GRAS SAF project and products

K. B. Lauritsen[1], H. Gleisner[1], M. E. Gorbunov[2], F. Rubek[1], S. Syndergaard[1] and M. B. Sørensen[1]

[1] *Danish Meteorological Institute, DK-2100 Copenhagen, Denmark*
[2] *Institute for Atmospheric Physics, Moscow, Russia*
www.grassaf.org

Abstract

The GRAS SAF is part of EUMETSATs network of Satellite Application Facilities (SAFs) under the EUMETSAT Polar System. The objectives of the GRAS SAF are to deliver operational radio occultation products from the GRAS occultation instruments (Global Navigation Satellite System Receiver for Atmospheric Sounding) onboard the three Metop satellites and to supply the Radio Occultation Processing Package (ROPP) containing modules for variational assimilation. The leading entity of the GRAS SAF is the Danish Meteorological Institute (DMI) and this is also the physical location of the operational GRAS SAF processing and archiving center. The other project partners are the European Center for Medium-range Weather Forecasts (ECMWF, UK), the IEEC (L'Institut d'Estudis Espacials de Catalunya, Barcelona, Spain), and the Met Office (Exeter, UK). The GRAS SAF started the operational phase in March 2007 and will start to deliver validated GRAS products in the second half of 2008. The GRAS data products consist of profiles of refractivity, temperature, and humidity (near-real time) and bending angle, refractivity, temperature, and humidity (offline and re-processing). We present results for refractivities retrieved from bending angles from EUMETSAT and compare them to ECMWF analyses.

Because raw GPS radio occultation (RO) data are based on measurements of time and the assumptions are known, RO data are also well suited for climate monitoring and climate research. The self-calibrating property should allow for relatively straight forward inter-comparison of data from different satellites and RO instruments which is required to construct long time series covering many years and even decades. Our GRAS SAF offline profiles will regularly be processed into global and regional climate data in support of these activities. We are currently undertaking studies on how to best exploit the GRAS data, both for construction of an accurate single-source climate data base with known error characteristics of the data and for provision of global climate monitoring. We discuss how to derive climate data from the RO profiles, and how to estimate the error characteristics, random observational and sampling errors, and systematic biases of such climate data.

1. Introduction

The basic principle of the radio occultation (RO) method is that a GPS receiver onboard a low-orbiting satellite tracks GPS signals as the transmitting satellite sets or rises behind the Earth. Due to refraction in the ionosphere and the neutral atmosphere the signal is delayed and its path bent, enabling calculation of the bending angle (BA). Assuming spherical symmetry and using the Abel transform together with statistical optimization one then obtains the index of refraction (or refractivity); see e.g. [Gobiet and Kirchengast, 2004]. In order to arrive at the temperature and humidity as a function of height or pressure one can use a 1D-VAR variational approach; see e.g. [Healy and Eyre, 2000].

The radio occultation method should be regarded as complementary to passive atmospheric sounders; it has a high vertical resolution in atmospheric regions where passive techniques are marginally useful, and it operates on completely different measurement principles, [Collard and Healy, 2003]. The fact that RO measurements do not merely reproduce other measurements is clearly shown within the field of NWP, where assimilation of RO data has a substantial positive impact. Within the field of climate monitoring (and for detection of climate change) the possibilities to accurately observe climate trends and to make bias corrections from independent measurements based on completely different measurement principles, are very important, see e.g. [Leroy et al., 2006]. One of the key advantages of RO measurements is that they can be assimilated without bias correction. Therefore, they can potentially improve the assimilation of satellite radiance measurements by correcting model biases and providing ‘anchor points’, to prevent adaptive, variational bias correction schemes drifting towards the NWP model climatology (see [D. Dee, 2008] these proceedings).

Forecast impact experiments using operational NWP systems to assimilate refractivity [Healy et al, 2005] and bending angle profiles [Healy and Thépaut, 2006] have demonstrated a clear positive impact, despite the relatively low number of RO observations. These results demonstrate that the RO measurements provide information that is complementary to that provided by the other observing systems and that they are a highly useful addition to the global observing network. As a result, RO measurements are now assimilated operationally at many centers worldwide.

In section 2 we give a short overview of the GRAS SAF. Section 3 presents the data and software products. In section 4 we show analyses of GRAS refractivity data. Section 5 contains a discussion of GPSRO climate applications and in section 6 we conclude.

2. The GRAS SAF

The GRAS SAF is a Satellite Application Facility (SAF) under EUMETSAT. The GRAS SAF is led by DMI with the three partner institutes, ECMWF (Reading, UK), IEEC (Barcelona, Spain) and Met Office (Exeter, UK). The development phase started in 1999 and spanned eight years. The GRAS SAF Processing and Archiving Center (GPAC) is now operational and will start providing GRAS data in 2008 [Lauritsen et al, 2006].

The scope of the GRAS SAF activities is to deliver products in near real time (NRT) as well as offline, at the level of geophysical parameters, based on the GPS radio occultation measurements by the GRAS instrument on Metop (see Fig. 1). One of the prime ways for improving present operational NWP analysis and products is the effective implementation and exploitation of satellite observations in the evolving NWP models for weather forecasts and climate change monitoring. The role of the GRAS SAF is to facilitate the input from the GRAS instrument on Metop to NWP and climate change models in order to increase the usage of satellite data in a more effective manner than possible today.

The operational GRAS SAF Processing and Archiving Center (GPAC) receives raw and preprocessed GPS radio occultation data from the GRAS instrument, processes these into vertical height profiles of refractivity, temperature, pressure, and humidity, and distributes these products continuously in NRT (near real time, within 3 hours from sensing) to numerical weather prediction users. The primary NRT input to the processing system is the GRAS level 1b data (bending angles) from EUMETSAT. In addition, offline and climate products (improved products, within 30 days from sensing) are produced for climate monitoring users. The offline products take advantage of data not available within the NRT timeliness constraints, like e.g. precise satellite orbits, NWP reanalysis. A third objective of the GRAS SAF is to supply the software package ROPP (Radio Occultation Processing Package) containing observation operators for 3D/4D-VAR assimilation of radio occultation data into numerical weather prediction models.

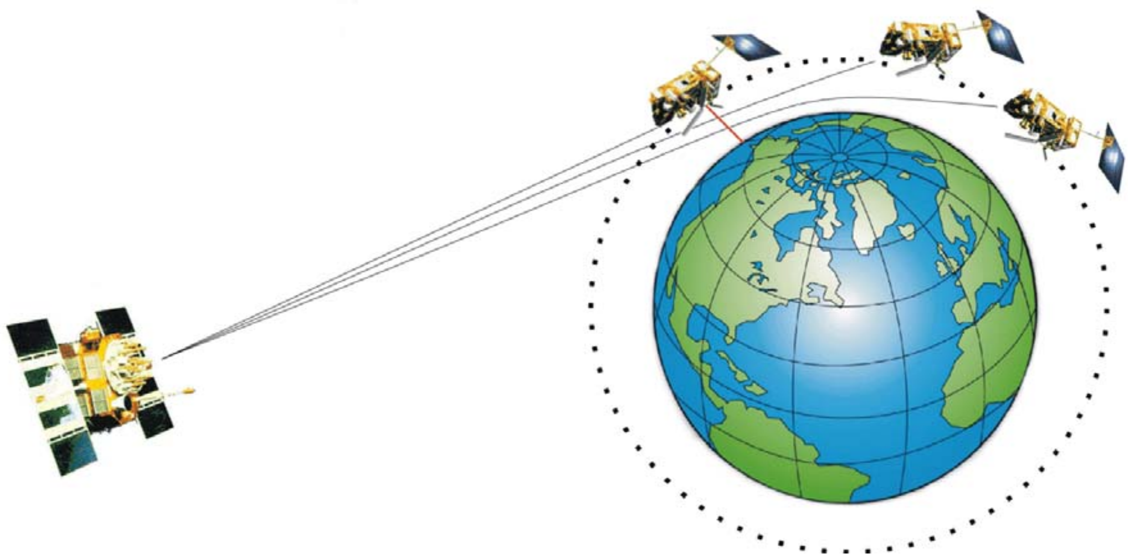

Figure 1: The basic principle behind the radio occultation technique: radio signals from the GPS satellite (left) are received by the orbiting Metop satellite, shown at three consecutive times. The ray path is characterized by its impact parameter and bending angle. The inversion of the measured signal leads to vertical profiles of atmospheric parameters (indicated by the short, red line).

3. Data and software products

3.1. Product overview

The GRAS SAF's primary products are the Level 2 products, which consist of profiles of refractivity, pressure, temperature and humidity, processed in near-real time (NRT), within 3 hours of observation. This time constraint may mean that processing is simplified and some ancillary data may not be available in time. Therefore, NRT products may not represent the optimum possible quality although it will still meet user requirements for NWP input data. However, the GRAS SAF will also re-process the radio occultation data in offline mode using advanced algorithms and post-processed GPS and Metop precise orbit information and including other auxiliary data, which may not have been available on the time scale of the near-real time product. Offline products will be available to users within 30 days of observation time. Figure 2 shows the processing steps in the GRAS SAF system. Details about the processing steps and the canonical transform method ('CT2') can be found in [Gorbunov, 2002, 2007], [Gorbunov and Lauritsen, 2006], and [Gorbunov et al, 2006].

The product domain will be global, and from the surface to a maximum height of 80 km. The height range of individual Level 2 profiles produced by the SAF depends on the output of the GRAS instrument and EUMETSAT's processing up to Level 1b. A large fraction of the profiles are expected to extend below 2 km. Data will be provided as a function of height (ellipsoidal height, height above mean sea level, and geopotential height), or as function of time. Product details are given in the Detailed Products Description Document [GRAS SAF DPDD, 2002] and the Product User Manual [GRAS SAF PUM, 2008].

The GRAS SAF will also provide monthly, seasonal, and annual averages of temperature, geopotential heights, humidity, refractivity and bending angle, primarily in low-resolution 3D gridded and zonally gridded formats, but also in the form of global and hemispheric averages and as graphical products. The climate data will be delivered together with estimates of the error characteristics, where the observational errors will be estimated through a procedure that will include other observational data sets, whereas the sampling errors will be estimated through a simulation process (see Section 5).

In addition, the GRAS SAF also supplies the ROPP software to assist in assimilating RO profiles into NWP and other models [GRAS SAF ROPP, 2008]. ROPP is developed by the Met Office and will be supplied as a library of software modules. Since end-users' operational systems have specific software standards, interfacing requirements and other constraints, the ROPP software deliverable cannot be treated as 'black box' modules. The GRAS SAF software deliverables will have the status of example, fully working, but non-operational code, with stand-alone test harnesses and supporting test datasets. Some modification by users for their specific operational environment is to be expected.

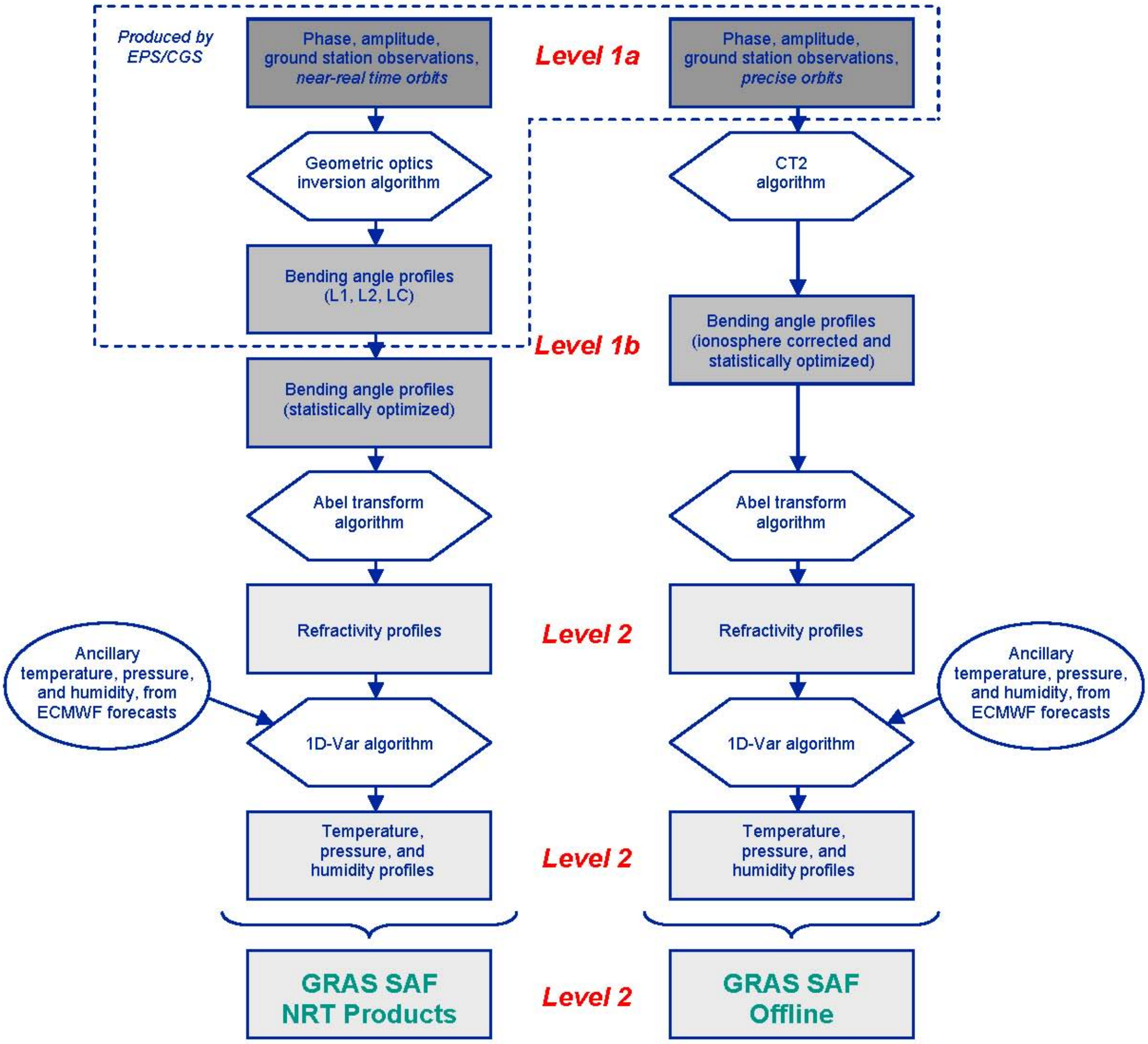

Figure 2: Schematic showing of the processing steps for GRAS SAF NRT and Offline products. The input for NRT processing are bending angles from EUMETSAT (EPS/CGS) whereas the input for offline and re-processing are phases, amplitudes, and orbits.

3.2. GRAS SAF archive and retrieval facility

The interface with the end users is through the GRAS SAF Archive and Retrieval Facility (GARF) web site: www.grassaf.org. NRT products are disseminated to the subscribing end users through the Regional Meteorological Data Communication Network RMDCN (WMO Region 6 standard on GTS) as well as via the EUMETCast network. Offline products are made available through subscription or on individual request at the GARF FTP server or they can be mailed on DVDs. The planned climate data products will be available in the same way as the offline products.

At the GARF web site users can register, search, browse, select and order archived data. In addition, archived GRAS SAF products can be ordered through EUMETSAT's UMARF service (Unified Meteorological Archive and Retrieval Facility). UMARF and GARF both offer search capability for end user requests for all archived GRAS SAF products. UMARF registers users and provides ordering forms, price information and invoices to the users, and sends the product ordering forms to the GRAS SAF, which is responsible for delivery of the requested products.

4. GRAS refractivity data

Since spring 2008, EUMETSAT are producing operational GRAS bending angles based on version 2.11 of the Product Processing Facility (PPF) [Luntama et al, 2007]. These data are received over EUMETCast and processed at the GRAS SAF. Analyses of the measured GRAS data show that they are of high quality. The processing in the PPF 2.11 is based on geometric optics and accordingly the BA data below 10 km are not optimal for NWP and refractivity calculations. The BA data also exhibit a bias above about 32 km due to specific instrument and antenna corrections that is not fully implemented in the current PPF. As a result, the high altitude BA bias also propagates to a (positive) bias in the refractivity.

The processing to refractivity is based on the L1 and L2 bending angles processed by geometrical optics at EUMETSAT. The statistical optimization is done together with the ionosphere correction using the optimal linear combination [Gorbunov, 2002]. In order to eliminate impact parameter ambiguities a method consisting of finding the nearest monotonic impact parameter sequence with respect to the L2-norm is employed [Gorbunov, 2007]. The identification of the climatology is done according to the following steps: 1) Use the MSIS refractivity profile consistent with the location of the profile; 2) forward model the MSIS profile to bending angle; 3) calculate fitting factor from linear regression of the data to the climatological model bending angle in the height interval 30-50 km; 4) multiply the climatological BA with fitting factor; 5) calculation of strongly smoothed ionospheric signal L1-L2; 6) estimate ionospheric signal and noise covariance using the part of the profile above 50 km; 7) estimate signal covariance from the mean deviation of the observed BA to the model BA using data in the interval 12-35 km; 8) carry out optimal linear combination using the covariances.

In Figs. 3 and 4 we compare the obtained refractivities with ECMWF analyses. In order to eliminate outliers we perform a quality check and flag data as non-nominal if one of the following is true: 1) Refractivity profile does not reach below 20 km; 2) One or more points in the refractivity profile below 35 km differ by more than 10% from the corresponding profile obtained from the most recent ECMWF forecast; 3) Refractivity profile reach below model surface; 4) Altitude is not monotonically increasing; 5) Refractivity is negative. The combined QC currently flags about 7% of the data as 'bad'.

The results in the left panel of Fig. 3 (all occultations) show that below 8 km, the bias is less than 0.1-0.3%. In the range 8–25 km the overall bias is small but slightly negative (maximum of 0.2%) between 14 and 22 km, and slightly positive (less than 0.1%) between 22 and 25 km. Above 25 km we see an increasing positive bias reaching about 2% at 40 km and exceeding 6% at 50 km. Below 8 km the standard deviation is varying, but less than 1.2%. The standard deviation is 0.5–0.7% in the range 8–25 km, and increases above to about 1.5% at 40 km and exceeds 4% at 50 km. For low latitudes (Fig. 3), the standard deviation is generally larger than for all occultations in the 8–25 km range; it is at a maximum of about 0.9% between 15 and 20 km. At 40 km it is about 1.5% and at 50 km it is about 3.5%. A negative bias is observed below 8 km.

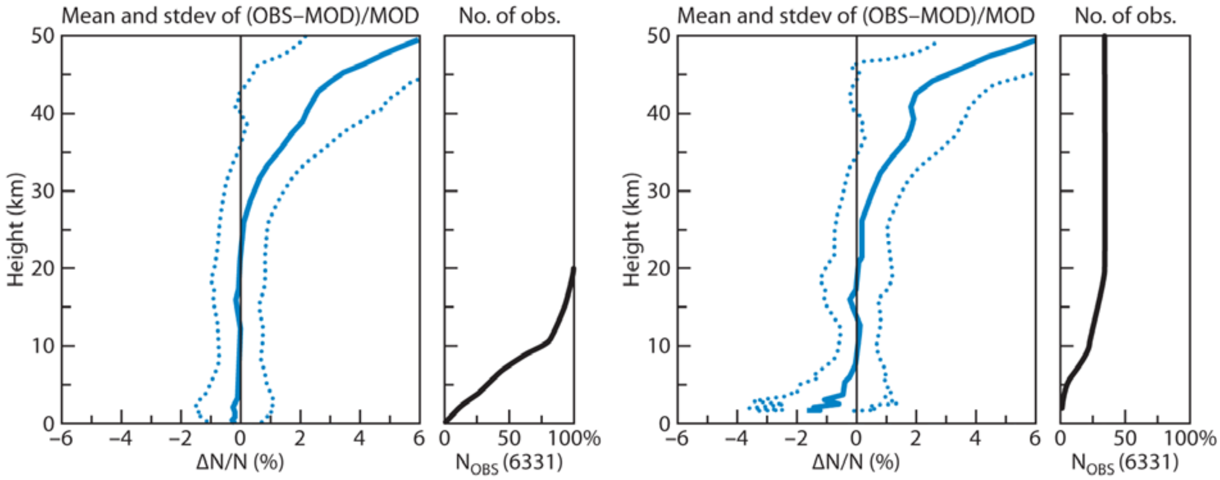

Figure 3: GRAS Refractivity results for the period 1-16 May 2008 (PPF 2.10 data) compared to ECMWF analyses: all occultations (left panel) and low latitude occultations (right panel). Solid blue line indicates the bias and the dashed lines indicate the 1-sigma standard deviations on both sides. The number of observations as a function of altitude included in the various statistics is given to the right of the respective statistic plot.

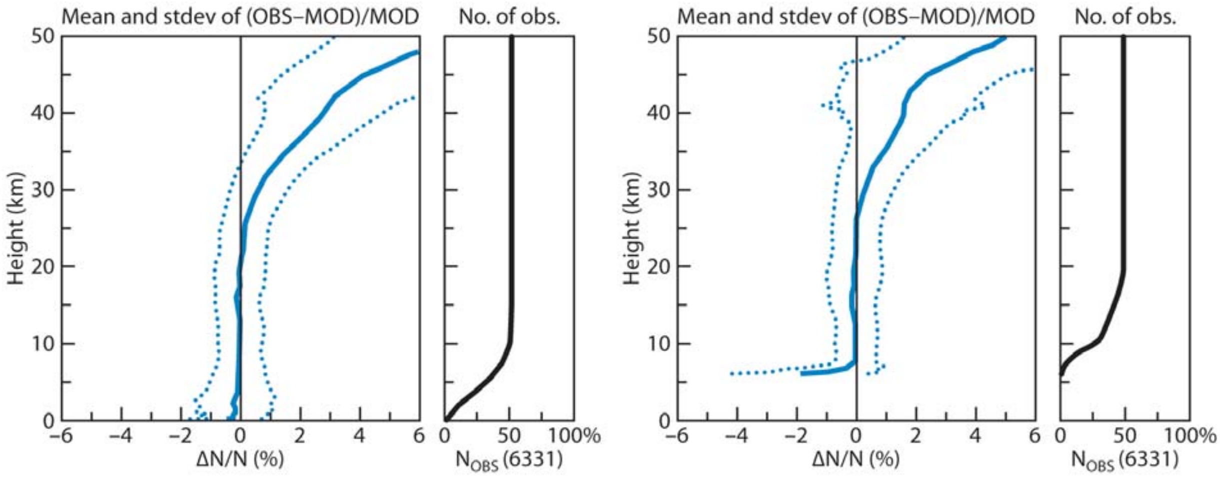

Figure 4: GRAS Refractivity results for the period 1-16 May 2008 (PPF 2.10 data) compared to ECMWF analyses: setting occultations (left panel) and rising occultations (right panel). Solid blue line indicates the bias and the dashed lines indicate the 1-sigma standard deviations on both sides. The number of observations as a function of altitude included in the various statistics is given to the right of the respective statistic plot.

5. RO based climate data

5.1. Background and rationale

Many of the characteristics of RO data suggest them as a near-ideal resource for climate studies, particularly the global coverage, the all-weather capability, and the self-calibrated nature of the RO data [e.g., Leroy et al., 2006; Foelsche et al., 2007]. The latter property which distinguishes RO from most other satellite observational techniques should allow for a relatively straight-forward inter-comparison of data from different satellites and RO instruments, which is required to construct multi-mission time series covering many years and even decades. EUMETSATs Polar System with its planned series of three Metop satellites now provides an opportunity to establish an RO based global climatology of a high quality covering a long time span. Together with data from the CHAMP, GRACE-A and COSMIC missions this will help us meet the requirements of a wide range of climate data users and the scientific community in general.

5.2. GRAS SAF climate data

5.2.1. Current plans

The GRAS SAF will provide monthly, seasonal, and annual averages of temperature, geopotential heights of fixed pressure levels, humidity, refractivity, and bending angle, primarily as a low-resolution zonal (latitude-level) grid, but also in the form of global and hemispheric averages. The climate data will be provided as both numerical and graphical products. We also plan for the provision of estimates of the observational and sampling errors, which is essential for a correct use of such data. The observational errors (including instrumental errors and errors arising in the processing into profile data) will be estimated through a validation procedure that will include other observational data sets, whereas the sampling errors will be estimated through a simulation process (see below). With the aim of becoming a fully operational data set according to EUMETSAT standards, the climate data will go through a formal review process. The current time plan for the expected start of operations is second quarter of 2010 (see table 1).

Table 1: GRAS SAF climate data products and time plan for expected start of operations.

Climate data products	2D Zonal grid: climate + errors	Time resolution	Spatial resolution	*Formats, graphical*	*Formats, numerical*	*Time plan*
CBA: bending angle	yes	Monthly	5 deg latitude	PNG, JPG	ASCII, netCDF	Q2 2010
CRG: refractivity	yes	Monthly	5 deg latitude	PNG, JPG	ASCII, netCDF	Q2 2010
CTE: temperature	yes	Monthly	5 deg latitude	PNG, JPG	ASCII, netCDF	Q2 2010
CHG: spec. humidity	yes	Monthly	5 deg latitude	PNG, JPG	ASCII, netCDF	Q2 2010
CZG: geopot height	yes	Monthly	5 deg latitude	PNG, JPG	ASCII, netCDF	Q2 2010

5.2.2. Implementation and prototype climate data

Using the method of averaging into equal-angle grid boxes, we simply take all observed RO profiles that fall within a grid box and within a suitable averaging time interval (1 month, 3 months, or a year) and average them into a mean profile. The averaging needs to be done on a set of fixed heights. These could be chosen as a set of fixed geopotential heights, a set of mean-sea level (orthometric) heights, or a set of fixed-pressure levels.

Even though straight forward in practice, some effort is needed to ensure that the climate data are as free as possible from biases or systematic errors. Such biases can, e.g., arise from the selection of data based on some quality criteria. They can also arise from the retrieval procedure itself, particularly for data that result from inversions in the later stage of the retrieval chain. Another source of bias comes from the fact that the Metop observational platform consists of a single satellite in a near-polar, Sun-synchronous orbit at a low height, resulting in a temporal under-sampling, particularly of the diurnal cycle (see next section).

These limitations are more important for the construction of climate data than for the corresponding meteorological data. The fundamental reason for this is the higher sensitivity of climate data to small, but long-term and consistent, variations in observational biases. As an example, the current focus on detection of human influences on the climate requires temperature trends of the order of 0.1 K/decade, or 0.01 K/year, to be detected. A careful consideration of selection, processing, and sampling biases, and an understanding of how they may change over time, is needed to reliably discern such weak trends against a background of climate variability.

As a part of the development of the GRAS SAF climate data products, we have developed a set of prototype products based on CHAMP data (Fig. 5). The purpose of these prototype products is to test the processing chain and the algorithms, and to demonstrate the usefulness of the chosen methods.

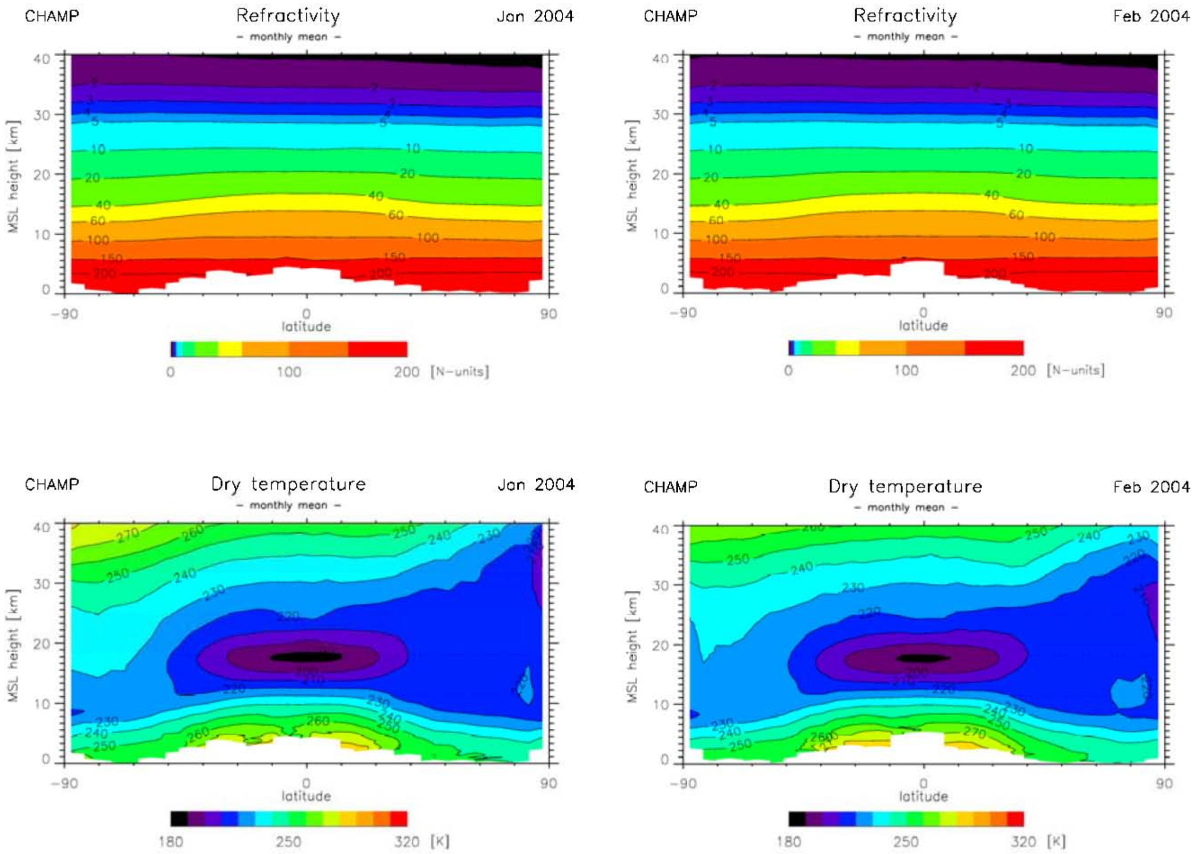

Figure 5: GRAS SAF prototype climate data products based on CHAMP RO data. The prototype data consist of zonal monthly mean refractivity (and related data such as dry temperature) for the year 2004. Note, above 10 kilometers the dry temperature is essentially identical to the ordinary temperature.

5.3. Sampling the climate system

5.3.1. Spatial and temporal sampling

Every day, around 650 vertical profiles are observed by the GRAS/Metop instrument, giving a total number of roughly 20,000 profiles per month. The profiles are irregularly distributed across the globe, providing a good overall spatial coverage. The spatial density of RO profiles is nearly constant in longitude, whereas in latitude the spatial density varies by a factor of 2 (per square degree) or by a factor of 5 (per square kilometer). Hence, the number of RO profiles per month in 5 degree equal-angle grid boxes range from about 500 at mid-latitudes to 250 in the tropics and near the poles.

This is the ideal case where no profiles are deemed bad. In reality, we could expect a loss of RO data at low altitudes in the tropics. Nevertheless, the spatial sampling of the climate system appears to be good enough to produce monthly means with a lower spatial resolution, or seasonal means with a somewhat better resolution. For the resulting climate data, there is a trade-off between spatial resolution and random errors. The spatial resolution that can be obtained depends on the observational errors, i.e., the errors of the individual profiles, and on the temporal sampling characteristics in relation to the variability of the climate system, predominantly the synoptic variability and the diurnal cycle.

A common characteristic of observations from a polar, Sun-synchronous orbit is a good spatial sampling combined with temporal under-sampling, particularly of the diurnal cycle [Pirscher et al., 2007]. We find that over a broad mid-latitude interval, the climate system is sampled at two local times separated by 12 hours whereas at high latitudes, either day-time or night-time observations tend to dominate

5.3.2. Estimation of sampling errors

The GRAS SAF will thus provide RO based climate data. For optimal use of such data it is necessary to know something about the associated uncertainties. Figs. 6 and 7 indicate a means to estimate the associated errors through simulation. In Fig. 6, we have constructed a set of 'sim-observed' data by sampling the ERA-40 reanalysis data set at the locations and times of GRAS occultations during a full month. 'Sim-observed' climate data are then constructed by averaging these data into grid boxes. If the ERA-40 data have the same statistical properties as the actually observed data, the 'sim-observed' climate data will be affected by the same sampling errors as the real observations. The true data is hidden to us, but as we know the 'sim-true' data, we may compute the errors introduced by an incomplete sampling. This was done for one particular August month. Sampling many (20 to 30) August months provides a means to discriminate between a

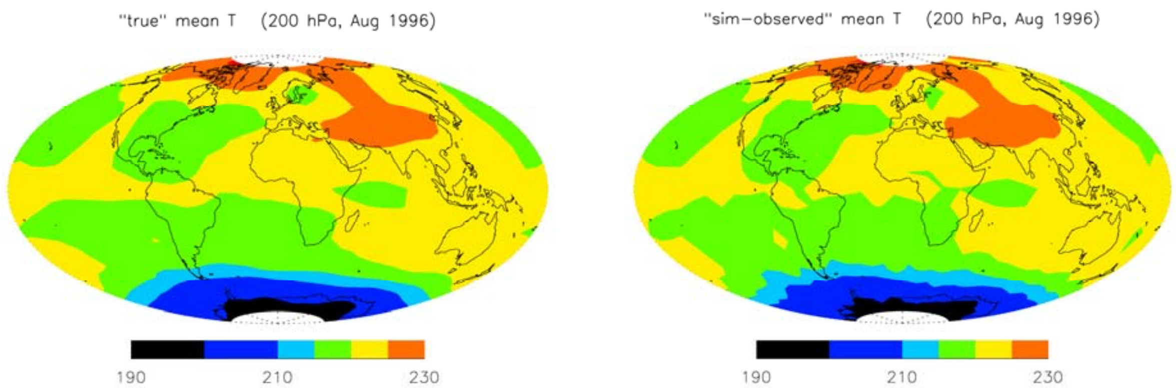

Figure 6: Monthly mean temperatures in latitude-longitude grid boxes: 'sim-true' mean temperatures in the left panel, and 'sim-observed' temperatures in the panel to the right. The 'sim-observations' were obtained by sampling the ERA-40 reanalysis data set at the same locations and times as actual Metop/GRAS observations, while the corresponding 'sim-true' mean temperatures were obtained from the full set of ERA-40 data. The distribution of errors is shown in Fig. 7.

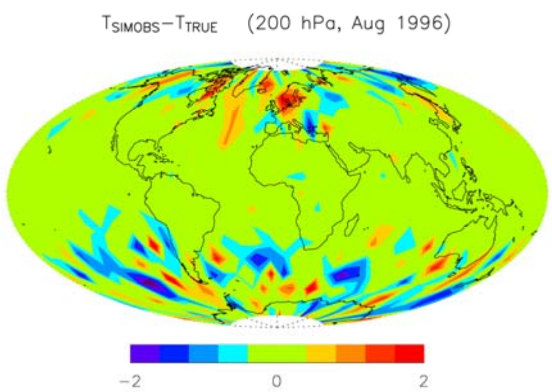

Figure 7: The differences between the 'sim-observed' and 'sim-true' mean temperatures as shown in Fig. 6, demonstrating the sampling errors that would be expected for this type of binning-and-averaging situation. The errors form elongated structures in the latitudinal direction, indicating the need for grid boxes that are larger in the longitudinal direction.

random component and a systematic component of the sampling errors. This procedure, although in a constrained form, can also be used operationally to estimate the sampling errors of the actual observations. Note that this kind of simulation only includes the sampling errors – the observation errors needs to be independently estimated and incorporated into the simulations.

6. Conclusions and outlook

The GRAS SAF Processing and Archiving Center is part of EUMETSAT's network of Satellite Application Facilities. The objective of the GRAS SAF is to deliver operational radio occultation products from the GRAS occultation instruments onboard the three Metop satellites. We also supply the software package ROPP (Radio Occultation Processing Package) for 3D/4D-VAR assimilation of radio occultation data into numerical weather prediction models. All our data and products can be obtained from our GRAS SAF Archive and Retrieval Facility (GARF) website: www.grassaf.org

Outcome of NWP assimilation impact trials have confirmed the positive prospects of assimilating radio occultation measurements operationally. Once operational, the GRAS SAF will supply continuous, operational radio occultation data for weather forecasts (in near-real time) and for climate research as an integrated part of EUMETSAT's polar system. Future growth potential includes e.g. GALILEO reception capability on future Metop satellites and inclusion of occultation data from other RO satellites (e.g. CHAMP, COSMIC) in the GRAS SAF processing related to climate applications.

Analyses show that the quality of GRAS measurements is very good. The refractivity results show that the relative differences compared to ECMWF analyses are about 0.6% for the height range 10-25 km. GPS radio occultation data are based on measurements of time and the assumptions are known and the RO data is therefore well suited for climate monitoring and climate research. We are currently undertaking studies on how to best exploit the GRAS data, both for construction of an accurate single-source climate data base with known error characteristics of the data and for provision of global climate monitoring. Our investigations also try to address how to estimate the error characteristics, random observational and sampling errors, and systematic biases of such climate data.

Acknowledgments

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