Validation Report: Offline Level 3 gridded data

Version 1.1

14 May 2020

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Ref: SAF/ROM/DMI/REP/GRD/002

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DOCUMENT CHANGE RECORD

Version	*Date*	*By*	*Description*
1.0	16/3 2020	HGL	Version for the ORR12 review.
1.1	14/5 2020	HGL	Updated version after ORR12 review implementing the following changes and ORR12 RIDs: Editorial changes and typos: RIDs 085, 086, 115. Executive summary: Added text about data versions, and data used in the validation [RIDs 088, 105]. Section 1.1.1: New section describing the data versions and listing the data being validated [e.g., RIDs 092, 105]. Section 1.2.2: Added reference [RID 103]. Sections 2.1, 2.2: Updated text related to satellites, time periods, and PPF versions [RIDs 104, 105]. Section 2.5: Added info on the ERA5 time step [RID 108]. Section 2.7: Added statement about no QC differences between Metop satellites [RID 106]. Section 3.1.1: Added information on tropopause heights [RID 112]. Section 3.1.2: Added discussion about seasonality in RO-ERA5 differences [RID 087]. Section 3.2: Minor text update [RIDs 088, 089]. Section 3.2.1: Minor addition to the text [RID 113]. Figure 6: Updated tropopause height panel [RID 112]. Figures 15, 17: Changed plot titles [RIDs 091, 094]. Section 4: Added discussion on circularity when using ERA5 both in data retrieval and in testing [RID 095].

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 GRAS 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 Level 3 Offline data is based on measurements by the Metop Radio Occultation (RO) mission, which includes data from three satellites: Metop-A, -B, and -C. The Level 3 data consist of monthly means on a global latitude-altitude grid (5 degrees in latitude by 200 meters in altitude), averaged from a large number of near-vertical profiles of relevant geophysical variables, including bending angle, refractivity, temperature, and humidity. The profile data (Level 1B and Level 2) have been generated by the ROM SAF from excess phase and amplitude data (Level 1A) provided by EUMETSAT.

Version 1.0 of the ROM SAF Offline data covers the time period from January 2017 to July 2019. After an update of the processing software, and a switch of ancillary input data from ERA-Interim to ERA5, the plan is to continue with a new data product version 1.1 that will cover the time period from August 2019 and onward. The present document provides a validation of that new version of ROM SAF Offline data.

For the purpose of validating the Offline data, we generated 34 months of data with the software used for the v1.1 data: the 3 months August-October 2019 that will become part of the ROM SAF public release, and an additional validation dataset only intended for internal use covering January 2017 to July 2019. The validation is based on a) comparing the Level 3 RO data with the corresponding ERA5 data, b) comparing Level 3 data from different Metop satellites, and c) comparing Level 3 data product version 1.1 with version 1.0. In addition to this, we check the compliance with the product requirements using the methods described in the Product Requirements Document (PRD). Finally, we define an updated set of service specifications to be used in the operational monitoring of the Level 3 Offline data.

We conclude that the ROM SAF Level 3 Offline gridded monthly mean data are of high quality, that they meet the expectations we have on a ROM SAF data product, and that they comply with the product requirements as stated in the Product Requirements Document. We find that the evolution from data product version 1.0 to version 1.1 have not introduced any major new features that were not expected. The issues that were detected during the validation, and that requires further investigations, are not of a character that prevent the data products from being released.

1. Introduction

1.1 Purpose of the document

This document describes the validation of the ROM SAF Offline Level 3 data which consists of gridded monthly means. The data are generated by the ROM SAF processing system using Level 1B and Level 2 profile data as input, together with ancillary information from ECMWF reanalysis data. The product requirements baseline is defined in the ROM SAF Product Requirements Document (PRD) [AD.3], and the methods and algorithms used in the generation of the Level 3 data products are described in the Algorithms Theoretical Baseline Document (ATBD) [RD.6].

An extensive range of plots with a direct bearing on the validation of the climate data can also be found on the ROM SAF web site (http://www.romsaf.org). Those plots should be studied in conjunction with the present report.

1.1.1 List of data products being validated in this report

The ROM SAF Level data products being validated in this report are listed in Table 1. They consist of Level 3 *Offline data products* that are generated on a regular basis for non-time-critical applications based on algorithms that may have evolved somewhat from the last reprocessing to reflect the latest scientific developments.

Version 1.0 of the ROM SAF Offline data covers the time period from January 2017 to July 2019. After an update of the processing software, and a switch of ancillary input data from ERA-Interim to ERA5, the plan is to continue with a new data product version 1.1 that will cover the time period from August 2019 and onward. The present document provides a validation of the ROM SAF Level 3 Offline data version 1.1.

Table 1. List of EPS ***offline data products*** covered by this Validation Report. The Level 1A input data to the ROM SAF processing is obtained from the EUMETSAT Secretariat.

Product ID	Product Name	Product acronym	Satellite input	Prod. version
GRM-93	Offline bending angle grid	OBGMEA	Metop-A	1.1
GRM-94	Offline refractivity grid	ORGMEA	"	"
GRM-95	Offline temperature grid	OTGMEA	"	"
GRM-96	Offline specific humidity grid	OHGMEA	"	"
GRM-97	Offline dry geopotential height grid	OZGMEA	"	"
GRM-98	Offline dry temperature grid	ODGMEA	"	"
GRM-99	Offline dry pressure grid	OYGMEA	"	"
GRM-191	Offline tropopause height grid	OCGMEA	"	"
GRM-53	Offline bending angle grid	OBGMEB	Metop-B	1.1
GRM-54	Offline refractivity grid	ORGMEB	"	"
GRM-55	Offline temperature grid	OTGMEB	"	"
GRM-56	Offline specific humidity grid	OHGMEB	"	"
GRM-57	Offline dry geopotential height grid	OZGMEB	"	"
GRM-58	Offline dry temperature grid	ODGMEB	"	"
GRM-59	Offline dry pressure grid	OYGMEB	"	"
GRM-192	Offline tropopause height grid	OCGMEB	"	"
GRM-73	Offline bending angle grid	OBGMEC	Metop-C	1.1
GRM-74	Offline refractivity grid	ORGMEC	"	"
GRM-75	Offline temperature grid	OTGMEC	"	"
GRM-76	Offline specific humidity grid	OHGMEC	"	"
GRM-77	Offline dry geopotential height grid	OZGMEC	"	"
GRM-78	Offline dry temperature grid	ODGMEC	"	"
GRM-79	Offline dry pressure grid	OYGMEC	"	"
GRM-193	Offline tropopause height grid	OCGMEC	"	"
GRM-83	Offline bending angle grid	OBGMET	Metop	1.1
GRM-84	Offline refractivity grid	ORGMET	"	"
GRM-85	Offline temperature grid	OTGMET	"	"
GRM-86	Offline specific humidity grid	OHGMET	"	"
GRM-87	Offline dry geopotential height grid	OZGMET	"	"
GRM-88	Offline dry temperature grid	ODGMET	"	"
GRM-89	Offline dry pressure grid	OYGMET	"	"
GRM-194	Offline tropopause height grid	OCGMET	"	"

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, 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] ROM SAF ATBD: Level 1B bending angles, SAF/ROM/DMI/ALG/BA/001.

[RD.2] ROM SAF ATBD: Level 2A refractivity profiles, SAF/ROM/DMI/ALG/REF/001.

[RD.3] ROM SAF ATBD: Level 2A dry temperature profiles, SAF/ROM/DMI/ALG/TDRY/001.

[RD.4] ROM SAF ATBD: Level 2B and 2C 1D-Var products, SAF/ROM/DMI/ALG/1DVAR/002.

[RD.5] ROM SAF ATBD: Level 2C tropopause height, SAF/ROM/DMI/ALG/TPH/001.

[RD.6] ROM SAF ATBD: Level 3 gridded data, SAF/ROM/DMI/ALG/GRD/001.

[RD.7] ROM SAF Validation Report: Reprocessed Level 3 Gridded Data, SAF/ROM/DMI/REP/GRD/001.

[RD.8] The ROPP Pre-processor Module User Guide, SAF/ROM/METO/UG/ROPP/004.

[RD.9] The ROPP 1D-Var Module User Guide, SAF/ROM/METO/UG/ROPP/007.

[RD.10] Simmons, A., et al., Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5.1, *ECMW Technical Memoranda*, 859, 2020.

[RD.11] Foelsche, U., et al., Refractivity and temperature climate records from multiple radio occultation satellites consistent with 0.05%, *Atmos. Meas. Tech.*, 4, 2007-2018, 2011.

[RD.12] Steiner, A. K., Lackner, B. C., Ladstädter, F., Scherllin-Pirscher, B., Foelsche, U., and Kirchengast, G., GPS radio occultation for climate monitoring and change detection, *Radio Sci.*, 46, RSOD24, 2011.

[RD.13] Gleisner, H., Latitudinal binning and area-weighted averaging of irregularly distributed radio occultation data, GRAS SAF Report 10, 2010.

[RD.14] Ho, S.-P., et al., Estimating the uncertainty of using GPS radio occultation data for climate monitoring: Inter-comparison of CHAMP refractivity climate records 2002-2006 from different data centers, *J. Geophys. Res.*, 114, D23107, 2009.

[RD.15] Steiner, A. K., et al., Quantification of structural uncertainty in climate data records from GPS radio occultation, *Atmos. Chem. Phys.*, 13, 1469-1484, 2013.

1.3 Acronyms and abbreviations

ATBD	Algorithm Theoretical Baseline Document
CDAAC	Cosmic Data Analysis and Archive Center
CDOP	Continuous Development and Operations Phase (EUMETSAT)
CDR	Climate Data Record
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
DMI	Danish Meteorological Institute; ROM SAF Leading Entity
ECMWF	European Centre for Medium-range Weather Forecasts
EPS	EUMETSAT Polar Satellite System
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites
GNSS	Global Navigation Satellite System
GPAC	GNSS Processing and Archiving Center
GPS	Global Positioning System (US)
GRAS	GNSS Receiver for Atmospheric Sounding (EPS/Metop)
GRIB	GRIdded Binary (WMO)
ICDR	Interim Climate Data Record
IEEC	Institut d'Estudis Espacials de Catalunya
L1	GPS carrier frequency, 1575.42 MHz
L2	GPS carrier frequency, 1227.6 MHz
LC	L Corrected (through linear combination of L1 and L2)
LEO	Low Earth Orbit
Met Office	United Kingdom Meteorological Office
Metop	Meteorological Operational Polar satellite (EUMETSAT)
MSL	Mean Sea Level
netCDF	Network Common Data Format
NRT	Near Real Time
NWP	Numerical Weather Prediction
PRD	Product Requirements Document (ROM SAF)
RO	Radio Occultation
ROM SAF	Radio Occultation Meteorology SAF (former GRAS SAF)
ROPP	Radio Occultation Processing Package (ROM SAF)
SAF	Satellite Application Facility (EUMETSAT)
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 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 (SAF Level 2 for EPS), (ii) 150 min after measurement (SAF online products for EPS-SG Global Mission); (iii) 125 min after measurement (SAF online products 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].

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

[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)

1.5 Overview of this document

This document is organized as follows:

Chapter 1: Contains the introduction.

Chapter 2: Contains an overview of the Level 1B and Level 2 profile data used as input to the Level 3 processing. It also contains an overview of the Level 3 gridded data, the Level 3 processing, and a list of the quality screening tests.

Chapter 3: Contains the main validation results.

Chapter 4: Contains a check of the compliance with the Product Requirements.

Chapter 5: Contains a suggestion for updated Service Specifications.

Chapter 6: Contains the main conclusions of the validation.

2. Background

2.1 Satellites and time coverage

The satellites and the time periods covered by the ROM SAF Offline data products are given in Table 2. The Offline dataset versions used in the present validation, based on these satellites, are described in Sections 3.2 and 3.3.

Satellite	Time period
Metop-A	January 2017 – present
Metop-B	January 2017 – present
Metop-C	March 2019 – present

***Table 2**. Metop satellites and time periods covered by the ROM SAF Offline data products.*

2.2 Level 1A input data

The ROM SAF data used in this report are 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.

2.3 Level 1B and Level 2 profile data

The starting point for the ROM SAF Level 3 processing is a large number of near-vertical profiles, one for each occultation: bending angle, $\alpha(a)$, refractivity, $N(H)$, dry pressure, $p_{\mathrm{dry}}(H)$, dry temperature, $T_{\mathrm{dry}}(H)$, dry geopotential height, $Z(H_{p\mathrm{dry}})$, temperature, $T(H)$, specific humidity, $q(H)$, and tropopause height, H_{TP}. Here, H is the mean-sea level (MSL) altitude, a is the impact parameter, H_p is the pressure height (a logarithmic measure of pressure), and $H_{p\mathrm{dry}}$ is the dry-pressure height [RD.6]. The “dry” variables are retrieved from the refractivity under the assumption that the influence of water vapour can be ignored. This is a valid assumption in the upper troposphere and in the stratosphere, where the “dry” variables are accurate approximations for the corresponding physical quantities. The retrievals of the geophysical profile data are described in the associated ATBDs [RD.1-4], while the retrieval of tropopause height has its own ATBD [RD.5].

The bending angle, refractivity, and dry profiles are provided on relatively dense vertical grids reaching up to well above the region where the RO measurements provide useful information on the neutral atmosphere. The temperature and humidity profiles are given on a standard set of vertical levels ranging from the surface up to around 80 km, near the top of the atmospheric model used as *a priori* in the retrieval. Each occultation has an associated reference location and time, which is used in binning the data.

The Offline Level 1B and Level 2 profile data v1.1 were retrieved with the GPAC-2.4.0 system, which includes the ROPP-9.0 software package (an internal release with adaptions made by the DMI) and the 1DV-4.2 software.

2.4 Level 3 gridded data

The ROM SAF Offline data consists of profile data (Level 1B and Level 2) and gridded data (Level 3). The Level 3 data incorporates gridded monthly means and associated quantities (standard deviations, data numbers, sampling error estimates, etc.) of:

- Bending angle, $\alpha(a)$
- Refractivity, $N(H)$
- Dry pressure, $p_{\mathrm{dry}}(H)$
- Dry temperature, $T_{\mathrm{dry}}(H)$
- Dry geopotential height, $Z_{\mathrm{dry}} = Z(H_{p\mathrm{dry}})$
- 1D-Var temperature, $T(H)$
- 1D-Var specific humidity, $q(H)$
- Tropopause height, H_{TP}

As described in Section 2.3, H is the MSL altitude, a is the impact parameter, and $H_{p\mathrm{dry}}$ is the dry-pressure height [RD.6]. The monthly means, and the associated variables, are defined on zonal grids, 200 meters in height by 5 degrees in latitude [RD.6].

The raw data numbers available from the three Metop satellites Metop-A, -B, and –C are shown in Figure 1. In 2017 and 2018, Metop-A and –B provided almost equal number of occultations, nearly 700 per day. In February 2019, Metop-C started to provide data, and from March 2019 we get around 2000 occultations per day from the three Metop satellites.

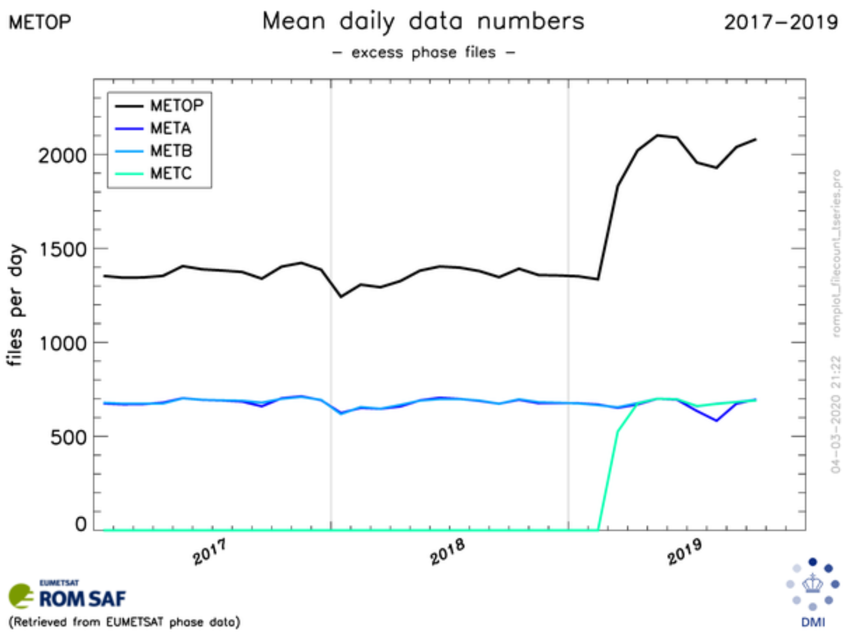

Figure 1. *Number of occultations available for Offline data generation from the three Metop satellites Metop-A, Metop-B, and Metop-C. The black line shows the total number of occultations from all three satellites.*

All RO missions have a relatively uniform distribution of data numbers in longitude, whereas the latitude distribution is non-uniform [RD.13]. Figure 2 shows the longitudinal (left-hand panels) and latitudinal (middle panels) distributions of data numbers per unit area for Metop. The non-uniform latitudinal distribution is a consequence of the GNSS and LEO satellite orbits in combination with the limb-sounding observing geometry of the RO instrument. The distributions are relatively similar for different RO missions, with the main differences due to the inclination of the orbits.

The Sun-synchronous orbits of the Metop satellites make the local-time distribution highly non-uniform (Figure 2, right-hand panel). At low- and mid-latitudes, the observations only cover a few hours in the morning and few hours in the evening.

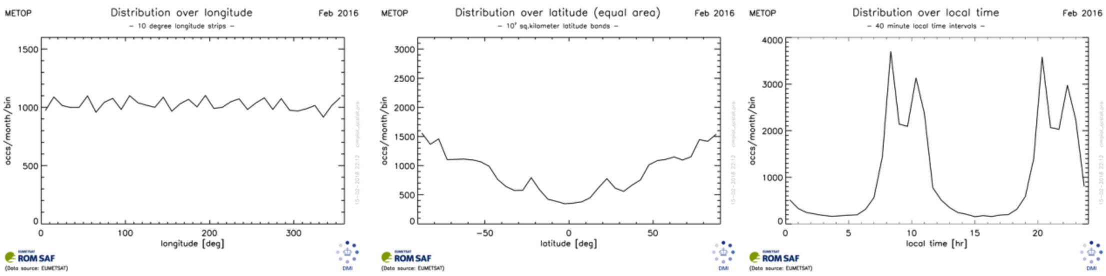

Figure 2. *Distribution of occultations over longitude (left panel), latitude (middle panel), and local time (right-hand panel) for the Metop mission. On a monthly time scale the distributions over longitude are relatively uniform, while the latitude distribution is far from uniform.*

2.5 ERA5 reanalysis data

ERA5 reanalysis data from ECMWF [RD.10] are used both for sampling-error correction of the Level 3 gridded monthly mean data, and as *a priori* in the 1D-Var retrieval of Level 2b profile data. The reanalysis fields are obtained from ECMWF as GRIB files holding data on a 1.0˚x1.0˚ latitude-longitude grid, as well as on a coarser 2.5˚x2.5˚ grid. The lower resolution is used for the sampling-error correction, as it is roughly comparable to the horizontal resolution of RO measurements.

Each occultation has reference latitude, longitude, and time associated with it. To retrieve reanalysis profiles co-located with the observations, we interpolate (bi-linearly) from the model grid to the reference location, followed by linear interpolation between adjacent 3-hourly time steps. For the 1D-Var retrievals, we use short-term forecasts rather than the analysis fields. In that case, the interpolation in time is made between two model forecast lead times. Further details on this are found in [RD.4].

For each observed profile we thus obtain a corresponding co-located model profile, which is mapped to refractivity, bending angle, and 'dry' variables using forward-model routines from the ROPP-9.0 software package [RD.9].

The use of ERA5 data as comparison reference for the validation has some limitations [RD.10]. First, there is a risk for circularities: RO data are assimilated by the ERA5 reanalysis system and ERA5 data are used in the generation of the some of the geophysical variables retrieved from the RO measurements. This is briefly discussed in Section 3.2. Second, the ERA5 data records exhibit bias shifts due to changes in the global observing system, particularly in the early years when fewer data were available for assimilation. This may obscure the validation results.

2.6 ROM SAF Level 3 processing

The Level 3 gridded data are generated from the Level 1B and Level 2 profile data through rather straight-forward *binning and averaging* [RD.6]. A set of equal-angle latitudinal bins are defined and all valid observations that fall within a latitude bin and calendar month undergo a weighted averaging to form a zonal mean for that latitude and month. The purpose of the weighting is to more closely approximate an area-weighted average.

The sampling errors are estimated by sub-sampling an atmospheric model (currently, the ERA5 reanalysis) at the observed times and locations. Based on these estimates, we do a sampling-error correction, or adjustment, by subtracting the estimated sampling errors from the observed means [RD.11,12,15]. The errors remaining after the sampling-error correction are referred to as residual sampling errors.

The uncertainty of the monthly mean is estimated as a combination of the per-profile measurement uncertainties and the uncertainties due to the residual errors remaining after the sampling-error correction [RD.6]. In principle, there is also a structural uncertainty due to algorithmic choices and underlying processing assumptions, but these are not explicitly quantified by the ROM SAF Level 3 algorithms. However, the ROM SAF has participated in activities with the explicit purpose to quantify structural uncertainties by comparing independent processing of the same input data. Results from these studies have been published in the scientific literature [RD.14,15].

In summary, the RO Level 3 gridded data products are generated by the following steps:

1) quality control and flagging of profiles that are identified as non-nominal (‘bad’)
2) vertical interpolation of profiles onto a regular Level 3 height grid
3) weighted averaging into monthly latitude bins
4) estimation of sampling errors in the monthly means
5) estimation of uncertainties (measurement and sampling) in the monthly means
6) estimation of *a priori* information in the monthly means
7) formatting of the Level 3 gridded data and meta-data into netCDF files

The generation of zonally gridded monthly mean data is followed by further averaging into seasonal and annual means, and into regional, hemispheric, and global means.

The Offline Level 3 gridded data, which are validated in the present document, were retrieved with the ROMCLIM-1.3 software.

2.7 Quality control of profiles

The purpose of the quality control is to identify profiles that are likely to provide an invalid representation of the atmosphere. Before processing the atmospheric profiles into gridded monthly-mean data, all profiles are checked against a set of criteria indicating non-nominal conditions (listed in Table 3). Some of these criteria are seldom met – they are only a basic sanity check to ensure that corrupt data do not affect the climate data (*QC-0*). Other tests are designed to identify occultations with degraded bending-angles (*QC-2*), that could be regarded as outliers (*QC-3*), or that have problems with the 1D-Var processing (*QC-4*). The actual quality control limits are effectively a compromise between the need to remove "bad" profiles and the wish to keep "good" profiles.

The first step (*QC-0*) in the quality screening procedure is a basic check to ensure that the bending angle (refractivity) profile reaches above 60 km and below 20 km impact altitude (MSL altitude). Bending angles must fall within the range -1 to 100 mrad, and refractivities must fall within the range 0 to 500 N-units. The independent variables (impact altitudes and MSL altitudes) are required to vary monotonously.

In the next step (*QC-2*), the noise properties of the L2 signal and the degree of fit of the raw LC bending angle to the background bending angle is checked. The *L2 quality score* quantifies the degradation of the L2 signal through the RMS difference of the L1 and L2 impact parameter series obtained from a radio-holographic analysis [RD.8]. The two *SO scaling factors* quantify the degree of fit to a background bending angle profile. This QC step also includes a requirement that the background bending-angle data should only play a minor role below 40 km altitude, which is indicated by the *LC weighting factor*.

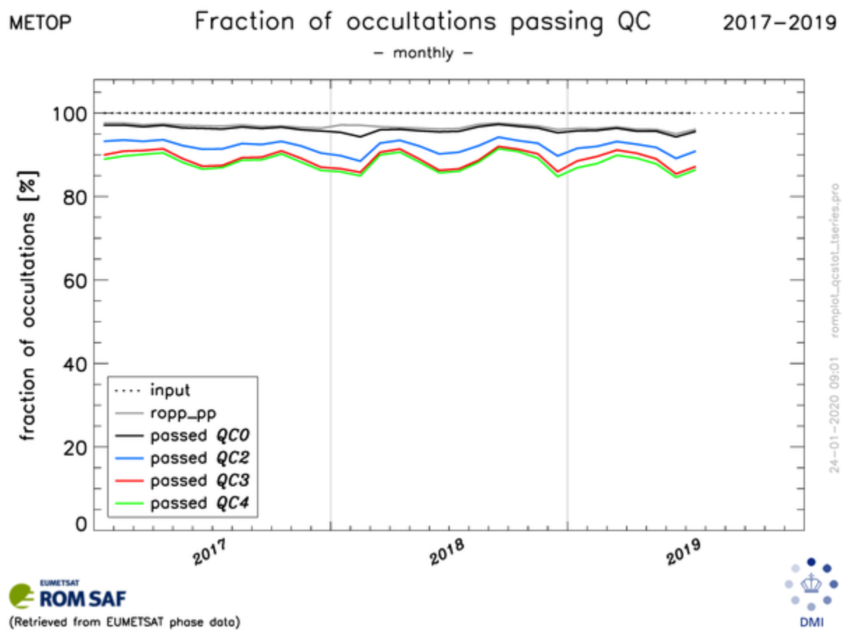

Figure 3. *Fraction of occultations available for the Level 3 gridded data generation, after the consecutive QC steps. QC-0 is a fundamental sanity check of bending-angle and refractivity profiles, QC-2 is a check based on the L2 and SO quality scores, QC-3 consists of systematic removal of outliers through comparison with ERA5, and QC-4 is a check on the 1D-Var solution.*

The next QC step (*QC-3*) removes data identified as outliers. This is done by comparing the observed bending angles, refractivities, and dry temperatures to ECMWF reanalysis data within specified height intervals.

If an occultation does not pass one or several of the above tests, the bending angle, refractivity, and dry variables are marked as non-nominal. Otherwise, they are regarded as nominal, and the refractivity profiles are passed on to the 1D-Var processing. This is followed by another QC step (*QC-4*) which checks the quality of the 1D-Var solution. If the occultation passes all tests up to, and including, *QC-3*, but fails in *QC-4*, the bending angle, refractivity, and dry-variable profiles are used, while the wet profiles obtained from the 1D-Var solution are discarded. The percentages of data remaining after the sequence of QC tests are shown in Figure 3. On average, around 10-15% of the occultations are rejected, with no discernible differences between the Metop satellites.

QC-0: basic sanity check
Identification of occultations with too small vertical extension, too few useful data points, the presence of invalid data points, or height variables that form a non-monotonous series.
- $\alpha(H_a)$ must reach below 20 km and above 60 km - $\alpha(H_a)$ values must fall within valid range: [-1,100] mrad - H_a values must form a monotonous series - $N(H)$ must reach below 20 km and above 60 km - $N(H)$ values must fall within valid range: [0,500] N-units - H must form a monotonous series
QC-1: (not used)
QC-2: bending angle quality
Checking of a) the quality of the bending angles, as quantified by the noise on the L2 impact parameter series, b) the fit of the raw LC bending angle to a background bending angle profile, and c) that the background bending-angle data only play a minor role below 40 km altitude.
- L2 quality score must be less than 30.0 - SO scaling factor 1 must fall in the interval [0.92,1.08] - SO scaling factor 2 must fall in the interval [0.60,1.40] - LC weighting factor must be larger than 0.90 below 40 km altitude
QC-3: identification of outliers
Identification of outliers by comparing with ECMWF reanalysis data mapped to refractivity, bending angle, and dry temperature.
- α must deviate from reanalysis by less than 90% between 10-40 km - N must deviate from reanalysis by less than 10% between 5-35 km - N must deviate from reanalysis by less than 20% below 5 km - T_{DRY} must deviate from reanalysis by less than 20 K between 30-40 km
QC-4: quality of 1D-Var solution
Identification of occultations that have problems converging at an acceptable 1D-Var solution.
- the 1D-var algorithm must converge within 25 iterations - the penalty function $2J/N_{obs}$ must be smaller than 5.0 at convergence

Table 3. *Summary of the ROM SAF quality control of the Level 1 and 2 data used as input to the Level 3 processing. QC-1 is currently not used operationally.*

3. Gridded data comparisons

The purpose of the validation is to demonstrate that the ROM SAF Level 3 Offline monthly-mean data products have the expected quality and characteristics, and that the Level 3 data products meet the formal requirements as stated in the ROM SAF Product Requirements Document (PRD) [*AD.3*]. The latter is done by demonstrating that the gridded monthly mean data are consistent with the reference data (here, ERA5), using the methods and accuracy specifications described in the PRD.

The Level 3 data set to be validated contains 8 geophysical variables distributed over latitude and height. The data used in the validation covers a time period of nearly 3 years. Some selection of data and properties to be investigated is obviously required. In the present validation report we have chosen the following:

- Comparison of the Level 3 Offline monthly-mean data with the corresponding ERA5 reanalysis data (Section 3.2);
- Comparison of Level 3 Offline monthly-mean data retrieved from Metop-A, -B, and –C, respectively (Section 3.3);
- Comparison of the Level 3 Offline monthly-mean data product version 1.1 with version 1.0 (Section 3.4);

3.1 Comparison with ERA5 reanalysis data

In this section, the ROM SAF Offline Level 3 monthly-mean data are compared to the corresponding means generated from co-located ERA5 reanalysis short-term forecasts.

There are a few issues to consider when comparing observed RO data with reanalysis data. First, RO data have been assimilated by the ERA5 reanalysis system [RD.10]. Second, the ERA5 short-term forecasts have been used as *a priori* data in the ROM SAF 1D-Var processing of temperature and humidity profiles [RD.4]. These two factors complicate the choice of reference for the comparison. We have chosen to use ERA5 short-term forecast data as reference. By doing so, we avoid comparison of two data sets (RO and ERA5) containing the same observational data, which would be the consequence of using ERA5 analysis data as reference. However, the ERA5 forecast data have a significant influence on the comparison of geophysical variables obtained by 1D-Var retrieval – temperature and humidity – particularly at altitudes and/or latitudes where the background information dominates the 1D-Var solution.

Throughout the RO-ERA5 comparison it should be acknowledged that ERA5 data is not the truth. In some cases, we are able to spot problems with the reanalysis data from differences with respect to the observational RO data. The RO–ERA5 comparisons can also be used to check the consistency of data from different RO missions or different RO satellites, and they are further used to demonstrate the formal compliance with the ROM SAF PRD requirements (Section 4).

In Section 3.1.1 we show RO–ERA5 time-averaged differences on a latitude-height cross-section for all eight variables up to 50 km (the humidity only up to 12 km). In Section 3.1.2 we show RO–ERA5 difference time-height plots for globally averaged data, as well as data averaged in 5 broad latitude bands.

3.1.1 RO-ERA5 differences on latitude-height cross section

In Figure 6 we show the spatial pattern of differences between RO data and ERA5 obtained by temporal averaging over the length of the time series from January 2017 to October 2019. Hence, the two last months of the year is slightly under-represented in the average. We do this averaging for all 8 geophysical variables included in the ROM SAF Level 3 Offline data product.

The dominant feature in the bending angle and refractivity plots are a positive bias extending between 30 and 45 km and covering all latitudes. In the dry temperature plot we find a strong negative bias of more than 2 K around 40 km. We also note a hemispheric asymmetry in the dry variables and in the refractivity, which is consistent with findings in the validation of the ROM SAF Climate Data Record v1.0 [RD.15]. The tropopause height based on the dry temperatures lapse rate exhibit a characteristic pattern with negative biases at mid-latitudes.

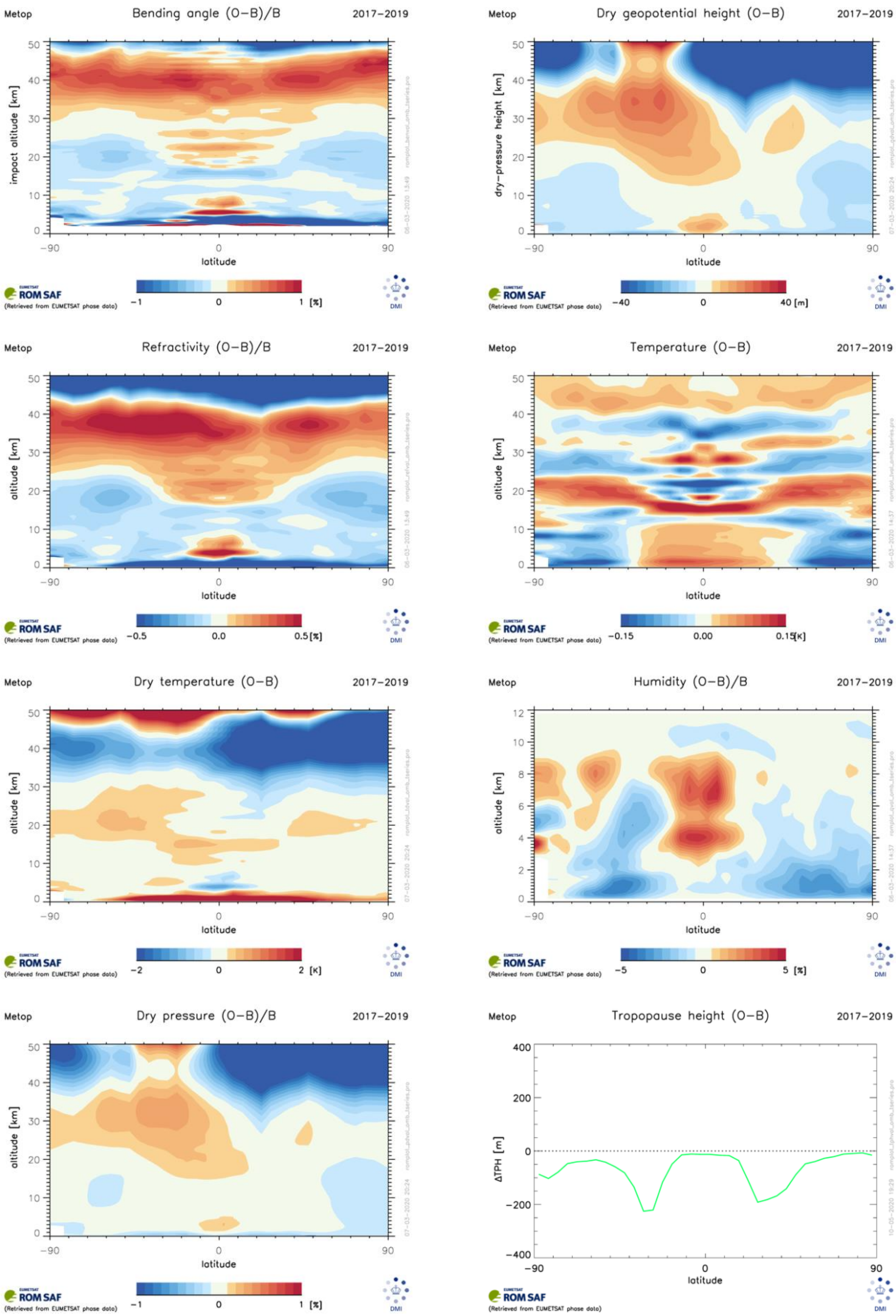

Figure 6. *RO-ERA5 differences on a latitude-height cross-section. The time averages are computed for the 34-month period January 2017 to October 2019. The RO data include all Metop satellites (ROM SAF Level 3 data products GRM-83 to 89 and GRM-194).*

3.1.2 RO-ERA5 difference time-height plots

In Figs. 7a-f we show spatial averages of the differences, in five latitude bands as well as globally. The data are presented as time-height plots extending up to 50 km and covering the time period from January 2017 to October 2019. Data are shown for bending angle, refractivity, dry temperature, temperature, humidity, and tropopause height.

As in the spatial plots in Section 3.1.1, the dominant feature in the bending angle and refractivity plots is a positive bias extending between 35 and 45 km and covering all latitudes. We also find a pronounced seasonal cycle in the RO-ERA5 differences, particularly at high latitudes. The seasonality is strongest at high altitudes, but is still visible at 30 km. It should be noted that we find similar variations in Metop–ERA-Interim differences, as well as in COSMIC–ERA-Interim differences [RD.7]. In the validation of the Level 3 reprocessed data [RD.7], we also found that observed inter-mission differences at high latitudes and altitudes, for example Metop-COSMIC, are more than an order of magnitude smaller than the Metop-ERA5 differences found here. The cause of the seasonal variations in the RO-ERA5 differences is unknown, but we find it likely that they are caused predominantly by ERA5.

In the dry temperature plots we find a strong negative bias around 40 km, and the same type of seasonality as in the bending angle and refractivity plots. The humidity differences between RO and ERA5 are dominated by positive biases at low latitudes and a seasonal cycle at mid-latitudes between 8 and 12 km. There are no discernible impacts on the RO-ERA5 differences by the introduction of Metop-C data in March 2019.

Metop – ERA5
Bending angle

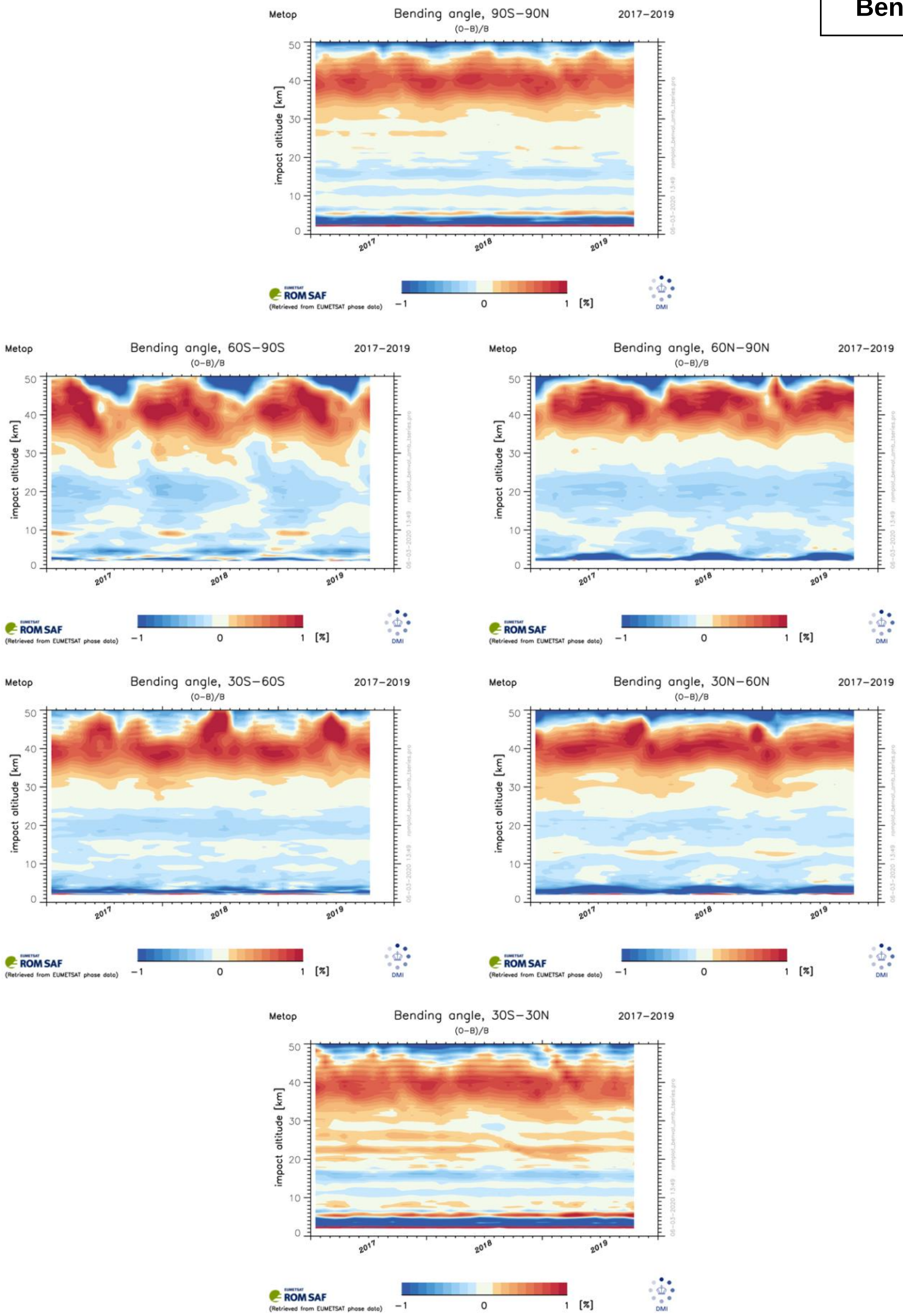

Figure 7a. *RO-ERA5 bending angle differences on a time-height plot, for Level 3 monthly-mean Metop data aggregated into 5 broad latitude bands plus global data.*

Metop – ERA5
Refractivity

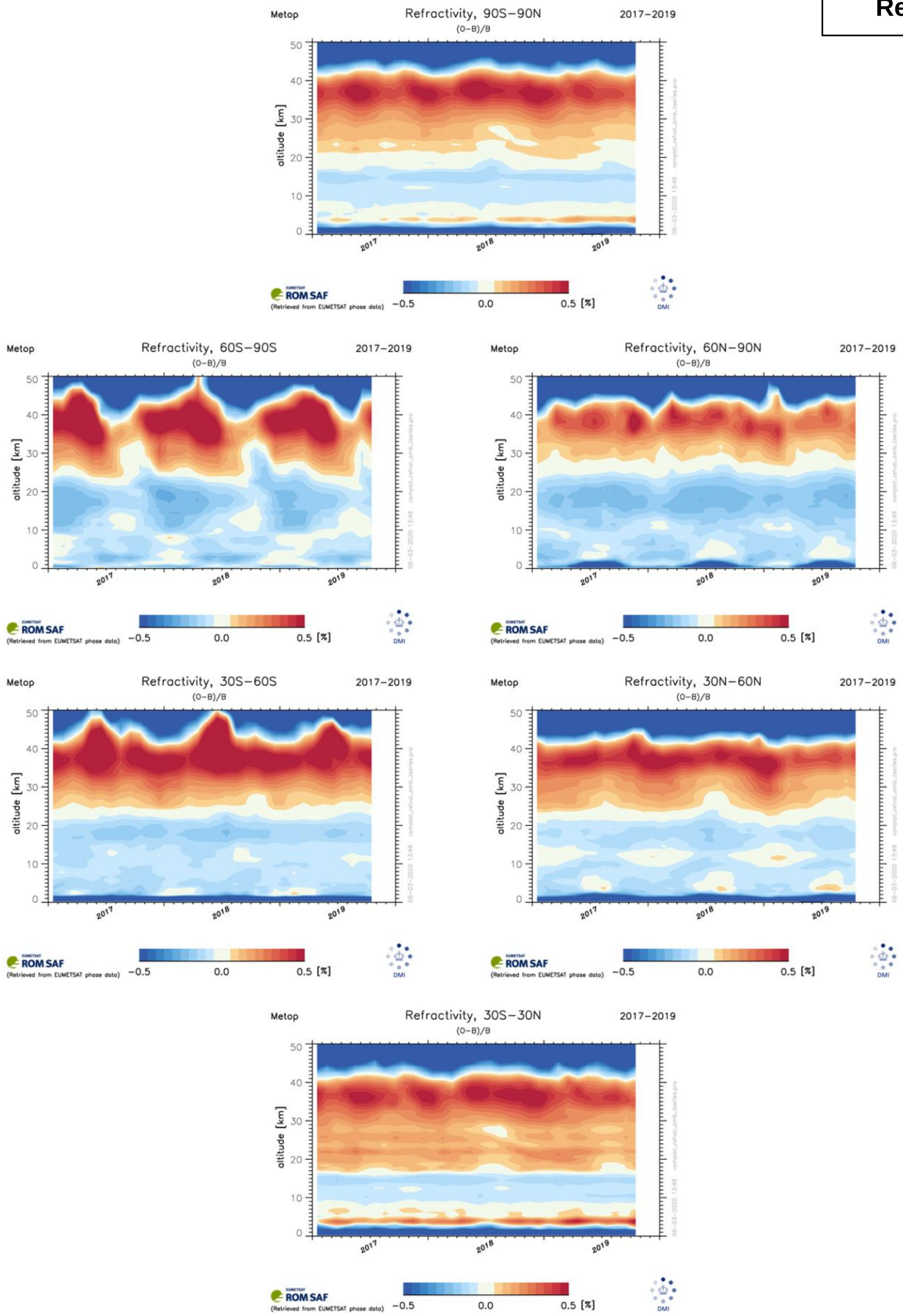

Figure 7b. *RO-ERA5 refractivity differences on a time-height plot, for Level 3 monthly-mean Metop data aggregated into 5 broad latitude bands plus global data.*

Metop – ERA5
Dry temperature

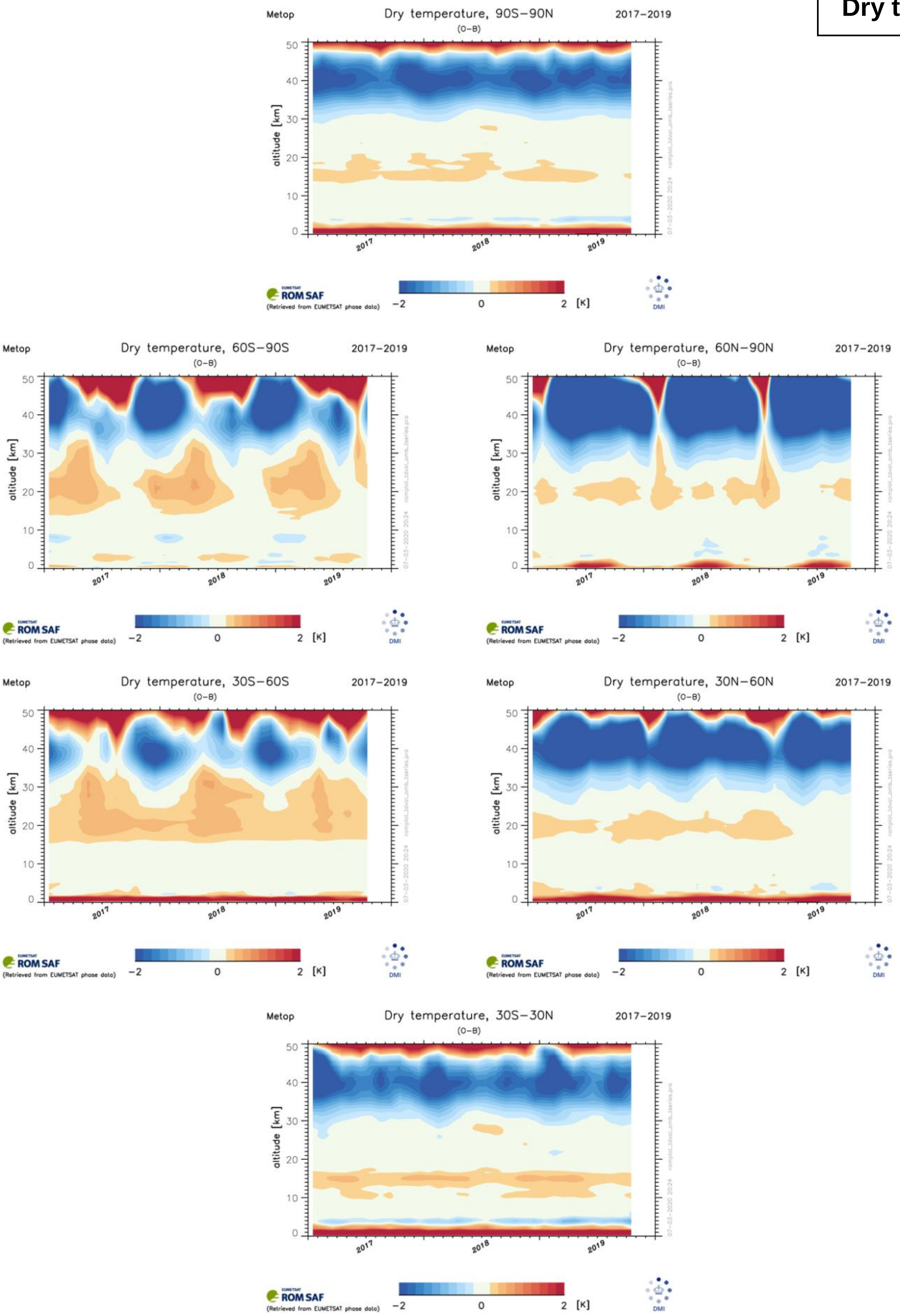

Figure 7c. *RO-ERA5 dry temperature differences on a time-height plot, for Level 3 monthly-mean Metop data aggregated into 5 broad latitude bands plus global data.*

Metop – ERA5
Temperature

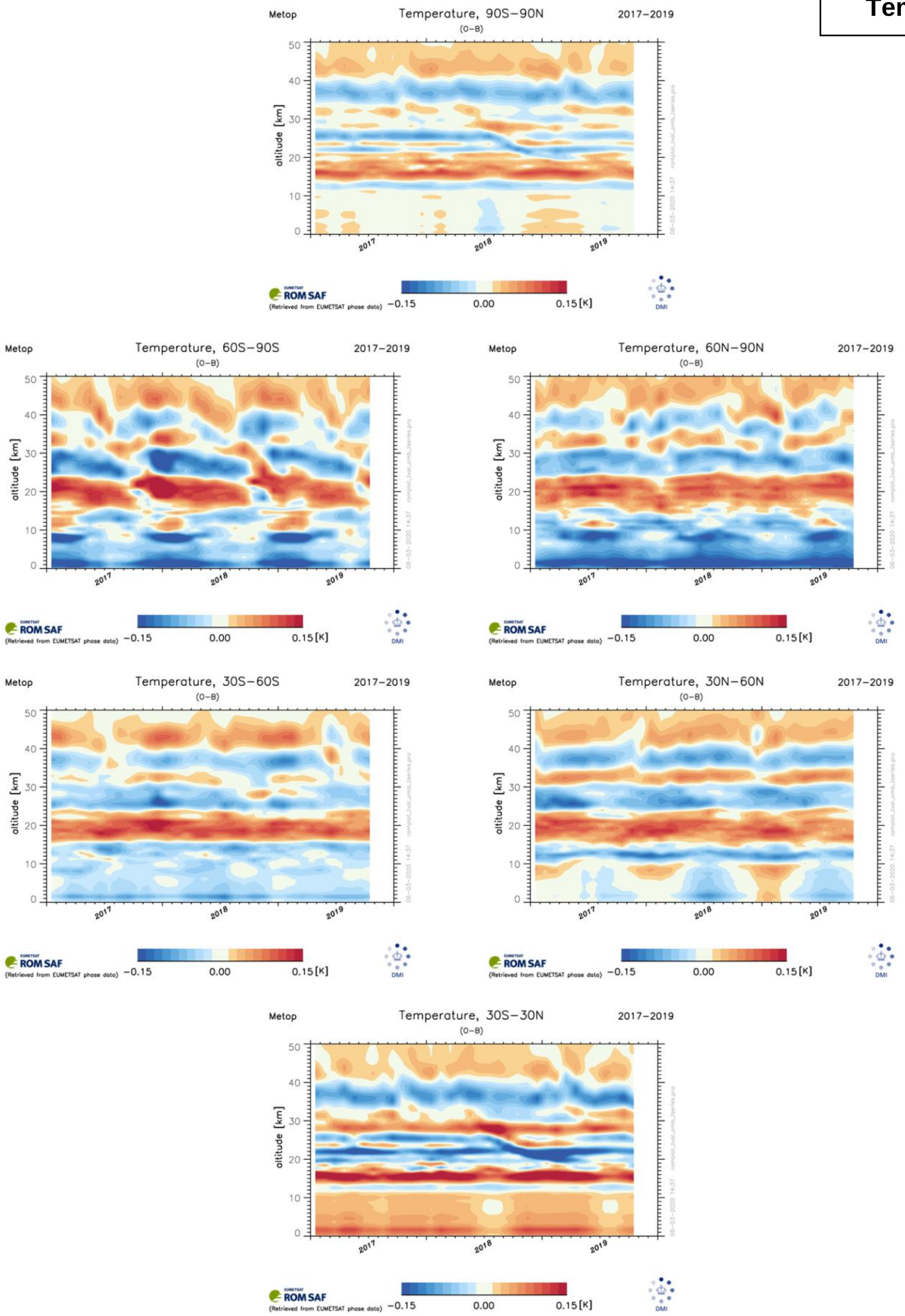

Figure 7d. *RO-ERA5 temperature differences on a time-height plot, for Level 3 monthly-mean Metop data aggregated into 5 broad latitude bands plus global data. The temperature profiles are retrieved by 1D-Var processing.*

Metop – ERA5
Humidity

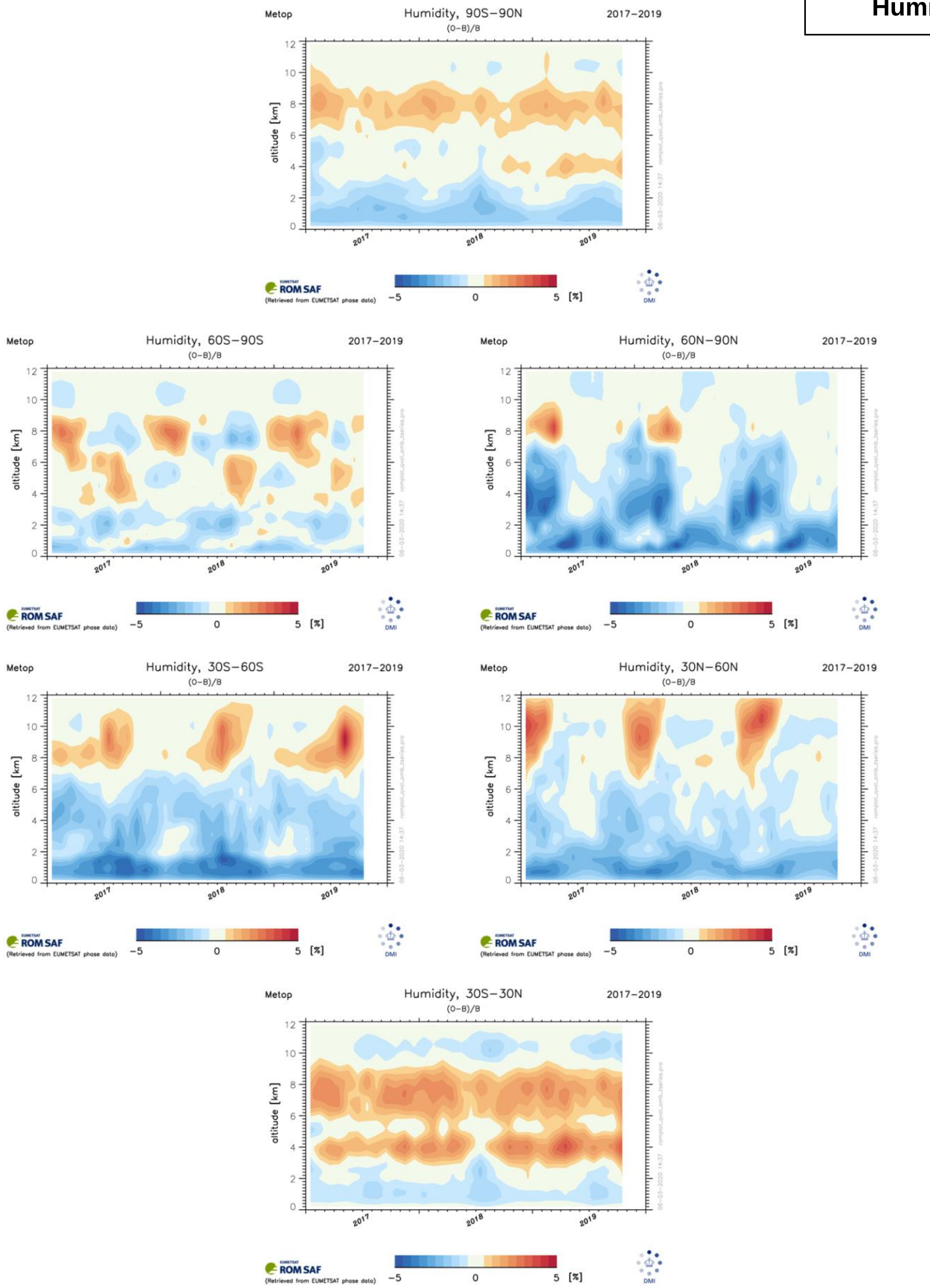

Figure 7e. *RO-ERA5 humidity differences on a time-height plot, for Level 3 monthly-mean Metop data aggregated into 5 broad latitude bands plus global data. The humidity profiles are retrieved by 1D-Var processing.*

Metop – ERA5
Tropopause height

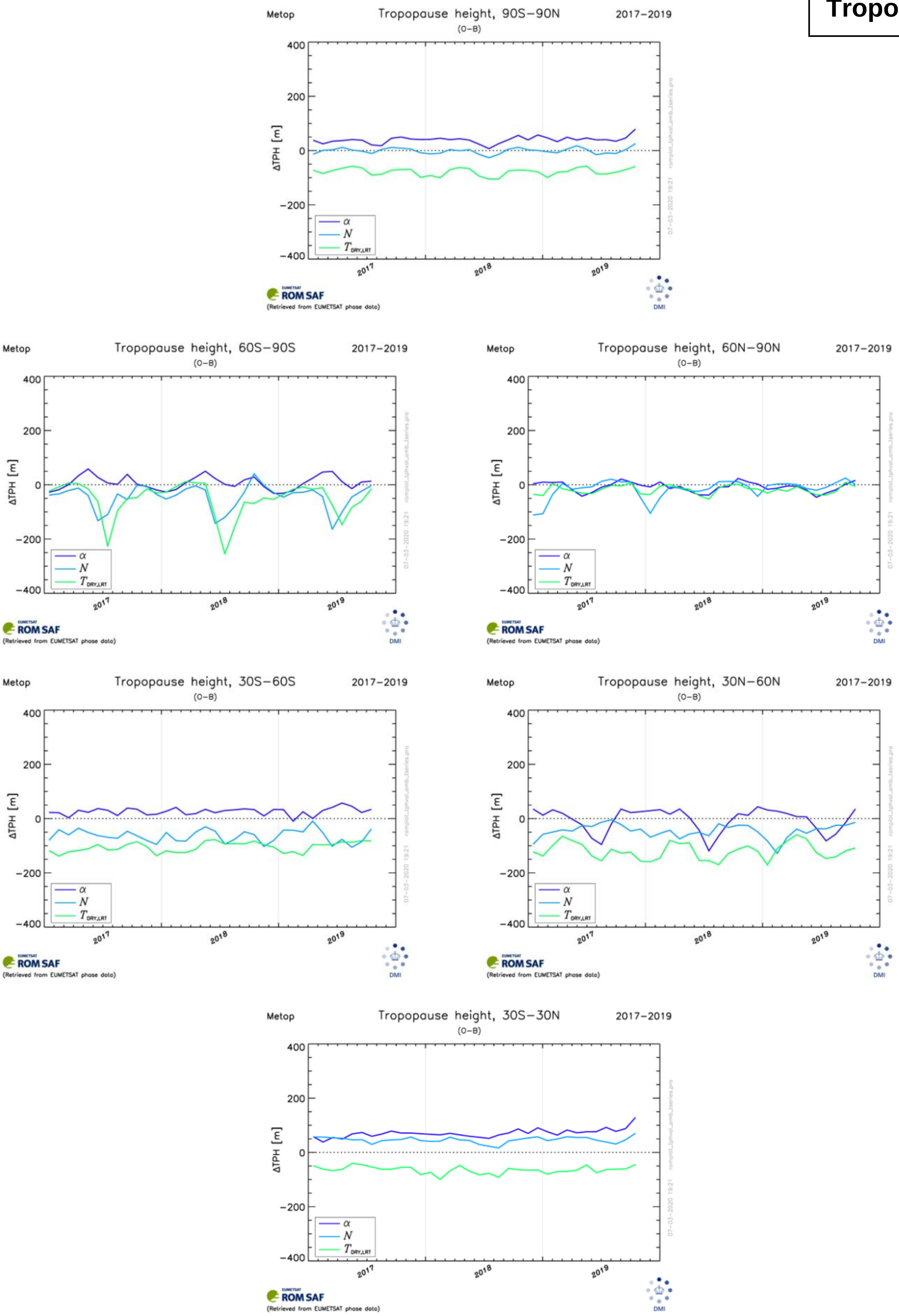

Figure 7f. *RO-ERA5 tropopause height differences as function of time, for Level 3 monthly-mean Metop data aggregated into 5 broad latitude bands plus global data.*

3.2 Comparison between Metop satellites

Gridded monthly mean data generated from different Metop satellites are expected to differ only by random errors (profile measurement errors and the random component of the residual sampling errors). Any differences in excess of these errors are potential signs of systematic differences due to data processing or RO instrument, or due to differences in the sampling characteristics that are not fully compensated for by the sampling-error correction.

For the purpose of validating the Offline data, we generated 34 months of data with the software used for the v1.1 data: the 3 months August-October 2019 that will become part of the ROM SAF public release, and an additional validation dataset only intended for internal use covering January 2017 to July 2019. We here use the combined 34-month data record to study differences between the Metop satellites. The satellite data sets are:

- Metop-A: January 2017 to October 2019
- Metop-B: January 2017 to October 2019
- Metop-C: March 2019 to October 2019
- Metop: January 2017 to October 2019 (all Metop-A, -B, and -C data)

For each of these data sets we compute gridded monthly mean anomalies with sampling-error correction applied (using the all-Metop 2017-2018 data as reference; see *Gleisner et al.* (2019) [RD.15] for how to compute anomalies). Section 3.2.1 shows time series of global and low-latitude anomalies for bending angle, refractivity, dry temperature, and humidity, together with the differences between the single-satellite and the all-Metop anomalies. Section 3.2.2 shows time-height plots of Metop-A minus Metop-B differences for globally averaged bending angle, refractivity, and dry temperature.

3.2.1 Metop satellite difference time series

The left columns of Figs. 9 to 12 show the global and low-latitude anomalies for bending angle, refractivity, dry temperature, and humidity. The right-hand columns show the corresponding differences between the single-satellite and the all-Metop anomalies.

The left-hand columns of Figs. 9 to 12 show that there is fundamentally an excellent agreement between the Level 3 data records retrieved from different Metop satellites. The level of agreement should be evaluated in relation to the variability of the time series itself. Above 8 km the plotted lines fall almost perfectly on top of each other which indicate very small Level 3 uncertainties (not including common systematic errors). Differences between the satellites are evident, e.g., in bending angle below 8 km, in dry temperature above 30 km, and in the humidity time series.

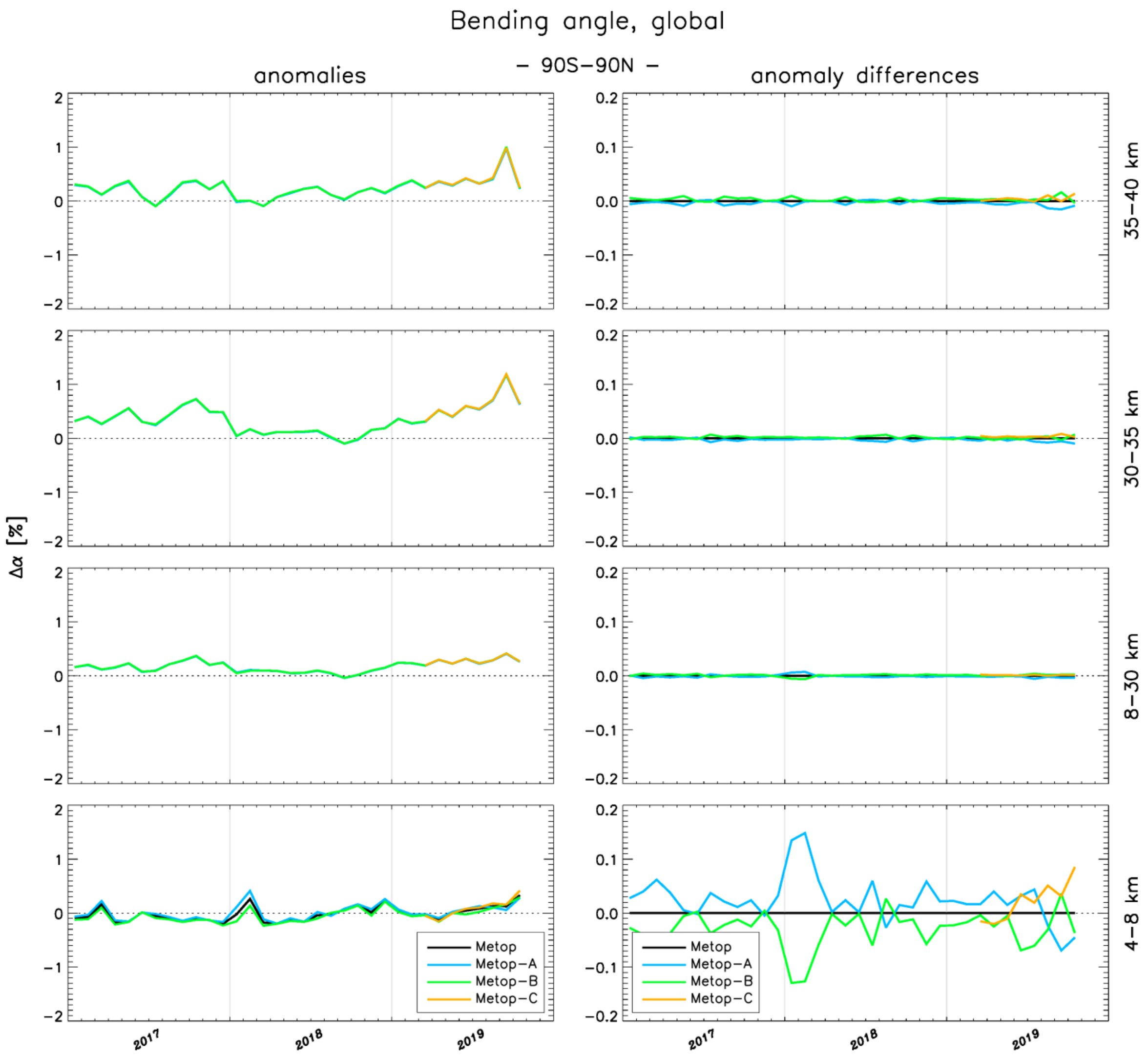

***Figure 9a.** Left column: global monthly mean bending angle anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

In the right-hand columns of Figs. 9 to 12, we have magnified the small differences between the anomalies. In the lower troposphere there is a Metop-A vs. Metop-B difference on the order of 0.1-0.2% in bending angle. That bending angle difference increases to about 0.5% during the first few months of 2018. The increased Metop-A vs. Metop-B differences in the beginning of 2018 propagate to all the other geophysical variables, also the humidity. It coincides in time with a GRAS RO instrument tracking loop campaign, which almost certainly is the cause of these differences.

It should be noted that this validation report only applies to the Offline v1.1 data record from August 2019 and onward. The above mentioned Metop satellite differences are only discussed to better understand the capabilities of the v1.1 processing software. The satellite differences in the beginning of 2018 do not directly affect the Offline v1.1 data products.

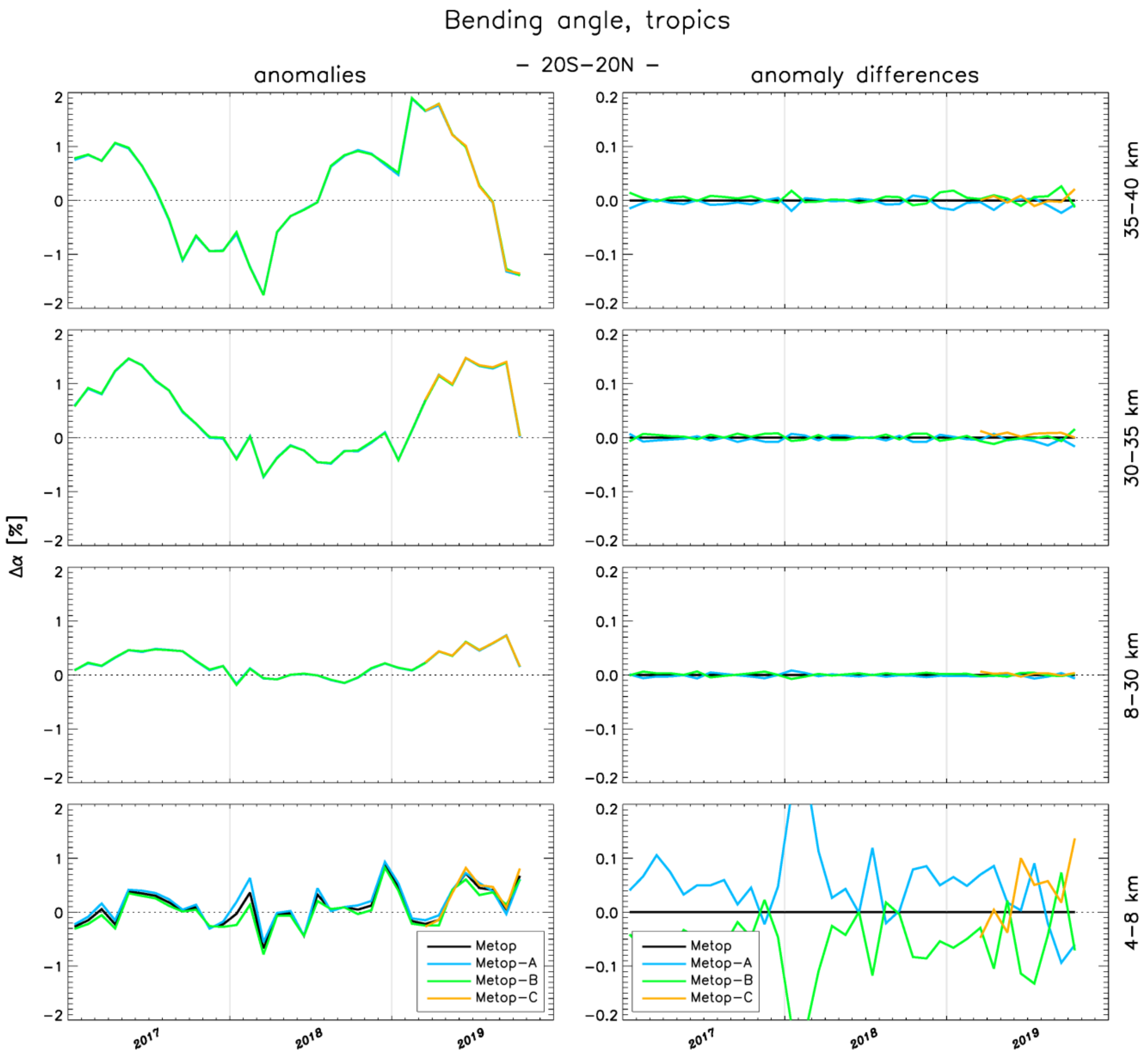

Figure 9b. *Left column: low-latitude monthly mean bending angle anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

However, there is a Metop-A vs. Metop-B difference developing from August 2019 with a potential impact on the Offline v1.1 data products. It is most evident at high altitudes in the dry temperature data records (the right-hand plots of Figs. 11a and b), but it can also be seen in refractivity (Figs. 10a and b) and bending angle (Figs. 9a and b). As described in Section 4.2.2, it is likely that this satellite difference is present at all altitudes and all latitudes.

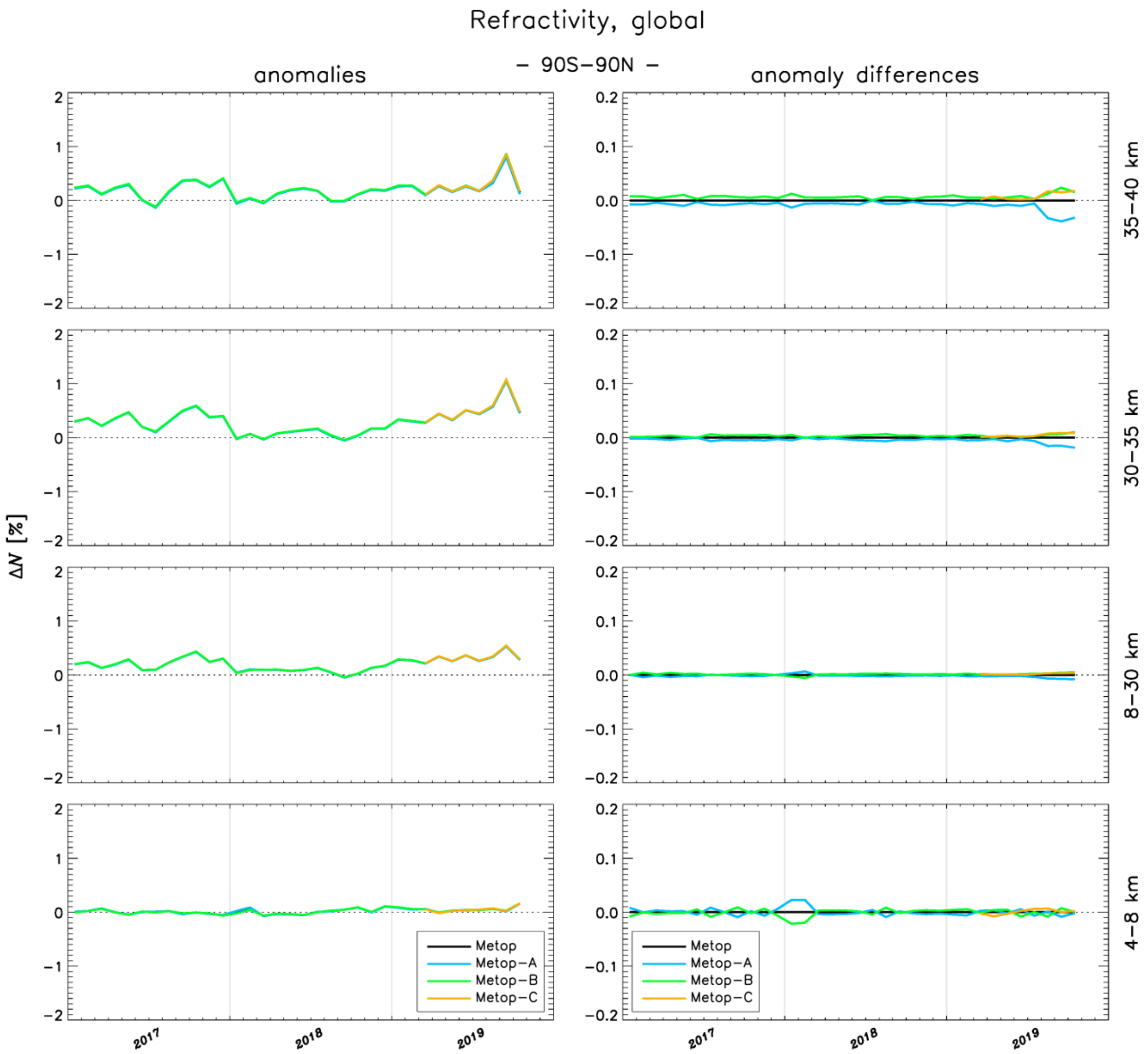

Figure 10a. *Left column: global monthly mean refractivity anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

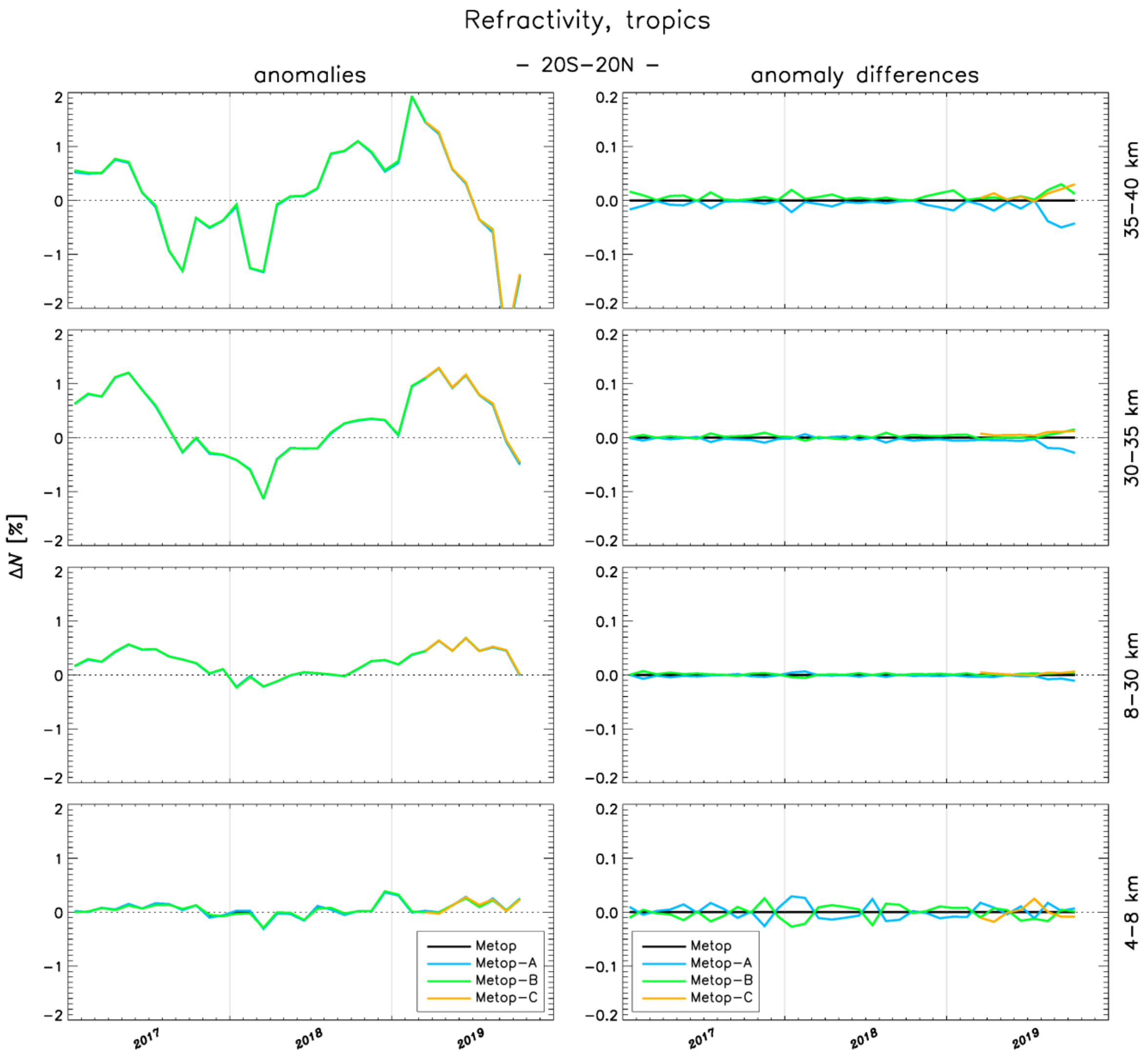

Figure 10b. *Left column: low-latitude monthly mean refractivity anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

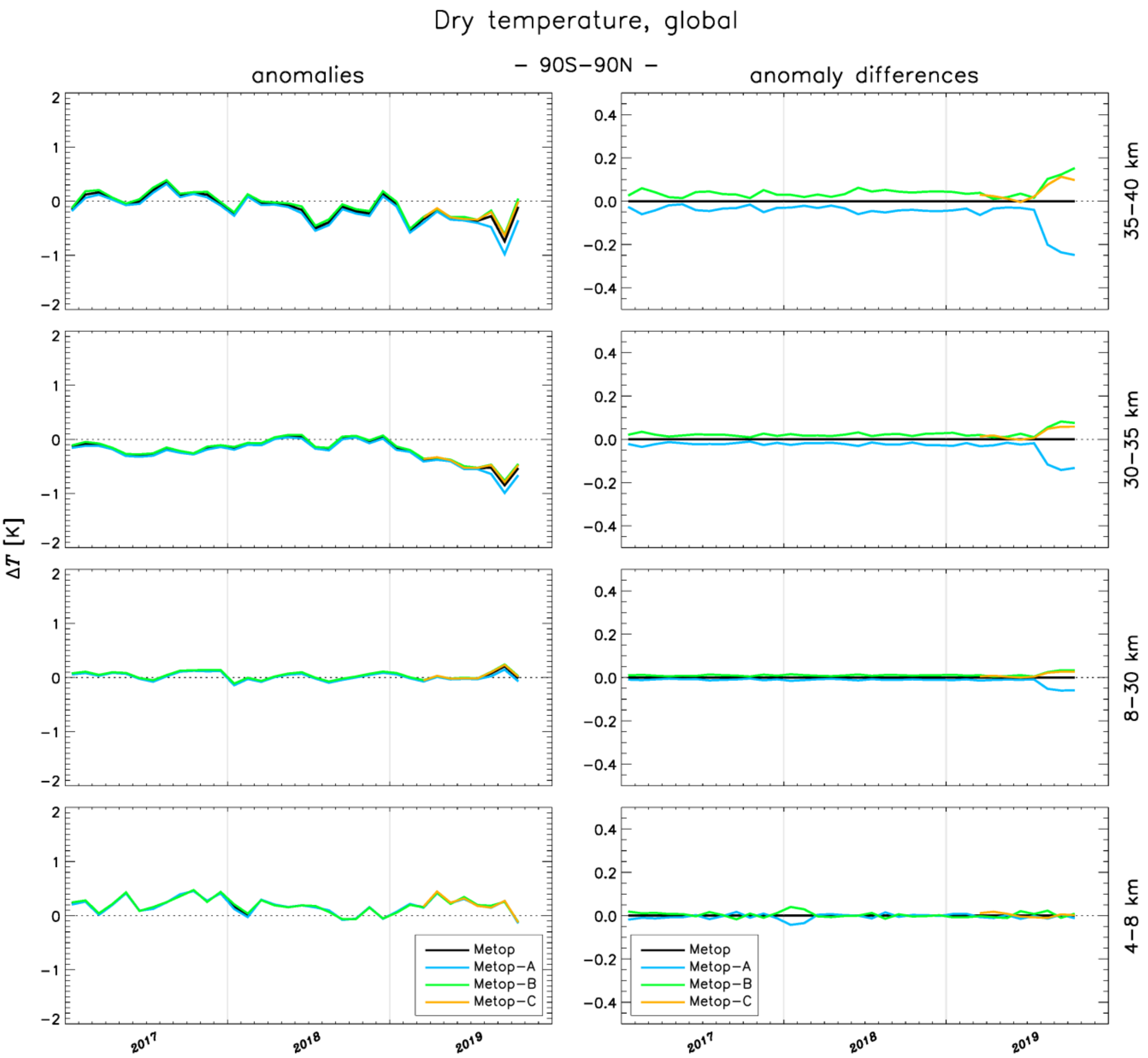

Figure 11a. *Left column: global monthly mean dry temperature anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

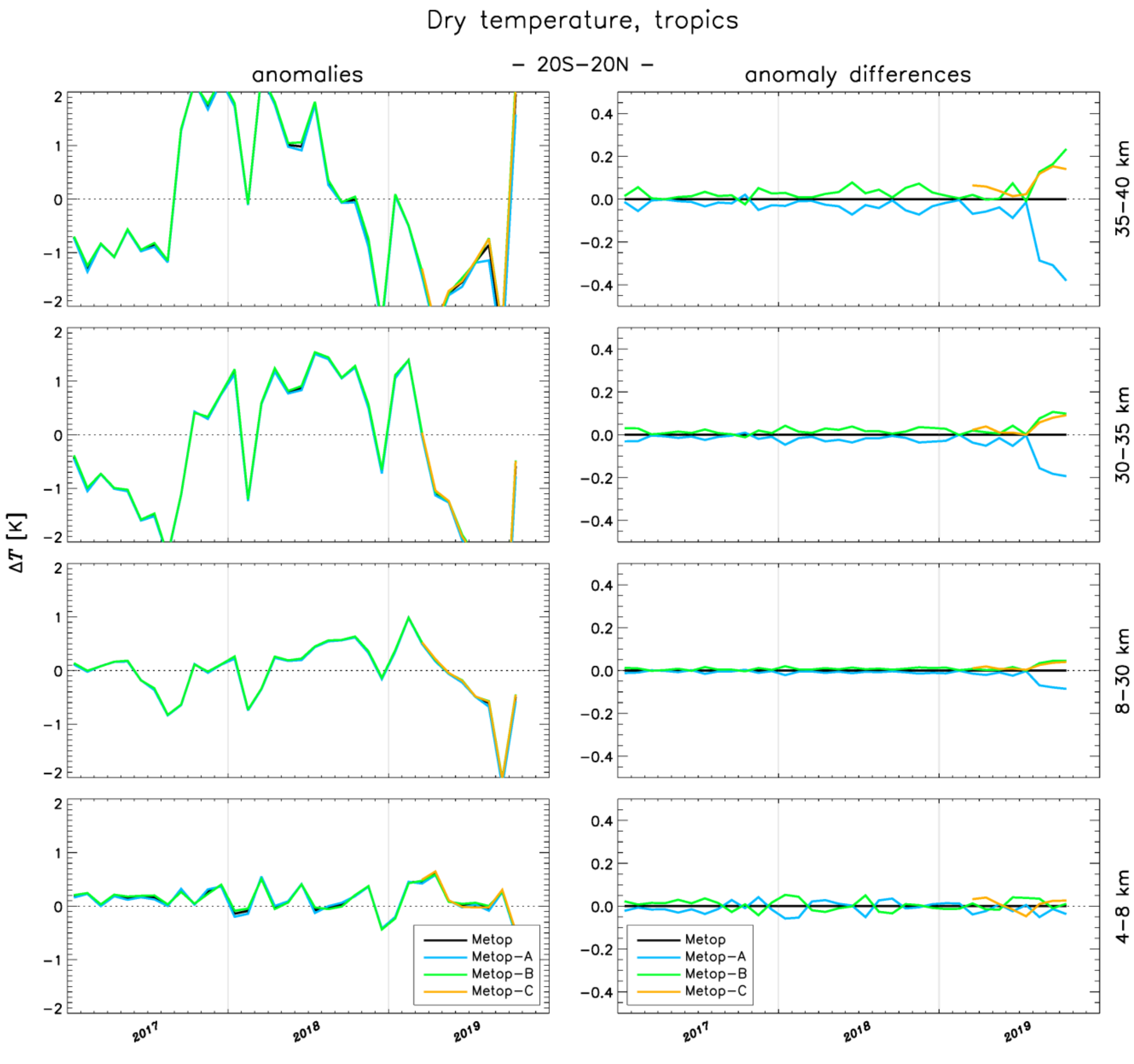

Figure 11b. *Left column: low-latitude monthly mean dry temperature anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

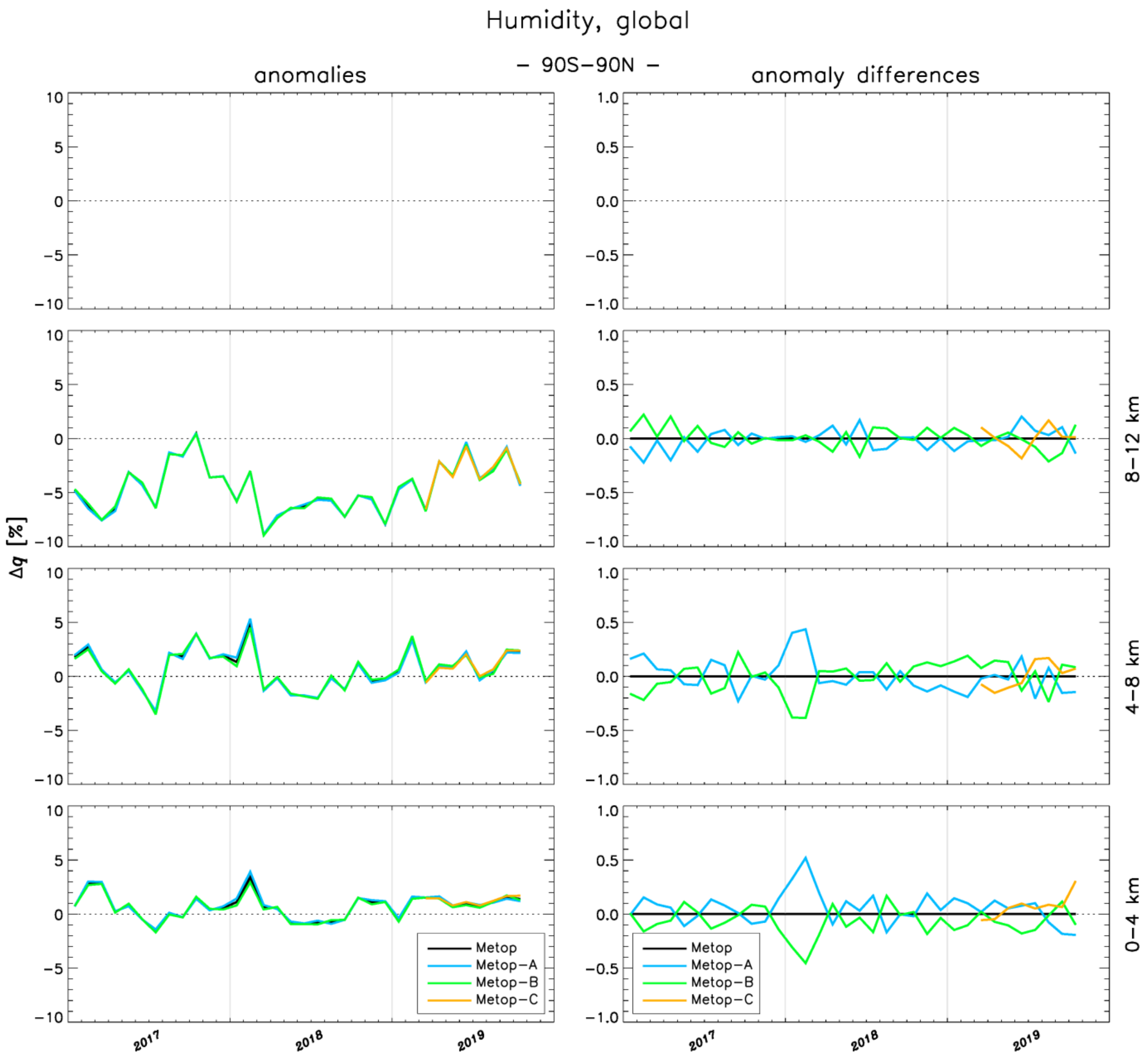

Figure 12a. *Left column: global monthly mean humidity anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

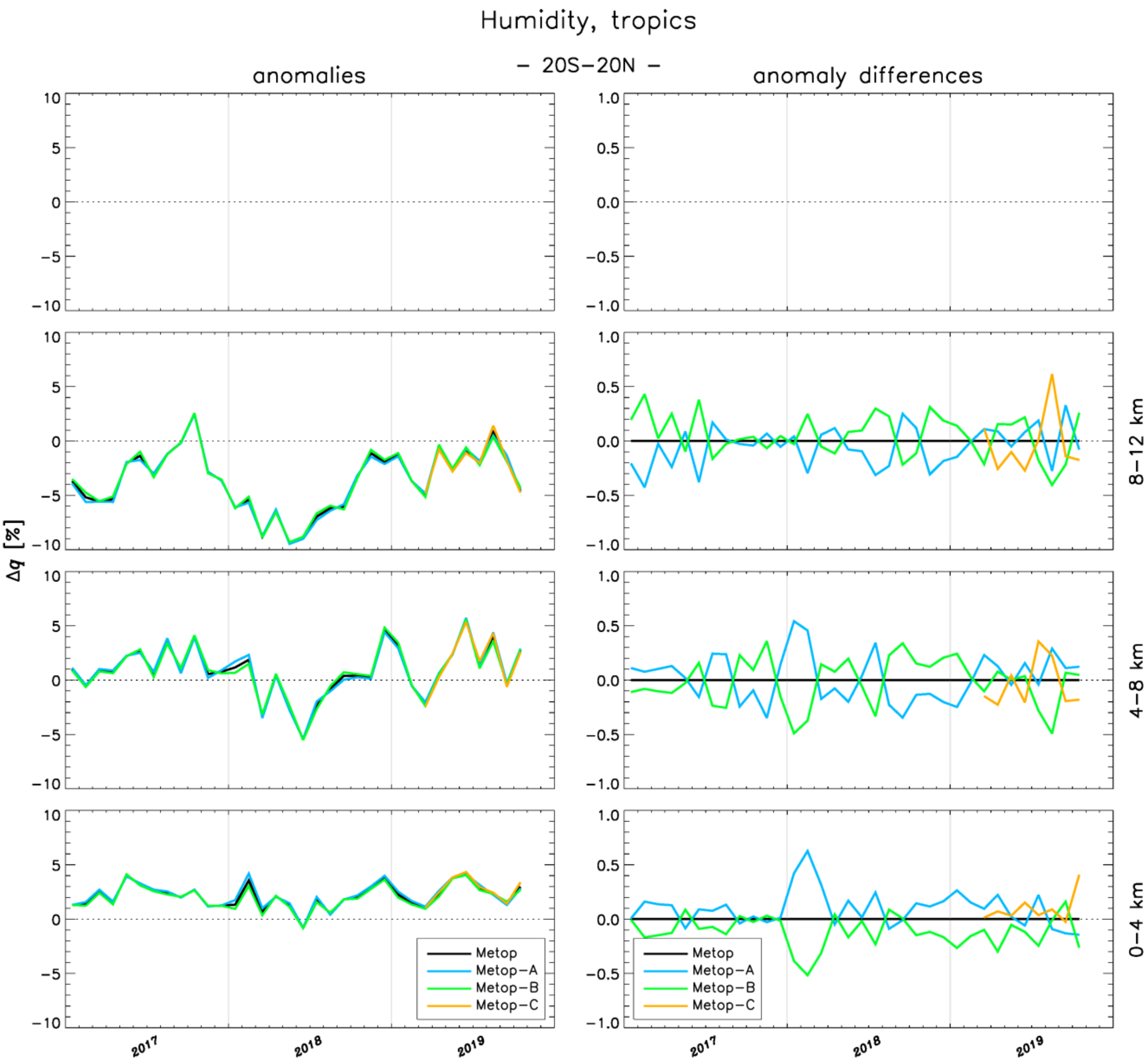

***Figure 12b.** Left column: low-latitude monthly mean humidity anomalies for Metop-A, -B, -C, and all Metop satellites. Right column: differences between the anomalies based on the individual Metop satellites and those based on all Metop satellites.*

3.2.2 Metop-A – Metop-B difference time-height plots

The satellite difference plots in Section 3.2.1 show that from August 2019 there is an increasingly larger difference between Metop-A and the other satellites. This difference is most evident at high altitudes, 35-40 km, and for dry temperature, although it is seen also in bending angle and refractivity.

In Figure 13, we plot Metop-A minus Metop-B differences up to 60 km for globally averaged and sampling-error corrected bending angle, refractivity, and dry temperature. We can identify the same satellite differences as in the time series plots in Figures 9 to 11. Here, the differences appear to continue all the way down to the surface. Other plots (not shown here) indicate that this phenomenon is also found at all latitudes.

The cause of the differences between Metop-A and the other Metop satellites, which developed from August 2019, is currently unknown. We note, however, that there was a significant Metop-A anomaly reported on 30 July 2019 which resulted in a transition to a thruster controlled mode whereby pointing was maintained by thruster firings, rather than reaction wheels. Apparently, the Metop-A spacecraft and all instruments were fully recovered and back to normal operations by 8 August 2019. Whether this incident is somehow related to the development of the Metop satellite differences that we see in our plots is currently unknown.

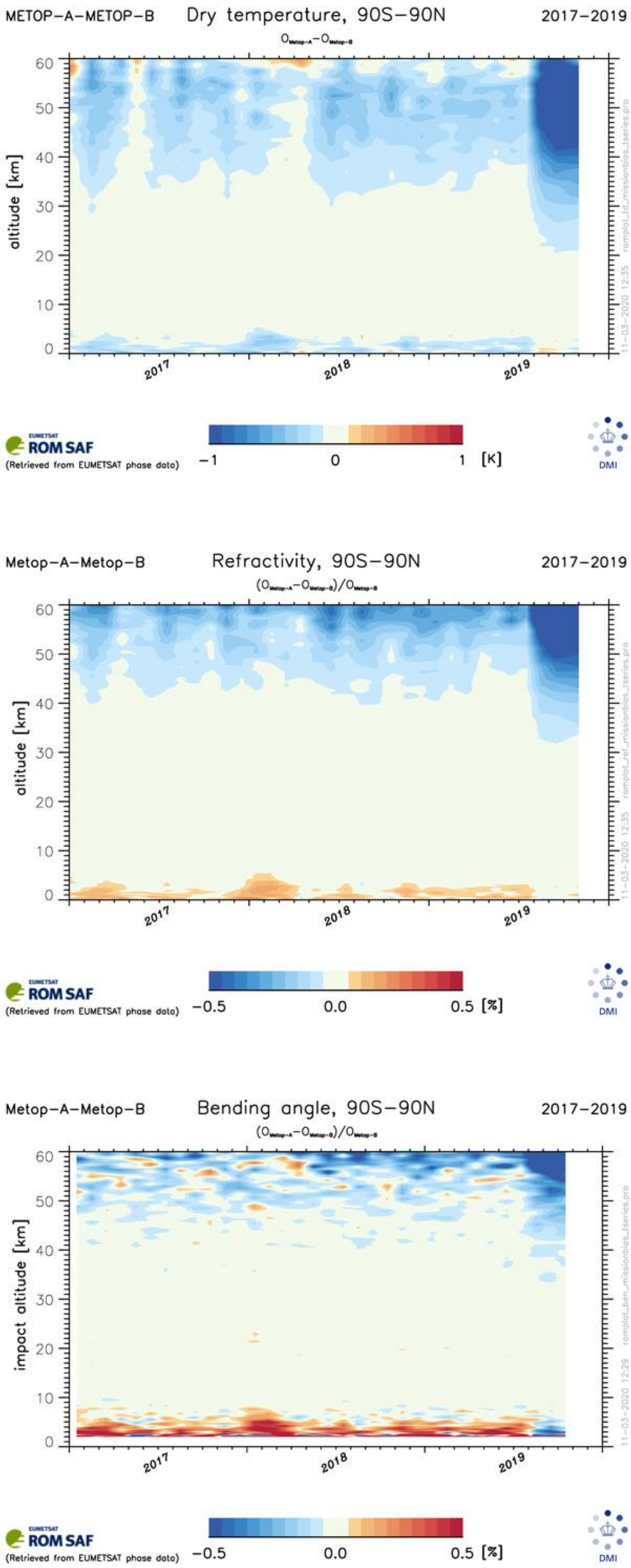

Figure 13. *Globally averaged Metop-A–Metop-B differences for monthly mean bending angle (lower panel), refractivity (middle panel), and dry temperature (upper panel), from January 2017 to October 2019. The gridded monthly mean data have been sampling-error corrected.*

3.3 Comparison between Offline data products v1.1 and v1.0

The main changes introduced by the transition from v1.0 to v1.1 are: a) second-order ionospheric correction ("kappa correction") of bending angles, and b) the use of ERA5 reanalysis instead of ERA-Interim reanalysis, with implications for the 1D-Var processing of humidity and temperature, the quality control procedures, and the sampling-error correction of gridded monthly mean data. The largest impacts are expected from the change of *a priori* (background) in the 1D-Var retrievals and from the kappa correction. In this section we present some plots related to these changes.

There is a 31-month overlap between the Offline v1.0 data and the validation dataset generated with the software for v1.1 data. We use these overlapping datasets to study differences between data product versions. Section 3.3.1 shows v1.1 – v1.0 differences for bending angle, refractivity, and dry temperature up to 60 km altitude, covering the altitudes and geophysical variables where we expect to find clear impacts of the kappa correction. Section 3.3.2 shows v1.1 – v1.0 differences for refractivity, temperature, and humidity up to 40 km (the humidity only up to 12 km), where the latter two variables are retrieved through 1D-Var processing which is known to be affected by the switch from ERA-Interim to ERA5.

3.3.1 Impacts of kappa correction

The kappa correction was introduced into the Offline data products v1.1. We expect to find impacts mainly in the upper stratosphere and above. We can also expect to find time variations in the impacts, as well as a certain latitudinal structure.

Figure 14 shows globally averaged v1.1 – v1.0 differences for bending angle, refractivity, and dry temperature up to 60 km altitude. The time series starts in January 2017 and ends in July 2019 when the generation of v1.0 data stopped. No sampling error correction was applied to minimize potential effects of the shift from ERA-Interim to ERA5. There is still a potential effect from slightly different QC that cannot be avoided, but we assume that effect to be minimal. The magnitude of the impact in globally averaged bending angle is about 0.05-0.10% at 50 km, while in globally averaged dry temperature it is about 0.1 K at an altitude of 30 km and 0.2 K at 40 km.

Figure 15 shows time averaged, but latitudinally resolved, v1.1 – v1.0 differences for bending angle, refractivity, and dry temperature up to 60 km altitude. We find a latitudinal pattern with three local maxima, the largest one at the equator and two smaller peaks at around 70 deegres south and north.

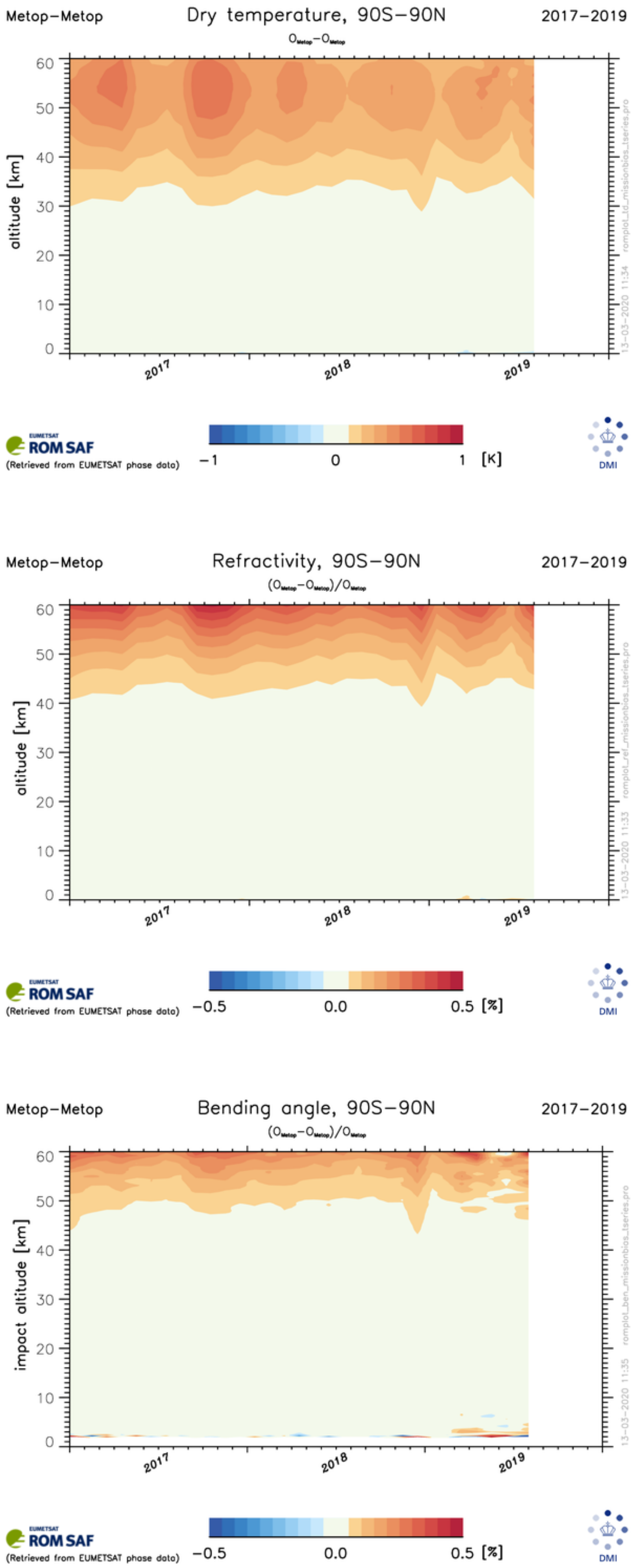

Figure 14. *Globally averaged v1.1–v1.0 differences for monthly mean bending angle (lower panel), refractivity (middle panel), and dry temperature (upper panel), from January 2017 to July 2019. Here, the gridded monthly mean data were not sampling error corrected.*

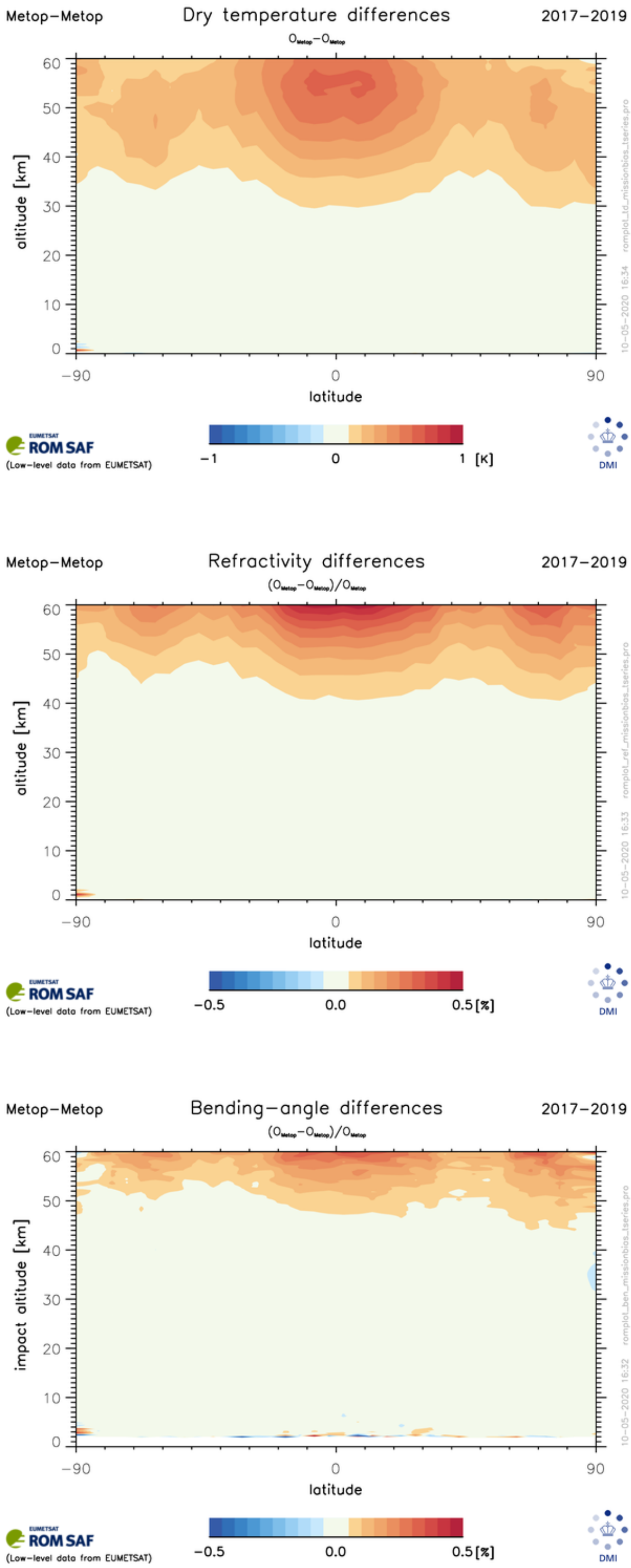

Figure 15. *Time averaged v1.1–v1.0 differences for bending angle (lower panel), refractivity (middle panel), and dry temperature (upper panel), from January 2017 to July 2019. Here, the gridded monthly mean data were not sampling error corrected.*

3.3.2 Impacts of switch from ERA-Interim to ERA5

During 2019 ECMWF stopped the generation of the ERA-Interim reanalysis. It was replaced by the ERA5 reanalysis (for observing dates before 2007 the recommendation is to use ERA5.1). As a consequence, the ROM SAF Offline processing switched from ERA-Interim to ERA5, which is used in the Offline product version 1.1 from August 2019 and onward.

The largest impacts by the use of ERA5 instead of ERA-Interim are expected to be those from the change of *a priori* (background) in the 1D-Var retrievals. This has consequences for the 1D-Var processing of humidity, temperature, and surface pressure. There are also consequences for the quality control procedures and for the sampling-error correction of gridded monthly mean data. In this section we present some plots related to these impacts, with a focus on the variables generated through a 1D-Var retrieval.

Figure 16 shows globally averaged v1.1 – v1.0 differences for refractivity, temperature, and humidity up to 40 km (the humidity only up to 12 km). The time series starts in January 2017 and ends in July 2019 when the generation of v1.0 data stopped. In general we find smaller values of specific humidity in v1.1 compared to v1.0. In globally averaged data, the humidity is up to 10% smaller for v1.1 in the 9-12 km altitude range. In the lower troposphere, in the 1-2 km altitude range, the humidity in v1.1 is about 2-3% smaller than in v1.0. There is a seasonal cycle in the globally averaged v1.1 – v1.0 differences, whereby the differences in the 9-12 km altitude range are larger during northern hemisphere winter. The globally averaged v1.1 – v1.0 temperature differences are relatively small below about 25 km. At higher altitudes, the temperature differences become larger and at an altitude of about 35 km they exceed 1 K. The refractivity differences are small, with discernible differences only in the lower troposphere. These are presumably a consequence of the switch from ERA-Interim to ERA5 in the sampling-error correction, which is a bit surprising. The causes of this will have to be investigated.

Figure 17 shows latitudinally resolved time averaged v1.1 – v1.0 differences for refract-tivity, temperature, and humidity up to 40 km (the humidity only up to 12 km). For humidity, we find a significant latitudinal variation. The v1.1 – v1.0 humidity differences are predominantly negative, but particularly at low latitudes we find atmospheric layers where humidity actually is larger in v1.1 than in v1.0. Concerning the refractivity differences, most likely related to the sampling-error correction, we find that they are concentrated to low- and mid-latitudes.

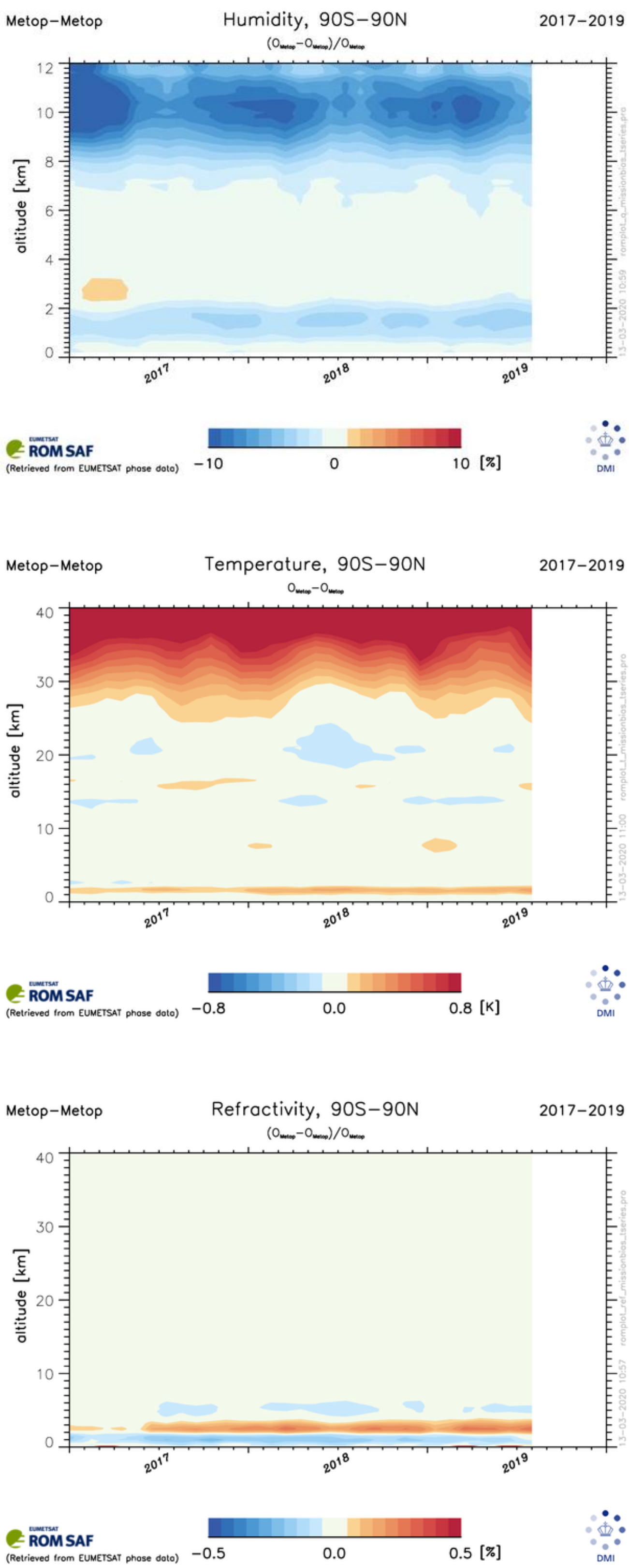

Figure 16. *Globally averaged v1.1–v1.0 differences for monthly mean refractivity (lower panel), temperature (middle panel), and humidity (upper panel), from January 2017 to July 2019. The temperature and humidity profiles were obtained through 1D-Var retrievals, and the gridded monthly mean data were sampling error corrected.*

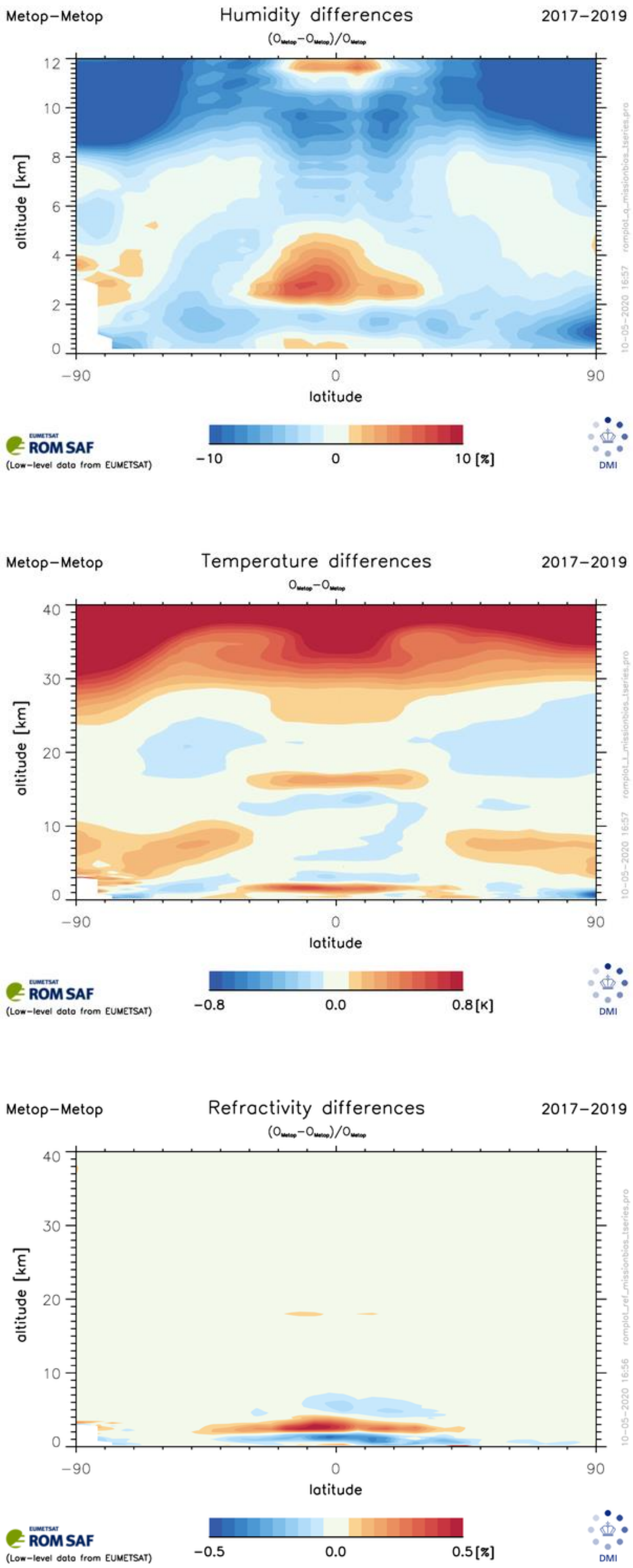

Figure 17. *Time averaged v1.1–v1.0 differences for refractivity (lower panel), temperature (middle panel), and humidity (upper panel) including data from January 2017 to July 2019. The temperature and humidity profiles were obtained through 1D-Var retrievals, and the gridded monthly mean data were sampling error corrected.*

4. Compliance with product requirements

The product requirements express the commitment of the ROM SAF team for the development of data products. The formal requirements for the ROM SAF data products are stated in the PRD [AD.3]. There are three sets of accuracy requirements (*threshold*, *target*, and *optimal*). The requirements are defined as functions of height (except for the tropopause height requirements). In the present report, the PRD accuracy requirements are colour coded: orange for *threshold*, yellow for *target*, and green for *optimal*. Data that do not reach the threshold are coded with *red* colour.

The compliance with the PRD accuracy requirements is determined in the following way. First, we define 3 latitude regions: tropics (30˚S–30˚N), mid-latitudes (30˚N–60˚N and 30˚S–60˚S), and polar (60˚N–90˚N and 60˚S–90˚S), and 3 altitude regions: low (0-8 km), middle (8-20 km), and high (20-50 km). That defines 9 broad latitude-height regions. Each of these 9 regions includes several hundred monthly values (though not independent, the data are more or less strongly correlated). For each observed monthly value, we compute the absolute deviation from ERA5, |O-B|, and determine whether the absolute deviation is smaller than the threshold, target or optimal accuracies. We then determine the PRD compliance for the latitude-height region by requiring that at least 60% of the monthly mean data within that region reach the corresponding accuracy.

Hence, the *formal compliance with the PRD requirements is based on the 60% percentiles of the absolute deviation from ERA5, within 9 broad latitude-height regions*. This quantity is also used in the definition of the Service Specifications (Section 6).

It should be noted that here is a degree of circularity arising from the fact that the ERA5 short-term forecasts have been used as *a priori* data in the ROM SAF 1D-Var processing of temperature and humidity data. At altitudes and/or latitudes where the background information dominates the 1D-Var solution, ERA5 data have a significant influence on the RO-ERA5 comparison of 1D-Var temperature and humidity. However, even though the differences found in the comparisons cannot be naively interpreted as an expression of errors in ERA5 or in the RO data, such comparisons can nevertheless be useful to detect unexpected anomalies in the retrievals.

In section 3.1 we compared the RO data with ERA5 reanalysis data. Those comparisons provide a context for the check against the formal PRD requirements. One conclusion is that at least some of the deviations from the optimal accuracies relative to the PRD requirements are most likely caused by biases in ERA5, and are not due to the observed RO data. The degree of compliance with the PRD requirements partly depends on the choice of data set used for comparison.

In Figures 18a-d, we present plots of the formal compliance with the PRD requirements for all eight geophysical variables for Metop-A, -B, -C, and for the all-Metop Level 3 data. Note that it is only the last three months (August to October 2019) that are being formally validated. The preceding period, starting in January 2017, is only provided as a context.

All ROM SAF Level 3 Offline data products are compliant with the PRD requirements (no red cells in Figs. 18a-d). The lowest degree of compliance is found for the dry variables at high altitudes, but also for the refractivity. These are regions where some biases relative to ERA5 are to be expected. A certain degree of seasonality in the compliance is also observed, particularly at high altitudes.

We conclude that the ROM SAF Level 3 Offline monthly mean data products are formally compliant with the PRD requirements.

Metop-A

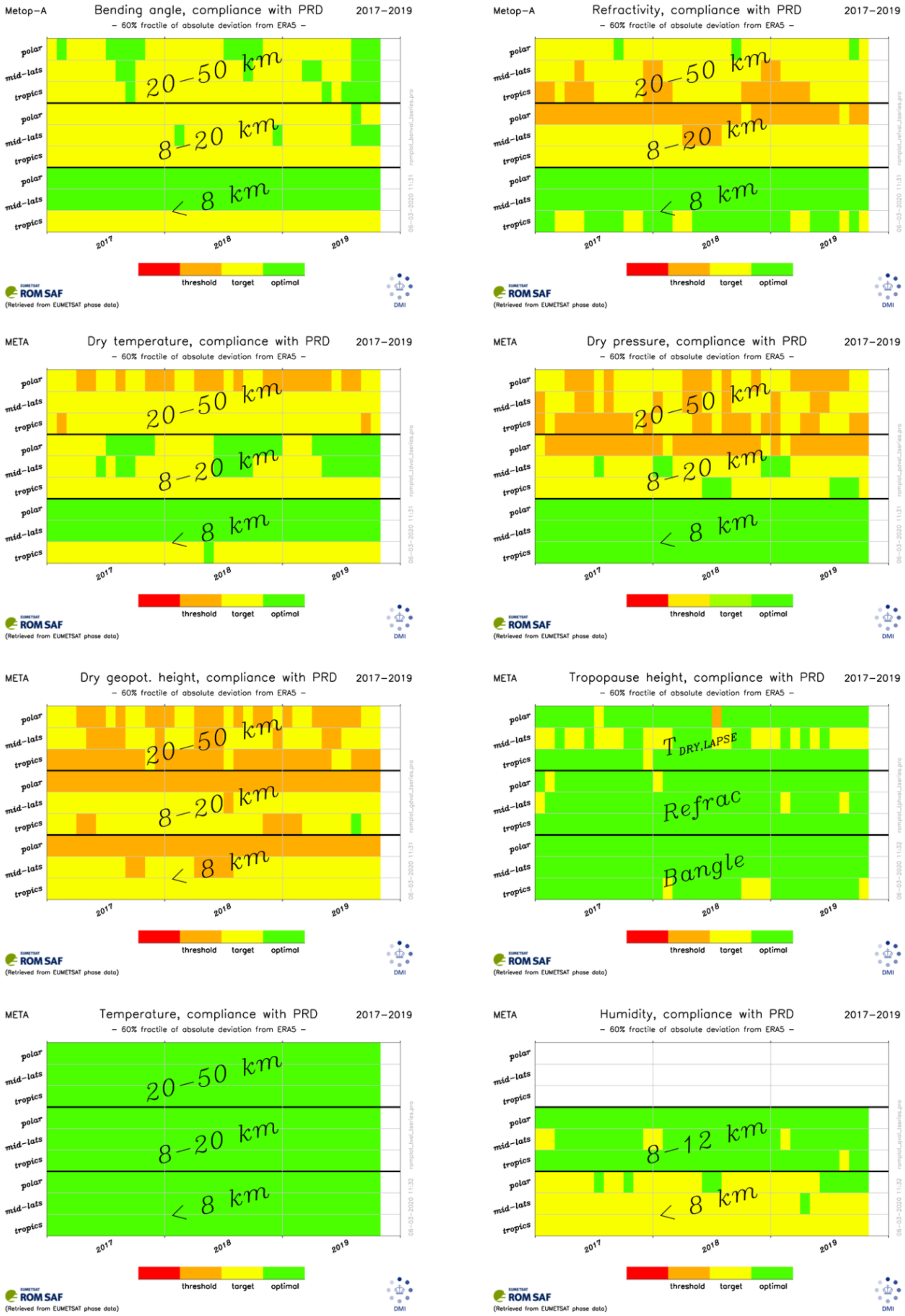

Figure 18a. *Compliance with the PRD requirements for monthly mean Metop-A data, based on the 60% percentile of the |O–B| distribution within 9 broad latitude-height regions. Red colour indicates non-compliance. Note that it is only the last three months (August to October 2019) that are being formally validated here.*

Metop-B

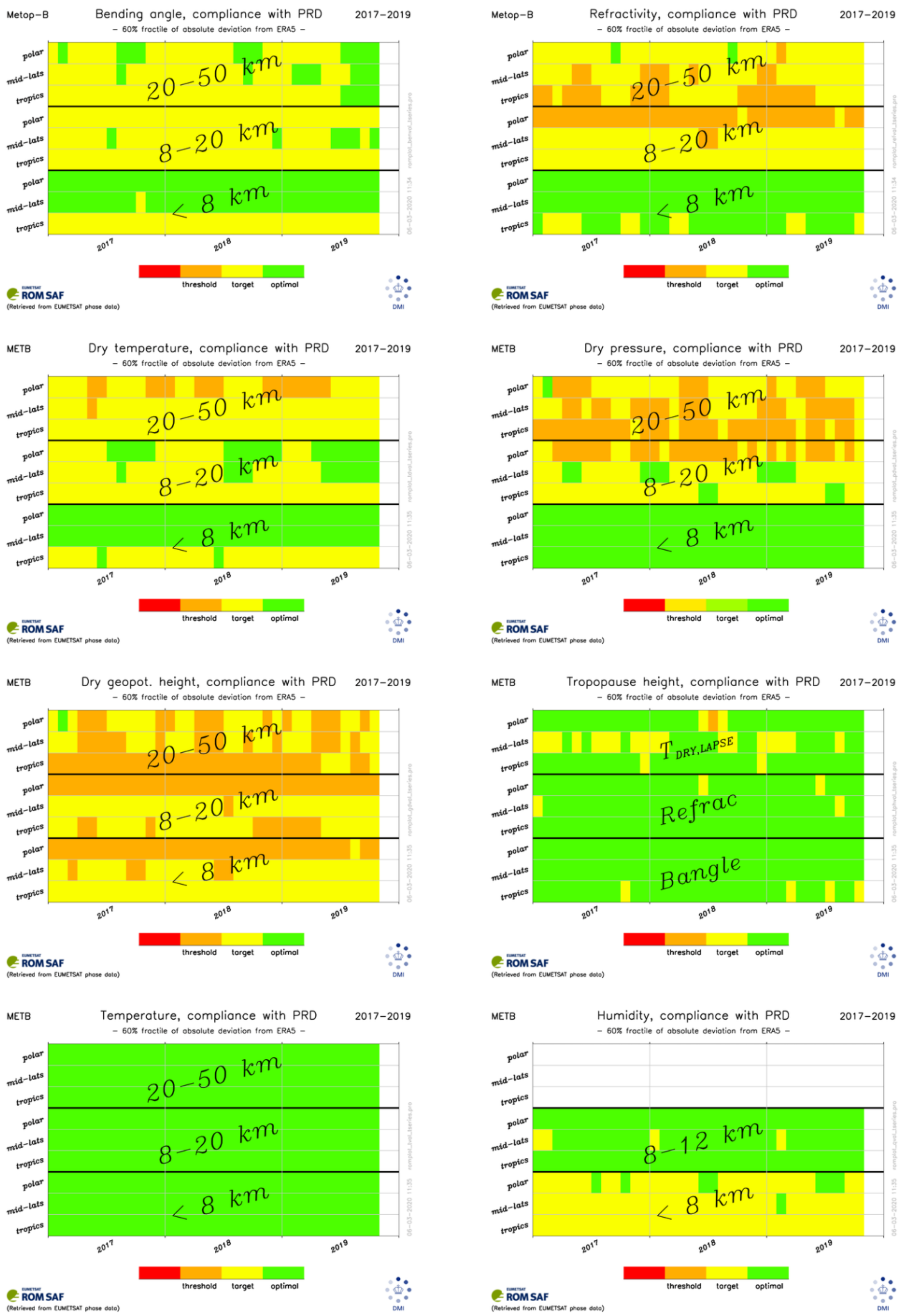

Figure 18b. *Compliance with the PRD requirements for monthly mean Metop-B data, based on the 60% percentile of the |O–B| distribution within 9 broad latitude-height regions. Red colour indicates non-compliance. Note that it is only the last three months (August to October 2019) that are being formally validated here.*

Metop-C

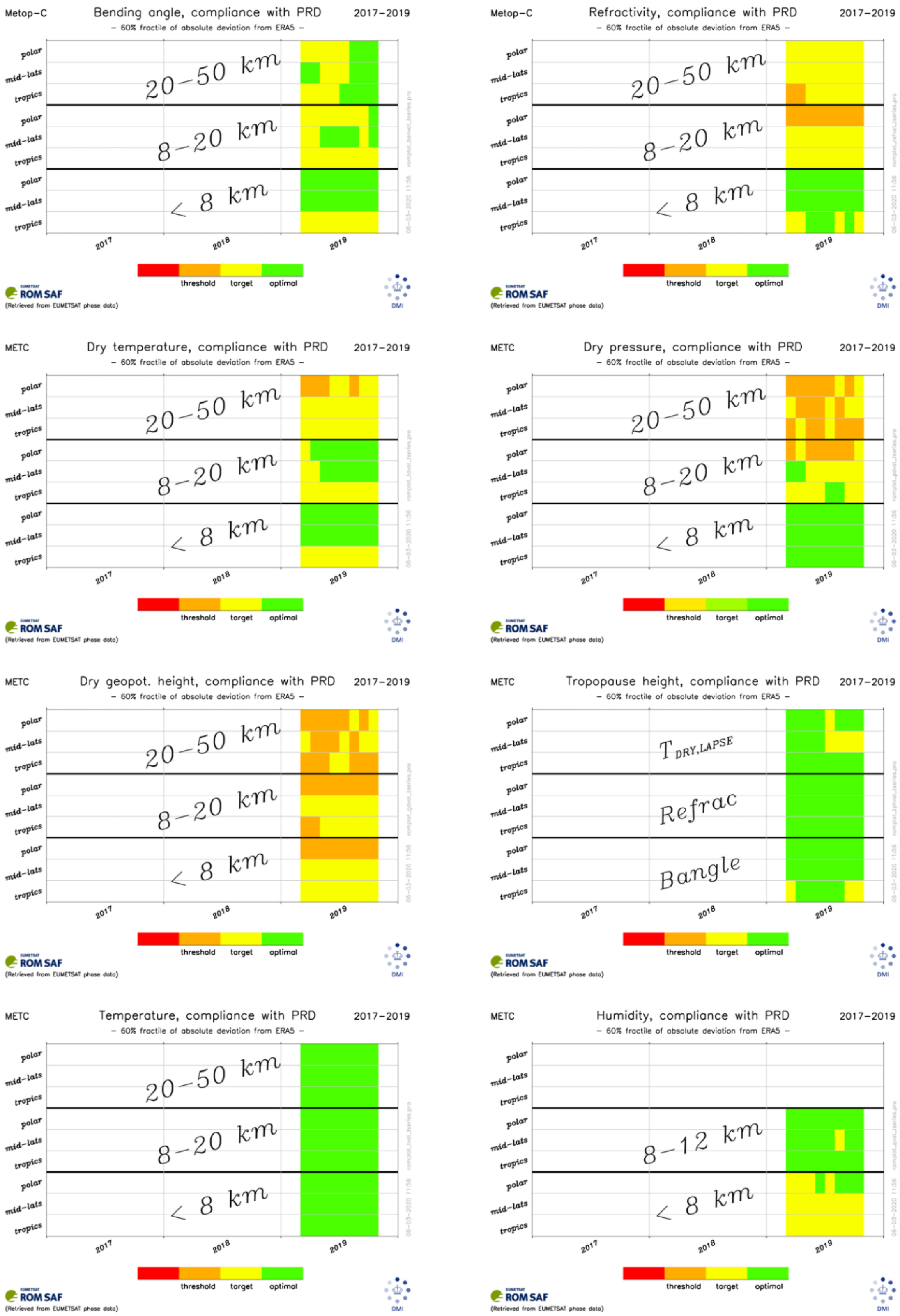

Figure 18c. *Compliance with the PRD requirements for monthly mean Metop-C data, based on the 60% percentile of the |O-B| distribution within 9 broad latitude-height regions. Red colour indicates non-compliance. Note that it is only the last three months (August to October 2019) that are being formally validated here.*

Metop

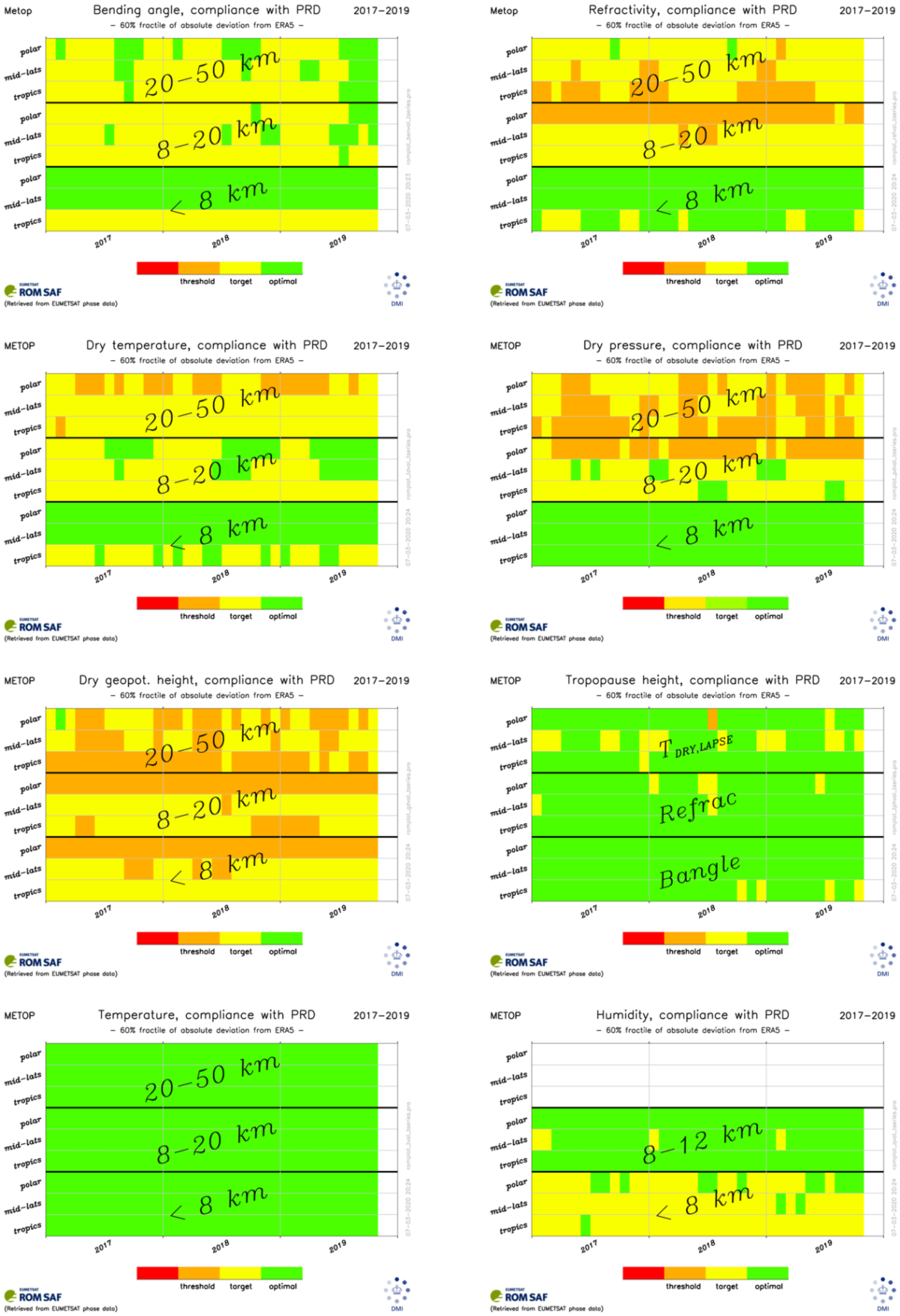

Figure 18d. *Compliance with the PRD requirements for monthly mean Metop data, based on the 60% percentile of the |O-B| distribution within 9 broad latitude-height regions. Red colour indicates non-compliance. Note that it is only the last three months (August to October 2019) that are being formally validated here.*

5. Service specifications

The Service Specifications describe the commitments by the ROM SAF related to the services and products provided to the users. These commitments include a set of operational accuracy targets that should be met by the Level 3 gridded data products, and which should be regularly monitored and documented as a part of normal operations.

The accuracies proposed to be included in the service specifications for the Level 3 Offline data products are listed in Table 4. The methods used for comparing RO data with the service specifications are identical to the methods defined in the PRD. Compliance is determined by requiring that *a certain percentile of the absolute deviations from ERA5 are smaller than the corresponding specifications* as stated in the Service Specifications Document. For refractivity and the dry variables we use the median (50% percentile) while for the other variables we use the 60% percentile, similar to the PRD. The service specifications agree to the *target accuracies* in the PRD requirements. The outcome of the regular monitoring against the service specifications is provided on the ROM SAF web page.

Table 4. *Proposed Service Specifications for the ROM SAF Level 3 Offline data products. The accuracies are stated separately in three height layers; below 8 km, 8-25 km, and 25–50 km (for humidity only up to 12 km). Where both absolute and relative numbers are given, the requirement is given by the greater of these two.*

GRM-93–99, GRM-191 (Metop A) **GRM-53–59, GRM-192 (Metop B)** **GRM-73–79, GRM-193 (Metop-C)** **GRM-83–89, GRM-194 (Metop)**
Bending angle
25 – 50 km: 0.3 % or 0.6 μrad[1] 8 – 25 km: 0.3 % 0 – 8 km: 3.0 – 0.3 %
Refractivity
25 – 50 km: 0.24 % or 0.012 N-units[1] 8 – 25 km: 0.24 % 0 – 8 km: 2.4 – 0.24 %
Dry temperature
25 – 50 km: 0.3 – 3.0 K 8 – 25 km: 0.3 K 0 – 8 km: 1.5 – 0.3 K
Dry pressure
25 – 50 km: 0.12 – 0.60 % 8 – 25 km: 0.12 % 0 – 8 km 0.60 – 0.12 %
Dry geopotential height
25 – 50 km: 6 – 60 m 8 – 25 km: 6 m 0 - 8 km: 6 m
Temperature
25 – 50 km: 0.3 – 3.0 K 8 – 25 km: 0.3 K 0 – 8 km: 1.0 – 0.3 K
Specific humidity
8 – 12 km: 4.0 % 0 – 8 km: 4.0 %
Tropopause Height
200.0 m
[1] Whichever is greater. [2] An accuracy interval means a linearly changing quantity between the two values over the given height interval.
Methods for validation
Nine broad latitude-height regions (tropics, mid-latitudes, high latitudes and low, middle, high altitudes) are defined. The absolute values of the differences between the monthly-mean RO data and the ERA5 reanalysis data are computed on the Level 3 grid. Each value is compared to the service specification valid for that altitude. The compliance with the Service Specifications are determined, within each region and for each calendar month, by requiring that 60% (bending angle, temperature, humidity, tropopause height) or 50% (refractivity, dry variables) of the absolute differences are smaller than the corresponding specification.

6. Conclusions

We conclude that the ROM SAF Level 3 Offline gridded monthly mean data are of high quality, that they meet the expectations we have on a ROM SAF data product, and that they comply with the product requirements as stated in the PRD [AD.3]. We find that the evolution from data product version 1.0 to version 1.1 have not introduced any major new features that were not expected. The issues that were detected during the validation, and that requires further investigations, are not of a character that prevent the data products from being released. These issues are described in Section 6.1 below.

6.1 Limitations

As a result of the validation activity a few new issued appeared. These are:

- From August 2019 Metop-A appears to develop a bias relative to the other Metop satellites. It is most evident at high altitudes in the dry temperature data records, but it can also be seen in refractivity and bending angle and it may be present at all altitudes and all latitudes. This Metop-A bias requires further investigation, and also monitoring to follow its evolution in time. The potential relation with a significant Metop-A anomaly that occurred on 30 July 2019 should be clarified.

- Comparison of Level 3 data versions 1.1 and 1.0 reveals differences that appear to be caused by the sampling error correction. The differences are small and can mainly be seen in the lower troposphere at low- and mid-latitudes. These differences are most likely a consequence of the switch from ERA-Interim to ERA5 in the sampling-error correction. The cause of these differences will have to be investigated.