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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.

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Response to the comments of Reviewer #1

We thank the reviewer for the detailed review and the helpful and constructive comments which we fully took into account in the revision of the paper. Please see our detailed response below.

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Two main questions

1. *Is this climatology of sufficient interest to the readers of AMT to warrant publication?*

   Yes, there is a community of researchers who will be interested in the generation and quality of BAROCLIM as well as it's application. Primary end-users will be researchers who work in the field of RO data processing. We will point at these end-users in the revised version of the manuscript (see specific comments below).

   BAROCLIM is not yet publicly available but we anticipate that it will be included in a future release of the radio occultation processing package ROPP. This will also be noted in the revised manuscript.

   We are aware that bending angle is not a well-known atmospheric parameter. We therefore included a paragraph in Sect. 1 ("Introduction"), which briefly describes the meaning of bending angle and what it depends on. This paragraph reads:

   The RO bending angle can be used as a climate variable (Ringer and Healy, 2008). In the upper troposphere and above (where moisture is negligible), it mainly depends on atmospheric density, which again depends on pressure and temperature. This means that a change in bending angle can be caused by changes of all these parameters. This has to be kept in mind when analyzing atmospheric variability in terms of bending angle. However, the use of bending angle as climate variable is superior to other RO-derived atmospheric quantities that are sensitive to the additional use of a priori information used in the retrieval (see below).

2. *And does the paper give a sufficient description of the new climatology that it can be used as a stand-alone reference for it?*

   A detailed description of BAROCLIM is important because there is a community

of researchers who will be interested in using this climatology. The generation of BAROCLIM is described in detail in the AMTD manuscript, where we also included a discussion of potential errors and suggested and demonstrated its use as a priori information in RO retrievals. In the revised manuscript we will emphasize that BAROCLIM does not represent a long-term mean but has limitations due to the six- or seven-year F3C RO record (see specific comments below). We feel confident that the revised manuscript can be used as a stand-alone reference after taking into account the Reviewer's other comments and suggestions (see below).

Specific comments

- *Regarding the first question, I can believe there is a community of researchers who might productively use the climatology, but I'm not quite sure who they are. Identifying the end-users is important because, as noted by the authors, the dataset has some limitations, and these limitations will be more or less consequential depending on the use to which the data is put.*

  BAROCLIM was originally developed to be used as a priori information for bending angle initialization in RO data processing. Thus, the primary end-users of this climatology will be researchers who work in the field of RO data processing. We will identify these end-users in the manuscript. We will add in Sect. 1 ("Introduction"):

  However, it is of very high utility to obtain a quick and reasonable estimate of the atmospheric mean state as required, e.g., within the retrieval of atmospheric parameters from remote sensing measurements.

  Furthermore, we will write in Sect. 6 ("Summary, conclusions, and outlook"):

  BAROCLIM was originally developed to be used as a priori information for bending angle initialization in RO data processing.

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- *One claim made by the authors is that the climatology "can be used to detect deficiencies in current state-of-the-art analysis and reanalysis products from numerical weather prediction centers." The bar is quite high for such use, and I don't think the paper makes a convincing case for it. There are some comparisons with ECMWF, but the ECMWF analyses use the F3C data as input so these are not entirely clean comparisons. The authors write that differences between BARO-CLIM and ECMWF "rather show deficiencies in ECMWF than in BAROCLIM", but I do not see definitive evidence for this claim.*

In December 2006 ECMWF started assimilating RO bending angles below 40 km (Healy, 2007). From March 2009 onward (since IFS cycle 35r2), ECMWF assimilates RO data up to 50 km (S. Healy, ECMWF, personal communication, October 2014; see also http://old.ecmwf.int/products/data/operational_system/evolution/evolution_2009.html). RO measurements have the potential to correct model biases, but the RO bending angle is only one of many variables assimilated in the ECMWF system.

Despite of the assimilation of RO, we found noticeable differences between BAROCLIM and ECMWF above 35 km. The reason for these differences is that ECMWF assumes an exponentially increasing RO observational error above 30 km (see http://www.uni-graz.at/opac2010/pdf_presentation/opac_2010_healy_sean_presentation40.pdf), which limits the impact of RO on ECMWF analyses at high altitudes.

To assess whether the bias should be attributed either to RO or to ECMWF, we calculated monthly mean differences between RO and ECMWF bending angles for 30° latitude bands (six bands from 90°S to 90°N) and analyzed them as a function of time. Figure 1 below exemplarily shows these differences for southern hemisphere low latitudes. This figure clearly shows a changing bias characteristics with time and differences between these two data sets are distinctively smaller at the end of the time series than at the beginning of the time series.

The lower bound of the 2 % difference, for example, moves upward from approximately 48 km end of 2006 to 58 km end of 2012.

Changing quality of RO measurements cannot explain these temporal changes because we only used RO data from the Formosat-3/COSMIC (F3C) constellation, applied the same data processing for the entire record, and monitored F3C data quality (Schwärz et al., 2013) and found no degradation with time. Temporal changes of RO measurements can potentially be explained by residual ionospheric errors due to their dependence on the solar cycle (Danzer et al., 2013). Solar activity was very low from 2007 to 2009 and increased from 2010 onward. During high solar activity RO bending angles may be slightly negatively biased. Thus, increasing residual ionospheric errors would indeed reduce positive RO minus ECMWF biases but (i) they cannot explain the vertical bias structure in general and (ii) they are too small to explain these big changes with time.

However, these decreasing differences can be explained by operational improvements in the ECMWF's operational global meteorological forecasting model IFS (Integrated Forecast System). To improve performance of the deterministic forecast system, ECMWF regularly revises its system. Changes include, for example, additional assimilation of satellite measurements, change of the weight of assimilated data, updates of bias correction procedures for satellite data, or model updates, see http://old.ecmwf.int/products/data/operational_ system/evolution/. Some of these changes strongly improve the quality of operational ECMWF analysis data at high altitudes.

The remaining question is, where ECMWF biases come from and if other satellite data are also able to detect these deficiencies. As noted in the paper, ECMWF biases at high altitudes have also been found with satellite measurements from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument on Envisat and from the Microwave Limb Sounder (MLS) instrument on the Aura satellite (Chauhan et al., 2009). Further comparisons of ECMWF analy-

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ses and temperature data from MIPAS and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER, an instrument on the TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite) also reveal a similar bias structure in ECMWF analyses above 35 km (see Fig. 2 below). Note that this plot shows ECMWF minus MIPAS/SABER differences rather than MIPAS/MLS/BAROCLIM minus ECMWF differences as shown by Chauhan et al. (2009) and our manuscript. Temperature differences between ECMWF and MIPAS/SABER are approximately 2 K at 40 km and increase to more than 5 K at 60 km. Differences between MIPAS and SABER, however, are comparatively small (not shown). We thus conclude that ECMWF analysis biases above 35 km are real.

After discussions with Sean Healy, ECMWF, we learned that the bias above 35 km might be related to the bias correction of assimilated radiances from satellite measurements. The bias at 50 km, is most likely attributable to data from the AMSU-A channel 14, which is assimilated without bias correction.

We will rewrite in Section 4.2 ("Comparison to ECMWF"):

Positive BAROCLIM minus ECMWF analysis differences above 35 km ($<$ 1 %) and above 50 km ($>$ 2 %) are mainly attributable to biases in ECMWF analyses rather than to BAROCLIM. In general, these biases above 35 km might be related to the bias correction of assimilated radiances from satellite measurements whereas the specific bias above 50 km is most likely attributable to data from AMSU-A channel 14, which are assimilated without bias correction (S. Healy, ECMWF, personal communication, October 2014).

Similar ECMWF biases at high altitudes have been found with satellite measurements from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument on the European environmental satellite ENVISAT and from the Microwave Limb Sounder (MLS) instrument on the U.S. Aura satellite (Chauhan et al., 2009). Further comparisons of ECMWF analyses and temperature data

from MIPAS and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER, an instrument on the U.S. TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite) also revealed a similar bias structure in ECMWF analyses above 40 km (J. Innerkofler, WEGC, personal communication, October 2014). All these comparisons consistently showed that ECMWF temperatures are too high at high altitudes yielding a negative measurement minus ECMWF temperature bias. When pressure biases are small, a negative temperature bias corresponds to a positive refractivity bias, which in turn corresponds to a positive bending angle bias (see e.g., Scherllin-Pirscher et al., 2011b) as shown in Fig. 5.

- *Another proposed use of the data is as a priori information for RO profile retrievals. I believe this would be a reasonable use of the data, and I think the authors should give more consideration to this application in describing the data. For one thing, I am not sure how one would access and use the data as prior information. I could not find a weblink to the data, either in the paper itself or online, or a description of data formats or other details that would enable community us of the data. Is BAROCLIM intended as a publicly available dataset? Otherwise I am not sure that readers of AMT would feel strongly motivated to read about it.*

We will include this information in the manuscript in Sect. 3.4 ("BAROCLIM spectral model"):

The BAROCLIM spectral coefficients (stored in a NetCDF-file) as well as the Fortran-90 code needed to reconstruct bending angles from these coefficients are designed to be included in a future release of the ROPP software. The ROPP is free of charge after registration at http://www.romsaf.org.

Furthermore, we will write in Sect. 6 ("Summary, conclusions, and outlook"):

BAROCLIM spectral coefficients and the reconstruction code, which is needed to obtain bending angles, are designed to be included in a future release of the

Radio Occultation Processing Package (ROPP). This RO package can be downloaded for free after registration at http://www.romsaf.org.

- *Another issue is that the dataset has some limitations, which may or may not be severe depending on the intended use. If the data is intended for use as prior information for retrievals, the limitations of the data can be evaluated against the tolerances required for that purpose.*

We agree, but it would require a more comprehensive study. All datasets (or models) have limitations. Future studies will likely reveal limitations in BAROCLIM as well. We would welcome such studies. They could help in pointing out the weak areas and eventually lead to improvements in future models of the same kind. At the moment we are not able to quantify the possible limitations with confidence (see later), but the study that we have done in this paper, leading to Figs. 6 and 7, showed that BAROCLIM is likely a better prior for retrievals than MSIS.

- *While the authors assess various kinds of errors in the data, I do not believe they give sufficient consideration to the limitations imposed by the 6-year period of record. As one point of comparison, the standard period for "climate normals" is 30 years, the reason being that the climate system has a variety of natural modes and oscillations, many of which have substantial decadal and even multi-decadal variability. If the 6 years of the climatology coincide with the positive or negative phase of a low-frequency oscillation, they will skew the climatology towards that phase. Even modes which are not specifically low-frequency can have runs of multiple years with a bias towards one phase or the other, for example the run of positive years of the AO in the 1990s.*

This is a very good point. We will mention this limitation in the paper. The knowledge of the long-term mean state of the stratosphere, mesosphere, and above is limited due to the lack of globally available and reliable long-term measure-

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ments. Analysis products from numerical weather prediction centers cannot be used to estimate the mean atmospheric state over 30 years because of their changes/improvements in data assimilation techniques (see discussion above). Even though reanalyses are based on a fixed assimilation model, changes in the assimilated observations also yield changes in the quality of reanalyses and shifts in their time series. Thus, it is difficult to quantify potential biases imposed by the six- or seven-year record used to construct BAROCLIM.

To analyze variability modes with impact on the troposphere and/or stratosphere, we downloaded indices of Pacific Decadal Oscillation (PDO)[1], Arctic Oscillation (AO)[2], Antarctic Oscillation (AAO)[3], El Niño–Southern Oscillation (ENSO)[4], and Quasi Biennial Oscillation (QBO)[5]. After normalizing each index to its largest absolute value from 1981 to 2013, we calculated temporal means for the 30-year climate normal 1981 to 2010 and for the 7-year RO record 2006 to 2012. These mean values are shown in Table 1 for each month.

The table clearly shows that the PDO was in a negative phase from 2006 to 2012. Furthermore, ENSO was somewhat skewed towards La Niña conditions (positive values of the SOI indicate La Niña episodes). QBO at 30 hPa seems to be skewed towards easterly winds but AO and AAO do not show a consistent pattern since means strongly vary for different months.

While QBO, AAO, AO, and ENSO have well known influence above the troposphere (e.g., Baldwin et al., 2001; Sexton, 2001; Ambaum and Hoskins, 2002; García-Herrera et al., 2006), the influence of the PDO on middle atmo-

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[1]http://jisao.washington.edu/pdo/PDO.latest

[2]http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii. table

[3]http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/monthly.aao.index.b79.current. ascii.table

[4]http://www.cpc.ncep.noaa.gov/data/indices/soi

[5]http://www.cpc.ncep.noaa.gov/data/indices/qbo.u30.index

Table 1. Temporal mean of different normalized climate indices. Means are calculated from 1981 to 2010 (left) and from 2006 to 2012 (right).

	PDO	AO	AAO	SOI	QBO
Jan	+0.13/−0.19	+0.02/−0.04	+0.02/+0.23	+0.00/+0.24	+0.00/−0.23
Feb	+0.21/−0.20	−0.04/−0.13	+0.02/+0.13	−0.00/+0.25	−0.00/−0.15
Mar	+0.26/−0.26	+0.01/+0.10	+0.04/+0.09	+0.00/+0.36	+0.00/−0.07
Apr	+0.25/−0.17	+0.04/+0.20	−0.01/−0.14	+0.00/+0.40	−0.00/−0.09
May	+0.32/−0.19	+0.04/+0.02	−0.00/+0.12	−0.00/+0.06	+0.00/−0.10
Jun	+0.16/−0.12	−0.03/−0.22	−0.06/+0.12	−0.00/+0.12	+0.00/−0.12
Jul	+0.16/−0.22	−0.05/−0.21	+0.02/−0.02	+0.00/+0.19	−0.00/−0.02
Aug	+0.11/−0.34	+0.06/−0.21	+0.04/−0.11	−0.00/+0.18	−0.00/+0.00
Sep	+0.04/−0.46	−0.01/+0.24	+0.03/+0.06	−0.00/+0.29	+0.00/−0.02
Oct	−0.05/−0.40	+0.00/−0.14	+0.04/+0.17	+0.00/+0.19	+0.00/−0.02
Nov	−0.06/−0.41	−0.00/+0.11	−0.06/−0.22	+0.00/+0.23	+0.00/−0.06
Dec	+0.03/−0.30	−0.05/−0.08	+0.09/+0.35	−0.00/+0.34	+0.00/−0.08

sphere characteristics is unknown, at least to the authors knowledge. However, due to the influence of ENSO in the middle atmosphere, BAROCLIM could be skewed towards warmer stratosphere conditions at low latitudes (larger densities yield larger bending angles) and cooler stratosphere conditions at high latitudes (smaller bending angles) (García-Herrera et al., 2006). The interpretation of the skewness of the QBO has to be done with care since (i) temperature is in phase with wind shear rather than with wind itself and (ii) the QBO propagates downward from approximately 50 km to 16 km at a speed of about 1 km per month (Baldwin et al., 2001).

We will add in Sect. 1 ("Introduction"):

BAROCLIM is based on measurements from 2006 to 2012. Since this period is much shorter than the standard period for climate normals (30 years), BARO-CLIM does not represent a long-term mean.

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- *At the end of the paper the authors mention the possibility of looking at conditions for sudden stratospheric warmings (SSWs) with their data, but they don't address the fact that the SSW events of the six years in their record will be aliased into their climatology. In a 6-year climatolgy only 6 months go into each monthly average, so even one or two SSWs could skew the climatology for a single climatological month.*

Being aware that reanalysis data are affected by changes in assimilated observations and model biases, we downloaded reanalysis data from ECMWF (ERA-Interim) from 1981 to 2013 and compared the 30 years climate normal 1981–2010 to the BAROCLIM period 2006–2012 in terms of temperature. We used these data to better quantify potential biases imposed by the short RO record.

The 2006 to 2012 period is indeed skewed towards too warm stratosphere conditions in northern hemisphere winter (see Fig. 3 below). This warm bias is caused by two major Sudden Stratospheric Warming (SSW) events, which occurred in January 2009 and 2010. The bias is larger than 4 K at northern hemisphere polar latitudes.

We included a paragraph in Sect. 4.1 ("Error sources"), which addresses this issue. This paragraph reads:

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.

Figure 3 below does not reveal potential biases attributable to the influence of ENSO (too warm stratosphere conditions at low latitudes and too cold stratosphere conditions at high latitudes, see above). However, there could be a small

bias at tropical latitudes due to the influence of the QBO. Downward progression of the QBO would yield alternating positive and negative anomalies as seen e.g., in Fig. 3 in April and July. Unfortunately, this bias structure could also result from errors in assimilated data (see discussion of BAROCLIM minus ECMWF differences).

We thus write in Sect. 4.1 (Error sources):

Other potential biases associated with the short RO record (e.g., influence of QBO and ENSO) were estimated to be small.

• *What are the consequences of the short period of record? If the data is used as prior information for RO retrievals, what errors will come from the representativeness error in BAROCLIM, and will they matter? Possibly the prior information has most of its impact at upper levels which are relatively insensitive to the relevant climate modes. That would be fortunate, but on the other hand the upper levels are influenced by the auxiliary data from MSIS which is used to generate BAROCLIM.*

Good point! It depends on how BAROCLIM is used in the retrievals. In this paper we show two different ways described at the beginning of Sect. 5 ("Use of BAROCLIM in RO profile retrievals"; the two methods termed Col and SF). The SF method is less sensitive to biases in the climatology because an attempt is made to find a best fit to the data at high altitudes regardless of latitude and season/month (i.e., we take a profile from the climatology that does not necessarily correspond to the latitude and season of the retrieval). We will clarify this in the text 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 con-

ditions 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.

- *The paper doesn't give much information on MSIS, for instance the period of record (which ends in 2000 and thus does not overlap with the F3C period) or the distribution of data sources that go into it. Presumably much of the data comes from incoherent scatter radar stations, but I am not sure how these are distributed over the globe. For the lower troposphere MSIS likely uses data from analysis or reanalysis products, and my impression is that the authors would prefer to have a climatology which is independent of analysis products generated from model-based assimilation systems.*

We did not use the most recent MSIS version (NRLMSISE-00) and we did not use MSIS as is. We used bending angles obtained from forward modeled MSIS refractivities that in turn were based on a modification of the original MSIS-90 model (this work was done in 1995). The details are described in Sect. 2 ("Data"). We will insert the following in the text:

The MSIS-90 model is based on data from several satellites, incoherent scatter radar stations, and rocket probes as well as from tabulations from the Middle Atmosphere Program (MAP) Handbook 16 (Hedin, 1983, 1987, 1991).

We now write in the abstract:

Beside RO bending angles we also use data from the Mass Spectrometer and Incoherent Scatter Radar (MSIS) model (modified for RO purposes) to expand BAROCLIM in a spectral model, which (theoretically) reaches from the surface up to infinity.

In Sect. 6 ("Summary, conclusions, and outlook") we write:

Since mean RO profiles become more noisy above 60 km (in a fractional sense) and are error dominated above 80 km, we used a priori information from the Mass

Spectrometer and Incoherent Scatter Radar (MSIS) climatology modified for RO purposes and . . .

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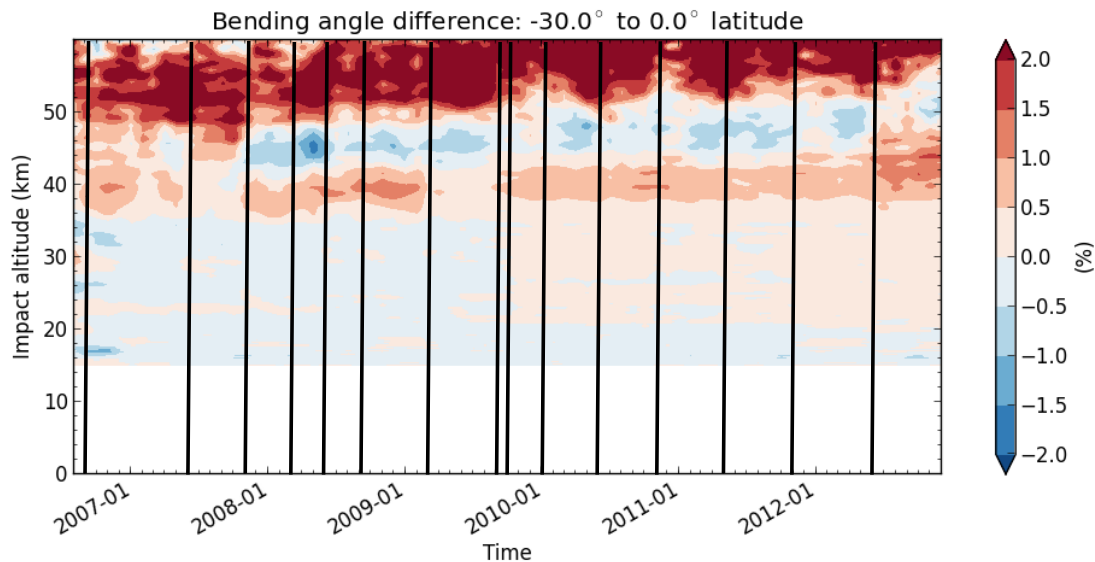**Fig. 1.** RO minus ECMWF differences from August 2006 to December 2012 (BAROCLIM time period) as a function of impact altitude up to 60 km. Black lines indicate IFS cycle changes.
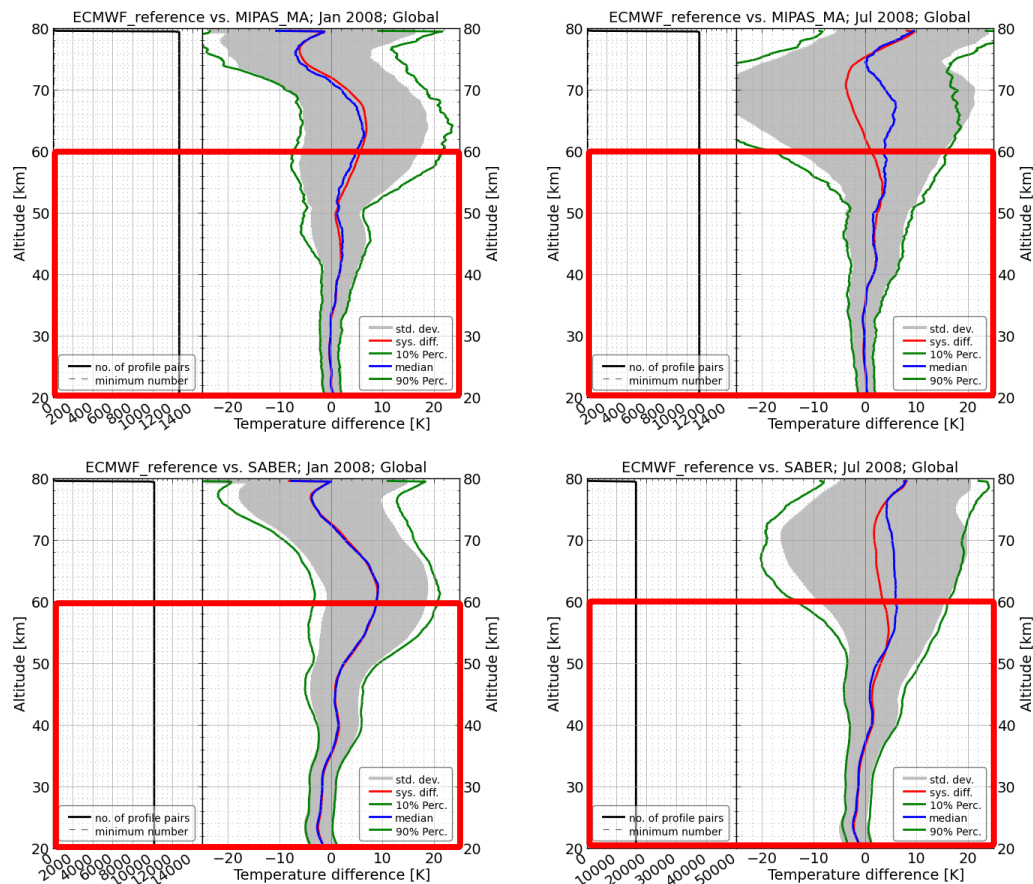
Fig. 2. Global statistics of temperature differences between ECMWF and MIPAS (top) and ECMWF and SABER (bottom) for January 2008 and July 2008. Figure courtesy of Josef Innerkofler, WEGC, October 2014.
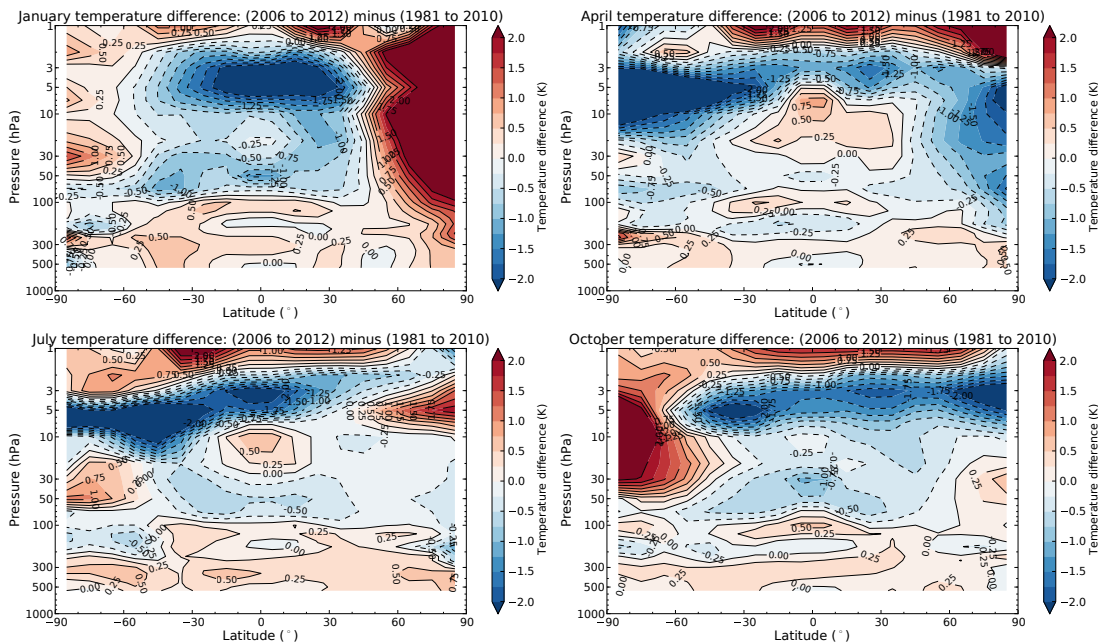
Fig. 3. Temperature difference between mean ERA-Interim temperature from 2006 to 2012 and mean ERA-Interim temperature from 1981 to 2010 as a function of latitude and pressure for different months.