Author's Response to Referee #2

We would like to thank referee #2 for the thorough evaluation of our manuscript. We have answered all comments below (for easier comparison the referee comments are included in *italic*).

General comments:

#1: The abstract could be rewritten with major points of conclusion from this study.

- *check grammar and language*
- *re-structure and consider the way of presenting. For instance, the method of API may be presented immediately after the first sentence.*
- *L17. The authors use different terms, e.g., upper initialization, upper boundary value, and top. They need to be clear, precise and consistent.*

#1: Related to the comment of referee #1 we have already restructured our abstract in order to clarify open questions. We invite you to read answer #1 to referee #1, this should also help with some of your concerns.

Regarding different terms: Thank you very much for your input. We will limit the number of terms by replacing “upper boundary value” with “top value”, and “upper initialization” with “high altitude initialization” throughout the entire manuscript.

#2: P2L4, is that only in UTLS? Why?

#2: The core region of RO data is the UTLS. Studies show highest consistency between different data sets in that respective altitude range, see e.g., Steiner et al. (2013). The reasons are ionospheric residuals and a decreasing signal-to-noise ratio with increasing altitude (see e.g., Danzer et al., 2013). In the lower troposphere (below 7 km) – which is not the focus of this study - the error budget is dominated by horizontal variations of refractivity, and consequent deviations from the spherical symmetry assumption (e.g., Healy, 2001). The data can be affected by signal multi-path and super-refraction, and the temperature retrieval requires background information (e.g., Sokolovskiy et al., 2010).

We invite you to read a more detailed answer in our response to referee #1, question #4, and in related citations, given e.g., on p2/l17. Furthermore, we also intend to add further

information in our manuscript (see also question #4/referee #1).

#3: P2L30, "up to high altitudes", how high is it? "introduced an alternative approach", I guess it is not an alternative approach, but a different application? Please clarify.

#3: The BAROCLIM spectral model reaches formally up to infinity. The idea of the model is to use the average bending angles (which are also combined at altitudes above about 60 km with the MSIS-90 climatology) as a priori information in the statistical optimization step of the processing of individual bending angle profiles. Details of the BAROCLIM spectral model are given by Scherllin-Pirscher et al., 2015. At the DMI the model has been implemented as their background climatology in the new ropp processing system. The difference to our approach is that BAROCLIM serves as a background climatology for the statistical optimization step of individual bending angles, while we avoid statistical optimization completely and process climatologies.

#4: What is the major benefit of the API method? While it is comparable to IPI below 35 km, I see it is not very helpful in extending the accuracy of retrieval above 35km. Is it computational efficient? If so, can the authors provide the computational cost of the API and IPI?

#4: The major benefit is that bending angles are used up to 80 km altitude instead to about 35 km altitude, when statistical optimization is applied. The aim is always to use less background in the data, and the hope is - with less background, that the utility of the climatologies can be pushed above 35 km. Furthermore it is much faster, e.g., the difference to processing 500 profiles or just one profile. See also specific comment #1 to referee #1, where we stated to add:

Introduction on p. 2, after line 31.

The advantages of the API approach are the following, a) the reduction of background in the data, b) the circumvention of the complicated statistical optimization step (a known reason for differences between processing centers), c) the API approach is much faster in computation.

Furthermore we extend the paragraph on p.2, line 33

...The aim of the API approach is to produce high quality climatologies, with well characterized errors, which might push current limits in altitude further, enabling the study of stratospheric climatologies above 35 km.

In the discussion on p. 19, line 3 we add the following sentences:

The latter result might suggests that API dry temperature climatologies can be used up to 40

km, pushing current limits of the utility of RO data in the stratosphere.

#5: "The averaging of a large number of profiles suppresses noise in the data, enabling observed bending angle data to be used up to 80 km without the need of a priori information." I do not understand. Can the authors explain more on this? which figures or results support this point and how? I did not see the connection of the current results to benefit of using bending angle data between 35 and 80 km.

#5: The averaging of the data leads to a rather smooth mean bending angle profile up to an altitude of 80 km, compared to the noisy individual profiles, which suffer with increasing altitudes from increasing problems with measurement noise and also ionospheric residuals. This manuscript is not a proof of concept paper. It is a follow up comparison investigation, focusing on the comparison between two processing centers. For better context we added an additional paragraph in the abstract introducing the problem of RO data at high altitudes (see answer #1 to referee #1). For the basic introduction and analysis of the method please see Gleisner and Healy (2013), and also the paper about the application to CHAMP data, Danzer et al. (2014). Regarding the benefits, please see answer #4.

#6: Definitions of M and N in Equation 3 do not seem correct.

#6: Thank you very much for noticing! In the definition of M is a mistake in the numerator. It is $(ab)^2$ and not ab^2. We will correct it immediately.

#7: Many figures and results lack of complete explanation. I just list some of them as below,

a) *Figure 1, "only negligible implications are found". Why are the dry temperatures retrieved using different Rc identical? What does "implications" mean? What is the reason for the large differences between 2–8 km?*

b) *Figure 2, please explicitly provide what the dashed straight lines are. I think impact height is more accurate than impact altitude?*

c) *Figure 3, what is the reason for the greater than 0.8 % difference around tropopause in refractivity? What is the reason for the large differences in the lower atmosphere (near surface)? What does altitude mean in the y axis? Is it impact height? How is the percentage calculated? Is the difference normalized by something?*

d) *Figure 4, there is no description at all. What is the purpose of putting this figure?*

e) *Figure 5, what does "data show again a slight increase" mean? What increases? Again, what is the explanation for the near surface differences? Figure 9, the authors could provide more explanation for the large differences in the northern high latitudes.*

f) *Figure 10, "increasing" to about +/- K is not accurate. It seems the patterns among the choices are different for the bins in the northern/southern hemisphere. Are the results showing here season dependent?*

#7:

a) The local radius of curvature (Rc) can be illustrated in two extreme ways. On the one hand as "local radius of curvature in north-south (meridian) direction, i.e., M(φ)" and on the other hand as "local radius of curvature in east-west (normal to meridian) direction, i.e., N(φ)". Their largest difference is at the equator, while at the poles they are equal:

   See also https://en.wikipedia.org/wiki/Earth_radius#/media/File:EarthEllipRadii.jpg

   We will write on p. 4, line 26:

   "… differences increase in the tropics between about 2 km and 8 km. The reason is that the local radius of curvature in north-south (meridian) direction, i.e., M(φ), and the local radius of curvature in east-west (normal to meridian) direction, i.e., N(φ), show maximum differences at the equator, while at the poles they are equal. When building a mean Rc, M(φ) and N(φ) were either averaged by using the Mean or the Gaussian formula (Eq. 3 and Eq. 4). In case of a single RO measurement the radius of curvature is a result of the momentary orbit geometry of the two involved satellites (GNSS and LEO). Using as a third formulation a simple averaging of all radii of curvature in a bin, we therefore find the largest differences between ± 30 degrees latitude (see l.h.s. Fig. 1). However, the impact of the different formulations of Rc on dry temperature was found to be negligible in the stratosphere, see r.h.s. of Fig. 1. The variations are between about … "

b) The dashed lines at 50 km and 60 km are simply a help to mark the transition region of the medmean bending angles. We will include this in the text for clarifications.

   The difference "Impact Height" to "Impact Altitude": Impact Height is the height above the ellipsoid, using the WGS-84 model. Impact Altitude is the height above the geoid (see Scherllin-Pirscher et al., 2017). One altitude is not more accurate than the other.

c) In this study the focus is the stratosphere, and hence, we only discuss dry parameters. It is however a very valid question which we also answered in question #5 to referee #1.

The altitude in the y-Axis means altitude above the geoid.

Yes, the percentage is normalized. The figures show for refractivity the relative difference, as in the primary paper Gleisner and Healy (2013). Thank you very much for this comment. We will add a sentence to the paper on p. 8, after the sentence from line 10:

All refractivity differences are studied as relative differences (given in percentage), while the temperature differences are studied in absolute differences (given in Kelvin).

d) The description is given on p.9, line 6, continuing to p.10, lines 1-2. The plot shows the mean bending angle profiles of the DMI relative to ECMWF analysis for January 2011.

e) Regarding the sentence “data show again a slight increase” we have to apologize. The word “again” needs to be deleted → “data show a slight increase relative to ...”.

Concerning the near surface differences, please see answer #5 to referee #1.

The large northern high latitude differences are related to an upper stratosphere lower mesosphere (USLM) disturbance in January 2011 (Greer et al., 2013) and a very cold stratospheric Arctic winter in 2010/2011. Please see answer 4 to referee #1.

f) Thank you very much. We will rewrite the sentence in the following way:

“... increasing to about a 2-3 K difference at 35 km altitude relative to ..”

No, the results are not season dependent (see also in more detail the answers #3 and #6 to referee #1). The large northern high latitude differences are due to the very cold stratospheric Arctic winter.

#8: Summary and discussion: Instead of repeating the major steps of what was already presented, the authors need to highlight the major points, and discuss the limitation and generalization of this study.

#8: We will follow the suggestion of you and referee #1. Large parts of the summary will be rewritten. Parts of the revised text are already specifically written down in our answers to you and referee #1.

Minor comments:

We do not list the complete number of minor comments. However, we thank the referee for the thorough reading of the manuscript and will perform the necessary changes according to

your suggestions.

Only minor comments, which require an answer, are listed here:

*#1: P2L8-L9, "NWP centers **will** always assimilate data that are as close as possible to the original measurement; in case of RO **these** are atmospheric bending angles, which can be assimilated without any bias correction." What do the authors mean by will? and what does "these" mean?*

#1: We will rephrase the sentence in the following way:

"At most NWP centers, RO data are assimilated in the form of bending angles, not in the form of geophysical variables retrieved from the bending angles. Climate monitoring based on RO data, on the other hand, requires the full range of geophysical parameters, from refractivity ....."

#2: P4L24, what do the authors mean by 5° -zonal? Please be clear and precise.

#2: Monthly 5°-zonal COSMIC data means all data of the COSMIC mission from one month, averaged in 5°x360° latitude x longitude steps.

#3: P8L21, what does the "RO core region of 35 km" mean?

#3: The RO core region of 35 km is the region between 5 km to 35 km, where highest data quality is found. See also answer #2. Clarifications will be included in the revised manuscript.