Validation Report: Offline Level 1B bending angle, Level 2A refractivity, Level 2A dry temperature products

Version 1.1

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DOCUMENT CHANGE RECORD

Version	*Date*	*By*	*Description*
Version 1.0	16 March 2020	SSY	Version prepared for the ORR12 review
Version 1.1	15 May 2020	SSY	Updated version implementing the following RIDs from the ORR12 review: – RID 071: Added Annex A: Figures with monthly profile statistics from the internal website. – RID 072: Section 3.1.2: Included a bit more detail about the Metop-A anomaly and provided a reference. – RID 074: Section 3.3: Changes to figures to avoid the removal of the zero grid line near the key box in the plots. – RID 075: Chapter 5: Included a short text at the start of Sections 5.1 and 5.2. – RID 076: Chapter 6: Corrected a typo. – RID 118: Chapter 3: Clarified the use of the two nearest 3-hourly forecasts for time interpolation. In addition the following changes were made: – Section 2.1: Clarified the range of PPF versions used in the validation. – Section 2.2: Included a reference to the previous offline validation. – Chapter 6: Added Section 6.1: Listing a number of limitations relevant for the offline products in general (not exclusively for v1.1).

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing centre under EUMETSAT which is responsible for operational processing of radio occultation (RO) data from the Metop and Metop-SG satellites and radio occultation data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, humidity, and other geophysical variables in near real-time for NWP users, as well as reprocessed Climate Data Records (CDRs) and Interim Climate Data Records (ICDRs) for users requiring a higher degree of homogeneity of the RO data sets. The CDRs and ICDRs are further processed into globally gridded monthly-mean data for use in climate monitoring and climate science applications.

The ROM SAF also maintains the Radio Occultation Processing Package (ROPP) which contains software modules that aid users wishing to process, quality-control and assimilate radio occultation data from any radio occultation mission into NWP and other models.

The ROM SAF Leading Entity is the Danish Meteorological Institute (DMI), with Cooperating Entities: i) European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, ii) Institut D'Estudis Espacials de Catalunya (IEEC) in Barcelona, Spain, and iii) Met Office in Exeter, United Kingdom. To get access to our products or to read more about the ROM SAF please go to: `http://www.romsaf.org`.

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Executive Summary

The ROM SAF offline products are based on Radio Occultation (RO) measurements made by the GRAS instruments onboard the Metop satellites. The Level 1B and 2A data validated in this report consist of individual profiles of bending angle, refractivity, and dry temperature. The profiles have been generated by the ROM SAF from excess phases, amplitudes, and orbit data (Level 1A) provided by the EUMETSAT Secretariat.

The bending angle, refractivity, and dry temperature products are validated by statistical comparisons to reference data, including ERA5 forecasts and ECMWF operational forecasts, as well as the previous version of the offline products. We also verify that the quality is fairly consistent between the three Metop satellites, verifying in particular that the quality of the offline products from Metop-C are on a par with those from Metop-A and Metop-B. In the lower troposphere, comparisons reveal biases in all products for all satellites, which increase to about 3% near the surface at low latitudes.

Based on the comparisons to ERA5 forecasts, we define new Service Specifications for the ROM SAF Level 1B and 2A offline products.

1 Introduction

1.1 Purpose of document

This document describes the validation results for the ROM SAF offline Metop Level 1B and Level 2A products, version 1.1.

The report is submitted for an Operational Readiness Review in order to decide on the operational status of the offline products.

1.1.1 List of offline products being validated in this report

Table 1.1: *List of offline products covered by this report.*

Product ID	Product name	Product acronym	Product type	Operational satellite input	Dissemination means	Dissemination format
GRM-08	Offline Bending Angle	OBAMEA	Offline product	Metop-A Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-46	Offline Bending Angle	OBAMEB	Offline product	Metop-B Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-66	Offline Bending Angle	OBAMEC	Offline product	Metop-C Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-09	Offline Refractivity Profile	ORPMEA	Offline product	Metop-A Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-47	Offline Refractivity Profile	ORPMEB	Offline product	Metop-B Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-67	Offline Refractivity Profile	ORPMEC	Offline product	Metop-C Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-101	Offline Dry Temperature Profile	ODPMEA	Offline product	Metop-A Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-103	Offline Dry Temperature Profile	ODPMEB	Offline product	Metop-B Level 1A data from EUM Secretariat	web	BUFR/netCDF
GRM-105	Offline Dry Temperature Profile	ODPMEC	Offline product	Metop-C Level 1A data from EUM Secretariat	web	BUFR/netCDF

1.2 Applicable and Reference documents

1.2.1 Applicable documents

The following list contains documents with a direct bearing on the contents of this document:

[AD.1] CDOP-3 Proposal: Proposal for the Third Continuous Development and Operations Phase (CDOP-3); Ref: SAF/ROM/DMI/MGT/CDOP3/001 Version 1.2 of 31 March 2016, Ref: EUM/C/85/16/DOC/15, approved by the EUMETSAT Council at its 85th meeting on 28-29 June 2016.

[AD.2] CDOP-3 Cooperation Agreement: Agreement between EUMETSAT and DMI on the Third Continuous Development and Operations Phase (CDOP-3) of the Radio Occultation Meteorology Satellite Applications Facility (ROM SAF), Ref. EUM/C/85/16/DOC/19, approved by the EUMETSAT Council and signed at its 86th meeting on 7 December 2016.

[AD.3] ROM SAF Product Requirements Document, Ref. SAF/ROM/DMI/MGT/PRD/001.

1.2.2 Reference Documents

The following documents provide supplementary or background information, and could be helpful in conjunction with this document:

[RD.1] 46th Meeting of the EUMETSAT STG-OPSWG, Phasing of Metop Satellites: from 3 Metop to 2 Metop, Cover Note, EUM/STG-OPSWG/46/19/DOC/05, 2019.

[RD.2] Burrows, C., Healy, S., and Culverwell, I., Improvements to the ROPP refractivity and bending angle operators, Ref: SAF/ROM/METO/REP/RSR/015, 2013.

[RD.3] Healy, S. B. and Culverwell, I. D., A modification to the standard ionospheric correction method used in GPS radio occultation, *Atmos. Meas. Tech.*, *8*, 3385–3393, doi:10.5194/amt–8–3385–2015, 2015.

[RD.4] ROM SAF, Validation Report: Reprocessed Level 1B bending angle, Level 2A refractivity, Level 2A dry temperature CDR v1.0 products, SAF/ROM/DMI/REP-/ATM/001, 2018.

[RD.5] ROM SAF, WMO FM94 (BUFR) specification for radio occultation data, SAF/ROM/METO/FMT/BUFR/001, 2019.

[RD.6] ROM SAF, Validation Report: Near Real-Time Level 2A Refractivity Profiles: Metop-C (GRM-60), SAF/ROM/DMI/RQ/REP/003, Version 1.1, 2019.

[RD.7] ROM SAF, Algorithm Theoretical Baseline Document: Level 1B Bending angles., Ref. SAF/ROM/DMI/ALG/BA/001, Version 2.0, 2020.

[RD.8] ROM SAF, Algorithm Theoretical Baseline Document: Level 2A Refractivity profiles., Ref. SAF/ROM/DMI/ALG/REF/001, Version 2.0, 2020.

[RD.9] ROM SAF, Algorithm Theoretical Baseline Document: Level 2A dry temperature profiles., Ref. SAF/ROM/DMI/ALG/TDRY/001, Version 2.0, 2020.

1.3 Acronyms and abbreviations

ATBD	Algorithm Technical Baseline Document
BUFR	Binary Universal Format for data Representation

CDOP	Continous Development and Operations Phase
DMI	Danish Meteorological Institute
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	EUMETSAT Polar satellite System
EPS-SG	EPS Second Generation
ERA	European Reanalysis
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite System
GPAC	GNSS RO Processing and Archiving Centre
GRAS	GNSS Receiver for Atmospheric Sounding
ICDR	Interim CDR
IEEC	Institut d'Estudis Especials de Catalunya (Spain)
Metop	Meteorological Operational polar satellites (EUMETSAT)
NCO	Numerically Controlled Oscillator
NRT	Near Real-Time
NWP	Numerical Weather Prediction
QC	Quality Control
RO	Radio Occultation
ROM SAF	Radio Occultation Meteorology SAF (former GRAS SAF)
ROPP	Radio Occultation Processing Package
SAF	Satellite Application Facility (EUMETSAT)
UK	United Kingdom
UKMO	UK Meteorological Office (aka: Met Office)
WMO	World Meteorological Organization

1.4 Definitions

RO data products from the Metop and Metop-SG satellites and RO data from other missions are grouped in *data levels* (Level 0, 1, 2, or 3) and *product types* (NRT, offline, CDR, or ICDR). The data levels and product types are defined below[1]. The lists of variables should not be considered as the complete contents of a given data level, and not all data may be contained in a given data level.

Data levels:

Level 0: Raw sounding, tracking and ancillary data, and other GNSS data before clock correction and reconstruction;

Level 1A: Reconstructed full resolution excess phases, total phases, pseudo ranges, SNRs, orbit information, I, Q values, NCO (carrier) phases, navigation bits, and quality information;

Level 1B: Bending angles and impact parameters, tangent point location, and quality information;

Level 2: Refractivity, geopotential height, "dry" temperature profiles (Level 2A), pressure, temperature, specific humidity profiles (Level 2B), surface pressure, tropopause

[1] Note that the level definitions differ partly from the WMO definitions: `http://www.wmo.int/pages/prog/sat/dataandproducts_en.php`

height, planetary boundary layer height (Level 2C), ECMWF model level coefficients (Level 2D), quality information;

Level 3: Gridded or resampled data, that are processed from Level 1 or 2 data, and that are provided as, e.g., daily, monthly, or seasonal means on a spatiotemporal grid, including metadata, uncertainties and quality information.

Product types:

NRT product: Data product delivered less than: (i) 3 hours after measurement (ROM SAF Level 2 for EPS); (ii) 150 min after measurement (ROM SAF Level 2 for EPS-SG Global Mission); (iii) 125 min after measurement (ROM SAF Level 2 for EPS-SG Regional Mission);

Offline product: Data product delivered from less than 5 days to up to 6 months after measurement, depending on the requirements. The evolution of this type of product is driven by new scientific developments and subsequent product upgrades;

CDR: Climate Data Record generated from a dedicated reprocessing activity using a fixed set of processing software[2]. The data record covers an extended time period of several years (with a fixed end point) and constitutes a homogeneous data record appropriate for climate usage;

ICDR: An Interim Climate Data Record (ICDR) regularly extends in time a (Fundamental or Thematic) CDR using a system having optimum consistency with and lower latency than the system used to generate the CDR[3].

1.5 Overview of this document

Chapter 2 gives the background for the validation, and Chapter 3 contains the validation results. Compliance with product requirements is discussed in Chapter 4, whereas Service Specifications are determined in Chapter 5. Conclusions are made in Chapter 6.

[2] (i) GCOS 2016 Implementation Plan; (ii) `http://climatemonitoring.info/home/terminology`

[3] `http://climatemonitoring.info/home/terminology` (the ICDR definition was endorsed at the 9th session of the joint CEOS/CGMS Working Group Climate Meeting on 29 March 2018).

2 Background

2.1 EUMETSAT data

The validation in this report is based on level 1A data from the NRT environment at the EUMETSAT Secretariat, PPF 4.4–PPF 4.6. The ROM SAF orders these data from the EUMETSAT Data Centre on a monthly basis, and supplements them with occasional missing level 1A data from the NRT stream that are already archived at the ROM SAF.

2.2 ROM SAF processing

The product version number of the offline products validated in this report is 1.1. This reflects an upgrade from the previous version 1.0 (cf. Section 6.3 in [RD.4]), and indicates that all products are processed with the same software.

The offline bending angles, refractivities, and dry temperatures were retrieved at the ROM SAF at DMI using GPAC system version 2.4.0, with ROPP software version 9.0 as a key integral part. Details on the offline processing are described in the ATBDs [RD.7, RD.8, RD.9]. The Quality Control (QC) of the data analysed in this report is done with ROM SAF QC version 0.1.3.

The GPAC system returns the bending angle, refractivity, and dry temperature in both high-resolution (with a vertical spacing of about 100 m in the interval where measurements were made) and in low-resolution (247 pre-defined levels between the surface and 60 km). The high-resolution profiles are written to a netCDF file together with other key parameters. The low-resolution profiles are also stored in a netCDF file, but additionally also in BUFR format. The low-resolution profiles are thinned/interpolated versions of the high-resolution profiles without any smoothing. Each occultation is marked either nominal or non-nominal (same for low- and high-resolution) according to the QC checks described below. The quality flag definitions are given in the WMO FM94 (BUFR) Specification For Radio Occultation Data [RD.5]. For the validation we have used only nominal high-resolution data passing all QC checks.

2.3 Quality control

The QC checks and the limits given below are generally based on many years of experience with the processing of radio occultation data at the ROM SAF. The limits were chosen after careful analyses and consideration in order to flag “bad” profiles while not erroneously flagging too many “good” profiles.

The bending angle products are quality controlled and flagged as non-nominal if one of the following is true:

- Excess phase processing is flagged as non-nominal by the provider
- The L2 quality score is larger than a value of 30 (cf. [RD.7, section 3.2.11])
- Retrieved impact parameter is not monotonically increasing

- There are no valid bending angles below 20 km or above 60 km impact height (valid values are between -0.001 and 0.1 rad)
- Optimized bending angle is different from the background profile used for statistical optimization by more than 5 μrad at any point above 60 km impact height
- Bending angle is different from the bending angle extracted from ERA5 forecasts by more than 90% at any point between 10 km and 40 km impact height
- Refractivity processing is flagged as non-nominal

The refractivity and dry temperature products are quality controlled and flagged as non-nominal if one of the following is true:

- Bending angle processing is flagged as non-nominal
- The factor used for scaling the climatology to fit the data below 40 km is different from 1.0 by more than 8% (cf. [RD.8, section 3.2.1])
- The factor used for scaling the climatology to fit the data above 60 km is different from 1.0 by more than 40% (cf. [RD.8, section 3.2.1])
- The weight given to the climatology in the statistical optimization exceeds 10% at any point below 40 km
- Retrieved altitude is not monotonically increasing
- There are no valid refractivities below 20 km or above 60 km altitude (valid values are between 0 and 500 N-units)
- Refractivity is not positive at all altitudes
- Refractivity is different from the refractivity extracted from ERA5 forecasts by more than 20% at any point below 5 km
- Refractivity is different from the refractivity extracted from ERA5 forecasts by more than 10% at any point between 5 km and 35 km
- Dry temperature is different from the dry temperature extracted from ERA5 forecasts by more than 20 K at any point between 30 km and 40 km

The refractivity and dry temperature are both Level 2A data, and share the same quality flag. We note that the dry temperature is retrieved from the refractivity by ignoring the presence of water vapour. This means that the dry temperature is close to the physical temperature if the water vapour contribution to the refractivity is small, which is generally the case in the upper troposphere and in the stratosphere. In general, dry temperature should be considered a variable in its own right, with sometimes large departures from the physical temperature in the lower troposphere. When comparing to ERA5 forecasts, the ERA5 forward modelled dry temperature is derived from the ERA5 forward modelled refractivity in the same manner as the dry temperature product is derived from the refractivity product (except that the forward modelled dry temperature is constrained by the physical temperature at the top of the model). The forward modeling to bending angle, refractivity, and dry temperature was done with the

ROPP software version 9.0, which include the vertical interpolation approach described in [RD.2].

As seen, all products are essentially subject to the same quality checks since refractivity (and dry temperature) is flagged if bending angle is flagged and vice versa. Thus, the nominal/non-nominal status apply to all of bending angle, refractivity, and dry temperature.

3 Profile comparisons

In this chapter we compare profiles of bending angle, refractivity, and dry temperature from the ROM SAF offline stage processing (GPAC 2.4.0) with reference data[1] from various sources. The monthly profile statistics, should be seen as representative examples serving two purposes:

1. To illustrate the general quality of the offline products
2. To illustrate the difference to previous offline products

The following sections discuss comparisons in a number of ways. In each section, new ways of comparing data are introduced before they may be used again for specific illustrations in the following sections. In all cases we show comparisons for both setting and rising occultations.

In most cases a background is used to give relative differences. This is indicated in the x-label of the plots with (O-B)/B or (O-C)/B. The C symbolizes the reference data that the comparison is against if it is not against a forecast, whereas the B is always either ERA5 forecasts or ECMWF operational forecasts. This is done to avoid divisions by very small numbers (or sometimes negative numbers) when the reference data are not necessarily very smoothly declining at high altitudes.

The references that the offline profiles are compared to are:

- ERA5 forecasts
- ECMWF operational forecasts
- Optimized bending angle
- Previous version of offline product

ERA5 forecasts were extracted from $1^\circ \times 1^\circ$ GRIB files at the reference location of the given occultation (not varying with height), and interpolated to the time of the occultation using the two nearest 3-hourly forecasts (from the same forecast cycle with forecast periods of 3, 6, 9, 12, and 15 hours). ECMWF operational forecasts were also extracted from $1^\circ \times 1^\circ$ GRIB files at the reference location, but not interpolated in time; profiles were extracted only from the nearest 6-hourly forecast (forecast periods of either 6 or 12 hours). In both cases the forecast profiles were forward modelled to bending angle, refractivity, and dry temperature.

Most plots contain three panels showing monthly statistics of the mean difference to the reference, the standard deviation of the difference, and either the vertical correlation of the difference at 15 km with that over the rest of the profile, or the percentage of nominal observations in the lowest 10 km, from which also the reduction at the lowest altitudes can be seen. In the following we refer to the latter as the penetration statistics.

[1] The use of the word 'reference' here and in the following does not imply that these data are necessarily closer to the truth than the occultation data.

The correlation is the ordinary Pearson correlation using relative differences, and is mostly shown for the refractivity products because these are the products where the correlations best reveal possible degradation due to L2-extrapolation in the troposphere, whereas for bending angle and dry temperature, the correlations are only affected to a smaller degree. Although vertical correlations exist at all altitudes, we have chosen to show only the correlation of the difference at 15 km with that over the rest of the profile because possible degradation due to the L2-extrapolation appears to be largest between 10 km and 20 km. Consequently, these curves always peak at 15 km, where the correlation by construction equals one. The number of samples included in the correlation plots is generally different at each level, depending on how far down the profiles reach.

The number of observations only count nominal occultations and is mostly (when given in percent) relative to the total number of profiles that were processed for a given period. These panels are only shown for bending angle, since the numbers are the same for refractivity and dry temperature, only shifting the curves a bit at the bottom due the difference between altitude and impact height. Altitude is the mean sea level altitude, i.e, relative to the geoid. Impact height is the impact parameter with the radius of curvature subtracted.

To limit the number of possible plots in this report, we show the monthly profile statistics for a few months only, and use October 2019 as the baseline month[2]. The quality of the data in these months are considered to be representative of the general quality of the offline products. As a justification for this, Annex A contains plots of monthly global profile statistics from the ROM SAF internal website monitoring for each of the first nine months of 2019.

In the interest of overview when reading this report, and to limit the number of pages, we have chosen to include up to nine plots of monthly profile statistics on each page. This makes the figures quite small, and in some cases it can be difficult to see all details in a paper print-out. However, the resolution in the electronic version of the document should be high enough to see all details on a computer screen.

[2] October was chosen for no particular reason other than it is the last month we have processed with GPAC 2.4.0 for validation of the new offline products

3.1 Comparison across satellites

In this section we show the statistics against ERA5 forecasts for the three different Metop satellites to point out differences and similarities. We use the baseline month (October 2019) and show global statistics as well as statistics separated into latitude bands. These are:

Low latitudes: 30°S to 30°N

Mid latitudes: 60°S to 30°S and 30°N to 60°N

High latitudes: 90°S to 60°S and 60°N to 90°N

The points to be made from this section are that the three Metop satellites show fairly similar statistics in bending angle, refractivity, and dry temperature. The main exception is that Metop-A shows notable bias differences between setting and rising occultations at high altitudes in refractivity and dry temperature. This is not fully understood, but may be related to the anomaly suffered by Metop-A on 30 July 2019. For all three satellites, there are different biases between setting and rising occultations at low altitudes, especially at low latitudes. These are believed to be fundamentally linked to the instruments and their tracking; the differences near the surface at low latitudes are more than 3% in bending angle, which are reflected in refractivity and dry temperature, though with a little smaller magnitudes.

3.1.1 Bending angle

Figure 3.1 shows six plots (each with three panels) of the monthly global profile statistics of bending angle for the three Metop satellites for October 2019. The left plots show the total statistics, whereas the right plots show the statistics separated into setting and rising occultations. The top plots show the statistics for Metop-A, the middle plots for Metop-B, and the bottom plots for Metop-C. Figures 3.2, 3.3, and 3.4 show the same for low, mid, and high latitudes.

The (O-B)/B means are very similar among the three satellites in all latitude bands. However, for all three satelites we see a notable difference between setting and rising occultations in the lower troposphere. These differences are not fully understood, but are believed to be due to the rising not being tracked as low as setting occultations. This is also reflected in the panels showing the number of observations below 10 km. The differences between setting and rising occultations near the surface at low latitudes are more than 3%. In the lowest part of the troposphere (around ~3 km impact height), all satellites are considerably negatively biased against ERA5. The total biases at low latitudes are about 3%. Part of the biases may be related to super refraction in the moist planetary boundary layer, where the signal may be temporarily lost, posing severe challenges for the tracking and the processing. It should be noted, however, that if very sharp negative vertical gradients are detected in the reference model data (here ERA5), the reference below that impact height is not computed, and the comparisons consequently do not include such points.

The (O-B)/B standard deviations are also very similar among the three satellites; it is generally slightly larger for rising than for setting occultations at high altitudes, in particular for Metop-A at mid latitudes.

The percentage of profiles passing the quality control is almost independent of latitude band

and is generally more than 95% for setting occultations, and about 90% for rising occultations; it is a little larger for Metop-A for rising occultations, which is not understood. Generally, the penetration into the lowest few kilometers is a little better for setting than for rising occultations. The sudden decrease in the number of observations below 5 km impact height at high latitudes is related to the Antarctica, where the orography and the ice sheet limit the penetration.

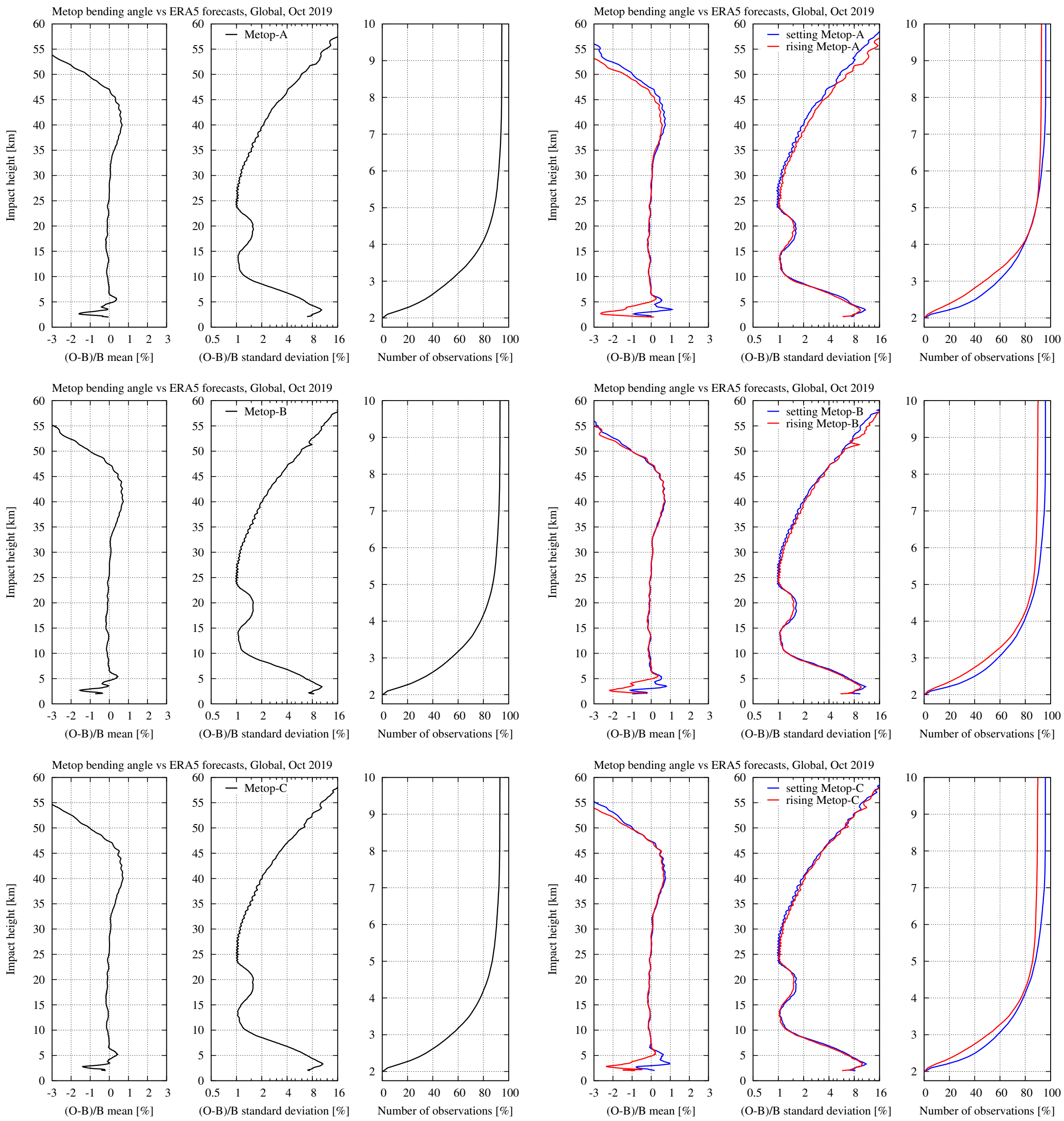

Figure 3.1: *Monthly global profile statistics of bending angle for the three Metop satellites.*

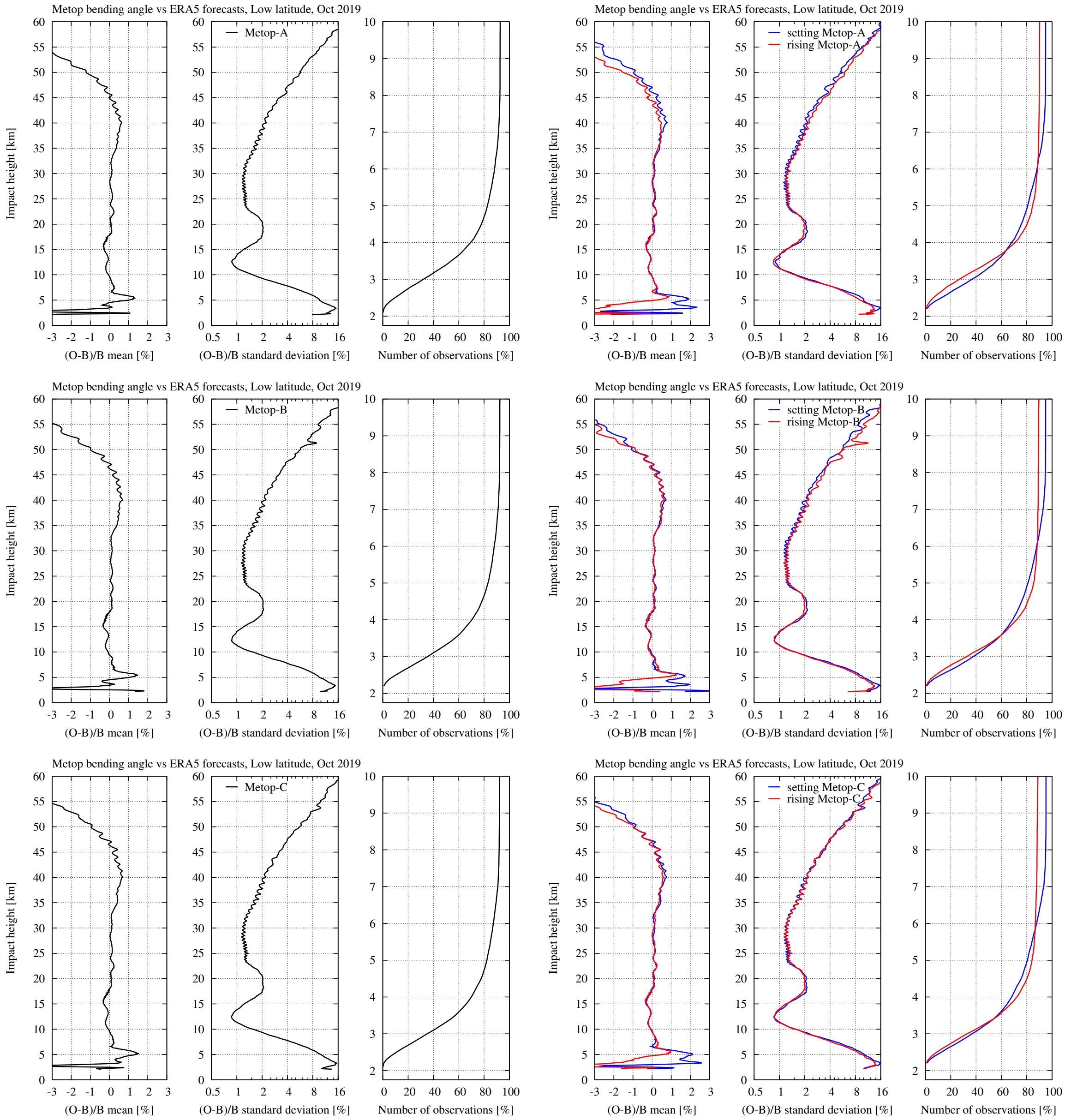

Figure 3.2: *Monthly low latitude profile statistics of bending angle for the three Metop satellites.*

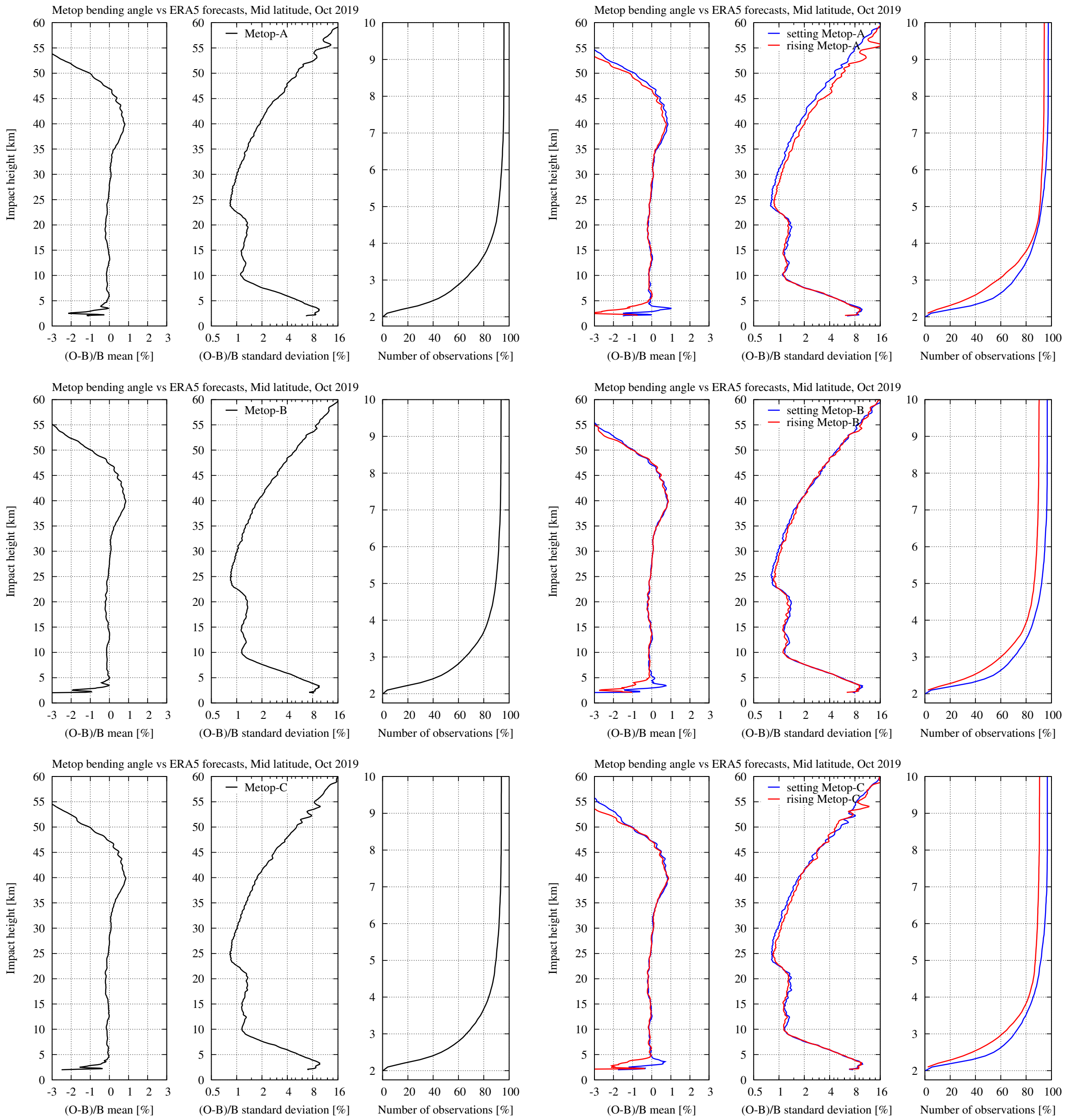

Figure 3.3: *Monthly mid latitude profile statistics of bending angle for the three Metop satellites.*

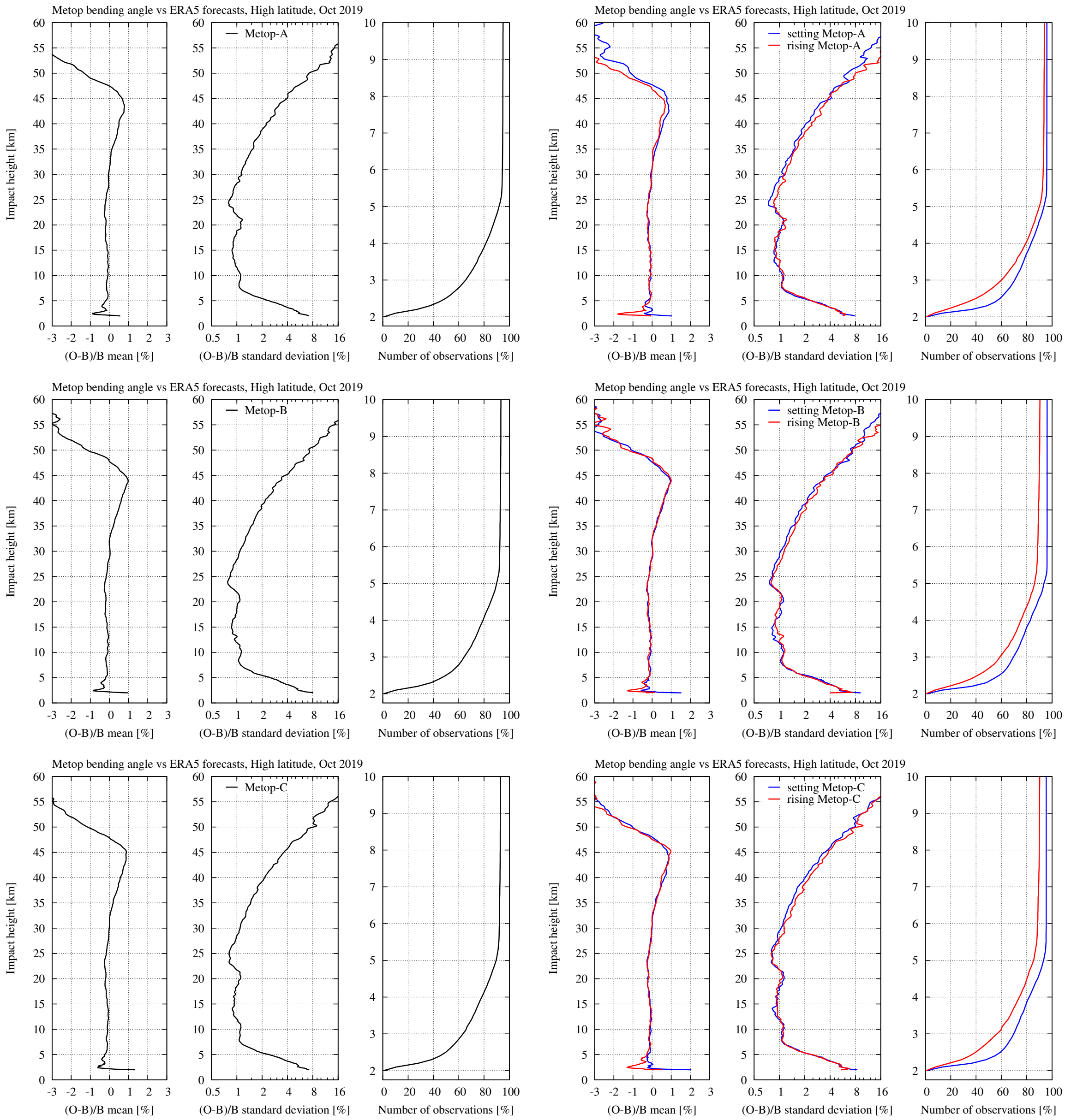

Figure 3.4: *Monthly high latitude profile statistics of bending angle for the three Metop satellites.*

3.1.2 Refractivity

In this subsection we show and discuss the plots for refractivity corresponding to the plots for bending angle in the previous subsection. Figure 3.5 shows the global statistics, whereas Figs. 3.6, 3.7, and 3.8 show the statistics for low, mid, and high latitudes. Instead of the number of observations in the third panel of the plots, we here show the vertical correlations of the difference at 15 km with that over the rest of the profile.

The comments made about the (O-B)/B means for bending angle also apply to the refractivity, although the magnitude percentage wise is a little smaller, and the altitude of the largest biases is below 1 km (as opposed to 3 km impact height). Additionally, Metop-A is slightly differently biased above ~40 km in all latitude bands compared to ERA5, which seems to be coming from slightly more negatively biased rising occultations compared to setting occultations than for the other two satellites. This is not fully understood, but preliminary investigation reveals that there is a slight change in the Metop-A statistics (compared to the other two satellites) since around the time when Metop-A suffered a significant anomaly on 30 July 2019. The Metop-A anomaly resulted in a transition to a thruster controlled mode whereby pointing was maintained by thruster firings, rather than reaction wheels [RD.1]. The Metop-A spacecraft and all instruments were fully recovered by 8 August 2019. Whether this incident is somehow related to the differences seen for Metop-A here is currently unknown.

The (O-B)/B standard deviations between 5 km and 15 km are slightly larger for rising than for setting occultations at high latitudes for all satellites. This is understood to be a consequence of the L2-extrapolation into the troposphere. The larger standard deviation is accompanied by a broadening in the vertical correlations as can be seen in the third panels of the plots. This indicates that differences to ERA5 forecasts are to the same side at adjacent altitudes, and that the error made over a wide vertical range when doing the L2-extrapolation is mostly either positive or negative for a given occultation. The larger standard deviation and vertical correlations at higher latitudes might be interpreted as a larger uncertainty in the extrapolation at higher latitudes.

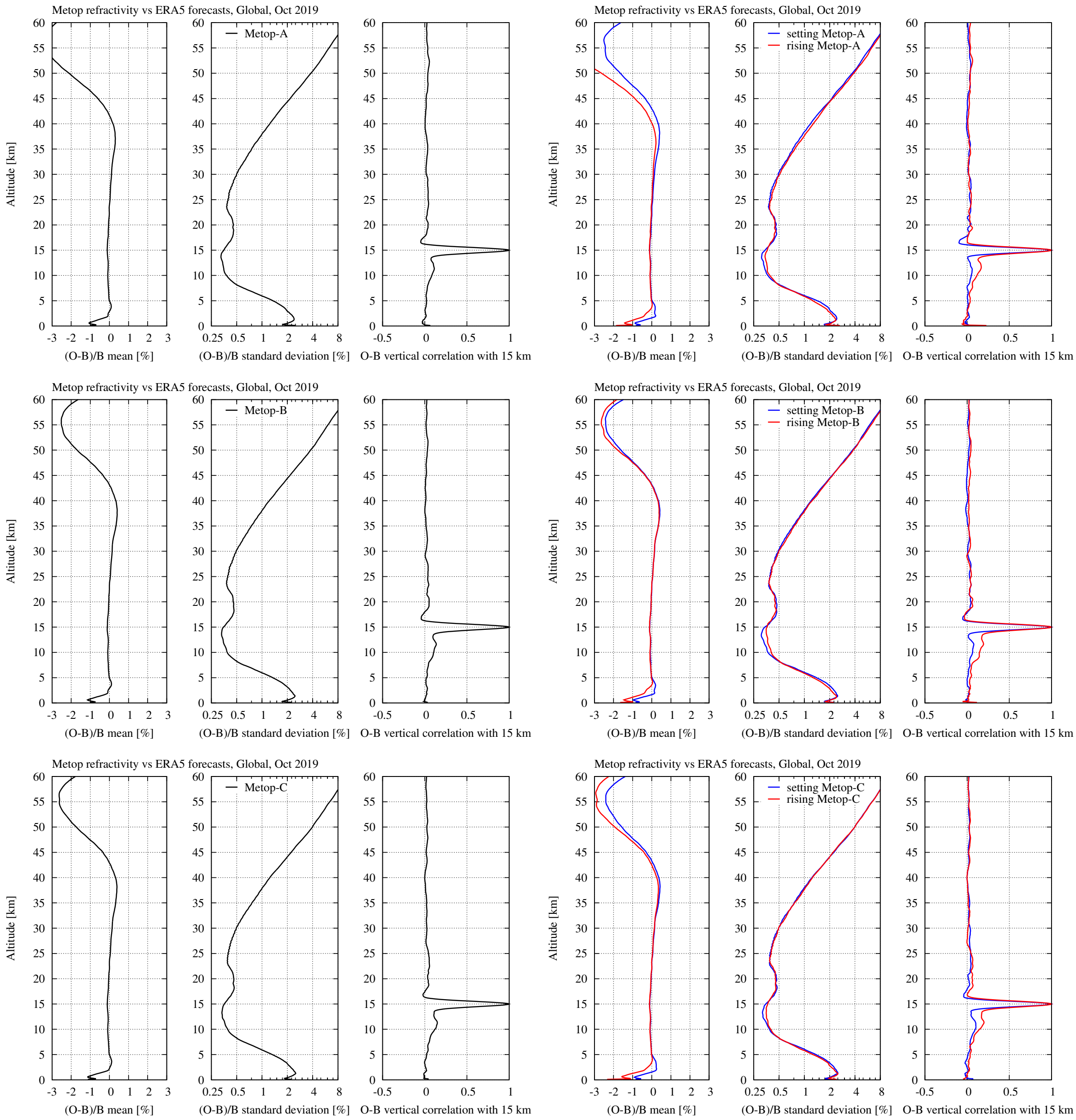

Figure 3.5: *Monthly global profile statistics of refractivity for the three Metop satellites.*

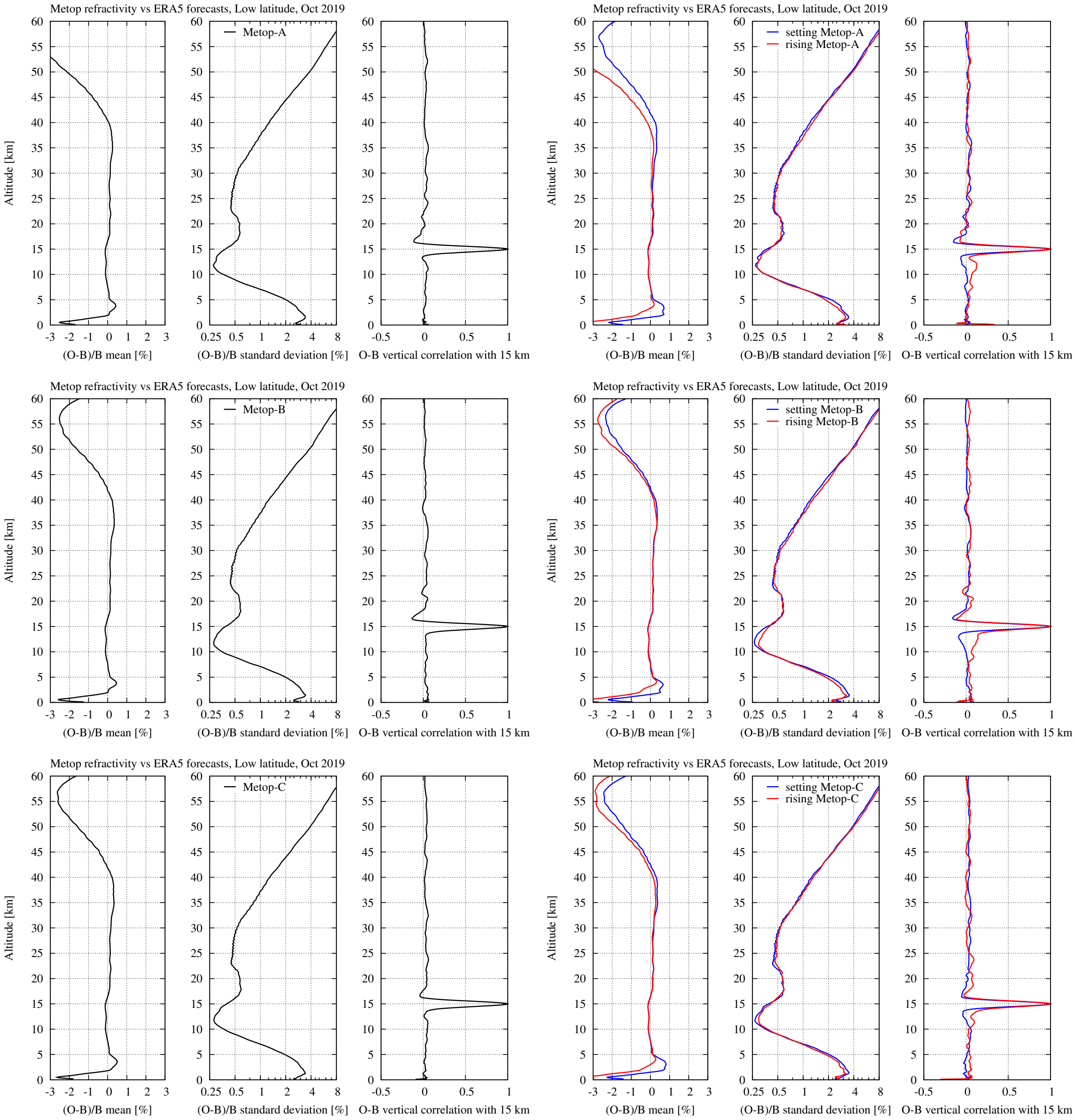

Figure 3.6: *Monthly low latitude profile statistics of refractivity for the three Metop satellites.*

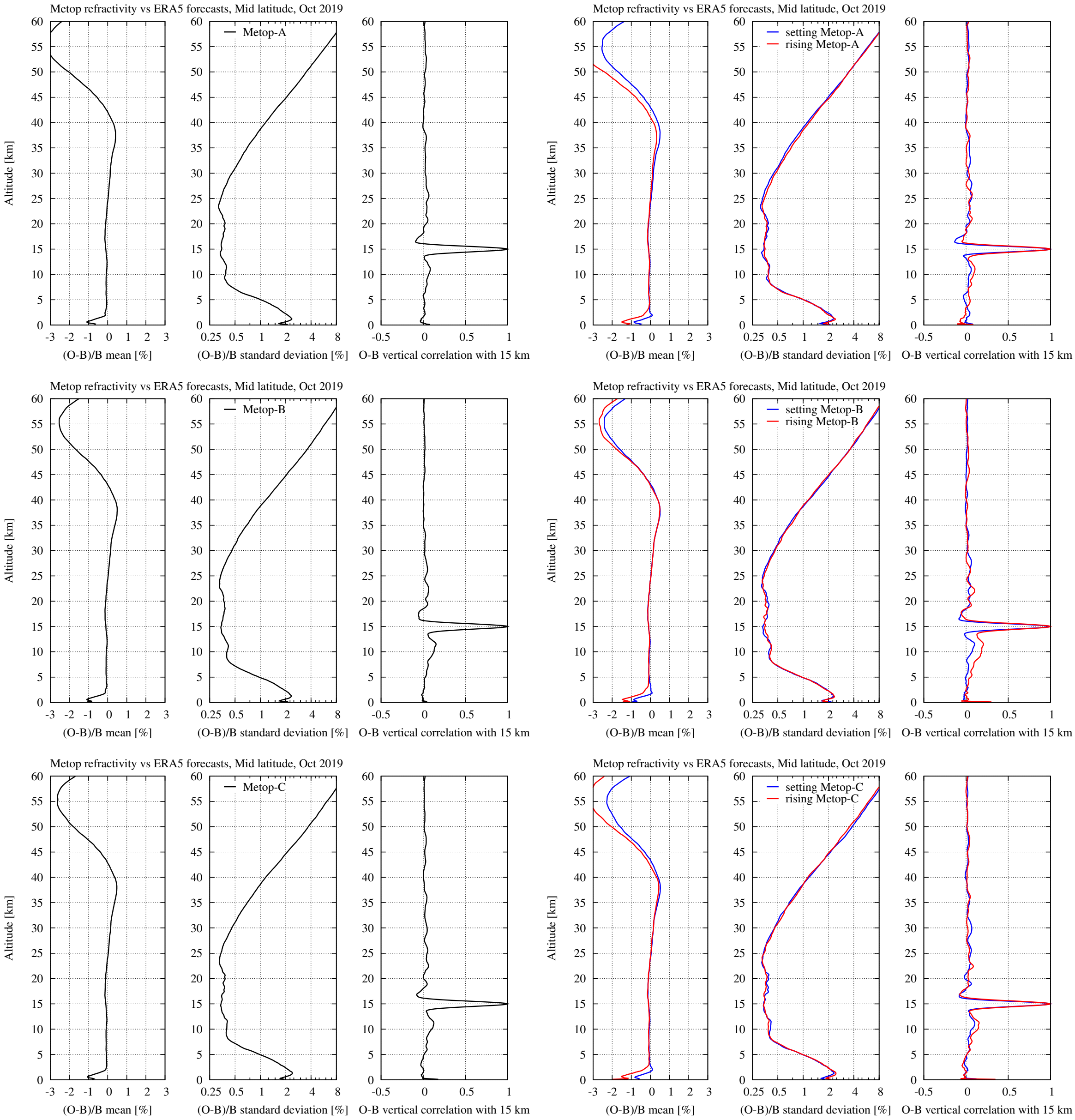

Figure 3.7: *Monthly mid latitude profile statistics of refractivity for the three Metop satellites.*

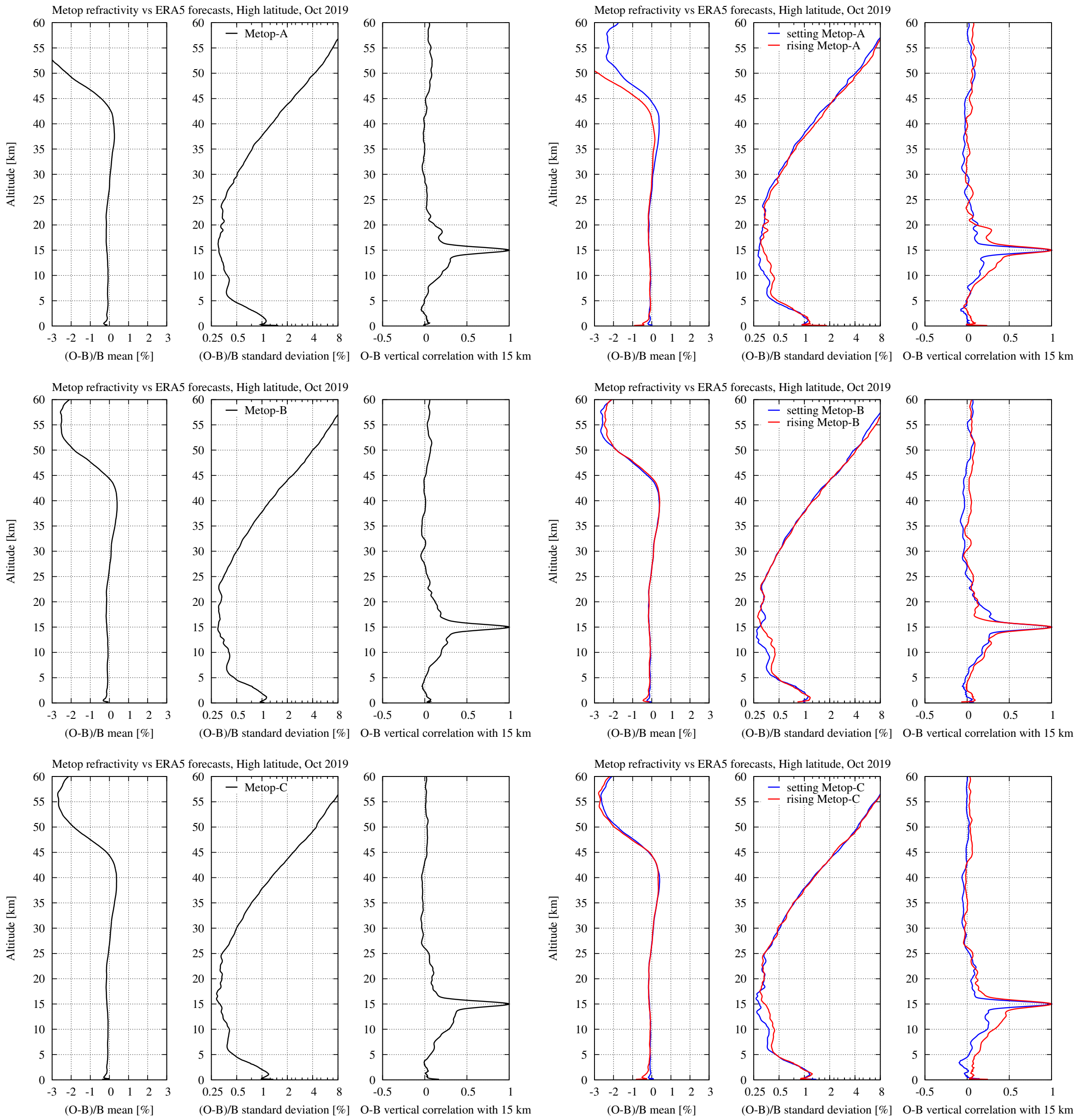

Figure 3.8: *Monthly high latitude profile statistics of refractivity for the three Metop satellites.*

3.1.3 Dry temperature

The plots for dry temperature, corresponding to the plots for bending angle and refractivity in the previous subsections, are shown in Figs. 3.9, 3.10, 3.11, and 3.12 .

The (O-B)/B means are basically a mirror of the ones in refractivity up to about 35 km, being a consequence of the equation relating refractivity (N), dry temperature (T), and dry pressure. The relation leads to $\Delta N/N \approx -\Delta T/T$, as long as the pressure difference is small enough to be ignored. When we here plot O-B for dry temperature, the mirroring to (O-B)/B in refractivity is less obvious, but can still be recognized. The mirroring is discussed more in Section 3.2. The means are fairly similar among the three satellites, although Metop-A is a bit different at high altitudes as already mentioned in the previous subsection. This becomes more evident in dry temperature because the differences propagate to slightly lower altitudes than in refractivity (visible in dry temperature down to about 30 km).

The standard deviations in dry temperature reflect more or less the ones in refractivity, although the effects of the L2-extrapolation are a little smaller than for refractivity. The apparent fact that the dry temperature statistics are less sensitive to the effects of the L2-extrapolation is not understood in detail, but we conclude that it is a consequence of the error propagation from refractivity to dry temperature.

The vertical correlations are somewhat similar for the different satellites. Interestingly, the statistical differences to ERA5 at altitudes above 20 km correlate slightly with the differences at 15 km. Again, the details of this are not understood, but we conclude that it is a consequence of the error propagation from refractivity to dry temperature.

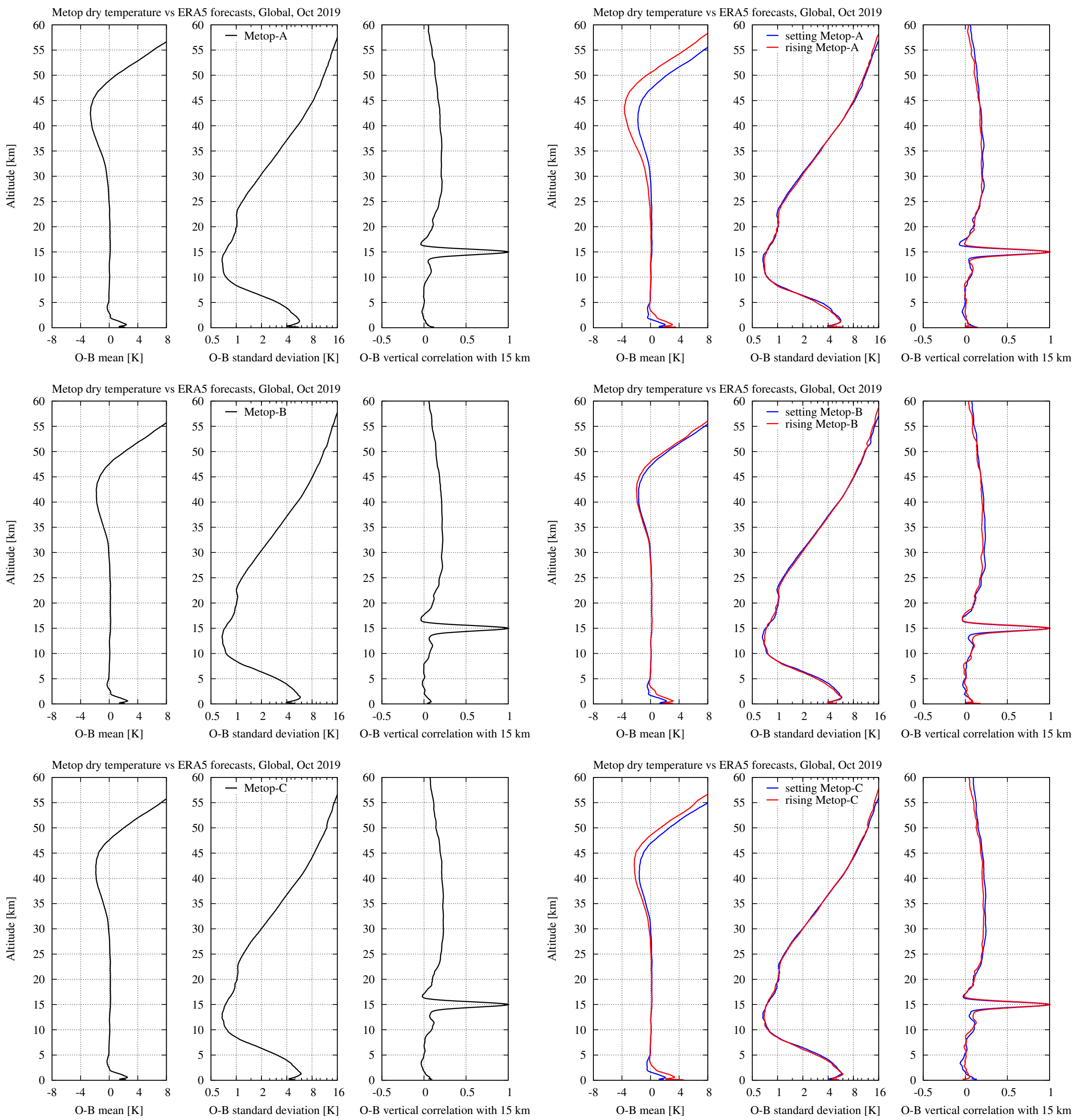

Figure 3.9: *Monthly global profile statistics of dry temperature for the three Metop satellites.*

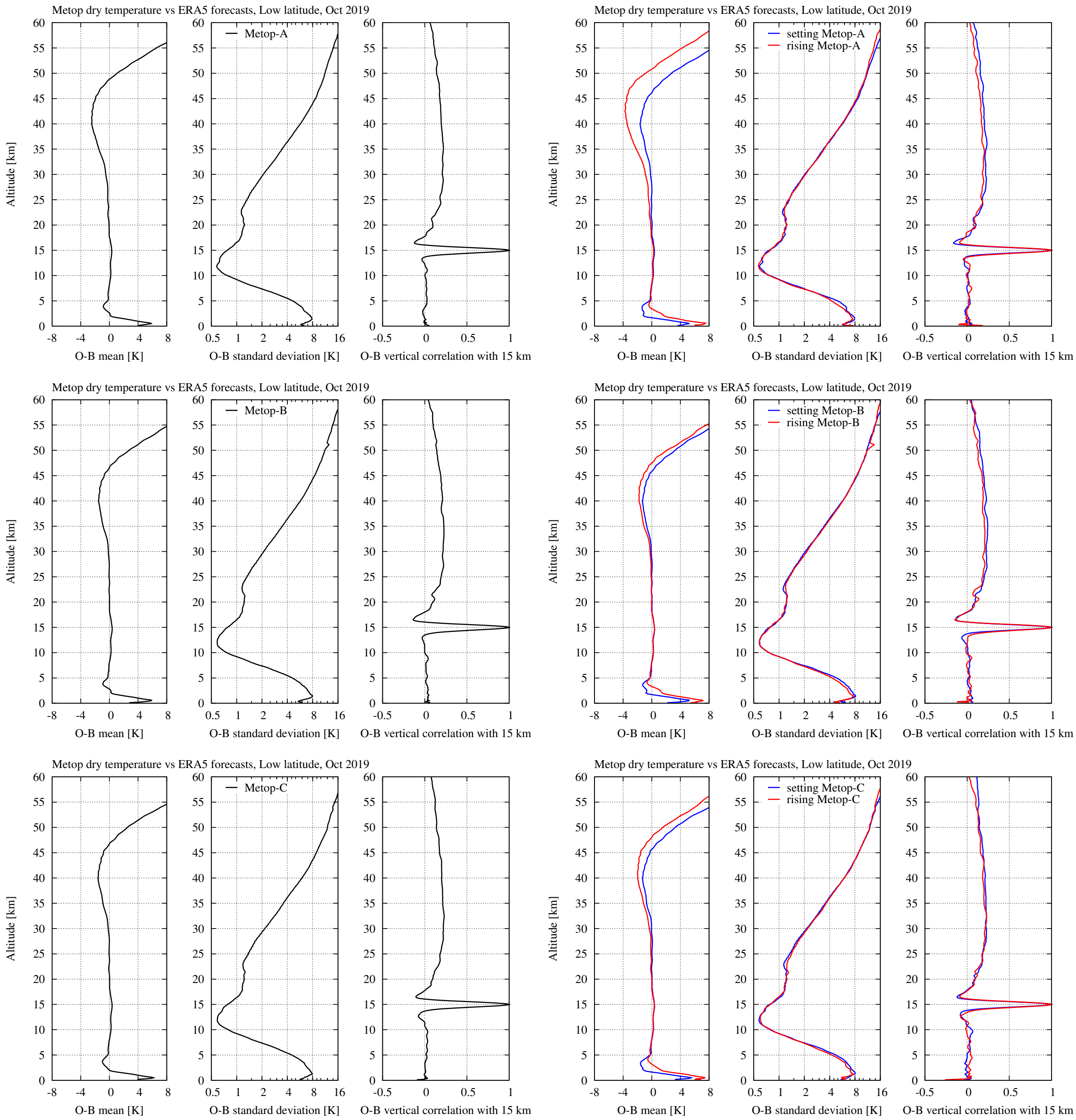

Figure 3.10: *Monthly low latitude profile statistics of dry temperature for the three Metop satellites.*

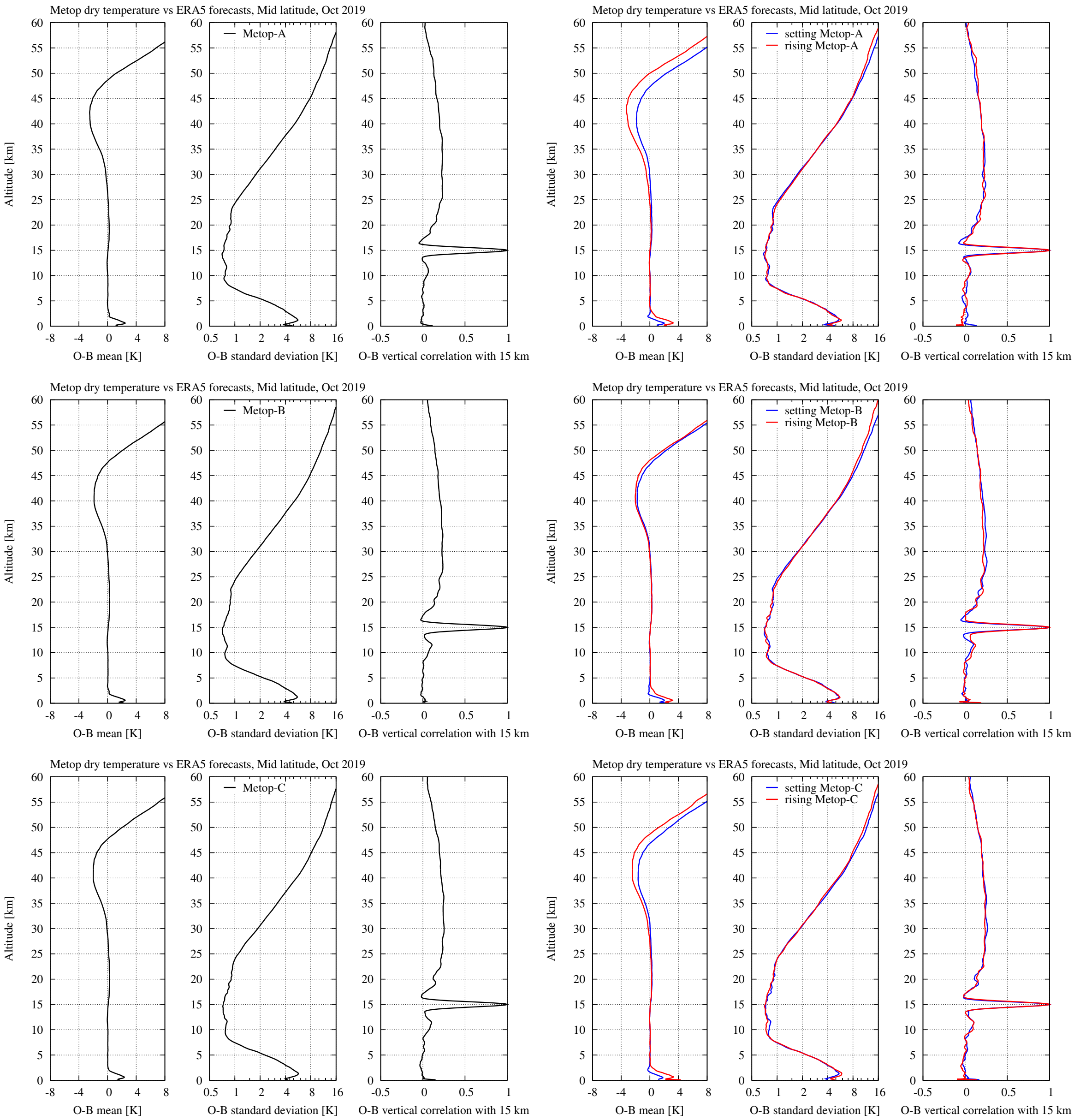

Figure 3.11: *Monthly mid latitude profile statistics of dry temperature for the three Metop satellites.*

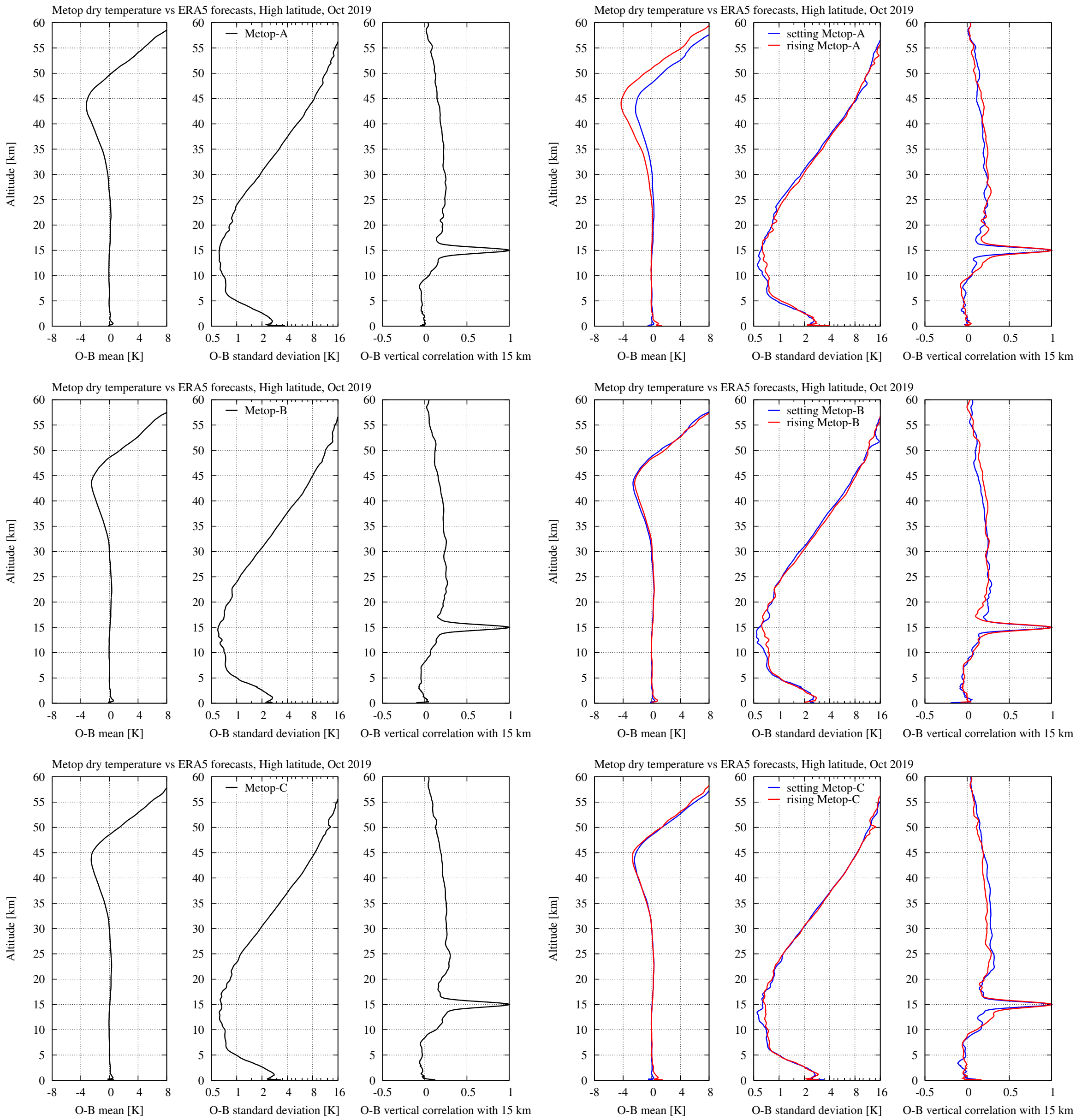

Figure 3.12: *Monthly high latitude profile statistics of dry temperature for the three Metop satellites.*

3.2 Comparison against different background models

The purpose of the statistics shown in this section is to demonstrate that the (O-B)/B mean being different from zero at high altitudes (especially above 30 km), seen in most plots throughout this report, is to a large degree due to systematic biases in the model data (ERA5 forecasts and ECMWF operational forecasts) rather than in the occultation data. We show the statistics for Metop against both ERA5 forecasts and ECMWF operational forecasts and discuss the differences, and also discuss the impact of the statistical optimization on the means and standard deviation.

The points to be made from this section are that comparisons to different forecast models give very different results at altitudes above 30 km. The similarities between the (O-B)/B means of Metop setting and rising occultations, as well as the very small differences in the mean between optimized and non-optimized bending angles up to at least 60 km, suggest that the occultation data in the mean at high altitudes may be more accurate than the models they are compared to. There are no indications that the statistical optimization introduces significant systematic biases below 50 km in the refractivity or dry temperature means.

3.2.1 Bending angle

Figure 3.13 shows the monthly global profile statistics of bending angle when compared to ERA5 forecasts and ECMWF operational forecasts for October 2019 (in the plots labelled ERA5 and ECMWF, respectively), for all three Metop satellites together. The left plots show the total statistics, whereas the right plots show the statistics separated into setting and rising occultations.

The (O-B)/B means above 45 km are quite different for the two background models, indicating that much of the bias at high altitudes could be due to whichever model we compare against. There are also small differences between 15 km and 35 km. The positive bias of more than 0.5% compared to either model around 40 km are believed to be due to a well known bias in the ERA5 and ECMWF operational models in this altitude range [RD.6].

The (O-B)/B standard deviations are notably smaller in the comparisons to ERA5 forecasts around 25–40 km and around 10–15 km, than in the comparisons to ECMWF operational forecasts. However, it should be kept in mind that some of the quality control checks described in Section 2.3 use the ERA5 forecasts as a reference, and it is therefore likely that this, at least in part, is the reason for the smaller standard deviation when comparing the nominal occultations against ERA5.

To illustrate that the statistical optimization does not introduce appreciable biases at high altitudes when going from bending angle to refractivity (via the optimized bending angle), Fig. 3.14 shows the statistics of the bending angle for October 2019 against the optimized bending angle between 40 km and 70 km. The (O-C)/B means (C in the numerator here being the optimized bending angle) up to 60 km are rather small when compared to the means in Fig. 3.13, giving evidence that no systematic bias seems to be introduced in this step, at least not under normal circumstances, and at least not below 60 km impact height. The (O-C)/B standard deviations in Fig. 3.14 reflect that the bending angles at high altitudes are more noisy than the optimized bending angles. Below 40 km (not shown) the means and standard deviations are virtually zero as a result of the downward decreasing weight given to the background used for statistical optimization.

Figure 3.15 shows the statistics for the optimized bending angle against ERA5 and ECMWF operational forecasts, confirming the unaltered means and reduced standard deviations at high altitudes.

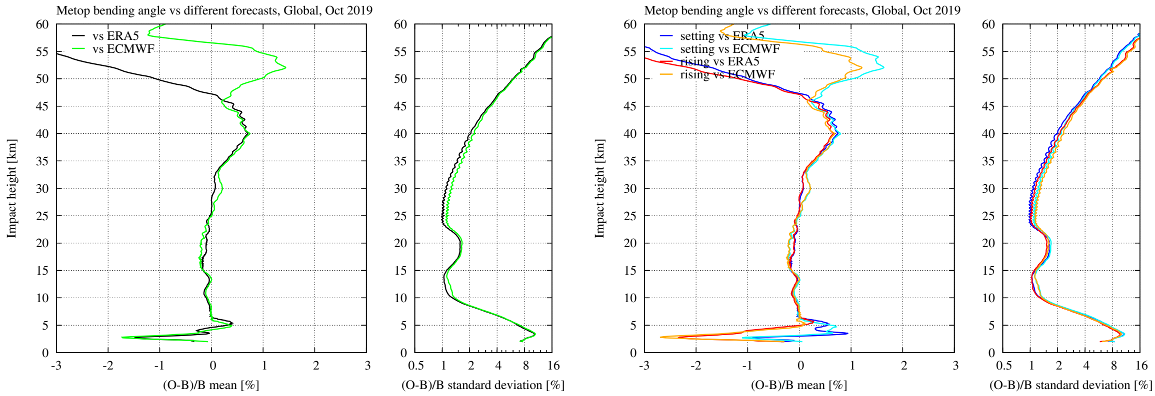

Figure 3.13: *Monthly global profile statistics of bending angle against different forecasts.*

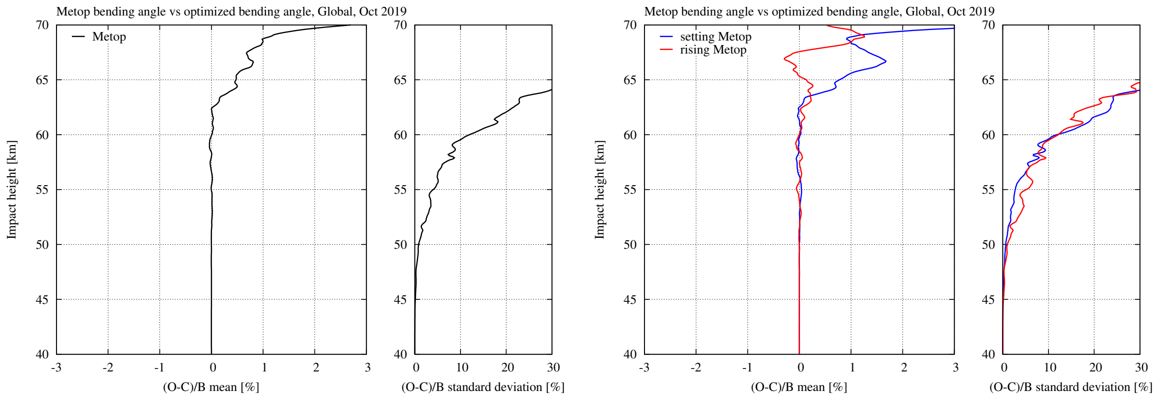

Figure 3.14: *Monthly global profile statistics of bending angle against optimized bending angle.*

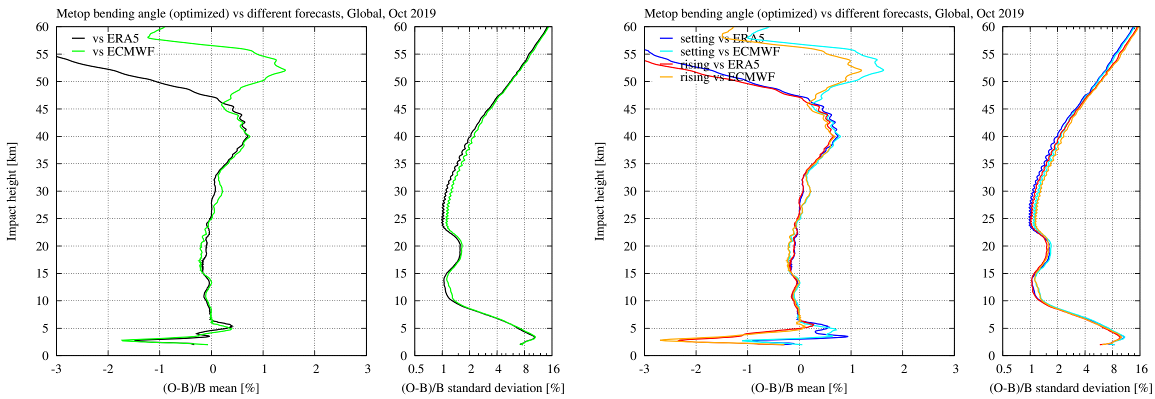

Figure 3.15: *Monthly global profile statistics of optimized bending angle against different forecasts.*

3.2.2 Refractivity

The plots in this subsection (Fig. 3.16) illustrate how the means and standard deviations against both ERA5 forecasts and ECMWF operational forecasts in Fig. 3.15 propagate to refractivity. We note the somewhat similar (O-B)/B means in bending angle and refractivity, and in the light of the smaller differences between the different Metop satellites, setting and rising occultations, as well as the comparisons in Fig. 3.14, we conclude that the means of the offline refractivity products at high altitudes are likely more accurate than the means given by the forecast models.

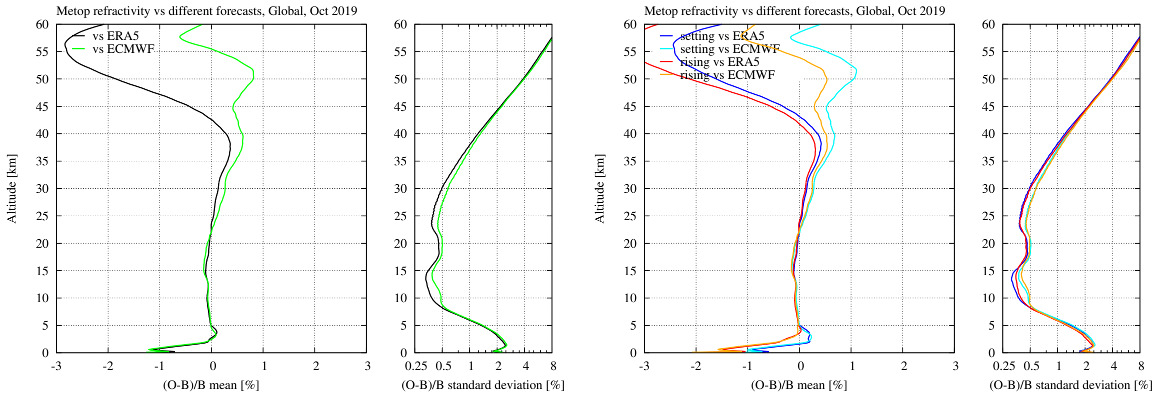

Figure 3.16: *Monthly global profile statistics of refractivity against different forecasts.*

3.2.3 Dry temperature

The plots for dry temperature, corresponding to the plots for refractivity, are shown in Fig. 3.17. The O-B means are basically mirroring those in Fig. 3.16 up to about 30 km. Above 30 km, the mirroring breaks down because the (O-B)/B mean in the dry pressure becomes appreciable. Note that the mirroring would be exact at all altitudes if we were to calculate the dry temperature statistics in percent, and use the derived dry pressure as the vertical coordinate when plotting both refractivity and dry temperature statistics. For reference the corresponding plots for dry pressure are shown in Fig. 3.18.

Although the (O-B)/B mean in dry pressure becomes appreciable above 35 km, (even above 20 km in the comparison against ECMWF operational forecasts) and seemingly contribute to a larger O-B mean in dry temperature above this altitude (at least in comparison against ERA5 forecasts), it should be kept in mind that the temperatures and pressures in the forecast models may be more biased than the occultation data.

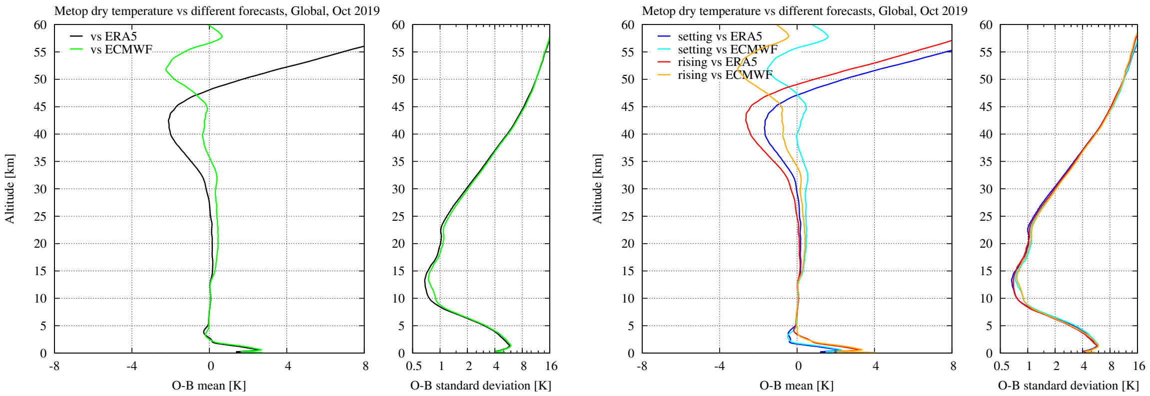

Figure 3.17: *Monthly global profile statistics of dry temperature against different forecasts.*

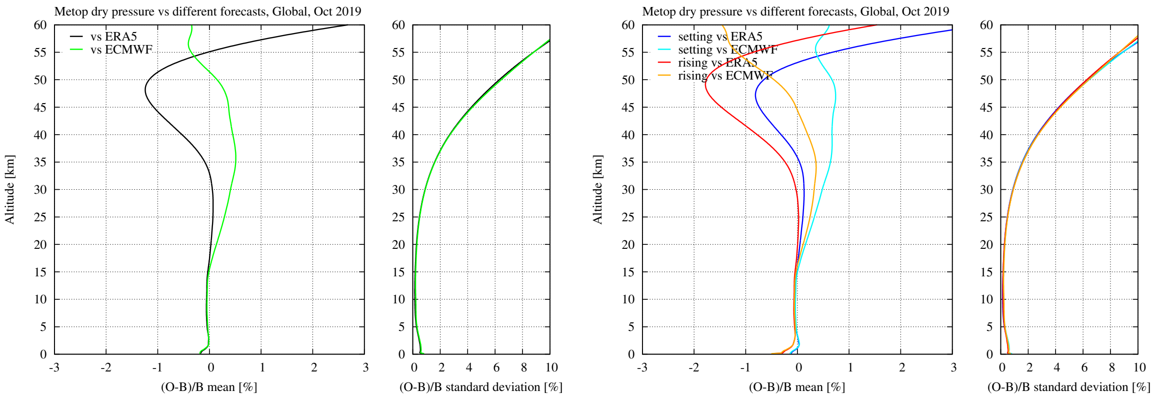

Figure 3.18: *Monthly global profile statistics of dry pressure against different forecasts.*

3.3 Comparison against previous offline products

In this section we look at the statistical comparisons between the offline products v1.1 and the corresponding previous offline products v1.0. Again we show global statistics as well as statistics separated into latitude bands. The previous offline products (v1.0) are available to users from the ROM SAF website for the period January 2017 through July 2019 (`https://www.romsaf.org/oflpage.php?pubmode=pub`). The new offline products (v1.1) will become available to users with the first month being August 2019. For the purpose of validation, though, a beta version of v1.1 has been processed for January 2017 through October 2019, which allows comparisons all the way back to January 2017. Although it is a beta version, we will in the following refer to it as just v1.1. The main difference between v1.0 and v1.1 for the offline bending angle, refractivity, and dry temperature products, is that the v1.1 algorithms include a higher order ionospheric correction [RD.7, RD.8, RD.9] after [RD.3]. Other differences are that v1.1 use ERA5 instead of ERA-Interim for some of the quality control checks, and that it includes Metop-C. For the comparisons here we use only Metop-A and Metop-B data for the months of January 2017 and July 2019 to illustrate the effect of the higher order ionospheric correction at different times in the solar cycle, which peaked in 2014. Thus, the effect should be larger in 2017 than in 2019.

The points to be made from this section are that the offline products v1.1 are more positive at high altitudes (as expected) than the previous offline products v1.0. The mean differences are largest for January 2017 at low latitudes where they are about 0.1%, 0.2%, and 0.5 K at 55 km for bending angle, refractivity, and dry temperature, respectively. The corresponding numbers for July 2019 are about half of those.

3.3.1 Bending angle

Figure 3.19 shows the monthly global profile statistics of bending angle, for the Metop-A and Metop-B satellites together, for January 2017 and July 2019. These are direct comparisons of v1.1 to v1.0 bending angle as a function of impact height between 15 km and 60 km. As in previous sections, the left plots show the total statistics, whereas the right plots show the statistics separated into setting and rising occultations. Figures 3.20–3.22 show the same for low, mid, and high latitudes.

The (O-C)/B means between the two data sets (C in the numerator here being v1.0 data; B in the denominator is the ECMWF operational forecasts) increase nearly exponentially with impact height, reaching about 0.1% at 55 km for January 2017 at low latitudes, where the effect of the higher order ionospheric correction is largest. The mean difference is about half of that for July 2019. The effect is smaller at mid and high latitudes, and less dependent of the solar cycle at high latitudes, where the means for January 2017 and July 2019 are very similar.

The (O-C)/B standard deviations increase similarly with impact height, being a little larger in size than the mean differences, in particular at high latitudes. The small wiggles on the (O-C)/B standard deviations, in particular at high latitudes, are due to a few cases of interpolation differences in the processing of the two data sets in combination with cases where the bending angles themselves have large vertical variability; they are not caused by the higher order ionospheric correction.

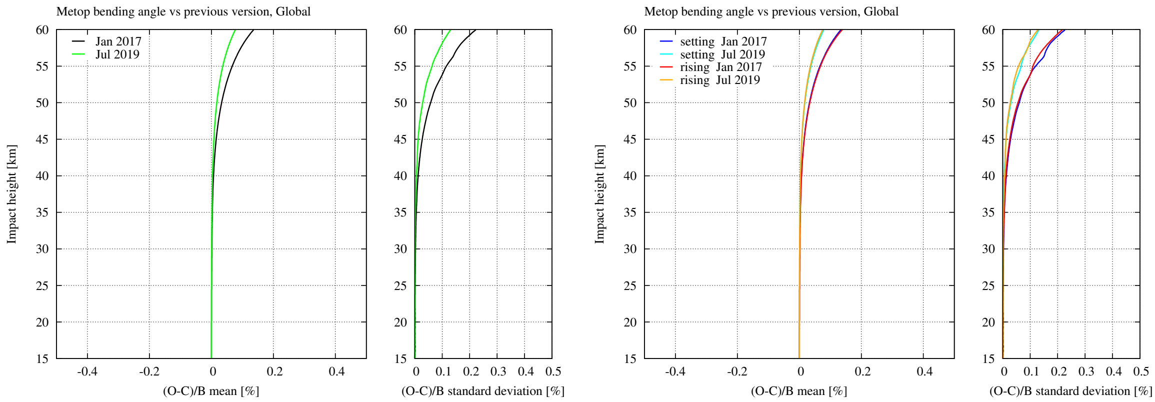

Figure 3.19: *Monthly global profile statistics of bending angle (v1.1) against the bending angle from the previous version (v1.0).*

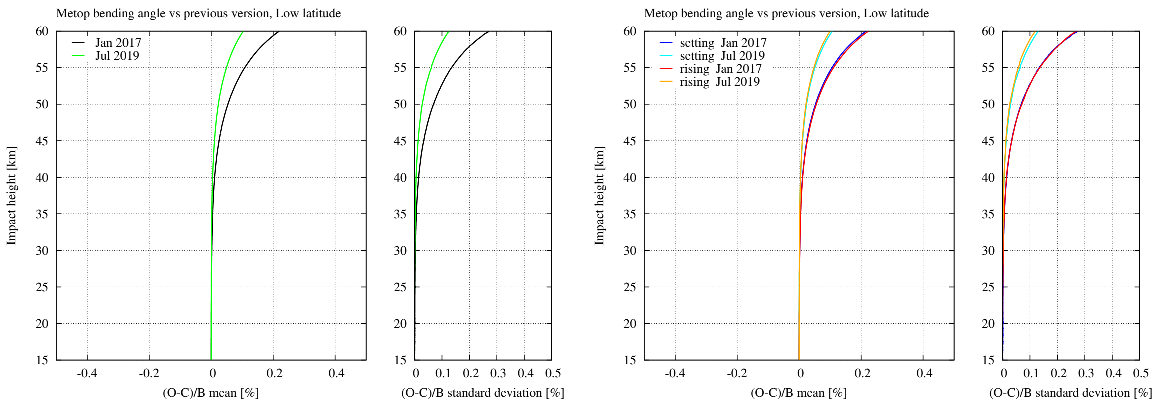

Figure 3.20: *Monthly low latitude profile statistics of bending angle (v1.1) against the bending angle from the previous version (v1.0).*

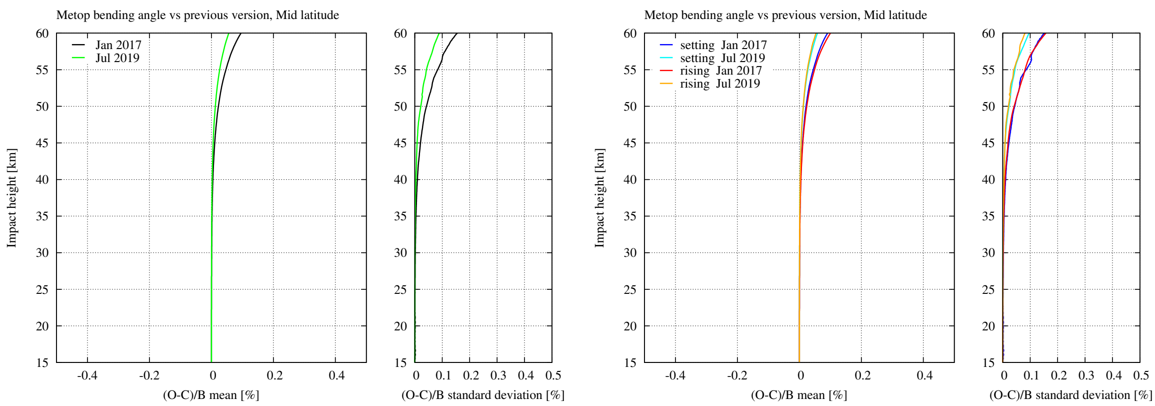

Figure 3.21: *Monthly mid latitude profile statistics of bending angle (v1.1) against the bending angle from the previous version (v1.0).*

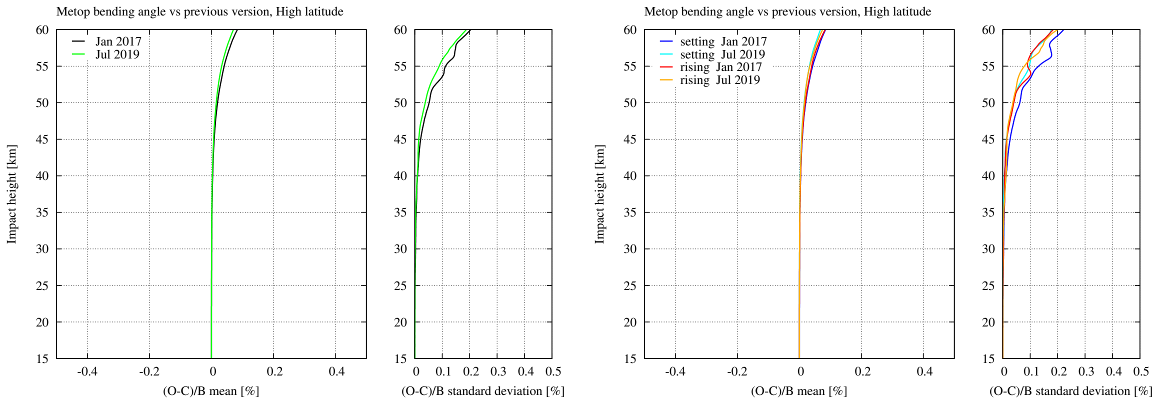

Figure 3.22: *Monthly high latitude profile statistics of bending angle (v1.1) against the bending angle from the previous version (v1.0).*

3.3.2 Refractivity

Figures 3.23–3.26 show the plots for refractivity, corresponding to Figs. 3.19–3.22. Similar comments about the means and standard deviations can be made for refractivity as for bending angle, but the values are somewhat larger percentage wise, reflecting how differences like these propagate from bending angle to refractivity. The (O-C)/B mean is largest at low latitudes, where it reaches 0.2% at 55 km for January 2017.

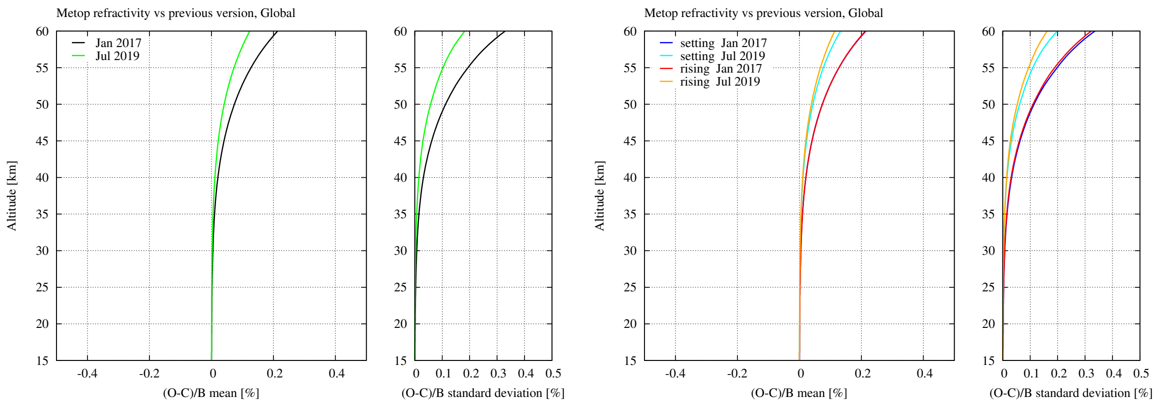

Figure 3.23: *Monthly global profile statistics of refractivity (v1.1) against the refractivity from the previous version (v1.0).*

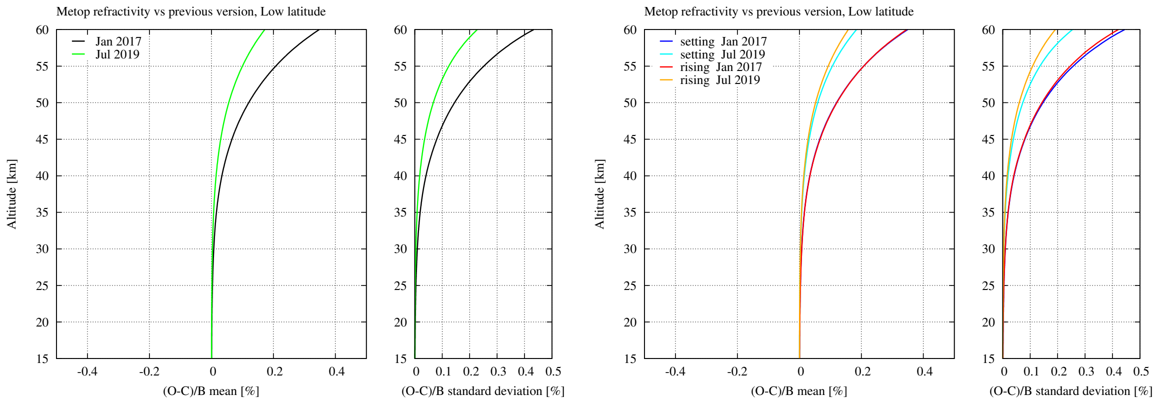

Figure 3.24: *Monthly low latitude statistics of refractivity (v1.1) against the refractivity from the previous version (v1.0).*

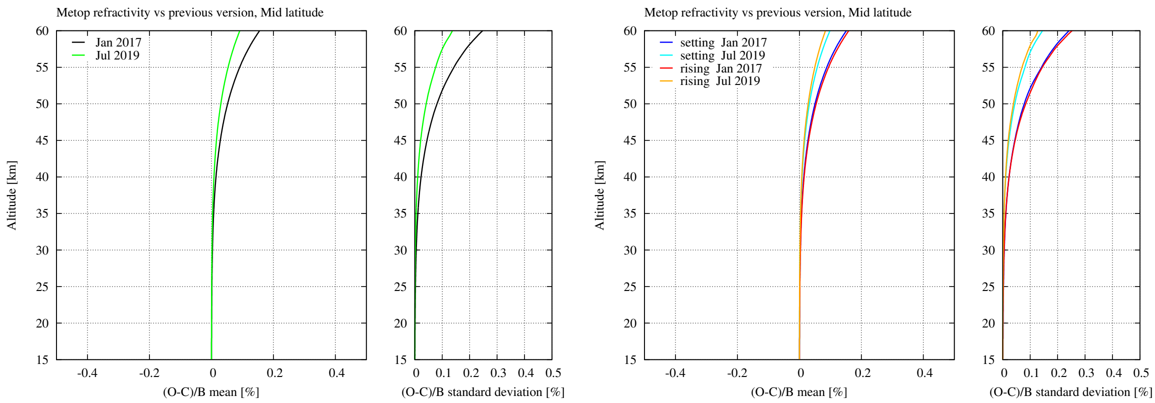

Figure 3.25: *Monthly mid latitude statistics of refractivity (v1.1) against the refractivity from the previous version (v1.0).*

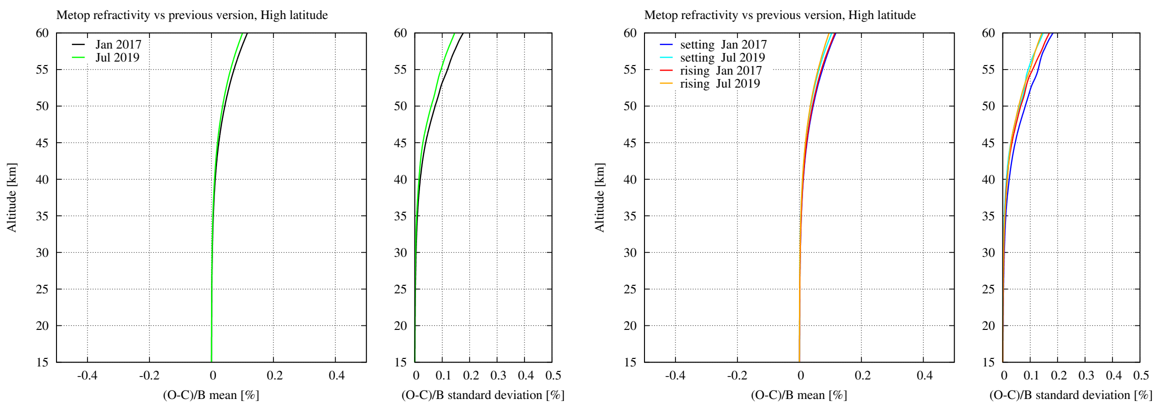

Figure 3.26: *Monthly high latitude statistics of refractivity (v1.1) against the refractivity from the previous version (v1.0).*

3.3.3 Dry temperature

Figures 3.27–3.30 show plots for dry temperature corresponding to the ones for bending angle and refractivity, reflecting how the differences propagate from refractivity to dry temperature. Similar comments can be made for dry temperature as for bending angle and refractivity, although in the case of dry temperature the means and standard deviations do not increase nearly exponentially with altitude all the way up. The (O-C)/B mean is again largest at low latitudes, where it reaches 0.5 K at 55 km for January 2017.

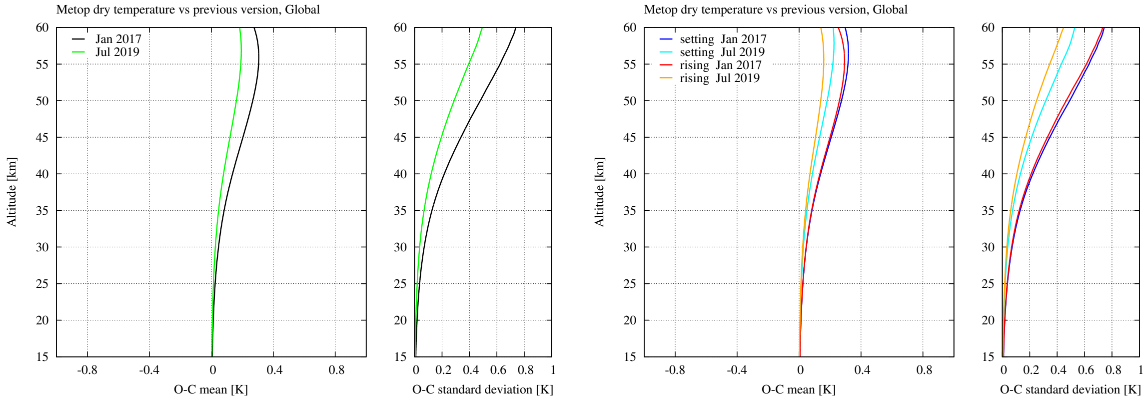

Figure 3.27: *Monthly global profile statistics of dry temperature (v1.1) against the dry temperature from the previous version (v1.0).*

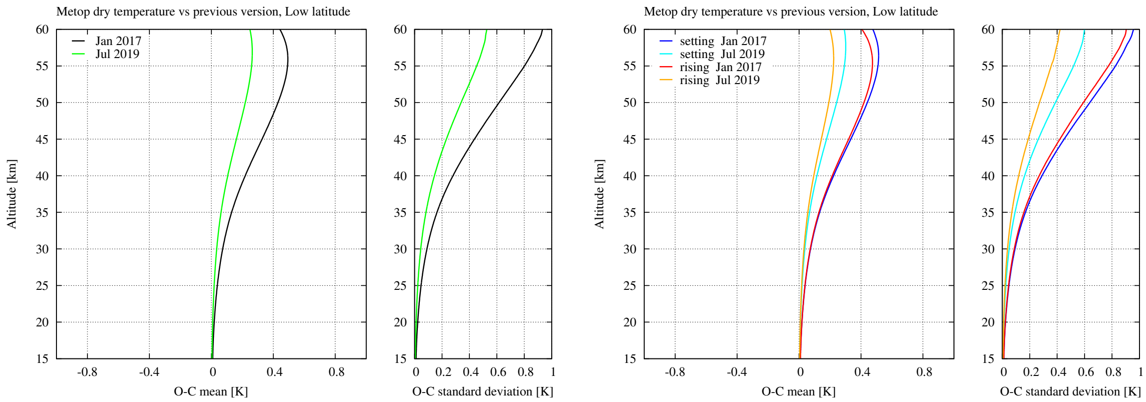

Figure 3.28: *Monthly low latitude statistics of dry temperature (v1.1) against the dry temperature from the previous version (v1.0).*

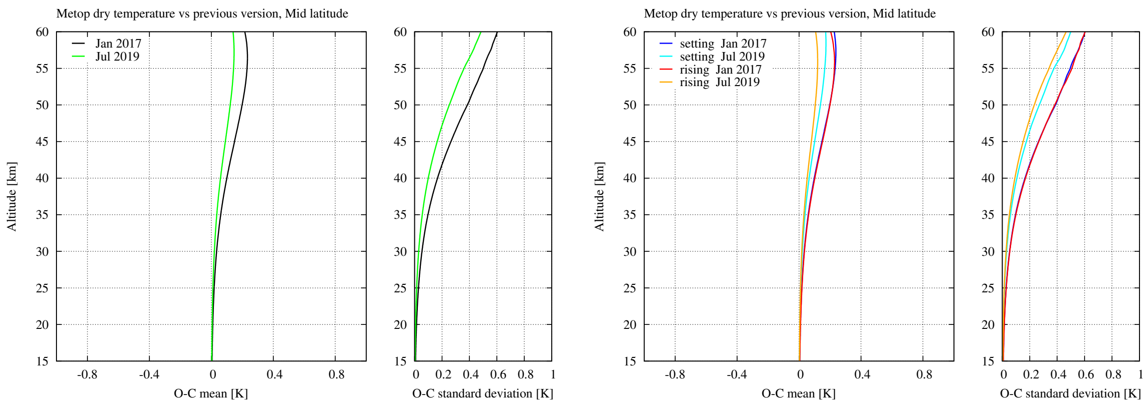

Figure 3.29: *Monthly mid latitude statistics of dry temperature (v1.1) against the dry temperature from the previous version (v1.0).*

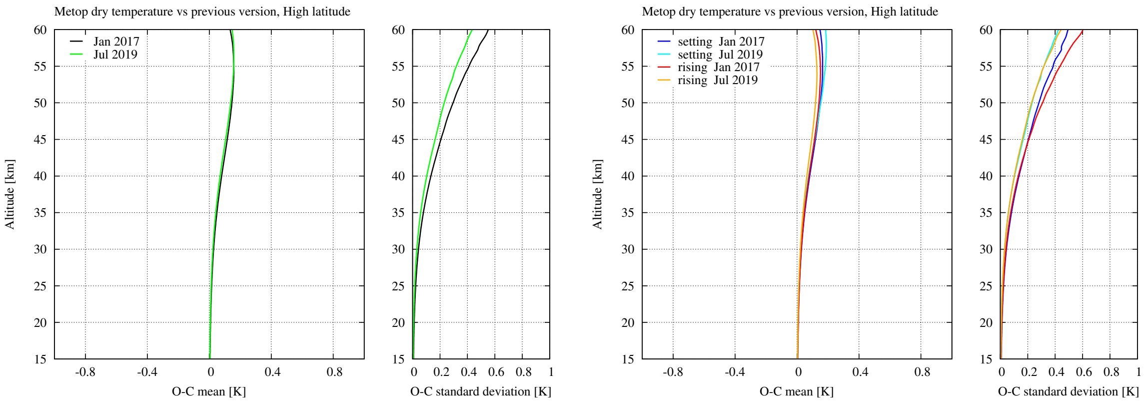

Figure 3.30: *Monthly high latitude statistics of dry temperature (v1.1) against the dry temperature from the previous version (v1.0).*

4 Compliance with Product Requirements

The product requirements are given in tables in [AD.3], and compliance with the product requirements for the previous version of the offline products (v1.0) is visualized in the plots at `https://www.romsaf.org/quality/sesp.php`. The offline products (v1.0 as well as v1.1) are mostly within the requirements, except at low altitudes at low latitudes. However, the current product requirements only concern the standard deviation against ECMWF forecasts (not possible biases), and the numbers are not sufficient to assess whether the products are of state-of-the-art quality. New product requirements for future use, based on the Service Specifications given in Section 5, will be defined at a later time.

5 Service Specifications

In this chapter we give the Service Specifications for the nine products in Table 1.1. The Service Specifications are determined from the so-called ’vertical mean time series’ plots that for the previous version of the offline products can be found at `https://www.romsaf.org/quality/vertical_mean_time_series.php`. Using the drop-down menus at that site, it is possible to inspect a large number of plots for different missions and their individual satellites, for different products compared to both ERA-Interim forecasts and ECMWF operational forecasts, for different latitude bands and hemispheres, and for both setting and rising occultations separately, differenced, or combined. Figures 5.1–5.3 shows the vertical mean plots relevant for the determination of the Service Specifications of the new offline products (v1.1), with the red dashed lines indicating the specification for the previous offline products (v1.0). The reason for the necessity for new Service Specifications is that the specification for the previous offline products were based on comparison to ERA-Interim, which has now been terminated. Thus, the Service Specifications given in the tables in the sections below are based on Figures 5.1–5.3 comparing the offline products (v1.1) against ERA5 forecasts, globally, for setting and rising occultations combined, for all three Metop satellites together. Each figure consists of a number of panels showing the time series of the biases and standard deviations calculated as averages of the monthly statistics over certain vertical intervals. The biases are calculated as the absolute value of the monthly (O-B)/B means (or O-B for dry temperature) and the biases and standard deviations are then averaged over the vertical intervals. The numbers in the tables are determined by visual inspection of these panels, ignoring a few occasional outliers.

It should be emphasized that the Service Specifications are highly reliant upon the comparisons to ERA5 forecasts, and that these in turn are not perfect; they are only approximate representations of the true state of the atmosphere.

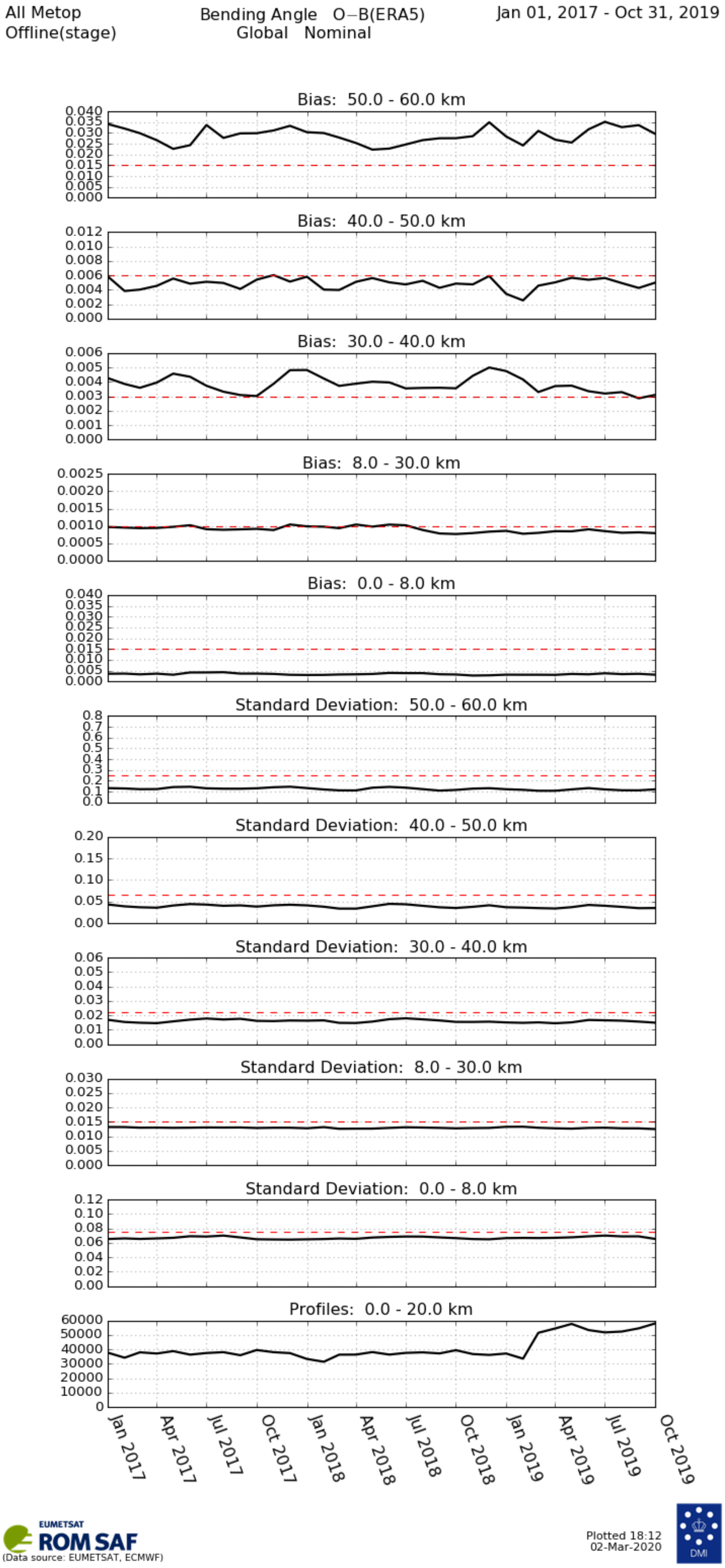

Figure 5.1: *Vertical mean time series for the Metop offline bending angle products (v1.1). The red dashed lines indicate the Service Specifications for the previous products (v1.0).*

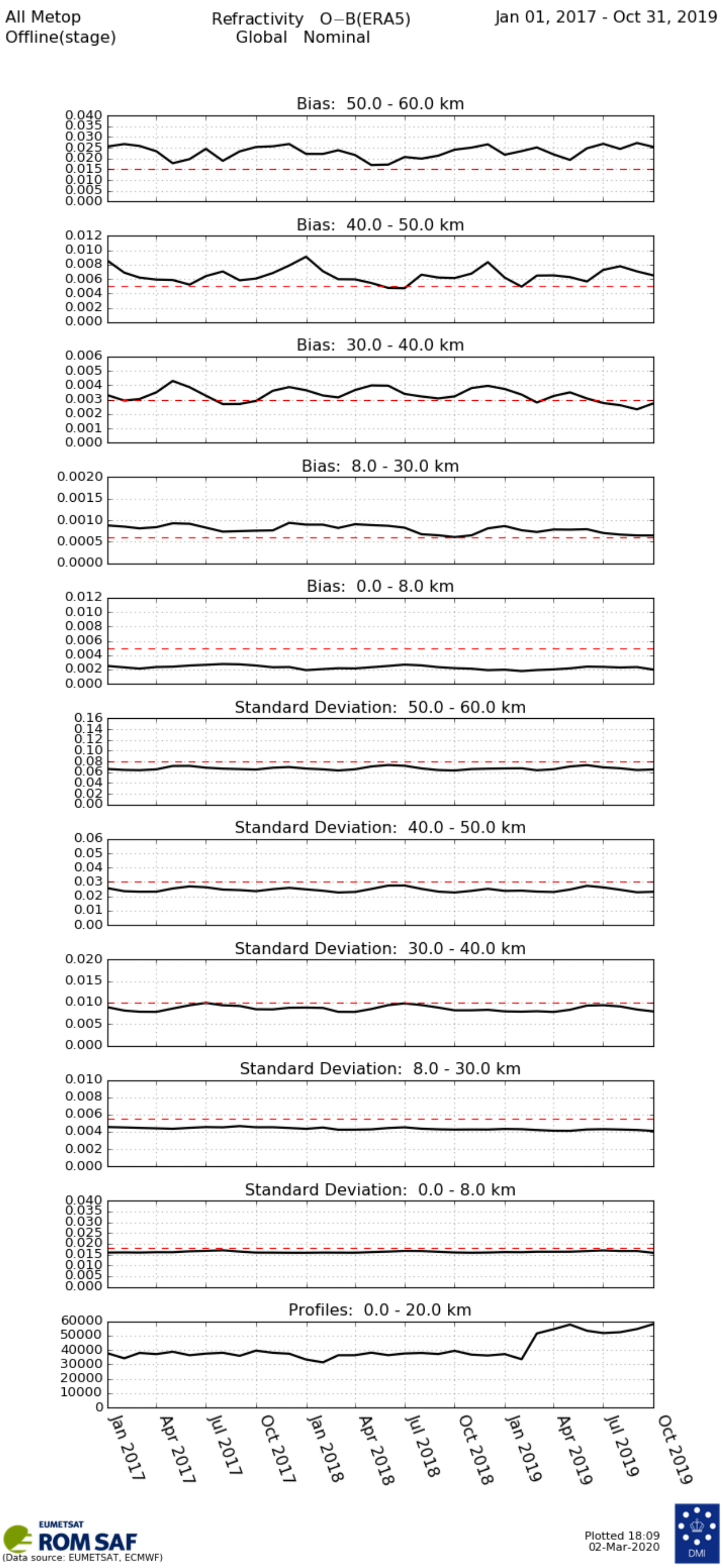

Figure 5.2: *Vertical mean time series for the Metop offline refractivity products (v1.1). The red dashed lines indicate the Service Specifications for the previous products (v1.0).*

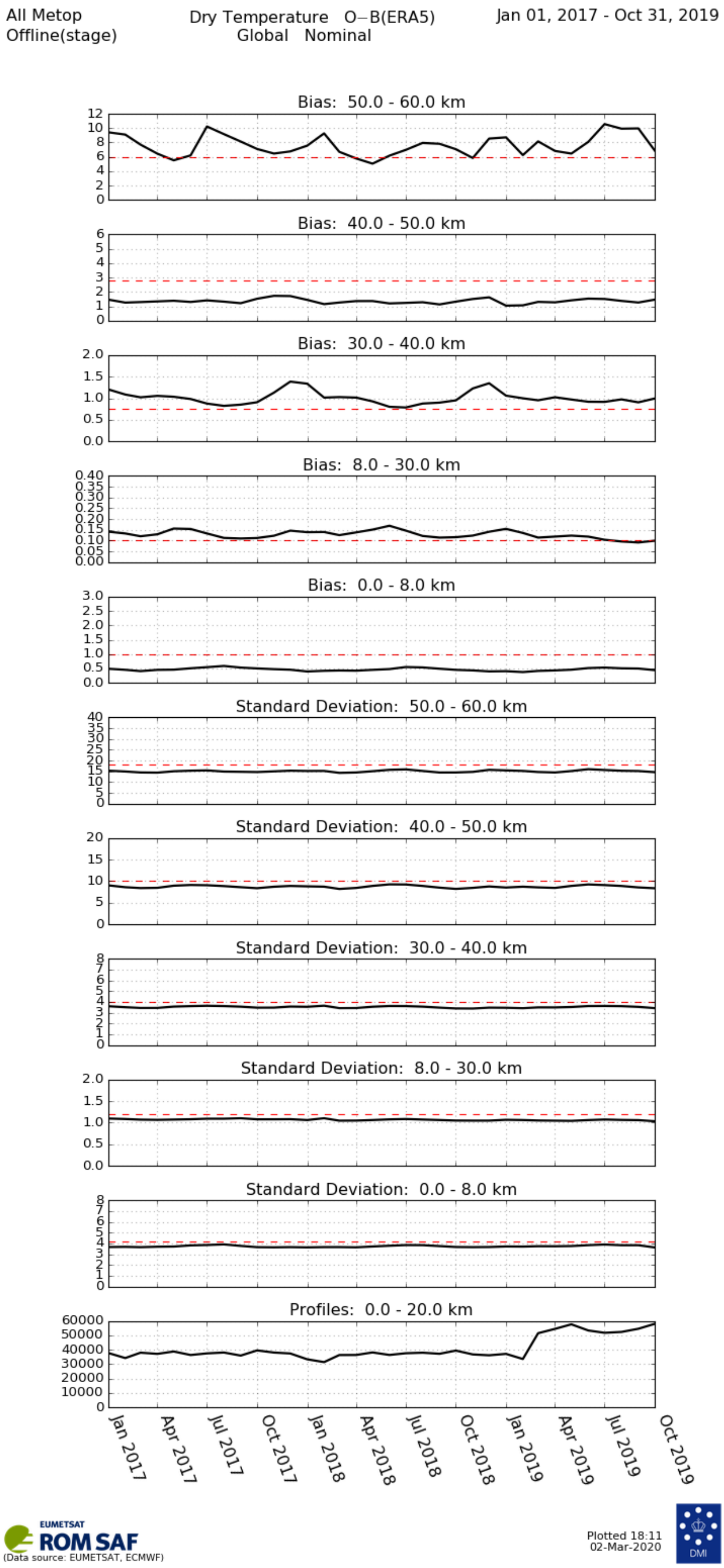

Figure 5.3: *Vertical mean time series for the Metop offline dry temperature products (v1.1). The red dashed lines indicate the Service Specifications for the previous products (v1.0).*

5.1 Bending angle

Table 5.1 gives the new Service Specifications for the Metop offline bending angle products based on the time series in Figure 5.1.

Table 5.1: *Service Specifications for the Metop offline bending angle products v1.1.*

GRM-08 **GRM-46** **GRM-66**	**Offline bending angle (Metop-A)** **Offline bending angle (Metop-B)** **Offline bending angle (Metop-C)**	**OBAMEA** **OBAMEB** **OBAMEC**	
Type	Offline Product		
Applications and Users	Climate and atmosphere researchers		
Characteristics and Methods	Hi-res wave optics retrieval and ionospheric correction		
Operational Satellite Input Data	Metop-A, B, C Level 1A from EUMETSAT Secretariat		
Other Operational Input Data	ECMWF operational and ERA5 FC, AN		
Dissemination			
Format	Means	Timeliness	
netCDF BUFR	Web	30 d	
Service Specification			
Bias	Standard deviation		
0 – 8 km: 0.5 % 8 – 30 km: 0.1 % 30 – 40 km: 0.5 % 40 – 50 km: 0.6 % 50 – 60 km: 3.5 %	0 – 8 km: 7.5 % 8 – 30 km: 1.5 % 30 – 40 km: 2.0 % 40 – 50 km: 5.0 % 50 – 60 km: 15 %		
Notes	The values are based on the comparison to ERA5 forecasts from January 2017 to October 2019.		
Verification/Validation Methods	First calculation of profiles of mean and standard deviation of (Product – ERA5 forecasts). Bias is then calculated as the absolute value of the mean. Bias and standard deviation are then averaged linearly over vertical intervals.		
Coverage, Resolution			
Spatial Coverage	Spatial Resolution	Vertical Resolution	Temporal resolution
global	RO resolution	hi-res wave optics sampling; interpolated to 247 fixed levels	RO resolution

5.2 Refractivity and dry temperature

Table 5.2 gives the new Service Specifications for the Metop offline refractivity and dry temperature products based on the time series in Figures 5.2 and 5.3.

__Table 5.2:__ Service Specifications for the Metop offline refractivity and dry temperature products v1.1.

GRM-09 GRM-47 GRM-67 GRM-101 GRM-103 GRM-105	**Offline refractivity profile (Metop-A) Offline refractivity profile (Metop-B) Offline refractivity profile (Metop-C) Offline dry temperature profile (Metop-A) Offline dry temperature profile (Metop-B) Offline dry temperature profile (Metop-C)**	**ORPMEA ORPMEB ORPMEC ODPMEA ODPMEB ODPMEC**	
Type	Offline Product		
Applications and Users	Climate and atmosphere researchers		
Characteristics and Methods	Statistical optimization, Abel transform, and hydrostatic integration		
Operational Satellite Input Data	Metop-A, B, C Level 1A from EUMETSAT Secretariat		
Other Operational Input Data	ECMWF operational and ERA5 FC, AN		
Dissemination			
Format	Means	Timeliness	
netCDF BUFR	Web	30 d	
Service Specification			
Bias	Standard deviation		
Refractivity Profile			
0 – 8 km: 0.3 % 8 – 30 km: 0.1 % 30 – 40 km: 0.4 % 40 – 50 km: 0.8 % 50 – 60 km: 3.0 %	0 – 8 km: 1.8 % 8 – 30 km: 0.5 % 30 – 40 km: 1.0 % 40 – 50 km: 3.0 % 50 – 60 km: 8.0 %		
Dry temperature Profile			
0 – 8 km: 0.6 K 8 – 30 km: 0.15 K 30 – 40 km: 1.4 K 40 – 50 km: 1.8 K 50 – 60 km: 10 K	0 – 8 km: 4.2 K 8 – 30 km: 1.2 K 30 – 40 km: 4.0 K 40 – 50 km: 10 K 50 – 60 km: 18 K		
Notes	The values are based on the comparison to ERA5 forecasts from January 2017 to October 2019.		
Verification/Validation Methods	First calculation of profiles of mean and standard deviation of (Product – ERA5 forecasts). Bias is then calculated as the absolute value of the mean. Bias and standard deviation are then averaged linearly over vertical intervals.		
Coverage, Resolution			
Spatial Coverage	Spatial Resolution	Vertical Resolution	Temporal resolution
global	RO resolution	hi-res wave optics sampling; interpolated to 247 fixed levels	RO resolution

6 Conclusions

The overall conclusion is that the Level 1B and 2A offline products are of a very high quality, and mostly within the product requirements, except at low altitudes at low latitudes. However, the current product requirements only concern the standard deviation against ECMWF forecasts (not possible biases), and the numbers are not sufficient to assess whether the products are of state-of-the-art quality. New product requirements for future use, based on the determined Service Specifications in this report, will be defined at a later time.

The quality of the offline products is fairly similar among the three Metop satellites, at all altitudes and in all latitude bands. The main exception is that Metop-A shows notable bias differences between setting and rising occultations at high altitudes for the baseline month used for comparisons (October 2019). This is not fully understood, but may be related to the anomaly suffered by Metop-A on 30 July 2019. For all three satellites, there are different biases between setting and rising occultations at low altitudes, especially at low latitudes. These are believed to be fundamentally linked to the instruments and their tracking.

The higher order ionospheric correction, being the main difference from the previous version of the offline products, seems to give results as expected.

The use of ERA5 instead of ERA-Interim in some of the quality control checks is not discernible in the quality of the data, but as a results of the differences between ERA5 and ERA-Interim, new Service Specifications using ERA5 as a reference have been defined.

We conclude that the quality of the Level 1B and 2A offline products is similar to the quality of the corresponding previous offline products, with the addition of the higher order ionospheric correction. The quality of the offline products for Metop-C is on a par with the quality of the offline products for Metop-A and Metop-B.

6.1 Limitations

During the course of the validation of the ROM SAF CDR v1.0 [RD.4], which also included the validation of the offline v1.0 products, a few minor issues appeared. Some of these issues are still relevant for the offline v1.1 products, and in some cases the character of the issues is a little different for the offline products (both v1.0 and v1.1) than for the CDR v1.0 products. These issues are listed below as limitations together with the issues already mentioned above.

Limitations of the ROM SAF offline products are:

- Biases in all products below 8 km impact height (6 km altitude), largest at low latitudes; near the surface at low latitudes, these biases are about 3% in all products when compared to ERA5 forecasts, and different for setting and rising occultations
- A slight change in the Metop-A statistics (compared to Metop-B and Metop-C) since around the time when Metop-A suffered a significant anomaly on 30 July 2019; this seems to come from slightly more negatively biased rising occultations compared to setting occultations, in particular at very high altitudes

- Small systematic biases at high altitudes of order 0.1 μrad in bending angle (and corresponding biases in refractivity and dry temperature), depending on local time and hemispheres, and different for setting and rising occultations; percentage wise, these biases increase with altitude and are for the offline products (which are based on near real-time orbits) about twice as large than for the corresponding ROM SAF CDR v1.0 products (which were based on reprocessed orbits), and also have a seasonal dependence[1]

- Small negative constant biases in rising occultations between 10 km and 20 km, up to about ~0.1% in bending angle and refractivity, and largest in the morning local time; these biases were significantly reduced with the firmware upgrades uploaded to the Metop-A and Metop-B instruments on 1 August 2018; the firmware upgrade was also uploaded to Metop-C before it became operational

- Larger standard deviations and vertical correlations between 10 km and 20 km for rising occultations, mostly so for refractivity, and largest at high latitudes; these larger standard deviations and vertical correlations were also significantly reduced with the firmware upgrades on 1 August 2018

[1] These findings were reported at the 6th Radio Occultation Science Advisory Group meeting on 8 May, 2019 (ftp://ftp.eumetsat.int/out/Presentations/06/12_rosag6_romsafactivity_ssy.pptx), and are supported by the vertical mean time series of the previous offline products at `https://www.romsaf.org/quality/vertical_mean_time_series.php`.

A Annex

A.1 Monthly profile statistics for the first nine months of 2019

The following figures are taken from the ROM SAF internal website monitoring, and are based on the ROM SAF offline stage processing (GPAC 2.4.0) used for the validation in this report. They serve to illustrate the similarity in the statistics against ERA5 forecasts for different months, and justify the good representativeness of using a few months for the more in depth comparisons in this report. They all show global statistics for each of the first nine months of 2019. Figure A.1 shows the statistics for bending angle, Figure A.2 for refractivity, and Figure A.3 for dry temperature.

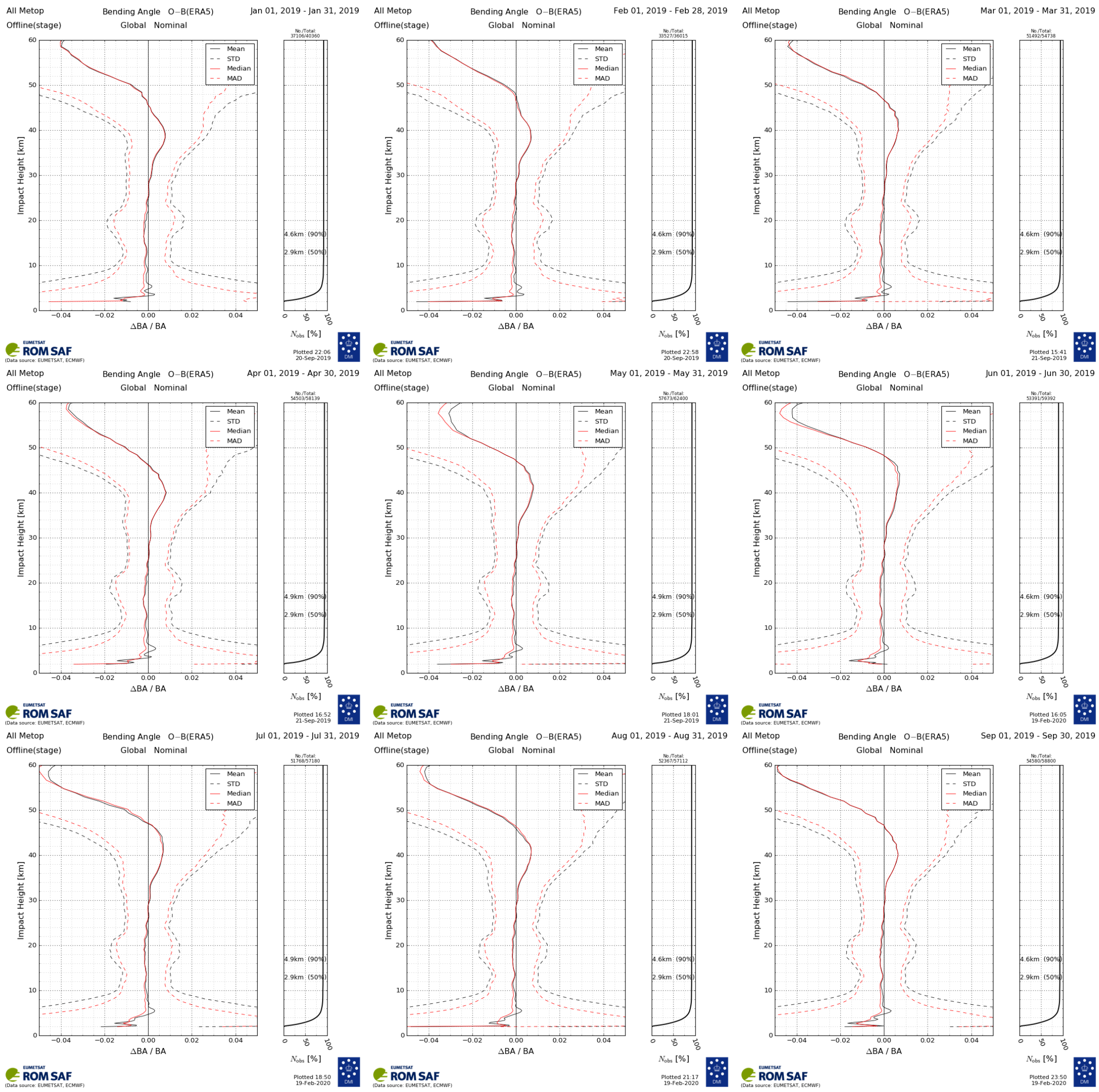

Figure A.1: *Monthly global profile statistics of bending angle against ERA5 forecasts*

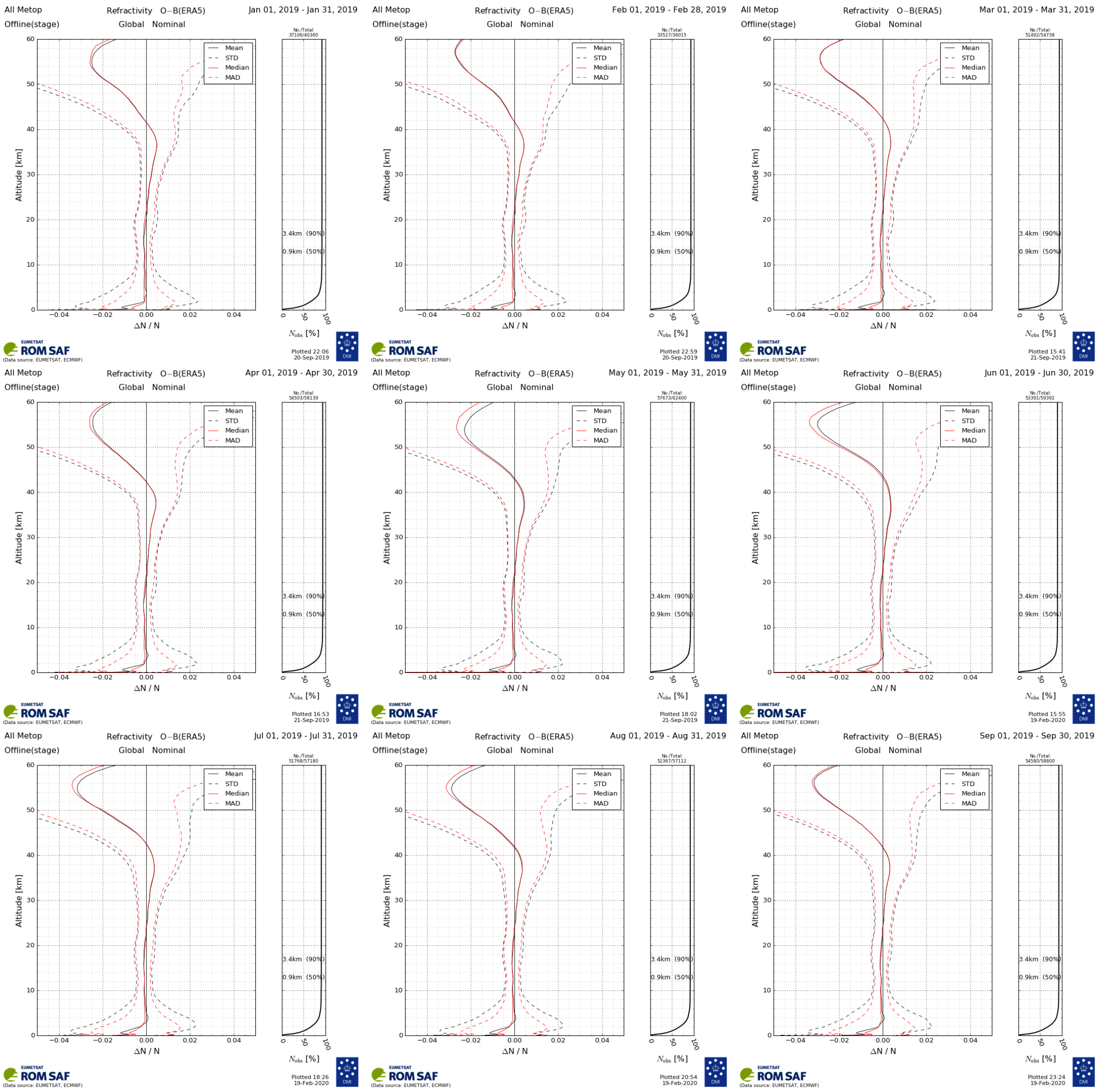

Figure A.2: Monthly global profile statistics of refractivity against ERA5 forecasts

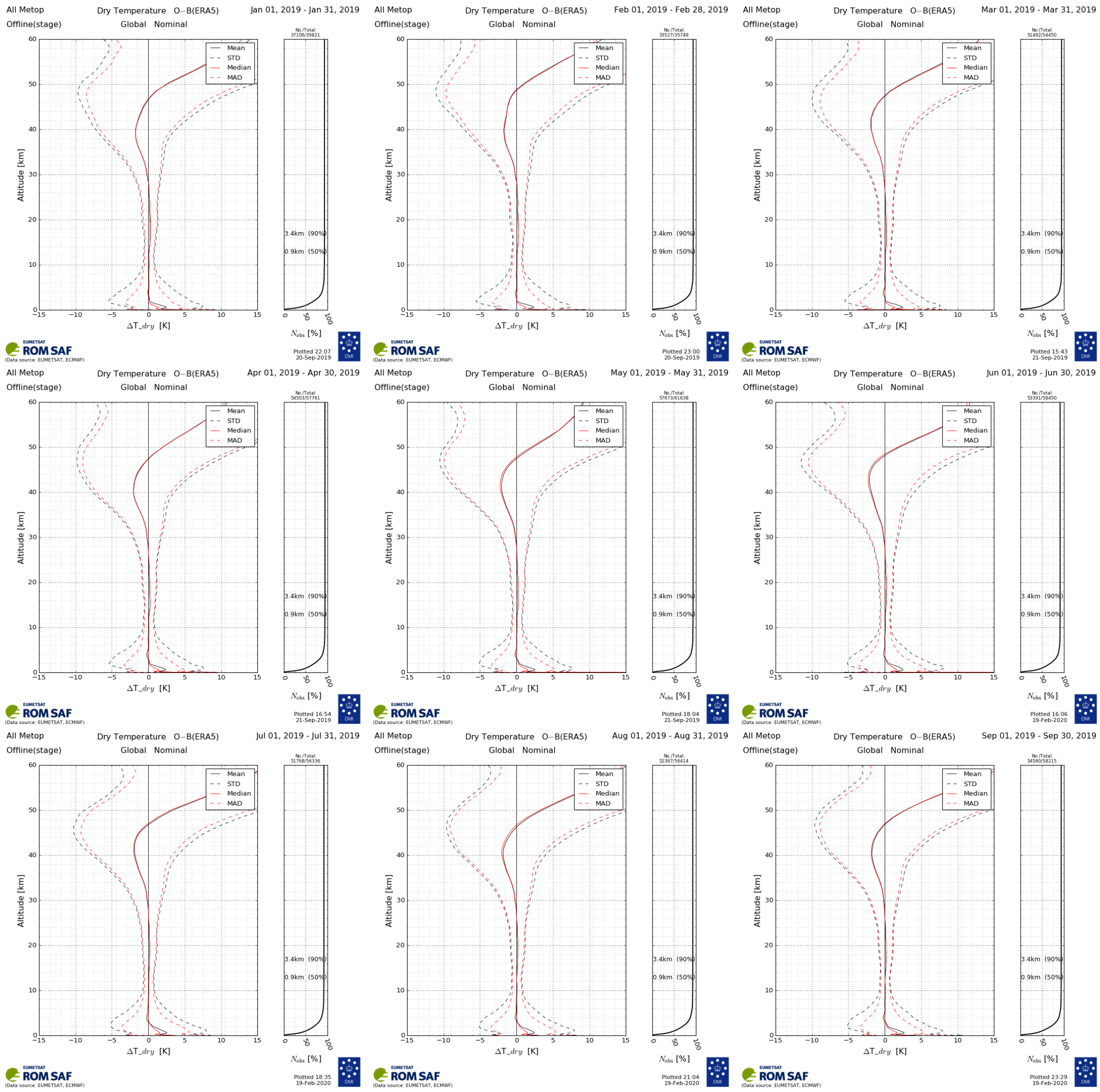

Figure A.3: Monthly global profile statistics of dry temperature against ERA5 forecasts