Validation Report: Interim Climate Data Record (ICDR) product version 1.1

Version 1.1

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ROM SAF Consortium
Danish Meteorological Institute (DMI)
European Centre for Medium-Range Weather Forecasts (ECMWF)
Institut d'Estudis Espacials de Catalunya (IEEC)
Met Office (UKMO)

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DOCUMENT AUTHOR TABLE

	Author(s)	Function	Date
Prepared by:	Hans Gleisner	ROM SAF Climate Coordinator	16/9 2020
Reviewed by (internal):	Johannes K. Nielsen	ROM SAF Scientist	9/7 2020
Reviewed by (internal):	Stig Syndergaard	ROM SAF Design Coordinator	9/7 2020
Approved by:	Kent B. Lauritsen	ROM SAF Project Manager	16/9 2020

DOCUMENT CHANGE RECORD

Version	Date	By	Description
1.0	9/7 2020	HGL	First version for ICDR v1.1 checkpoint meeting
1.1	16/9 2020	HGL	Correction of ”March” to “August” in table 2.1

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 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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List of Contents

Executive Summary

The ROM SAF Interim Climate Data Record (ICDR) is based on GRAS radio occultation (RO) measurements by the Metop mission. Version 1.0 of the ROM SAF ICDR covers the time period from January 2017 to July 2019. It provides a continuation of the ROM SAF CDR v1.0 which ended in December 2016. After an update of the processing software, which includes a switch of ancillary input data from ERA-Interim to ERA5, the ROM SAF starts generation of ICDR version 1.1 covering the time period from August 2019 and onward.

The purpose of the present validation report is to show that ICDR v1.1 can be used to extend ICDR v1.0 from August 2019. In addition, we also aim to show that the ICDR, starting in January 2017, can be used to extend the CDR v1.0 which ended in December 2016. Hence, the focus of the validation is to study the continuity of the data series across the CDR/ICDR and ICDR v1.0/v1.1 transitions, and to assess whether those transitions are associated with variations of the time series that are likely to degrade the quality of the combined climate records.

We assess the continuity across the ICDR v1.0/v1.1 transition by inspection of RO minus ERA5 monthly mean difference time series from January 2017 to January 2020. The continuity across the CDR/ICDR transition is similarly assessed from RO minus ERA-Interim differences. This differencing removes most of the variability originating in the climate system itself. Errors that are common to the RO and reanalysis data are also removed by the differencing. Only errors that are not shared by the two data sources remain. Our assessment has a focus on whether the variations across the transitions, and the variability following the transitions, are qualitatively and quantitatively different from the time variations in the preceding difference time series.

We conclude that the change of data product version from ICDR v1.0 to v1.1 in August 2019 has negligible impacts on bending angle, refractivity, the dry variables, tropopause heights, 1D-Var temperatures below 30 km, and humidity below 8 km. For 1D-Var temperatures above 30 km, the use of ICDR v1.1 from August 2019 may be limited for certain applications. Similarly, for the 1D-Var humidity above 8 km, outside of the low-latitude region 30˚S - 30˚N, the use of ICDR v1.1 is limited for certain types of application. We also conclude that the change of data product from CDR v1.0 to ICDR v1.0 in January 2017 has negligible impacts on the general quality of the RO data products, and that the combined CDR/ICDR data set can be used as continuous time series of climate data.

1. Introduction

1.1 Purpose of the document

This document describes the validation of the ROM SAF Interim Climate Data Record (ICDR) v1.1, which includes Level 1B bending angle, Level 2 refractivity, dry temperature, temperature, specific humidity, pressure, surface pressure and tropopause height data, and Level 3 gridded monthly mean data. The data are generated by the ROM SAF GPAC 2.4.0 processing system using EUMETSAT Metop Level 1A GRAS data as input, together with ancillary information from ECMWF ERA5 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 1B, 2 and data products are described in the Algorithms Theoretical Baseline Documents (ATBDs) [RD.1, RD.2, RD.3, RD.4, RD.5, RD.6].

1.1.1 List of data products being validated in this report

The ROM SAF data products being validated in this report are listed in Table 1.1. They consist of Level 1B bending angle, Level 2 refractivity, dry temperature, temperature, specific humidity, pressure, surface pressure and tropopause height data, and Level 3 monthly mean gridded data. The ICDR is generated on a regular basis with the same algorithms as a corresponding CDR but using currently available input data. The purpose of the ICDR is to extend the CDR until data from the next reprocessing become available. Version 1.0 of the ROM SAF ICDR covers the time period from January 2017 to July 2019. After an update of the processing software, which includes a switch of ancillary input data from ERA-Interim to ERA5, the ROM SAF starts generating ICDR version 1.1 covering the time period from August 2019 and onward.

Table 1.1 List of *Interim Climate Data Records* covered by this Validation Report. The Metop Level 1A input data to the ROM SAF processing is obtained from the EUMETSAT Secretariat.

Product ID	Product Name	Product acronym	Satellite input	Product version
GRM-29-L1-B-I1	ICDR bending angle	IBAMET	Metop	1.1
GRM-29-L2-R-I1	ICDR refractivity profile	IRPMET	Metop	1.1
GRM-29-L2-D-I1	ICDR dry temperature profile	IDPMET	Metop	1.1
GRM-29-L2-T-I1	ICDR temperature profile	ITPMET	Metop	1.1
GRM-29-L2-P-I1	ICDR pressure profile	IPPMET	Metop	1.1
GRM-29-L2-H-I1	ICDR specific humidity profile	IHPMET	Metop	1.1
GRM-29-L2-S-I1	ICDR surface pressure	ISPMET	Metop	1.1
GRM-29-L2-C-I1	ICDR tropopause height	ICHMET	Metop	1.1
GRM-29-L3-B-I1	ICDR bending angle grid	IBGMET	Metop	1.1
GRM-29-L3-R-I1	ICDR refractivity grid	IRGMET	Metop	1.1
GRM-29-L3-D-I1	ICDR dry temperature grid	ITGMET	Metop	1.1
GRM-29-L3-Y-I1	ICDR dry pressure grid	IHGMET	Metop	1.1
GRM-29-L3-Z-I1	ICDR dry geopotential height grid	IZGMET	Metop	1.1
GRM-29-L3-T-I1	ICDR temperature grid	IDGMET	Metop	1.1
GRM-29-L3-H-I1	ICDR specific humidity grid	IYGMET	Metop	1.1
GRM-29-L3-C-I1	ICDR tropopause height grid	ICGMET	Metop	1.1

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, Ref: SAF/ROM/DMI/ALG/BA/001

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

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

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

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

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

[RD.7] Gleisner, H., Latitudinal binning and area-weighted averaging of irregularly distributed radio occultation data, GRAS SAF Report 10, 2010

[RD.8] 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.9] 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.10] Steiner, A. K., et al., Quantification of structural uncertainty in climate data records from GPS radio occultation, Atmos. Chem. Phys., 13, 1469-1484, 2013

[RD.11] Dee, D. P., et al., The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quart. J. Roy. Meteorol. Soc., 137, 553–597, 2011

[RD.12] Simmons, A., et al., Global stratospheric temperature bias and other stratospheric aspects of ERA5 and ERA5.1, ECMW Technical Memoranda, 859, 2020

[RD.13] Gleisner, H., Lauritsen, K. B., Nielsen, J. K., Syndergaard, S., Evaluation of the 15-year ROM SAF monthly mean GPS radio occultation climate data record, Atmos. Meas. Tech., 13, 3081–3098, 2020

[RD.14] The ROPP Pre-processor Module User Guide, Ref: SAF/ROM/METO/UG/ROPP/004

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 (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].

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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

Chapter 1: This chapter contains the purpose and references and definitions used in the document.

Chapter 2: This chapter contains background information about satellite and reanalysis input data, RO data products, and the QC tests applied to the data.

Chapter 3: This chapter contains the validation of ICDR v1.1 and comparisons to CDR v1.0 and ICDR v1.0.

Chapter 4: This chapter contains the conclusions and also mentions limitations of the ICDR v1.1 products.

2. Background

2.1 Satellites and time coverage

The Metop satellites used in the generation of ROM SAF ICDR version 1.0 and version 1.1 data products are listed in Table 2.1. The table also shows the time periods during which each Metop satellite contributed to the ICDR data.

Table 2.1 Metop satellites contributing to the ROM SAF ICDR data products, and the time periods during which they contributed data to the ICDRs.

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

2.2 Level 1A input data

The ROM SAF ICDR data products version 1.1 validated in this report are based on Metop level 1A GRAS data from the NRT environment at the EUMETSAT Secretariat, GRAS product versions PPF 4.4 to PPF 4.6. The ROM SAF retrieves these data from the EUMETSAT Data Centre, and supplements them with occasional missing level 1A GRAS data from the NRT stream that are already archived at the ROM SAF.

2.3 Level 1B and Level 2 profile data

The ROM SAF Level 1B and Level 2 profile data consist 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, $q(H)$, pressure, $P(H)$, surface pressure, P_{surf}, 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. In the troposphere the influence from water vapour on the observed refractivity is not negligible. We thus have a temperature-humidity ambiguity which can only be resolved by introducing additional data on temperature and humidity. This is done through a 1D variational (1D-Var) procedure in which the observed refractivity profile is combined with a model profile in a statistically optimal way considering the errors and vertical error correlations of both the observations and the a priori data. The model profiles are taken from ECMWF reanalysis short-term forecasts. The retrievals of the geophysical profile data are described in more depth 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, humidity and pressure 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 generating Level 3 binned and averaged data.

The ICDR Level 1B and Level 2 profile data v1.0 were retrieved with the GPAC 2.3.2 system, with the ROPP-8.1 software package. The ICDR v1.1 data were retrieved with the GPAC 2.4.0 system, which includes the ROPP-9.0 software package (with adaptions made by the DMI) and the 1DV-4.2 software [RD.4].

2.4 Level 3 gridded data

The ROM SAF Level 3 data consists of gridded monthly means and associated quantities (standard deviations, data numbers, sampling error estimates, etc.) of the same geophysical variables as for the Level 1B and Level 2 data. The monthly means, and the associated variables, are defined on zonal grids, 200 meters in height by 5 degrees in latitude [RD.6].

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 [RD.7]. The sampling errors are estimated by sub-sampling an atmospheric model (ERA-Interim or ERA5) at the observed times and locations. Based on these estimates, the gridded monthly means are sampling-error corrected by subtracting the estimated sampling errors from the observed means [RD.8, RD.9, RD.10]. The generation of the Level 3 gridded data are described in more depth in the associated ATBD [RD.6].

The ICDR v1.0 Level 3 gridded data were retrieved with the romclim-1.2 software, while romclim-1.3 was used to generate the ICDR v1.1 Level 3 data.

2.5 ERA-Interim and ERA5 reanalysis data

ECMWF reanalysis data (ERA-Interim or ERA5) [RD.11, RD.12] are used as *a priori* in the 1D-Var retrieval of Level 2B temperature and humidity 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 sampling-error correction of the Level 3 gridded monthly mean data.

Each occultation has a 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 6-hour time steps (in the case of ERA-Interim) or 3-hour time steps (in the case of ERA5). 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 the dry variables using forward-model routines from the ROPP software package.

The use of ECMWF reanalysis data (ERA-interim or ERA5) as comparison reference for the validation has some limitations. First, there is a risk for circularities: RO data are assimilated by the reanalysis systems and reanalysis data are used as background data in the generation of the some of the geophysical variables retrieved from the RO measurements. Second, the reanalysis 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 [RD.13]. This may obscure the validation results.

2.6 ROM SAF data quality control

The purpose of the quality control done as a part of the RO data processing is to identify occultations that are likely to provide an invalid representation of the atmosphere. All occultations are checked against a set of criteria indicating non-nominal conditions (listed in Table 2.2). 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. Other tests are designed to identify occultations with degraded bending-angles, occultations that could be regarded as outliers, or occultations that encounter problems with the 1D-Var processing. 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 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, 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.14]. 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*.

The next QC step 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 which checks the quality of the 1D-Var solution. If the occultation have passed all tests up to this point, but fails in the 1D-Var tests, the bending angle, refractivity, and dry-variable profiles are used, while the wet profiles obtained from the 1D-Var solution are discarded. On average, around 10-15% of the occultations are rejected in the QC tests, with no discernible differences between the Metop satellites.

Table 2.2 Summary of the ROM SAF quality control tests applied to the Level 1B bending angle data and the Level 2 profile data.

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
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
Identification of outliers
Identification of outliers by comparison 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
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

3. Validation

The purpose of the validation is to show that ICDR v1.1 can be used to extend ICDR v1.0 from August 2019. In addition, we also aim to show that the ICDR, starting in January 2017, can be used to extend the CDR which ended in December 2016. Hence, the focus of the validation is to study the continuity of the data series across the ICDR v1.0/v1.1 and the CDR/ICDR transitions, and to assess whether those transitions are associated with variations of the time series that are likely to degrade the quality of the combined climate records.

Version 1.0 of the ROM SAF ICDR covers the time period from January 2017 to July 2019. It provides a continuation of the ROM SAF CDR v1.0 which ended in December 2016. After an update of the processing software, which included a switch of ancillary input data from ERA-Interim to ERA5, the ROM SAF plans to continue generating ICDR version 1.1 covering the time period from August 2019 and onward.

In Section 3.1 we assess the continuity across the CDR/ICDR transition by plotting RO-ERA-Interim monthly-mean difference time series from December 2006 to July 2019. This differencing removes most of the variability originating in the climate system itself. Also errors that are common to the RO and reanalysis data are removed by the differencing. Only errors that are not shared by the two data sources remain. Here, it must be emphasized that for some geophysical variables and in some regions it can be questioned whether ERA-Interim provide a stable enough reference against which to accurately measure temporal stability of the RO data. Even though the ERA-Interim reanalysis system in itself does not change with time, the evolving global observing system leads to time-varying biases [RD.11]. In particular, between about 8 and 30 km, the RO data records are likely to have a better temporal stability than ERA-Interim [RD.13]. Our assessment has a focus on whether the variations across the CDR/ICDR transition, and the variability following the transition, are qualitatively and quantitatively different from the time variations in the preceding CDR difference time series.

In Section 3.2 we do a similar assessment of the continuity across the ICDR v1.0/v1.1 transition using ERA5 as a comparison reference. For this part of the validation we also used a 31-month set of data, covering the time period from January 2017 to July 2019, processed with the software used for the ICDR v1.1 data. This data set is referred to as the "v.1.1 test data" and is only intended for internal use to provide further insights about the differences between ICDR v1.0 and v1.1.

The quality of the tropopause height and pressure profile and surface pressure products are not discussed in detail in the present document. These products are consistent with, respectively, the quality of the dry variables and the temperature and humidity profiles of the ICDR v1.1 products (see the discussion on the following pages in this chapter).

3.1 Transition from CDR to ICDR in January 2017

The ROM SAF CDR v1.0 covers the time period from late 2006 throughout December 2016. It was generated using EUMETSAT reprocessed Level 1A data as input (see Section

2.2). A matching ICDR starts in January 2017, providing a continuation of the CDR. The ICDR is generated by the ROM SAF using EUMETSAT near-real time Level 1A data as input (see Section 2.2) and is updated at regular intervals. In this section we present plots related to the transition from the CDR to the ICDR in January 2017.

Figures 1 to 3 show monthly mean differences between combined CDR/ICDR data records and co-located ERA-Interim short-term forecasts, vertically and horizontally averaged. We note that there are various biases between the RO data and ERA-Interim, particularly at the lowest and highest altitudes. There is also a tendency to seasonal variations in the RO-ERA-Interim differences, and in some geophysical variables and at certain altitudes we find long-term trends and inter-annual variability in the difference time series. However, for the purpose of validating the ICDR we are not interested in these biases per se; the validation is focused on assessing the continuity across the transition from CDR to ICDR.

For the bending angles and refractivity (Fig. 1), for the dry variables (Fig. 2), and for tropopause heights (not shown here), there are only weak discernible impacts from the CDR-ICDR transition. By “weak” we here mean that the variations across the CDR-ICDR transition, and the variability following the transition, are qualitatively and quantitatively no different from the time variations in the preceding CDR difference time series. In some cases, apparent changes in the time series do not appear exactly coincident with the transition, but rather follows it with a certain delay. Examples are globally averaged refractivity, 30-40 km, (Fig. 1, upper right panel, light-blue line) and dry temperature, 8-30 km, (Fig. 2, upper left panel, green line).

For the 1D-Var variables (Fig. 3) we also find weak impacts in association with the CDR-ICDR transition, mostly following the transition with a certain delay. Compared to the geophysical variables mentioned above, the 1D-Var variables exhibit more pronounced bias shifts in the RO-reanalysis difference time series. However, the variations across the CDR-ICDR transition, and the variability following the transition, are relatively small compared to the variability of the CDR difference time series.

We conclude that the change of data product from CDR v1.0 to ICDR v1.0 in January 2017 has negligible impacts on the general quality of the RO data products, and that ICDR v1.0 can be used as an extension of CDR v1.0 forming a long, continuous time series of climate data.

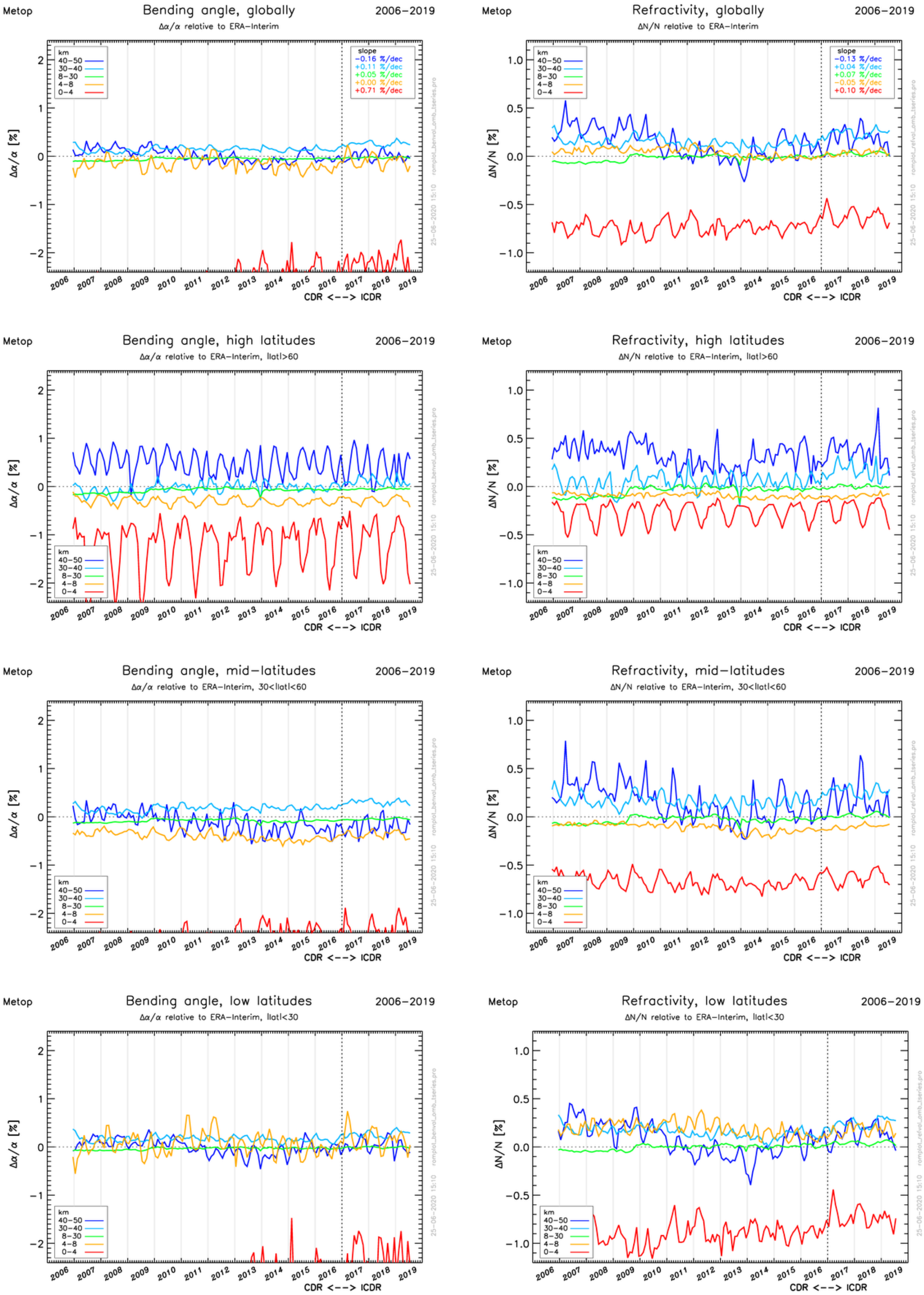

Figure 1. *Monthly mean differences between combined CDR/ICDR v1.0 data records and co-located ERA-Interim short-term forecasts, vertically and latitudinally averaged. Bending angle to the left, refractivity to the right.*

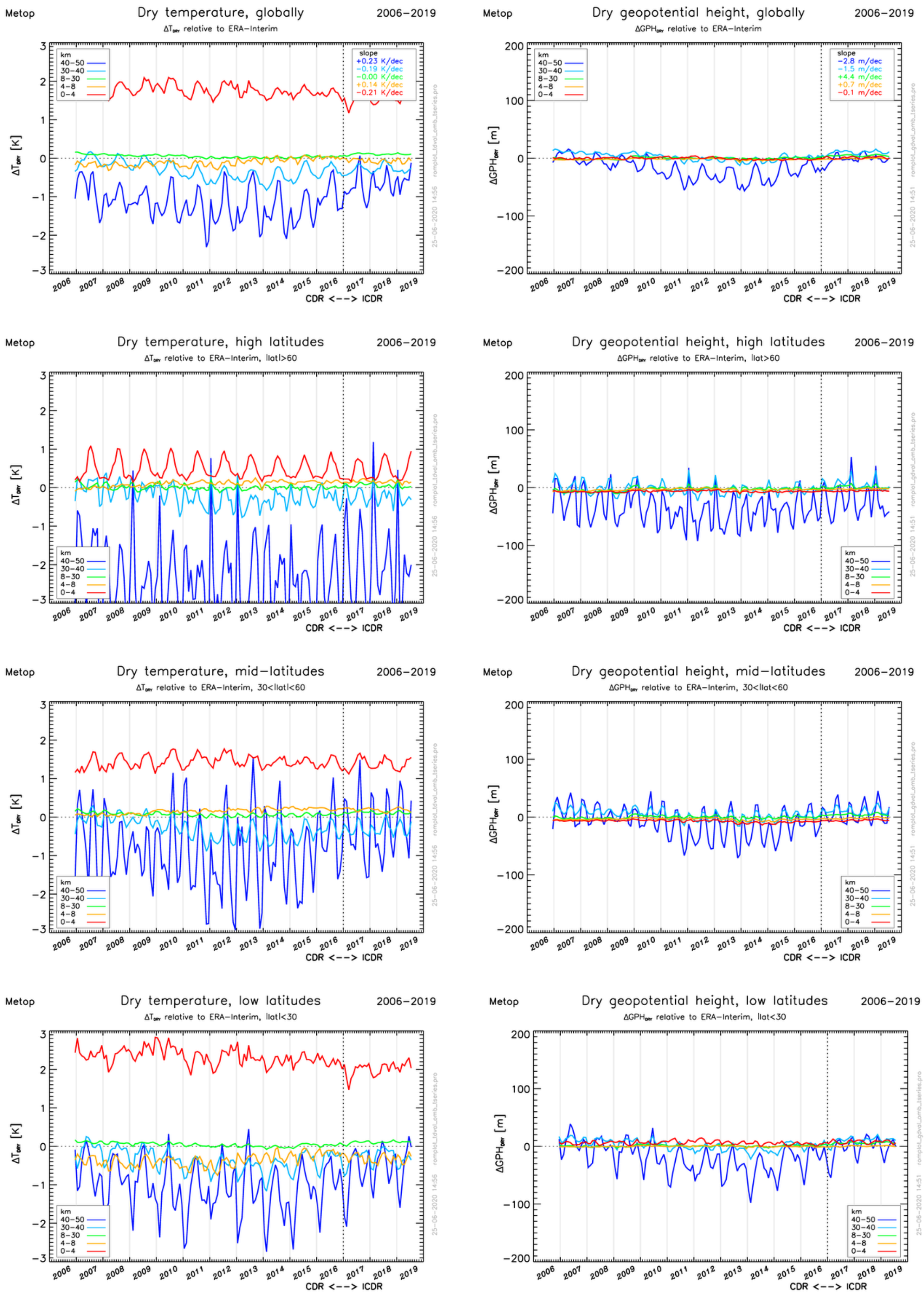

Figure 2. *Monthly mean differences between combined CDR/ICDR v1.0 data records and co-located ERA-Interim short-term forecasts, vertically and latitudinally averaged. Dry temperature to the left, geopotential heights of dry pressure to the right.*

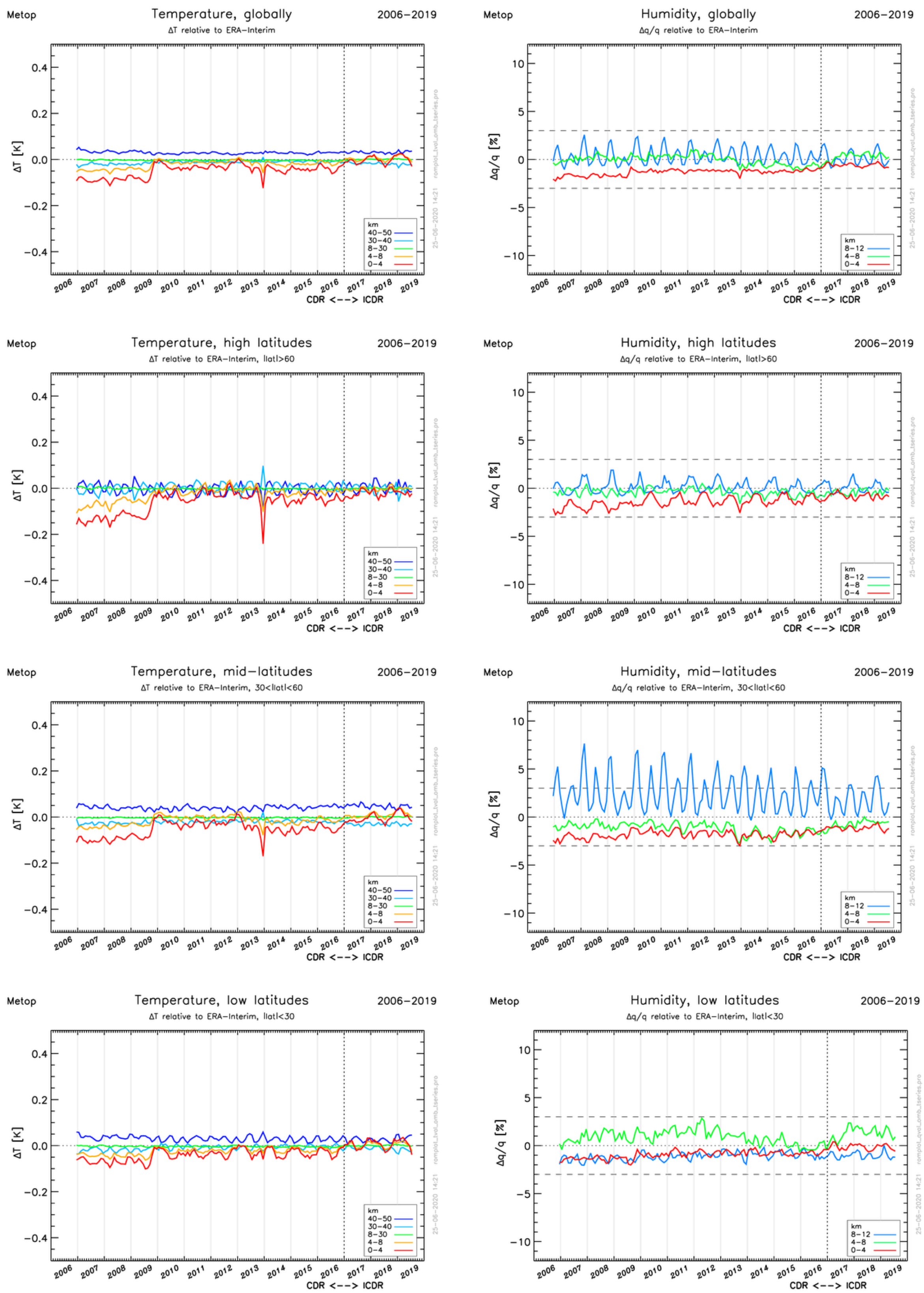

Figure 3. *Monthly mean differences between combined CDR/ICDR v1.0 data records and co-located ERA-Interim short-term forecasts, vertically and latitudinally averaged. 1D-Var temperatures to the left, 1D-Var humidity to the right.*

3.2 Transition from ICDR v1.0 to v1.1 in August 2019

ECMWF stopped the production of ERA-Interim reanalysis data on 31st August 2019, as it was replaced by ERA5. On 1st August 2019 the ROM SAF shifted from ERA-Interim to ERA5 in the generation of ICDR data, and as a result the ICDR data products shifted version from v1.0 to v1.1. The largest impacts on the ICDR data are expected from the change of *a priori* (background) in the 1D-Var retrievals, but some impacts on the ROM SAF quality control procedures cannot be ruled out. In this section we present plots related to these changes.

Figures 4 to 6 show monthly mean differences between combined ICDR v1.0/v1.1 data records and co-located ERA5 short-term forecasts, vertically and horizontally averaged. We note that there are biases between the RO data and ERA5, particularly at the lowest and highest altitudes. There is also a tendency to seasonal variations in the RO-ERA5 differences, and in some cases (e.g., bending angles below 4 km) we find a long-term trend in the difference time series. However, *for the purpose of validating the ICDR we are only interested in the continuity across the transition from v1.0 to v1.1.*

For the bending angles and refractivity (Fig. 4), for the dry variables (Fig. 5), and for tropopause heights (not shown here), there are no discernible impacts from the v1.0-v1.1 transition. The variations across the transition are qualitatively and quantitatively similar to the time variations in the difference time series before the transition. This conclusion is supported by the very small differences between the “v1.1 test data” and the v1.0 data during the time period January 2017 to July 2019. An example of is shown for refractivity in Fig. 7. The bending angles and the dry variables exhibit similarly small differences (not shown here) between the “v1.1 test data” and the v1.0 data.

For the 1DVar variables (Fig. 6) there is a clear impact from the v1.0-v1.1 transition. The RO-ERA5 differences are notably smaller following the transition. This is expected as a consequence of the influence of the *a priori* data on the 1D-Var data products. The v1.0 1D-Var data before the transition are based on ERA-Interim, while the v1.1 1D-Var data after the transition are based on ERA5. Throughout the combined v1.0/v1.1 time period we use ERA5 as a comparison reference. Hence, the smaller differences after the transition.

The 1D-Var temperature plots (Fig. 6, left-hand column) show that in the 8-30 km interval, where the 1D-Var temperature has highest sensitivity to RO observations, there are only small impacts from the v1.0-v1.1 transition, below 0.1 K. Above 30 km we find nearly stepwise temperature changes up to 1 K as a result of the ICDR version change in August 2019, positive in the 30-40 km interval and neutral or negative above this. Fig. 8 shows height-resolved temperature differences between the “v1.1 test data” and the v1.0 data in 5 latitude bands and globally, confirming the impacts we find at the v1.0-v1.1 transition in the RO-ERA5 difference data.

The 1D-Var humidity plots (Fig. 6, right-hand column) show that below 8 km there are changes up to a few percent as a result of the ICDR version change in August 2019, both on the positive and negative side. Above 8 km, outside of the low-latitude region 30˚S-30˚N, the impacts from the v1.0-v1.1 transition are larger. We can expect stepwise negative humidity changes (v1.1 is drier than v1.0) up to 5-15% at the transition. Fig. 9

shows height-resolved humidity differences between the “v1.1 test data” and the v1.0 data in 5 latitude bands and globally, confirming the impacts we find at the transition in the RO-ERA5 difference data.

The impacts that the ICDR version change in August 2019 has on the data records should be assessed against all other time variations in the combined data records consisting of Metop CDR v1.0, ICDR v1.0, and ICDR v1.1, and also against the required accuracies of the data records. The 1 K changes that we find in the temperature records in Fig. 6 are much larger than any fluctuations that we see in the combined CDR/ICDR data record in Fig. 3. In the humidity plots of Fig. 6 we have indicated the difference interval -/+ 3.0%, which is the approximate range of RO-ERA-Interim fluctuations of the combined CDR/ICDR data records in Fig. 3. The RO-ERA5 humidity differences below 8 km are well within this range for the combined v1.0/v1.1 data record, while the 8-12 km layer is far outside.

We conclude that the change of data product version from ICDR v1.0 to v1.1 in August 2019 has negligible impacts on bending angle, refractivity, the dry variables, tropopause heights, 1D-Var temperatures below 30 km, and humidity below 8 km. For 1D-Var temperatures above 30 km, the use of ICDR v1.1 from August 2019 may need to limited for certain applications, in particular those in which long-term variability and trends are important. Similarly, for the 1D-Var humidity above 8 km, outside of the low-latitude region 30˚S-30˚N, the use of ICDR v1.1 may need some limitations. See Section 4.1 where the associated limitations are summarized.

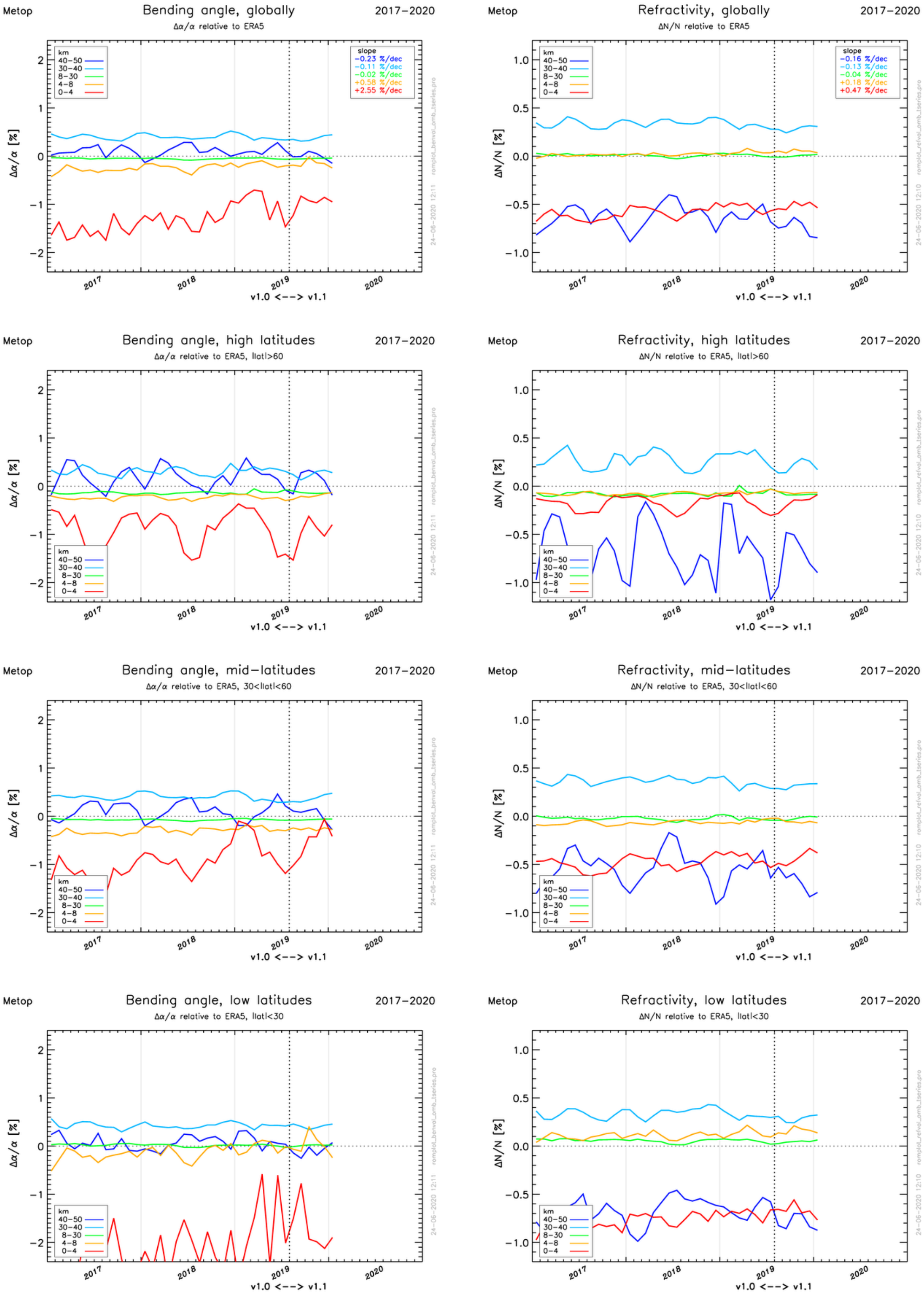

Figure 4. *Monthly mean differences between combined ICDR v1.0/v1.1 data records and co-located ERA5 short-term forecasts, vertically and latitudinally averaged. Bending angle to the left, refractivity to the right.*

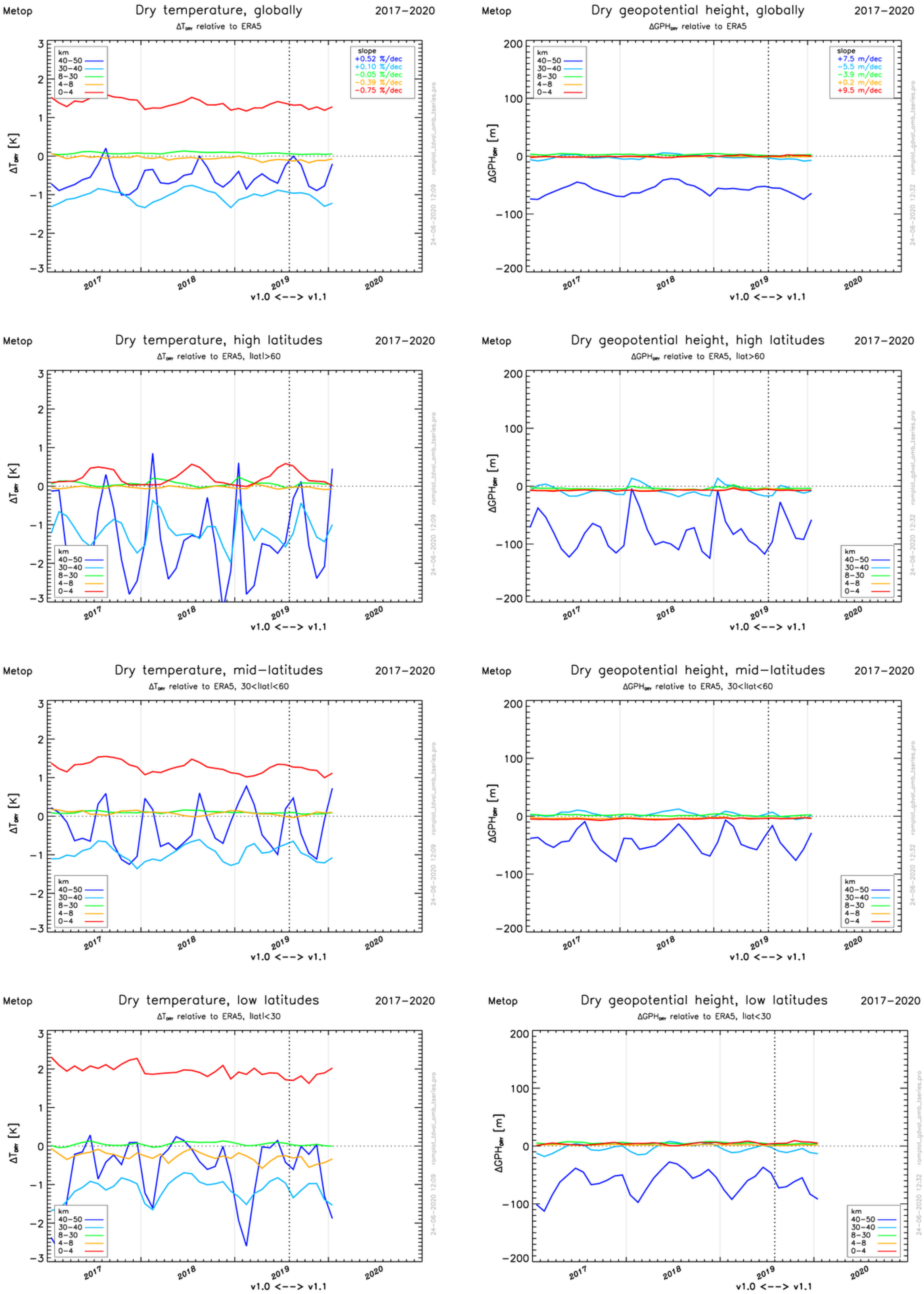

Figure 5. *Monthly mean differences between combined ICDR v1.0/v1.1 data records and co-located ERA5 short-term forecasts, vertically and latitudinally averaged. Dry temperatures to the left, geopotential heights of dry pressure to the right.*

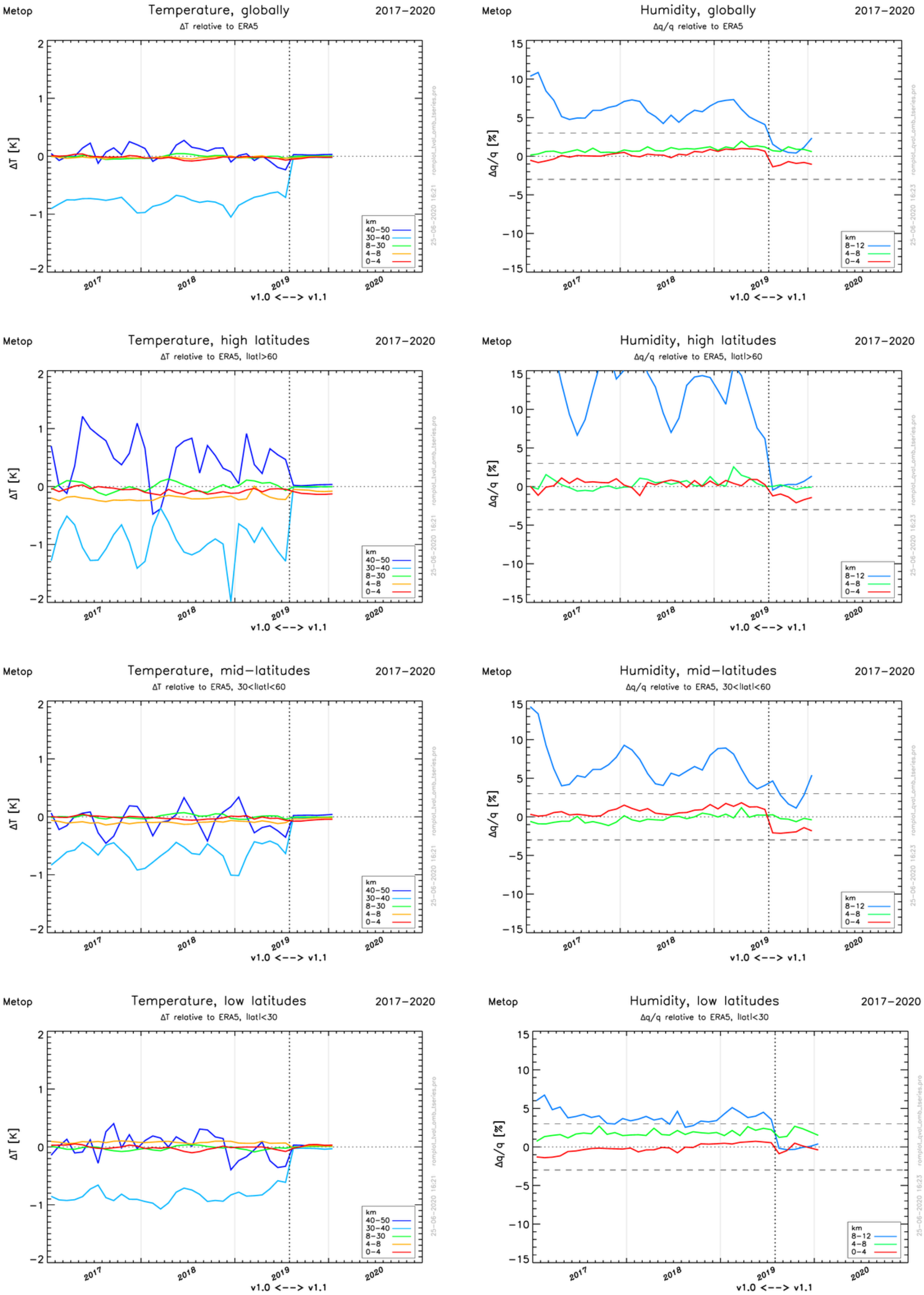

Figure 6. *Monthly mean differences between combined ICDR v1.0/v1.1 data records and co-located ERA5 short-term forecasts, vertically and latitudinally averaged. 1D-Var temperatures to the left, 1D-Var humidity to the right.*

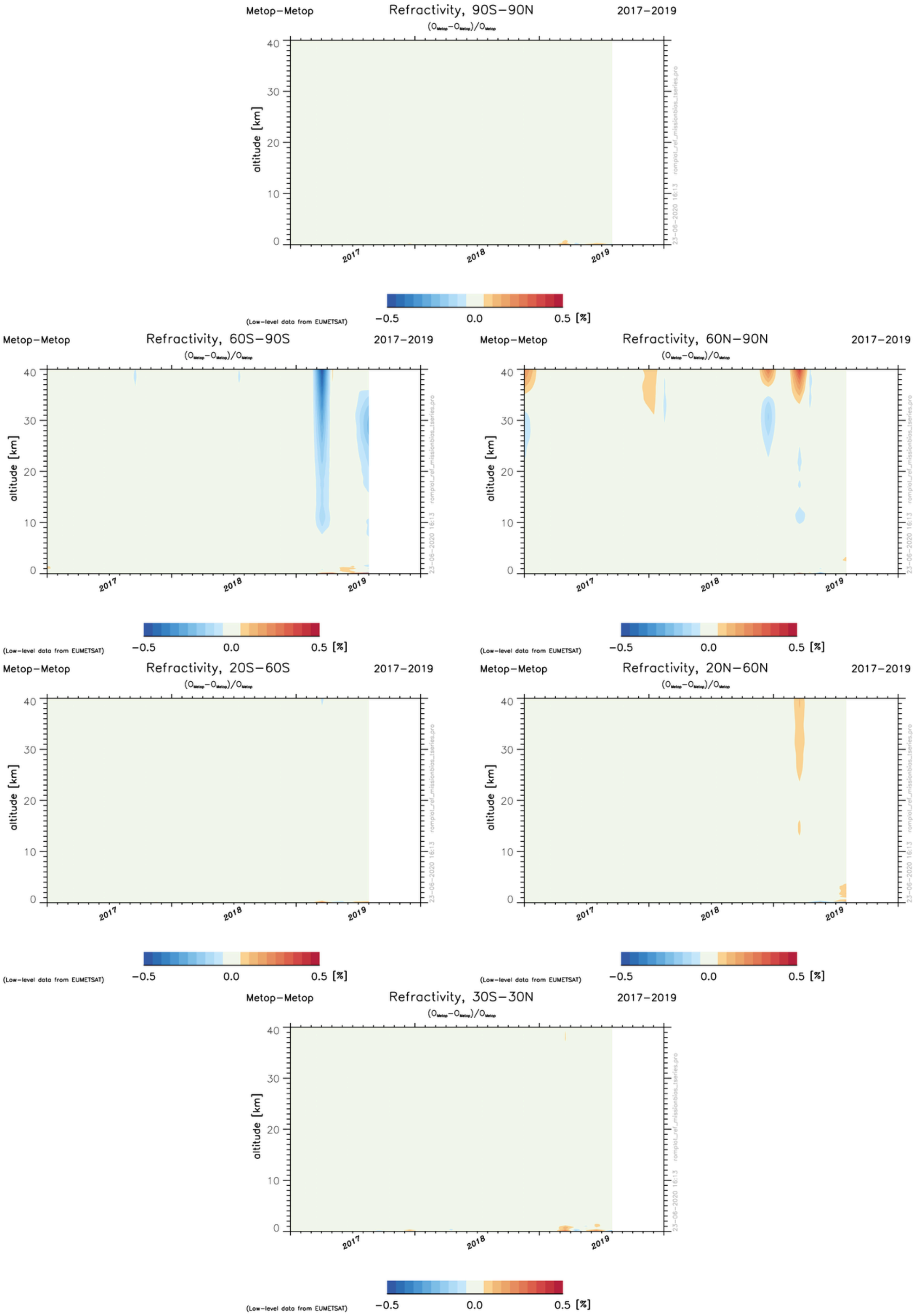

Figure 7. *Monthly mean differences between the ICDR "v1.1 test data" and the v1.0 data products, for refractivity from January 2017 to July 2019 averaged in different latitude zones.*

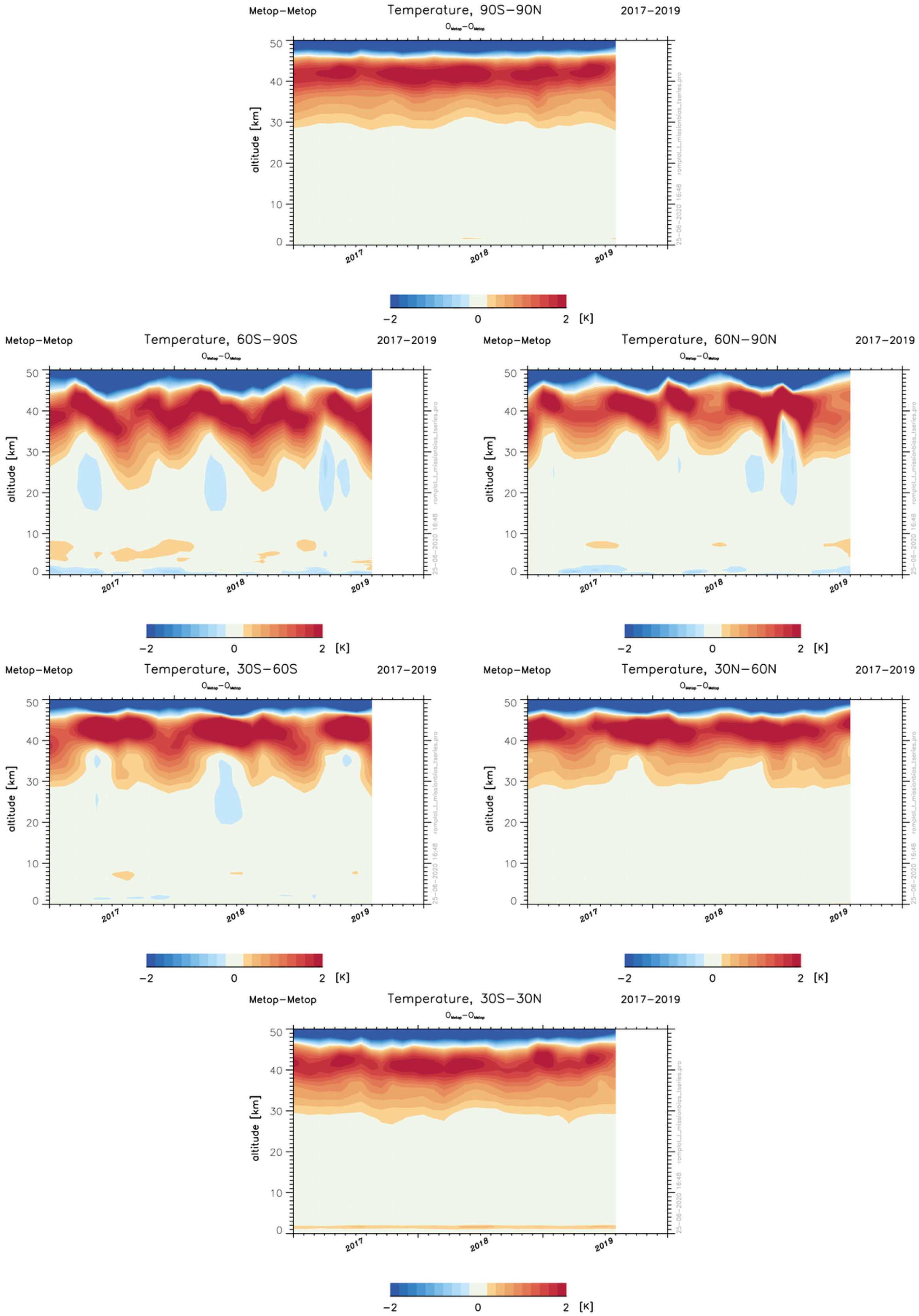

Figure 8. *Monthly mean differences between the ICDR "v1.1 test data" and the v1.0 data products, for 1DVar temperature from January 2017 to July 2019 averaged in different latitude zones.*

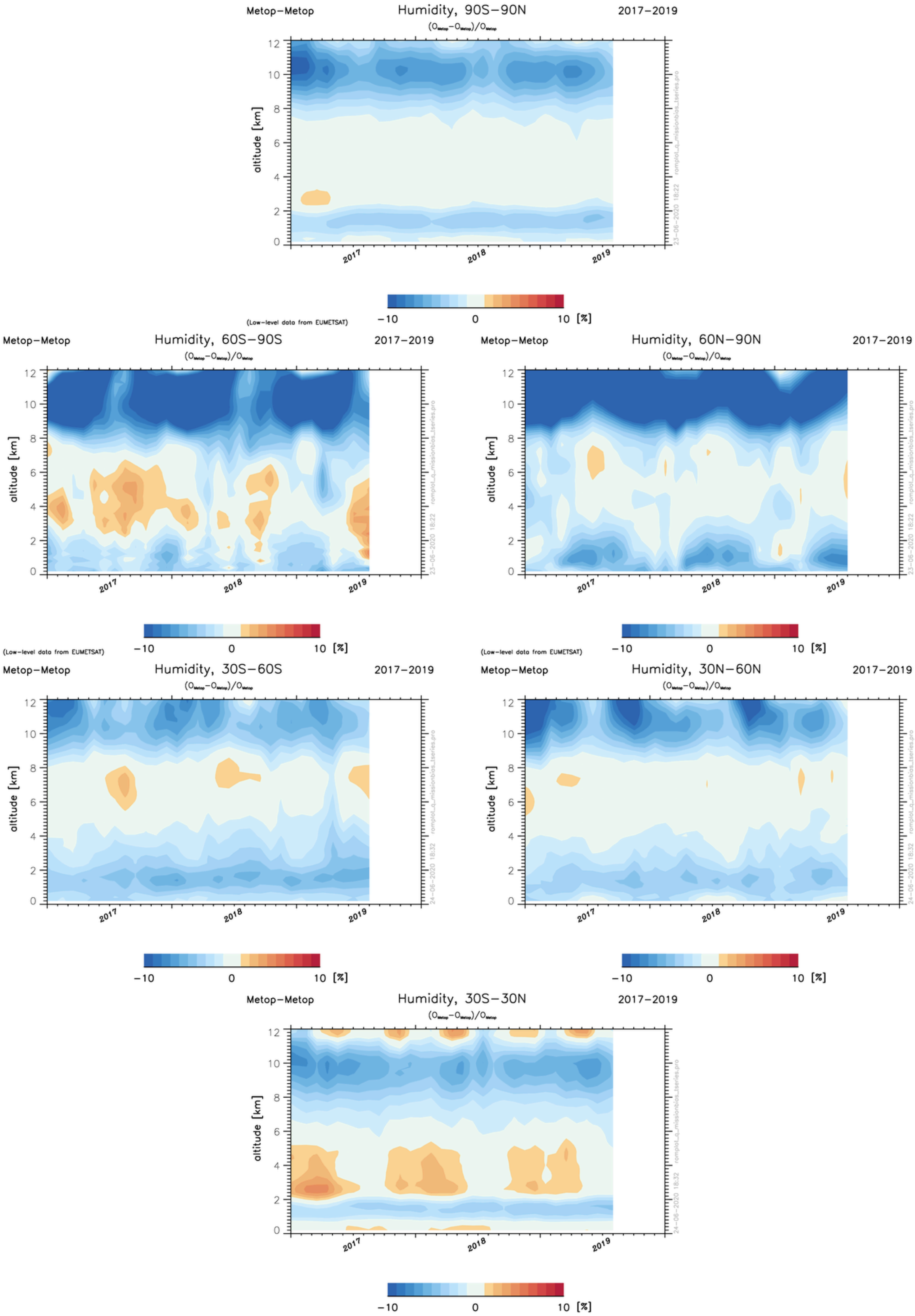

Figure 9. *Monthly mean differences between the ICDR “v1.1 test data” and the v1.0 data products, for 1DVar humidity from January 2017 to July 2019 averaged in different latitude zones.*

4. Conclusions

The ROM SAF Interim Climate Data Record (ICDR) is based on GRAS radio occultation (RO) measurements by the Metop mission. Version 1.0 of the ROM SAF ICDR covers the time period from January 2017 to July 2019. It provides a continuation of the ROM SAF CDR v1.0 which ended in December 2016. After an update of the processing software, which includes a switch of ancillary input data from ERA-Interim to ERA5, the ROM SAF starts generation of ICDR version 1.1 covering the time period from August 2019 and onward.

We conclude that the change of data product from CDR v1.0 to ICDR v1.0 in January 2017 has negligible impacts on the general quality of the RO data products, and that ICDR v1.0 can be used as an extension of CDR v1.0 forming a long, continuous time series of climate data. We also conclude that the change of data product version from ICDR v1.0 to v1.1 in August 2019 has negligible impacts on bending angle, refractivity, the dry variables, tropopause heights, 1D-Var temperatures below 30 km, and humidity below 8 km. For 1D-Var temperatures above 30 km, the use of ICDR v1.1 from August 2019 may need to limited for certain applications, in particular those in which long-term variability and trends are important. Similarly, for the 1D-Var humidity above 8 km, outside of the low-latitude region 30˚S-30˚N, the use of ICDR v1.1 may need some limitations. These limitations are also summarized in Section 4.1 below.

4.1 Limitations

In this validation the following limitations on the use of ICDR v1.1 were identified:

- ICDR v1.1 1D-Var temperatures above 30 km exhibit biases relative to the previous ICDR v1.0. The temperatures change up to 1 K as a result of the ICDR version change in August 2019, positively between 30 km and 47 km and switching to negatively above this. For certain applications, e.g., those where long-term variability and trends are important, the ICDR v1.1 1D-Var temperature data above 30 km should be used with caution.

- ICDR v1.1 humidity below 8 km exhibit biases up to a few percent relative to the previous ICDR v1.0. Above 8 km, outside of the low-latitude region 30˚S-30˚N, we find nearly stepwise negative humidity changes (v1.1 is drier than v1.0) up to 5-15% as a result of the transition from ICDR v1.0 to v1.1. For certain applications, e.g., those where long-term variability and trends are important, the ICDR v1.1 humidity data above 8 km, outside of the low-latitude region 30˚S-30˚N, should be used with caution.