FIRST RESULTS OF THE ASSIMILATION OF COSMIC DATA FOR WEATHER FORECASTING APPLICATIONS AT ENVIRONMENT CANADA

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Abstract

We present results of tests made at Environment Canada (EC) as part of the process to transition GPS Radio Occultation (GPSRO) data to operations. These data are expected to enter the parallel processing stream in December 2007. The tests shown here include data from missions CHAMP, GRACE and COSMIC. The latter provides about 85% of the data volume.

The results show a consistent improvement in the entire stratosphere, as measured with a broad range of verification tools. The improvement is smaller in the troposphere, and especially in the tropics. Although some regions are more positively impacted than others, there are no regions where the performance is degraded.

INTRODUCTION

The GPSRO technology has advanced to become an operationally reliable source of meteorological data. Missions CHAMP (Wickert et al., 2001), GRACE (Beyerle, 2005) and COSMIC (Anthes et al., 2000) have demonstrated the required performance in accuracy, consistency and timeliness. The long term mission METOP/GRAS (Loiselet et al., 2000), first to be explicitly designed for operational use, will provide data during the next 15 years. Several follow-on projects also exist (Wickert, 2007, Rocken 2007) that are at different stages of planning and implementation.

A GPSRO instrument has a low cost, moderate size, small weight and low power requirements. It is thus easy to add such an instrument as secondary payload to other missions. This instrument could also be main payload of mini-satellite missions. There are also prospects (Smith, 2007) for the next generation of radio occultation receivers that will gather signals from satellite radio-navigation systems other than GPS, such as GALILEO or GLONASS, to further increase the volume of data per receiver.

The above properties of radio occultation technology imply that it is reasonable to assume that these data will be available in significant volumes in the long term, and likely in volumes even larger than at present, making them relevant for long term operational meteorology. Within this context, an effort was made to develop the capability to assimilate GPSRO data in EC’s operational data assimilation and weather forecasting system. The tests show that the performance of the system is significantly improved. Consequently, these data are scheduled for parallel implementation in December 2007, leading to operational implementation in early 2008.
THE ASSIMILATION AND FORECAST SYSTEM, AND THE EXPERIMENT SETUP

In its current operational version, EC’s data assimilation and forecast system (Côté et al., 1998; Gauthier et al., 1999) performs data assimilation in 4D-Var mode. The model has a global grid with a horizontal resolution of 800x600 points (~33km grid size), 58 vertical levels, and a lid at 10 hPa (~30 km). For testing purposes, the assimilation system has options to perform data assimilation in 3D-Var or 3D-Var-FGAT (First Guess at Appropriate Time) modes, which consume considerably less computing power than assimilation in 4D-Var mode. The tests presented here are performed in 3D-Var-FGAT mode. In a broad range of cases, the impact of a modification (be it a change to the model, to the list of data to be assimilated, or other details) in 3D-Var-FGAT provides a good estimation of the impact of the same modification in 4D-Var mode (Laroche, 2005). Notable exceptions, however, are short-lived or fast-changing atmospheric structures. Other than the assimilation mode, these tests are performed following the same procedure as the operational system, including the same vertical and horizontal resolution, and the same physical parameterizations. 4D-Var tests are now underway, with preliminary results confirming that the impact shown in the 3D-Var-FGAT experiments is also seen in 4D-Var. Consequently we expect that the results shown here are representative of the final 4D-Var experiments.

The data assimilated consists of data that is currently assimilated operationally:
- Radiosondes
- Surface observations
- Aircraft measurements
- AMSU-A, AMSU-B, and GOES satellite radiances
- Wind profilers
- Atmospheric motion vectors

plus a number of new observations that are scheduled to be operationally assimilated within the next few months:
- Supplementary atmospheric motion vectors
- Winds from ocean scattering (Quicksat)
- Aqua-AIRS and SSM/I satellite radiances

In one of the experiments (hereafter “control experiment”) only the above list of data is assimilated. In the other experiment (hereafter “GPS experiment”), the above list of data plus the available GPSRO data are assimilated. The experiments cover the period from 20 December 2006 to 21 January 2007 (or 32 days).

THE GPSRO DATA

In the GPS experiment, GPSRO data that is available in near real time is assimilated. For the period studied, refractivity profiles as a function of MSL height from CHAMP, GRACE and COSMIC are available. COSMIC is a major contributor, with about 85 % of the data volume. The COSMIC mission forms a constellation of six satellites, and each COSMIC satellite has antennae pointing in the forward and aft directions, and thus gathers both rising and setting occultations.

Data is provided by the University Corporation for Atmospheric Research (UCAR), for missions CHAMP and COSMIC, and by the GeoForschungsZentrum (GFZ), for missions CHAMP and GRACE. No statistically significant difference is found between data from different satellites, or between rising and setting occultations. A small systematic difference (of the order of 0.05% of the refractivity) is found between data from the two providers. However, this is only a small fraction of the expected error of the data (in the range of 0.5-1%), and is thus neglected. Consequently, GPSRO data from all sources are considered to have a statistically identical behaviour in this experiment.

The GPSRO data (refractivity as a function of MSL height) is filtered with the following criteria:
- No two profiles separated by less than 300 km within 45 min.
- Data below 4 km MSL is not assimilated
- Data below 1 km from the surface is not assimilated
- Data above model lid is not assimilated
- Data departing by more than five percent from the background are rejected
The amount of data rejected is about 15% of the received data, most of it due to the clipping below 4 km and above the lid. The remaining data is vertically thinned to about 1 datum/km. Each profile is scanned bottom-up. Above an accepted datum, all data less than one km above itself is rejected. The next remaining datum is accepted, and the process is repeated until the model lid is reached.

The specification of the expected observation error of the GPSRO data is found to be a major issue. Theoretical estimates of this error (Kursinski et al., 2000) indicate that it should not be larger than 1% of the refractivity in the entire vertical range of EC’s forecast model (i.e. 0-30 km). In the upper troposphere and lower stratosphere, it should be as low as 0.2% of the refractivity. However, these theoretical estimates account only for the pure observation error, whereas the a priori observation error required for data assimilation must account also for the representativity error.

Several tests have been made at EC with different estimates of the observation error for GPSRO, all closely following the abovementioned theoretical estimates, but accounting in different ways for the representativity error. Regardless of the details of the specification of the observation error, these tests consistently show that assimilating GPSRO data leads to a clear positive impact in the stratosphere, extending down to the troposphere at high latitudes. These improvements are very robust, persisting not only over different possible error specifications, but also across several model resolutions, assimilation modes, and over different seasons (Aparicio and Deblonde, 2007). However, the performance in the tropical troposphere is critically dependent on the details of the specification of the a-priori observation error, and most of the possible specifications lead to a negative impact in this region.

In the tropical troposphere, large O-F (Observation minus 6h Forecast) differences are common. When these large discrepancies appear, they extend over a broad portion of a profile, and are not limited to isolated data points, indicating that the model describes an atmospheric regime substantially different from what is observed. Assimilation of any datum, however, is likely to improve the analysis only on the condition that the atmospheric regime of the model is already substantially close to that observed. This prompted the following strategy for the estimation of the a-priori observation error:

- A-priori error is not static. In order to accommodate for the representativity error and the difference between observed and model regimes, the a-priori observation error is estimated from the structure of O-F within a profile
- It is estimated through a weighted quadratic average of the O-F difference, within the profile:

\[
\left( \frac{E_i}{F_i} \right)^2 = \frac{\sum_j e \left( \frac{h_j - h_i}{D} \right)^2 \left( \frac{O_j - F_i}{F_j} \right)^2}{\sum_j e \left( \frac{h_j - h_i}{D} \right)^2}
\]

- If E/Fi as defined above has a value smaller than 0.002, it is taken to be 0.002 (i.e. 0.2% of the background refractivity). Typical values are between 0.005 and 0.01 (i.e. 0.5 % to 1% of the background refractivity).

The O-F differences, and the estimated error E, are normalized by the forecast F, so their values change slowly with height. The weight is a Gaussian whose spread D is taken to be 5 km. This weight structure was taken to allow for a different behaviour in the troposphere, tropopause and stratosphere. An example of a profile, and the error estimated with the above procedure are shown in Figure 1.

As the error estimate is a weighted average performed within a profile, rather than a global average over several weeks or months, it has the potential to adjust to flow-dependent situations, as well as to respond dynamically to the quality of the forecast. An inaccurate forecast dynamically decreases the weight of the data being assimilated. An accurate forecast dynamically increases the weight of data. Tests performed with this procedure show that the benefits of GPSRO data assimilation in the description of the stratosphere and the high-latitude troposphere are retained. By contrast, the impact in the tropical troposphere is neutral or slightly positive.
RESULTS

The experiments cover the period 2006-12-20:00.00 to 2007-01-21:12.00 (32 days). Several verification procedures are applied to compare the performance of the GPS and control experiments. These include:

- O-F verifications: Assimilated data are compared at the background check stage. A smaller O-F standard deviation and bias indicates a better experiment. This is done with radiosonde data and with GPSRO data. As GPSRO data is distributed worldwide and very evenly, it is in itself an excellent source of “truth” data.
- Radiosondes: Bias and standard deviation profiles for several regions.
- Anomaly correlation: For forecast ranges of several days, using as “truth” the analyses of each experiment.

O-F verifications:

These statistics are constructed with data at the O-F level, with F the background field (6h forecast) during the assimilation procedure. The O-F values are evaluated before the data is assimilated. For completeness, the O-F values of GPSRO data below 4 km and above the model lid (~30 km) are evaluated during the experiment. Their statistical behaviour is thus also shown here. These data, however, are not assimilated.

The accuracy of the 6h forecast (measured with GPSRO as truth) is improved in the GPS experiment for the entire atmosphere. This is shown in Figure 2 (left panel). The standard deviation of the forecast is smaller than in the control experiment by 5-40%, especially in the stratosphere. The impact is smaller in the troposphere, and especially in the tropics. This is expected for three reasons. Firstly, data below 4 km are discarded. Secondly, most of the water vapour is located in the low troposphere. The assimilation procedure must resolve the ambiguity between temperature and water vapour, which reduces the potential impact of the assimilation of a GPSRO datum. Thirdly, the heterogeneity in the tropical troposphere is in general a challenge during data assimilation. The impact in the polar troposphere is, on the other hand, clearly positive.
The Northern Hemisphere is also better sampled by other data sets, and the impact of assimilation of new data is consequently smaller. This is noticeable in both plots, but especially in the radiosonde temperature plot (right panel of Figure 2).

Figure 2: Verification with GPSRO data (left) and radiosonde temperatures (right). The figures show the ratio of the standard deviation of the O-F innovations between the GPS and control experiments. A ratio below 1 in a pixel indicates that the standard deviation of the GPS experiment is smaller, and is coloured in red. A ratio above 1 indicates that the standard deviation of the control experiment is smaller, and is coloured in blue. The innovations of GPSRO data above the model lid (~30 km) and below 4 km are evaluated for completeness, but these data are not assimilated.

Radiosonde verification:

These tests show the bias and standard deviation profiles of radiosonde O-F values of winds (UU and VV components), geopotential height GZ, temperature TT and dew point depression ES, averaged over several world regions. Results for the northern hemisphere and southern hemisphere are shown in Figure 3. The standard deviation is reduced in both hemispheres, but especially in the southern hemisphere. The magnitude most impacted is the temperature. In both hemispheres, the standard deviation of the temperature is better in the GPS experiment with a statistical significance of over 90% in most pressure layers, and over 99% in most of the stratosphere. Statistically significant positive impacts appear also in the wind for both hemispheres, especially in the 100-300 hPa region in the southern hemisphere. Also relevant is a moderate, but statistically significant, improvement in the moisture field of the southern hemisphere.

Whereas the impact on the standard deviation is overwhelmingly positive, these tests show some mixed results when measured through the bias, in general with high statistical significance. The size of the bias however, is sufficiently small and has a minor meteorological impact. This has been traced to the fact that most observations are vertically geolocated in pressure, whereas radio occultations are geolocated in height, which easily leads to a bias between different kinds of data. Efforts are underway to improve the consistency across the different possible geolocations.
Figure 3: Verification with radiosonde data, for Northern Hemisphere (left set of panels) and Southern Hemisphere (right set), evaluated with winds (UU and VV components), geopotential height GZ, temperature TT and dew point depression ES. Lines show the bias (dashed) and standard deviation (solid). The control experiment is shown in blue and GPS experiment in red. Whenever the difference between both experiments is statistically significant (above 90%), the side is coloured for the experiment with better performance. This is done at the left of each panel if the difference in bias is statistically significant, and at the right of each panel for the standard deviation.

Verification against analyses:

Forecasts were launched up to 120h (5 days). Using as “truth” each experiment’s analyses, several verification tools can be used. Two are shown here:

- The anomaly correlation (Figure 4) for forecast ranges of 0-120h. In the figure, results for the temperature at pressure levels of 500 hPa and 100 hPa are shown, for both hemispheres. The results are positive in general. Again, the southern hemisphere is most impacted, with positive results at both pressure levels. The northern hemisphere has moderately positive results at the upper level, and neutral at the lower one.

- The root mean square (RMS) between the forecast and the analysis (Figure 5). The worldwide change in the RMS for the temperature field, with and without assimilation of GPSRO data, is shown in the figure, for the 120 h forecast range at 500 hPa. A substantial reduction in the temperature RMS can be seen over large areas of the globe, notably the southern mid-latitudes and pole. The impact in the tropics is neutral, whereas the northern hemisphere presents areas of slightly positive and slightly negative results, but always close to neutral. No area is substantially degraded.
Figure 4: Anomaly correlation, verifying forecasts against each experiment's own analysis. The panels show the anomaly correlation for temperature at 500 hPa (two left panels) and 100 hPa (two right panels), for both the northern hemisphere (far-left and centre-right panels) and southern hemisphere (centre-left and far-right panels). The GPS experiment is shown as a solid line. The control experiment is shown as a dotted line.

**CONCLUSIONS**

The performance of EC's assimilation and forecast system after the assimilation of available NRT GPSRO data is tested with several verification tools, and the different measures of performance give coherent results. These are especially positive in the entire stratosphere and in the southern hemisphere. The temperature field is particularly impacted in a positive manner. Smaller impacts, but also positive and statistically significant, are seen in the wind and moisture fields. The tropical troposphere shows a comparatively small impact in all fields. The northern troposphere shows a moderate, but positive impact, consistent with the fact that it is already sampled by many other data sources. The north versus south difference indicates that GPSRO is closing data gaps in regions that
are poorly sampled by other data. The introduction of a dynamic error estimation, which increases or decreases data weight as a function of the performance of the system, successfully avoids poor performance in the tropics.

In agreement with the a-priori expectations for these data, the positive impact in the temperature field in dry regions of the atmosphere is clearly obtained. These data are also a-priori expected to provide a good measure of the moisture field in the troposphere and especially in the tropics. This latter expectation is only partially fulfilled, and further refinements are necessary. The global impact is nevertheless clearly positive. In the light of these results GPSRO data will enter the parallel test phase at Environment Canada in December 2007, which should lead to operational implementation in early 2008.

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REFERENCES


