Collective Answers to Referee Comments

Additionally to all changes listed below, we followed the suggestions of referee #1 and #2 and asked a native speaker to perform final manuscript proofreading.

Author's Response to Referee #1

We would like to thank referee #1 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: In the abstract:

Page 1, Line 7:

‘Above that altitude some background information for the Abel integral is still necessary.‘ Is this a conclusion drawn from this present study? If it is, why it is not explained or discussed in the manuscript at all. The only relevant paragraph is

‘The basic idea of the API approach is that averaging of the data in bending angle space suppresses the noise in the data, so that the observed bending angle can be used up to 80 km and the SO step becomes largely obsolete. Above 80km some kind of background information is still necessary. ‘ in Page 3. If it is not a conclusion of this study, it is not appropriate mention it in the abstract.

#1:We tried to keep the abstract as concise as possible, but we agree with the referee that some additional information is needed for context. Therefore, we added at the top of the abstract:

Global Navigation Satellite System (GNSS) Radio Occultation (RO) data allow for the retrieval of near vertical profiles of atmospheric parameters like bending angle, refractivity, pressure and temperature. The retrieval step from bending angle to refractivity, however, involves an Abel integral, whose upper limit is infinity. RO data are practically limited to altitudes below about 80 km and the observed bending angle profiles show decreasing signal-to-noise ratio with increasing altitude. Some kind of high-altitude background data are therefore needed, in order to perform this retrieval step (this approach is known as “high-altitude initialization”). Any bias in the background data will affect all RO data products beyond bending angle. A reduction of the influence of the background is therefore desirable – in particular for climate applications. Recently, …

Furthermore we will add on p.3, line 21/22:

Above 80 km the bending angle still needs to be extended, since the Abel integral is over infinity and the bending angle is not zero above 80 km. Different extensions of the bending angle are tested in this study, see description in Sect. 2.1 and Sect. 2.2

We will also add the following citation on p. 3, line 27:

(for details see Gleisner and Healy, 2013; Danzer et al. 2014).

#2: The authors compare results with multiple data, namely the reanalysis data , and satellite data MIPAS and SABER

I have some questions here:

1) If there is a very good agreement between the MIPAS and SABER temperature data, as you mentioned in Page 7 Line 8, what is the point to compare your results with both of them?

2) Each satellite instrument has its own sensitive altitude range and accuracy. Have you consider the accuracy of the satellite data themselves?

3) You may also need to talk about the horizontal resolution of these data and its potential influence on the comparison.

#2**:** MIPAS and SABER provide independent measurements of the atmosphere, using different retrievals. Therefore we are convinced that it is useful to compare RO data with both data sets. Even if data sets are in good agreement it is valuable to see if the new data set is in line with the reference data sets. MIPAS and SABER data sets show high accuracy results in the stratosphere, and are hence interesting for a dry atmosphere comparison study. The second paragraph on p.7, lines 10-15 gives an overview of how MIPAS and SABER temperature data sets compare relative to WEGC RO data using a standard processing (Innerkofler, 2015). We think it is interesting to see if similar results are achieved relative to those reference data sets when comparing RO API data sets with different high altitude expansions, instead of RO IPI data sets. However, we see that this has to be put in a better context.

We will extend the discussion and include another paragraph in Sect. 6, p.18, after line 28:

The temperature comparison study of RO API data sets relative to ECMWF analysis, MIPAS, and SABER data sets shows for both, the WEGC and the DMI exptop case, similar temperature biases as Innerkofler (2015) found in his study analyzing global RO IPI temperature data sets. RO API, ECMWF analysis data, and MIPAS data agree within +-1K, up to 40 km. Above 40 km they begin to show larger differences than when analyzing global RO IPI data. Furthermore, the 3K temperature bias of SABER data could also clearly be illustrated relative to RO API data.

Concerning the horizontal resolution:

It is true that the underlying observational data sets have different horizontal resolutions. However, these data are not directly compared. Comparisons are made between data that have been averaged in monthly latitude bins, which are identical for the RO, ECMWF, MIPAS, and SABER data sets. The different horizontal resolutions of the underlying data is not a major problem for these heavily averaged data sets.

#3: Clearly your inversion results vary with latitudes, but does the accuracy of your inversion result vary with seasons? And will your inversion results influenced by humidity? Although it is the 'dry temperature' you are studying, water vapor in the atmosphere may significant influence the excess phase, right?

#3: The influence of humidity is important in the troposphere and has also been studied by Danzer et al. (2014). For the present study, where we analyze the influence of the high altitude initialization - which is important in the stratosphere, the influence of humidity is negligible. We also do not look at seasonal dependence of the API method. However, a long term study of the API method has already been performed in a previous work of us with CHAMP data (Danzer et al., 2014), where data sets from September 2002 until September 2008 have been analyzed. The study did not indicate that the accuracy of the inversion itself does depend on season. However, the study showed that differences relative to reference data sets increase towards higher latitudes, for both, the API and IPI inversions. We focus in this study on the three COSMIC test months January to March 2011, since this work is a follow-up investigation of Gleisner and Healy (2013), who also tested the same three months at the DMI .

#4: Please try to explain why the largest differences are around 35 km in fig. 5-7, 9-10.

#4: We are not completely sure if this remark refers to the general increase in differences beyond 35 km altitude (Fig. 5, 6) or to the larger differences relative to ECMWF analysis at high northern latitudes (Fig. 7,9), therefore we tried to answer both:

1) The “core region” of RO data is between 5 km to 35 km, hence the dashed line in the figures is always plotted at 35 km. The high accuracy in this region has been shown in previous studies, such as Steiner et al. (2013), who showed that consistency between different sets from different processing centers is highest in the UTLS. Hence, regarding the API approach, it is not surprising that differences also start to increase above that respective altitude. We emphasize that the RO – ECMWF biases above 35 km that we see here are not related to the API method. They are generally seen in all RO - ECMWF comparisons (see also Figures 5,6,7 in Gleisner and Healy (2013) which compares API and IPI relative to ECMWF analysis).

However, we see that it is necessary to emphasize this more strongly in the manuscript and we will discuss this in Sect. 6 Summary and discussion. According to your suggestion, we will rewrite this section and extend the discussion part.

On page 2, line 4 we will add:

The altitude range from 5 km to 35 km is therefore commonly regarded as the “core region” of the RO technique.

Furthermore, on p. 18, line 9.

… The observed RO – ECMWF biases above 35 km are not related to the API method. They are generally seen in all RO - ECMWF comparisons when applying the standard processing (see comparison of API and IPI relative to ECMWF analysis in Figures 5,6,7 in Gleisner and Healy (2013)). In that context it is interesting to see that different handling of the top value above 80 km also propagates down to that respective altitude. ...

On p. 18, after line 22 the following paragraph:

Steiner et al. (2013) showed in a comparison study of climate data products from six international processing centers that different high altitude initialization approaches affect uncertainties in CHAMP RO data from about 25 km upwards. Largest differences between processing centers are found towards increasing altitudes and at high latitudes. This has also been demonstrated for the API approach in a prior study analyzing CHAMP data (Danzer et al., 2014), where differences relative to ECMWF analysis also increased towards high altitudes and latitudes. Also the API approach shows an increasing sensitivity above 35 km altitude when comparing different high altitude expansions for the bending angle, as well as, comparing WEGC and DMI processing centers. The illustrated propagation of uncertainties downwards through the API retrieval chain to about 20 km in dry temperature has also been observed in prior studies for standard retrievals from different processing centers (Foelsche et al., 2011; Ho et al., 2012; and Steiner et al., 2013).

2) On p.14, lines 3-5, we will add another paragraph, including two reference:

Differences relative to ECMWF analyses are lager at northern high latitudes, which could be related to different sampling of the upper stratosphere lower mesosphere (USLM) disturbance in January 2011 (Greer et al., 2013). Related to that, the Arctic winter 2010/2011 has been notified as one of the coldest stratospheric winters on record (Sinnhuber et al., 2011).

#5: Why there are large differences in tropics and mid-latitudes near surface in fig. 5-7,9 and how does the inversion from negative to positive differences formed, e.g. at ~2-3km in the tropics in fig.5

#5: The focus of the study is the stratosphere, where the API method has decisive advantages in comparison with the IPI method. The main purpose of figures 5-7 and 9 are to show the impact on the stratospheric refractivity retrievals by different factors, such as, DMI/WEGC differences and different high-altitude expansions. The refractivity bias structure in the low- and mid-latitude troposphere in the lowest few kilometers seen in figures 5-7 and 9 is not caused by the API method. The bias structure is well-known and is also seen in the IPI method relative to ECMWF analysis. Please see Figures 5,6,7 in Gleisner and Healy (2013). However, the error at the lowest ~2 km is probably due to the use of a mean radius of curvature. This error can also seen in the comparison of API to IPI in Figure 4 of Gleisner and Healy (2013).

We will therefore add (page 10, line 15):

Please note that the focus of this study is the stratosphere and that we therefore show dry parameters, which are not fully adequate to characterize moist regions in the lower troposphere. The refractivity bias structure in the low- and mid-latitude troposphere in the lowest few kilometers relative to ECMWF is not caused by the API method. It can also be seen for the IPI method (see Figures 5,6,7 in Gleisner and Healy (2013)). However, the error at the lowest ~2 km is probably due to the use of a mean radius of curvature.

#6: All your results are based on COSMIC excess phase from Jan to Mar 2011. So I guess if your results depend on seasons, your conclusions are only valid in January to March. Please refine the way that you describe your conclusion.

#6: Please see answer #3. Furthermore, for clarifications we will include the following sentences in Sect. 6:

p.2, line 33

In this study, we test different implementations of the API approach at the Danish Meteorological Institute (DMI) and the Wegener Center for Climate and Global Change (WEGC) and validate them against independent data. We analyze three COSMIC test months from January to March 2011, following the investigations of Gleisner and Healy (2013). A long term API data set study has already been performed for the complete CHAMP period (Danzer et al., 2014), and is not part of this investigation.

#7: In Sect. 6 Summary and discussion, the authors summarized the study and talked about the outlook of the study. I would say Sect. 6 is only a summary but not a decent discussion at all. In fact, in the whole manuscript, the authors have made a very comprehensive comparison, but they focused only on the 'fact' but ignored the 'reason'. I suggest the authors add a separate section of discussion before the summary, in which all the problems and uncertainties of the present study should be discussed in a more detailed manner. And in the section of summary and/or conclusion, the authors should show readers very clear the conclusion from this present study, not from previous study or future work.

#7: According to your suggestion we will rewrite Sect. 6 and extend the discussion part. Furthermore we will rename Sect. 6 to "Summary, discussion and outlook"

Specific comments:

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

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

#1: *Page 2, line 4*

numerical weather prediction (NWP) and climate monitoring in the upper troposphere and lower stratosphere (UTLS) (however, I believe the GPS RO data do not only valuable in the UTLS but in both troposphere and stratosphere, and one or more references are needed here.)

#1: We thank the referee for his valuable comment about the utility of RO data: You are right, but the highest quality (and the highest impact on NWP analyses) is clearly achieved in the UTLS. We will change the first sentence of the introduction to:

... Monitoring, *in particular* in the Upper Troposphere and Lower Stratosphere (UTLS).

The general goal is to expand this altitude range and to increase the utility of RO data (towards the bottom, as well as towards increasing altitude). This study attempts to increase the utility in the (upper) stratosphere.

The citations are given in the same paragraph in the next three lines (p.2, lines 5-7), first referring to NWP, then to Climate.

We will add to the 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.

#2: Figure 1: Left panel: what does the blue dashed line indicate? Please explain.

#2: Thank you for noticing. It is the standard deviation of AvProf. We will write:

p.4, line 26

(Eq. 2, AvProf – blue line, its standard deviation - blue dashed line)

#3: I would strongly recommend that the authors find a native English speaker to check the manuscript for grammar and structural problems.

#3: We will follow your suggestion and have asked a native speaker to perform final proof-reading of the revised manuscript.

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.

Comparison study of COSMIC RO dry air climatologies based on average profile inversion

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Abstract.

Global Navigation Satellite System (GNSS) Radio Occultation (RO) data enable the retrieval of near vertical profiles of atmospheric parameters like bending angle, refractivity, pressure and temperature. The retrieval step from bending angle to refractivity, however, involves an Abel integral, whose upper limit is infinity. RO data are practically limited to altitudes below about 80 km and the observed bending angle profiles show decreasing signal-to-noise ratio with increasing altitude. Some kind of high-altitude background data are therefore needed, in order to perform this retrieval step (this approach is known as "high-altitude initialization"). Any bias in the background data will affect all RO data products beyond bending angle. A reduction of the influence of the background is therefore desirable - in particular for climate applications.

Recently a new approach for the production of GNSS radio occultation climatologies has been proposed. The idea is to perform the averaging of individual profiles ~~already~~ in bending angle space and ~~propagating~~ then propagate the mean bending angle profiles through the Abel transform. Climatological products of refractivity, density, pressure, and temperature are directly retrieved from the mean bending angles.

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. ~~Above that altitude some~~ Some background information for the Abel integral is still necessary above 80 km.

This work is a ~~follow up~~ follow-up study, having the focus on the comparison of the average profile inversion climatologies (API) from the two processing centers WEGC and DMI, studying monthly COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) data from January to March 2011. The impact of different backgrounds above 80 km is tested, and different implementations of the Abel integral are investigated. Results are compared for the climatological products against ECMWF ~~analysis~~analyses, MIPAS, and SABER data.

It is shown that different implementations of the Abel integral have ~~only~~ little impact on the ~~average profile inversion~~ API climatologies. On the other hand, different ~~expansions~~ extrapolations of the bending angle profile above 80 km play a key role on the resulting monthly mean refractivities above 35 km altitude. Below that respective altitude the API climatologies show a good agreement between the two processing centers WEGC and DMI. Due to the downward propagation within the retrieval,

effects of the ~~upper~~ high altitude initialization lead to differences in dry temperature climatologies ~~already at~~ down to 20 km altitude.

Applying ~~at both centers~~ an exponential extrapolation to the bending angles above 80 km ~~,~~ at both centers, the dry temperature climatologies agree ~~between~~ among WEGC, DMI, ECMWF analysis, and MIPAS up to 35 km altitude within ± 0.5 K, and up to 40 km altitude within ± 1 K. We conclude that the API retrieval is a valid approach up to the lower stratosphere~~the average profile inversion is a valid - and in computation time much faster - alternative for the production of~~. It is a computationally effcient alternative method for producing dry atmospheric RO climatologies.

1 Introduction

The Global Navigation Satellite System (GNSS) Radio Occultation (RO) technique (e.g., Kursinski et al., 1997; Steiner et al., 2001; Anthes, 2011) is ~~meanwhile accepted as~~ accepted as a valuable data source for ~~Numerical Weather~~ numerical weather prediction (NWP) and ~~Climate Monitoring in the Upper Troposphere and Lower Stratosphere~~ climate monitoring, in particular in the upper troposphere and lower stratosphere (UTLS). The altitude range from 5 km to 35 km is commonly known as the "core region" of the RO technique. Due to their high accuracy, RO data have significantly reduced systematic errors in global weather analyses (e.g., Healy and Thépaut, 2006; Cardinali, 2009) and their potential for climate monitoring has been demonstrated with ~~simulations~~ simulation studies (e.g., Leroy et al., 2006; Ringer and Healy, 2008; Foelsche et al., 2008b) and analyses (e.g., Foelsche et al., 2008a, 2009; Ho et al., 2012; Steiner et al., 2013).

~~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~~At most NWP centers, RO data are assimilated in the form of bending angles. Climate monitoring based on RO data, on the other hand, ~~shall comprise all the atmospheric parametersdown the retrieval chain~~requires the full range of geophysical parameters, from refractivity via density and pressure, to temperature, since ~~they~~ the geophysical variables change differently in different parts of the atmosphere (Foelsche et al., 2008b), and temperature data are desired for comparison with data from ~~different~~ other sources.

RO climatologies from different satellite missions like ~~CHAMP (~~Challenging Minisatellite Payload ~~) and COSMIC (~~(CHAMP) and Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) are very consistent (within 0.05 %) up to 30 km altitude (temperature) and 35 km altitude (refractivity), when the same retrieval scheme is used for all data ~~(Foelsche et al., 2011)~~(Foelsche et al., 2011). Data processed from different centers show differences due to structural uncertainty, which is still small at the bending angle level, but ~~increase~~ increases through the retrieval chain (Ho et al., 2012; Steiner et al., 2013). The retrieval step from bending angle to refractivity is a major source for structural uncertainty, ~~since~~ because it requires background information at high altitudes, where individual RO profiles are too noisy. When ~~data~~ the observations and background are combined by statistical optimization, the observations are inversely weighted with the assumed measurement error. A bias in the background profile will result in a bias in the retrieved profile down to an altitude that depends on the noise of the data. The hydrostatic integral in the retrieval step from density to pressure will also lead to a further downward propagation of potential biases in background data. An unbiased high altitude background - or data with low noise up to high altitudes - would therefore be highly beneficial.

~~Ao et al. (2012); Gleisner and Healy (2013) introduced the idea that~~ Ao et al. (2012) and Gleisner and Healy (2013) suggested that the impact of high altitude background information could ~~become (largely) obsolete~~ be reduced in climate applications ~~,~~ when averages over many RO profiles are used. In both studies average refractivity profiles have been obtained by averaging many COSMIC bending angle profiles in a domain and then inverting this average bending angle profile to a single refractivity profile (instead of averaging refractivity profiles, which have been obtained by inverting individual bending angle profiles). Danzer et al. (2014) have successfully applied this average profile inversion approach (API) to CHAMP data, which are more challenging due to their higher noise level. Scherllin-Pirscher et al.

(2015) introduced an alternative approach, where averaged COSMIC profiles are used to build a bending angle climatology up to high altitudes, which can then be used as background for the retrieval of individual profiles.

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 a much faster computation.

In this study, we test different implementations of the API approach at the Danish Meteorological Institute (DMI) and the Wegener Center for Climate and Global Change (WEGC), and validate them both against independent data. We analyze three COSMIC test months from January to March 2011, following the investigations of Gleisner and Healy (2013). A long term API data set study has already been performed for the complete CHAMP period (Danzer et al., 2014), and it is not part of this investigation. The aim of the API approach is to produce high quality climatologies, with well characterized errors, which might push current limits in altitude further upwards, enabling the study of stratospheric climatologies above 35 km.

The structure of this paper is as follows: SectionSect. 2 explains the method and the different implementations at WEGC and DMI, section. Section 3 describes the dataset, and sectionSect. 4 shows result of the comparison climatologies obtained by API and ("traditionally") by averaging individual profiles obtained by IPI (individual profile inversion). In sectionsingle profile processing. In Sect. 5 we compare the different API implementations and validate them against data from MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) and SABER (Sounding of the Atmosphere using Broadband Emission Radiometry), and against ECMWF (European Centre for Medium-RangeWeather Forecasts Medium-Range Weather Forecasts (ECMWF) analyses, followed by a summary and conclusions in sectionSect. 6.

2 Average Profile Inversion

The retrieval step from bending angle profiles to refractivity profiles is described by an Abel transformationuses an Abel transform, which relates the refractive index n to the bending angle α:

$$\ln n(x) = \frac{1}{\pi} \int_{x}^{\infty} \frac{\alpha(a)}{\sqrt{a^2 - x^2}} da \,, \tag{1}$$

where a is the impact parameter and $x = nr$, with r being the radius vector of a point on the ray path. The Abel integral over to infinity raises a problem, since RO data are practically limited in altitude to about 80 km. Furthermore, the observed bending angle profiles suffer from a decreasing signal-to-noise ratio with increasing altitude. The need for an extrapolation step together with the handling of the noisy bending angles requires a high-altitude initialization. This is traditionally introduced performed at most of the RO processing centers through a statistical optimization step (SO), where observations and background information are combinedand , and are weighted inversely with the respective errorserror statistic (details of different implementations see Ho et al. (2009, 2012)). Different processing centers use different kinds of background information (e.g. from climatological models such as MSIS (Mass Spectrometer and Incoherent Scatter Radar (MSIS), or meteorological data such as ECMWF analysis) and different implementations of the statistical optimization step (e.g., Gorbunov, 2002; Gobiet and Kirchengast, 2004; Lohmann, 2005).

The basic idea of the API approach is that averaging of the data in bending angle space suppresses the noise in the data, so that the observed bending angle can be used up to 80 km and the SO step becomes largely obsolete. Above 80 km ~~some kind of background information is still necessary.~~ the bending angle still needs to be extended, because the Abel integral upper limit is infinity and the bending angle is not zero above 80 km. Different extrapolations of the bending angle are tested in this study, as described in Sect. 2.1 and Sect. 2.2

The main steps of the ~~average profile inversion~~ API retrieval can be summarized as a) generation of the average bending angle as a function of impact altitude, b) change of height variable from impact altitude to impact parameter, a, using an average radius of curvature, $\overline{R}_c$, c) ~~expansion~~ extrapolation of the average bending angle profiles to infinity, which we introduce as "high altitude ~~expansion~~extrapolation", d) retrieval of the average refractivity as a function of $x = nr$ using the Abel transform (Eq. 1), and e) change of height variable to ~~mean-sea~~ mean sea level altitude, using the same radius of curvature as in step b). For details see Gleisner and Healy (2013); Danzer et al. (2014).

2.1 WEGC implementation

The latest implementation of the inversion of the individual profiles at WEGC is currently in an experimental state. It is based on the so-called base-band method (Kirchengast et al., 2016, 2017). ~~As input data, excess~~ Excess phase profiles provided by the COSMIC Data Analysis and Archiving Center (CDAAC) of the University Corporation for Atmospheric Research (UCAR), Boulder, Colorado were used as input data. From these data bending angle profiles are calculated by applying a combined geometric optics (see Appendix A in ~~?~~the study by Schwarz et al. (2018)) and wave optics (Gorbunov and Lauritsen, 2004; Gorbunov and Kirchengast, 2018) bending angle retrieval. To obtain ionosphere-free bending angles, the method of Sokolovskiy et al. (2009) is applied on the calculated bending angles. ~~After that each~~ Each bending angle profile is then statistically optimized using an ECMWF short-range bias corrected forecast as background profile (Li et al., 2013, 2015). ~~As a next step the refractivity is~~ The refractivity is then calculated, applying the method described by Syndergaard and Kirchengast (2016) in Appendix B~~in Syndergaard and Kirchengast (2016) on the residual state~~. Dry pressure and dry temperature are obtained by ~~evaluating~~ computing the hydrostatic integration (once more on the residual state, c.f., Appendix A ~~in~~ by Schwarz et al. (2017)). The monthly climatologies are then obtained by averaging the individual profiles into latitude bins.

The API processing at WEGC follows the basic description ~~of Sec.~~given in Sect. 2. The mean, median, and so-called medmean bending angle climatologies are calculated. Medmean uses mean bending angle values ~~up to~~ below 50 km, median values above 60 km, and a linear combination inbetween (Gleisner and Healy, 2013). Together with the average bending angles, the average radii of curvature are built, where we test three different implementations of mean $\overline{R}_c$ (see Eq. 2 - Eq. 4, and Fig. 1). The first formulation of $\overline{R}_c$ follows Gleisner and Healy (2013), and is determined as a sum of all single radii of curvature per bin ($R_{c,i}$ with occultation i), divided by the number of occultations m in a bin:

$$\overline{R}_c = \frac{1}{m}\sum_{i=1}^{m} R_{c,i}\ . \qquad (2)$$

As an alternative formulation we test the Earth's mean radius of curvature at latitude φ:

$$\overline{R}_c = \frac{2}{\frac{1}{\mathrm{M}} + \frac{1}{\mathrm{N}}} \ , \tag{3}$$

with $\mathrm{M}(\varphi) = \frac{\mathrm{ab}^2}{((\mathrm{a}\cdot\cos\varphi)^2+(\mathrm{b}\cdot\sin\varphi)^2)^{3/2}}$ $\mathrm{M}(\varphi) = \frac{(\mathrm{ab})^2}{((\mathrm{a}\cdot\cos\varphi)^2+(\mathrm{b}\cdot\sin\varphi)^2)^{3/2}}$, $\mathrm{N}(\varphi) = \frac{\mathrm{a}^2}{\sqrt{(\mathrm{a}\cdot\cos\varphi)^2+(\mathrm{b}\cdot\sin\varphi)^2}}$, a is the Earth's equatorial radius of 6378.1370 km, and b is the Earth's polar radius of 6356.7523 km (WGS84, World Geodetic System 1984). Furthermore we study the formulation of Earth's Gaussian radius of curvature at latitude φ (Torge, 2001):

$$\overline{R}_c = \frac{\mathrm{a}^2\mathrm{b}}{(\mathrm{a}\cdot\cos\varphi)^2 + (\mathrm{b}\cdot\sin\varphi)^2} \ . \tag{4}$$

The l.h.s. left panel of Fig. 1 compares the mean radius of curvature, using the three different formulations of $\overline{R}_c$ (Eq. 2 to Eq. 4), studying monthly 5°-zonal COSMIC data from January 2011. Obviously, the Mean $\overline{R}_c$ (green line) and the Gaussian $\overline{R}_c$ (red dashed line) show almost no differences (Eq. 3 and Eq. 4, respectively). Compared to the average $\overline{R}_c$ per bin (Eq. 2, AvProf - blue line, its standard deviation - blue dashed line) differences increase in the tropics between about 2 km and 8 km. Studying the impact of those differences on resulting dry temperature climatologies (r.h.s. 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 $\overline{R}_c$, 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 computed for the GNSS and Low Earth Orbit (LEO) satellite orbits at a given time. Using as a third formulation, a simple averaging of all radii of curvature in a bin, we therefore find the largest differences between ±30° latitude (see left panel of Fig. 1), only negligible implications are found. The different implementations . However, the impact of the different formulations of $\overline{R}_c$ lead to variations of 1/1000 K on the dry temperature was found to be negligible in the stratosphere, see right panel of Fig. 1. The variations are between about 0.001 K to about a few 1/100 K 0.01 K up to 80 km altitude, comparing the same monthly 5°-zonal (5° latitude × 360° longitude) COSMIC climatology.

For evaluating the Abel integral, different methods for the upper boundary values at Different high altitude extrapolations above 80 km have been tested(high altitude expansion). Initially we study monthly means of ECMWF analysis fields converted to refractivity, as value for the Abel integral from infinity to 80 km (Kirchengast et al., 2017). The These data sets are labeled as "fulltop". As an alternativealso , an exponential extrapolation of the bending angles to infinity is tested (exptop), where scale height and fitting coefficient are calculated from a log-linear fit to each average bending angle profile. Furthermore, the case of setting the average bending angles to zero above 80 km is studied (notop). Additionally a sensitivity study from the fulltop value to notop in 1/5 incremental steps is performed (notop= 0, top1$=\frac{1}{5}$fulltop, top2$=\frac{2}{5}\cdot$fulltop, top3$=\frac{3}{5}\cdot$fulltop, top4$=\frac{4}{5}\cdot$fulltop, fulltop). For an overview of all data sets see Tab. 1.

Finally the average bending angles are forwarded propageted through the Abel integral using the base-band method, and are further they then are processed as described for the individual profile processing at WEGC.

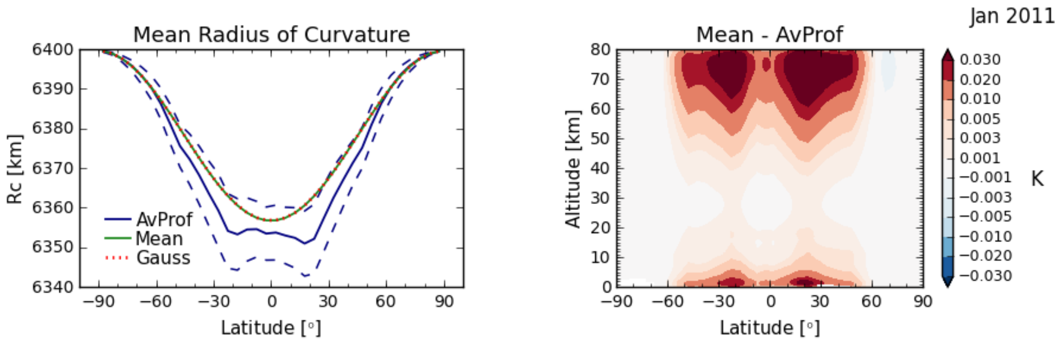


Figure 1. ~~l.h.s.~~left: Comparing different implementations of the mean radius of curvature $\overline{R}_c$, analyzed for a 5°-zonal COSMIC climatology from January 2011.
~~r.h.s.~~right: Dry temperature difference, comparing the implementation of $\overline{R}_c$ using Eq. 3 (Mean) to Eq. 2 (AvProf).

2.2 DMI implementation

The DMI data based on the standard IPI processing were obtained from a reprocessed climate data record provided by the ~~ROM SAF~~Radio Occultation Meteorology Satellite Application Facility (ROM SAF), which is a decentralized RO ~~Satellite Application Facility under EUMETSAT. The COSMIC data in this data set~~ SAF under the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The ROM SAF COSMIC data are based on input data from the CDAAC~~archive at UCAR~~ /UCAR archive. The individual bending angle profiles are calculated using a combination of geometric optics and wave optics approaches, followed by smoothing and merging with a background profile taken from the BAROCLIM climatology (Scherllin-Pirscher, 2013; Scherllin-Pirscher et al., 2015). The statistical-optimization step is followed by an ~~inverse~~ Abel transform, to retrieve the refractivity profile, and a hydrostatic integration to retrieve the dry-temperature profile (Lauritsen et al., 2011). The monthly climatologies are then obtained by averaging the ~~invidual~~ individual profiles into latitude bins.

The API processing used by DMI in the present study is described in more detail ~~in~~ by Gleisner and Healy (2013). The average bending-angle profiles are computed as a combination of mean (~~up to 50 km~~below 50 km), median (above 60 km), and a linear combination of the two (from 50 km to 60 km). The statistical analysis is done on a common impact altitude grid, which is mapped to an impact parameter grid using an average radius of curvature, $\overline{R}_c$, according to Eq. 2. This is followed by an ~~extension~~ extrapolation of the average bending angle profile from the top of the profile up to infinity assuming a constant scale height of $7.5\,\mathrm{km}$, in contrast to WEGC, which calculates the scale height individually for each mean bending angle. The exponential extrapolation of the bending angles is called “exptop” in the data sets. The Abel transform (Eq. 1) is then used to retrieve refractivity as function of $x = nr$, which is mapped to mean-sea level altitude, H, using the mean radius of curvature, $\overline{R}_c$.

In the present study, DMI used an implementation of the ~~inverse~~ Abel transform provided by the ROM SAF ~~ROPP software package~~ Radio Occultation Processing Package (ROPP) (Culverwell et al., 2015). This assumes that the bending angle, α, can be approximated as a linear function of impact parameter, a, between successive grid points. The sub-integrals between the grid points can then be solved analytically, and the refractivity at a certain height, x, is simply given by a sum of the contributions from the atmospheric layers from height x to the top of the atmosphere.

3 Data sets

We analyze occultations from the six-satellite mission ~~FORMOSAT-3~~Formosa Satellite Mission 3/COSMIC (F3C) for the year 2011, from January until March. Excess phase profiles and precise orbit information were retrieved from the UCAR/CDAAC database and then further converted into bending angle profiles and dry air profiles (referred to as Level L2a processing) at the WEGC and also at the DMI, using the rOPS-ex (reference Occultation Processing System-experimental) and ROPP version 8~~(the ROM SAF Radio Occultation Processing Package)~~, respectively. ~~The processing chain from~~ We call the processing chain of a single bending angle profile ~~down~~ to dry temperature ~~we introduce as~~ the "individual profile inversion" (IPI). In ~~a next step~~the next step, the profiles were binned into monthly 5°-zonal climatologies (IPI climatologies) at both processing centers.

~~Furthermore~~The WEGC and DMI API climatologies were produced, using the same COSMIC ~~satellite~~ data sets, ~~average profile inversion climatologies (API climatologies) were produced,~~ as described in ~~See~~Sect. 2. The API climatologies are available ~~from bending angledown to~~ for bending angle, refractivity and dry temperature (L2a processing) on a monthly 5°-zonal grid. At the WEGC, the API climatologies were produced using processing routines from rOPS-ex (Abel inversion, hydrostatic integral), and at the DMI, ROPP processing routines were used~~from the ROPP, respectively~~. We tested different high altitude extrapolations in the API processing ~~different high altitude expansions~~ (see description in ~~See~~Sect. 2). An overview of the data sets and all data versions (fulltop, exptop, etc.) is given in Tab. 1. ~~For clarification of the different data versions and their notations~~ To aid clarity, we give two examples:

The label "WEGC (L1b DMI) - fulltop" refers to an input bending angle climatology generated at the DMI (Gleisner and Healy, 2013), hence "L1b DMI", and then forwarded through processing routines from WEGC, using the WEGC high altitude ~~expansion~~ extrapolation "fulltop". On the other hand, "DMI (L1b DMI) - exptop" uses the same bending angle input climatology from the DMI, ~~and forwards the climatology through~~ but produces the climatology with the DMI processing routines, using the "exptop" high altitude ~~expansion. So basically~~ extrapolation. So in summary, those two processing versions share the same input bending angle climatology, but differ ~~in the further~~ processing (WEGC and DMI)~~and~~ , and in their handling of the ~~top~~ extrapolation (fulltop and exptop).

As reference data sets, co-located ~~ECMWF (European Centre for Medium-Range Weather Forecasts)~~ profiles from ECMWF analysis data were studied on 5° latitudinal bins. The analysis data fields were used ~~in~~ at a T42L91 resolution, since the T42 horizontal resolution matches the horizontal resolution of RO data (∼300 km). The ECMWF analysis climatologies were used as reference data sets from bending angle down to temperature (i.e., Level L2a climatologies), see Tab. 2.

~~Furthermore we~~ We also use data from the MIPAS ~~(Michelson Interferometer for Passive Atmospheric Sounding) and SABER (Sounding of the Atmosphere using Broadband Emission Radiometry)~~ and SABER instruments as reference data sets~~to RO climatologies~~. The MIPAS instrument, onboard ~~ENVISAT (Environmental Satellite~~ Environmental Satellite (ENVISAT), operated from July 2002 until April 2012, providing global temperature, pressure, and trace gas observations in an altitude range from about 6 km to 70 km. SABER, onboard the ~~TIMED (~~Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, measures data since 2001, providing temperature, pressure, density, geopotential height, and trace species. The coverage is nearly global, between 52°S - 82°N and 82°S - 52°N, respectively, alternating every two months, providing a continuous coverage from 52°S - 52°N, in an altitude range from about 10 km to 180 km. A validation study of MIPAS temperature in the middle atmosphere showed good agreement ~~to~~ with SABER temperature (< 0.5 K) in mid-latitude in the upper troposphere (García-Comas et al., 2012).

~~At WEGC a master thesis has been conducted, performing~~ Innerkofler (2015) performed a profile to profile inter-comparison study between WEGC RO OPSv5.6 data ~~(Schwärz et al., 2016)~~ and ECMWF, MIPAS, and SABER data~~(Innerkofler, 2015)~~. The study shows good agreement between ECMWF ~~analysis~~ analyses and RO data up to 80 km, with temperature differences of about ± 1 K. MIPAS data also show good agreement up to 40 km altitude with differences of about ± 1 K~~, between~~ . Between 40 km to 50 km height ~~,~~ these differences increase to about ± 2 K. In contrast to MIPAS, SABER data show a cold bias of 3 K between 20 km to 35 km. From 35 km to 45 km altitude the differences decrease to ± 2 K.

Table 1. Data sets from the COSMIC mission, studying always monthly 5°-zonal climatologies of the dry atmosphere.

Date	Processing	Inversion	L1b Bending Angle Climatology/Profiles	Parameters	Extrapolation	Label
01-03 2011	rOPS-ex	API, IPI	L1b WEGC-ex	α, N, ρ, p, T	fulltop	WEGC (L1b WEGC)
01-03 2011	ROPP	API, IPI	L1b DMI	α, N, T	exptop	DMI (L1b DMI)
01-03 2011	rOPS-ex	API	L1b DMI	α, N, ρ, p,T	fulltop	WEGC (L1b DMI)
01-03 2011	rOPS-ex	API	L1b DMI	α, N, ρ, p,T	exptop	WEGC (L1b DMI)
01-03 2011	rOPS-ex	API	L1b DMI	α, N, ρ, p,T	notop	WEGC (L1b DMI)
01 2011	rOPS-ex	API	L1b DMI	α, N, ρ, p,T	top1, top2, top3, top4	WEGC (L1b DMI)
01-03 2011	ROPP	API	L1b DMI	α, N, T	notop	DMI (L1b DMI)

Table 2. Reference data sets to Tab. 1, studying monthly 5°-zonal climatologies.

Date	Reference Data	Version	Vertical Range	Parameters	Global Sampling	Label
01-03 2011	ECMWF analyses	T42L91	91 model levels	N, ρ, p, T	4 times/day	ECMWF
01-03 2011	MIPAS data	ML2PPv7.03	6 km - 80 km ~3 km resolution	p, T	~800 profiles/day	MIPAS
01-03 2011	SABER data	GATSv2.05	10 km - 80 km ~2 km resolution	ρ, p, T	~1500 profiles/day	SABER

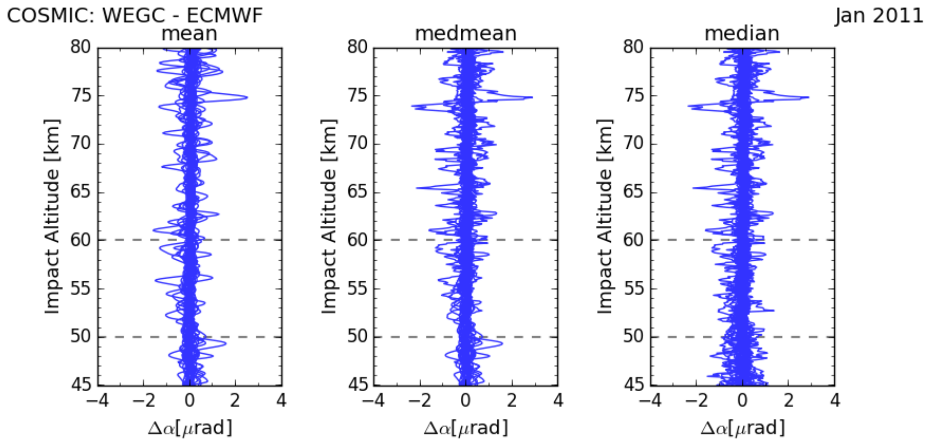


Figure 2. L1b WEGC: Bending angle difference of mean, medmean, and median relative to ECMWF ~~analysis~~analyses, ~~analyzing~~ for January 2011.

4 WEGC API climatologies

We start our analysis with the investigation of API climatologies from WEGC. API climatologies have already been thoroughly tested at the DMI (Gleisner and Healy, 2013; Danzer et al., 2014), showing very good agreements between API and IPI refractivity climatologies up to 35 km altitude.

Initially, we investigate monthly 5°-zonal rOPS-ex bending angle climatologies (WEGC L1b) for the COSMIC satellite mission ~~and~~ for January 2011. ~~Fig.~~Figure 2 shows the difference of the mean, medmean, and median bending angles relative to co-located ECMWF ~~analysis~~analyses. The dashed grey lines mark the transition region of the medmean bending angles. Obviously the bending angles show strong variations relative to ECMWF ~~analysis~~analyses. We emphasize that those bending angles are only recently generated experimental data, which is one reason why we later on continue our analysis based on DMI bending angles.

As a next step we compare API to IPI climatologies, using the ~~rops-ex~~ rOPS-ex bending angles (WEGC L1b) as input for the API and IPI processing. ~~Fig.~~ All refractivity differences are studied as relative differences given as a percentage, while the temperature differences are given in Kelvin. Figure 3 shows the difference between API and IPI refractivity (left column) and dry temperature (right column) climatologies, from January to March 2011 (top to bottom). Analyzing the refractivity differences, the API and IPI climatologies show almost identical results up to 40 km altitude. ~~Only~~ The largest differences are around the tropopause, and in the height range between 40 km to 50 km~~altitude differences~~ , and they vary between about 0.2 % and 0.6 %. This confirms the ~~result~~ results from previous studies~~that the average profile inversion~~ , that the API method is a valid alternative to the ~~individual profile inversion~~IPI approach, since no significant differences are introduced.

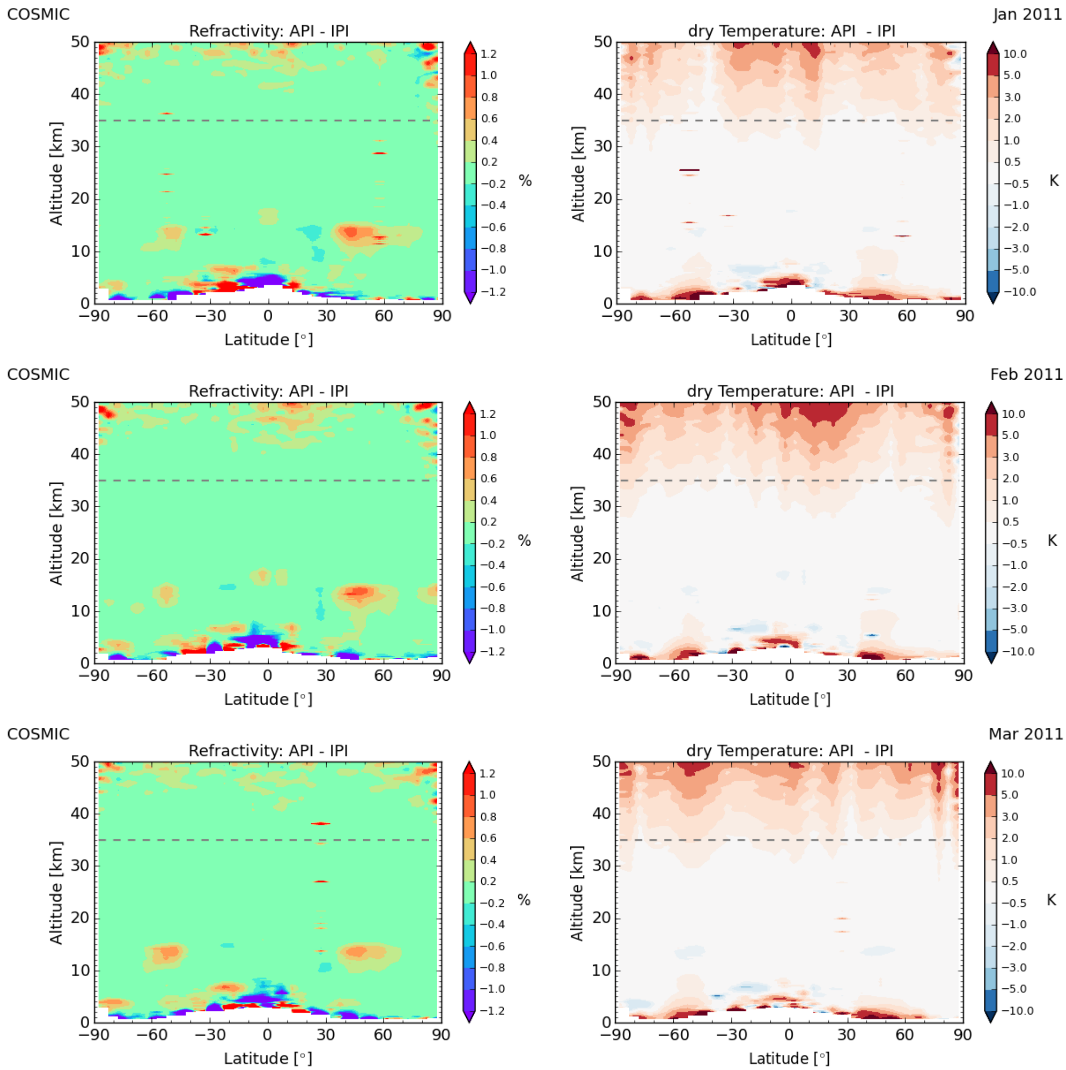


Figure 3. WEGC: Difference between ~~average profile inversion (~~API ~~)~~ and ~~individual profile inversion (~~IPI ~~)~~climatologies, analyzed for refractivity (left column) and dry temperature (right column), using L1b WEGC bending angles as input, studied from January to March 2011 (top to bottom).

~~Continuing the processing down to dry temperature and studying the differences between the two approaches, the~~ The API and IPI dry temperature climatologies agree within the RO core region of 35 km altitude (lower stratosphere) very well. Above ~~that height~~35 km, differences start to increase ~~with~~ by about 1 K every 3 km to 5 km altitude.

Summarizing the main results from this analysis: First, it was possible to successfully implement the API approach at the WEGC, as it has been done in previous studies at the DMI. Second, the API approach does not introduce major differences within the RO core region of 10 - 35 km. Hence, it is a valid alternative for climate analysis in the lower stratosphere.

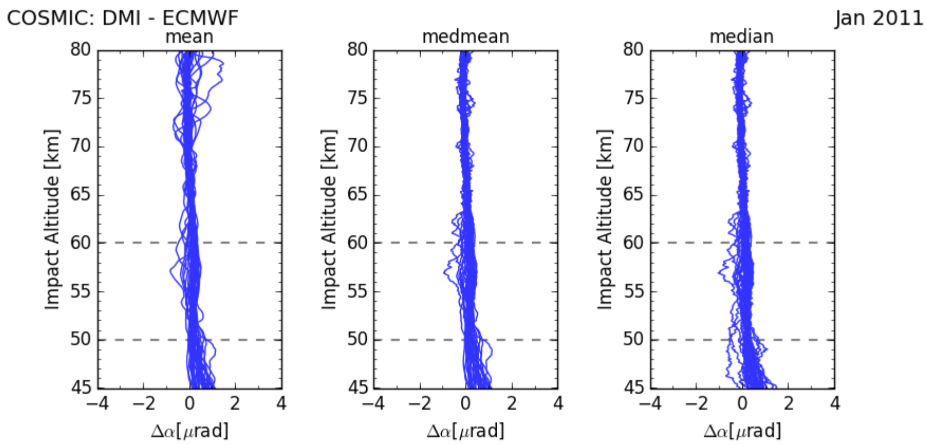


Figure 4. DMI: Bending angle difference of mean, medmean, and median relative to ECMWF ~~analysis~~analyses, studying Jan 2011.

5 Comparison of WEGC and DMI API climatologies

The main focus of this study is a thorough comparison of API climatologies ~~between the two processing centers~~ from the WEGC and DMI. Since we want to understand how differences enter in the processing from API bending angle climatologies to refractivity climatologies, we decided to always use the same input bending angle climatology for both processing systems. For practical reasons we chose to study bending angle climatologies from the DMI, labeled as DMI L1b, since WEGC rOPS-ex is still in the development process (see Fig. 2). ~~Fig.~~Figure 4 shows the monthly 5°-zonal mean, medmean, and median bending angle climatologies relative to ECMWF ~~analysis~~ analyses for January 2011. The February and March 2011 ~~show a very similarbehavior, hence~~ results are very similar, so we only present results for one month here.

In the Abel integral we use ~~as estimate for the central bending angle value per bin the mean-median combination called medmean , since at higher altitudes~~ medmean bending angles, because the mean value suffers from large-scale wiggles ~~and the median becomes a more robust estimate~~ at high altitudes (see discussions ~~in~~ given by Gleisner and Healy (2013), Danzer et al. (2014)).

5.1 API refractivity climatologies

In this section~~we show a first comparison~~, we show comparisons of API refractivity climatologies ~~between processing centers, i.e.,~~ from the WEGC and DMI. In Fig. 5~~we investigate~~, we show the difference of API refractivity climatologies relative to co-located ECMWF ~~analysis~~analyses, from January until March 2011. The left column corresponds to WEGC processing, while the right column corresponds to the DMI processing routines. ~~What strikes out in this plot series~~ A striking feature is that the ~~results at WEGC~~ WEGC differences above 35 km (left column) are always much larger relative to ECMWF, ~~compared to~~ than the DMI results (right column). Below 35 km results are in general very consistent between WEGC and DMI~~, however~~. However, in the tropopause region the ~~data show again~~ WEGC data show a slight increase relative to ECMWF and compared

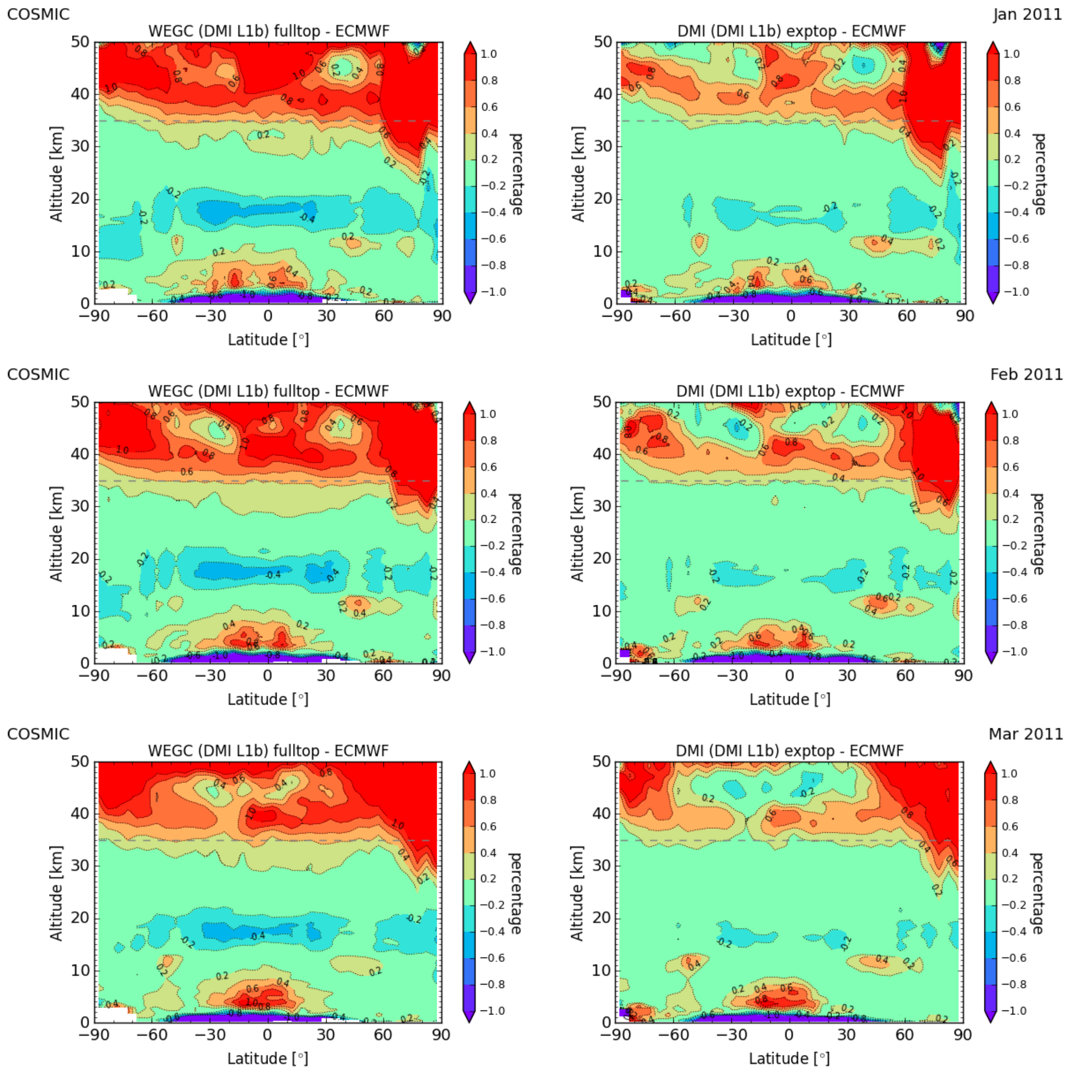


Figure 5. API refractivity climatologies relative to ECMWF ~~analysis~~analyses, comparing WEGC processing (left column) to DMI processing (right column), from Jan 2011 to Mar 2011, using the same bending angle profiles as input (DMI L1b).

to the DMI. Since both processing centers are using the same input bending angle climatologies (DMI L1b), these differences can only enter through ~~alternativ~~ alternative handling of the ~~top~~ extrapolation (fulltop and exptop) and ~~also different~~ in the implementations of the Abel integral. Note that the main focus of this study is the stratosphere, and that we therefore show “dry” parameters, which are not fully adequate to characterize moist regions in the lower troposphere. Specifically the refractivity bias structure in the low- and mid-latitude troposphere in the lowest few kilometers relative to ECMWF is not caused by the API retrieval. It can also be seen for the IPI method (see Figs. 5,6,7 shown by Gleisner and Healy (2013)). However, the error at the lowest $\sim$2 km is probably due to the use of a mean radius of curvature.

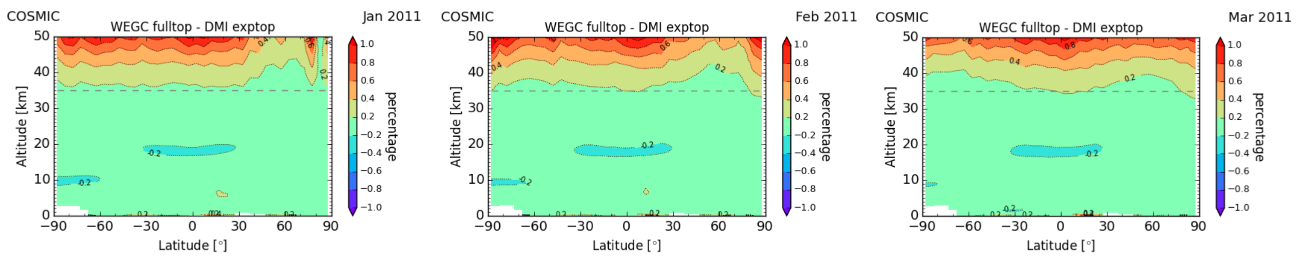


Figure 6. API refractivity climatologies difference between WEGC and DMI processing from Jan 2011 to Mar 2011, using the same bending angle profiles as input (DMI L1b).

In order to illustrate the discrepancies between WEGC and DMI more ~~strongly~~clearly, Fig. 6 ~~studies directly~~ shows the differences between the two API climatologies. Clearly the plot series confirms for all months that WEGC and DMI processing are almost identical up to 35 km~~altitude, only in the tropopause region we find differences of about 0.2 %~~, with the largest differences of 0.2 % in the tropopause region.

Nevertheless, we want to understand the occurring differences between WEGC and DMI, which is why we try to separate the underlying factors in the next two sections, i.e, the high altitude ~~expansion~~ extrapolation and the Abel integral.

5.2 Testing the impact of the Abel integral

~~In~~ Fig. 7 ~~the sole~~ shows the influence of different implementations of the Abel integral ~~is investigated, exemplary shown on~~ for January 2011. ~~To realize that we~~ We also switch off the high altitude ~~expansion~~ extrapolation at both processing centers and set the bending angle climatologies to zero above 80 km (top row, notop)~~. Furthermore, as a test, we~~ , and initialize the bending angles at both centers with an exponential extrapolation (bottom row, exptop).

~~Obviously, results become immediately very similar~~ Clearly results show consistency between the two processing centers WEGC and DMI, once the high altitude ~~expansion~~ extrapolation is handled in the same way. Notop (first row), as well as, exptop (second row) agree very well between WEGC and DMI, even above 35 km altitude. ~~Only in the region~~ However, there are small differences around the tropopause~~small differences exist~~.

~~Once again,~~ The discrepancies are more clearly illustrated by studying differences directly between WEGC and DMI (Fig. 8). ~~We find the already noticed~~ The 0.2 % differences in the tropopause region are clear. Furthermore we see that differences start to increase above 40 km with 0.2 % for the notop case (left plot). Almost identical results are found up to 50 km altitude for the exptop case (right plot), with small exceptions in the high altitude ~~polar north~~ north polar region. Since integration starts at 80 km altitude only in the notop case, absolute values at 50 km are smaller than for the exptop case, and the same absolute difference corresponds to a higher relative difference. Hence differences begin to increase at already 40 km altitude for notop.

To sum up, these results suggest that the handling of the top has a significant influence on the API refractivity climatologies above 35 km. On the other hand, different implementations and discretizations of the Abel integral seem to lead to only small

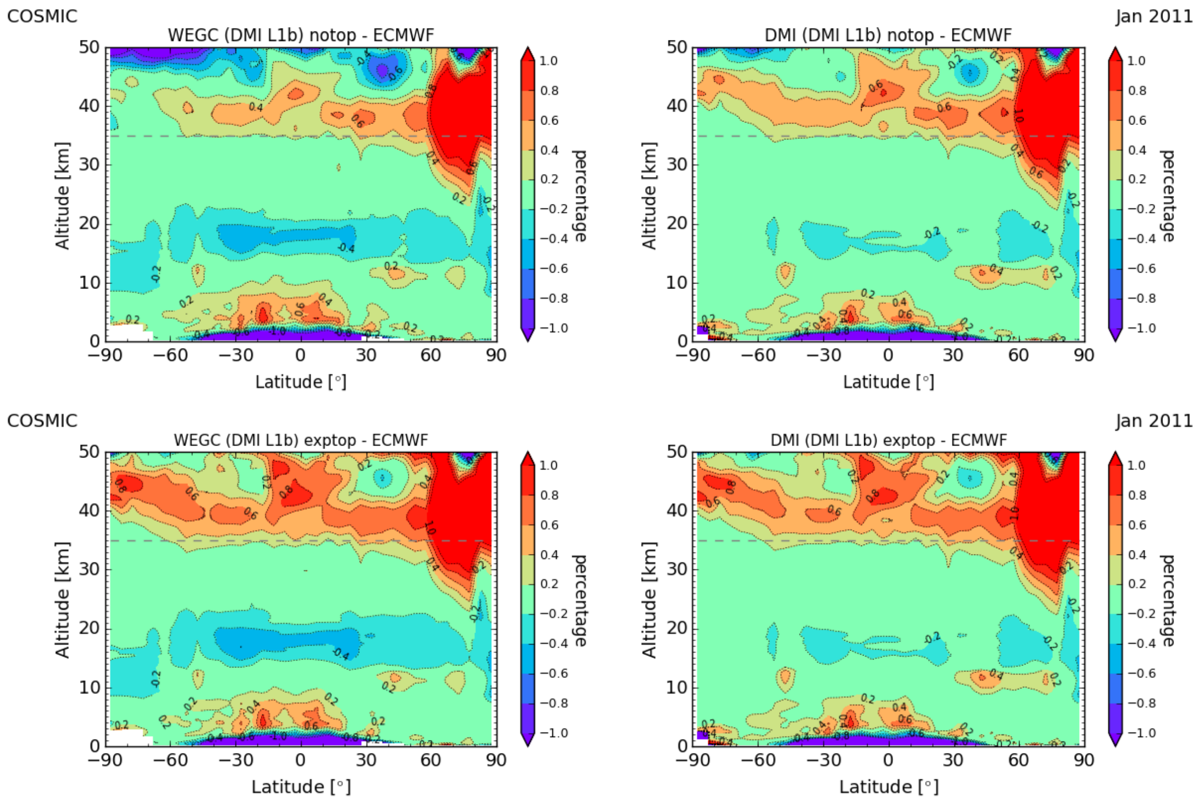


Figure 7. API refractivity climatologies relative to ECMWF ~~analysis~~analyses, comparing WEGC processing (left) to DMI processing (right), studying notop (first row) and exptop (second row), exemplary for Jan 2011.

differences, mainly in the tropopause region. Hence we conclude that in the context of the ~~average profile inversion~~ API approach, a major focus should be ~~laid~~ on the handling of the bending angle profiles above 80 km.

5.3 Testing the impact of different high altitude ~~expansions~~extrapolations

This section presents a first attempt to address the high altitude ~~expansion~~extrapolation. From the initial testing of the WEGC and DMI API processing, it is clear that the ~~choice of the top~~ extrapolation approach has a substantial ~~effect~~ impact on the resulting refractivity climatologies above 35 km. The question of how to handle the ~~top~~ extrapolation of the bending angles is of course a general question, ~~also in respect~~ and it also applies to individual profile processing. The rOPS-ex of WEGC is still in the development process, ~~where at the moment a lot of effort is put into answering that question~~and this is an area of ongoing research.

In a first analysis we investigate the sensitivity of the API refractivity climatologies with respect to different top values, for January 2011. We start in Fig. 9 from a top value of zero and increase the top value in 1/5 incremental steps, until reaching the

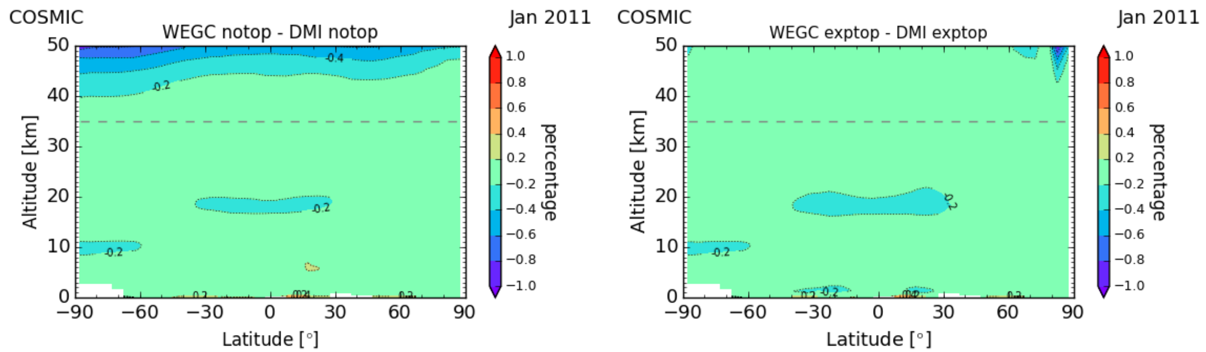


Figure 8. Difference between WEGC and DMI API refractivity climatologies, studying notop (left plot) and exptop (right plot), exemplary for Jan 2011.

fulltop value of the rOPS-ex. Clearly, the results are insensitive to different top values below 35 km, while errors increase at 40 km already up to 1 % relative to ECMWF ~~analysis~~ analyses for the fulltop value.

Figure 10a ~~investigates~~ shows the difference of single API refractivity climatologies ~~relative to ECMWF analysis~~ compared to ECMWF analyses for six example zonal bins up to 50 km, ~~comparing the above shown different choices of the top value. Obviously~~ showing the sensitivity to the extrapolation value. Clearly the notop choice usually agrees better with ECMWF, while the fulltop value shows largest differences ~~within slightly above~~ of around 1 % at 50 km. ~~Differences between the varying choices of the top start to increase at the usual characteristic altitude of 35 km , with a maximal spread~~ The sensitivity above 35 km is clear, with the largest differences between notop and fulltop of about 1 % at 50 km altitude. Only in northern high latitudes differences are larger relative to ECMWF ~~analysis~~analyses, which could be related to different sampling of the upper stratosphere lower mesosphere (USLM) disturbance in January 2011 (Greer et al., 2013). Related to that, the Arctic winter 2010/2011 has been notified as one of the coldest stratospheric winters on record (Sinnhuber et al., 2011).

~~Accordingly, Fig.~~ Figure 10b shows dry temperature differences relative to ECMWF for the same mean API climatologies. The plot ~~nicely~~ illustrates the downward propagation of the handling of the top value. ~~At around 20 km~~ The altitude differences start to increase above 20 km between the different choices of initialization, increasing to about ~~±1 K at 35 km~~ a 2-3 K difference at 35 km altitude relative to ECMWF ~~analysis~~analyses. Above 35 km altitude it depends on the choice of the initialization how fast differences increase. The choices of top3, top4 and fulltop seem to agree better relative to ECMWF ~~analysis~~ analyses than notop and small initialization values, such as top1 and top2. This is not surprising, since it is clearly wrong to ~~act as if~~ assume the bending angle is zero above 80 km. We also compared the different choices of top values amongst each other and also against the choice of exptop. It seems that the values of top3 and top4 are comparable with exptop, i.e., an exponential extrapolation.

5.4 API dry temperature climatologies

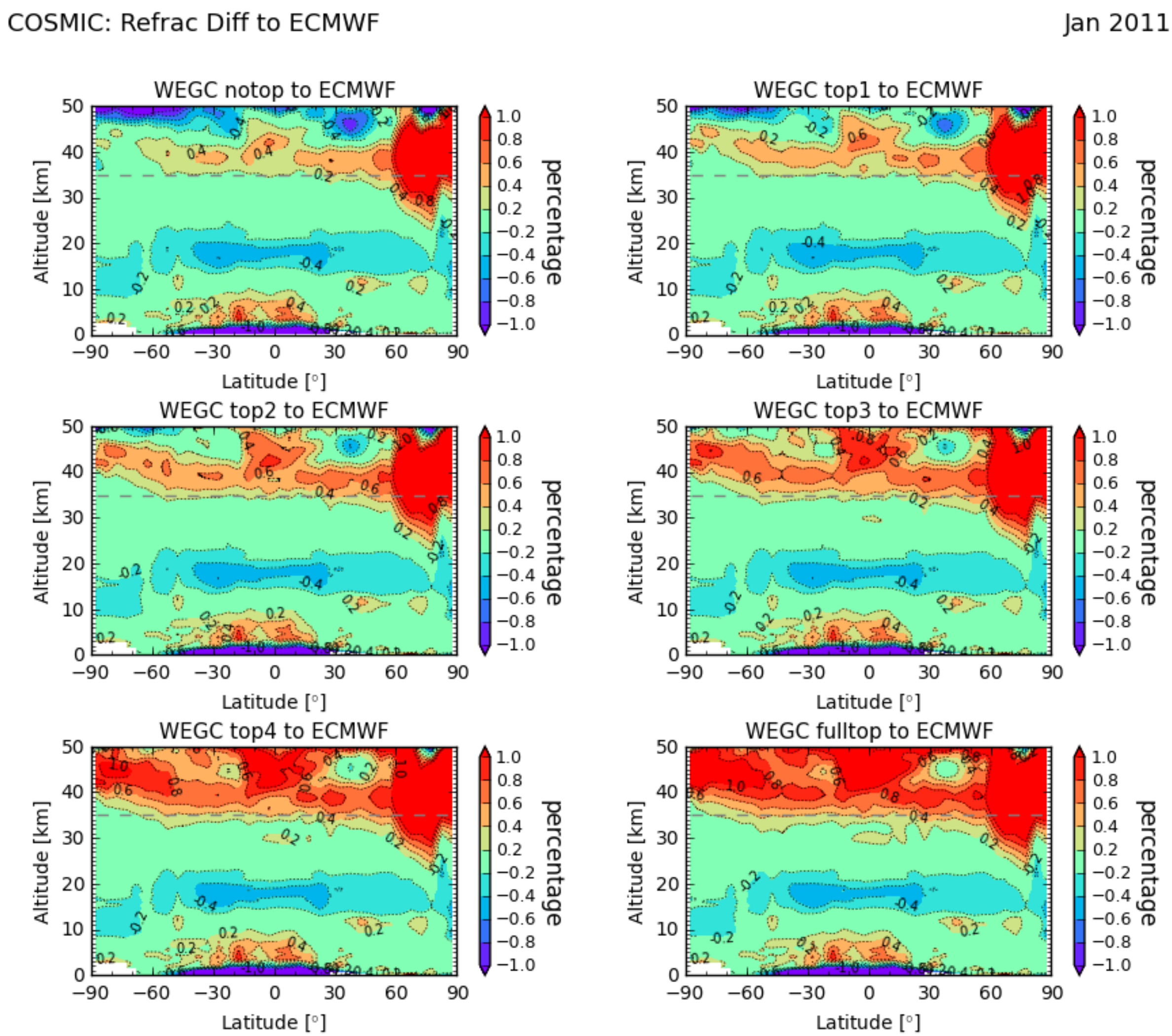
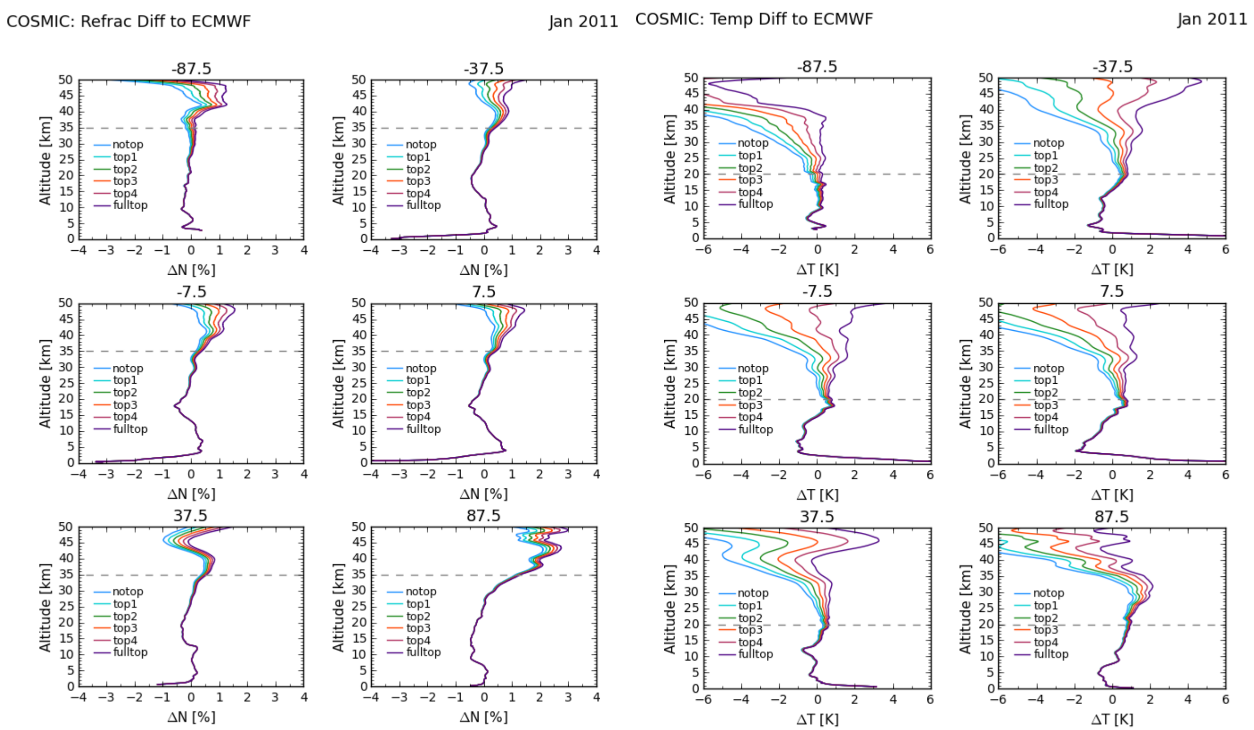


Figure 9. Sensitivity of API refractivity climatologies relative to different handling of the high altitude ~~expansion~~extrapolation, analyzed against ECMWF ~~analysis~~analyses. The plots start from a top value of zero (notop) and increase in 1/5 incremental steps (top1, top2, top3, top4) to the full value (fulltop).

~~Finally~~ In this section we analyze dry temperature differences relative to the three reference climatologies ECMWF ~~analysis~~analyses, MIPAS, and SABER. In Fig. 11 we compare WEGC processing and DMI processing, ~~furthermore different choices of the top value are investigated~~and include changes to the extrapolation. From top to bottom, we analyze WEGC fulltop, WEGC exptop, DMI exptop, and WEGC notop, using as input the bending angle climatology DMI L1b data. Starting with the first column, obviously RO API climatologies are in good agreement with ECMWF ~~analysis~~ analyses up to 35 km altitude. Above ~~that altitude~~ 35 km, differences start to increase, depending on the choice of the ~~upper~~ high altitude initial-

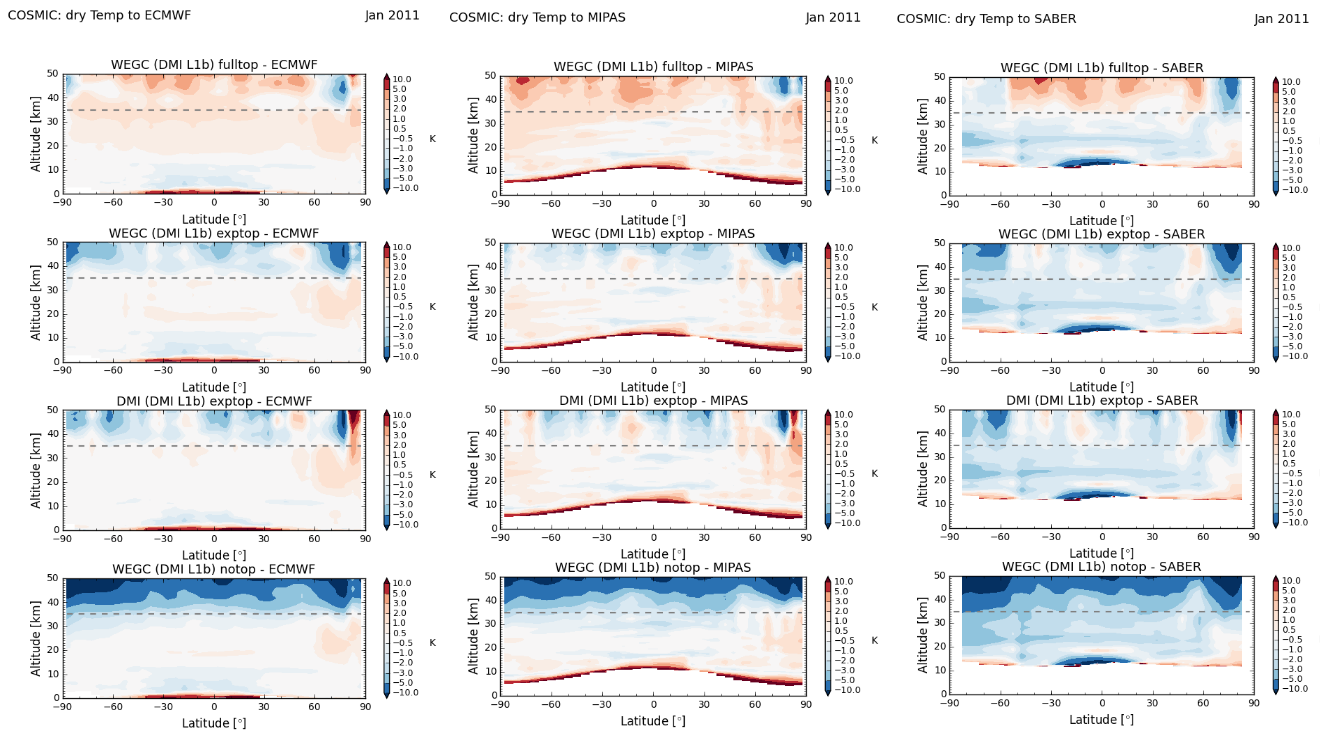


(a) N - ECMWF ~~analysis~~analyses. (b) T_{dry} - ECMWF ~~analysis~~analyses.

Figure 10. Sensitivity of single climatological profiles relative to different handling of the altitude above 80 km, analyzed against ECMWF ~~analysis~~analyses.

ization. In principle notop makes no physical sense, which is why the differences are getting very large relative to ECMWF ~~analysis~~analyses. The choice exptop leads to very similar results between WEGC (second plot) and DMI (third plot) processing and agrees ~~also up to almost 40 kmaltitude very good with ECMWF analysis~~with ECMWF analyses up to 40 km. Temperature differences vary from 0 K to about -1 K. For the choice fulltop, differences are larger (first plot), starting at 20 km height with about 0.5 K, increasing to about 1 K at 40 km altitude. In general, differences to ECMWF ~~analysis~~ analyses tend to be larger at northern high latitudes (USLM disturbance).

~~Analyzing~~ Comparing the dry temperature climatologies ~~in reference~~ to MIPAS data, the general ~~behaviour~~ behavior seems to be relatively similar to ECMWF ~~analysis.~~ analyses. The WEGC and DMI exptop cases (second and third plot) agree well up to around 40 km altitude. ~~Only around~~ There are small differences in the tropics up to 35 km altitude~~small areas~~ , of -0.5 K up to -1 K~~exist.~~ . The WEGC fulltop shows stronger differences around the poles compared to MIPAS than when compared to ECMWF ~~analysis~~analyses. On the other hand, SABER data (third column) show much larger differences also in the lower stratosphere up to values of about -3 K. ~~This~~ However, this is due to a cold bias of SABER data of about 3 K between 20 km to 35 km altitude (Innerkofler, 2015). Furthermore, SABER data show a reduced profile statistics between 90°S to 55°S (about



(a) T_{dry} - ECMWF ~~analysis~~analyses. (b) T_{dry} - MIPAS. (c) T_{dry} - SABER.

Figure 11. API dry temperature differences relative to different reference climatologies, comparing API processing between WEGC and DMI, studying different high altitude ~~expansions~~ extrapolations (fulltop, exptop, notop)~~.~~, for Jan 2011.

400 profiles per bin, usually about 1500 profiles per latitude bin), for January 2011. The reduced statistics is clearly reflected in the SABER plots (third column, Fig. 11).

In Fig. 12 we ~~analyze the differences of~~ show the differences between the three reference climatologies themselves. We want to understand up to which altitude they show good agreement between each other. ~~Obviously~~Clearly, up to almost 40 km height ECMWF ~~analysis~~ analyses and MIPAS (first plot) agree very well, although they ~~show little~~ still show differences of about ±0.5 K in the tropical lower stratosphere, and the poles. In the polar region, temperature differences start to increase above 40 km altitude. On the other hand, SABER exhibits clearly the cold bias in reference to ECMWF ~~analysis~~ analyses (second plot) and MIPAS (third plot) between 20 km to 35 km.

~~Summarized~~To summarize, since ECMWF ~~analysis~~ analyses and MIPAS agree well up to altitudes of about 40 km, they appear to serve as suitable reference climatologies up to this height. Hence, we conclude from our analysis that the exponential extrapolation of WEGC exptop and DMI exptop (second and third row of Fig. 11) is a good choice for the high altitude ~~expansion~~ extrapolation of the API bending angle climatologies. Data sets between API RO climatologies (WEGC exptop and DMI exptop), ECMWF ~~analysis~~analyses, and MIPAS agree very well up to 35 km altitude and within ±0.5 K to ±1 K at 40 km altitude.

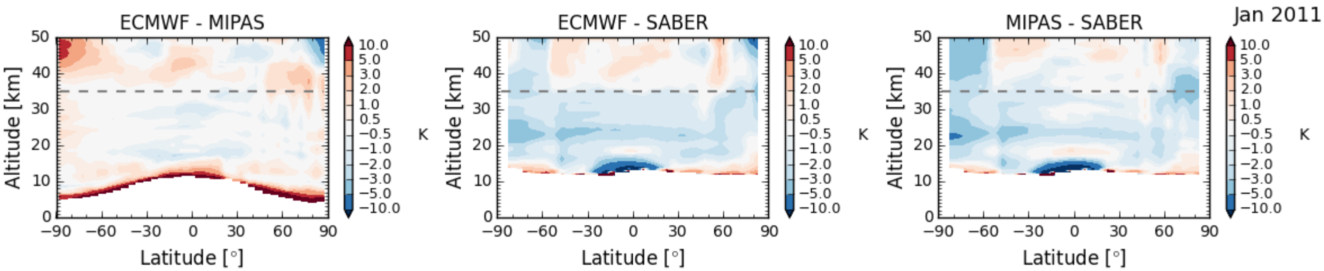


Figure 12. Dry temperature differences between reference climatologies.

6 Summary, discussion and outlook

This work is a follow-up investigation ~~of~~ on the so-called ~~average profile inversion (API)~~API retrieval method. The main idea of this method is to propagate average bending angles, instead of individual profiles through the Abel transform. The ~~principle method has been already tested successfully with~~ approach has already been successfully tested at DMI COSMIC data (Gleisner and Healy, 2013), as well as ~~on~~ with CHAMP data (Danzer et al., 2014)~~, at the Danish Meteorological Institute (DMI). This work here has the focus on~~ . The main focus of our work is a comparison of ~~the new approach between two processing centers, i.e.,~~ different implementations of the API approach at the WEGC and DMI.

We started our analysis with a first attempt to ~~adress~~ address the issue of calculating a single mean radius of curvature, $\overline{R_c}$, for a whole bin, although there can be strong variations of R_c from profile to profile. We tested different implementations of mean $\overline{R_c}$ and found that the largest differences are in the tropical area. However, studying the implications of the differences on the RO API dry climatologies, we find negligible impact, which supports the API approach.

Next we tested the API approach in the WEGC processing and compared it to WEGC IPI processing. Although the WEGC rOPS-ex processing system is still in development, we can conclude that differences between the two methods are very small up to 40 km altitude on refractivity level. Regarding dry temperature climatologies, differences start to exceed ± 1 K above 35 km height. Hence we conclude that the API ~~method~~ retrieval is a valid alternative to the standard inversion for dry atmospheric climatologies up to about 35 km, confirming previous work at refractivity level at the DMI.

For the comparison study between WEGC and DMI we decided to use ~~always~~ the same input bending angle climatologies from DMI, studying monthly 5°-zonal COSMIC data from January until March 2011. ~~That way we can~~ This approach was adopted to understand differences, which enter through the different processing systems, and not through the input climatology. The bending angle climatologies are used up to 80 km altitude, above that there is the need for some kind of high altitude ~~expansion~~ extrapolation due to the Abel ~~integral over infinity.~~ integration to infinity. The WEGC used monthly ECMWF analysis refractivity fields ~~as top values~~to extrapolate, while DMI performed an exponential extrapolation with a fixed scale height. Studying the resulting refractivity climatologies, we found that differences between the processing centers start to ~~enter at the altitude of~~ emerge at altitudes above 35 km, see Fig. 5 and Fig. 6. ~~Hence, the choice of the top~~ The observed RO - ECMWF biases above 35 km are not related to the API retrieval. They are generally seen in all RO - ECMWF comparisons when applying the standard processing (see comparison of API and IPI relative to ECMWF analyses in Figs. 5,6,7 shown by Gleisner and Healy (2013)). In that context, it is interesting to see how the extrapolation above 80 km also propagates down to that respective altitude35 km. This initial analysis showed that the handling of the top extrapolation is a substantial issue in the average profile inversionfor the API retrieval.

In a second step we decided to test solely the influence of the different implementations of the Abel integral on our resulting refractivity climatologies. To be able to study that simplify the system, we switched off the high altitude expansion extrapolation of the average bending angles at both processing centers (notop). Furthermore we tested both, at WEGC and DMI, an exponential extrapolation (exptop) . As a consequence, results became suddenly very similar between at the WEGC and DMI. This led to good agreement between the WEGC and DMI. For notop, the mean refractivities were now almost identical up to 40 km, while for exptop they even agreed up to 50 km. Only It was only in the tropopause region differences of 0.2 % appeared remained (Fig. 7 and Fig. 8). We conclude that the different implementations of the Abel integral do only play a minor role, however and that the handling of the top extrapolation has a much larger influence.

Next we analyzed the sensitivity of the mean climatologies to the choice of the top value. In that respectespecially , Fig. 10 is of interest, since it shows the impact of the top value extrapolation on single mean refractivity climatologies, as well as on the mean dry temperature climatologies. Differences in refractivity start to increase above 35 km altitude, and for dry temperature above 20 km altitude. Steiner et al. (2013) showed in a comparison study of climate data products from six international processing centers that different high altitude initialization approaches affect uncertainties in CHAMP RO data from about 25 km upwards. The largest differences between the processing centers are found towards increasing altitudes and at high latitudes. This has also been demonstrated for the API approach in a prior study analyzing CHAMP data (Danzer et al., 2014), where differences relative to ECMWF analyses also increased towards high altitudes and latitudes. Also the API approach shows an increasing sensitivity above 35 km altitude, when comparing different high altitude extrapolations for the bending angle, as well as, comparing WEGC and DMI processing centers. The propagation of errors downwards through the API retrieval chain to about 20 km in dry temperature shown here, has also been observed in prior studies for standard retrievals from different processing centers (Foelsche et al., 2011; Ho et al., 2012; Steiner et al., 2013).

Finally, we investigated dry temperature climatologies with respect to the following three different reference data sets: ECMWF analysisECMWF analyses, MIPAS, and SABER. Furthermore, we We also compared different choices of the high altitude expansion extrapolation (fulltop, exptop, notop) and also in the WEGC and DMI processing (see Fig. 11). In general RO API data sets agree well with the reference data sets up to 35 km altitude. For the case of an exponential extrapolation (exptop) they even have a good agreement up to 40 km altitude, for both the processing system at WEGC and DMI. Only the fulltop choice leads to enhanced differences starting at about 20 km altitude with 0.5 K, increasing to about 1 K at 40 km altitude. The temperature comparison study of RO API data sets relative to ECMWF analyses, MIPAS, and SABER data sets shows for both, the WEGC and the DMI exptop case, similar temperature biases as Innerkofler (2015) found by analyzing global RO IPI temperature data sets. RO API, ECMWF analysis data, and MIPAS data agree within ±1 K, up to 40 km. Above 40 km they begin to show larger differences than when analyzing global RO IPI data. Furthermore, the 3 K temperature bias of SABER data could also clearly be illustrated relative to RO API data.

~~As a next step~~ In further work we plan to investigate the issue of ionospheric residuals in the bending angle data. For that, we will apply the higher order ionospheric correction method ~~which was introduced by Healy and Culverwell (2015), and further investigated by Danzer et al. (2015); Angling et al. (2017). The~~ (Healy and Culverwell, 2015; Danzer et al., 2015; Angling et al., 2017). This correction method is based on the difference of the L_1/L_2 bending angles squared and a scaling term κ, which depends on solar zenith angle, solar flux and altitude. It will be interesting to see if residual ionospheric noise in the data will get reduced - and data quality of the climatologies can be raised to higher altitudes.

In ~~general~~ summary we conclude that the ~~average profile inversion~~ API retrieval is a valid, and in respect to computation time even much faster alternative for the production of dry atmospheric RO climatologies. It shows a robustness between the processing centers WEGC and DMI up to about $35\,\mathrm{km}$ altitude, if different high altitude ~~expansions~~ extrapolations are used. Applying ~~at both centers~~ an exponential extrapolation, at both centers produces dry temperature climatologies ~~agree between~~ that agree with each other, ECMWF ~~analysis~~ analyses and MIPAS climatologies up to $40\,\mathrm{km}$ altitude within $\pm 1\,\mathrm{K}$. The latter result might suggests that API dry temperature climatologies can be used up to $40\,\mathrm{km}$, pushing current limits of the utility of RO data in the stratosphere.

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