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Impacts of RO mission differences on trends in multi-mission data records

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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: https://www.romsaf.org

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Abstract

The ROM SAF CDR v1.0 COSMIC and Metop data records during 2007–2016 are characterised by a relatively constant offset between the two missions. The magnitude of the offset vary with latitude and altitude. During the same time period the weight of Metop in a combined RO data set increase from contributing less than 20% to about 70% of data. These two factors in combination (constant offset and changing data numbers) are expected to introduce a spurious trend in the multi-mission data record MULTI.

We have investigated differences in bending angle, refractivity, and dry temperature trends amongst 10-year time series (2007–2016) of RO data based on Metop, COSMIC, and the multi-mission data set MULTI, all of them part of the ROM SAF monthly-mean gridded CDR v1.0. We find two types of differences: a) positive MULTI trend biases relative to Metop and COSMIC, and b) negative Metop trend biases relative to COSMIC. The first effect is found in all three studied variables, starting at 15-25 km and increasing upward. The second effect is most evident in dry temperature, starting around 25-30 and increasing uppward. It is also present in refractivity, but only above 40 km, and most likely also in bending angle at even higher altitudes.

The variation of the two effects with altitude and across geophysical variables lead us to believe that the first effect is caused by the constant offset between Metop and COSMIC in combination with time-varying data numbers, and the second effect is caused by time-varying high-altitude biases between Metop and COSMIC that are propagated downward in the retrieval chain from bending angle to dry temperature. There are reasons to believe that the near-constant offset between Metop and COSMIC is caused by under-sampling of the diurnal cycle in the Metop data that is not fully compensated for by the sampling-error correction methods applied to the gridded data. There are several possibilities as for the source of the high-altitude biases: e.g., systematic differences of instrumental or ionospheric origin, or differences in the initialization of bending angles. Mitigation of the impacts of the two effects on the computed trends requires that we address the underlying causes at their origin, in the retrieval software or elsewhere in the processing system. Further investigations are needed to more firmly establish the root causes of the trend differences and the best way to reduce the impacts of these.

Finally, it should be noted that the trend differences discussed in this report, which are consequences of systematic errors in the monthly-mean gridded CDRs and ICDRs, do not prevent us from using the data in studies of climate trends. The trend biases vary with altitude. Depending on which geophysical variable that is studied the biases are small at sufficiently low altitudes in the stratosphere.

Contents

1 Background

The ROM SAF Climate Data Record version 1.0 (CDR v1.0), covering the 15-year time period 2002-2016, was validated and reviewed during July 2018 followed by the formal release in February 2019. The released data set consists of four separate data records based on the CHAMP, GRACE, COSMIC, and Metop Radio Occultation (RO) satellite missions (Table 1.1). A fifth data record (denoted MULTI in Table 1.1), generated by averaging of data from all four missions, was reviewed but not released. The four single-mission data records include both the individual atmospheric profile data and the corresponding gridded monthly-mean data, while the multi-mission data record consists only of gridded monthly-mean data.

During the Delivery Readiness Review for Reprocessing 1 (DRR-RE1) in July 2018, the question of RO mission differences was discussed [DRR-RE1 Review Board Report, 2018]. It was noted that, even though the inter-mission differences are quite small in the altitude region 8 to 30 km, they may still have an impact on the homogeneity and temporal stability of the multi-mission data record. In particular, there was a concern that the offsets between Metop and COSMIC may not be insignificant. When Metop data numbers increase while COSMIC data numbers decrease (Fig. 2.1), a nearly constant offset between Metop and COSMIC may introduce spurious long-term trends in the multi-mission data record. Such offsets could be caused by systematic errors in the underlying profile data or by differences in the sampling characteristics that are not fully compensated for by the sampling-error correction methods applied to the gridded data.

Following recommendations by the DRR-RE1 review board, the ROM SAF Steering Group tasked the Project Team to quantify the impact of the inter-mission offsets and to investigate the potential to mitigate the offsets in order to have a more homogeneous multi-mission data record [DRR-RE1 Review Board Report, 2018]. The present ROM SAF report mainly addresses the impacts on the long-term trends, while the issue of how to reduce the inter-mission biases is only briefly discussed.

In Section 2, the observed RO mission differences are described, while in Section 3 the impacts of these differences are quantified by the errors in the trends introduced over different time periods. In Section 4, the potential to mitigate the impacts of the inter-mission differences is briefly discussed. The main conclusions are summarized in Section 5. The Appendix provides a set of time series plots in support of the discussions in Section 3.

Table 1.1: ROM SAF Level 3 data products (gridded monthly means) included in CDR v1.0.

Product ID	Mission	Time coverage
GRM-28-L3-R1	MULTI	2001-09 to 2016-12
GRM-29-L3-R1	Metop	2006-12 to 2016-12
GRM-30-L3-R1	COSMIC	2006-07 to 2016-12
GRM-32-L3-R1	CHAMP	2001-09 to 2008-09
GRM-33-L3-R1	GRACE	2007-03 to 2016-12

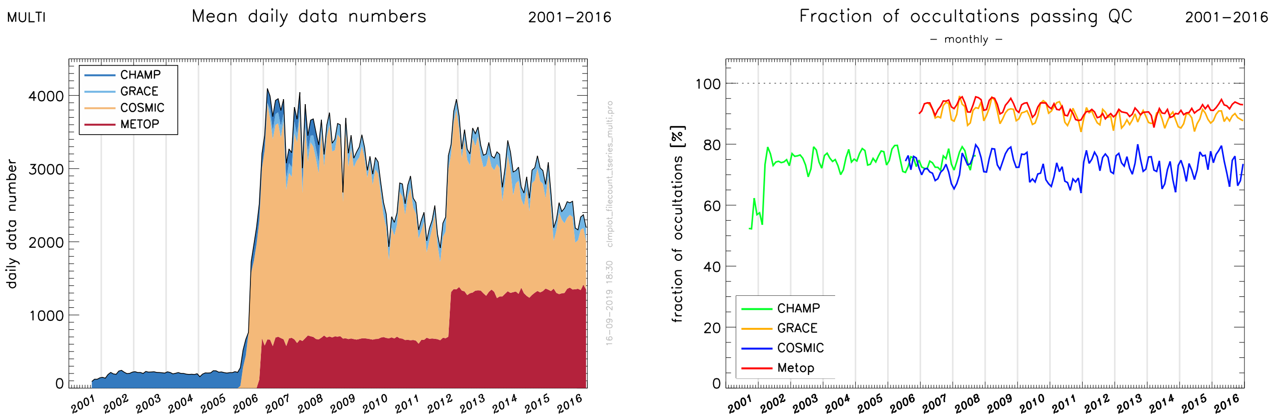

Figure 2.1: Left panel: Mean daily number of occultation events used in the generation of the ROM SAF climate data records, based on the four RO missions CHAMP , GRACE, COSMIC, and Metop. Right panel: Fraction of occultations available for the generation of gridded monthly mean data, after quality screening of the input profile data.

2 RO mission differences

Differences between single-mission climatologies may be caused by random and systematic errors in the RO profile data, by differences in the processing or algorithmic choices, or by differences in the sampling characteristics that are not fully compensated for by the sampling-error correction methods applied to the gridded data. Since there is no inter-calibration between satellites or instruments (at the level of geophysical variables) such differences may lead to temporal inhomogeneities and spurious long-term variability in multi-mission data records, as new RO satellite missions replace older ones. In this section, we introduce some of the RO mission differences with a focus on systematic errors and residual sampling error. For version 1.0 of the CDR there are some differences in the processing of the missions (Metop data are based on input from EUMETSAT, the other missions are based on input from UCAR) but these do not have an impact on the results or conclusions, and will not be further discussed. A more comprehensive description is found in [*Gleisner et al.*, 2020].

2.1 Data numbers

The ROM SAF CDR v1.0 includes data from four RO missions: CHAMP, GRACE, COSMIC, and Metop. In total, the four RO missions include nearly 12 million occultations collected from September 2001 to December 2016. After removal of data based on quality screening, about 10 million atmospheric profiles remain for generation of the CDRs.

As shown in Fig. 2.1, the time series starts in September 2001 with a relatively small number of CHAMP data, about 200 per day. The CHAMP data stopped after September 2008. From March 2007 and throughout the CDR time period, GRACE contributed another

150 occultations per day. The data numbers increased dramatically with the launch of the COSMIC mission and the first Metop satellite in 2006. During 2007–2009 the mean daily number of occultations peaked at well above 3500. The launch of the second Metop satellite, in combination with an update of the operational mode of the COSMIC mission, led to a second peak in the daily data numbers in 2013.

During the time period 2007 to 2016, the weight of Metop in relation to COSMIC changed substantially. In 2007, Metop contributed less than 20% of the total number of occultations, while towards the end of 2016 about 70% of the occultations were from Metop. After 2006 the weight of CHAMP and GRACE data in a multi-mission data set is small.

2.2 Sampling characteristics

The finite number of observations made by an RO mission is not enough to fully account for all variability within the bins, leading to a sampling error in the gridded data. The RO satellite missions have different instrument characteristics, satellite orbits, and observation numbers and, hence, have different abilities to capture the dominating modes of variability. Apart from synoptic-scale variability, leading to quasi-random sampling errors, the variability within the bins is dominated by diurnal and semi-diurnal cycles, meridional (latitudinal) gradients, and zonal (longitudinal) variations.

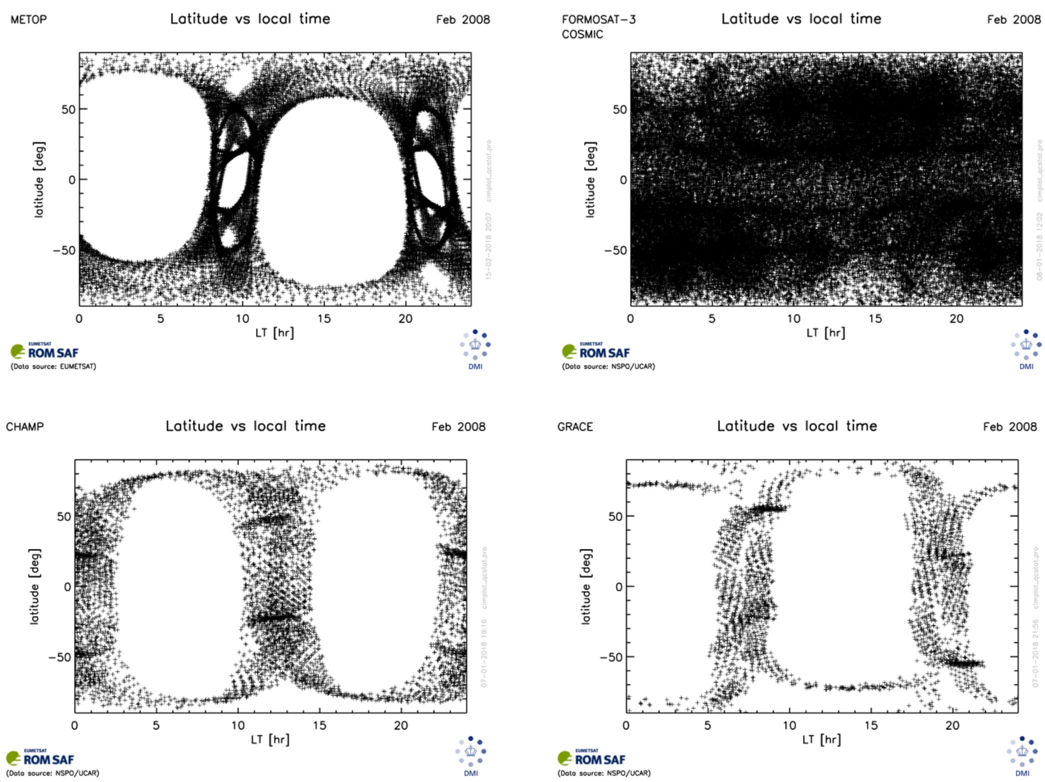

Figure 2.2: Latitude and local time for occultation events from the Metop, COSMIC, CHAMP, and GRACE missions. The overall distribution of Metop occultations (upper left panel) remains fixed with time, while the CHAMP and GRACE patterns slowly drift in local time. The COSMIC pattern (upper right) also drift in local time, about twice as fast as CHAMP.

RO instruments are flown by satellites in low-Earth orbits, at altitudes between 500 and 1000 km and with orbital periods around 100 minutes. With a careful selection of orbital parameters (mainly inclination) the orbit will be Sun-synchronous, i.e., the local solar time (LST) for the equatorial crossings do not change with universal time. An example is the series of Metop satellites, which always crosses the equator at 09:30 and 21:30 LST (see Fig. 2.2). For other orbital parameters, the satellites drift in local time. The CHAMP and GRACE satellites have orbital inclinations of 87° and 89°, respectively, which correspond to a drift that makes them cover all local times over a period of 4 months and 5 months, respectively. The lower panels of Fig. 2.2 shows the latitude-local time distributions for CHAMP and GRACE in February 2008. Over time, these distribution patters slowly drift to the left in the plots.

The COSMIC mission originally consisted of 6 satellites with 72° orbital inclination and drift rates with respect to the Sun roughly twice as large as CHAMP. With 6 satellites spread out in local time, a nearly complete local-time coverage was achieved. However, from around 2014 or 2015 the gradual loss of satellites started to have a visible impact on the distribution of observations in local time.

The ROM SAF climate monitoring pages at http://www.romsaf.org/climate_monitoring provide more information on the distributions of occultation events for the various missions.

2.3 Single-mission climatologies

RO measurements are sometimes referred to as "calibration free" or "self-calibrating", e.g. [*Angerer et al.*, 2017]. This is an expression of the fact that at the level of bending angle or geophysical data there is no inter-calibration between satellites or missions. Any differences between RO missions due to systematic errors are assumed to be small. The differences between single-mission climatologies are often expected to be dominated by random or quasi-random errors originating in random RO profile errors and residual sampling errors.

However, as shown in [*Gleisner et al.*, 2020], even though there is a high degree of consistency between the RO satellite missions, there are actually some remaining systematic differences. We have computed monthly mean anomalies of bending angle, refractivity, and dry temperature for the four RO missions CHAMP, GRACE, COSMIC, and Metop. The anomalies were computed on the 200 meter by 5° zonal grid, followed by vertical and horizontal averaging into global (90°S–90°N) and tropical (20°S–20°N) means. The same anomaly reference, based on RO data from the time period 2007-2016, was used for all four RO missions.

The left columns of Figs. 2.3–2.8 show the anomaly time series for bending angle, refractivity, and dry temperature, for global averages as well as tropical averages. The monthly mean anomalies are vertically averaged in four height layers: 4-8 km, 8-30 km, 30-35 km, and 35-40 km. The columns to the right show the differences of the CHAMP, GRACE, and Metop time series relative to COSMIC. Here, COSMIC is chosen as comparison reference because it provides the longest record of the four missions and because it has a good local-time coverage.

In moist regions of the atmosphere, below about 6 to 8 km, there are relatively large differences between the missions that at present prevent us from generating long multi-mission data records. This is seen in the lower panels of Figs. 2.3–2.8. Such multi-mission time series would not have the temporal stability necessary for studies of atmospheric variability or long-term trends. These current limitations of the RO data in the troposphere is not further discussed here.

The highest consistency between RO missions are found from the middle troposphere to the middle stratosphere, roughly 8 to 30 km. From an altitude around 30 km, the differences between the missions start to increase upward. The magnitude of the inter-mission differences (right columns of Figs. 2.3–2.8) must be evaluated in relation to the variability of the time series itself (left columns). This variability occurs on a broad range of time scales, from intra-seasonal variations to decadal variations and long-term climatological trends. Note that the y-axis scale in the difference plots are expanded compared to the anomaly plots in order to visualize the differences.

In the 8–30 km height range, the time-averaged Metop-COSMIC differences are roughly 0.02%, 0.04%, and 0.05 K for globally averaged bending angle, refractivity, and dry temperature. The corresponding numbers for tropical averages are about 0.05%, 0.08%, and 0.10 K, respectively.

The CHAMP-COSMIC and GRACE-COSMIC differences exhibit rather stable oscillations with peaks that reach about the same magnitude as the relatively constant Metop-COSMIC differences. Hence, the CHAMP and GRACE time-averaged differences relative to COSMIC are smaller than the corresponding Metop-COSMIC differences. We note that the oscillation periods are about 4 months and 5 months, respectively for CHAMP and GRACE, closely corresponding to the precession rates of the satellite orbits. This behaviour could be explained as a consequence of the sampling-error correction not being able to fully compensate for the effects of under-sampling the diurnal and semi-diurnal cycles. This explanation would also be consistent with the near-constant Metop-COSMIC differences.

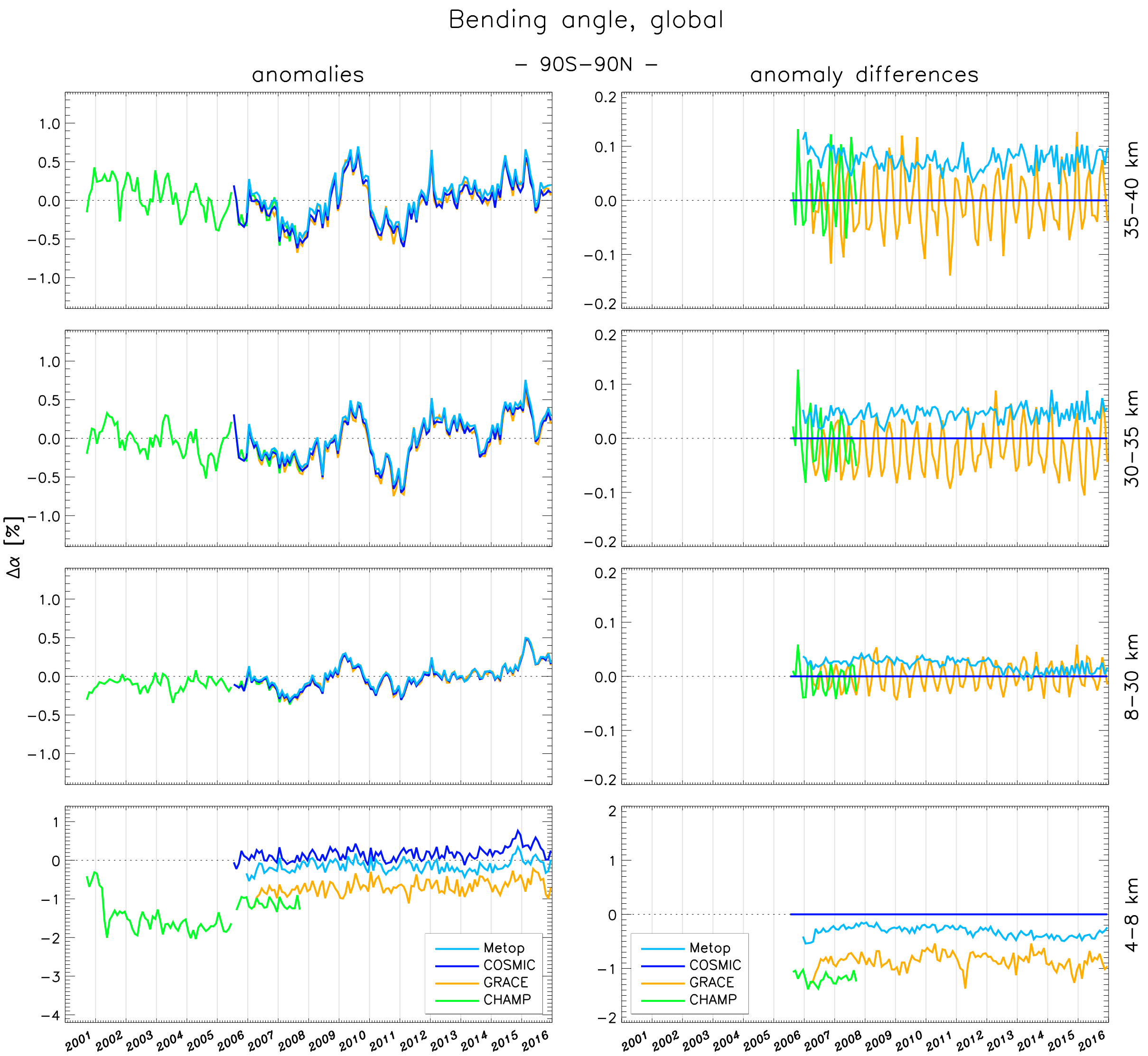

Figure 2.3: Global monthly mean bending angle anomalies for the four RO missions (left panels) and differences of CHAMP, GRACE, and Metop with respect to COSMIC (right panels). From bottom to top, the panels show the 4-8 km, 8-30 km, 30-35 km, and 35-40 km height layers. Note that for the lowest plots, the vertical axes have been compressed to accommodate the larger differences between the missions.

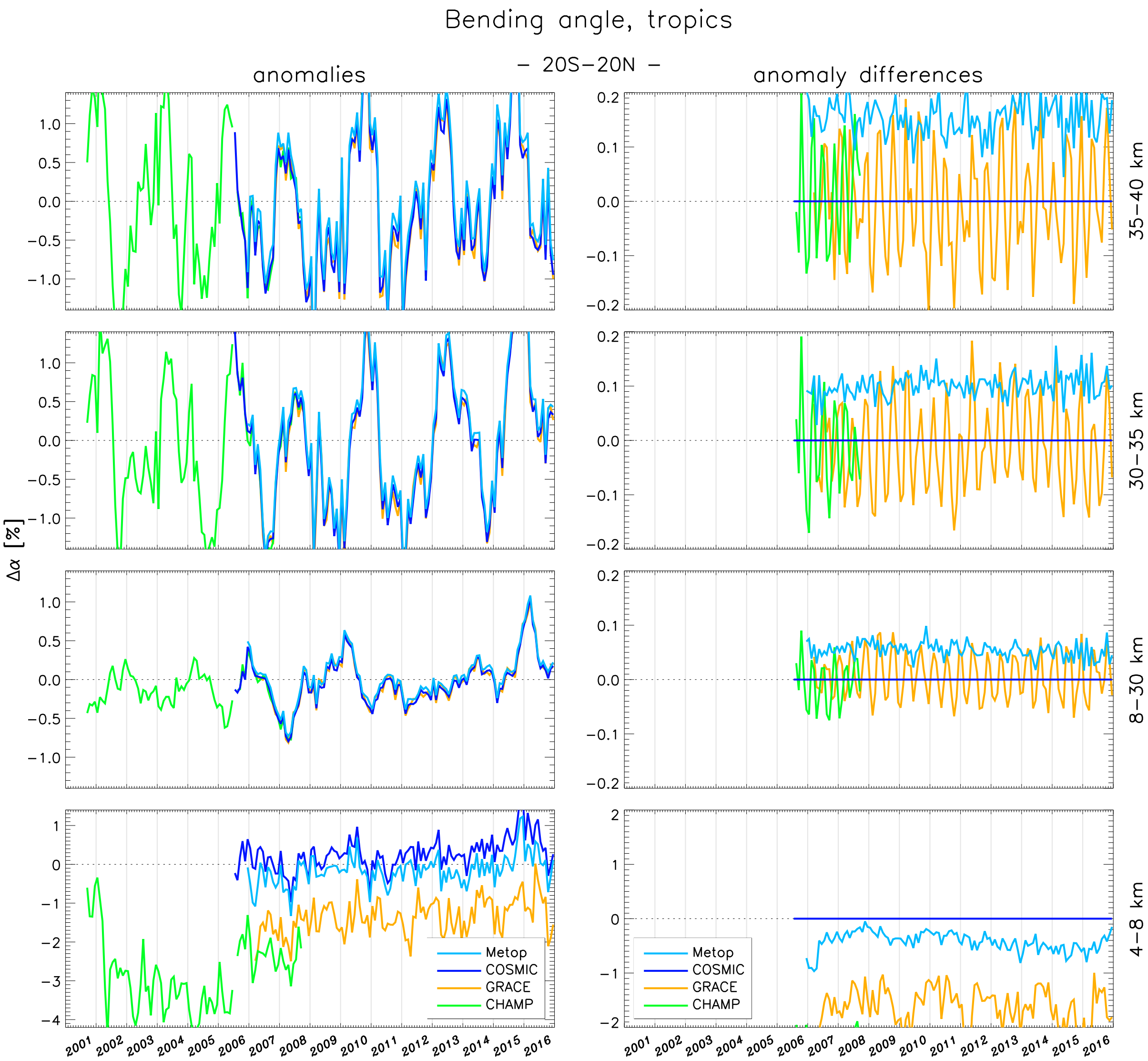

Figure 2.4: Tropical monthly mean bending angle anomalies for the four RO missions (left panels) and differences of CHAMP, GRACE, and Metop with respect to COSMIC (right panels). From bottom to top, the panels show the 4-8 km, 8-30 km, 30-35 km, and 35-40 km height layers. Note that for the lowest plots, the vertical axes have been compressed to accommodate the larger differences between the missions.

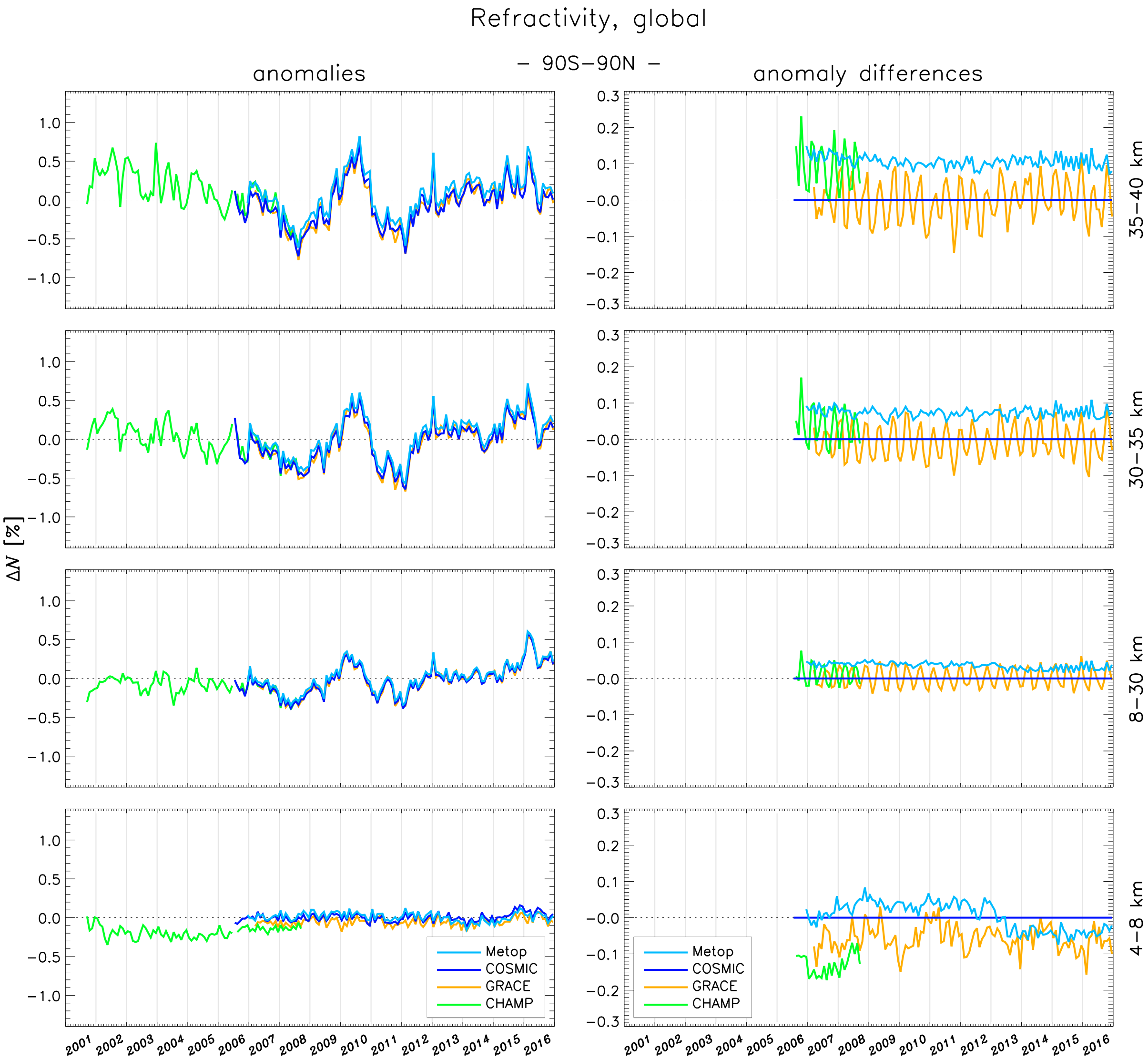

Figure 2.5: Global monthly mean refractivity anomalies for the four RO missions (left panels) and differences of CHAMP, GRACE, and Metop with respect to COSMIC (right panels). From bottom to top, the panels show the 4-8 km, 8-30 km, 30-35 km, and 35-40 km height layers.

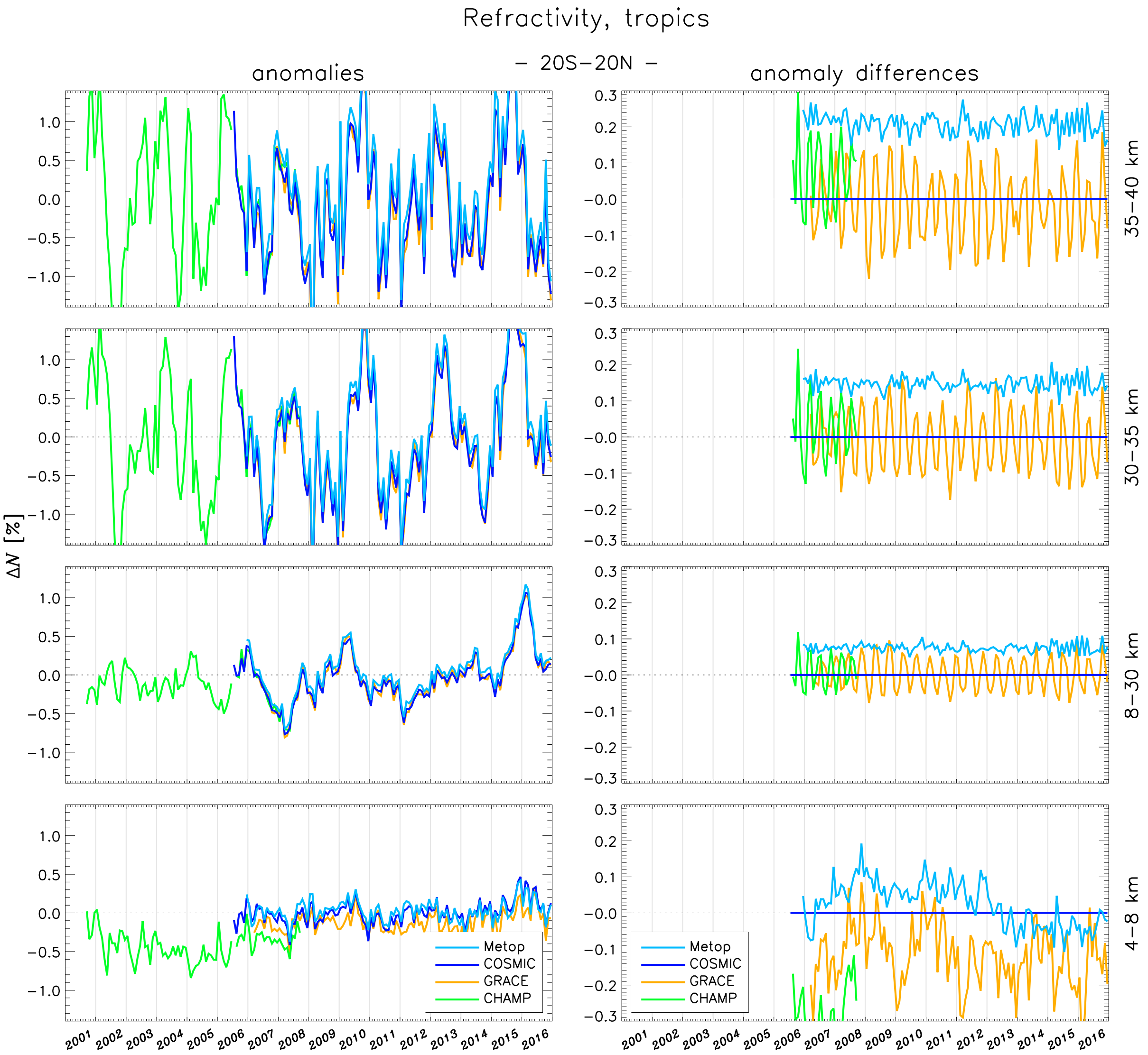

Figure 2.6: Tropical monthly mean refractivity anomalies for the four RO missions (left panels) and differences of CHAMP, GRACE, and Metop with respect to COSMIC (right panels). From bottom to top, the panels show the 4-8 km, 8-30 km, 30-35 km, and 35-40 km height layers.

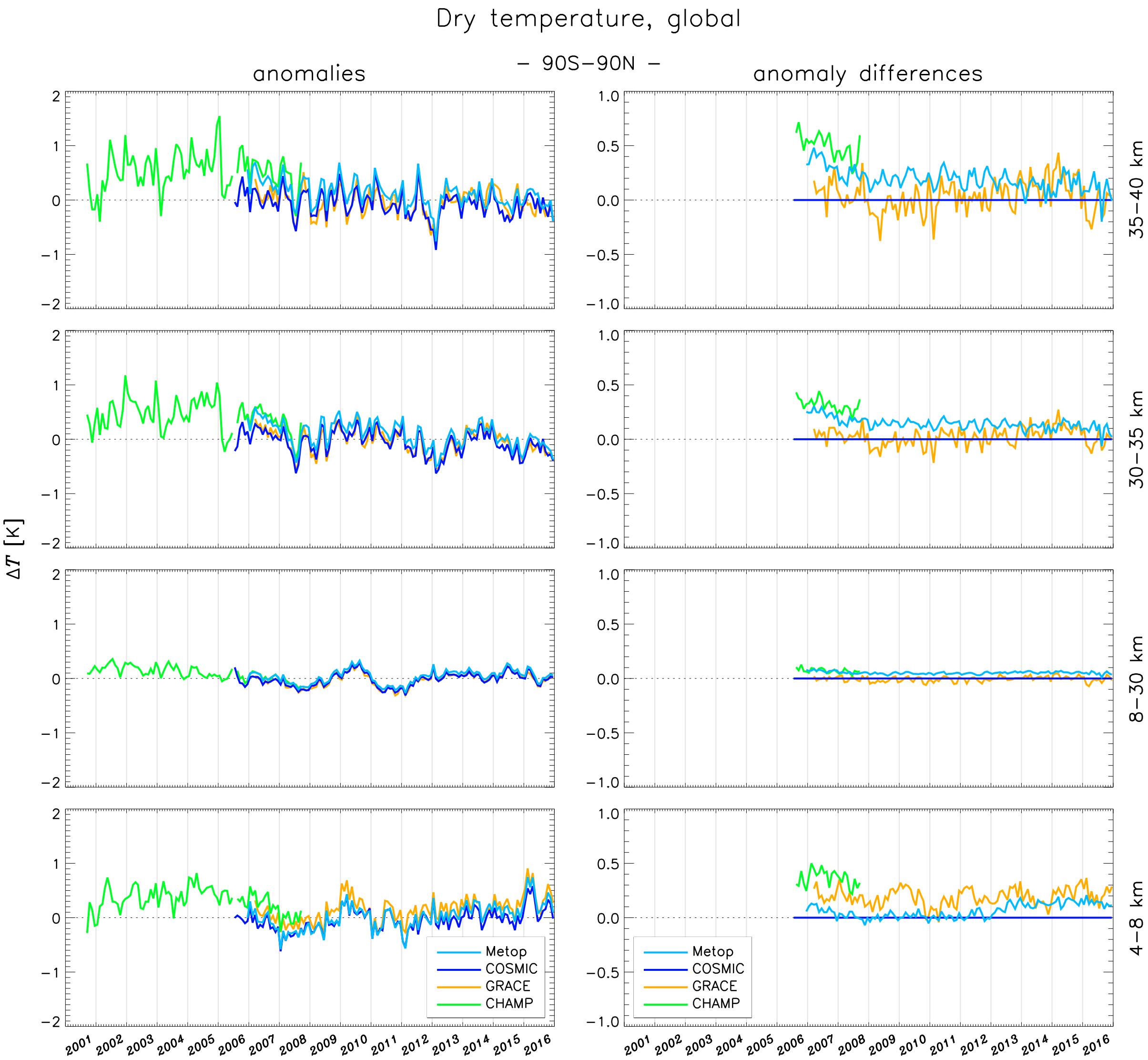

Figure 2.7: Global monthly mean dry temperature anomalies for the four RO missions (left panels) and differences of CHAMP, GRACE, and Metop with respect to COSMIC (right panels). From bottom to top, the panels show the 4-8 km, 8-30 km, 30-35 km, and 35-40 km height layers.

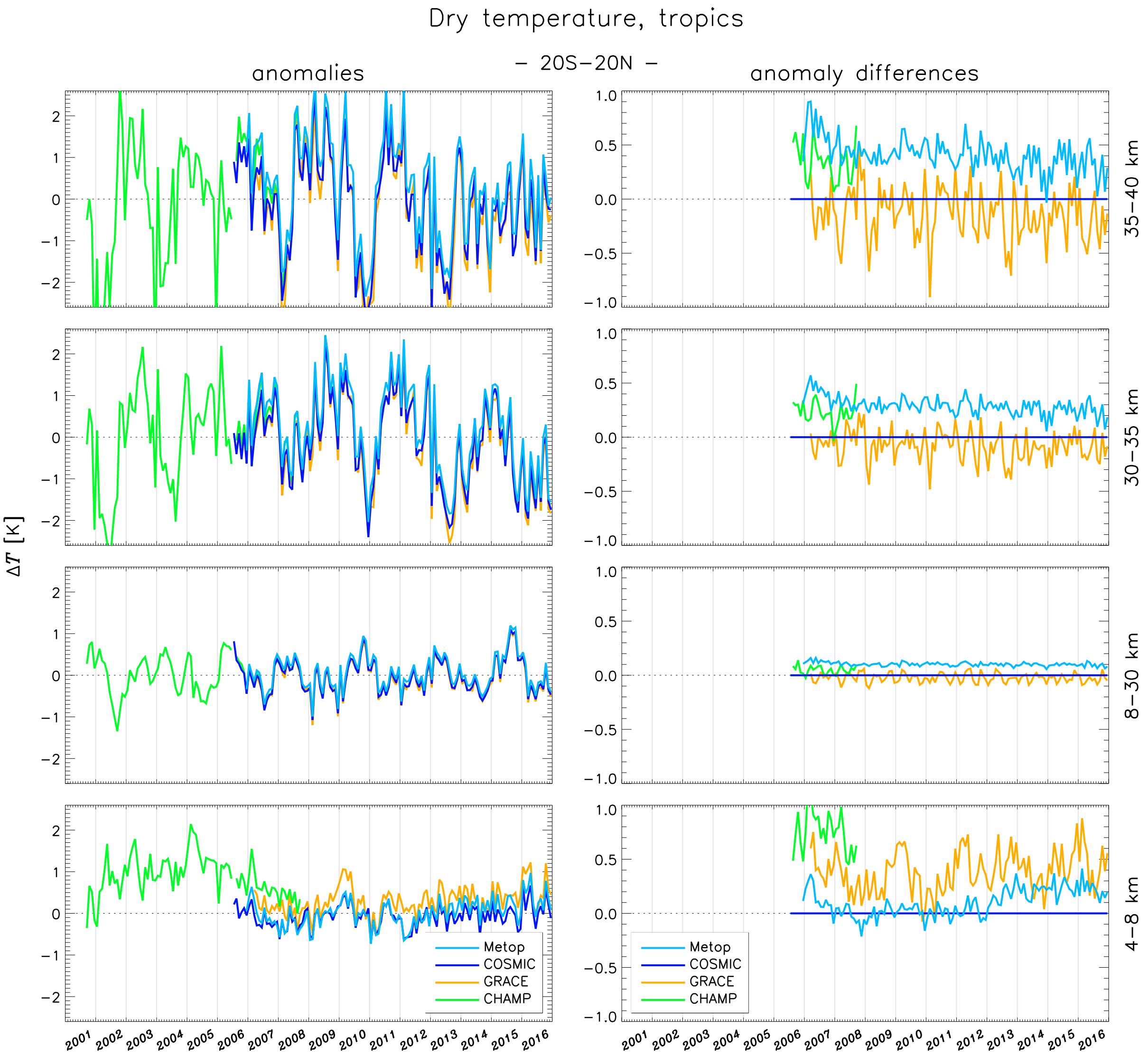

Figure 2.8: Tropical monthly mean dry temperature anomalies for the four RO missions (left panels) and differences of CHAMP, GRACE, and Metop with respect to COSMIC (right panels). From bottom to top, the panels show the 4-8 km, 8-30 km, 30-35 km, and 35-40 km height layers.

3 Impacts of mission differences

Even though the inter-mission differences described in Section 2.3 are quite small they may still have an impact on the homogeneity and temporal stability of multi-mission data records. The Metop-COSMIC differences for the bending angle and refractivity anomalies are relatively constant in time, while the differences for the dry temperature anomalies are more variable. All differences increase with altitude from a minumum around 15-25 km.

Constant Metop-COSMIC differences in combination with time-varying data numbers may introduce spurious long-term trends in multi-mission data records. The spurious trends would show up as systematic differences between trends derived from MULTI data and trends derived from either Metop or COSMIC. Ideally, the trends derived from Metop and COSMIC should be very similar, and the differences between those trends and the MULTI trends would increase with altitude as the Metop-COSMIC anomaly differences increase with altitude. The existence of such spurious trends are here investigated by the differences amongst the trends derived from the Metop, COSMIC, and MULTI data records during the 10-year period 2007–2016, when both Metop and COSMIC data were available in sufficient numbers.

The MULTI CDR starts in 2002 and continues up to 2016, and after that it can be extended by the Metop ICDR. To assess the impact of Metop-COSMIC differences on trends derived from the longest possible ROM SAF CDR+ICDR time series, we also investigate the differences amongst the trends derived from three different constructions of multi-mission data records during the 18-year period 2002–2018. The constructions differ in the relative amounts of Metop and COSMIC data used in the time period 2007-2016. Before and after that period the three time series are identical.

3.1 Impacts on 10-year trends 2007-2016

From 10-year time series (2007 to 2016) of gridded monthly mean bending angle, refractivity, and dry temperature anomalies, vertically averaged in 5-km height layers and horizontally averaged globally (90S-90N) and at low latitudes (20S-20N), we compute trends by ordinary linear regression. The purpose is only to detect differences amongst the data sets. Ten years is not enough to describe any underlying climatological trends, considering the magnitude of the climate variability.

Fig. 3.1 shows the trend differences of the missions relative to COSMIC. The bending angle and refractivity trend differences (Fig. 3.1, upper and middle panels respectively) exhibit systematic deviations between MULTI and the other two missions, while the trends derived from Metop and COSMIC data are relatively similar. These results are consistent with a spurious trend in the multi-mission data record caused by the Metop-COSMIC differences. The positive biases in the MULTI bending-angle and refractivity trends introduced by this effect increase from close to zero around 15-25 km to about 0.10 %/decade in the tropics and 0.05 %/decade globally around 40 km.

The differences between the MULTI trends and the single-mission COSMIC and Metop trends are clearly seen in the Appendix, where the MULTI anomaly time series are plotted together with 10-year trend lines. In Figure A.2, the refractivity anomalies at high altitudes in the tropics (upper left panel) clearly show that the 10-year trend lines for COSMIC and Metop are more or less parallel while the MULTI trend line have a slightly different slope.

The lower panel in Fig. 3.1 shows the trend differences relative to COSMIC for dry temperature. The positive bias in the MULTI trends are found here as well. However, we also observe something else: the Metop and COSMIC trends differ systematically above about 25-30 km, and the differences grow larger with altitude as the Metop trend biases become successively more negative reaching about -0.2 K/decade in the 35-40 km interval. There are indications in data from above 40 km (not shown here) that the negative Metop-COSMIC trend difference is found in refractivity as well, and most likely also in bending angle at even higher altitudes. In Figure A.3, the plots for dry temperature shows that the COSMIC and Metop 10-year trend lines have different slopes, and that the differences increase with altitude.

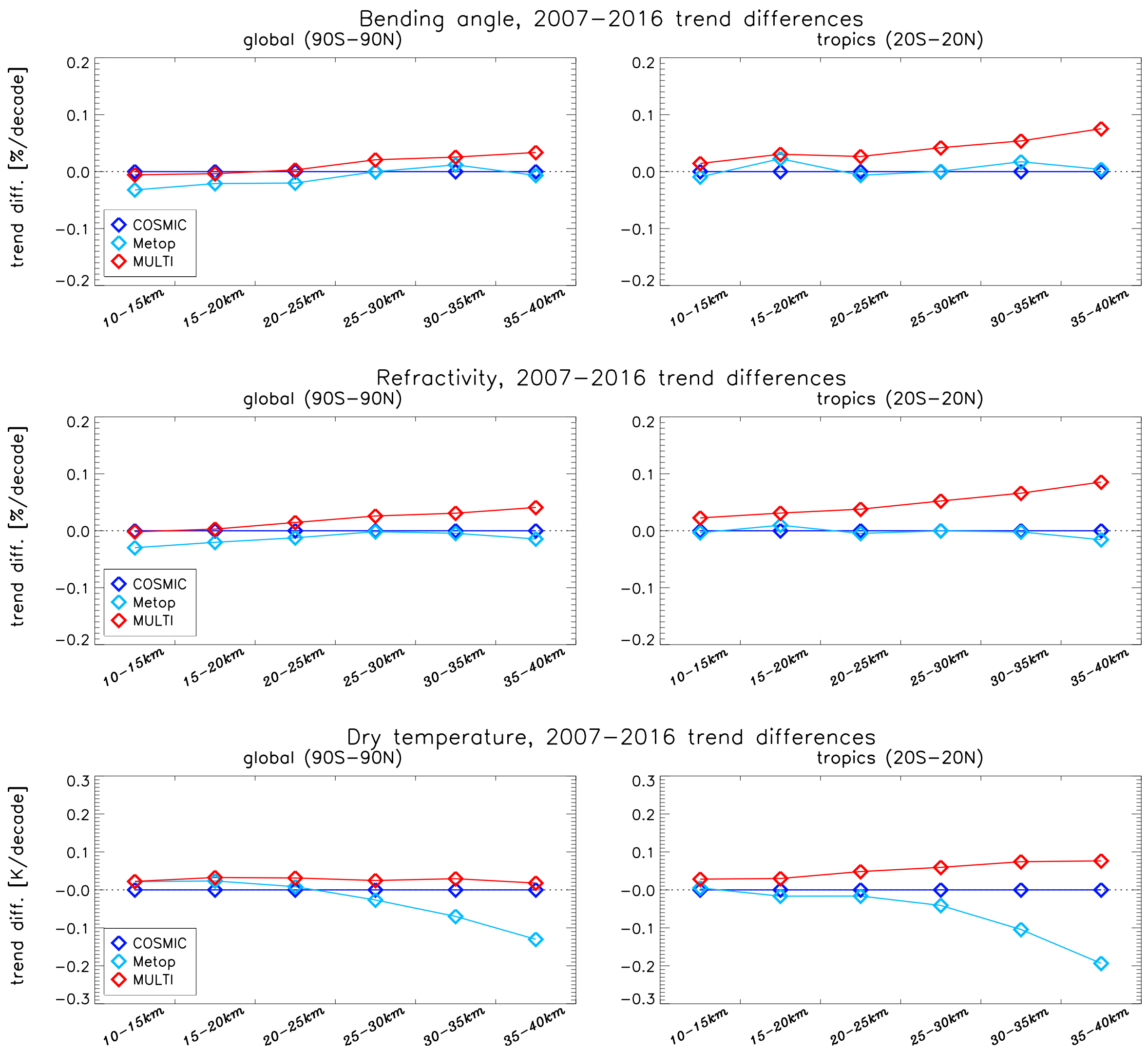

Figure 3.1: Trend differences relative to COSMIC for 5-km vertical averages, globally (left panels) and at low latitudes (right panels). See also the Appendix, where COSMIC, Metop, and MULTI 10-year trend lines are plotted on top of MULTI time series.

Apparently, we can identify two separate effects in the trend difference plots in Fig. 3.1: a) positive MULTI trend biases relative to Metop and COSMIC where the latter missions have nearly the same trends, and b) negative Metop bias relative to COSMIC, with the MULTI bias still positive although it starts to decrease as the negative Metop bias grows. The first effect is found in all three studied variables, starting at 15-25 km and increasing upward. The second effect is most evident in dry temperature, starting around 25-30 and increasing with altitude. However, it is present in refractivity as well, but only above 40 km, and is most likely also present in bending angle at even higher altitudes.

The variation of the two effects with altitude and across geophysical variables lead us to believe that the first effect is caused by the constant offset between Metop and COSMIC in combination with time-varying data numbers, and the second effect is caused by time-varying high-altitude biases between Metop and COSMIC that are propagated downward in the retrieval chain from bending angle to refractivity and dry temperature.

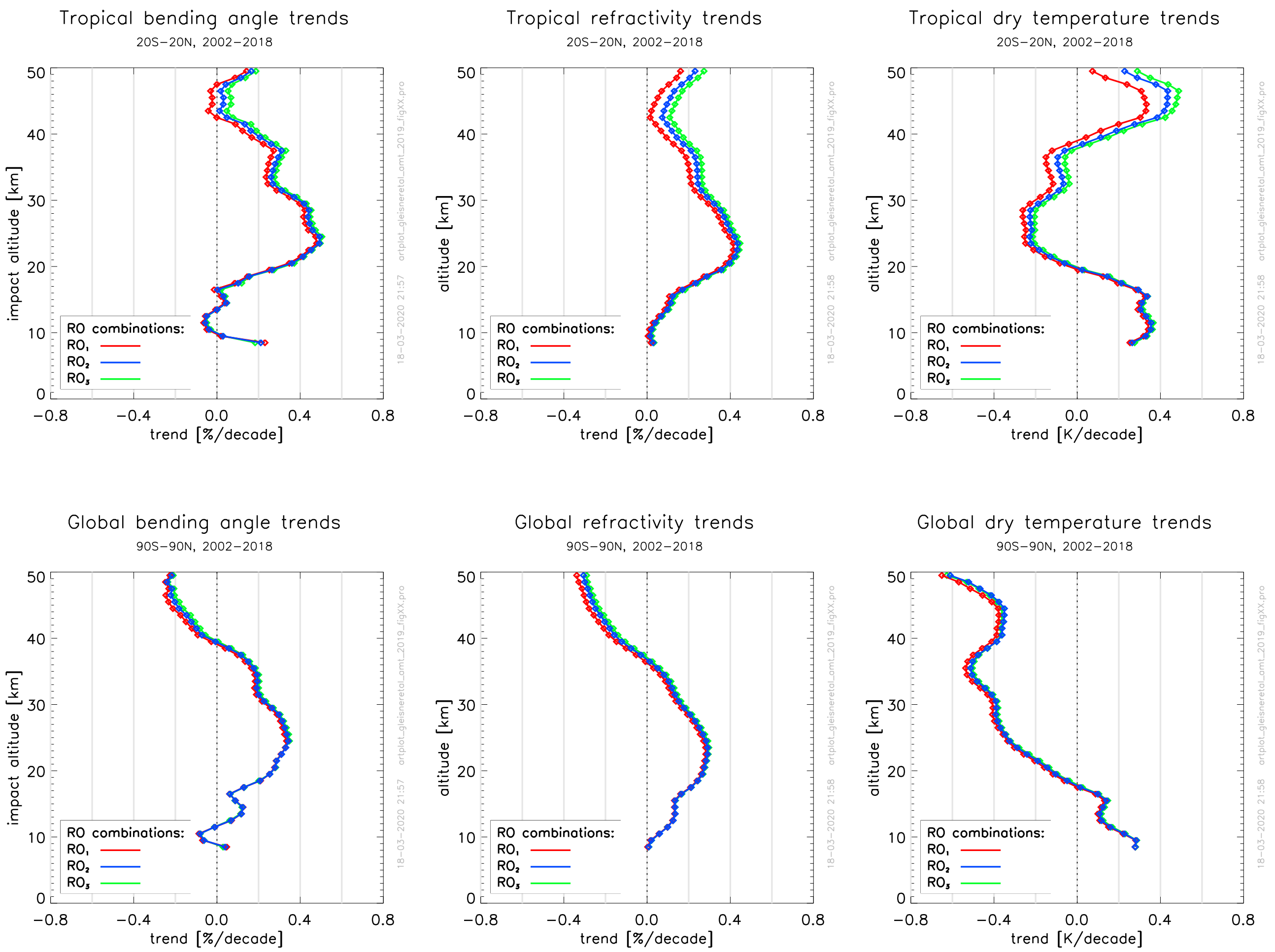

Figure 3.2: Trends vs altitude for 1-km vertical averages, globally (lower panels) and at low latitudes (upper panels). For each geophysical variable, the 2002–2018 trends have been computed using three different combinations of RO missions.

3.2 Impacts on 17-year trends 2002-2018

In the previous section we investigated the 2007–2016 trends for the Metop, COSMIC, and MULTI monthly-mean data. However, for actual studies of climatological trends, such as those done to contribute to the 6th IPCC assessment report, we use the longest possible time series. The MULTI data record starts already in 2001. It is based on CHAMP data up to 2006 when both the COSMIC data and, a few months later, the Metop data became available. After 2016, the climate data record (CDR) can be extended by the interim climate data record (ICDR) based on Metop data. In this section we investigate the consequences for the 2002–2018 trends of using three different RO mission combinations during the 2007-2016 time period. Before 2007 and after 2016 the three time series are identical. We refer to them as RO_1, RO_2, and RO_3:

RO$_1$ COSMIC during 2007–2016. MULTI CDR before that. Metop ICDR after that.

RO$_2$ MULTI during 2007–2016. MULTI CDR before that. Metop ICDR after that.

RO$_3$ Metop during 2007–2016. MULTI CDR before that. Metop ICDR after that.

Fig. 3.2 shows the 2002–2018 trends for bending angle, refractivity, and dry temperature. The trends are computed by ordinary linear regression from anomalies that have been vertically averaged in 1-km layers and horizontally averaged, globally (90S-90N) as well as in the tropics (20S-20N). We find that the trends differ somewhat. The differences become larger with altitude and are larger in the tropics than globally. At an altitude of 40 km in the tropics, we find differences in the bending angle and refractivity trends up to 0.1 %/decade and differences in dry temperature trends of about 0.2 K/decade. This can be regarded as a realistic estimate of the overall impact of Metop-COSMIC differences on a long multi-mission time series.

4 Discussion

Our interpretation of the detected trend differences amongst the RO missions and mission combinations is that a) the multi-mission data record MULTI has a positive trend bias relative to both COSMIC and Metop due to the near-constant offset between Metop and COSMIC during a time period when the weight of Metop data increased drastically, and b) there is a high-altitude time-varying bias between Metop and COSMIC anomalies that is propagated downward in the retrieval chain from bending angle to refractivity and dry temperature, and that has an impact on the computed trends.

Unlike atmospheric sounding data from other types of satellite based remote-sensing techniques, we do not inter-calibrate between RO instruments at the level of geophysical data. Reduction of the impacts of the two effects (referred to above as **a** and **b**) on the computed trends can only be achieved by addressing the underlying causes at their origin in the retrieval software or in the processing system. To do that we need to have a correct understanding of the source of errors and their propagation to the CDRs.

The offset between Metop and COSMIC is believed to be caused by under-sampling of the diurnal cycle in the Metop data, in combination with imperfect sampling error correction. The methods used to compensate for differences in the sampling characteristics are simply not able to fully handle the diurnal cycle. A better understanding of these sampling issues, and an improved ability to compensate for them, may be the best way forward to reduce the Metop-COSMIC offsets. It should be emphasized that unlike most RO mission differences, which are caused by systematic errors in the underlying profile data, this particular error – if correctly interpreted – is intrinsic to the monthly-mean gridded data.

High-altitude time-varying biases between Metop and COSMIC will be propagated downward in the retrieval chain and may show up as Metop-COSMIC trend biases with a strong altitude dependence, primarily in dry temperature but also in refractivity, and depending on the source of the Metop-COSMIC biases, also in bending angle. There are several possibilities as for the source of the high-altitude biases: e.g., systematic differences of instrumental or ionospheric origin, or differences in the initialization of bending angles. The dependence of the trend differences on altitude, latitude, season, and geophysical variables, as well of impacts found in individual occultations, will have to be further investigated.

Finally, it should be noted that the trend differences discussed in this report, which are consequences of systematic errors in the monthly-mean gridded CDRs and ICDRs, do not prevent us from using the data in studies of climate trends. The trend biases vary with altitude. Depending on which geophysical variable that is studied the biases are small at sufficiently low altitudes in the stratosphere.

5 Conclusions

Studies of the ROM SAF CDR v1.0 [*Gleisner et al.*, 2020] have shown that the COSMIC and Metop data records during 2007–2016 are characterised by a relatively constant offset between the two missions. The magnitude of the offset vary with latitude and altitude. During the same time period the weight of Metop in a combined RO data set increase from contributing less than 20% to about 70% of data. These two factors in combination (constant offset and changing data numbers) can be expected to introduce a spurious trend in the multi-mission data record MULTI.

We have identified differences between trends in bending angle, refractivity, and dry temperature computed from different satellite missions and different combinations of satellite missions. In a shorter time series covering the time period from 2007 to 2016 we find two types of difference: a) positive MULTI trend biases relative to Metop and COSMIC, and b) negative Metop trend biases relative to COSMIC. The first effect is found in all three studied variables, starting at 15-25 km and increasing upward. The second effect is most evident in dry temperature, starting around 25-30 and increasing uppward. It is also present in refractivity, but only above 40 km, and most likely also in bending angle at even higher altitudes. The positive biases in the MULTI bending-angle and refractivity trends increase from close to zero around 15-25 km to about 0.10 %/decade in the tropics and 0.05 %/decade globally around 40 km. The Metop trend biases relative to COSMIC become successively more negative with altitude and reach about -0.2 K/decade in the 35-40 km interval.

The variation of the two effects with altitude and across geophysical variables leads us to believe that the first effect is caused by the constant offset between Metop and COSMIC in combination with time-varying data numbers, and the second effect is caused by time-varying high-altitude biases between Metop and COSMIC that are propagated downward in the retrieval chain from bending angle to dry temperature.

Mitigation of the impacts of the two effects on the computed trends requires that we address the underlying causes at their origin, in the retrieval software or in the processing system. To do that we need to have a correct understanding of the source of errors and their propagation to the CDRs. There are reasons to believe that the near-constant offset between Metop and COSMIC is caused by under-sampling of the diurnal cycle in the Metop data that is not fully compensated for by the sampling-error correction methods applied to the gridded data. There are several possibilities as for the source of the high-altitude biases: e.g., systematic differences of instrumental or ionospheric origin, or differences in the initialization of bending angles. Further investigations are needed to more firmly establish the root causes of the trend differences and the best way to mitigate the impacts of these.

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Appendix

17-year time series, covering 2002 to 2018, and 10-year trend lines for 2007 to 2016.

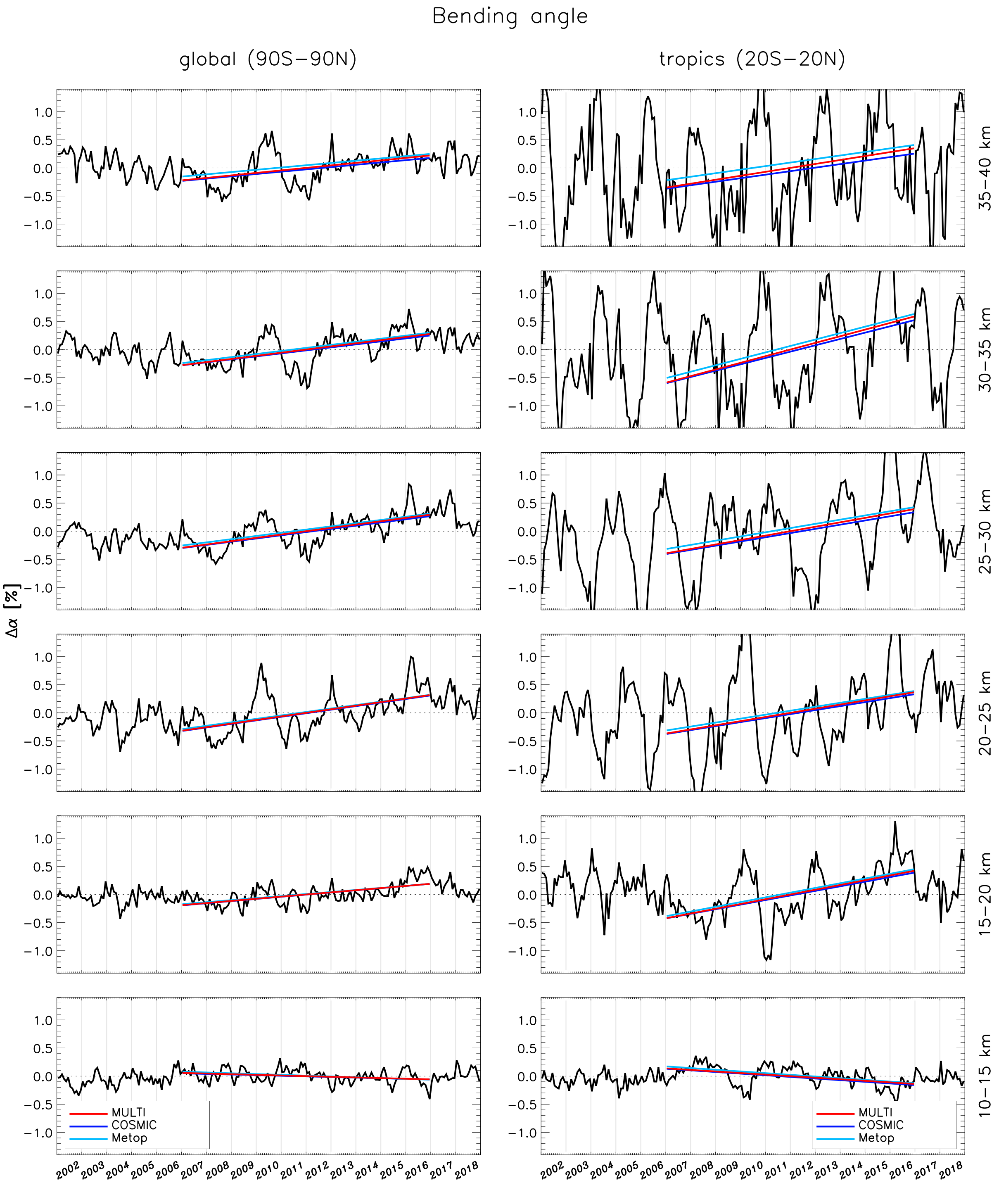

Figure A.1. Monthly mean bending angle anomalies for the multi-mission data record, globally to the left and tropics to the right. From bottom to top, the panels show the 10-15 km, 15-20 km, 20-25 km, 25-30 km, 30-35 km, and 35-40 km height layers. The coloured lines show 2007–2016 trend lines for the MULTI, COSMIC, and Metop missions respectively.

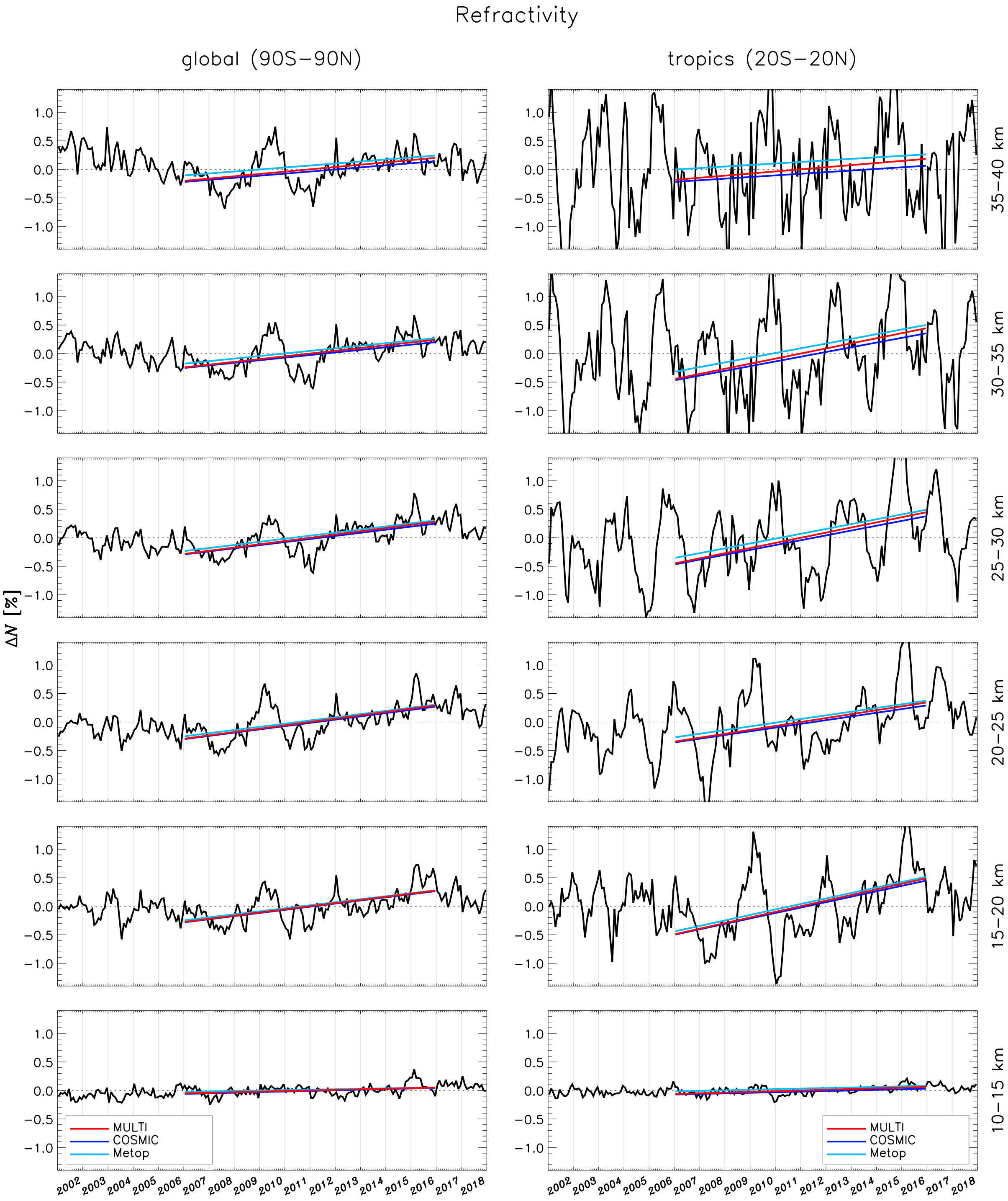

Figure A.2. Monthly mean refractivity anomalies for the multi-mission data record, globally to the left and tropics to the right. From bottom to top, the panels show the 10-15 km, 15-20 km, 20-25 km, 25-30 km, 30-35 km, and 35-40 km height layers. The coloured lines show 2007–2016 trend lines for the MULTI, COSMIC, and Metop missions respectively.

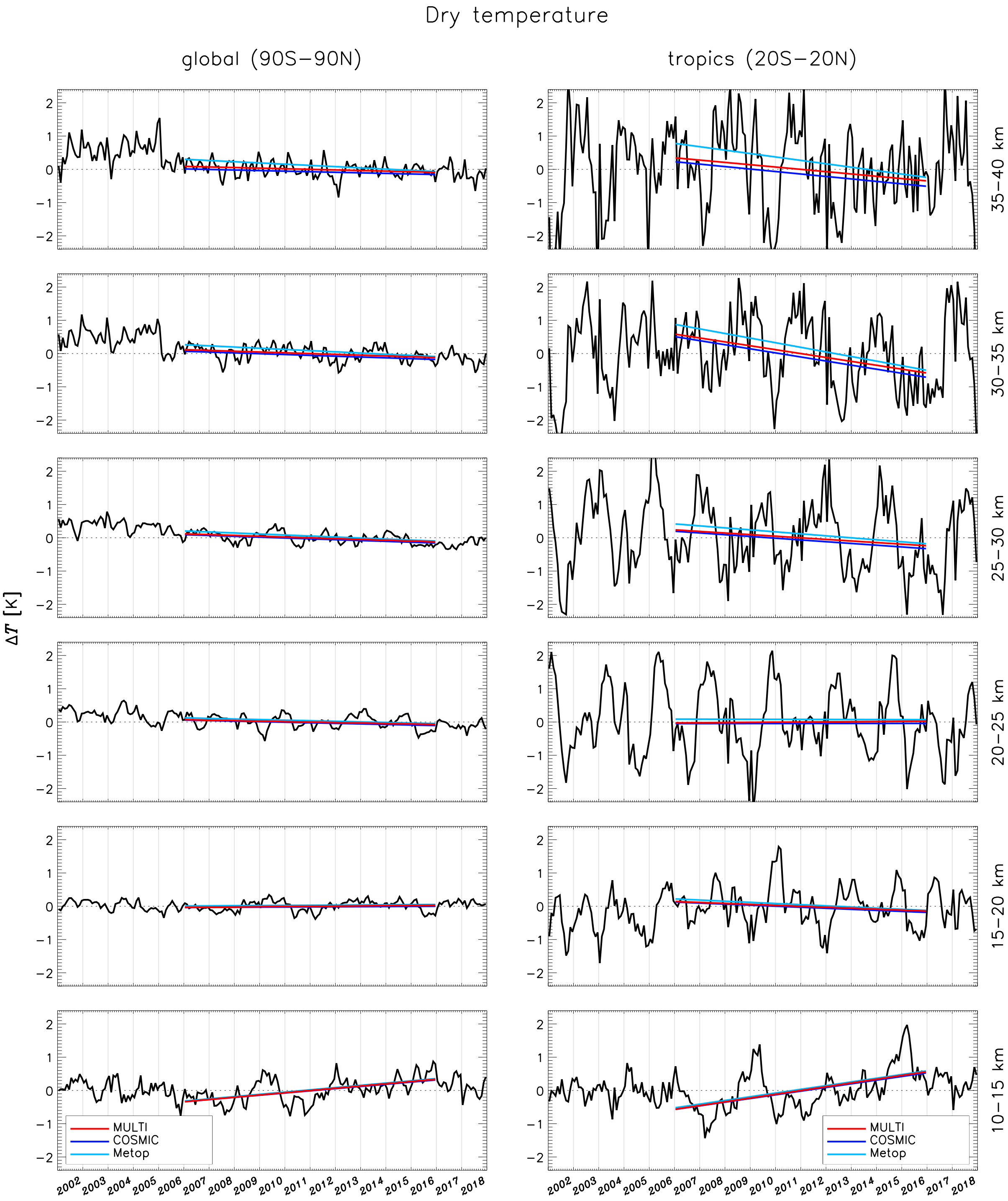

Figure A.3. Monthly mean dry temperature anomalies for the multi-mission data record, globally to the left and tropics to the right. From bottom to top, the panels show the 10-15 km, 15-20 km, 20-25 km, 25-30 km, 30-35 km, and 35-40 km height layers. The coloured lines show 2007–2016 trend lines for the MULTI, COSMIC, and Metop missions respectively.

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SAF/GRAS/METO/REP/GSR/004	Error function calculation in ROPP
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