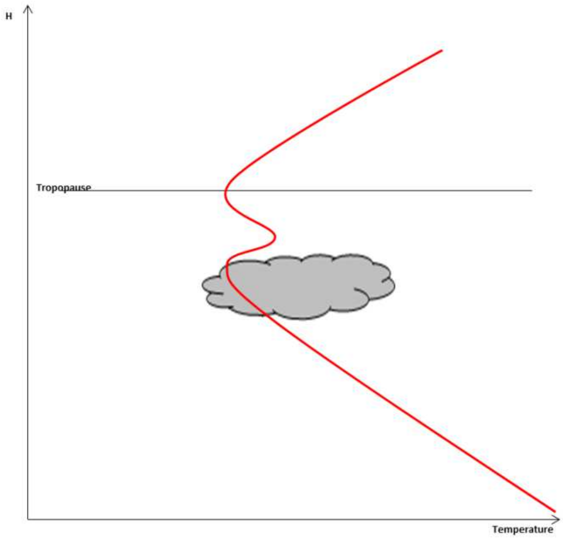

Figure 1. The double tropopause during convection: the lowest temperature inversion corresponds to the cloud top and the highest temperature inversion corresponds to the tropopause.

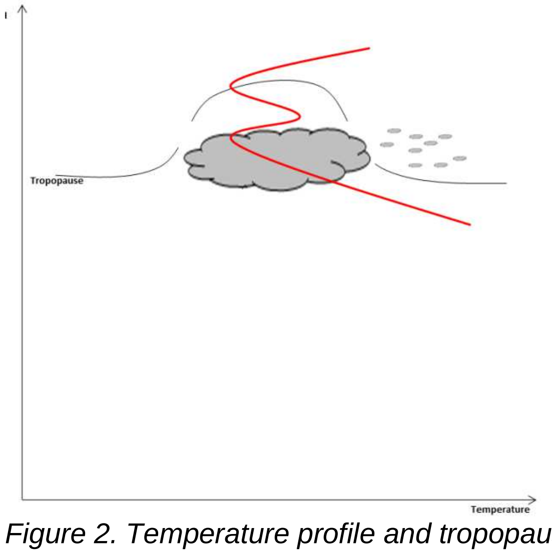

Figure 2. Temperature profile and tropopause altitude when the convection reaches the climatological tropopause altitude.

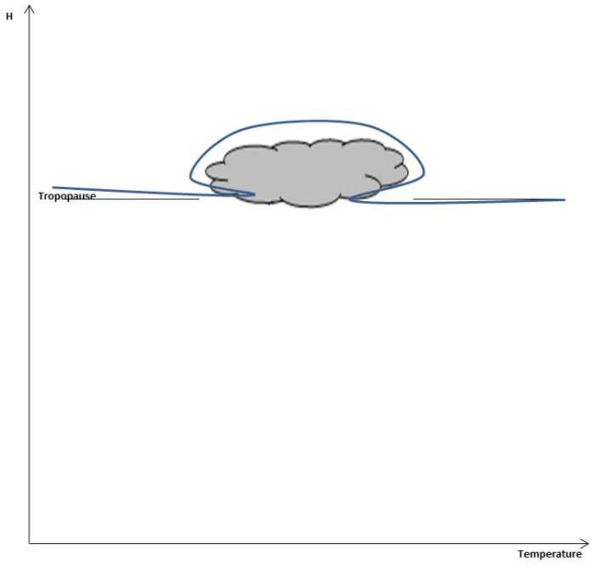

Figure 3. Once the convection is gone, the previous tropopause conditions are re-established.

4. Part of the methodology was unclear to me. RO measurements are associated with a TC if they occur "in a time window of 6 hours and a space window of 600 km" with respect to the TC center. Why is such a strange criterion used? At the time of the RO measurement, the TC center is physically located somewhere. Why not associate an RO measurement with a TC if it is within a certain distance of the TC center at the time of the RO measurement? It seems it would be simple to linearly interpolate the TC positions to the time of the RO measurement, thereby requiring only a distance threshold. I do not think this will have much impact on the results – in 6 hours with a 5-m/s translation speed, the TC would move 100 km, which is small compared to 600 km – but the criterion is strange enough that I got hung up on it as I was reading.

>>> We have used this methodology because most of the TC monitoring centers provide the best track information every 6 hours and the diameter of a TC is usually of the order of at least 600 km. This is the same conditions that we have used in previous analysis (i.e. Biondi et al., 2013) and it is the same methodology used in similar papers such as Vergados et al.(2014). We agree that the interpolation could avoid using the temporal window, but it could introduce similar uncertainties.

5. Finally, what is the horizontal footprint of the RO measurements? This information is necessary for me to understand whether these measurements could be sampling an individual cloud updraft, a collection of updrafts, or some average on the scale of the entire TC. Also, it would be helpful to give the vertical resolution.

>>> Horizontal and vertical resolution of GPS RO is not fixed. The resolution somewhat depends on the geometry of the GPS and the LEO satellites and on the processing technique, i.e., geometric optics (GO) retrieval or wave optics (WO) retrieval. The vertical resolution is about 0.5 km in the troposphere to about 1 km in the lower stratosphere for GO processed data (e.g., Kursinski et al., 1997). A higher vertical resolution is achieved for WO processed data of down to about 100 m in the lower troposphere (Gorbunov et al., 2004). The horizontal resolution

is about 1.5 km across-ray and ranges along-ray from about 60 km (WO) to 300 km (GO (Melbourne et al., 1994; Kursinski et al., 1997). In this work we use WO processed RO data in the troposphere and thus have a comparatively high resolution in the troposphere.
So, in summary, the horizontal resolution ranges from about 60 km to 300 km and the vertical resolution ranges from about 100 m in the lower troposphere to about 1 km in the stratosphere. However limiting the study within a certain range of altitudes and using the coordinates of tangent points close to the cloud top feature, the uncertainties can be reduced (Vergados et al., 2014) and it is possible to analyze small structures such as TC eyewall.

We added the following text in section 2.2:
"The vertical resolution ranges from about 100 m in the lower troposphere to about 1 km in the stratosphere (Gorbunov et al., 2004; Kursinski et al., 1997). The horizontal resolution is about 1.5 km across-ray and ranges from about 60 km to 300 km along-ray (Melbourne et al., 1994; Kursinski et al., 1997)."

References:

Gorbunov, M. E., Benzon, H.-H., Jensen, A. S., Lohmann, M. S., and Nielsen, A. S.: Comparative analysis of radio occultation processing approaches based on Fourier integral operators, Radio Sci., 39, RS6004, doi:10.1029/2003RS002916, 2004.

Kursinski, E. R., Hajj, G. A., Hardy, K. R., Schofield, J. T., and Linfield, R.: Observing the Earth's atmosphere with radio occultation measurements using the Global Positioning System, J. Geophys. Res., 102, 23429–23465, 1997.

Melbourne, W. G., Davis, E. S., Duncan, C. B., Hajj, G. A., Hardy, K. R., Kursinski, E. R., Meehan, T. K., Young, L. E., and Yunck T. P.: The application of spaceborne GPS to atmospheric limb sounding and global change monitoring, JPL Publication 94-18, 147 pp., Jet Propulsion Lab, Pasadena, CA, 1994.

Scherllin-Pirscher, B., Steiner, A. K., Kirchengast, G., Kuo, Y.-H., and Foelsche U.: Empirical analysis and modeling of errors of atmospheric profiles from GPS radio occultation, Atmos. Meas. Tech., 4, 1875–1890, doi:10.5194/amt-4-1875-2011, 2011.

Vergados P., Luo, Z.-J., Emanuel, K., and Mannucci A. J.: Observational tests of hurricane intensity estimation using GPS radio occultations, J. Geophys. Res. Atmos., 119, doi:10.1002/2013JD020934, 2013.