ECMWF Feature article

from Newsletter Number 124 – Summer 2010

METEOROLOGY

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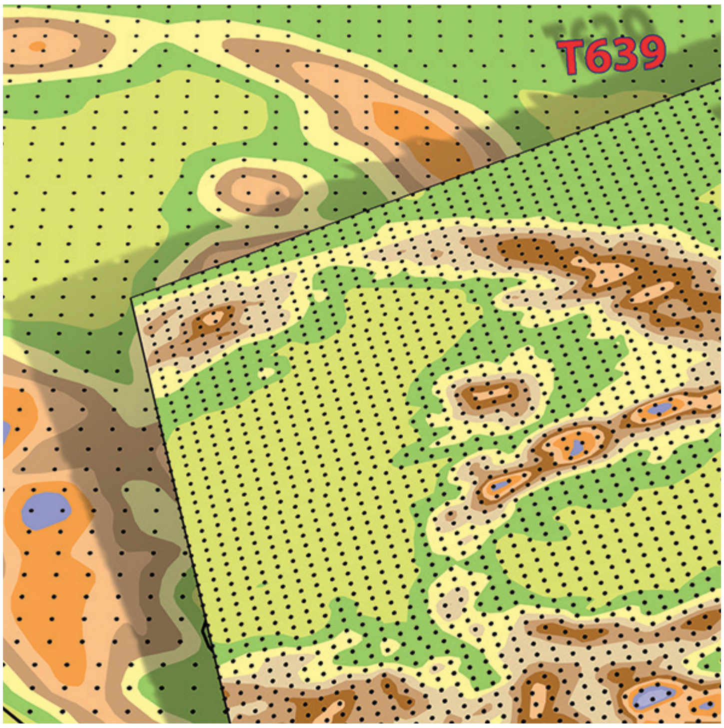

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doi:10.21957/ruetfdp5

This article appeared in the Meteorology section of ECMWF Newsletter No. 124 – Summer 2010, pp. 24–28.

Surface pressure information derived from GPS radio occultation measurements

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The possibility of deriving useful surface pressure information from satellite measurements has potentially important implications for the future design of the global network of conventional observations. Profiles of GPS radio occultation (GPSRO) bending angle can provide surface pressure information when they are assimilated in the four-dimensional variational (4D-Var) system.

We have recently performed a set of forecast impact experiments to investigate the ability of GPSRO measurements to provide useful surface pressure information when all conventional, synoptic and drifting buoy surface pressure measurements are removed from the NWP analyses. Somewhat surprisingly, we have found that removing the conventional surface pressure observations has limited impact on the medium-range surface pressure and geopotential height forecast scores in the southern hemisphere when GPSRO measurements are assimilated. However, we have also found that the surface pressure analyses produced with GPSRO measurements are extremely sensitive to relatively small biases in the NWP system when no conventional surface pressure observations are assimilated.

Background

Bending angle profiles derived from GPSRO measurements have been assimilated operationally at ECMWF since 12 December 2006 (see Healy, *ECMWF Newsletter No. 111*). They differ from satellite radiance measurements because they have much higher vertical resolution, and they can be assimilated without bias correction. To date, the main impact of GPSRO measurements has been on upper-tropospheric and lower-stratospheric temperatures. However, it is well known that profiles of pressure as a function of geopotential height can be derived from GPSRO measurements, and in theory it should also be possible to derive useful surface pressure information from the measurements using variational assimilation techniques. Physically, this information content arises because the bending angles are assimilated as a function of a height variable, known as the 'impact parameter' (see Box A).

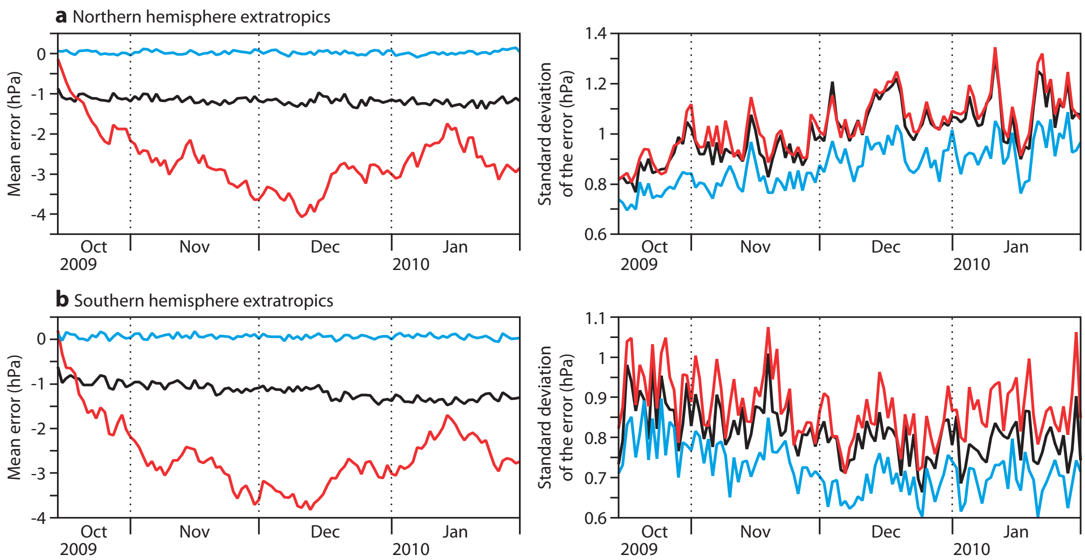

Figure 1 Time series of the mean error and standard deviation of the error of the 24-hour forecast of surface pressure, for the period 15 October 2009 to 31 January 2010, for (a) northern hemisphere and (b) southern hemisphere extratropics when conventional surface pressure observation measurements are removed (black line), both GPSRO and conventional surface pressure observation measurements are removed (red line), and for the full observing system (blue line). The verification is against the operational ECMWF analyses.

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The GPSRO height coordinate

A

Deriving surface pressure information from GPSRO observations requires accurate mapping of the NWP model output to the height coordinates used for GPSRO observations. ECMWF assimilates GPSRO bending angles as a function of a height variable, known as the ‘impact parameter’. This variable also arises in physics when describing the scattering of classical particles in a spherically symmetric potential, and there are strong similarities in the mathematics of this scattering problem and the calculation of the bending of radio waves in the atmosphere. Geometrically, the impact parameter is the radius of closest approach that a ray (or particle) would have had, in the absence of any bending (see box figure).

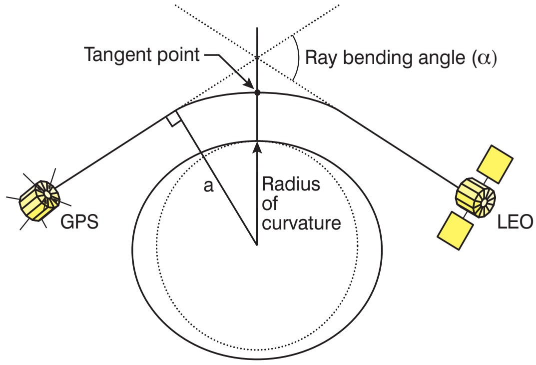

Illustration of the GPSRO geometry and the impact parameter 'a'.

Physically, the impact parameter is analogous to the angular momentum of a particle, and it is a conserved quantity along the ray path if the atmosphere is spherically symmetric, rather like the conservation of angular momentum of a classical particle in a spherically symmetric potential. This conservation property means that the impact parameter provides information on the height of the ‘tangent point’, when the ray’s path is tangent to the Earth’s surface, and the bending is largest.

The assimilation with respect to a height variable introduces some subtle problems in the use of GPSRO data, which are not generally encountered with other measurements. The ECMWF forecast model – in common with all other operational NWP models – assumes a spherical Earth for computational purposes. The surface of this sphere is assumed to be Mean Sea Level (MSL), and the geopotential heights are then given relative to this MSL.

The details of the actual geometrical shape of the Earth’s surface do not arise when assimilating other measurements. In contrast, GPS measurements are given relative to the ‘World Geodetic System 1984’ (WGS-84) reference ellipsoid, which itself is an approximation to the Earth’s geoid. More specifically, in the processing of GPSRO measurements, we introduce another level of approximation with the use of a ‘radius of curvature’, which defines the best spherical fit to the WGS-84 ellipsoid in the region of the observation.

Ultimately, when assimilating the GPSRO measurements, we have to interpret that ECMWF NWP model surface as if it was the geoid, and then in the forward operator use a correction factor known as the ‘undulation’, which is defined as the height of the geoid above the WGS-84 ellipsoid, in order to relate the NWP model output to the GPS observations. We also have to include the transformation between geopotential height and geometric height in the forward operator, to account for the fact the gravity varies as a function of height. Failure to include this transform introduces forward model banding angle biases that increase with the height of the tangent point. For example, at 30 km the forward modelled bending angle bias is around 2% if the transform is not included, and we typically assume an observation error of 1% at that level.

The assimilation of GPSRO measurements as a function of a height variable means that the integration of the hydrostatic equation is a component of the ‘observation operator’ (or ‘forward model’) used to simulate the bending angle measurements in the 4D-Var system. This introduces a clear, physically-based sensitivity of the simulated bending angle values with respect to the model surface pressure. Broadly speaking, increasing the surface pressure increases the simulated bending angles and, conversely, reducing the surface pressure reduces the simulated values. Theoretical information content studies – which essentially estimate the surface pressure errors before and after making a GPSRO measurement – have suggested that the measurements should contain useful surface pressure information, but demonstrating this in a full NWP system has been more problematic. This is partly a result of the measurement numbers.

The combined number of synoptic, METAR and ship measurements assimilated per day is typically around 100,000, and there are also 13,000 drifting buoy surface pressure observations. In contrast, there are only around 2,500 globally distributed GPSRO bending angle profiles assimilated per day. Therefore, we have investigated the ability of GPSRO measurements to constrain the surface pressure field in a degraded NWP system, when all conventional surface pressure observations are removed.

Assimilation experiments

The surface pressure information content of GPSRO measurements has been investigated in a series of assimilation experiments, covering the period 15 October 2009 to 31 January 2010. The experiments using Cycle 36r1 of the Integrated Forecasting System (IFS) are run at T511 resolution and use incremental 4D-Var assimilation. They have been designed to illustrate the information content of GPSRO measurements by selectively removing (or ‘blacklisting’) different combinations of observations from 4D-Var system.

Figure 1 shows the time series of the mean and standard deviation of the 24-hour surface pressure forecast errors in the northern hemisphere extratropics (20°–90°N) and southern hemisphere extratropics (20°–90°S) for three experiments:

- The full observing system assimilated operationally at ECMWF.
- The full observing system minus all conventional surface pressure observations.
- The full observing system minus all conventional surface pressure observations and all GPSRO measurements.

In general, the results in the tropics (20°N–20°S) are very similar, and we will not discuss them further in this article.

The verification scores are against the operational ECMWF analyses. The time series results clearly demonstrate that the GPSRO measurements provide a useful constraint on the surface pressure when compared to experiment where both the GPSRO and conventional surface pressure observations are removed, with both the standard deviation and mean of the errors being reduced. In particular, the mean errors when the GPSRO data are assimilated are reasonably stable in time, at around the –1 hPa to –1.5 hPa level, whereas they can be as large as –4 hPa when these measurements are not assimilated.

The GPSRO measurements have greatest impact on the standard deviation of the errors in the southern hemisphere extratropics with a reduction of around 0.06 hPa. However, it is also clear that at the short range the GPSRO measurements are not able to fully compensate for the loss of all the conventional surface pressures observations, particularly in the northern hemisphere extratropics where the standard deviation of the error with the full observing system is about 0.15 hPa smaller. This is probably not surprising given the number and the spatial distribution of conventional surface pressure measurements that have been removed from the 4D-Var.

The impact on the geopotential height scores is shown in Figure 2. The scores for the northern hemisphere extratropics are degraded throughout the entire forecast range as a result of removing the surface pressure observations, and the GPSRO measurements have little impact. This degradation is statistically significant at the 95% level from day-1 to day-6. However, in the southern hemisphere extratropics – where the number of conventional surface pressure observations is lower – the GPSRO measurements clearly have some impact. The differences between the GPSRO experiment and the full system are small but slightly negative from around day-4, but they are not statistically significant at 95% level.

Although the GPSRO measurements are able to reduce the surface pressure biases, one question is what causes the –1 hPa to –1.5 hPa bias when they are assimilated? The bending angle departure statistics when surface pressure measurements are blacklisted provide some insight. Figure 3 shows the bending angle departure statistics for the COSMIC-4 satellite with the full observing system and when the conventional surface pressure measurements are removed, but the GPSRO observations are assimilated. There is a clear reduction in the mean bending angle departures above 10 km when the surface pressure measurements are removed. In fact, we have been able to show that the surface pressure bias is related to the bending angle departures above 10 km, because it is virtually unchanged in experiments where the GPSRO measurements are blacklisted below 10 km.

The bias in the mean bending angle departures between 10–30 km with the full observing system is now a robust feature with all GPSRO instruments, including GRAS and COSMIC which are processed at different centres. This suggests that it originates from the NWP background rather than observations, and it is thought to be a combination of a warm temperature bias in the troposphere, combined with a cold bias in the stratosphere. When the conventional surface pressure observations are removed from the assimilation system, it appears that the biased bending angle departures are reduced by surface pressure increments. The surface pressure is almost being used as a ‘sink variable’, meaning it can be changed without degrading the fit to other observations. This transfer of biases is a common problem in satellite meteorology, when the assimilated quantities have a sensitivity to more than one atmospheric variable.

 doi:10.21957/ruetfdp5

In addition to the surface pressure information that can be derived directly as a result of the hydrostatic integration in the GPSRO forward model, the 4D-Var system should also be able to derive some information indirectly from the measurements. This will arise as the result of assumed 4D-Var background error correlations between upper temperatures and the surface pressure, and the fact that the forecast model used to provide the 4D-Var trajectory is hydrostatic. This contribution can be isolated by switching off the surface pressure sensitivity in the GPSRO observation operator. We have found that removing the hydrostatic term in the forward operator leads primarily to an increase in the standard deviation of the surface pressure errors, with only a small change in the surface pressure biases.

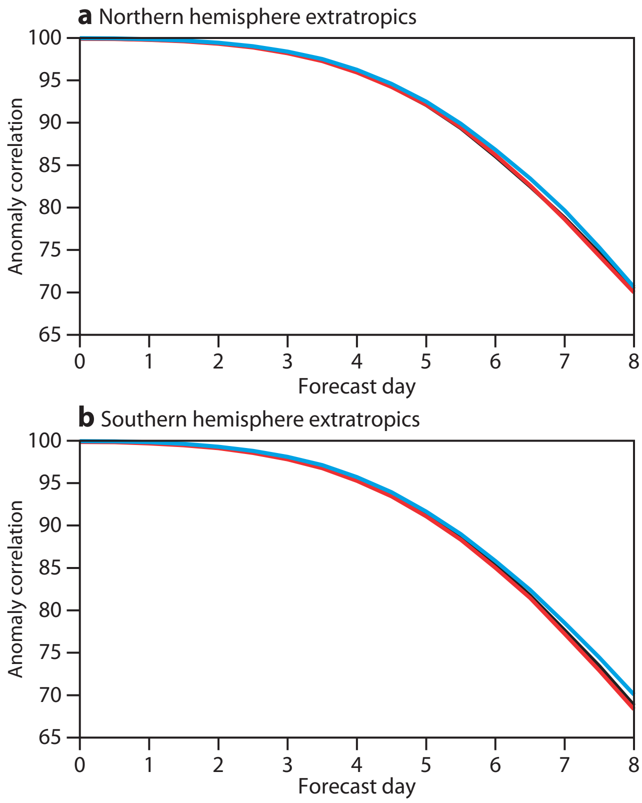

Figure 2 The 500 hPa geopotential height anomaly correlation scores for (a) northern hemisphere and (b) southern hemisphere extratropics when conventional surface pressure observation measurements are removed (black line), both GPSRO and conventional surface pressure observation measurements are removed (red line), and the full observing system (blue line). The statistics cover the period 1 November 2009 to 31 January 2010 and the verification is against operational ECMWF analyses.

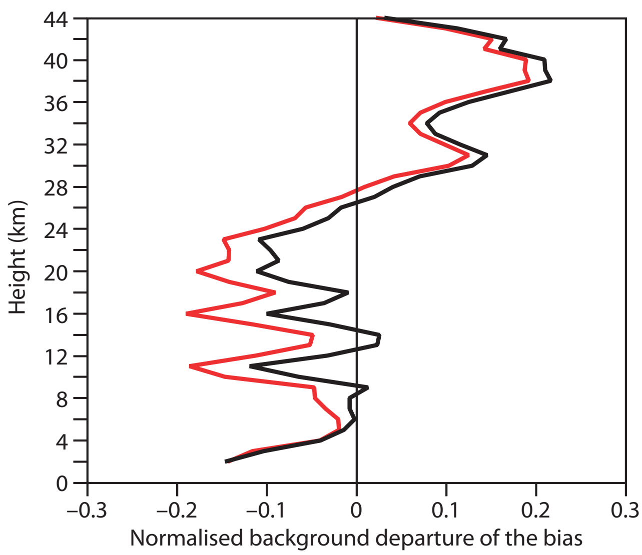

Figure 3 The noise normalised background departure of the bias for the COSMIC-4 satellite, when conventional surface pressure observations are blacklisted (black line) and for the full observing system (red line). The statistics cover the period 1 November 2009 to 31 January 2010.

Sensitivity to small biases

We can demonstrate the sensitivity of the surface pressure biases to relatively small changes in the assimilation of the GPSRO measurements, with an experiment where the GPSRO bending angles are effectively subjected to a bias correction of +0.1%. This has been achieved by reducing all the forward modelled bending angles by 0.1%. A perturbation of this amount in the bending angles corresponds approximately to shifting the height of the bending angle measurements by around 7 m in the vertical, because to first order the bending angles fall exponentially with height with a 7 km scale height. The impact on the surface pressure bias is shown in Figure 4, with the bias being reduced by around 0.7 hPa globally. Note that the smallest observation errors used in the assimilation of GPSRO measurements is 1% between 10–30 km, so the imposed perturbation is small when compared to the assumed observation errors used at ECMWF.

It must be emphasised that we are not advocating any bias correction of GPSRO measurements on the basis of these results, as the aim of this exercise is to highlight the observed sensitivity, but it is interesting to put a 0.1% perturbation in some context. It is not inconceivable that either processing of GPSRO bending angles from the raw phase and amplitude measurements, or the forward models used to assimilate the measurements, can introduce biases at the 0.1% level. In fact, recent operational processing changes at the University Corporation for Atmospheric Research (UCAR), introduced operationally on 12 October 2009, have shifted the stratospheric bending angles by around -0.2%. This has resulted in much better consistency with MetOP-A GRAS, but has increased the bias with respect to ECMWF short-range forecasts.

In relation to forward model accuracy, the empirical refractive index coefficients, which are used to convert pressure, temperature and water vapour information to refractive index values, have come under increasing scrutiny in recent years, and new laboratory measurements of the coefficients are probably required. In connection with this, Josep Aparicio at Environment Canada has also demonstrated that introducing non-ideal gas effects in GPSRO observation operators can introduce a systematic shift in the simulated observations which are of order 0.1%.

Another component of the observation operator that has been tested recently at ECMWF is the accuracy of the geopotential to geometric height transform. Our results suggest that the errors in this transform at 30 km are generally less than 1 m, although they can be as large as 5 m in isolated regions. Hence, there is no evidence of large-scale biases introduced by this transform which might translate into surface pressure biases of around -1.2 hPa.

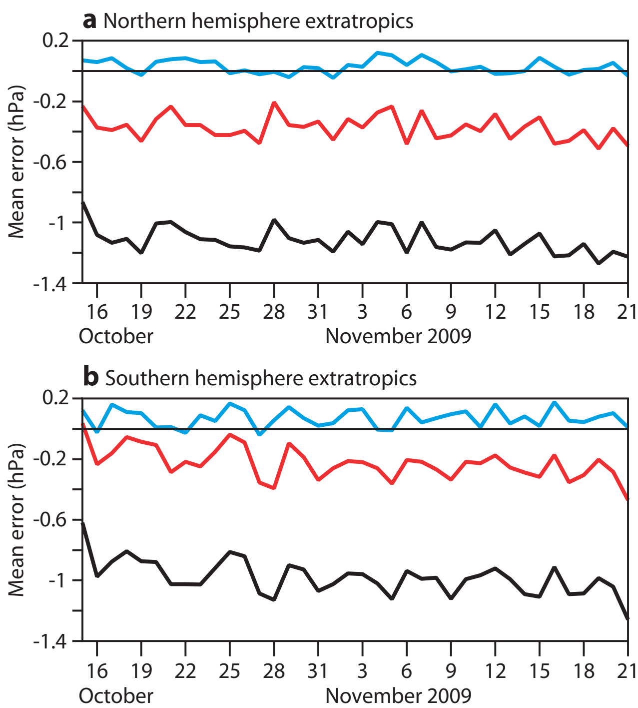

Figure 4 Time series of the mean error of the 24-hour forecast of surface pressure for (a) northern hemisphere and (b) southern hemisphere extratropics.when surface pressure measurements have been removed (black line), and when the forward modelled bending angles have been reduced by 0.1% (red line). The results with the full observing system are shown for reference (blue line).

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Removal of aircraft temperature measurements

The warm mid- and upper-tropospheric bias in ECMWF forecasts and analyses is partly caused by aircraft temperature measurements which are biased warm. These measurements will be bias corrected at ECMWF in the near future. Given the sensitivity of the GPSRO surface pressure biases to small changes in the assimilation system, we have investigated how they change in the GPSRO experiment when the aircraft temperature measurements are removed from the assimilation system.

Figure 5 shows the mean 24-hour surface pressure forecast errors when the aircraft measurements are removed. The impact is largest in the northern hemisphere extratropics, where the aircraft numbers are greatest. In the full system, when all observations are assimilated, GPSRO measurements tend to pull the analysis away from the aircraft temperatures, and produce a closer fit to radiosonde temperature observations. However, when the surface pressure observations are removed, this is no longer the case. It appears that the GPSRO measurements reduce the surface pressure, rather than fight the aircraft measurements and correct the temperature bias.

Figure 6 shows the 500 hPa geopotential anomaly correlation score for the southern hemisphere extratropics when both the aircraft temperature measurements and conventional surface pressure measurements are removed. From around day-4 onwards the results are essentially neutral when compared with the full observing system. The scores in the northern hemisphere extratropics still show a clear, statistically significant degradation.

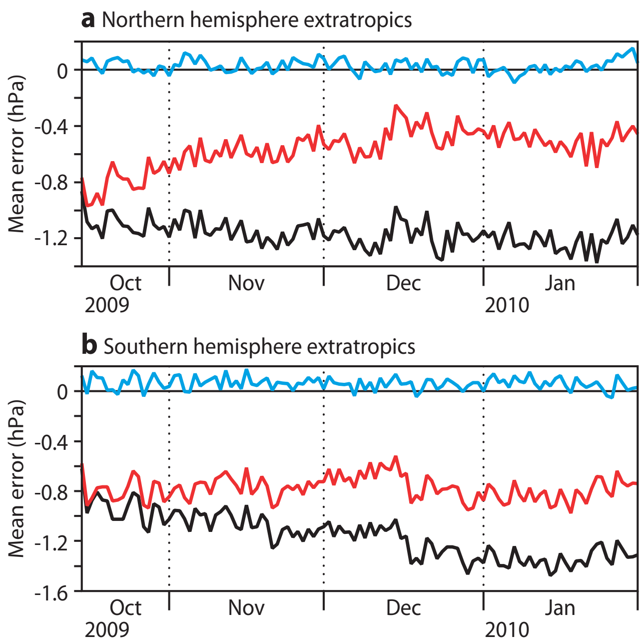

Figure 5 Time series of the mean error of the 24-hour forecast of surface pressure for (a) northern hemisphere and (b) southern hemisphere extratropics when aircraft temperature measurements and conventional surface pressure observations are removed from the assimilation system (red line). These are compared with the standard experiment where conventional surface pressure observations are removed but both GPSRO and aircraft temperature measurements are included (black line), and with the full observing system (blue line).

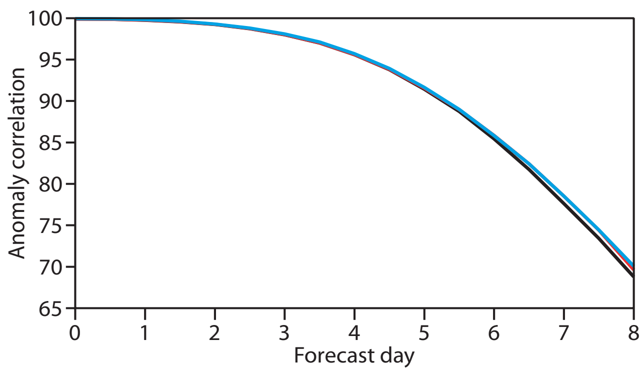

Figure 6 The 500 hPa geopotential height anomaly correlation scores for the southern hemisphere extratropics when aircraft temperature measurements and conventional surface pressure observations are removed (red line), conventional surface measurements are removed but both GPSRO and aircraft temperature measurements are included (black line), and for the full observing system (blue line).

Summary and future work

GPSRO measurements are an important source of upper-troposheric and lower-tratospheric temperature information. In addition, we have now demonstrated that GPSRO measurements contain surface pressure information, and that they are able to stabilise global NWP surface pressure biases at around the –1.2 hPa to –1.5 hPa level when all conventional surface pressure observations are removed from the 4D-Var assimilation system.

GPSRO measurements are not able to fully compensate for the loss of all of the surface pressure observations in the northern hemisphere extratropics, and the geopotential forecasts are clearly degraded over the entire forecast range. The impact of removing surface pressure observations in the southern hemisphere extratropics is also clear in the short-range forecasts, but by around day-5 the impact of the conventional observations is quite small. In fact, when aircraft temperature measurements are also removed, there is no degradation in the height scores from around day-4 the southern hemisphere extratropics. It is also interesting to note that the bending angles above 10 km provide most of the surface pressure information.

Given the respective observation numbers, it is intriguing to speculate how an order of magnitude increase in the number of GPSRO data would change the impact of the measurements, relative to that of the current conventional network. It would be interesting to investigate this further with observing system simulation experiments, or using ensemble data assimilation techniques. However, the present study has demonstrated how sensitive the GPSRO surface pressure analysis biases are to small changes in the bias characteristics of the observations, NWP background or forward model. Furthermore, we have also shown that the GPSRO observation operator can map temperature biases introduced by other measurements into a surface pressure bias.

Overall, the results suggest that the combined bending angle departure biases need to be smaller than 0.1%, which is currently a very stringent requirement. Obviously, given this situation it would be wrong to be overly reliant on the GPSRO measurements to constrain the surface pressure information, and conventional observation will remain an important component of the observing system. Nevertheless, the GPSRO measurements are likely to become increasingly important in this area as the data numbers rise.

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