ASSIMILATION INTO THE MET OFFICE 1.5KM GRID UKV NWP MODEL OF WATER VAPOUR RADIANCES FROM AREAS WITH LOW CLOUD

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Abstract

SEVIRI channel 5 water-vapour-sensing infrared radiances are now being assimilated operationally over low cloud in the Met Office UKV 1.5km-scale regional NWP model. Areas which are free of mid-level or high cloud are identified using a range of tests which utilise the SEVIRI radiance data and model background data. Radiance observations are selected which are deemed to not be significantly affected by the underlying low cloud. High spatial-resolution MHS clear and cloudy microwave radiances are also being assimilated into the UKV model. This manuscript studies the impact on Met Office verification scores of the satellite radiance observations currently used operationally in the UKV, and shows how these observations have helped alleviate problems with overly-dry regions above low clouds. Also presented is a possible upgrade to the method for assimilating SEVIRI channel 5 radiances in the UKV along with preliminary verification results. This upgrade would remove some inter-dependencies of the SEVIRI channel 5 assimilation on other systems.

INTRODUCTION

In 2009 the Met Office began routine cycling of the UKV convection-permitting NWP model. This regional model has 1.5km grid resolution over the United Kingdom, using spherical coordinates with a rotated pole to make the grid boxes as square as possible over the UK. This region is surrounded by a region with poorer grid resolution, with longitude spacing increasing smoothly to 4km to the East and West, and latitude spacing increasing smoothly to 4km to the North and South (see Figure 1).

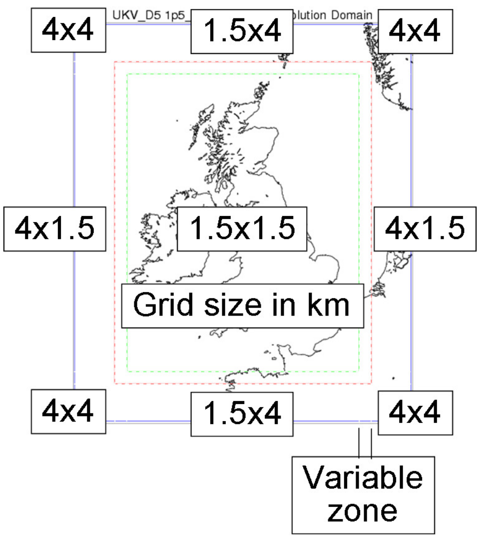

Figure 1: **The domain of the UKV model.**

The UKV model is nested within the 25km-grid Met Office global model, and has 3-hourly 3D-Var assimilation of a wide range of observation types (see Table 1 for observations used in September 2013), and also nudging of the model latent heat based upon differences between forecast precipitation and radar observations. For each 3D-Var analysis, the oldest observations accepted are from 90 minutes before analysis time (dependent on observation type, with only the observations closest to analysis time accepted for some observation types). There is an observations cut-off 75 mins after analysis time (so no observations arriving at the Met Office more than 75 mins after analysis time are assimilated). 36-hour forecasts are produced from each of the 3-hourly data assimilation cycles. The sea surface temperature used in the UKV remains fixed over the 36-hour forecast run, and comes from the Met Office 6km-resolution OSTIA analysis.

Observation type	**Mean number of observations used per day in VAR**
Aircraft temperature observations	19,000
MHS channels 3, 4 and 5	58,000
Atmospheric motion vectors from Meteosat	3,800
High-resolution ASCAT winds	1,200
GeoCloud cloud fraction	650,000
Ground GPS integrated water vapour	5,100
Radiosondes	73
Radar Doppler wind	26,000
SEVIRI radiances which are not significantly cloud-affected	39,000
Surface Synop reports (including visibility and cloud base observations), and also including temperature and relative humidity at 2m from UK Highways Agency roadside sensors	48,000
Wind profiler observations	1,500
Radar rain rate	Assimilated using latent heat nudging instead of VAR

***Table 1:* Observations assimilated in the UKV in September 2013.**

Regular monitoring of observed METEOSAT SEVIRI radiances against simulated radiances from Met Office NWP models revealed occasional dramatic departures of the simulated water-vapour channel radiances from the observations. The same problems were seen in the Met Office UK4 model (with near-identical data assimilation as the UKV, but a 4km model grid allowing cheaper trialling of changes). Results from a UK4 run with standard operational settings are shown in Figure 2. The simulated imagery of Figure 2a has a large dark region across the centre of the UK4 domain which is not seen in the observations. This was found to be due to a large volume of air with zero humidity in the model's mid- and upper-troposphere (where negative humidities output from the previous 3D-Var analysis had been reset to zero). Gross mid- and upper-tropospheric humidity errors such as these were found to occur relatively frequently above low cloud during stable atmospheric conditions (Figure 3 shows the synoptic conditions at roughly the same time as Figure 2).

The cause of these model departures was traced to the assimilation of cloud information (Renshaw and Francis, 2011) from a Met Office cloud analysis (the UKPP 3D cloud analysis, distinct from the Met Office NWP systems) combined with the assimilation of GPS (GNSS) Integrated Water Vapour (IWV) observations, within the 3D-Var data assimilation system. The cloud information was assimilated via humidity increments, with relatively large uncertainties in the total water content in the cloud (in some instances the humidity increments had a detrimental effect on the vertical representation and/or the water content of the cloud in the NWP model, although the horizontal distribution of cloud was often improved). GPS IWV observations then provided corrections to the total water content in the atmospheric column. At this time, satellite data was not being assimilated into the operational system in cloudy locations, leaving the mid- and upper-tropospheric humidity relatively unconstrained above low cloud (or below cirrus). A significant fraction of the GPS IWV correction was being applied in the mid- and upper-troposphere (where the humidity was relatively unconstrained due to the lack of satellite data, and the humidity changes in the VAR analysis were not competing with UKPP cloud information being assimilated lower down). In clear-sky regions SEVIRI radiances continued to constrain the upper-tropospheric humidity, as is highlighted by the influence of the SEVIRI observation at the circled location in Figure 2c. This seems to reduce the incidence of gross errors in humidity in the mid- and upper-troposphere, and forces more of the GPS IWV corrections to be applied in the lower troposphere, where on occasions when radiosonde observations were available, they were found to bring the model fields into closer agreement with observations.

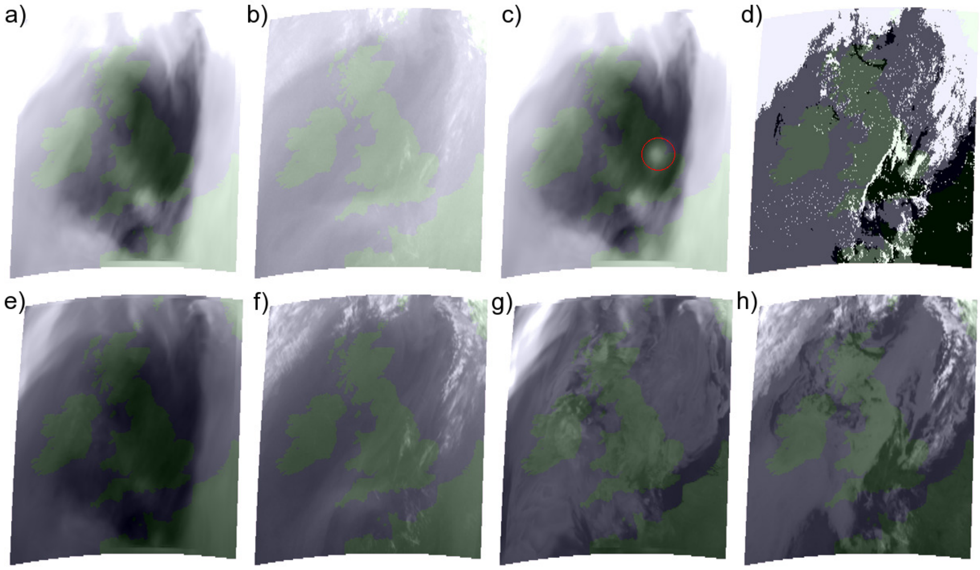

Figure 2: **SEVIRI simulated and observed imagery at 09Z on 14/10/2011 with grey level proportional to brightness temperature (white = cold) and blue/green hue determined by surface type (for geographic orientation but not representative of cloud transparency). Panel a) shows a simulated SEVIRI channel 5 image from the NWP background; panel b) shows the observations in channel 5 on the same colour scale as panel a; panel c) shows a simulated SEVIRI channel 5 image from the NWP analysis, with an obvious contribution from assimilating a clear SEVIRI observation in the east of England (circled in red); panel d) shows the cloud mask calculated from the observations, including breaks in the cloud over the east of England – high cloud in white, low cloud in grey; panel e) shows a simulated SEVIRI channel 6 image from the NWP background; panel f) shows observations in channel 6 on the same colour scale as panel e; panel g) shows a simulated SEVIRI channel 9 image from the NWP background; and panel h) shows the observations in channel 9 on the same colour scale as panel g.**

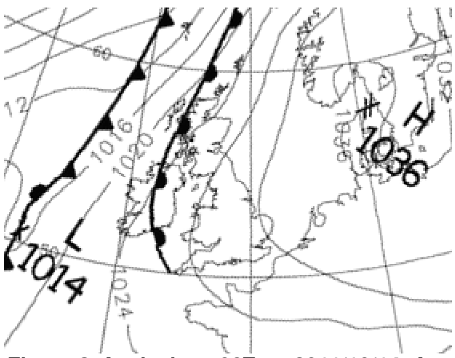

Figure 3: **Analysis at 06Z on 2011/10/14. A stable airmass was situated over northern Europe and the warm front over Ireland was weakening.**

PREVIOUS USE OF SATELLITE WATER VAPOUR CHANNELS IN CLOUDY REGIONS

In order to address the humidity errors described above, MHS channels 3, 4 and 5 were introduced in all sky conditions and SEVIRI water vapour channel 5 observations were introduced above low cloud. The changes were tested in the UKV in Met Office Parallel Suite 31 (PS31) for three months (running in parallel to the operational UKV) and were accepted into Met Office operations in January 2013. The changes were implemented in a way which only made use of existing cloud information and basic observational quality control, in order to allow rapid implementation and therefore address the humidity problems in the UKV as quickly as possible. The source of cloud information used was the Autosat system at the Met Office (see Francis et al 2006).

As part of the initial assessment of these changes, one month of trialling was performed in the UK4 model. These trials showed an overall improvement in the model skill when MHS data and additional SEVIRI channel 5 data were added as measured by a standard metric at the Met Office – the UK Index (which includes verification of many of the model fields which are most important to Met Office customers in the UK), as shown in Table 2.

Trial description	**Improvement in UK Index – British Isles (WMO 03):**
1. Adding SEVIRI channel 5 over low cloud	0.21%
2. Adding MHS data	0.38%
3. Adding SEVIRI channel 5 over low cloud and MHS data	0.74%

Table 2: **Trial results**

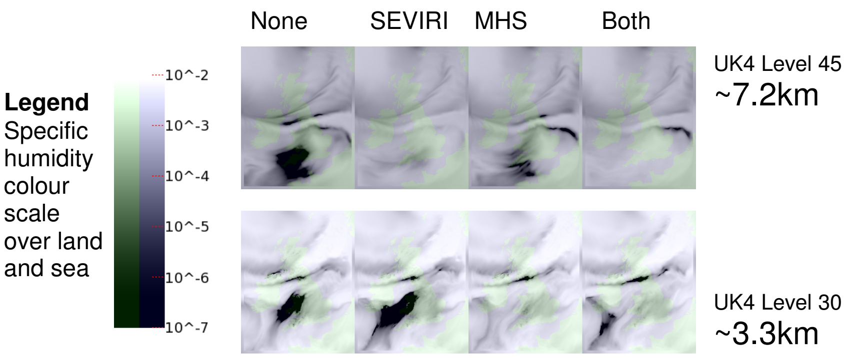

Figure 4: **Specific humidity in the control run (operational settings, with SEVIRI channels 5, 6, 7, 9 and 10 used in clear sky only and no MHS data) and in trials for 03Z on 13/02/2013. The trial labelled "SEVIRI" has additional SEVIRI water vapour channel 5 data over low cloud. The trial labelled "MHS" has additional observations from MHS channels 3, 4 and 5 at full MHS resolution. The trial labelled "Both" includes the additional SEVIRI channel 5 data and the additional MHS data.**

One of the limitations of the cloud information available at the time of implementation was that the Cloud-Top Pressure (CTP) estimate from the Autosat system associated with each SEVIRI observation was for a slightly different geographical location than the SEVIRI observation (typically offset by between 0km and 20km). This resulted from a parallax correction being applied to the CTP estimate for other purposes, which could not be easily removed. In order to minimise the risks from these geographic errors in CTP data, some simple additional quality control was included:

- Gross O-B check for window channel 9 being more than 15K colder than the background
- Ice-cloud detection test comparing the O-B value for channel 9 with the O-B value for channel 10, checking for differences greater than 0.75K

These tests were found to be successful in removing most of the problematic observations near the edges of clouds, where the CTP estimates were not reliable.

Another limitation of the cloud information available was that the CTP estimates are often based on the inversion in recent operational NWP forecasts. Use of such data in trials or parallel suites is not ideal as it makes the trial results dependent on the current operational system performance, so that it is not a clean trial of how it would perform if it were the operational system.

In view of these limitations, it was always intended that a more robust alternative approach was found for the calculation of CTP for the assimilation of SEVIRI channel 5 over low cloud.

IMPROVED DETERMINATION OF CLOUD TOP PRESSURE (CTP)

New code was developed within the observation pre-processing part of 3D-Var to estimate the CTP in order to remove the dependence on the Autosat system. A three-stage process was used for this, and the stages are listed in the following subsections.

1D-Var

A 1D-Var minimisation was performed for each observation using the same model background fields as are used for the data assimilation. This calculates an estimate of CTP using the method described in Pavelin et al 2008 (using RTTOV v9 and assuming a single layer of grey cloud). An uncertainty in the CTP is also calculated using the RTTOV Hessian (for the observational part of the 1D-Var cost function) – this is used to identify unreliable CTP values.

Stable layers

If the 1D-Var minimisation is unreliable (with a 1-σ error of 200hPa or greater, or a retrieved cloud top sufficiently low that cloud determination is found to be unreliable – corresponding to a pressure of 650hPa or greater) then an algorithm loops through the levels within the model background vertical profile finding the most likely cloud top based upon the calculated lapse rate and the relative humidity in each layer. If the observed channel 9 brightness temperature cannot be generated using (partial) grey cloud at the chosen cloud top, then the following, final CTP algorithm is used.

Stable layers with fit to brightness temperature

This final algorithm loops through the levels within the vertical profile finding the most likely cloud top based upon the calculated lapse rate, the relative humidity in each layer and the agreement between the RTTOV simulated brightness temperature for a grey cloud in this layer and the observed brightness temperature.

Use of SEVIRI channel 5

If one of the above algorithms produces a satisfactory result for the CTP, then this is used to determine whether the cloud is low enough that SEVIRI water vapour channel 5 can be assimilated above it. The criteria for determining if a cloud is sufficiently low is that the CTP is higher than 650hPa. This requires that the 1D-Var minimisation fails to retrieve a cloud top higher up than 650hPa, and one of the stable layers algorithms successfully selects a cloud top below 650hPa (i.e. pressure > 650hPa) which is consistent with the observed channel 9 brightness temperature.

This new approach to the assimilation of SEVIRI channel 5 over low cloud avoids the main limitations of the operational system and is hence more robust. The calculation of CTPs is done at the correct geographical locations for the observations, and it eliminates the dependence of the CTP pseudo-observations on the Autosat system and operational NWP system (only the cloud mask is taken from the Autosat system, which in turn uses model background fields from the operational NWP system for the generation of simulated radiances). As such it is preferable for operational use.

Results

Use of the new method for CTP determination for assimilation of SEVIRI channel 5 over low cloud was trialled in comparison with the current operational system. Two weeks of trials have been completed so far. The time period is not suitable for UK Index calculation (with insufficient occurrences of rainfall accumulations above 1mm in 6 hours to obtain meaningful statistical results, and there were insufficient occurrences of visibility below 1000m to obtain meaningful results in the visibility category of the UK Index). I have therefore restricted the results presented here to the following categories:
Total Cloud Amount: -0.016 (trial worse than control)
Cloud Base Height (3/8 Cover): 0.008 (trial better than control)
Surf Temp: -0.017 (trial worse than control)
Surf Wind: 0.015 (trial better than control)
Surf Vis < 4000m: 0.019 (trial better than control)
6 hr Precip Accum > 0.5mm: 0.018 (trial better than control)

None of the above values are statistically significantly non-zero (they are all consistent with no change in performance). This short trial at least shows that the modified SEVIRI channel 5 does not cause substantial problems with the above verification categories.

Figure 5 shows verification of Relative Humidity (RH) at 500 hPa for the trial and control. The trial performs significantly better for forecast lead times of 0 and 6 hours in terms of bias and RMS error at 500 hPa, and also has significantly better RMS errors at a 12-hour lead time. The RMS errors in RH are all either improved or neutral at low altitudes and short forecast ranges with the exception of the RMS error at the surface at t+0 which is increased by roughly 1 standard deviation (not shown).

Figure 6 shows verification of Temperature (T) at 500 hPa for the trial and control. The trial performs significantly better for forecast lead times of 0 to 18 hours in terms of bias and RMS error at 500 hPa. The RMS errors in T are all either improved or neutral at low altitudes and short forecast ranges with the exception (again) of the RMS error at the surface at t+0 which is increased by roughly 1 standard deviation (verification from lower altitudes not shown in the Figure).

These plots show significant improvements to the mid- and upper-tropospheric humidity and temperature from the modified SEVIRI channel 5 assimilation. This supports a switch-over to the new approach to CTP determination, reducing the dependence of the cloud data assimilation on the Autosat system.

In future the CTP and cloud fraction values derived in this way may also be assimilated directly into UKV 3D-Var in place of the Autosat values currently used (see e.g. Renshaw and Francis 2011), although that will represent a substantial piece of additional work.

CONCLUSIONS

The introduction in January 2013 of additional SEVIRI water vapour channel 5 observations and MHS channels 3, 4 and 5 in cloudy regions helped better constrain the mid- and upper-tropospheric humidity in the UKV model. This was found to be particularly useful in locations where humidity corrections from GPS IWV observations had spread higher up into the troposphere. Only SEVIRI channel 5 observations in locations where the cloud top is assessed to be at a pressure greater than 650hPa are used to avoid cloud-contamination of observations, with the observation selection based upon CTP data from the Met Office Autosat system.

Short trials are presented here which used an alternative derivation of CTP for the SEVIRI channel 5 quality control. The alternative derivation of CTP has a number of benefits over the current operational system, including making the CTP not inter-dependent on the pre-processing of cloud data on the Met Office Autosat system. These trials showed improvement to the upper tropospheric humidity and temperature, but no significant change to the surface and cloud verification parameters.

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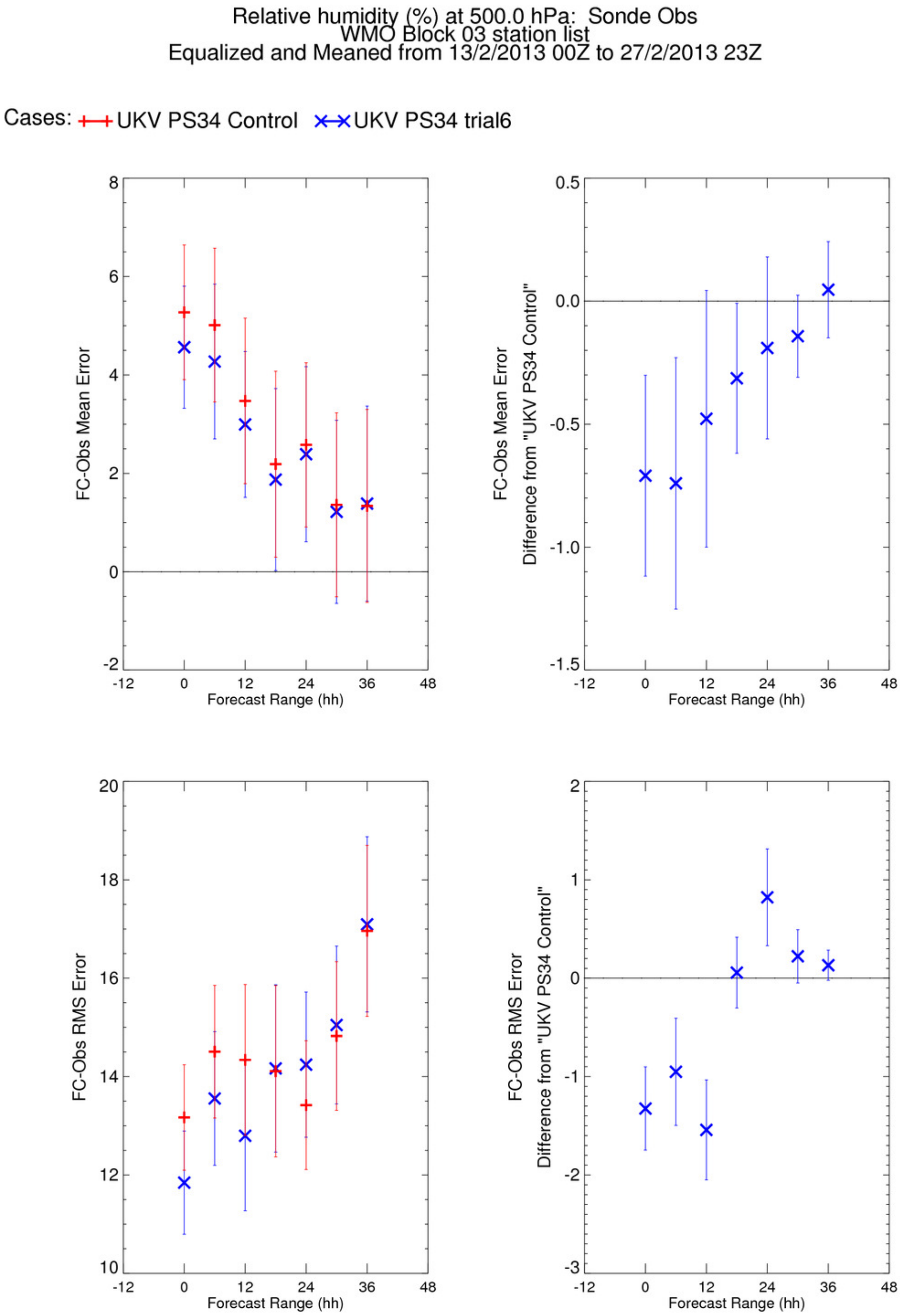

Figure 5: **Relative humidity verification at 500hPa. The red points labelled "control" show the verification using operational settings (selecting low cloud based upon cloud-top pressures determined with the "Autosat" system). The blue points labelled "trial6" show the verification using the new cloud-top-pressure-determination code. The trial performs significantly better for forecast lead times of 0 and 6 hours in terms of bias and RMS error at 500 hPa, and also has significantly better RMS errors at a 12-hour lead time.**

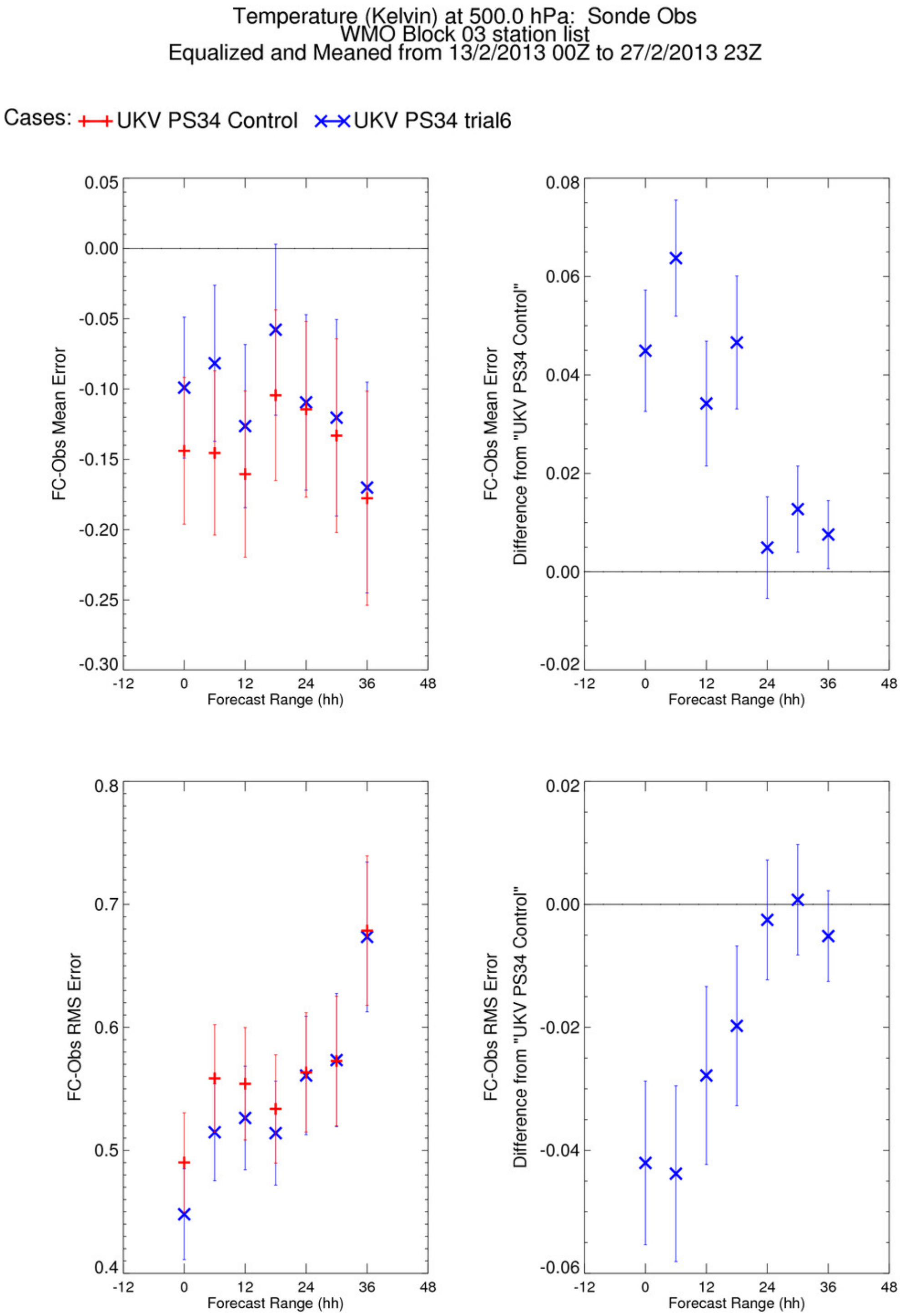

Figure 6: **Temperature verification at 500hPa. The red points labelled "control" show the verification using operational settings (selecting low cloud based upon cloud-top pressures determined with the "Autosat" system). The blue points labelled "trial6" show the verification using the new cloud-top-pressure-determination code. The trial performs significantly better for forecast lead times of 0 to 18 hours in terms of bias and RMS error at 500 hPa.**