New observations in the ECMWF assimilation system: Satellite limb measurements

Niels Bormann and Sean B. Healy

A new type of satellite data can now be assimilated at ECMWF: data from limb-sounding satellites. So far, only satellite data from Earth-looking nadir instruments have been used in the ECMWF system. In contrast, the new limb-sounding observations measure atmospheric properties along a line sideways through the atmosphere.

The limb-viewing geometry is well suited to give important information on the vertical structure of the atmosphere and to significantly improve ECMWF's analyses of the tropopause and stratospheric region. Weighting functions in the vertical are much sharper than usually encountered for nadir sounders, as most information typically stems from a shallow layer around the tangent point of the line-of-sight. Two types of limb sounding observations can now be assimilated:

- Bending angle profiles from global positioning system (GPS) radio occultation (RO).
- Emitted clear-sky limb radiances.

Experiments have been carried out at ECMWF using both types of limb measurements. So far the results have been very promising. The RO data leads to clear improvements in terms of stratospheric temperature biases, especially over Antarctica, whereas the limb radiances introduce considerable changes to mean analyses of temperature, humidity, and ozone in the stratosphere. Further research is required regarding the two-dimensional nature of the data. It is expected that eventually limb measurements will be routinely assimilated at ECMWF.

Limb sounding techniques

The GPS RO technique is based on very simple physics — Snell's law of refraction. The basic measurement geometry is illustrated in Figure 1. A radio signal is transmitted by a GPS satellite and measured with a receiver placed on a low earth orbit (LEO) satellite. The ray-path between the satellites is bent as a result of refractive-index gradients in the atmosphere, which in turn are related to gradients in temperature and humidity. The ray-bending angle, α, can be derived from the time required for the radio signal to propagate between the GPS and LEO satellites, and the motion of the LEO satellite enables the variation of α as a function of tangent height to be determined. The GPS RO concept has now been successfully demonstrated with the GPS/MET and CHAMP "proof of principle" missions, and from 2006 the GRAS instrument on METOP and the constellation of six satellites, COSMIC, will provide GPS RO measurements operationally.

The RO data provide high-accuracy information on temperature throughout the upper troposphere and the lower stratosphere, and limited moisture information in the upper troposphere. Good vertical resolution, global coverage and all-weather sounding capabilities make GPS RO data an extremely valuable new source of information. In contrast to other satellite observations, in principle GPS RO data should not require a bias correction. This is because, fundamentally, the observation is based on the precise measurement of a time-delay of the GPS signal along the ray-path. Furthermore, the forward modelling is relatively simple, and it is not reliant on spectroscopic parameters or the assumed concentrations of well-mixed gases, which can produce biases in simulated satellite radiances.

Niels Bormann is supported by the EU FP5 ASSET Project.
Sean Healy is supported by the EUMETSAT Fellowship Programme.

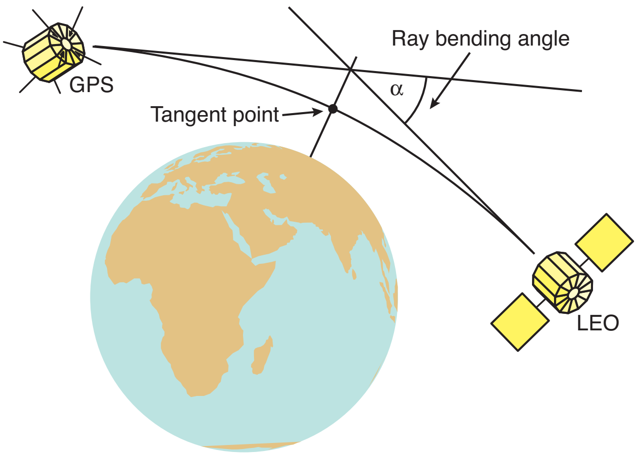

Figure 1 The geometry of a GPS RO measurement. A radio signal is emitted by the GPS satellite and measured with a receiver placed on the LEO. The path of the radio signal is bent as a result of refractive-index gradients in the atmosphere. The motion of the LEO satellite enables the variation of ray-bending with tangent height to be investigated.

The measurement principle for emitted limb radiances is based on measuring the radiation emitted from the Earth's limb for a given tangent altitude against a space background. In contrast to the GPS measurements, this is a passive measurement technique, involving only an instrument onboard a single low-earth orbiting satellite. Current instruments using this technique are the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) flying on the Envisat satellite, and the Microwave Limb Sounder (MLS) onboard EOS-Aura. Past missions include the MLS on the Upper Atmosphere Research Satellite (UARS) and the Improved Stratospheric and Mesospheric Sounder (ISAMS) also on UARS.

Limb radiances provide additional information on temperature and the chemical composition of the stratosphere to lower mesosphere. The limb geometry means that the emitting material along the line-of-sight is maximised, and therefore even gases with low concentrations can be detected, and temperature can be measured at higher heights than typically possible with nadir sounders. The limb radiance assimilation in the ECMWF system aims to improve the analyses of humidity and ozone in the stratosphere, and to

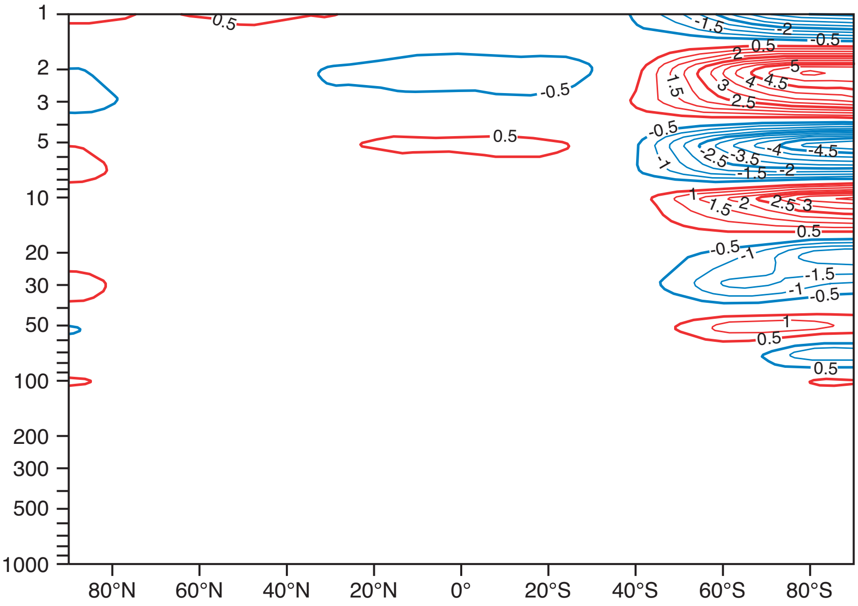

Figure 2 The zonally averaged mean differences in the CHAMP experiment minus the control temperature analyses, averaged over 1 June to 30 June, 2004.

add information on the vertical temperature structure in the stratosphere. It is the first time that limb radiances can be assimilated directly in an NWP model.

For both new types of observation we are assimilating a quantity that is as close as practical to the actual observations, instead of assimilating a retrieved profile derived by the data providers. This philosophy has proven very successful for the assimilation of data from nadir sounders at ECMWF and elsewhere, as it tends to simplify the specification of observation errors and biases. It also avoids the need to account for a priori information that might be used in the retrieval.

Limb observations are sensitive to the atmospheric conditions along the limb-viewing plane. This is a substantial difference to all other observations currently assimilated at ECMWF, as all other observations are mainly probing the atmosphere in a single profile. Considerable technical developments are underway to take into account the two-dimensional characteristics of the limb observations; as a first step we have performed assimilation experiments which assume that the limb observations are sounding a locally horizontally homogeneous atmosphere. In other words, these approaches use a single NWP profile at the assumed tangent point location to simulate the RO bending angles or limb radiances. Experimentation with this setup is ongoing, but the first results are looking very promising.

Experiments with RO data

In preparation for receiving GRAS and COSMIC data, a one-dimensional bending angle observation operator has been implemented in ECMWF's Integrated Forecasting System (IFS). The observation operator was developed by the EUMETSAT GRAS Satellite Application Facility (SAF) and it will be made available to the meteorological community. It has now been tested in a series of forecast impact experiments using CHAMP GPS RO measurements. CHAMP typically provides around 160 bending angle profiles per day and each profile contains approximately 160 bending angles. These data are assimilated without bias correction.

Despite the relatively low number of bending angles that are assimilated, the initial results have proved to be very encouraging. For example, Figure 2 shows the zonally averaged mean analysis differences of the CHAMP experiment minus the

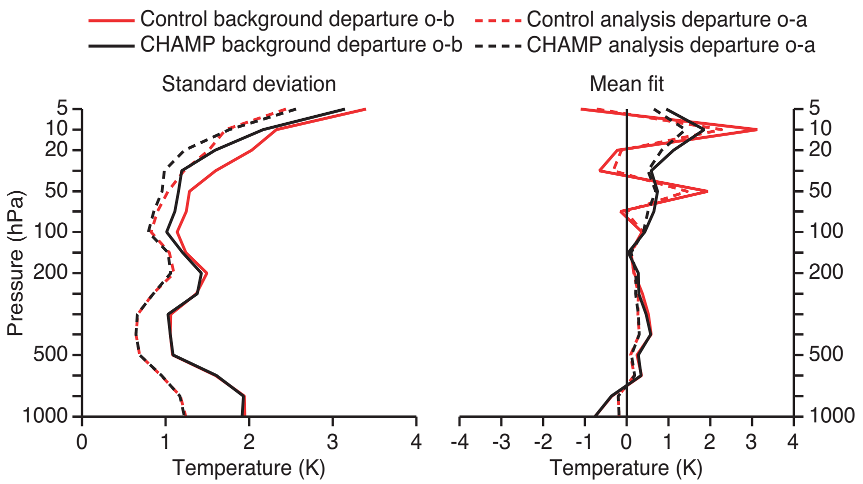

Figure 3 The mean and standard deviation of the background and analysis fit to radiosonde temperature measurements in Antarctica, from 1 June to 30 June, 2004.

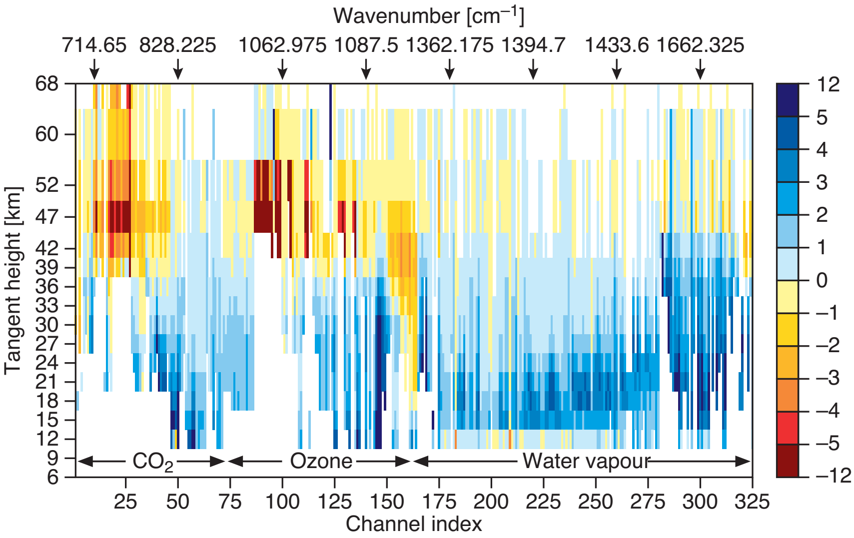

Figure 4 Bias between selected MIPAS clear-sky radiances and results simulated from short-term forecasts performed over the period 18–31 August 2003 from analyses without MIPAS data. The bias is shown as a function of channel index and tangent altitude. Wavenumbers (cm^{-1}) of some channels are indicated on the top axis for orientation purposes. The bias has been normalised by the MIPAS instrument noise.

control, for the period 1 June to 30 June, 2004. The control assimilates all the operational data that were used at that time; the CHAMP experiment is identical except for the use of CHAMP RO measurements in addition to these data. The most striking feature is over Antarctica, where there is a sharp, oscillatory structure in the mean analysis differences. The CHAMP GPS RO measurements improve both the mean and standard deviation of the background and analysis fit to radiosonde temperature measurements in this region, as illustrated in Figure 3. The "stratospheric ringing" in the mean fit to radiosondes over the winter pole is a well-known assimilation problem at ECMWF. The ability of the CHAMP data to introduce this kind of fine-scale structure, partially correcting these problems, is a clear indication of the accuracy and high vertical resolution of the measurement technique. More generally, assimilating the CHAMP measurements improves root-mean-square fit to lower-stratospheric radiosonde temperature measurements in the southern hemisphere, in the day-1 to day-5 forecast-range.

Experiments with limb radiances

The assimilation of limb radiances has been developed for data from MIPAS onboard the European Envisat satellite. MIPAS provides observations in the 685-2410 cm^{-1} region in 59,605 channels at very high spectral resolution (0.25 cm^{-1} in the original design). As it is unfeasible to assimilate data from all channels, we have selected a subset of MIPAS data with the aim to optimise the information content for a given number of observations.

The heart of the direct assimilation of limb radiances is a new fast radiative-transfer model that can simulate MIPAS radiances given the current state of the atmosphere (*Bormann et al.*, 2005). The development of this radiative transfer model has drawn heavily on the experience with fast radiative transfer modelling for nadir radiances accumulated at ECMWF and the NWP SAF over the last decade. The model is called RTMIPAS and it uses a regression approach, similar to that of the RTTOV fast radiative transfer model.

Comparisons between observed radiances and RTMIPAS-simulations highlight how MIPAS radiances detect large biases in the ECMWF model fields in the stratosphere. Figure 4 shows the bias between observed and simulated radiances, as a function of channel and tangent altitude, for a 14-day experiment during which MIPAS data were not assimilated. For a given tangent altitude, the sign of the bias is mostly the same for the majority of the channels considered. This consistency in the signal suggests that a large proportion of the bias is a result of biases in the model fields, since the weighting functions for most of the data shown in this figure peak around the tangent altitude. However, further work reveals, that some of the first guess bias shown in Figure 4 is also due to so-called radiance bias. This originates from inaccuracies in the spectroscopy used in the radiative transfer model, the calibration of the radiances, etc. Radiance biases need to be corrected prior to the assimilation, and the method used currently is similar to that employed operationally for AIRS nadir radiances. Developing approaches to separate between model and radiance biases is an area of active research.

The assimilation of MIPAS radiances leads to considerable changes in the mean analyses in the stratosphere, as the analysis aims to reduce the bias between model fields and observations. Figures 5 show the resulting changes in the mean analyses of temperature and humidity over a 14-day study period. Most noticeable is a moistening of the stratosphere. Assimilation of information on stratospheric humidity has recently become possible due to developments by *Hólm et al.* (2002), and MIPAS radiance assimilation provides a first test for these developments. Since so far no other observations are assimilated that provide information on stratospheric humidity it is hardly surprising that the assimilation of MIPAS data leads to such large adjustments for stratospheric humidity. Qualitatively, the adjustments introduced through the MIPAS radiance assimilation are in agreement with a known dry bias of the ECMWF stratosphere.

As a first check of whether the adjustments introduced through the radiance assimilation are reasonable, we have compared the model fields to ESA's MIPAS retrievals which were not used in the assimilation. These comparisons show that analyses with MIPAS radiances generally agree better with

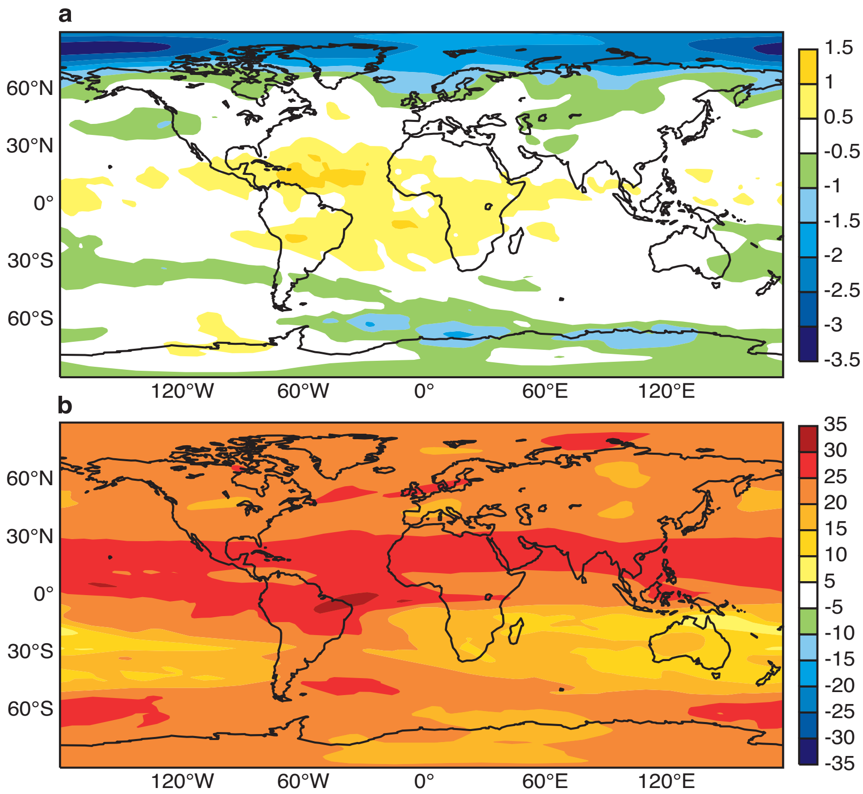

Figure 5 (a) Difference in the mean temperature analyses [K] at 5 hPa over the period 18–31 August 2003 between experiments with and without MIPAS radiance assimilation. (b) As (a), but for the relative difference in the mean humidity analyses [%] at 12 hPa.

MIPAS retrievals than analyses without MIPAS radiance assimilation (see Figure 6). This means that the information extracted by radiance assimilation is consistent with that provided through the MIPAS retrievals. This is an encouraging result, especially since the ESA retrievals have been derived separately from the ECMWF system from different subsets of MIPAS data and with a different radiative transfer model.

Comparisons between the analyses and other observations will be performed in the future to further evaluate the changes introduced through the MIPAS radiance assimilation. Unfortunately, few direct observations of stratospheric temperature, humidity and ozone are available, so retrievals from other satellite instruments may have to be used.

Use of two-dimensional observation operators

The forecast impact experiments using CHAMP bending angles and MIPAS radiances have been based on one-dimensional observation operators. This means that the simulated observations use NWP *profile* information at a single horizontal location. It is clear that ignoring the two-dimensional nature of limb measurements is an additional source of forward model error, which inhibits our ability to extract useful information. Therefore, ECWMF is currently investigating the use of two-dimensional observation operators for both measurement types. A two-dimensional version of RTMIPAS has been developed and extensively validated against simulated and observed radiances (*Bormann & Healy*, 2005). We have found that this substantially reduces the forward model error associated with horizontal gradients, for lower tangent altitudes and channels in strongly absorbing spectral regions. For these data, the line-of-sight weighting functions peak well away from the assumed tangent point, in the direction towards the receiver, thus increasing the sensitivity to horizontal gradients in the atmosphere.

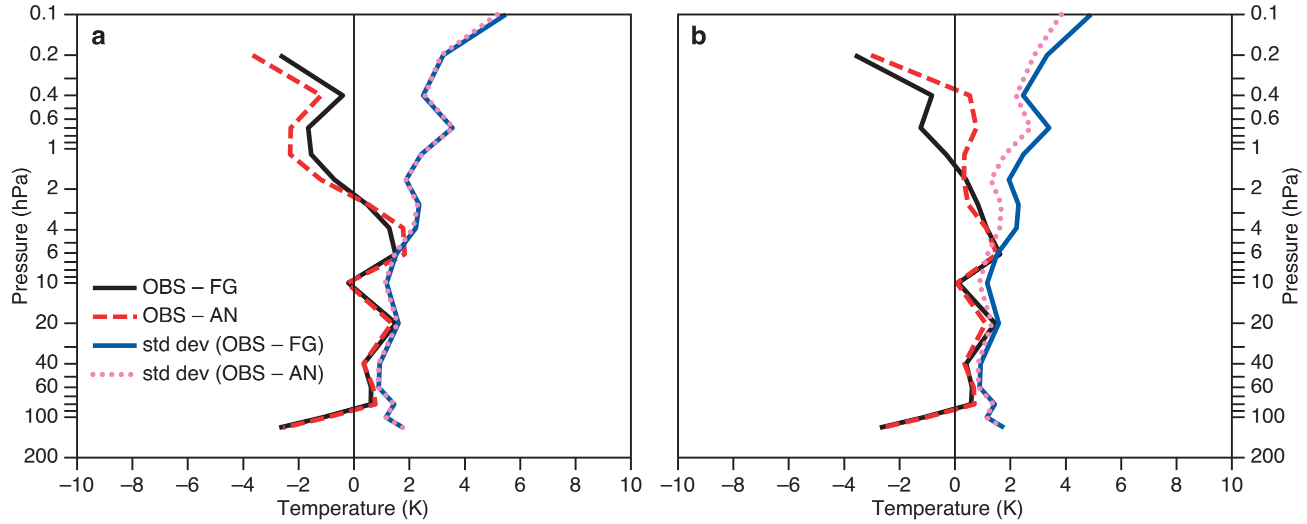

Figure 6 (a) First guess and analysis departure statistics for ESA's MIPAS retrievals over the southern tropics (0°–20°S) for an experiment without MIPAS radiance assimilation, covering the period 18–31 August 2003. (b) As (a), but for an experiment with MIPAS radiance assimilation.

In addition, we have started the first set of forecast impact experiments using a two-dimensional bending angle operator. This has involved significant restructuring and re-coding of the IFS by Mats Hamrud, in order to provide the GPS RO observation operator with information at a set of equally spaced horizontal locations, within the two-dimensional plane defined by the limb geometry of each occultation event. The preliminary results suggest that using the two-dimensional operator improves the root-mean-square fit to the observed bending angles by ~5%, for ray-paths close to the earth's surface, but this does not appear to have led to any clear improvement in the forecast scores. However, this is very much work in progress and further research is required.

Future work

The ultimate goal of this research project is the routine assimilation of limb measurements at ECMWF. We aim to operationally assimilate GPS RO bending angle measurements from CHAMP, GRAS and COSMIC during 2006. As MIPAS ceased routine operations in its original design in March 2004, the developments for the MIPAS limb radiance assimilation will primarily be used as a proof-of-concept study for limb radiance assimilation. Assimilation of MIPAS data over longer periods will allow a more detailed analysis of model behaviour and error characterisation in the stratosphere, for instance during the episode of the southern stratospheric vortex split in 2002. To this end, ECMWF is participating in the EU-funded ASSET project (Assimilation of Envisat DaTa) which will encompass intercomparisons of stratospheric analyses of chemical species produced with different assimilation systems and analysis methods. More generally, the developments for the assimilation of MIPAS radiances provide a framework for the assimilation of radiances from other limb sounders, such as the MLS on EOS-Aura.

FURTHER READING

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The local and global impact of the recent change in model aerosol climatology

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The impact of aerosol on local air quality and climate change is becoming an important topic of research. This is particularly the case for Asia where the so-called "Asian Brown Cloud" causes major health concerns and may have serious agricultural and economic consequences if aerosol can influence the climatological monsoon circulation. With these concerns in mind the ECMWF-coordinated "GEMS" project aims to improve our knowledge of atmospheric aerosol distribution (for further information see the article by Tony Hollingsworth in *ECMWF Newsletter No. 103*).

Here the impacts of a recent change in model aerosol climatology are investigated. It is found that the aerosol change (which is predominantly over North Africa) does influence the climatological North African monsoon circulation. In addition, it also has far wider impacts: affecting the winter extratropical circulation of each hemisphere and leading to improvements in medium-range forecast skill. These results suggest that the GEMS project could lead to further numerical weather prediction improvements and necessary advances in our understanding of climate change.

The old and new model aerosol climatologies

Until recently the aerosol climatology used in the ECMWF operational forecasting model (up to and including cycle Cy26r1) was based on that of *Tanre et al.* (1984). This climatology is specified as annual mean geographical distributions of various aerosol types: "maritime", "continental", "urban", "desert" and uniformly distributed stratospheric background aerosols, all with fixed vertical distributions. Figure 1(a) shows the geographical distribution of the total aerosol optical depth at 550 nm (an optical depth of *d* for a particular wavelength attenuates radiation at that wavelength by