

# Reanalysis applications of GPS radio occultation measurements

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## Abstract

Reanalyses of the past weather with a state-of-the-art data assimilation system and forecast models generate global multi-decadal time-series of meteorological quantities. These products are free of the changes brought about by operational upgrades of the model and data assimilation configuration. Reanalysis products can help better understand atmospheric variability and represent the first steps towards transparent products, results of global, integrated systems capable of tracking climate variations in the Earth system, using all available sources of information. However, one difficulty in combining multiple sources of information that vary over time is the issue of inter-instrument bias correction. Today's reanalyses are beginning to make use of variational bias correction algorithms to infer observation error biases contained, for example, in satellite radiance measurements. These algorithms rely on the availability of a sufficient number of pre-calibrated data (or data that do not require any bias correction) to anchor the system. Since GPS radio occultation measurements fit such requirements, they represent key information for data assimilation in a reanalysis. We present here preliminary results of the assimilation of CHAMP and COSMIC data in the current ECMWF reanalysis, ERA-Interim. We show an example of reduction of temperature model biases when COSMIC data are introduced.

## 1. Introduction

A reanalysis of the atmosphere consists in analyzing past weather, with a recent and consistent data assimilation system and forecast model throughout the entire time period. The advantages of this are three-fold. First, the four-dimensional meteorological fields and diagnostics such as budgets and fluxes produced by reanalyses are free of discontinuities caused by forecast model configuration and resolution changes. Second, reanalyses can use reprocessed observations and observations that arrived too late for operational assimilation, because a reanalysis does not need to operate under the same timely operational constraints as Numerical Weather Prediction (NWP) centers performing real-time weather analysis. Third, reanalyses enable impact assessments of observing system changes on the representation of the atmospheric state.

The main cause of discontinuity (model changes) found in classic NWP products is thus alleviated by the very concept of reanalysis. However, one major source of discontinuity that remains is the change in observing systems. Solutions such as variational bias correction can mitigate the breaks in mean signal imposed by changes due to satellite instrument drift and satellite system changes. The idea is to remove the bias in certain groups of observations (e.g., radiance measurements), by using the model and the remaining observations as reference. This requires the existence of proper observing systems to act as a reference (or anchoring).

GPS radio occultation produces global data coverage without the need for calibration or bias correction. The measurements observe the upper atmosphere and the Southern oceans which are otherwise void of high vertical resolution observations.

This paper is organized as follows. Section 2 summarizes the current reanalysis effort at ECMWF, with an emphasis on one aspect relevant to the auto-calibration feature of GPS radio occultation observations. Section 3 presents the use and the impact of GPS radio occultation data in the current reanalysis. Section 4 presents conclusions.

## 2. Current ECMWF Reanalysis: ERA-Interim

Major reanalyses of the atmosphere have been produced by the National Centers for Environmental Prediction (NCEP) in collaboration with the National Center for Atmospheric Research (NCAR), by the National Aeronautics and Space Administration Data Assimilation Office (NASA DAO), by the Japan Meteorological Agency (JMA), and by ECMWF. For example, ERA-40 [Uppala et al., 2005] covered the time period extending from 1957 to 2002, building on previous reanalysis experience (ERA-15) and on data gathered and cleaned-up by partner institutions.

The latest ECMWF reanalysis, ERA-Interim, covers the time period from 1989 to the present. Unlike ERA-40, this reanalysis uses an adaptive bias correction (variational bias correction).

### 2.1. Main characteristics of ERA-Interim

2.2. *The main system characteristics of ERA-Interim are:*

- T255 (~80km) horizontal resolution,
- 60 vertical layers; top level at 0.1 hPa,
- Improved model physics (ECMWF model cycle 31r2),
- Four-dimensional variational (4DVAR) analysis using a 12-hour time window,
- Revised humidity analysis, as compared to ERA-40,
- Wavelet-based background error covariances,
- Variational bias correction of radiance data and assimilation of rain-affected microwave radiances,
- Assimilation of the latest generation of satellite data that were not available for ERA-40 such as hyperspectral infrared measurements from the Atmospheric InfraRed Sounder (AIRS) and GPS radio occultation measurements.

The main improvements compared to ERA-40 are:

- Better fit to observations,
- Much better hydrological cycle,
- Improved stratospheric transport, and
- Improved forecast skill.

As of November 2008, ERA-Interim has reached March 2007 and is expected to catch up with real-time by early 2009. It will then continue as a Climate Data Assimilation System.

### 2.3. Variational Bias Correction

In ERA-40, bias adjustments for each satellite instrument and channel source were computed using a tuning procedure described in Uppala et al. (2005). In most cases, bias corrections for a given channel were kept fixed for the lifetime of the satellite.

ERA-Interim covers the data-rich era since the 1989, when satellite radiance measurements collected by passive sounders represent the greatest number of observations assimilated. The number of different sensors is also much greater in these years than earlier in the 20<sup>th</sup> century. These observations, based on various radiometer instruments, require a bias correction in order to evaluate the time-drift of the instruments as well as variations of the instrument's behaviour with its environment over time.

The variational bias correction method solves for the bias parameters directly in the radiance variational framework [Dee, 2004]. The bias parameters include a constant offset and coefficients that weigh the contribution of bias predictors (such as the instrument scan position and the atmospheric state) to the instrument observation error bias.

Formally, the analysis seeks the minimum of the variational cost function (noted  $J$ ) by adjusting for the model state vector  $\mathbf{x}$  and the bias parameters' vector  $\beta$ :

$$J[\mathbf{x}, \beta] = (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}_x^{-1} (\mathbf{x} - \mathbf{x}_b) + (\beta - \beta_b)^T \mathbf{B}_\beta^{-1} (\beta - \beta_b) + [y_0 - b_0(\mathbf{x}, \beta) - h(\mathbf{x})]^T \mathbf{R}^{-1} [y_0 - b_0(\mathbf{x}, \beta) - h(\mathbf{x})] \quad (1)$$

The notations are as follows:  $\mathbf{x}_b$  denotes the first-guess (or a priori or background) model state vector,  $\mathbf{B}_x$  is the model background error covariance matrix,  $\beta_b$  is the state vector of the initial estimate of the bias parameters,  $\mathbf{B}_\beta$  is the bias parameters' initial estimate error covariance matrix,  $y_0$  is the observation vector,  $\mathbf{R}$  is the observation error (measurement and representativeness errors) covariance matrix, and  $b_0(\mathbf{x}, \beta)$  is the vector of observation error bias as inferred from the model state vector (some of whose elements act as predictors) and the bias parameters' state vector. The observation operator  $h$  is used to map the background information into the observations' space.

The right-hand side of equation (1) includes three terms: the first term represents the model background constraint, the second term represents the bias parameters' initial estimate constraint, and the third term represents the observations' constraint. The weighting of the various constraints is accomplished by the corresponding error covariance matrices  $\mathbf{B}_x$ ,  $\mathbf{B}_\beta$ , and  $\mathbf{R}$ . Ultimately the observations serve to constrain the unknown parameters in the system. It is therefore very important, in order for the system to remain stable, to include a sufficient number of observations that are not bias corrected.

The raw measurement in the GPS radio occultation technique is a fraction of an electromagnetic wavelength. The stability of that metric depends on the stability of the transmitters which generate that signal. In fact, these transmitters are calibrated with respect to atomic clocks on-board the GPS satellites, which are themselves calibrated by atomic clocks on the ground. For that reason, the GPS radio occultation data represent a data source of particular importance in the late years of the ERA-Interim reanalysis.

### 3. Assimilation of GPS radio occultation measurements in ERA-Interim

#### 3.1. Data sources and methodology

The GPS radio occultation data from the German satellite CHAMP [Wickert et al., 2001] are assimilated in ERA-Interim from May 2001. The measurements from the six-satellite COSMIC constellation [Anthes et al., 2008] are assimilated from December 2006. The CHAMP and COSMIC datasets were provided by UCAR. CHAMP data were processed by CDAAC and COSMIC data were as received operationally at the time.

It is anticipated to assimilate the measurements from the GRAS instrument on-board the European satellite METOP. This will happen when ERA-Interim reaches the time when GRAS data were declared operational.

The bending angle GPS radio occultation data assimilation setup in ERA-Interim follows that presented by Healy and Thepaut [2006]. The noticeable differences are the additional use of bending angles:

- down to the surface, as long as the data pass all the quality controls, including the background check,

- only if they are reported with producer quality control flag indicating nominal processing,
- both from rising and setting occultations for COSMIC.

### 3.2. First assessment of the impact of GPS radio occultation measurements in ERA-Interim

The figure 1 below shows the time series of observation minus first-guess departures from the CHAMP satellite at 6 km altitude (between 5.5 and 6.5 km altitude), as a function of time in the Northern Hemisphere (NH) for a nearly six-year time span (May 2001- March 2007).

The annual cycle in departure standard deviations features a maximum during the NH summer, when the atmospheric moisture contents are larger. This season likely corresponds to a maximum in background and observation bending angle errors. The former error source may be explained by the large natural variability of water vapour which is still poorly observed by current observing systems, thus leading to large background errors. The latter error source may be explained by the increased difficulty to process GPS radio occultation data which propagated through moist atmospheres, as compared to dry atmospheres.

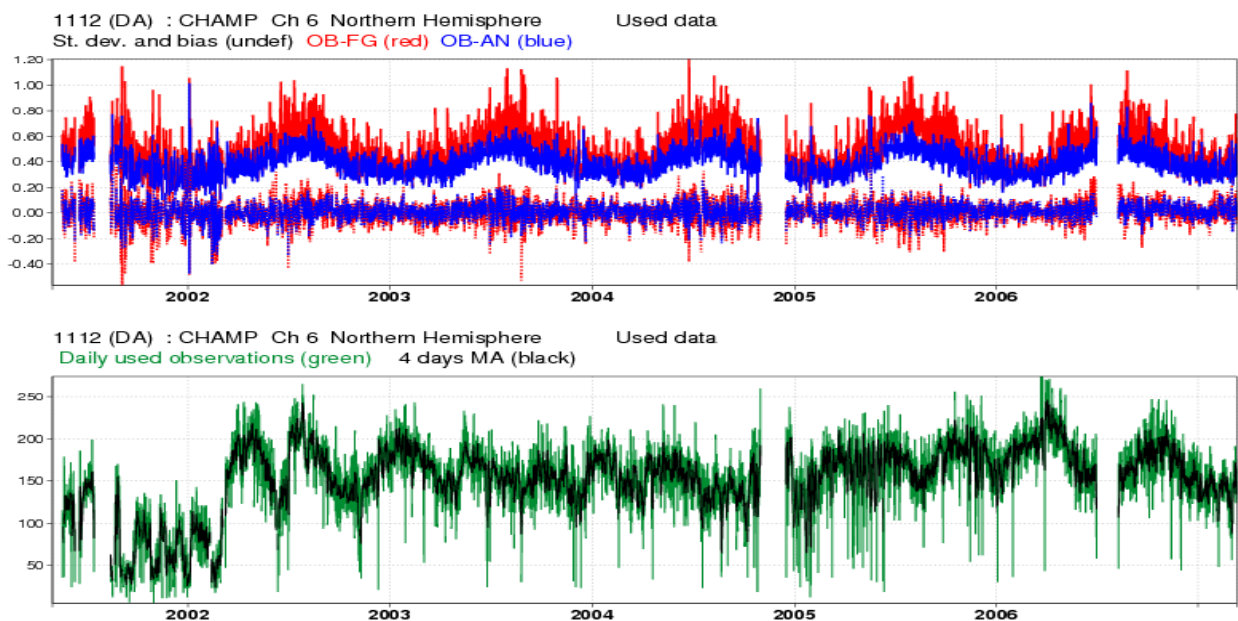


Figure 1: Top panel: Time series of CHAMP bending angle observation minus first-guess (red) and observation minus analysis (blue) departures (mean and standard deviation), for data assimilated in ERA-Interim (May 2001--March 2007), as a multiple of the assumed observation error (which is constant over time). Lower panel: number of data assimilated per day for the altitude layer 5.5-6.5 km.

One particularly striking effect of the assimilation of COSMIC data was to reduce drastically the temperature bias in otherwise under-observed regions such as the Southern Hemisphere 100 hPa pressure level. Figure 2 shows that both the first-guess and the analysis mean temperature departures of ERA-Interim with respect to radiosondes are reduced after 12 December 2006. The transient regime appears to be about a week long, after which the bias settles to a new equilibrium which is closer to zero.

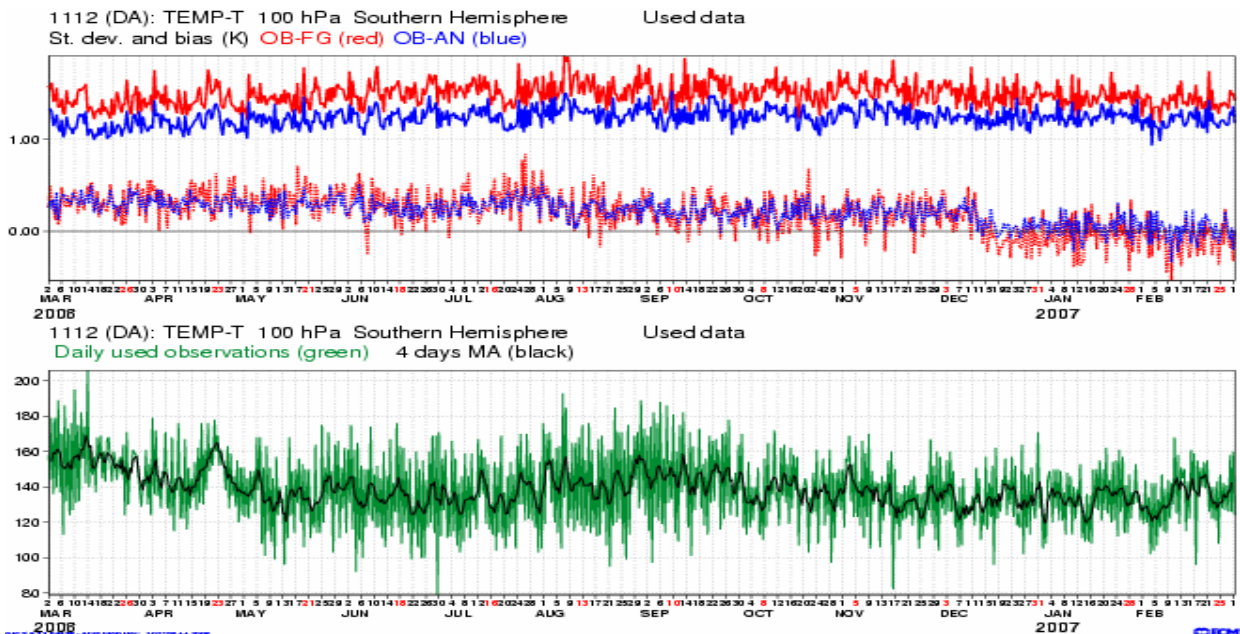


Figure 2: Top panel: Time series of radiosonde temperature observation minus first-guess (red) and observation minus analysis (blue) departures (mean and standard deviation), for data assimilated in ERA-Interim (May 2001--March 2007), in Kelvin. Lower panel: number of data assimilated per day for the pressure layer 150-75 hPa. Note the transition in the mean temperature departures (top panel) when COSMIC data are introduced in the assimilation on 12 December 2006.

### 3.3. Perspectives for reprocessed GPS radio occultation measurements in future reanalyses

Reanalysis offers an opportunity to exploit the information content of past GPS radio occultation not used in a global data assimilation framework at the time the observations were collected.

One motivation could be to evaluate the impact of a single satellite such as the CHAMP data on the variational bias correction. This could represent an impetus to carry out data reprocessing/recovery efforts on early GPS radio occultation missions such as GPS/MET and Oersted, in order to extract as many occultations as possible prior to the CHAMP era.

Future reanalyses could consider using reprocessed GRACE-A and SAC-C data. The GRAS-SAF already has plans to reprocess METOP GRAS data. Reprocessed COSMIC data would bring the advantage of containing more occultation profiles than were available in near-real time.

Reanalyses also offer an opportunity to evaluate, with long time-series, the differences between various processing schemes for GPS radio occultation measurements. By observing more variability, statistically significant conclusions may be reached more easily as regards which processing scheme offers the best products. UCAR currently makes a point of re-processing regularly the entire time-series of COSMIC data with the latest algorithms available.

## 4. Conclusions

Reanalyses of the atmosphere combine all the available meteorological observations in a state-of-the-art modelling and data assimilation framework. The difficulty when combining this information is preserving the original mean signal of each data source while at the same time alleviating problems due to satellite instrument degradation.

The ERA-Interim reanalysis uses GPS radio occultation data as anchoring data within a variational bias correction system. Preliminary results indicate that the assimilation of GPS radio occultation measurements reduce large-scale temperature biases in regions that are under-observed by high-vertical resolution instruments, such as the Southern Hemisphere lower stratosphere.

Prospects for future applications of GPS radio occultation data in reanalysis include the use of data that were not available in time for operational use, as well as data reprocessed with state-of-the-art algorithms.

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