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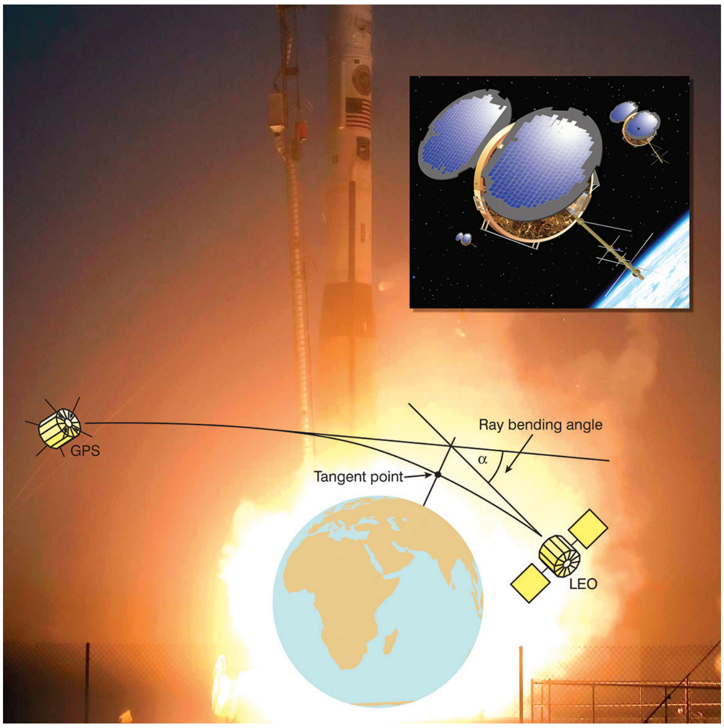

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Operational assimilation of GPS radio occultation measurements at ECMWF

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ECMWF became the first operational centre to assimilate GPS radio occultation (GPSRO) measurements from COSMIC satellites on 12 December, 2006. These measurements produce significant improvements in stratospheric temperature and height biases, particularly in the southern hemisphere.

The GPSRO measurements are globally distributed, have good vertical resolution and an all-weather capability. They are assimilated without bias correction and therefore provide potentially important “anchor points” for the recently introduced variational bias correction scheme (see *McNally et al.,* 2006, *ECMWF Newsletter No. 107*). The information content of the GPSRO measurements is complementary to that of high-resolution sounders, such as AIRS and IASI.

The first operational results at ECMWF, assimilating GPSRO measurements, have been very encouraging. They indicate that these measurements are a useful addition to the global observing network.

Background

The radio occultation measurement technique was pioneered by the planetary science community in the 1960s, and formed part of NASA’s Mariner 3 and 4 missions to Mars. The measurement is based on observing how the paths of radio waves propagating through an atmosphere are bent as a result of refractive index gradients. The original concept envisaged by the planetary scientists was a fleeting, fly-by encounter, as a spacecraft passed behind a planet, but it was noted as early as 1965 that the method could be adapted to study the Earth’s atmosphere. However, the required infrastructure – a constellation of radio transmitters orbiting the Earth – was considered unaffordable at that time.

In the late 1980s it was recognised that the 24 GPS satellites – primarily designed as a tool for precise positioning and navigation – would be a suitable source of radio signals, and the concept of GPS radio occultation (GPSRO) began to be explored. In 1995, work at the University Corporation for Atmospheric Research (UCAR) and the Jet Propulsion Laboratory (JPL) culminated in the launch of the “proof of concept” GPS/MET instrument into a low earth oribit (LEO). This mission placed a GPS receiver developed at JPL in space, and enabled the first GPSRO measurements to be made.

Figure 1 shows the geometry of the GPSRO measurement technique. A radio signal is transmitted by a GPS satellite, passes through the atmosphere and is measured with a GPS receiver placed on a LEO satellite, such as GPS/MET. The path is bent as a result of gradients in the refractive index of the atmosphere, which in turn can be related to gradients in the temperature and humidity. The ray bending angle, a, 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 a. as a function of tangent height to be determined. Temperature and humidity information can be derived from the bending angle profiles. The limb sounding geometry of the measurements means that they have good vertical resolution, focussed around the tangent point. They are also less prone to biases than other satellite measurements because they are based on the precise measurement of a time delay. 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.

The GPS/MET experiment was considered to be a major success. It demonstrated temperature profiles derived from GPSRO measurements were of sub-Kelvin accuracy for heights between 7 and 25 km, and this had important consequences.

- It led to a number of missions of opportunity, most notably CHAMP, which has provided GPSRO measurements since 2001.
- The GRAS GPSRO instrument was included on METOP, and it will provide operational data in 2007.
- The COSMIC proposal was formulated. This suggested placing the latest GPS receivers on a constellation of six LEO satellites, to provide ~2,500 globally distributed measurements per day, with near real time availability.

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The COSMIC mission (full title Formosat-3/COSMIC) is a joint US/Taiwanese venture. The six COSMIC LEO satellites were launched on 14 April, 2006 from Vandenberge Air Force Base in California. Although it will take until late 2007 for the constellation to reach its final orbital configuration, which is designed to optimise the sampling across the globe (see Figure 2), the measurements have been made available to the general community since 28 July, 2006.

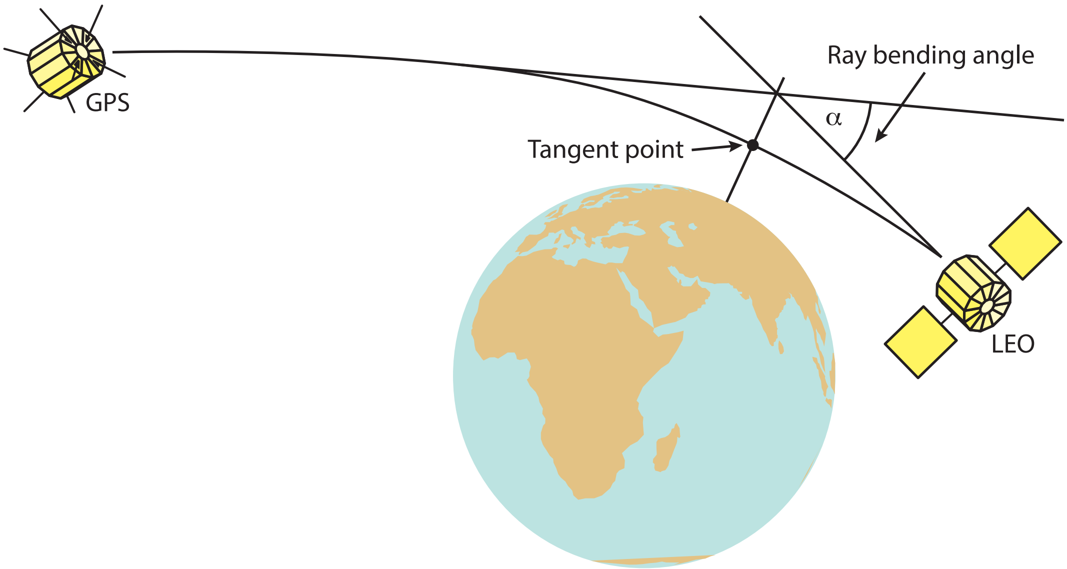

Figure 1 Geometry of a GPS RO measurement. A radio signal is emitted by the GPS satellite and measured with a receiver placed on the LEO. The path of the radio signal is bent as a result of refractive-index gradients in the atmosphere. The motion of the LEO satellite enables the variation of ray-bending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

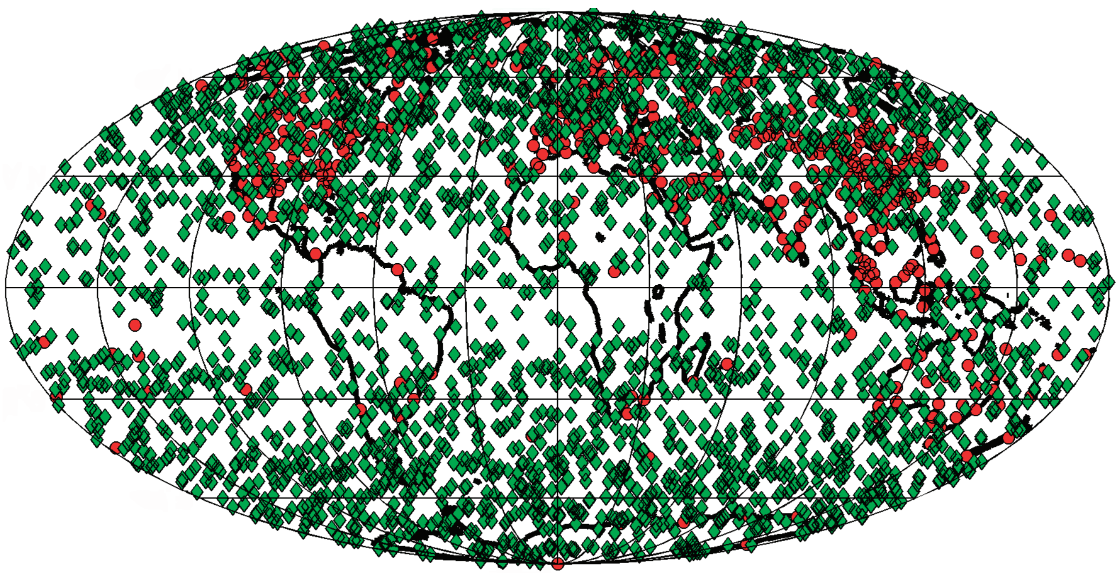

Figure 2 Global distribution of 2,500 COSMIC GPSRO measurements (green diamonds) over a 24-hour period, when the six satellites have reached their final orbital configuration. The red dots show the radiosonde network.

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Assimilation of GPSRO measurements at ECMWF

The assimilation of GPSRO measurements in numerical weather prediction (NWP) systems was first investigated at ECMWF by John Eyre in 1994. This work is considered to be important within the GPSRO community because it placed the occultation measurements within the context of variational assimilation for the first time. Also it introduced the community to the philosophy that the assimilated quantity should be as close to the actual observation as possible. The work concluded that the GPSRO measurements were potentially useful for NWP and that the direct assimilation of bending angle profiles was probably the best strategy for using the data. However, further progress at that time was difficult because there was no foreseeable date when the GPSRO measurements would be become routinely available for assimilation at operational centres. The subsequent success of the GPS/MET and CHAMP missions, and then the possibility of receiving measurements from COSMIC and GRAS in near-real-time, changed this situation. Therefore, recently ECMWF's Integrated Forecast System (IFS) has been modified to enable the assimilation of limb sounding measurements (see *Bormann & Healy,* 2005, *ECMWF Newsletter No. 105*), including GPSRO bending angles.

Two bending angle observation operators are implemented in the IFS.

- ***One-dimensional operator.*** The simplest operator provides a one-dimensional (1D) estimate of the bending angles. Essentially, this means that the two-dimensional, limb geometry of the measurement is ignored, and the bending is calculated using NWP profile information extracted at a single horizontal location, at the assumed tangent point location. The 1D bending angle operator used at ECMWF was developed by the EUMETSAT GRAS Satellite Application Facility (SAF) and will be available from the Met Office as part the Radio Occultation Processing Package (ROPP).
- ***Two-dimensional operator.*** The second bending observation operator is two-dimensional (2D), meaning that it uses NWP profile information extracted at a series of horizontal locations within a 2D planar slice of the atmosphere. This should reduce forward model error as a result of a more physically realistic simulation of the problem.

The 2D operator has been used in a series of forecast impact experiments with CHAMP measurements, but it requires further testing with COSMIC data before it is considered for use in operations at ECMWF. However, note that it will form part of ECMWF's contribution to future upgrades of the GRAS-SAF's ROPP from 2008.

GPSRO Assimilation Experiments

The pre-operational GPSRO experiments assimilate measurements from COSMIC, CHAMP and GRACE-A with the 1D bending angle observation operator. One of the novel aspects of the COSMIC mission is the ability to measure both rising and the more conventional setting occultations. In a rising occultation the LEO satellite emerges from behind the Earth, and progressively higher regions of the atmosphere are probed. The error characteristics of rising occultations are still under investigation and therefore they are not assimilated in the pre-operational experiments. The COSMIC measurements assimilated at ECMWF are processed at UCAR and are routed to ECMWF via NESDIS and the Met Office. The CHAMP and GRACE-A measurements are now made available in near-real-time by GFZ Potsdam, as a result of a project funded by the German Ministry of Education and Research.

Studies about theoretical information content, and early research experiments with measurements from CHAMP, have shown that GPSRO measurements should have a significant impact on upper-tropospheric and lower/mid-stratospheric temperatures, particularly in the southern hemisphere. In these assimilation experiments, the GPSRO measurements have a neutral impact in the lower troposphere, but they produce a clear positive impact in the stratosphere. The GPSRO measurements improve known stratospheric height and temperature biases.

Figure 3 shows the standard deviation and mean of the background departure (observation minus brackground) and analysis departure (observation minus analysis) for radiosonde height measurements in the southern hemisphere. Although the standard deviations are similar for operations and the GPSRO experiment, there is a clear improvement in the mean departures between 400 hPa and 70 hPa. It is important to note that the GPSRO measurements are assimilated without any bias correction, and therefore it is encouraging to see that assimilating these data improves the fit to radiosonde measurements. This also supports the idea that GPSRO should provide "anchor points" for the variational bias correction scheme by preventing the bias correction scheme from drifting to the climate of the NWP model.

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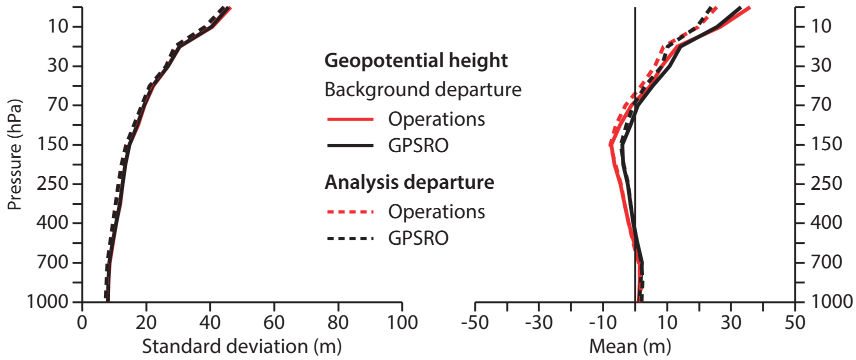

Figure 3 Standard deviation and mean of the forecast and analysis departures for radiosonde geopotential height measurements in the southern hemisphere for the GPSRO experiment and operations. The statistics are based on data from 81 radiosonde sites.

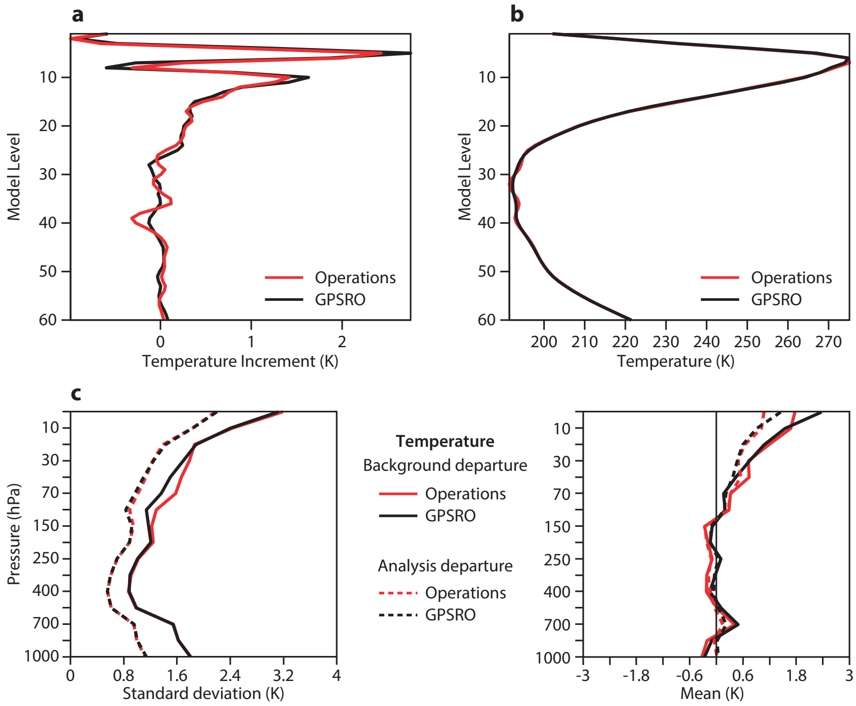

Figure 4 A vertical profiles of (a) mean temperature increments and (b) mean temperature analysis over the Antarctica on the uppermost 60 model levels for the GPSRO experiment and operations. (c) Shows the fit to radiosonde temperature measurements from 12 sites in Antarctica.

Figures 4(a) and 4(b) show the mean temperature increments and mean analysis state, respectively, for the GPSRO experiment and operations over Antarctica averaged over period 14 to 30 September, 2006. The operational temperature analysis over Antarctica has been prone to spurious oscillations in the stratosphere. These oscillations arise as a result of large, systematic temperature increments in the upper stratosphere caused by NWP model error, which are propagated downwards in the analysis, as a result of the correlations in background error covariance matrix. The oscillations are problematic because they are in the “null-space” of satellite radiance measurements. This essentially means that the radiances have no sensitivity – or are “blind” – to these perturbations, because they are averaged out by the broad vertical weighting functions. In contrast, the GPSRO measurements have very good vertical resolution and they can both resolve and then correct these unphysical oscillations in the analysis. The large increments near the model top are not affected significantly by the introduction of the GPSRO measurements, but they do constrain the increments that cause the oscillations lower down. Furthermore, Figure 4(c) shows that assimilating the GPSRO measurements generally improves the fit to radiosonde temperature measurements over Antarctica.

Improvements in the stratospheric temperature analyses improve the subsequent temperature forecasts. Figure 5 shows the forecast fit to radiosonde temperature measurements in the southern hemisphere at 200, 100 and 50 hPa. The improvements at 100 hPa and 50 hPa are statistically significant at the 5% level over the day-1 to day-5 forecast range. There are also statistically significant improvements at 100 hPa in the northern hemisphere and tropics.

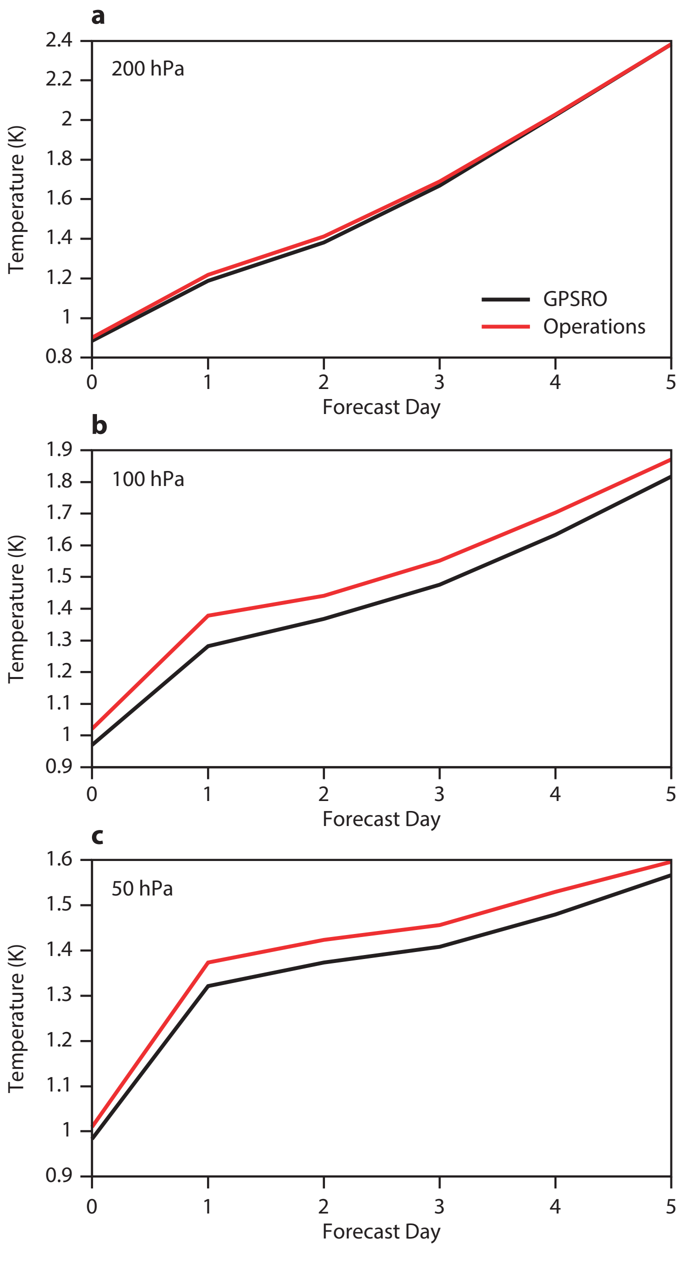

Figure 5 The r.m.s. fit to radiosonde temperature measurements over the southern hemisphere at (a) 200, (b) 100 and (c) 50 hPa over the day-1 to day-5 forecast range, for the GPSRO experiment and operations. The statistics are based on data from 61 radiosonde sites.

Implementation in operations

The COSMIC, CHAMP and GRACE-A GPSRO measurements became operational on 12 December, 2006, with the introduction of IFS cycle 31r2 (referred to as Cy31r2). The measurements have clearly improved some of the stratospheric height and temperature biases in the operational analyses. For example, Figure 6 shows a time series of the mean and standard deviation of the background and analysis departures from operations for radiosonde height and temperature measurements at 100 hPa in the southern hemisphere. The period starts on the first full day of Cy31r1 in operations, contains the change to Cy31r2 on 12 December and continues to the end of February, 2007. There is a clear improvement in the mean background departure for the radiosonde measurements with the introduction of Cy31r2. Similar improvements in the fit to radiosonde temperatures at 100 hPa are also evident in the northern hemisphere and tropics, although the magnitude is somewhat smaller. The vertical temperature oscillations over Antarctica have also been suppressed in Cy31r2.

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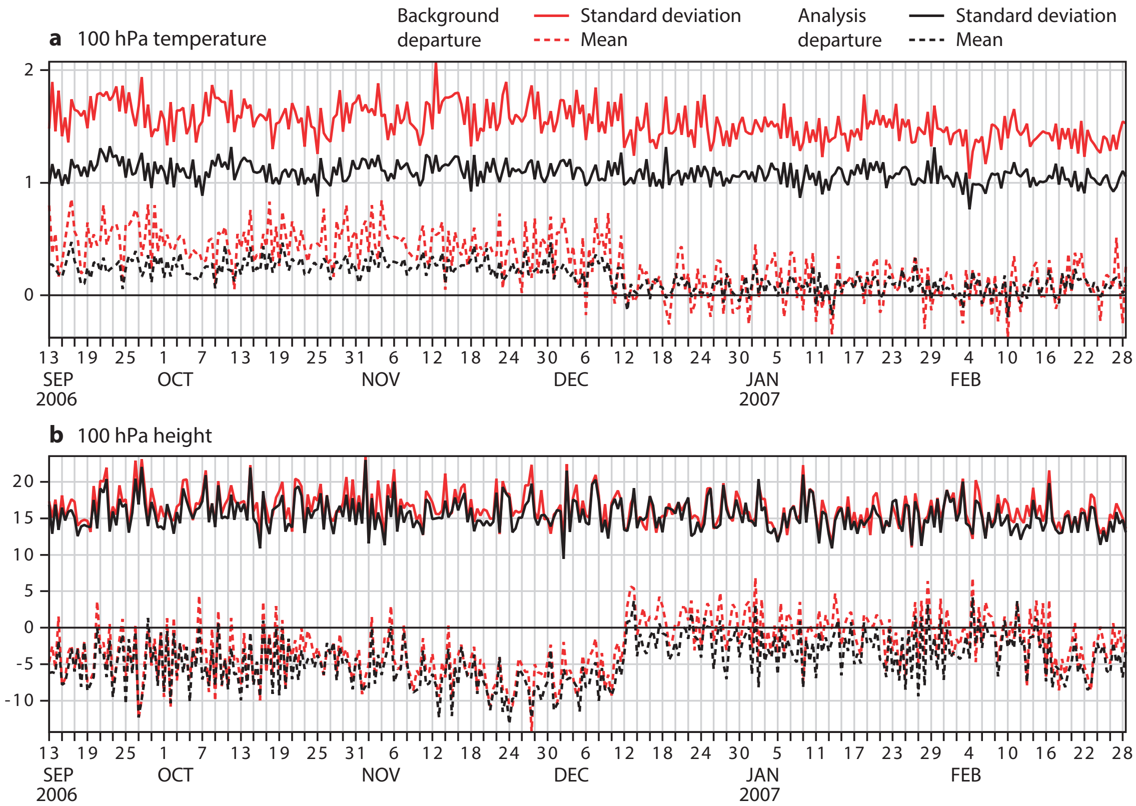

Figure 6 Time series of the mean and standard deviation of the operational background departure and analysis departure for (a) temperature and (b) height radiosonde measurements at 100 hPa. The sample numbers are typically 270 and 220 per day, for the temperature and height measurements, respectively.

Future work

The COSMIC, CHAMP and GRACE-A GPSRO measurements have been successfully assimilated in operations and measurements from GRAS will be available soon. ECMWF will monitor bending angle measurements from GRAS as soon as they become available, with a view to assimilating the data at the earliest opportunity. In addition, the exploitation of the existing data will be improved. For example, we currently assimilate over 1,000 occultations per day, but COSMIC is often producing over 800 rising occultations, which are not used. Ongoing research experiments, both monitoring and assimilating the rising occultations, suggest that their error characteristics are comparable to the setting occultations, and that they contain useful atmospheric information. Therefore, it is hoped to assimilate these data operationally during 2007. In addition, in operations GPSRO measurements with tangent point within 4 km of the Earth's surface are currently not used. These measurements potentially contain useful water vapour information and their utility will be investigated further.

We will also consider the use of the two-dimensional (2D) observation operator, which accounts for the limb nature of the measurements. A 2D operator should reduce the forward model errors in the lower-troposphere, and in research experiments assimilating CHAMP measurements we have found that it has improved the fit to observations. However, the reduced forward model errors do not appear to produce improved forecasts. Nevertheless, it will be important to investigate the impact of the 2D operators now that the number of GPSRO measurements has increased by over an order of magnitude.

In the wider context, it is interesting to note that GPSRO measurements have already proved useful in research experiments investigating the assimilation AMSU-A channel 14 radiances without bias correction. It has recently been found that fixing the bias correction of AMSU-A channel 14 to zero prevents the variational bias correction scheme drifting towards the model climate in the stratosphere. However, this modification can only be done when the GPSRO measurements are assimilated, otherwise it introduces spurious temperature oscillations in the stratosphere. This is a good example of two distinct satellite observing systems complementing each other and highlights the strengths of the GPSRO measurements.

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Overall, the first operational assimilation results at ECMWF suggest that GPSRO measurements are a useful addition to the global observing network. The vertical resolution of the GPSRO measurements, and the fact that they can be assimilated without bias correction, are important qualities because they mean that the measurements provide information that is complementary to the other observations. There are a number of possible improvements in the assimilation of GPSRO measurements that will be investigated soon, but it is important to emphasise that the first results at ECMWF have been very encouraging.

Further Reading

Anthes, R., C. Rocken & **Y.-H. Kou,** 2000: Applications of COSMIC to meteorology and climate. *Terr. Atmos. Ocean Sci.,* **11,** 115–156.

Bormann, N. & **S. Healy,** 2005: New observations in the ECMWF assimilation system: Satellite Limb measurements. *ECMWF Newsletter No. 104,* 13–17.

Eyre, J., 1994: Assimilation of radio occultation measurements into a numerical weather prediction system. *ECMWF Tech. Memo. No. 199.*

Healy, S. & **J.-N. Thépaut,** 2006: Assimilation experiments with CHAMP GPS radio occultation measurements, *Q.J.R. Meteorol. Soc.,* **132,** 605–623.

McNally, T., T. Auligné, D. Dee & **G. Kelly,** 2006: A variational approach to satellite bias correction. *ECMWF Newsletter No. 107,* 18–23.

Rocken, C., R. Anthes, M. Exner, D. Hunt, S. Sokolovskiy, R. Ware, M. Gorbunov, W. Schreiner, D. Feng, B. Herman,Y.-H. Kuo & **X. Zou,** 1997: Analysis and validation of GPS/ MET data in the neutral atmosphere. *J. Geophys. Res.,* **102,** 29,849–29,866.

Yunck, T., C.-H. Lui & **R. Ware,** 2000: A history of GPS sounding. *Terr. Atmos. Ocean Sci.,* **11,** 1–20.

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