GRAS SAF RADIO OCCULTATION PROCESSING CENTER

K. B. Lauritsen, H. Gleisner, A. Loescher, F. Rubek, and M. B. Sørensen

Danish Meteorological Institute, DK-2100 Copenhagen, Denmark

ABSTRACT

The GRAS SAF is part of EUMETSATs network of Satellite Application Facilities (SAFs) under the EUMETSAT Polar System (EPS). The objective of the GRAS SAF is to deliver operational radio occultation products from the GRAS occultation instruments (Global Navigation Satellite System Receiver for Atmospheric Sounding) onboard the three Metop satellites. The host institute is the Danish Meteorological Institute (DMI) and this will also be the physical location of the operational GRAS SAF processing center. The two other project partners are the IEEC (Institute d'Estudis Espacials de Catalunya, Barcelona, Spain) and the Met Office (Exeter, UK). The GRAS SAF will enter into the operational phase and deliver products from around the end of 2006 (given the current launch plans for Metop). The archiving of GRAS SAF products is done locally at the host institute with a user interface at the UMARF archive at EUMETSAT.

The basic principle of the radio occultation (RO) method is that a 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 index of refraction (or refractivity) and subsequently temperature and humidity as a function of height.

The operational GRAS SAF Processing and Archiving Center will receive raw and preprocessed GPS radio occultation data from the GRAS instrument, process these into vertical height profiles of refractivity, temperature, pressure, and humidity, and distribute these products continuously in NRT (near real time, within 3 hours from sensing) to numerical weather prediction users. In addition, offline products (improved products, within 30 days from sensing) will be disseminated to e.g. climate monitoring users. Another objective of the GRAS SAF is to supply a software package denoted ROPP (radio occultation processing package) containing tools for 4D-VAR-assimilation of radio occultation data into numerical weather prediction models. The results of such NWP assimilation impact trials using CHAMP data show a clear positive impact on NWP forecasts in the upper troposphere and lower stratosphere.

Because raw GPS radio occultation data are calibration free and the assumptions are known, RO data is also well suited for climate investigations and monitoring. 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.

1. THE GRAS SAF

The GRAS SAF is a Satellite Application Facility (SAF) being developed under the EUMETSAT program for SAFs. The GRAS SAF is hosted by DMI with the two partner institutes the Met Office (Exeter, UK) and the IEEC (Barcelona, Spain). The GRAS SAF developments were initiated in 1999 and will span approximately

eight years. The operational GRAS SAF Processing and Archiving Center will take over when the first Metop satellite is launched and providing data in 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 Figures 1 and 2). 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 GRAS SAF has finished the first part of the development phase and now focuses on the implementation, testing and upgrading of the system and software. To test the performance and accuracy of the GRAS SAF retrieval software, CHAMP radio occultation measurements are used as an important data source until Metop is launched. During the commissioning of the Metop satellite, the GRAS SAF will perform a full validation of the data products, the system and the software deliverables. Currently, the GRAS SAF system is about to complete the integration and verification testing activities.

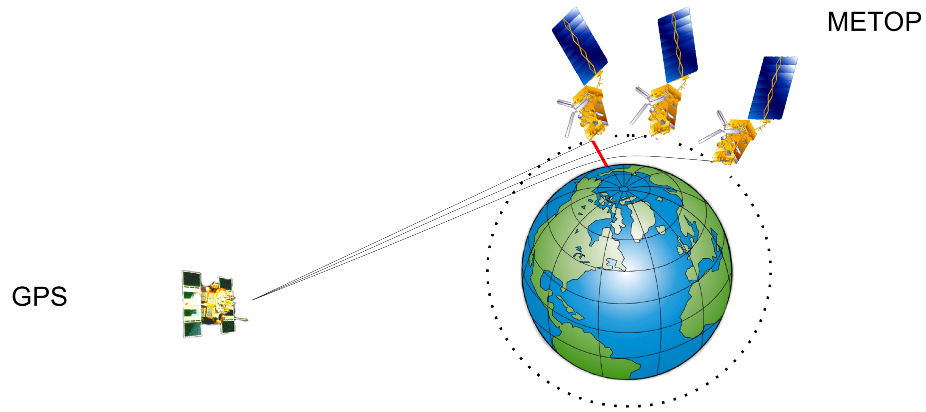

Figure 1. *The basic principle behind the radio occultation (RO) technique: radio signals from the GPS satellite are received by the orbiting Metop satellite, shown at three consecutive times. The ray path is characterized by its impact parameter and bending angle. The inversion of the measured signal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

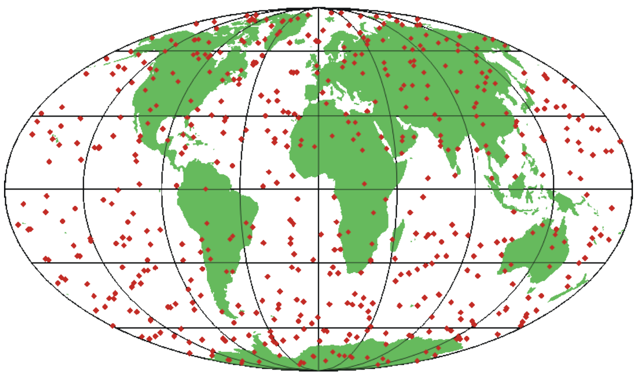

Figure 2. *Global distribution of radio occultation profiles during 24 hours (about 500 profiles).*

2. USER REQUIREMENTS

The raw measurements of phase and amplitude from the GRAS instrument (Level 0) will be processed into bending angle products at the EPS Core Ground Segment (CGS) (Level 1b). These level 1b data will be the basic input to the GRAS SAF. The GRAS SAF will then process and disseminate geophysical and atmospheric products, such as temperature and humidity profiles (Level 2).

		Temperature	Specific Humidity	Surface Pressure	Refractivity	Bending Angle
Horizontal Domain		Global	Global	Global	Global	Global
Horizontal Sampling		100–2000 km	100–2000 km	100–2000 km	100–2000 km	100–2000 km
Vertical Domain		Sfc–1 hPa	Sfc–100 hPa	Sfc (msl)	Sfc–1 hPa	Sfc–80 km
Vertical Sampling	**LT**	0.3–3 km	0.4–2 km	–	0.3–3 km	2–5 Hz
	HT	1–3 km	1–3 km	–	1–3 km	
	LS	1–3 km	–	–	1–3 km	
	HS	1–3 km	–	–	1–3 km	
Time Window		1–12 hrs	1–12 hrs	1–12 hrs	1–12 hrs	1–12 hrs
RMS Accuracy	**LT**	0.5–3 K	0.25–1 g/kg	0.5–2 hPa	0.1–0.5%	1 μrad or 0.4%
	HT	0.5–3 K	0.05–0.2 g/kg	–	0.1–0.2%	
	LS	0.5–3 K	–	–	0.1–0.2%	
	HS	0.5–5 K	–	–	0.2–2%	
Timeliness		1-3 hrs	1–3 hrs	1–3 hrs	1–3 hrs	1–3 hrs

Table 1. *GRAS/Metop user requirements for operational meteorology.*

		Temperature	Specific Humidity
Horizontal Domain		Global	Global
Horizontal Sampling		100–1000 km	100–1000 km
Vertical Domain		Surface to 1 hPa	Surface to 1 hPa
Vertical Resolution	**LT**	0.3–3 km	0.5–2 km
	HT	1–3 km	0.5–2 km
	LS	1–3 km	0.5–2 km
	HS	5–10 km	1–3 km
Time Resolution		3–24 hrs	3–24 hrs
RMS Accuracy	**LT**	0.5–3 K	0.25–1 g/kg
	HT	0.5–3 K	0.05–0.2 g/kg
	LS	0.5–3 K	–
	HS	1–3 K	–
Timeliness		30–60 days	30–60 days
Time Domain		> 10 years	> 10 years
Long-term Stability		< 0.1 K/decade	< 2% RH/decade
No. of profiles/ grid box/month		> 10	> 10

Table 2. *GRAS/Metop user requirements for climate monitoring.*

Bending angles will be provided for altitudes ranging from 80 km down to 5 km (for both setting and rising occultations), with the expectation that many events will extend to near the surface. The bending angle accuracy requirement is to be better than 1 μrad or 0.4% (whatever is larger). The impact parameter localisation in Earth coordinates is required to be better than 0.01° in longitudes and latitude, and better than 6 meters in altitude. The accuracy requirement on the bending angles is the basic design requirement for the GRAS instrument. We specify the requirements by atmospheric layers, defined as follows:

Lower Troposphere	(LT)	1000 – 500 hPa	(surface to 5 km)
Higher Troposphere	(HT)	500 – 100 hPa	(5 km to 15 km)

Lower Stratosphere	(LS)	100 – 10 hPa	(15 km to 35 km)
Higher Stratosphere/Mesosphere	(HS)	10 – 1 hPa	(35 km to 50 km)

The GRAS Science Advisory Group has identified several classes of users, as noted in the [GRAS SAG, 1998] Report. For the purpose of the GRAS SAF, we present user requirements for two major classes of users: operational meteorology (NWP) and climate. The requirements for operational meteorology, which reflect the limitation of a single GRAS instrument, are summarised in Table 1. The requirements for climate applications, which also reflect the limitation of a single GRAS instrument, are summarised in Table 2. Both table 1 and 2 are taken from the GRAS SAF User Requirement Document [URD, 2001]. In Figure 2, we show the global distribution of GRAS SAF profiles within 24 hours obtained by a simulation.

3. DATA AND SOFTWARE PRODUCTS

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 optimum algorithms and post-processed GPS and Metop precise orbit determination (POD) 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.

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 critically depends on the output of the GRAS instrument and processing up to Level 1b within the CGS. However, a large fraction of the profiles are expected to extend below 2 km. The geographical and temporal coverage of SAF products will be limited only by the characteristics of the radio occultation instrument and not by the processing algorithms. Data in the form of profiles will be provided as a function of height (ellipsoidal height, height above mean sea level, geopotential height and pressure), or as a function of time. The data products are summarised in Table 3, and details about the products can be found in the Detailed Products Description Document [DPDD, 2002].

The GRAS SAF will also provide software products (with associated User Guides) that implement procedures to assist in assimilating GRAS profiles into NWP and other models. The software products are developed by the Met Office and will be supplied as a library of software modules grouped into one package: the Radio Occultation Processing Package (ROPP). The overall content is included in Table 3. 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.

GRAS SAF Products List	Description of product
NRT Data products	
Refractivity profile	Refractive index as function of height at tangent point
Temperature profile	Temperature as function of height at tangent point
Pressure profile	Pressure as function of height at tangent point
Specific humidity profile	Specific humidity as function of height at tangent point
Surface pressure	Pressure estimate at surface level
Error covariance matrix	Error covariance matrix as average for all profiles
Offline Data Products	
Bending angle profile	Bending angle as function of impact parameter
Refractivity profile	Refractive index as function of height at tangent point
Temperature profile	Temperature as function of height at tangent point
Pressure profile	Pressure as function of height at tangent point
Specific humidity profile	Specific humidity as function of height at tangent point
Error covariance matrix	Error covariance matrix as average for all profiles

Climate Data Products	
Global map of temperature	Global map based on monthly averages of temperature profiles
Global map of specific humidity	Global map based on monthly averages of humidity profiles
Global map of geopotential height	Global map of monthly averages of geopotential height profiles
ROPP Software Deliverable	
1D-Var pre-retrieval software	Software module used to generate NRT temperature, pressure and humidity products from refractivity and a background profile
3/4D-Var assimilation software	Forward operators and their adjoints to allow for 3/4D-Var data assimilation of GRAS SAF and level 1b products into existing NWP models
Pre-processing tools	Pre-processing tools to assist the data assimilation of GRAS SAF and level 1b products

Table 3. *List of data and software products from the GRAS SAF.*

4. CLIMATE DATA PRODUCTS

4.1. 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. The latter property – which distinguishes RO from most other satellite observational techniques – allows for relatively easy inter-comparison of data from different satellites and RO instruments, which is required to construct long time series covering many years and even decades. Global coverage and long time series are essential to improve our understanding of the Earth's climate system.

The EUMETSAT Polar System, with its planned series of three Metop satellites, now provides an opportunity to create RO occultation based climatologies of high quality on a longer term. This will help us meet the requirements of both the scientific community and a wide range of climate data users. For these purposes, we are currently undertaking studies on how to best exploit the GRAS data, both for construction of a single-source climate data base with accurate estimates of the error characteristics of the data and for provision of global climate monitoring.

4.2. Methods and limitations

We are currently investigating three methods for construction of the climatologies: (1) relatively standard binning-and-averaging techniques, (2) bayesian fitting of global spherical harmonics to the observational data, and (3) 3D variational (3DVAR) assimilation of the RO data into averaged ECMWF analysis fields or into ERA-40 re-analysis fields. The first two methods generate true single-source climatologies. Unlike the assimilation approach, the first two methods do not depend on any other observational data than the RO profiles, and the binning-and-averaging approach is also fully independent of any assumptions about the structure of the spatial distributions. There is, however, a price to pay for this independence of underlying assumptions, namely a lower spatial resolution. Only the third approach can give something close to a high spatial resolution.

Regardless of the choice of method, there are certain limitations that need to be considered. Some of them arise 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. These limitations are more important for the construction of climate data than for the 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 0.01 K/year to be detected in the troposphere. A careful consideration of systematic instrumental and sampling biases, and an understanding of how they change over time, is needed to reliably discern such weak trends against a background of climate variability.

4.3. Climate data products

The GRAS SAF will provide monthly, seasonal, and annual averages of temperature, geo-potential heights, humidity, and refractivity in the form of global and hemispheric means as well as in a low-resolution globally gridded format. Figures 3 and 4 show results of an ongoing work to evaluate the methods for construction of climatologies and for quantifying the various sources of errors. A set of "observational" data is constructed by sampling the ERA-40 reanalysis data set at simulated Metop/GRAS locations and times. Climate data are then constructed by binning the data into 10x10 degree latitude-longitude grid boxes followed by a computation of monthly means within each grid box. In this way we retain realistic sampling properties of the "observed" climate, and a subsequent comparison of the "observed" climate data with the corresponding "true" data reveals the magnitude and nature of the sampling errors. This procedure, although in a constrained form, will also be used operationally to assess the sampling properties of the actual observations.

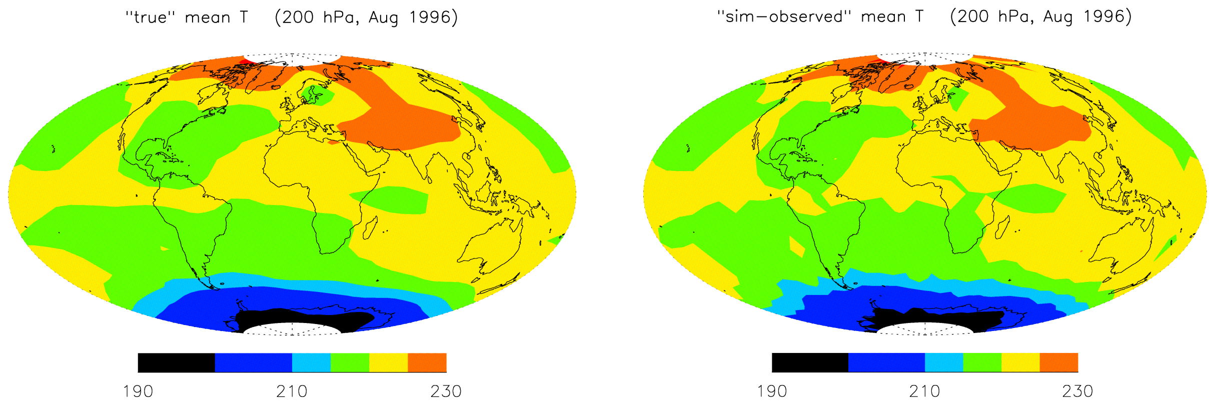

Figure 3. *Monthly mean temperatures in August 1996 in 10x10 degree grid boxes: "true" mean temperatures in the left panel, and simulated "observed" temperatures in the panel to the right. The "observations" were obtained by sampling the ERA-40 reanalysis data set at around 16,500 simulated Metop/GRAS observation locations and times, while the corresponding "true" mean temperatures were obtained from the full set of ERA-40 data. The distribution of errors is shown in Figure 4.*

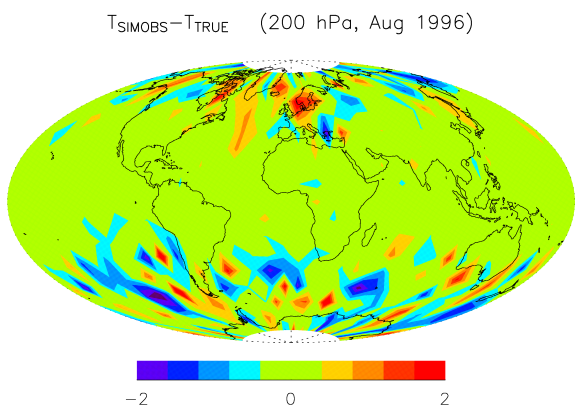

Figure 4*. The differences between the simulated "observed" and "true" mean temperatures as shown in Figure 3, demonstrating the sampling errors that would be expected for this type of binning-and-averaging method. The errors form elongated structures in the latitudinal direction, indicating the need for grid boxes that are larger in the longitudinal direction.*

4.4. Variational assimilation of RO data into ERA-40 fields

In another study, global fields of temperature, specific humidity and surface pressure from GRAS data are derived by a variational approach. On the one hand, users of the climate community demand single instrument observations over long periods of time, which are not "contaminated" by additional information. RO data itself is already close to that ideal kind of observation, thus RO-only products for the climate community are foreseen. The variational approach adds a valuable complementary data set, which enables us to study increments and gain information on the characteristics of combined products. The 3D-Var scheme is used to combine the GRAS data with background information in a statistical optimal way:

$$\mathbf{x}_a = \mathrm{Arg}\ \ \min\ \ J$$

$$J(\mathbf{x}) = J_b(\mathbf{x}) + J_o(\mathbf{x})$$

$$J(\mathbf{x}) = \frac{1}{2}\left\{(\mathbf{x}-\mathbf{x}_b)^{\mathbf{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + (\mathbf{y}-H(\mathbf{x}))^{\mathbf{T}}\mathbf{R}^{-1}(\mathbf{y}-H(\mathbf{x}))\right\}$$

The solution of the minimization problem requires the calculation of the gradient ∇J_{x_0} and can be performed either in terms of full fields $\mathbf{x}$ or in terms of an analysis of the increments $\delta\mathbf{x}$:

$$\nabla J_{x_0} \equiv \mathbf{B}_0^{-1}(\mathbf{x}_0 - \mathbf{x}_0^b) + \mathbf{H}^T\mathbf{R}^{-1}[H(\mathbf{x}_0) - \mathbf{y}] = 0$$

$$J(\delta\mathbf{x}_a) \ = \ J(\delta\mathbf{x} = \mathbf{x} - \mathbf{x}_b)$$

$$J(\delta\mathbf{x}) = \frac{1}{2}\left\{\delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x} + (\mathbf{H}\delta\mathbf{x} - \mathbf{d})\mathbf{R}^{-1}(\mathbf{H}\delta\mathbf{x} - \mathbf{d})\right\}$$

$$\mathbf{d} = \mathbf{y} - H(\mathbf{x})$$

$$\nabla J = \mathbf{B}^{-1}\delta\mathbf{x} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}\delta\mathbf{x} - \mathbf{H}^T\mathbf{R}^{-1}\mathbf{d}$$

where the analysis is found by adding the final increment to the first guess:

$$\mathbf{x}_a \ = \ \mathbf{x}_b + \delta\mathbf{x}_a$$

Here, $\mathbf{H}\delta\mathbf{x}$ can be replaced by the finite differences $H(\mathbf{x})\text{-}H(\mathbf{x}_b)$, where H is the potentially non linear observation operator, $\mathbf{H}$ the linear approximation of H, $\mathbf{x}$ the atmospheric state vector, $\mathbf{y}$ the observation vector, $\mathbf{R}$ and $\mathbf{B}$ are observation and background covariance matrices, respectively. This formulation is still prohibitively expensive from a numerical point of view, thus control space transformations are performed (projection onto the eigenvectors of the vertical part of $\mathbf{B}$), including preconditioning (division by the square root of the eigenvalues). The horizontal component of $\mathbf{B}$ is implemented by the use of recursive filters [Lorenc, 1992]. The observation operator H performs the interpolation from background fields to the observation location and the transformation from the state vector quantities to the observation quantity, in our case refractivity or possibly bending angles.

For such a system it is mandatory to have profound knowledge concerning the error characteristics of background and observations. The observation errors have been studied comprehensively due to the fact that a quasi-operational system is already in orbit (CHAMP). The choice of background and the determination of its errors is a more tricky issue. The current approach is to use ERA40 data (1980-1999) to derive background fields and the corresponding error characteristics on a monthly mean base. Since variances for these fields are directly available from ECMWF, the task of deriving the vertical and horizontal correlations is left. For system-trials global mean correlation matrices from the ECMWF IFS (2003) had been used, which are clearly inappropriate for the used background, but offer the possibility to perform run-time experiments. To perform an overall sanity check of the systems these correlations and appropriate global mean variances had been used with 24h forecast fields of August 2003. Within this setup the error characteristics are reasonable and should deliver reliable results. For these test runs 39 CHAMP occultations within +/– 3 hours around 00UTC of the 13.08.2003 had been used to produce an analysis with a corresponding 24h ECMWF forecast. Figure 5 shows the zonal mean analysis increment of the temperature analysis, Figure 6 the geolocation of the observations and the surface-pressure increments. The wave like structure within the temperature analysis increments depicts a known weakness of the ECMWF model at southern high latitudes at winter times. This result agrees well with other studies [Gobiet, 2005] showing the positive impact that RO data will have within NWP frameworks if operationally assimilated in the future [Healy, 2004].

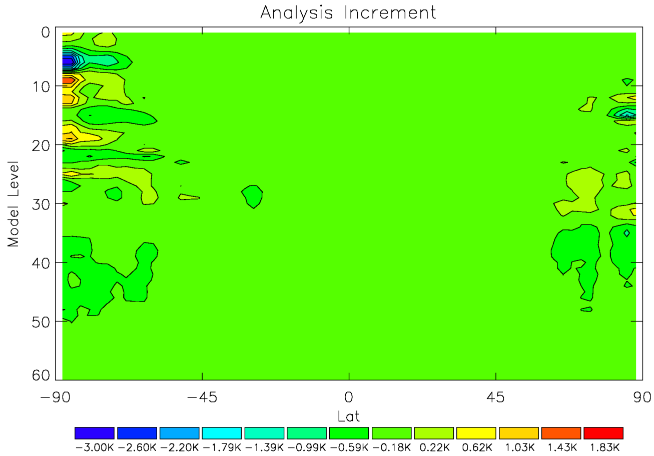

***Figure 5**. The zonal mean analysis increment of the temperature analysis.*

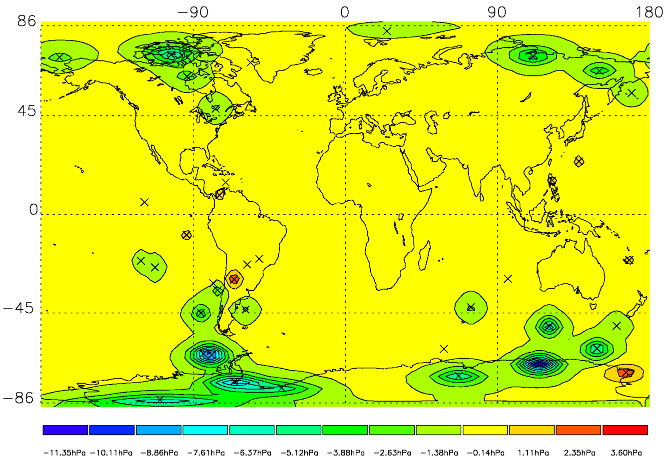

***Figure 6**. Geolocation of the observations and the surface-pressure increments.*

5. CONCLUSIONS AND OUTLOOK

The GRAS SAF Processing and Archiving Center is part of EUMETSATs 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. Currently, radio occultation data from the German CHAMP satellite are used in the processing for the integration and verification of the system.

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 climate research as an integrated part of EUMETSATs EPS 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. COSMIC) in the GRAS SAF processing.

GPS radio occultation data are calibration free and is therefore also well suited for climate investigations and monitoring. We are currently undertaking studies on how to best exploit the GRAS data, both for construction of a single-source climate data base with accurate error characteristics of the data and for provision of global climate monitoring.

6. REFERENCES

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