Atmos. Meas. Tech. Discuss., 7, C3837–C3848, 2014
www.atmos-meas-tech-discuss.net/7/C3837/2014/

Atmospheric Measurement Techniques Discussions

Interactive comment on "Generation of a Bending Angle Radio Occultation Climatology (BAROCLIM) and its use in radio occultation retrievals" *by* B. Scherllin-Pirscher et al.

B. Scherllin-Pirscher et al.

barbara.pirscher@uni-graz.at

Received and published: 21 November 2014

Response to the comments of Reviewer #2

We thank the reviewer for the constructive review and the important points raised. We took into account all the comments and revised the manuscript accordingly. Please see our detailed response below.

Comments:

1. *P8201, L3–7: BAROCLIM was compared with BA computed from ECMWF analysis. Since ECMWF has a top altitude of ∼80 km, its refractivity would need to be extended higher in order to compute the corresponding BA. Please explain how this is done.*

   Above the model top, ECMWF refractivity profiles are extended with co-located MSIS profiles fitted to ECMWF. Since this background information propagates down when computing bending angles from refractivities, our forward-modeled "ECMWF bending angles" contain MSIS-based information also below 80 km. For this reason we did not show and interpret differences between ECMWF and BAROCLIM above 60 km impact altitude.

   In the manuscript we added in Sect. 2 ("Data"):

   (above the ECMWF model top, refractivities were extended with MSIS profiles scaled to fit the ECMWF model at high altitudes).

2. *Sec 3.1: While I understand the need to exclude profiles with strong variability in forming the climatology, the multiple steps used in the QC here seem unnecessarily complicated. I believe it is far simpler to use robust statistics such as the interquartile range to exclude outliers. Just a comment/suggestion. I do wonder how BAROCLIM varies depending on the strictness of QC (and latitudes). It would be useful to quantify.*

   We tested several quality control (QC) procedures and applied them to different latitude bands and months before making our final choice. Even though there are several steps used in the QC, they are not very complicated. Evaluation of the external QC and the application of the ± 40 μrad- and the 20 μrad-QC can be done at once. Only the last step, the application of the 4σ-criterion, requires additional computations. We agree that using, e.g., the interquartile range for QC would also be possible but it would also require additional computations. During QC development we found that in the core region (upper troposphere up to the mesosphere), BAROCLIM does not vary strongly with QC.

To evaluate robustness of our QC, we also looked at differences between the mean and median before and after application of the 4σ-criterion. Since the median is a good and robust measure of the center of normally distributed values, it does not depend on QC. The mean, however, is affected by outlier profiles as seen in Fig. 1 below. This figure also shows that both median difference profiles are in very good agreement and they are also in good agreement with the mean difference profile after QC. The mean difference profile before QC, however, is negatively biased and exhibits more wiggles compared to the other difference profiles. Similar results were obtained for other latitude bands and seasons.

We could have used median profiles for BAROCLIM, but because the median is generally more jagged (see Fig. 1 below), we decided on using the mean.

3. *P8205, L13–15: Concerning the MSIS background error, the numbers seem very arbitrary. Can you provide some justification? I understand that the justification could possibly be found in the cited reference [Gobiet and Kirchengast 2004?], but it would be useful to summarize the rationale here as well.*

   In many cases, the error of a climatological background model σ_{m} is not well known. Typically it is assumed to be a constant fraction c of the background bending angle profile α_{m}, i.e., $\sigma_{\text{m}} = c\alpha_{\text{m}}$ with c ranging between 0.05 and 0.20 (Hajj et al., 2002; Gobiet and Kirchengast, 2004; Kuo et al., 2004).

   We followed Gobiet and Kirchengast (2004) and applied a background error of 15 % of the background bending angle profile between 62 km and 78 km. To avoid a too sharp transition at the top and the bottom end of statistical optimization, we assumed the background error to increase linearly from 0 % at 80 km to 15 % at 78 km and from 15 % at 62 km to 100 % at 60 km.

   We will add in the manuscript in Sect. 3.3 (“BAROCLIM discrete model”):

   While the linear increase of the relative error at the top and the bottom end of statistical optimization avoids too sharp transitions, the constant fraction of 15 % was determined empirically by Gobiet and Kirchengast (2004).

4. *P8205, L28 – P8206, L1–12: The use of measured BA for BAROCLIM in the lower troposphere was dismissed due to the fact that the lowest impact altitudes are different for individual profiles. As a result, the MSIS dry profiles were used instead. This seemed like a strange choice to me. Why not define an average lowest impact altitude based on the climatologically averaged BA profile? Even if there is uncertainty associated with that, it will surely be much better than using MSIS.*

   We chose a simple solution because focus is not on the lower part. The main reason for our choice was the reduced number of observations and reduced quality at the lowest altitudes. For the construction of the spectral model we needed to be able to define the bending angle corresponding to a tangent point height of zero (see description at the beginning of Sect. 3.4).

5. *P8206, L15: “cosine transition” should be defined or explained a bit more clearly.*

   Below a specific altitude level $z_{\text{top}} \in (10\ \text{km}, 12\ \text{km}, 15\ \text{km})$ (z_{top} depends on latitude), the mean RO bending angle α_{RO} is joined with the co-located MSIS bending angle α_{MSIS}. The gradual transition is applied using a cosine function with a defined width ($\Delta z = 5$ km).

   The cosine weighting function $w(z) \in (0 \ldots 1)$ is defined as

$$w(z) = \frac{1}{2}\left(1 + \cos\left(\pi \frac{z_{\text{top}} - z}{\Delta z}\right)\right)$$

   and the tropospheric bending angle α_{trop} is obtained from

$$\alpha_{\text{trop}} = w(z)\alpha_{\text{RO}}(z) + (1 - w(z))\alpha_{\text{MSIS}}.$$

In the manuscript we will rewrite in Sect. 3.3 ("BAROCLIM discrete model"):

We then applied a gradual transition using a cosine weighting function from the mean RO bending angle α_{RO} to the MSIS bending angle α_{MSIS}. This weighting function was defined as $w(z) = 1/2\,(1 + \cos(\pi(z_{\mathrm{top}} - z)/\Delta z))$ and the tropospheric bending angle α_{trop} was obtained from $\alpha_{\mathrm{trop}} = w(z)\alpha_{\mathrm{RO}}(z) + (1 - w(z))\alpha_{\mathrm{MSIS}}$.

6. *P8209, L10–17: Even though the error from the BAROCLIM spectral model is small, it is not negligible ~60 km or above. Can this be further reduced through an increase of Chebychev or zonal harmonic coefficients?*

   Differences between the BAROCLIM discrete model and the BAROCLIM spectral model close to 60 km result from remaining RO wiggles. These wiggles are caused by residual data noise of RO bending angles and are transferred to the BAROCLIM discrete model. The BAROCLIM spectral model, however, smooths out these wiggles. Even though this error could be reduced through an increase of Chebychev polynomials we wanted to smooth out these wiggles and decided on using 128 Chebychev polynomials.

   Errors above 80 km cannot be reduced through an increase of Chebychev or zonal harmonic coefficients. In general, these mesospheric errors are in the order of 1 % or 2 %. An error of 2 % at 80 km impact altitude corresponds to 0.006 μrad with a bending angle of 0.3 μrad. This error is distinctively smaller (more than an order of magnitude) than the residual ionospheric error (see Sect. 4.1 ("Error sources")).

7. *P8211, L7–9: "Systematic errors from MSIS a priori information used at high altitudes (below 70 km) are assumed to be small..." I don't see how you can be sure about that.*

   We did not use co-located MSIS profiles as a priori information at high altitudes. Instead, we performed a library search to find the best-fitting MSIS profile and

multiplied this profile with a fit factor obtained from least-squares adjustment (see Sect. 3.3). This way, we aimed at maximizing the information content of the RO data and at removing MSIS biases at high altitudes.

8. *P8213, L27–29 (Fig 6): Since the differences are zero below 30 km, I suggest limiting the y-axis to above 20 to 30 km to improve the clarify of the plots. There is no useful information below 30 km.*

   Thanks for this suggestion. We will restrict the y-axis of Fig. 6 to 30 km to 60 km.

9. *Fig 6: For the F3C results, the OPSv5.6 optimized BA is closest to raw BA. This surprises me given that OPSv5.6 used ECMWF for statistical optimization while BAROCLIM is directly based on F3C raw BA. Can you explain?*

   Climatological backgrounds such as BAROCLIM and MSIS are not always able to represent current atmospheric conditions and profiles extracted at specific latitudes and longitudes (i.e., co-located profiles) can be biased relative to the true atmospheric state. The search and fit algorithm implemented in EGOPS and used in this study searches for the best fitting profile within an impact altitude of 35 km and 55 km and fits this profile with a fit factor estimated from 45 km to 65 km (the optimal choice of these height intervals went beyond this study). Even when these profiles are used as a priori information in the retrieval, statistically optimized bending angle profiles can be biased relative to the true atmospheric state.

   Other approaches use two fitting parameters instead of only one (one more degree of freedom to tweak the climatology to better fit the data in some altitude range). In unpublished work using MSIS, this has shown to reduce biases further, but have not yet been verified with BAROCLIM.

   ECMWF short-range forecasts, which are used in the OPSv5.6 retrieval, are better at resolving synoptic atmospheric variability, and biases are, in general, small.

According to Fig. 6, the bias of OPSv5.6 retrieved bending angles of the other satellites (CHAMP, SAC-C, and GRACE-A) is also small, but due to the smaller number of measurements (and larger data noise), fluctuations are larger obscuring a clear picture.

Motivated by a question from another reviewer we will include the following clarification in Sect. 5:

With this approach we do not necessarily take a profile from MSIS/BAROCLIM corresponding to the latitude and season of the retrieval, but one that fits the data the best at high altitudes. Thus, with the SF approach we use MSIS/BAROCLIM as a library of different profiles representing different (average) atmospheric conditions on Earth. The approach should reduce sensitivity to biases in the climatology, although it does not guarantee that biases in the retrieved profiles are absent.

10. *Fig. 7: For BA, there is a clear negative bias in the lower troposphere from all the plots. However, the bias is absent in the refractivity. Why?*

    There is a negative refractivity bias close to the surface as well. It cannot be seen in Fig. 7 because we plotted refractivity results only above 2 km. Due to the difference between mean-sea-level (msl) altitude and impact altitude (0 km msl altitude approximately corresponds to 2 km impact altitude) Fig. 7 included near-surface statistics in bending angle but not in refractivity.

    Figure 2 below shows global statistics of bending angle systematic difference and refractivity systematic difference down to the surface. While the bending angle bias is larger than 5 % at an impact altitude of 3 km, the refractivity bias exceeds 2 % below 1 km msl altitude. These negative RO biases are consistent with findings from Sokolovskiy (2003).

    To be consistent with Fig. 6, we will restrict the y-axis of Fig. 7 to 30 km to 60 km in the revised manuscript.

11. *P8216, L1–4: "Our current BAROCLIM spectral model does not include profiles of particular atmosphere conditions arising, e.g., during and after sudden stratospheric warmings (SSW)." Why weren't they part of BAROCLIM? Were those profiles excluded during QC? "Since several major and minor SSW events occurred since 2006 it is possible to include such profiles in BAROCLIM." How? Do you really want to do that for a climatology?*

    No, we did not exclude profiles of particular atmospheric conditions. QC was the same for all RO profiles, also during and after SSWs. We meant that BAROCLIM does not include profiles, which specifically represent particular atmospheric conditions. We agree with the Reviewer that it might be very challenging to obtain mean profiles, which are typical for these events. The challenge arises from the limited number of profiles at high latitudes as well as extremely large atmospheric variability during these events. We will remove these sentences in the manuscript.

    Reviewer #1 pointed out that BAROCLIM even might be biased towards SSWs due to the very short F3C record. We included a paragraph in Sect. 4.1 (Error sources), which addresses the limitations imposed by the six- or seven-year period of record. This paragraph will read:

    However, since BAROCLIM is only based on measurements from six or seven years, BAROCLIM might be biased relative to the long-term mean atmospheric state over 30 years. During the BAROCLIM time period, e.g., several major Sudden Stratospheric Warming (SSW) events occurred in northern hemisphere winter (e.g., in January 2009 and 2010) yielding an RO climatology biased towards too high temperatures and too high atmospheric densities (i.e., too large bending angles) at northern high latitudes in these months.

12. *Would you use the derived BAROCLIM for RO retrievals outside 2006–2012? Please discuss.*

Yes, we recommend using BAROCLIM also for retrievals outside of 2006 to 2012. We will include in the manuscript at the end of Sect. 5:

We conclude that the results using BAROCLIM seem promising, in particular when used in combination with the SF approach. As mentioned, such an approach should reduce the sensitivity to possible biases in BAROCLIM because it is then merely used as a library of different profiles representative of different (average) atmospheric conditions. The fact that BAROCLIM is based on data from only one mission (F3C) and from a limited period of time (2006 to 2012) is therefore not so important in this context; BAROCLIM can be used in this way for other RO missions in the past and in the future as long as the climate in the upper stratosphere does not change drastically in terms of global variations of bending angle.

Minor comments:

13. *P8202, L4: "Bending angles, which are very noisy and/or contain unphysical values, can strongly affect the quality of a bending angle climatology." makes it sound like all bending angles are "very noisy". I suggest a change of wording here. Maybe "Some bending angles are very noisy and/or contain unphysical values; they could strongly affect the quality of the bending angle climatology if they were not properly excluded."*

    Thanks for this suggestions, we will rewrite this sentence accordingly.

14. *P8202, L24: "damage" → "degrade"*

    done

15. *P8202, L27: "non-negligible data noise at high altitudes" What does "non-negligible data noise" mean? Can you rephrase?*

    We rewrote this sentence. It now reads:

Inspecting remaining bending angle profiles after application of these first checks we still found some very noisy bending angle profiles (top panel of Fig. 2) and therefore applied an additional QC.

16. *I find that this paper has too many references that are not directly relevant. If length is an issue, I suggest removing some of the references.*

    We will remove the following references:

    - ENSO: Angell (1981); Scherllin-Pirscher et al. (2012)
    - QBO: Baldwin et al. (2001);
    - Climate change: IPCC (2013)
    - MJO: Zhang (2005)
    - Tropopause: Schmidt et al. (2005; 2006); Rieckh et al. (2014)
    - Planetary boundary layer: von Engeln et al. (2005)

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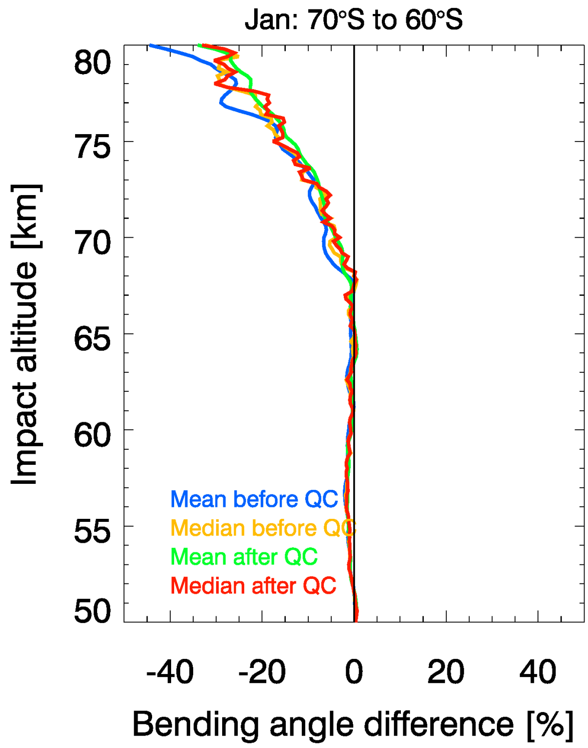

Fig. 1. Mean differences between RO bending angle and ECMWF bending angle before and after application of the 4σ -criterion. Results are shown for the 60°S to 70°S latitude band in January.

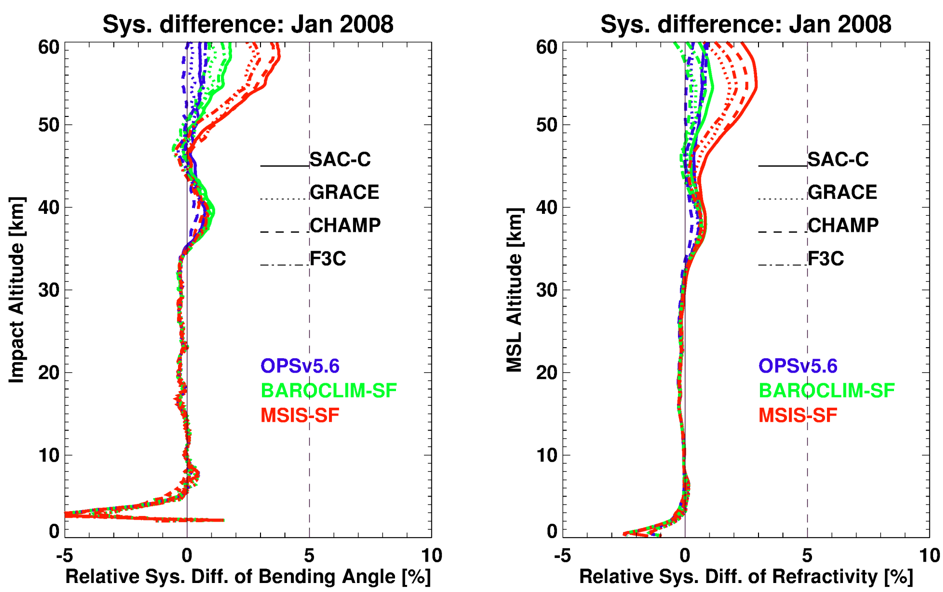

Fig. 2. Global statistics of systematic difference between RO retrievals and ECMWF analyses for January 2008. The left panel shows statistically optimized bending angle and the right panel refractivity.