EUMETSAT
ROM SAF
RADIO OCCULTATION METEOROLOGY

Validation Report: Reprocessed Level 2C tropopause height products

Version 1.2

20 December 2018

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 CHANGE RECORD

Version	***Date***	***By***	***Description***
0.1	25 May 2018	JKN	First version, used for internal ROM SAF review
1.0	8 June 2018	JKN	Version submitted for DRR-RE1 review. List of changes: - Included suggestions from SH and KBL. - Expanded and changed layout and number of chapters - Front page and first pages: Changed layout. - Ch. 1: Inserted “overview” section. - Sec. 2.2: Expanded algorithm description. - Ch. 3: Rewrote text and figure captions. Regenerated Figure 3.1 Moved PRD and SeSp to separate chapters (Ch 4. and Ch. 5). Renewed all time series figure. - Ch. 4: (Now Ch. 7) Modified conclusion to also mention products and metrics not under review.

DOCUMENT CHANGE RECORD ...*continued*

Version	*Date*	*By*	*Description*
1.1	4 September 2018	JKN	Updated version implementing the following RIDS for DRR-RE1 & ORRs review: - RIDs : 277, 278, 282, 283, 284, 286, 461, 462, 465, 470, 472, 476, 477, 478, 479, 480, 481, 483, 484, 485, 486, 487, 491, 492, 494, 495, 496, 497, 498, 499, 500, 502, 504, 508, 558, 559, 560 : Editorial changes implemented - RID : 482 : Removed coler from Fig. 3.5 3.6 - RID : 488 : Ch. 3 text inserted, close up plots added - RID : 494 : Sec. 3.3 bias signature explained - RID : 474 : Sec. 2.2 Table with mission periods inserted. - RID : 490 : Sec. 3.3 Text corrected. - RID : 496 : Sec. 3.3.1 Explanation of figures added in text, Lat < 30 ... removed. - RID : 501 : Ch. 4 Removed Fig. 4.1 and references to it. - RID : 506 : Added text about DLTH in section 2.2 - RID : 507 : Added text about 0.2 K bias in Ch. 6 In addition the following changes were made: Sec 3.3 access -> assess
1.2	20 December 2018	JKN	Updated version based on ICDR concept discussions at ROM SAF SG22: - ROM SAF description and definitions updated. - p7 Executive Summary rewritten. - p8 GRM table updated - p33 SeSps expanded and moved to Appendices.

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing center under EUMETSAT which is responsible for operational processing of GRAS radio occultation (RO) data from the Metop 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 Climate Data Record version 1 (CDR-v1.0) is based on data from the COSMIC, Metop, CHAMP and GRACE missions. The Interim Climate Data Record ICDR-v1.0 is a continuation of the (CDR-v1.0) for the Metop satellites only. The processing of the two data sets are performed with the same algorithm. These data have been reprocessed from Level 1A (excess phase) to Level 2 (profiles of meteorological parameters) and Level 3 (latitudinal gridded monthly means). The Level 1A data are provided by UCAR (COSMIC, GRACE, CHAMP and Metop) and EUMETSAT (Metop). The ROM SAF Offline Product (v1.0) is based on data from Metop, and it is produced with the same algorithm as CDR-v1.0, but this data stream may be subject to future algorithm updates. This report documents the validation of the Level 2C dry temperature lapse rate tropopause product from the CDR-v1.0 against ERA-I, and the conclusions applies for ICDR-v1.0 and ROM SAF Offline Data (v1.0) as well. It is concluded that the service specifications have to be relaxed because the retrieved tropopause deviates dramatically from the model tropopause in some regions, especially in cases with multiple tropopauses. This is not to be considered as a problem with the product.

The tropical and mid latitude dry temperature cold point tropopause temperature DCTT and height DCTH are of interest for studies of water vapor transport from the troposphere to the stratosphere. These products are also disseminated as a part of CDR1-v1.0, but not officially validated here. It is implicitly seen that the DCTT and DCTH are of same quality as the try temperature lapse rate tropopause temperature DLTT and height DLTH in the relevant latitude bands.

1 Introduction

1.1 Purpose of document

This purpose of this validation report is to assess the Level 2C dry temperature lapse rate tropopause height (DLTH) produced by the Radio Occultation Meteorology (ROM) Satellite Application Facility (SAF). The complete list of TPH products covered by this report is provided in Table 1.1. The product requirements baseline is the PRD [AD.3], and the methods and algorithms used to calculate the products are described in [RD.1].

1.1.1 Definitions of products being validated in this report

Table 1.1: *List of products covered by this Validation Report.*

Product ID	Product name	Product acronym	Product type	Mission	Dissemination means	Dissemination format
GRM-29-L2-C-R1	Reprocessed Tropopause height	RCHMET	CDR	Metop Level 1A data from EUM Secretariat	web	netCDF
GRM-30-L2-C-R1	Reprocessed Tropopause height	RCHCO1	CDR	COSMIC Level 1A data from CDAAC	web	netCDF
GRM-32-L2-C-R1	Reprocessed Tropopause height	RCHCHA	CDR	CHAMP Level 1A data from CDAAC	web	netCDF
GRM-33-L2-C-R1	Reprocessed Tropopause height	RCHGHA	CDR	GRACE Level 1A data from CDAAC	web	netCDF
GRM-29-L2-C-I1	Reprocessed Tropopause height	ICHMET	ICDR	Metop Level 1A data from EUM Secretariat	web	netCDF
GRM-24	Tropopause Height	TPH	OFL	Metop Level 1A data from EUM Secretariat	web	netCDF

1.2 Applicable and Reference documents

1.2.1 Applicable documents

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

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

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

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

1.2.2 Reference Documents

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

[RD.1] ROM SAF, Algorithm Theoretical Baseline Document: Level 2C Tropopause Height, SAF/ROM/DMI/RQ/REP/002, -.

[RD.2] ROM SAF, Validation Report: Reprocessed Level 2B and 2C 1D-Var CDR v1.0 products (Short title: Validation Report: Reprocessed 1D-Var products), SAF-/ROM/DMI/REP/1DVAR/001, -.

[RD.3] ROM SAF, Validation Report: Reprocessed Level 3 gridded CDR v1.0 products, SAF/ROM/DMI/REP/CLM/001, .

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

[RD.5] ROM SAF, The Radio Occultation Processing Package (ROPP) Applications Module User Guide, SAF/ROM/METO/UG/ROPP/005, .

[RD.6] ROM SAF, Algorithm Theoretical Baseline Document: Level 2B and 2C 1D-Var products, SAF/ROM/DMI/ALG/1DV/002, 2018.

[RD.7] ROM SAF, Algorithm Theoretical Baseline Document: Level 2A dry temperature profiles., Ref. SAF/ROM/DMI/ALG/TDRY/001, Version 1.5, 2018.

[RD.8] ROM SAF, ROM SAF website, http://www.romsaf.org/re1/, 2018.

[RD.9] Schmidt, T., Beta testing of ROPP 7.0, ROM SAF VS Report 22, DMI, 2013.

[RD.10] WMO, *Definition of the tropopause*, Bull. 6, World Meteorological Organisation, Geneva, 1957.

1.3 Acronyms and abbreviations

BG	Background
CDR1	ROM SAF Climate Data Record version 1.
CHAMP	Challenging Mini–Satellite Payload
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
DCTH	Dry Temperature Cold Point Tropopause Height
DCTT	Dry Temperature Cold Point Tropopause Temperature
DLTH	Dry Temperature Lapse Rate Tropopause Height
DLTT	Dry Temperature Lapse Rate Tropopause Temperature
DMI	Danish Meteorological Institute
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA-I	ERA-Interim (global atmospheric reanalysis)
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FA	Federated Activity
GLONASS	Global Navigation Satellite System (Russia)
GNSS	Global Navigation Satellite Systems (generic name for GPS, GLONASS and the future GALILEO)
GPL	General Public Licence (GNU)
GPS	Global Positioning System (US)
GRAS	GNSS Receiver for Atmospheric Sounding (onboard Metop)
IEEC	Institut d'Estudis Espacials de Catalunya
LEO	Low Earth Orbited
Metop	Meteorological Operational polar satellites (EUMETSAT)
NRT	Near Real Time
NWP	Numerical Weather Prediction
PCD	Product Confidence Data
Q/C	Quality Control
RO	Radio Occultation
ROM SAF	The EUMETSAT Satellite Application Facility responsible for operational processing of radio occultation data from the Metop satellites. Members are DMI (leader), UKMO, ECMWF and IEEC.
ROPP	Radio Occultation Processing Package
SAF	Satellite Application Facility (EUMETSAT)
TBD	To Be Determined
TP	Tangent Point
TPH	Tropopause Height
TPT	Tropopause Temperature
UKMO	United Kingdom Meteorological Office
UT1	Universal Time-1 (proportional to the rotation angle of the Earth)
UTC	Universal Time Coordinated
VAR	Variational analysis; 1D, 2D, 3D or 4D versions (NWP data assimilation technique)
VS	Visiting Scientist
VT	Valid or Verification Time
WMO	World Meteorological Organization

1.4 Definitions

RO data products from the GRAS instrument onboard Metop 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) 80 min after measurement (SAF Level 2 for EPS-SG Global Mission); (iii) 40 min after measurement (SAF Level 2 for EPS-SG Regional Mission);

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

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

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

[1] 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

The document is organized as follows:

Chapter 1: Contains the introduction

Chapter 2: Describes the processing and reprocessing context and the TPH algorithm.

Chapter 3: Contains comparisons between retrieved TPH and ERA-I TPH.

Chapter 4: Summarizes product requirements.

Chapter 5: Here we discuss open issues related to the tropopause products.

Chapter 6: Briefly summarizes and conclude the validation.

Appendices: Repeats service specifications for the ROM SAF CDR-v1.0, ICDR-v1.0 and Offline TPH (v1.0) products.

2 Background

2.1 Brief description of CDR v1.0

The processing of the ROM SAF Climate Data Record version 1.0 (CDR v1.0) was finalized in January 2018. The process leading up to the finalization included production of a beta version which was internally evaluated and also applied and analyzed by external scientists through Visiting Scientist studies and Federate activities. The ROM SAF tropopause products have not been evaluated or validated until now, thus this is the first assessment of these ROM SAF products.

2.2 Missions and time coverage

The missions, their respective satellites, and the covered periods for each mission are given in Table 2.1. It should be noted that for COSMIC not all RO instruments in the constellation have been operating in the full period, especially towards the end of the period, and for GRACE, both RO instruments are never in operation at the same time. Metop-B was only launched in September 2012, and RO operation started in October 2012. The very early data from CHAMP (until September 2001) has not been included.

Table 2.1: *Missions, satellites, and time periods in the ROM SAF reprocessing #1.*

Mission	Metop	COSMIC	CHAMP	GRACE
Satellites	Metop-A Metop-B	FM1; FM2; FM3 FM4; FM5; FM6	CHAMP	GRACE-A GRACE-B
Periods	Oct’06–Dec’16	Apr’06–Dec’16	Sep’01–Oct’08	Mar’07–Dec’16

2.3 Input data

The input Level 1A data for Metop (GRM-29-R1) are provided by the EUMETSAT Secretariat as part of their reprocessed Level 1A and 1B data, version 1.4. For COSMIC (GRM-30-R1), CHAMP (GRM-32-R1), and GRACE (GRM-33-R1), the input Level 1A data are provided by UCAR/CDAAC, more specifically, CDAAC reprocessed or post-processed atmPhs and (for COSMIC) gpsBit files. For the CDAAC data, not all missions and time periods share the same version number. Table 2.2 gives an overview of the different providers and the version numbers for the data used as input to the ROM SAF reprocessing #1, whereas Table 2.3 gives more detailed information about the different CDAAC versions and the used time periods.

Table 2.2: *Input data providers and versions.*

Mission	Metop	COSMIC	CHAMP	GRACE
Data provider	EUM. Secr.	UCAR/CDAAC	UCAR/CDAAC	UCAR/CDAAC
Input versions	1.4	2013.3520 2014.2860 2016.1120	2014.0140	2010.2640 2014.2760

Table 2.3: *CDAAC versions and time periods used in ROM SAF reprocessing #1.*

CDAAC version	CDAAC name	CDAAC processing mode	year.doy time period
2013.3520	cosmic2013	Re-processed	2006.112–2014.120
2014.2860	cosmic	Post-processed	2014.121–2016.365
2016.1120	cosmic	Post-processed	2016.366
2014.0140	champ2014	Re-processed	2001.245–2008.278
2010.2640	grace	Post-processed	2007.059–2014.089
2014.2760	grace	Post-processed	2014.090–2016.366

2.4 Description of TPH algorithm

The ROPP tropopause tool is developed to derive the tropopause height (TPH) and tropopause temperature (TPT) according to 4 different definitions: A bending angle based, a refractivity based and two temperature based tropopause definitions [RD.5]. The temperature tropopause can be derived either from the WMO definition [RD.10], where TPH is defined as "the lowest level at which the lapse-rate (Λ_{WMO}) decreases to 2° C/km or less, provided that the average lapse-rate between this level and all higher levels within 2 km does not exceed 2° C/km", or it can be derived from the cold point definition, where the TPH is defined as the altitude where temperature is at its minimum. In addition to the four mentioned methods there is also the choice of using dry temperature[1] or wet temperature[2]. In [RD.9] the different tropopause products are discussed. It was recommended to disseminate the cold point along with the WMO tropopause and not to reject double tropopause cases. The dry temperature lapse rate tropopause height (DLTH) has been chosen as the official tropopause product for ROM SAF CDR v1.0, but the other products are disseminated as well. Seen from a scientific point of view the dry tropical and mid latitude cold point temperature is an interesting property, due to its impact on stratospheric water vapour mixing ratio. The choice of DLTH as official product is mainly pragmatic: The lapse rate tropopause is more robust than the cold point tropopause and it is defined at mid and polar latitudes. The dry temperature is suitable for the purpose because it has higher resolution than wet temperature, and it is a very good approximation of the physical temperature near the relatively dry tropopause. The DLTH tropopause calculation is done on the un-thinned dry temperature in the atm file. There is no interpolation involved, and all missions are treated the same way. Implementation details are found in [RD.1] and [RD.5].

[1] The "dry" variables are retrieved from the refractivity simply by ignoring the presence of water vapour. 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. [RD.7].

[2] The "wet" temperature is retrieved through 1D-Var as described in [RD.6], combining observation and model information. The wet temperature is an accurate estimate of the physical temperature in the upper troposphere and lower stratosphere, but its vertical resolution is limited by the background model resolution.

3 Validation

The validation consists of an examination of quality control performance followed by a comparison of the retrieved DLTH to the ERA-I analysis DLTH.

3.1 Quality Control Performance

The tropopause Q/C procedure is described in [RD.1]. During the TPH calculation these consecutive checks are done:

r=0 Input data validity check

r=1 Input data depth check

r=2 Input data height check

r=3 Covariance transform sharpness above TPH check

r=4 Covariance transform sharpness below TPH check

r=5 Double tropopause height

r=6 TPH minimum height check

r=7 TPH maximum height check

The TPH Q/C procedure consists of 8 steps (r) of which only r=0,1,2,6 and 7. are relevant for the dry temperature lapse rate tropopause. The algorithm proceeds at any step if possible even if one of the Q/C criteria is not met. Two subsets of data have been chosen for evaluation of the QC performance (see tabel 3.1). The performance of the Q/C is illustrated in zonal plots in Figures 3.1, 3.2, 3.3 and 3.4.

Mission	Time interval	Number of profiles
Metop-A and B profiles	February 15-23, 2016	11427
CHAMP profiles	August 1-31, 2008	6320

Table 3.1: *Data chosen here for QC evaluation. The two subsets are chosen such to represent reasonably modern state of the art data (Metop 2016) and older classic data (CHAMP 2008), which could contain challenges, such as missing data on lower altitudes.*

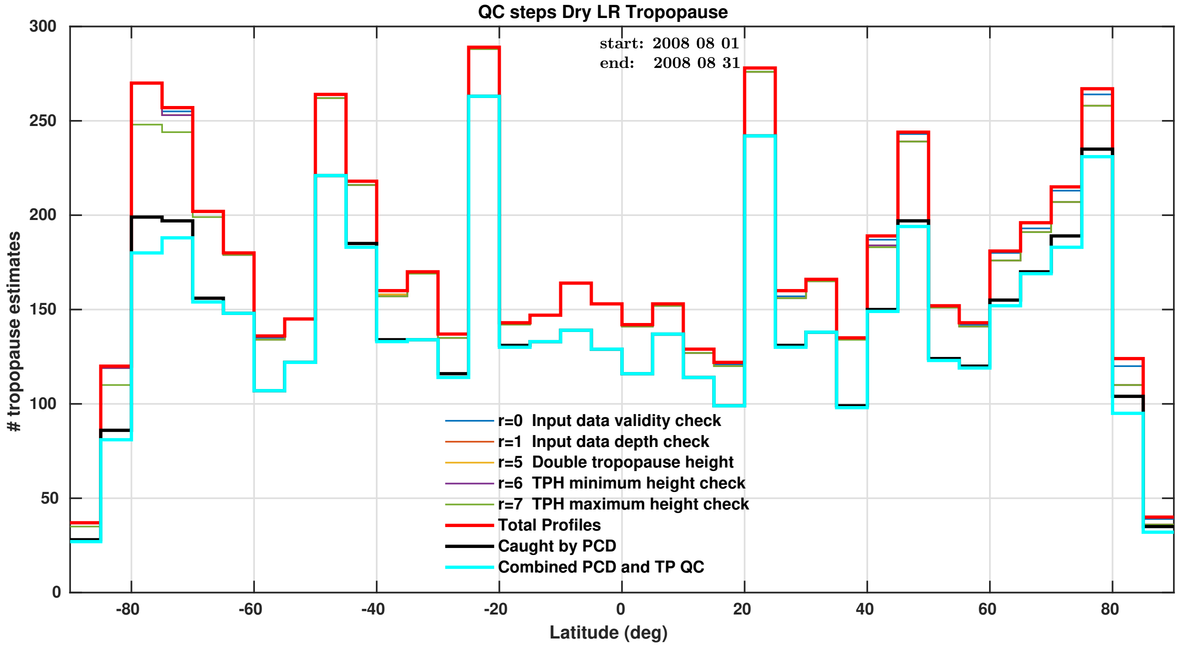


Figure 3.1: *Histogram showing the impact of different Q/C steps as function of latitude as reduction of total number of retrieved TPH estimates. CHAMP January 1-31, 2008, 6320 profiles in total. The PCD (Product Confidence Data) refers to the QC measure which is applied to the profile independently of the tropopause calculation, summarizing quality of Level 1B, 2A and 2B output for that particular profile.*

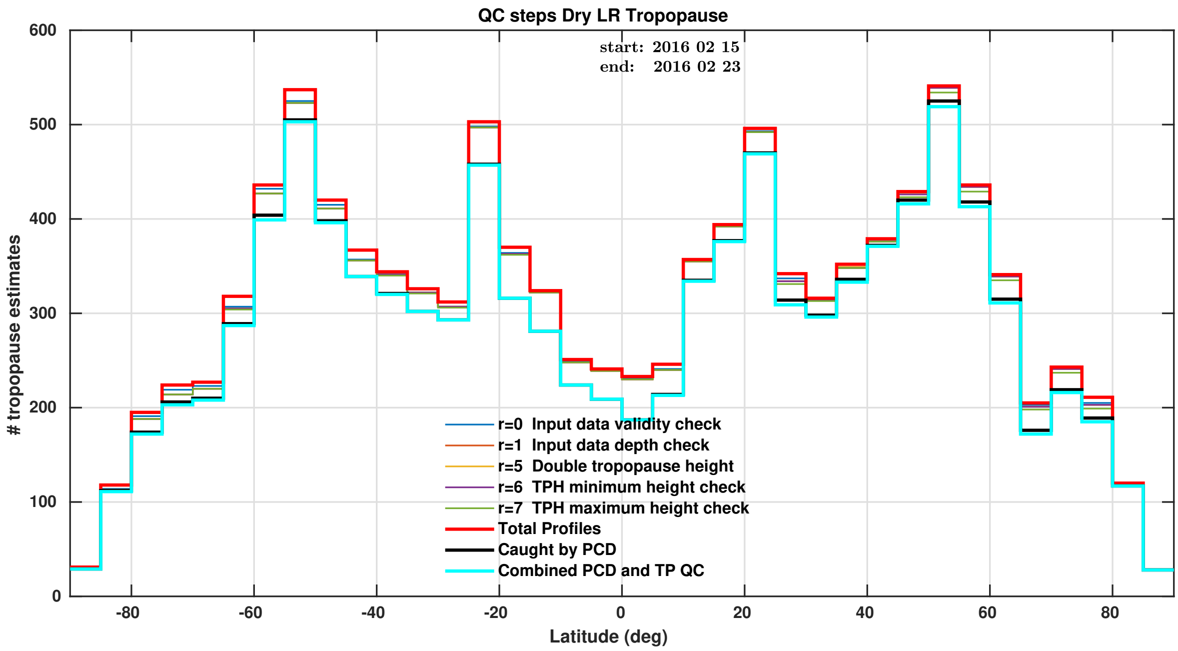


Figure 3.2: *Histogram showing the impact of different Q/C steps as function of latitude as reduction of total number of retrieved TPH estimates. Metop A/B February 15-23, 2016, 11427 profiles in total. The PCD (Product Confidence Data) refers to the QC measure which is applied to the profile independently of the tropopause calculation, summarizing quality of Level 1B, 2A and 2B output for that particular profile.*

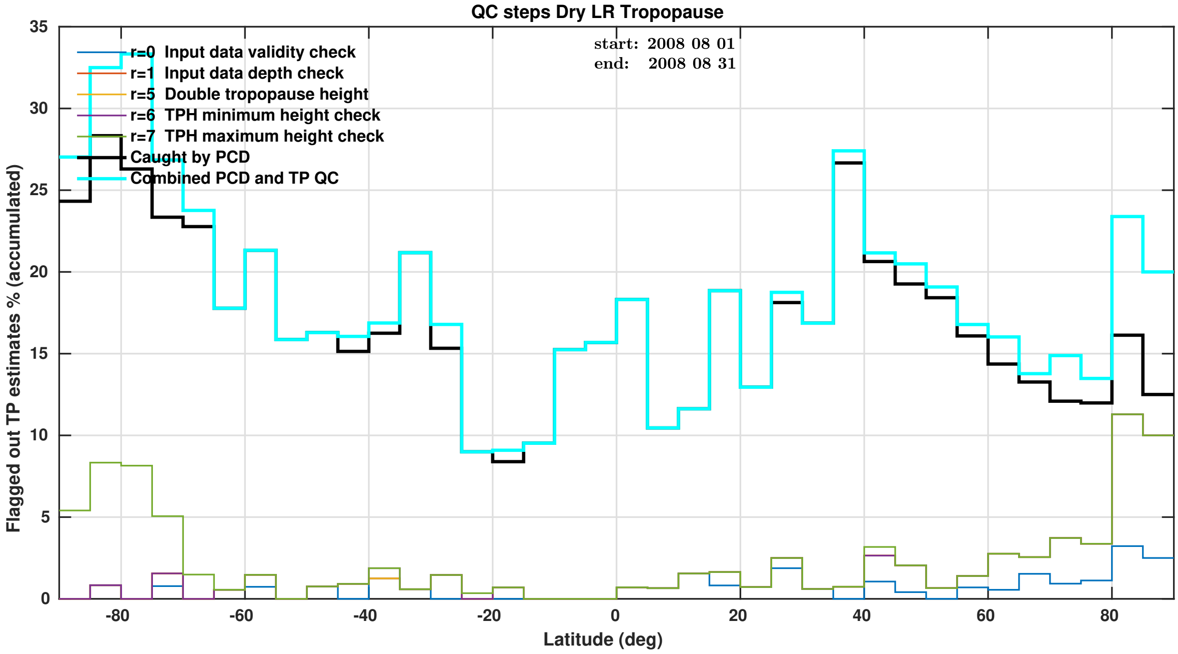


Figure 3.3: *Histogram showing the impact of different Q/C steps as function of latitude as percentage of all processed data. CHAMP January 1-31, 2008, 6320 profiles in total. The PCD (Product Confidence Data) refers to the QC measure which is applied to the profile independently of the tropopause calculation, summarizing quality of Level 1B, 2A and 2B output for that particular profile.*

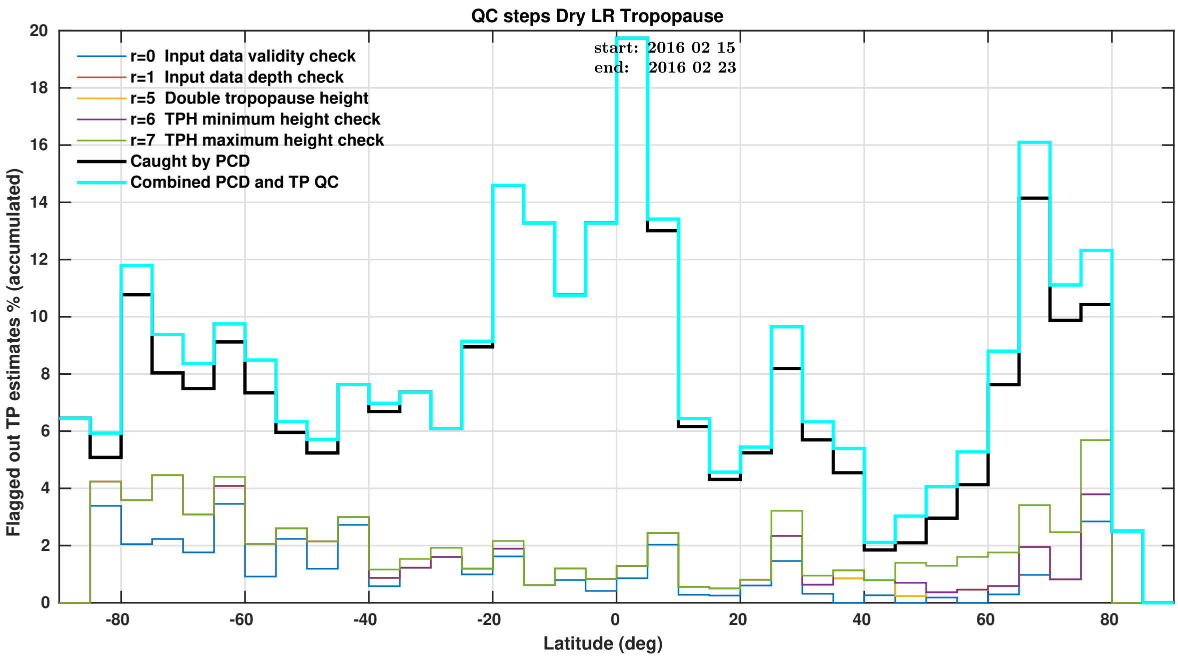


Figure 3.4: *Histogram showing the impact of different Q/C steps as function of latitude as percentage of all processed data. Metop A/B February 15-23, 2016, 11427 profiles in total. The PCD (Product Confidence Data) refers to the QC measure which is applied to the profile independently of the tropopause calculation, summarizing quality of Level 1B, 2A and 2B output for that particular profile.*

It turns out that the algorithm performs well in both cases without dropping more than a few percent of profiles. If anything the Metop-A/B data seems to be most problematic, near the poles, where roughly 4 % of all profiles cannot yield a tropopause estimate. But in all cases by far the most profiles are rejected by the PCD flag. For more detail about the QC performance in the production of Level 1B, 2A and 2B profiles, i.e. the Product Confidence Data, see [RD.3].

3.2 Comparison to ERA-I analysis

The ERA-I analysis dry temperature is calculated for each RO profile by first applying the forward model to the model state i.e. calculating the refractivity on the same levels as the observation and then calculating the dry temperature in same way as it is done for an observed RO profile [RD.7]. Hereafter the DLTH is calculated according to the WMO definition [RD.10] from the ERA-I analysis dry temperature.

3.2.1 Zonal plots

The latitude dependence of the dry temperature lapse rate tropopause is illustrated in Figures 3.5 and 3.6. Statistics as function of latitude are shown in Figures 3.7 and 3.9, using the same two data sets as in section 3.1. There is a substantial violation of the PRD standard deviation target value of 1 km, especially in the transition between tropics and subtropics.

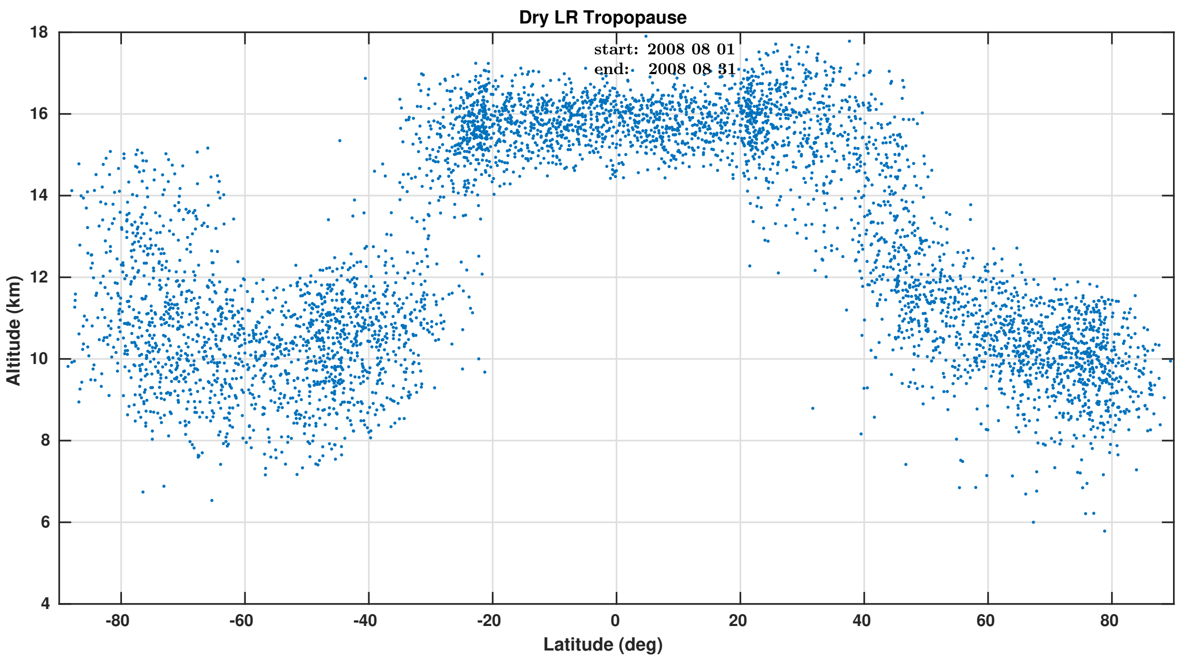


Figure 3.5: *CHAMP: Dry temperature lapse rate tropopause height as function of latitude. Same occultations as in Figure 3.3.*

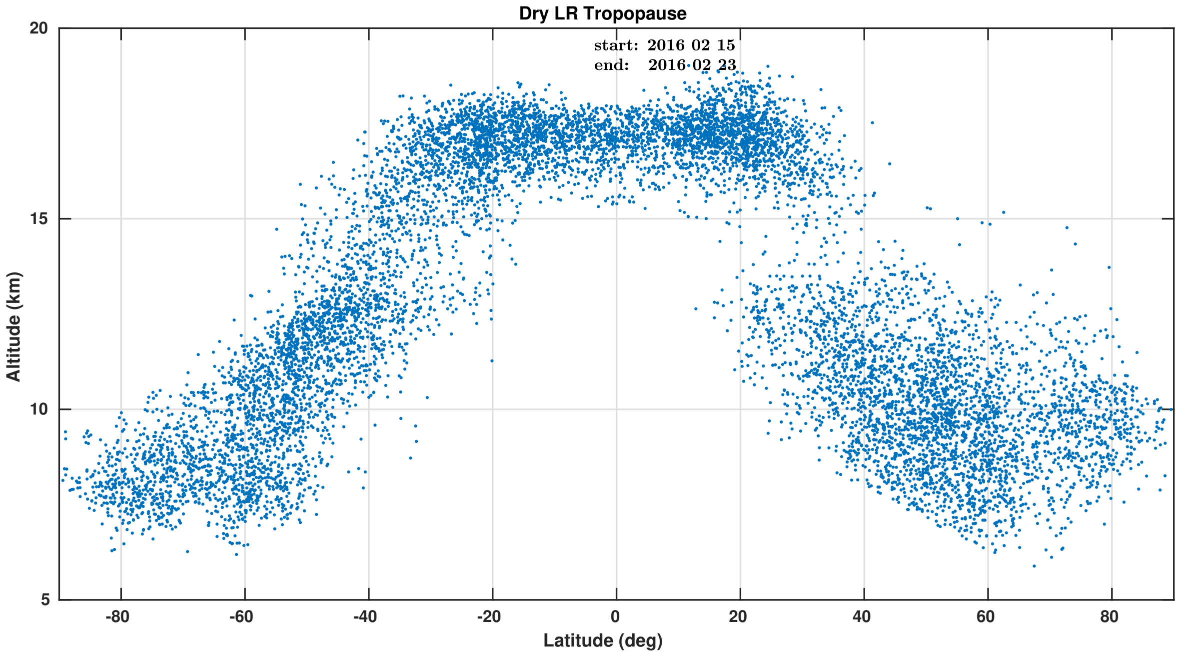


Figure 3.6: *Metop A/B: Dry temperature lapse rate tropopause as function of latitude. Same occultations as in Figure 3.3.*

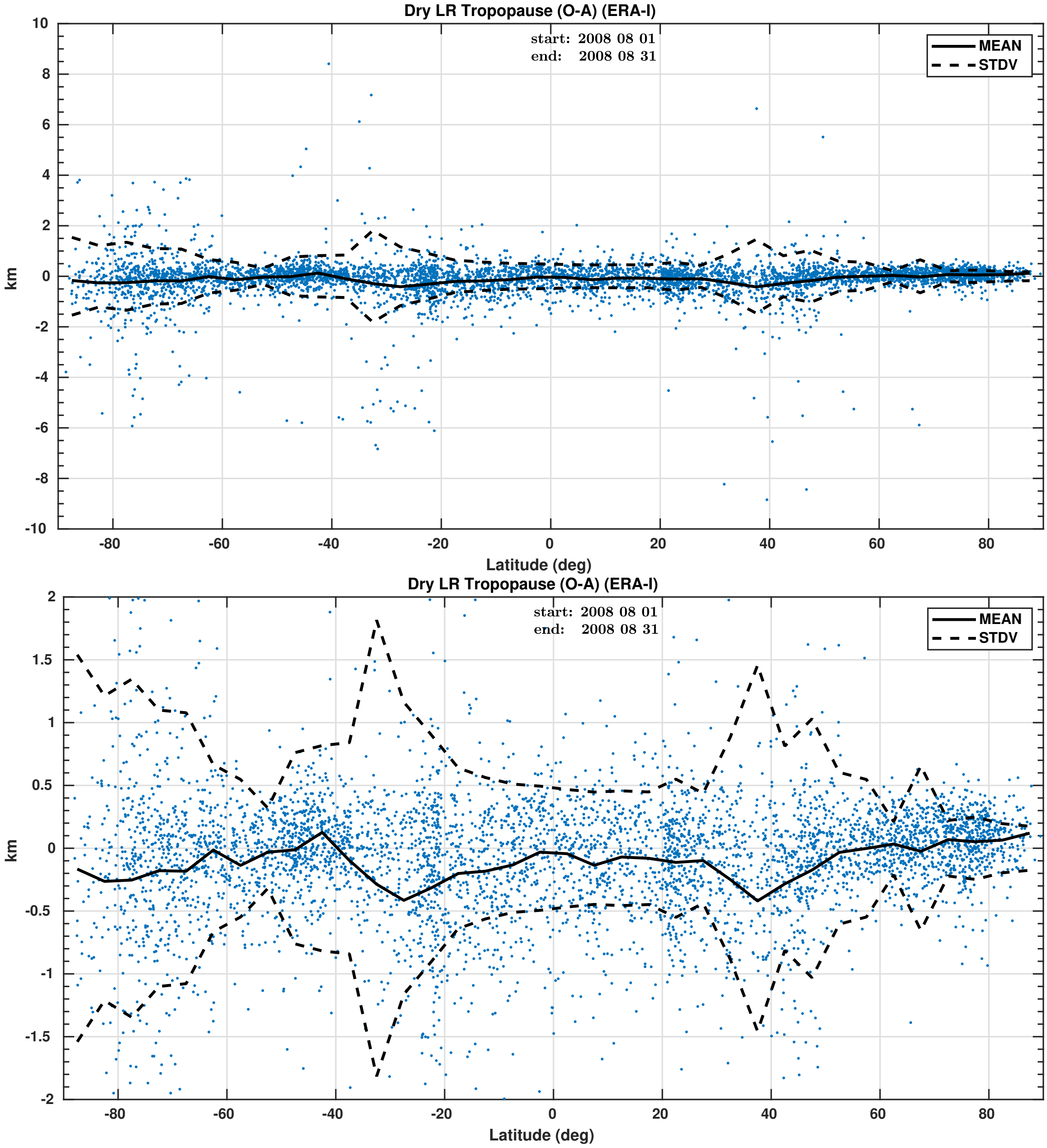


Figure 3.7: *CHAMP: Standard deviation and mean of retrieved dry temperature lapse rate tropopause height minus ERA-I analysis dry temperature lapse rate tropopause height as function of latitude. Same occultations as in Figure 3.3.*

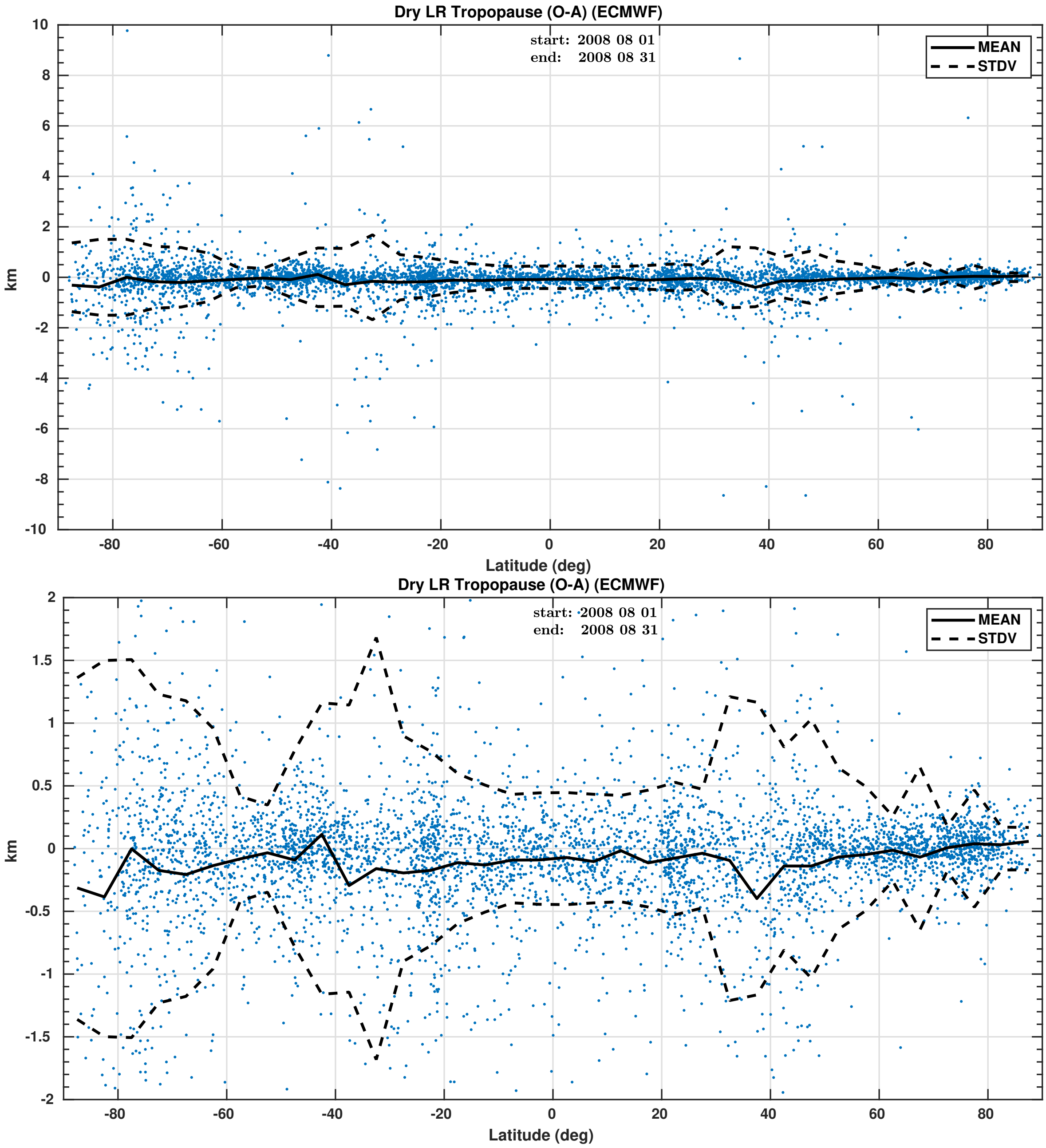


Figure 3.8: *CHAMP: Standard deviation and mean of retrieved dry temperature lapse rate tropopause height minus ECMWF operatonal analysis dry temperature lapse rate tropopause height as function of latitude. Same occultations as in Figure 3.3.*

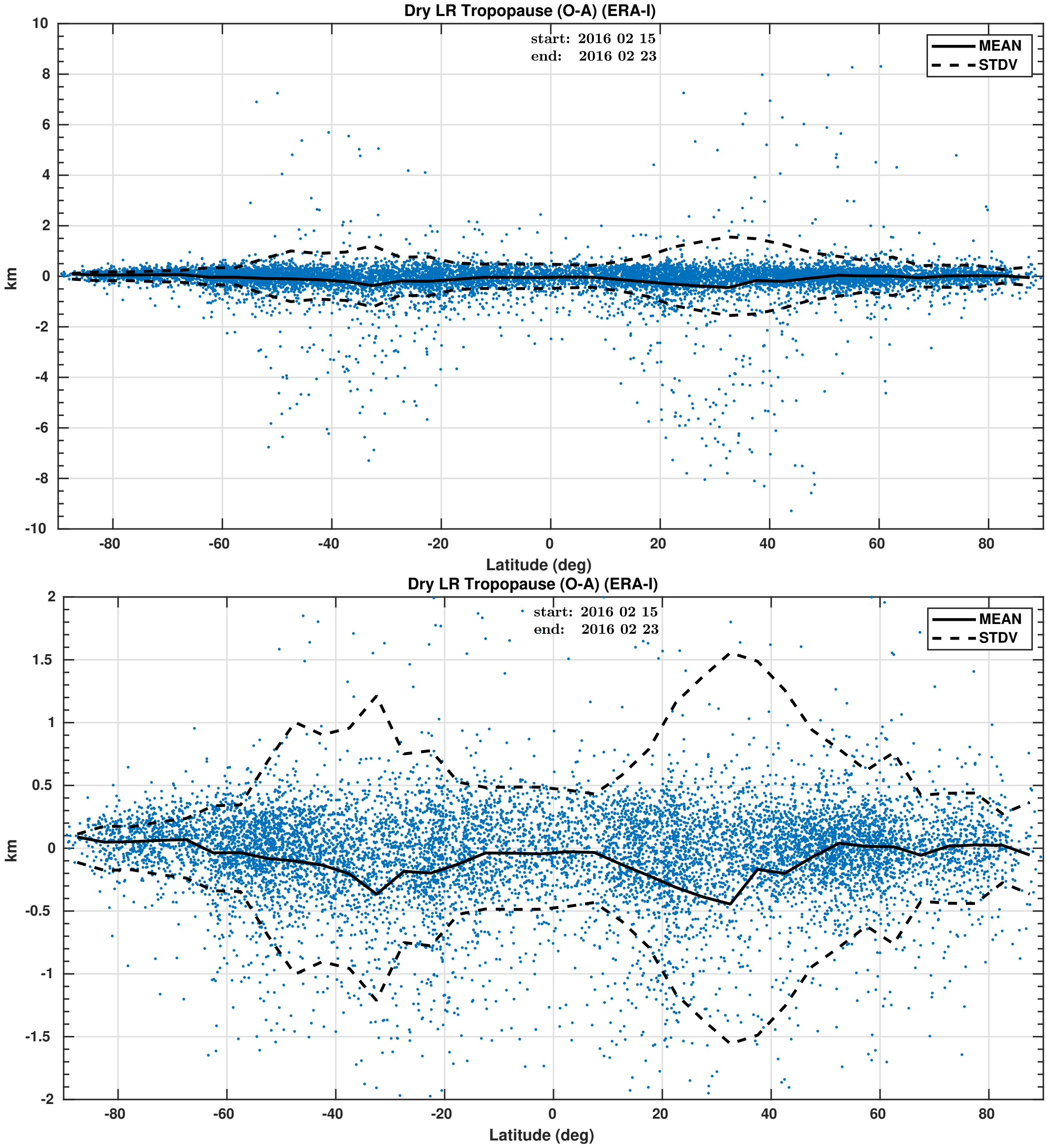


Figure 3.9: *Metop A/B: Standard deviation and mean of retrieved dry temperature lapse rate tropopause height minus ERA-I analysis dry temperature lapse rate tropopause height as function of latitude. Same occultations as in Figure 3.4*

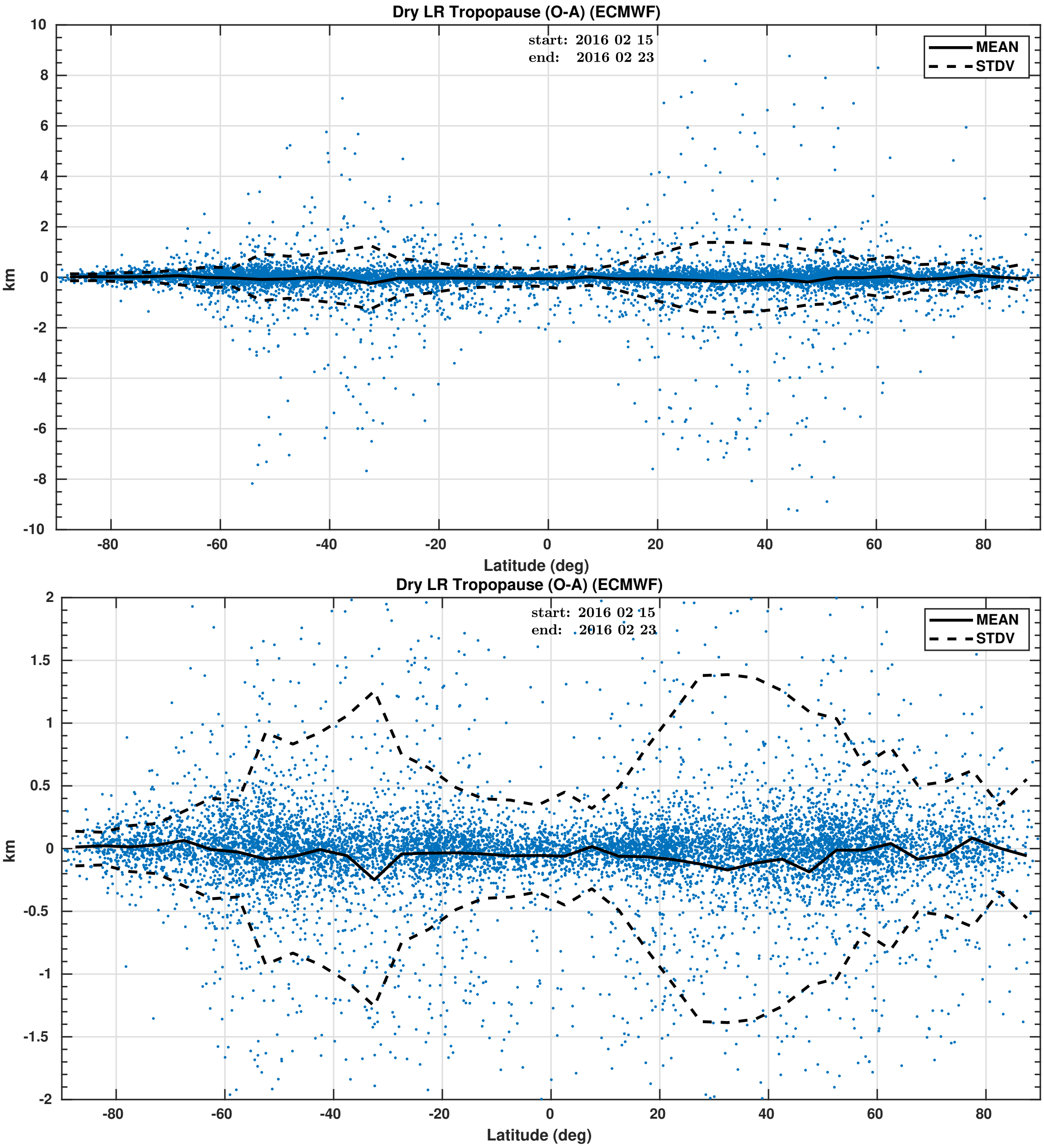


Figure 3.10: *Metop A/B: Standard deviation and Mean of retrieved dry temperature lapse rate tropopause height minus ECMWF operational analysis dry temperature lapse rate tropopause height as function of latitude. Same occultations as in Figure 3.4*

It is noticeable that the bias and standard deviation structure is very similar for CHAMP and Metop. The standard deviation is dominated by some extreme outliers, especially near ± 30 deg. These “errors” can be attributed to the presence of multiple tropopauses, and as such they are not really errors. The high resolution retrieved dry temperature has a tendency to cause the algorithm to find the lower tropopause more often than it is the case for the coarser model dry temperature. In Figures 3.8 and 3.10 we also compare to the ECMWF operational analysis. The discrepancies at mid latitudes are persistent in this comparison, but there is a slightly decreased standard deviation in the tropics in the 2016 (Metop A/B) data which is attributed to the increased vertical resolution of ECMWF (137 Levels), which was implemented 25 June 2013 (Cycle 38r2). ConIEEC | Institut d'Estudis Espacials de Catalunyasidering that the ERA-I level distance around the tropopause is in the order of 1 km (as illustrated in Figure 3.11) it is not a good objective to be as close to ERA-I as possible. Using the ECMWF operational data instead only decreases the standard deviation between -15 and 15 degrees latitude slightly. The reason that little improvement is seen outside the tropics is that the standard deviation is dominated by outliers.

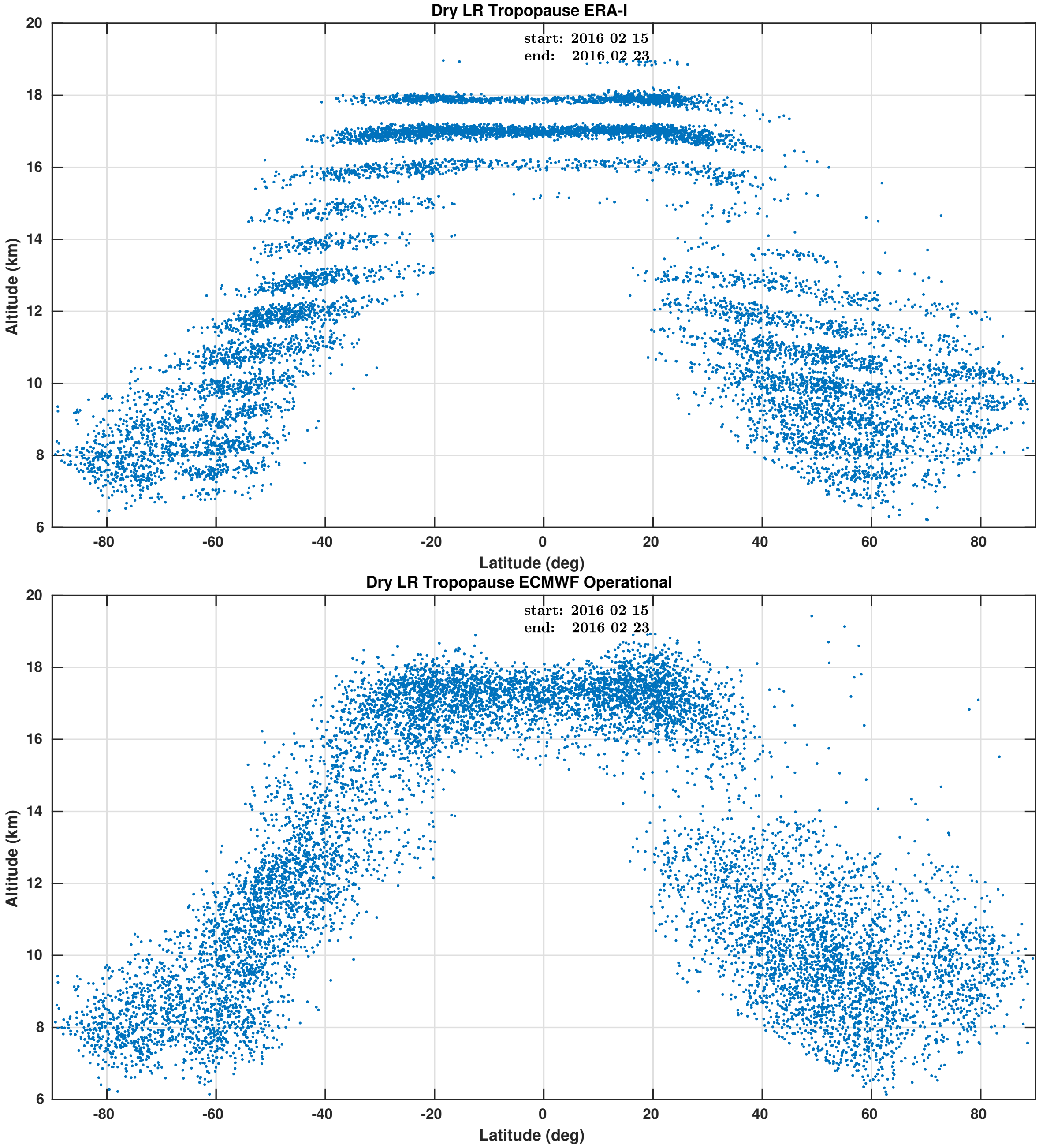
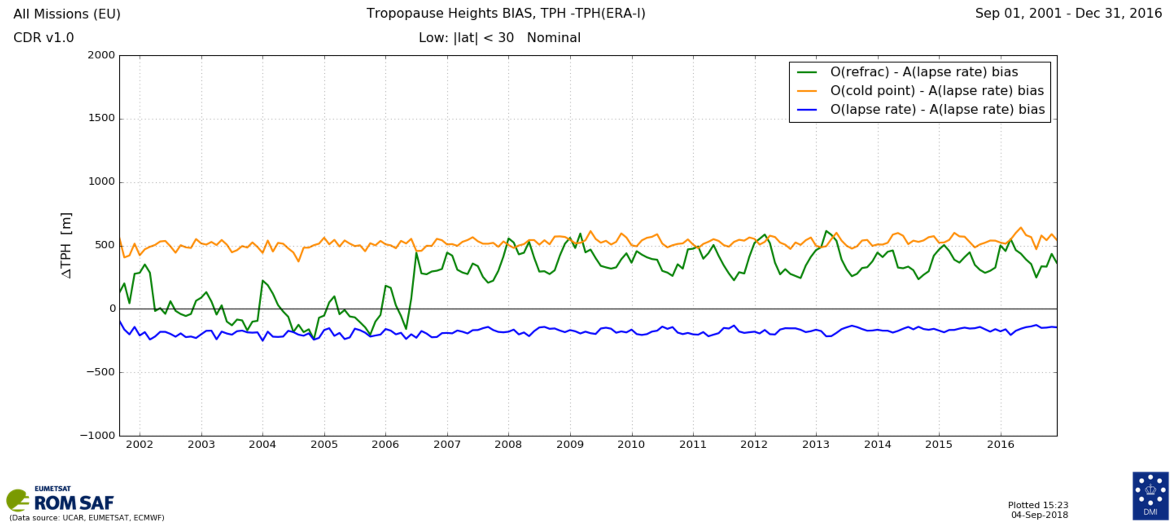


Figure 3.11: *Dry temperature lapse rate tropopause height of ERA-I analysis (top) and ECMWF operational analysis (bottom) as function of latitude, to illustrate the effect of ERA-I level structure. Same occultations as in Figure 3.9.*

3.3 Time series plots

All the time series plots in this report have been taken from www.romsaf.org/re1. They represent a minor selected fraction of the plots available for monitoring CDR-v1.0 on the web page. In Figure 3.12 biases of tropopause products are plotted with reference to the ERA-I analysis DLTH. It is noticed that the variation in mean values has the signature of the well known bias issues (2006 jump and 2013 spike) of ERA-I which are discussed in [RD.2] (Section 3.1). The tropopause temperature spike in November 2013 is due to a known fall-out of RO data in ERA-I assimilation. The dry temperature lapse rate (and cold point) tropopause heights are fairly stable and in accordance with ERA-I, while the refractivity based tropopause shows a 400 m upward jump early 2006, before RO is switched on in the ERA-I assimilation.

The early 2006 jump is seen all parameters [RD.2] and it is also seen in ERA-I - ECMWF analysis e.g. bottom plot of Figure 3.12. It can hardly be related to GNSS-RO since it appears before assimilation starts. But after the introduction of COSMIC assimilation December 2006, both the DLTT and DCTT drops 0.5 K compared to ERA-I DLTT. It is very likely, that the drop actually reflects an increase in ERA-I tropopause temperatures, since we can compare to an unintentional perturbation experiment in November 2013, where RO data has not been assimilated. During that event both DLTT and CPTT differences restores to the pre-2006 values. Furthermore the CHAMP data alone shows the same jump (Figure 3.13) when compared to ERA-I. The differences between missions has not been plotted specifically, but one can assess the difference by swapping the plots on [RD.8]. It is seen that the Metop tropopause temperature is in general a little larger that the COSMIC tropopause temperature. We conclude that the mean tropical DLTT and DCTT are stable and that the intermission differences are at least below 0.2 K.



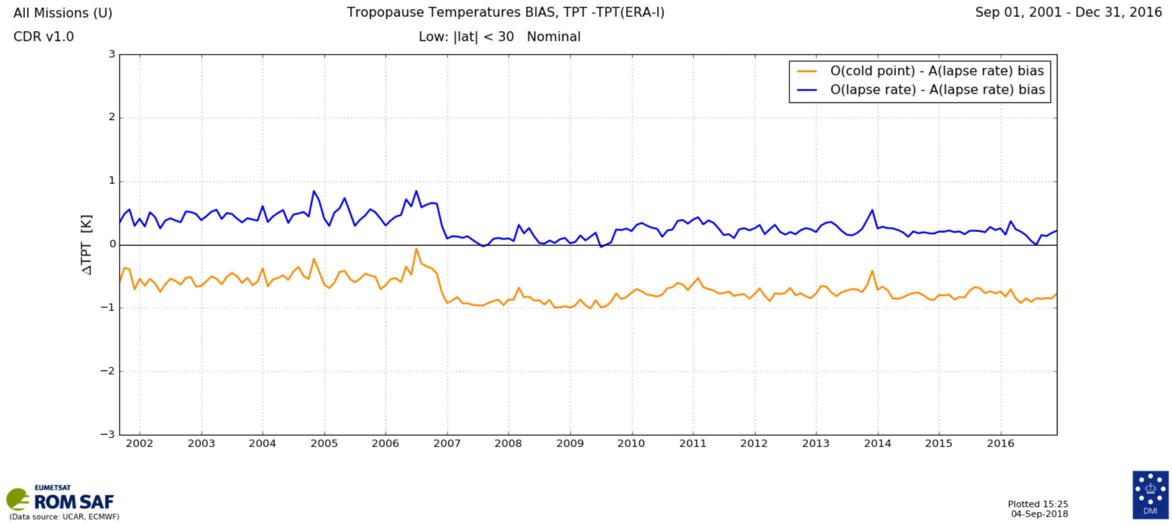


Figure 3.12: *Top: 4 different tropical tropopause height retrievals compared to ERA-I DLTH. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH. Bottom: 2 different tropopause temperatures (dry coldpoint and lapserate) compared to ERA-I dry temperature lapse rate tropopause temperature. See Section 3.3 for further discussion of the biases.*

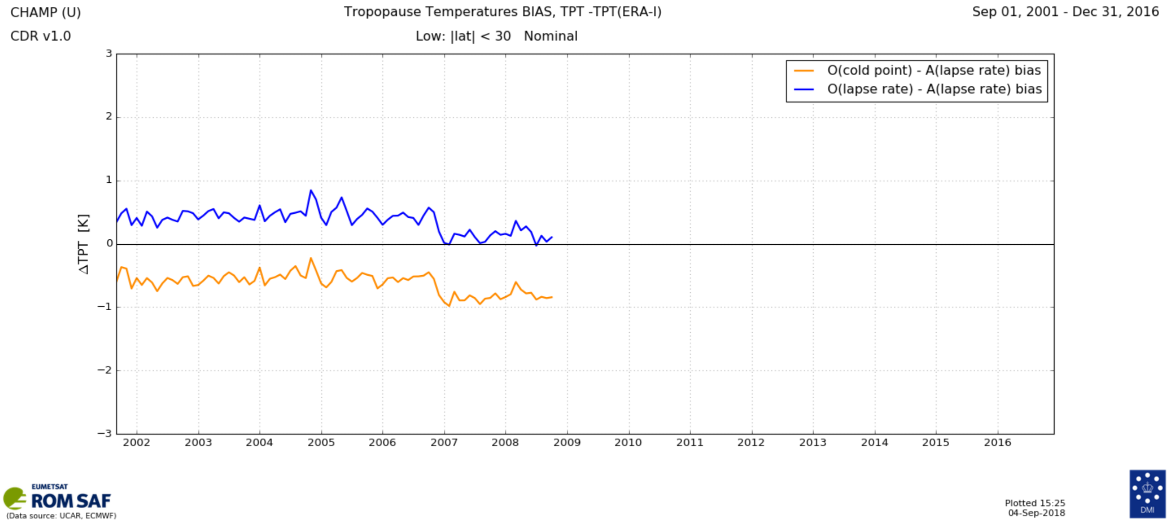


Figure 3.13: *Mean of different (tropical) tropopause temperature retrievals (ERA-I DLTH subtracted). CHAMP mission. Yellow: dry temperature cold point, blue: DLTH.*

By inspection of the [RD.8] plots related to DLTH it is verified that there is no noticeable difference in between the four missions, Metop, COSMIC, GRACE and CHAMP regarding the DLTH standard deviation. Therefore all the remaining plots are representing the whole CDR-v1.0, collecting all missions.

3.3.1 Standard deviation of DLTH in different latitude bands

A few plots are shown here to illustrate the performance in different latitude bands. Figures 3.14, 3.15 and 3.16 show the standard deviation of tropical, mid latitude and polar tropopause products, with the ERA-I analysis dry lapse rate tropopause subtracted. As expected the from the plots in section 3.2.1, there is largest deviations outside the tropics. In polar regions, north as well as south, there is an annual variability in the standard deviation which is related to ambiguity of the lapse rate tropopause definition in the polar winter.

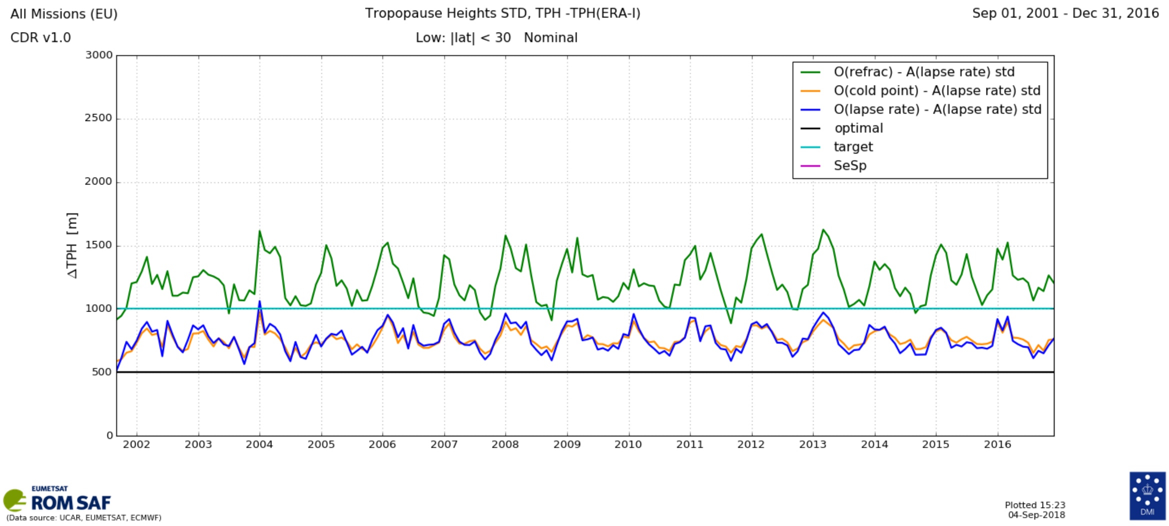


Figure 3.14: *Standard deviation of different (tropical) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH.*

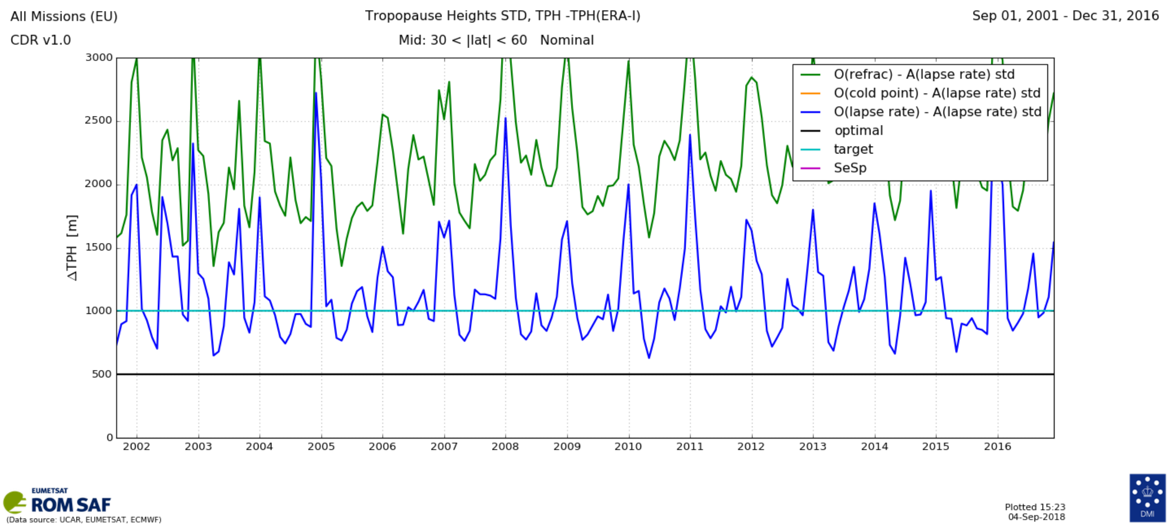


Figure 3.15: *Standard deviation of different (mid latitude) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined: Green: refractivity based, yellow: dry temperature cold point, blue: DLTH and "military green": ECMWF DLTH.*

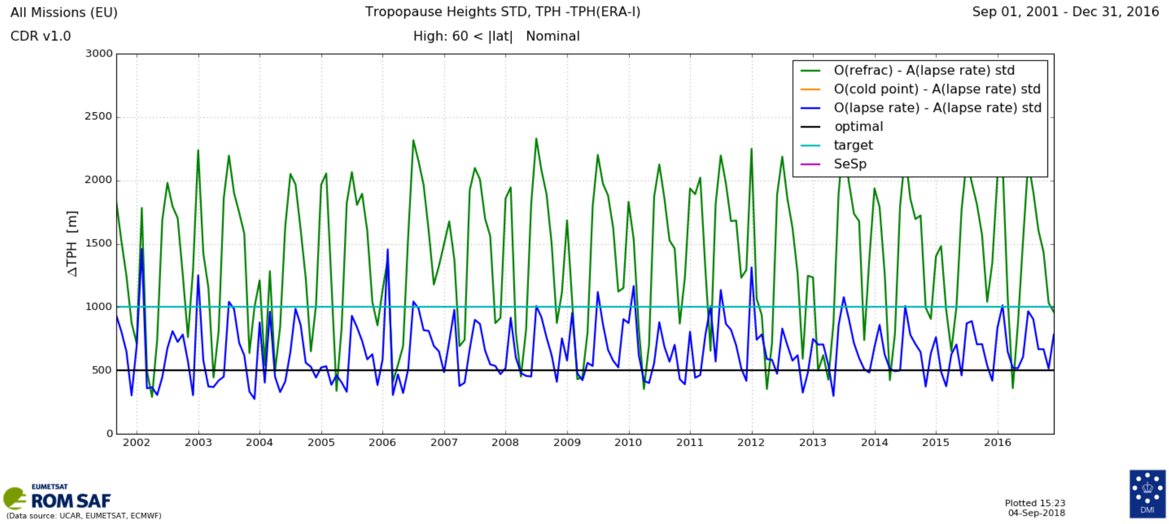


Figure 3.16: *Standard deviation of different (polar) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH.*

3.3.2 Polar Oscillation of Standard Deviation

In polar regions the large deviations between ERA-I and observed tropopauses have a cyclic signature. As seen in Figures 3.17 and 3.18 the standard deviation is largest in the polar winters.

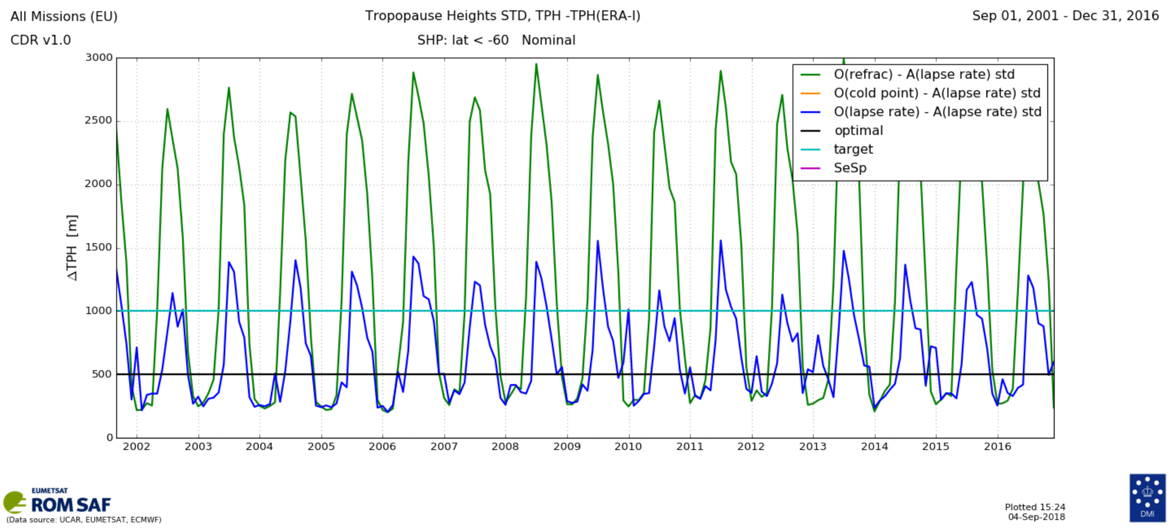


Figure 3.17: *Standard deviation of different (southern hemisphere polar) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH.*

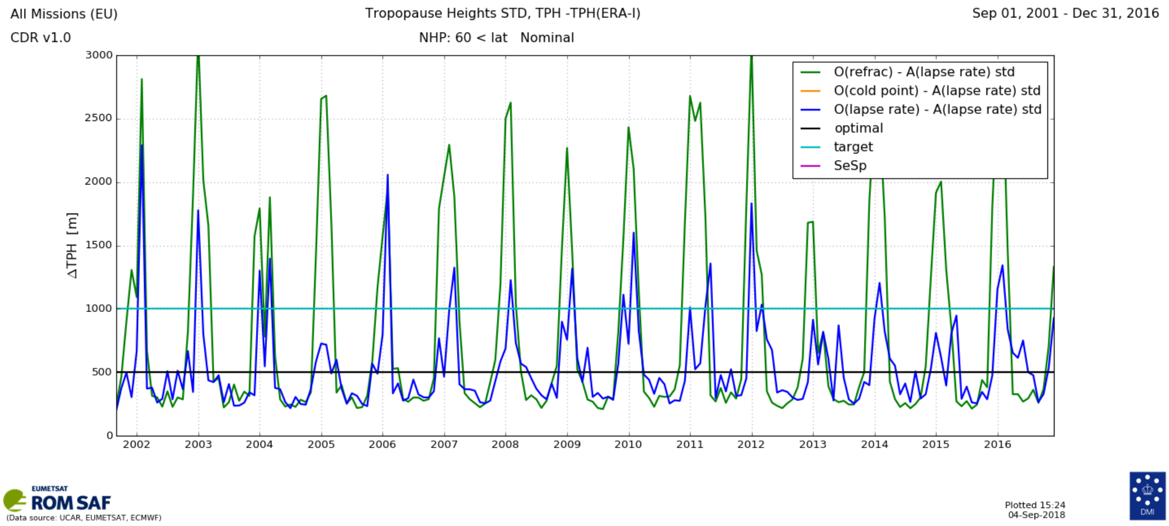


Figure 3.18: *Standard deviation of different (northern hemisphere polar) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH.*

3.3.3 Rising versus Setting TPH

In Figure 3.19 and 3.20 tropopauses from rising and setting occultations are shown separately. There is no noticeable difference in DLTH standard deviation between rising and setting occultations.

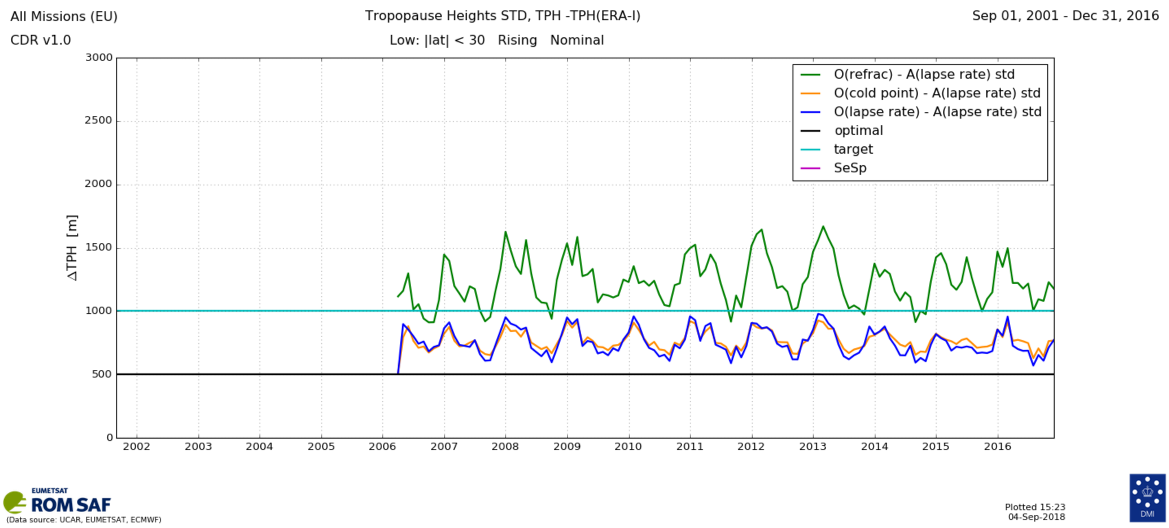


Figure 3.19: *Standard deviation of different (tropical rising occultations) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH.*

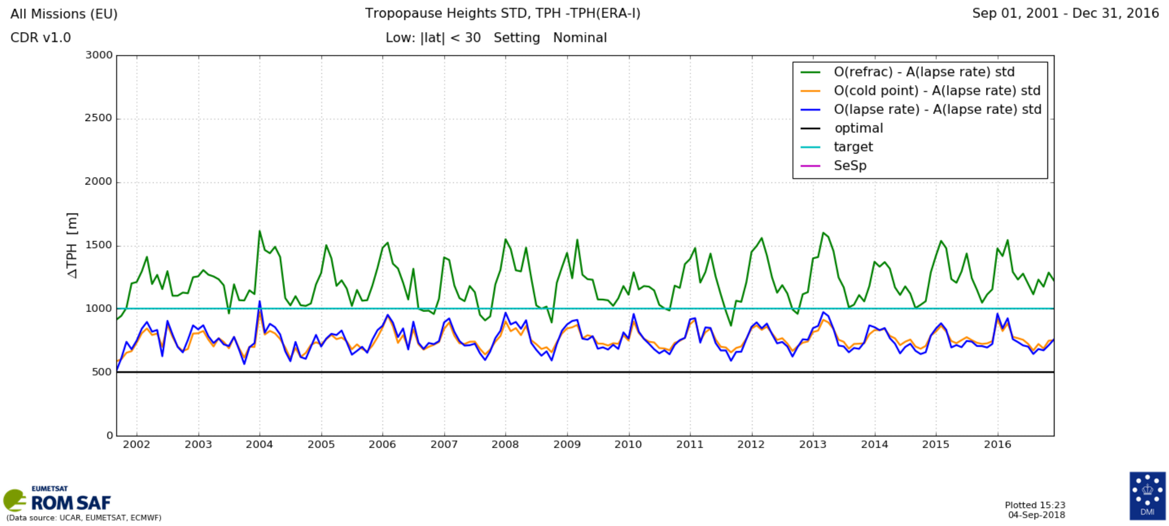


Figure 3.20: *Standard deviation of different (tropical setting occultations) tropopause height retrievals (ERA-I DLTH subtracted). All missions combined. Green: refractivity based, yellow: dry temperature cold point, blue: DLTH.*

4 Compliance with Product Requirements

For the TPH product the accuracy is defined as the standard deviation of the difference of (TPH product - model analysis) where "model analysis" is the time interpolated analysis from ERA-I.

The formal requirements for the ROM SAF data products are given in the Products Requirements Document [AD.3]. The requirements for the TPH product are formulated as standard deviations of the retrieved DLTH minus the ERA-I DLTH. Table 4.1 is summarizing the product requirements for the TPH-var products. The PRD target is violated at mid and high latitudes, while it is generally met in the tropics.

Table 4.1: *Threshold, Target, and Optimal accuracies for DLTH according to the PRD [AD.3]*

GRM-24/29/30/32/33			
Accuracy	Threshold	Target	Optimal
Standard deviation of Solution - Analysis	2 km	1 km	0.5 km
Verification/Validation Methods: Comparison to Re-analysis data.			
Coverage, Resolution			
Spatial Coverage	Spatial Resolution		
Global	RO resolution		

5 Open Issues

In polar regions, north as well as south, there is an annual variability in the standard deviation of the retrieved DLTH minus ERA-I DLTH, which reflects an apparent ambiguity of the lapse rate tropopause definition in the polar winter.

Neither the ERA-I or ECMWF analysis are suitable as DLTH reference, especially in the presence of multiple tropopauses. A validation against radiosondes, e.g. the GRUAN data set is desirable.

The stability of the combined mission tropopause temperature is questionable. There are biases of the order of 0.2 K between missions which defeats the possibility of calculating long term tropopause temperature trends. This issue should be addressed in the next reprocessing. The tropopause temperature bias is currently unexplained.

6 Conclusions

The DLTH has been validated and found to be generally sound.

The stochastic noise, standard deiation of retrieved tropopause products minus ERA-I tropopause, is stable with some annual variability, and the mean of the official DLTH product itself is stable. But the mean value of the dry temperature cold point seems to have some inter mission differences, with the Metop A/B tropopause being (less than) 0.2 K warmer than the COSMIC tropopause. CHAMP and GRACE DCTH are consistent with COSMIC.

The PRD target (standard deviation of retrieved tropopause minus ERA-I tropopause < 1 km) could not be reached at mid latitudes. This was rationalized as a consequence of poorly defined tropopause in ERA-Interim, and as such not directly related to the product.

The service specifications SeSp was modified to be adequate for the DLTH product by only applying the (standard deviation of retrieved tropopause - ERA-I < 1 km) criterion in a latitude band between -15 and 15 degrees.

The service specifications arrived at here will also apply for the offline TPH product in the ROM SAF ICDR (see Annex A).

Appendices

Annex I. Service Specifications CDR-v1.0

The Service Specifications describes 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 TPH product, and which are monitored regularly and documented as a part of normal operations.

The conclusion on the DLTH validation is that the SeSp should only be applied on a smaller latitude interval of ± 15 deg. This does not imply that the product is invalid outside this area. There is just not a reasonable way to compare to models at higher latitudes. If one restricts the SeSp to be applied only in the summer season at high latitudes these could also have been subject to SeSp. For simplicity this possibility has been omitted.

The latitude dependent DLTH validation may be summarized as follows: The product generally meets the PRD target (STDV≤ 1 km) in the tropics (Figure 3.14). At mid-latitude the requirements are nowhere near obeyed, due to double tropopause events (Figure 3.15). At high latitudes the target is mostly met except for systematic standard deviation increases in the polar winter (Figures 3.16,3.17 and 3.18).

As a consequence of the latitudinal dependence of standard deviation in Figures 3.10 and 3.8 we reduce the SeSp validation latitude range to include only a narrow latitude band; 15 deg. South to 15 deg. North, and keep the 1 km threshold value. The SeSp are summarized in Table 6.1

Table 6.1: Service specifications for the dry temperature lapse rate tropopause height

GRM-29/30/32/33-L2-C-R1	Tropopause height		
Type	CDR Data Set		
Applications and Users	Climate and atmosphere researchers		
Characteristics and Methods	Dry temperature lapse rate		
Operational Satellite Input Data	CDR level 1A Metop, COSMIC, CHAMP and GRACE from EUMETSAT Secretariat and UCAR CDAAC		
Other Operational Input Data	ECMWF ERA Interim fields		
Dissemination			
Format	Means	Timeliness	
netCDF	Web	n/a	
Service Specification			
1 km			
Verification/Validation Methods	Monthly standard deviation of (Product - ERA Interim analysis) based on all nominal dry temperature lapse rate tropopause retrievals in the latitude range		
Coverage, Resolution			
Spatial Coverage	Spatial Resolution	Vertical Resolution	Temporal resolution
15 deg. south to 15 deg. north	RO resolution	scalar	RO resolution

Annex II. Service Specifications ICDR-v1.0

Service specifications of ROM SAF Interim Climate Data Records ICDR-v1.0 are identical to service specifications for ROM SAF CDR-v1.0. The ICDR v1.0 is produced with the same processing chain as CDR v1.0. See also [RD.4]. The service specifications are repeated in table 6.2, which is a copy of table 6.1.

Table 6.2: *Service specifications for the dry temperature lapse rate tropopause height*

GRM-29-L2-C-I1	Tropopause height		
Type	ICDR Data Set		
Applications and Users	Climate and atmosphere researchers		
Characteristics and Methods	Dry temperature lapse rate		
Operational Satellite Input Data	ICDR level 1A Metop, COSMIC, CHAMP and GRACE from EUMETSAT Secretariat and UCAR CDAAC		
Other Operational Input Data	ECMWF ERA Interim fields		
Dissemination			
Format	Means	Timeliness	
netCDF	Web	n/a	
Service Specification			
1 km			
Verification/Validation Methods	Monthly standard deviation of (Product - ERA Interim analysis) based on all nominal dry temperature lapse rate tropopause retrievals in the latitude range		
Coverage, Resolution			
Spatial Coverage	Spatial Resolution	Vertical Resolution	Temporal resolution
15 deg. south to 15 deg. north	RO resolution	scalar	RO resolution

Annex III. Service Specifications ROM SAF Offline Data (v1.0)

Service specifications of ROM SAF Offline Data (v1.0) production are identical to service specifications for ROM SAF CDR-v1.0. The service specifications are repeated in table 6.3, which is a copy of table 6.1.

Table 6.3: *Service specifications for the dry temperature lapse rate tropopause height*

GRM-24	Tropopause height		
Type	Offline Data Set		
Applications and Users	Climate and atmosphere researchers		
Characteristics and Methods	Dry temperature lapse rate		
Operational Satellite Input Data	Offline level 1A Metop, COSMIC, CHAMP and GRACE from EUMETSAT Secretariat and UCAR CDAAC		
Other Operational Input Data	ECMWF ERA Interim fields		
Dissemination			
Format	Means	Timeliness	
netCDF	Web	30 d	
Service Specification			
1 km			
Verification/Validation Methods	Monthly standard deviation of (Product - ERA Interim analysis) based on all nominal dry temperature lapse rate tropopause retrievals in the latitude range		
Coverage, Resolution			
Spatial Coverage	Spatial Resolution	Vertical Resolution	Temporal resolution
15 deg. south to 15 deg. north	RO resolution	scalar	RO resolution