TECHNICAL MEMORANDUM

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Operational implementation of RTTOV-11 in the IFS

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March 2015

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

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Abstract

An interpolation algorithm is incorporated into RTTOV to map the input profiles to the RTTOV model coordinate and the Jacobians from the RTTOV model coordinate to the forecast model coordinate. The default in the ECMWF's IFS is the Rochon interpolator that was implemented in RTTOV-9 and remained unchanged in the RTTOV-10 upgrade. Experimental results indicate that the default interpolator commonly used operationally may show unphysical oscillations in Jacobians that may cause unphysical analysis increments.

The latest development of the radiative transfer code RTTOV-11 has been enhanced to provide improved profile interpolation from user levels to RTTOV levels and back again. This memorandum summarises the evaluation of RTTOV-11 for use in the operational assimilation system at ECMWF. Two of the new interpolation options (modes 3 and 5) are evaluated through comparisons of radiative transfer simulations with RTTOV-11 using default Rochon interpolator, and through an analysis of departure characteristics against observations. The impact on forecasts is also investigated through a series of assimilation experiments. Results show that enabling interpolation mode 5 ensures smooth Jacobians profiles required by the data assimilation calculations when the input profile levels are more densely-spaced than the coefficient levels. The performance in the IFS as measured by forecast skill, fit to observations and model run time supports the operational use of the RTTOV-11 and interpolation mode 5 with the ECMWF IFS cycle 41r1 in May 2015.

1 Introduction

This memorandum documents the evaluation of the latest version of the Radiative Transfer model for Television Infrared Observation Satellite Operational Vertical sounder (RTTOV) in the ECMWF system. RTTOV is used for radiance assimilation in a numerical weather prediction (NWP) model, simulating a range of space-borne infrared (IR) and microwave (MW) nadir scanning radiometers and is developed in the framework of the EUMETSAT-funded NWP Satellite Application Facility with joint contributions from UK Met Office, Météo France and ECMWF (Eyre, 1991; Saunders *et al.*, 2013; Matricardi *et al.*, 2004).

RTTOV version 11.1 was released in May 2013 and details on the main enhancements or their implementation can be found in Hocking *et al.* (2013) and Saunders *et al.* (2013). One of the main enhancements of RTTOV-11 is the improved profile interpolation from user levels to RTTOV coefficient levels and back again (Hocking, 2014). This will be described below, together with the results of the RTTOV-11 evaluation in the ECMWF's Integrated Forecast System (IFS). The new interpolation options have a primary aim to eliminate artefacts from the Jacobians encountered when using the default Rochon interpolator (Rochon *et al.*, 2007).

Another enhancement in RTTOV-11 is improved definition of RTTOV coefficient files for MW and IR radiometers. The new coefficient files are based on different atmospheric layering (54 rather than 44 or 51 levels) and the latest underlying spectroscopic parameters. As the RTTOV version 11 is compatible with RTTOV version 10 coefficient files, this last aspect is not covered in the present memorandum. An update of the coefficient files can be performed independently of the RTTOV code upgrade and studies are ongoing to investigate the performance of using the new MW and IR regression coefficient files in the data assimilation context (e.g. Lupu *et al.*, 2015).

This memorandum describes the upgrade of RTTOV used in ECMWF's IFS from version 10.2 to version 11.1 in section 2 and the evaluation of new options for vertical interpolation and Jacobian smoothing in section 3. The effect of the new interpolation methods has been evaluated in the ECMWF system through comparisons of temperature Jacobians for individual AMSU-A/MetOp-A channels in single cycle experiments and through an analysis of observations fits and impact on forecasts in 4D-Var assimilation experiments with the operational observing system. Conclusions are drawn in section 4.

2 Evaluation of the impact of RTTOV v11.1 in the IFS

2.1 Set-up of the assimilation experiments

RTTOV version 11.1 impact on analyses and forecasts has been assessed in the ECMWF assimilation system. To do so, two assimilation experiments covering a 4 month period (1 July 2013 to 8 November 2013) were set-up based on the model cycle 40r1 of the IFS and run with ECMWF's 4D-Var 12 hour assimilation system with a spatial model resolution of T511 (40 km) and 137 vertical levels with the model top at 0.01 hPa. Ten-day forecasts were run each day of the experiment from the 0 UTC and 12 UTC analysis. Both control and experiment use the same coefficient files from the IFS and the default Rochon interpolator and can be summarised as follows:

- RTTOV-10: Control ECMWF data assimilation and forecasting model with all operational observations (satellite and conventional) and using RTTOV version 10.2 (Bormann *et al.*, 2011).
- RTTOV-11: Same system configuration, except that RTTOV version 10.2 has been replaced with RTTOV version 11.1.

As there are no changes with scientific impact specific to the IFS-version of the use of RTTOV-11 and the same coefficient files were used in both experiments, we don't expect any scientific differences between the two experiments.

2.2 Analysis and forecast impact

To validate the RTTOV-11 implementation in the IFS, brightness temperatures simulated from the same first guess profiles with both RTTOV-11 and RTTOV-10 are compared for several different instruments on the first cycle on 1st July 2013 at 0 UTC. For both experiments data counts, J_o cost function and spectral norms are compared in 4D-Var trajectories. RTTOV-11 and RTTOV-10 experiments are bit-identical for the first 4D-Var trajectory, illustrating that the RTTOV-11 direct model output gives no difference in the simulated brightness temperature compared to the RTTOV-10 when the same profile is provided, for all infrared and microwave sensors assimilated. However, in the first 4D-Var minimisation and thereafter, the number of observations, the distance to observation function and the spectral norms show very small differences in the outputs. This is because the RTTOV-11 developments are not bit reproducible in the tangent linear and adjoint (TL/AD). Statistics of differences between first guess departures with RTTOV-11 and RTTOV-10 over the Northern Hemisphere extratropics for AMSU-A on NOAA-18, HIRS on MetOp-A and SSMIS on DMSP-17 for a 12 h assimilation period of the first cycle on 1 July 2013, 0 UTC are shown in Figure 1. The non-zero differences between the first guess departures from the two experiments are due to slightly different samples being used as results of small differences in the variational quality control checks (VarQC) that are performed in the minimisation.

Further testing over an extensive period was performed to ensure there are no scientific differences between versions 11.1 and 10.2 of the RTTOV. First guess and analysis departures statistics collected from 1 July 2013 to 8 November 2013 are compared for various microwave and infrared instruments. For illustration we focus on AMSU-A, SSMIS and IASI as shown in Figures 2-4. Here, the AMSU-A radiances

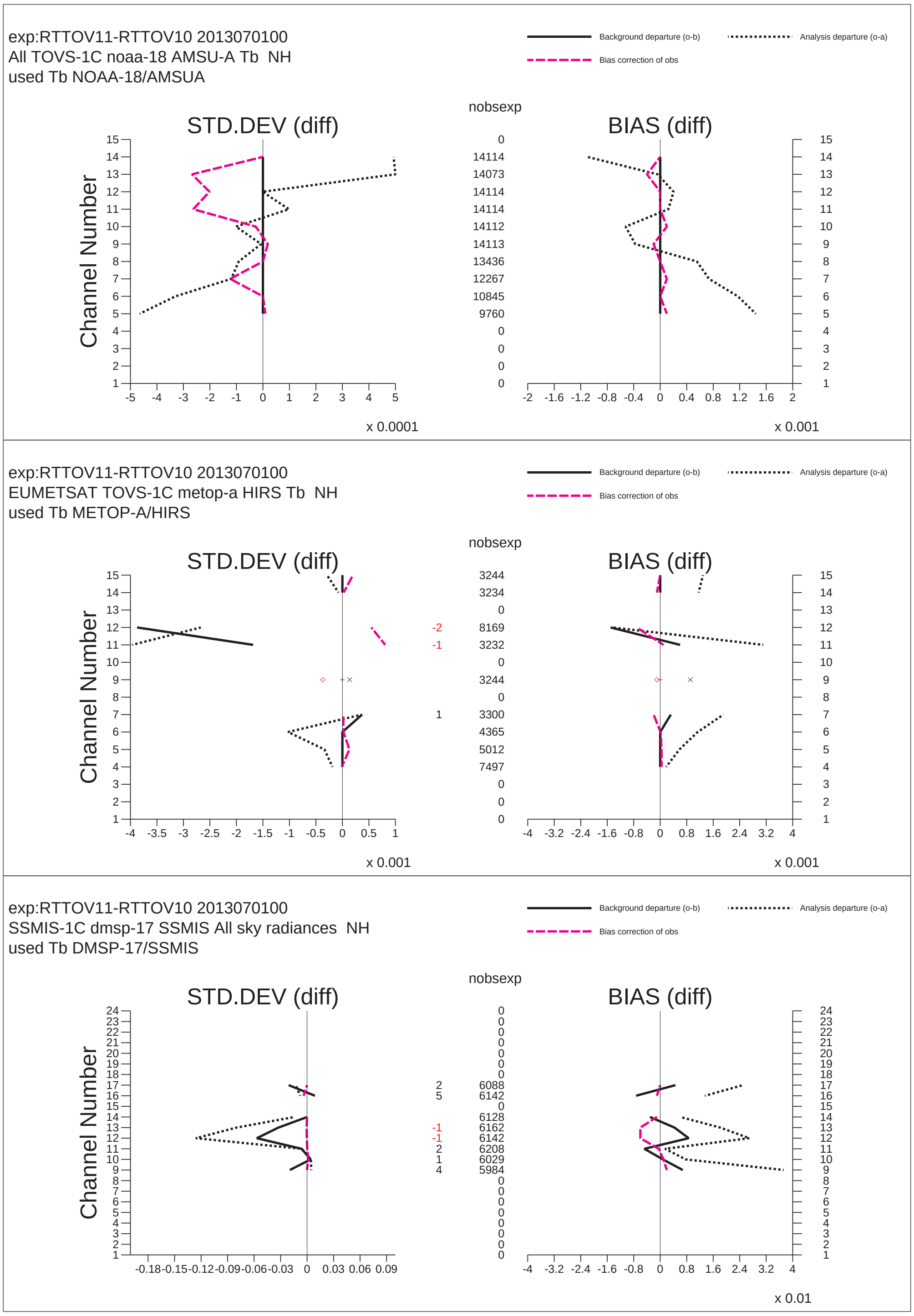


Figure 1: Departure statistics of differences between the RTTOV-11 experiment and the RTTOV-10 experiment for AMSU-A (top), HIRS (middle) and SSMIS (bottom) over the Northern Hemisphere extratropics for a 12 h period covering 1 July 2013, 0 UTC. The solid black line shows the difference between first guess departures from the two experiments, the dotted black line the difference between the analysis departure statistics. The difference in bias correction values from the two experiments is shown as a magenta line. The number of observations for the RTTOV-11 experiment are given in the middle, including the difference between the RTTOV-11 and the RTTOV-10 experiment. The statistics are based in used observations. Below each plot is a scaling factor to apply to the axis values.

from seven polar satellites were assimilated over land and sea surfaces in a framework that assume clear sky conditions in radiative transfer calculations, SSMIS radiances were used in all sky conditions only over sea, while IASI on MetOp-A radiances were assimilated in clear sky or completely overcast conditions over the ocean. The change to RTTOV-11 does not show any significant differences in standard deviations. The biases are almost unaltered as expected (not shown). For other assimilated observations, there is no significant impact on the departure statistics, suggesting no significant change to the quality of short range forecast or to the analysis.

The forecast impact results from the RTTOV-11 experiment are overall neutral, as shown in Fig. 5 for 500 hPa geopotential height. This is in good agreement with the neutral changes in terms of the first-guess departure statistics after bias correction noted for the microwave and infrared radiances. The run time for the RTTOV-11 experiment appear to be similar or reduced compared with the RTTOV-10 experiment.

In summary, the performance of RTTOV-11 in IFS as measured by forecast skill, fit to observations and model run time are the same or better (in the case of run time), supporting the upgrade of the RTTOV in the IFS from version 10.2 to version 11.1 in the model cycle 40r2.

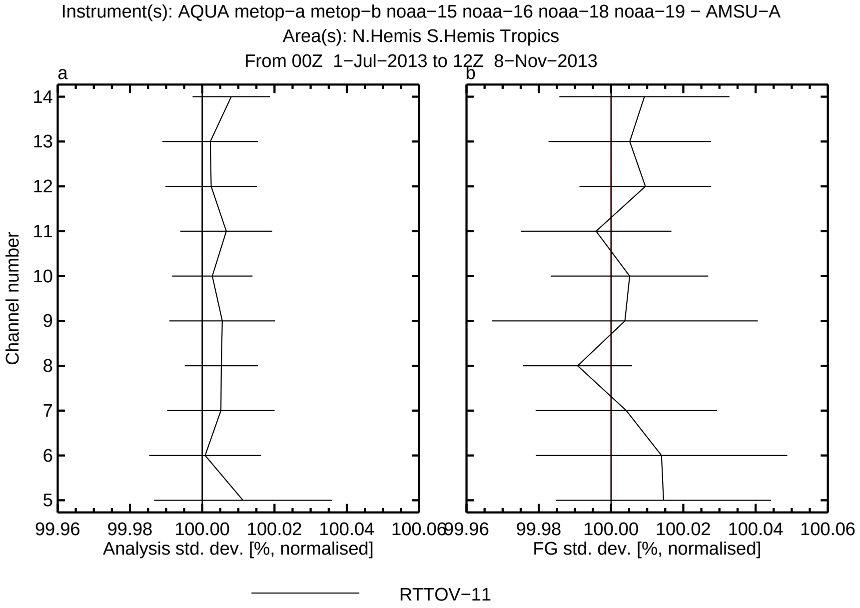


Figure 2: Normalised standard deviation of analysis departures (left) and FG forecast departures (right) for AMSU-A on 7 platforms fits. Standard deviations are normalised by those of the RTTOV-10 control experiment. Error bars indicate the 95% confidence interval.

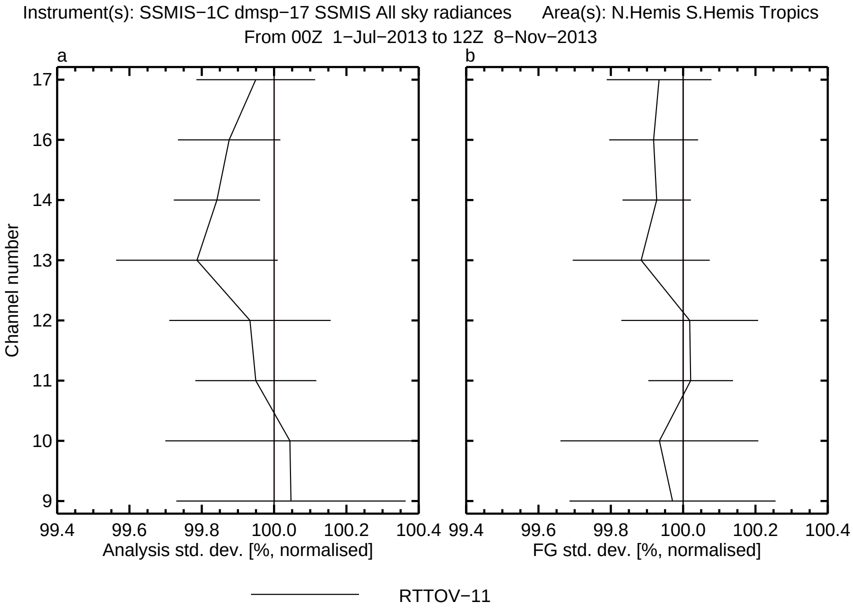


Figure 3: As Fig. 2, but for global SSMIS observations.

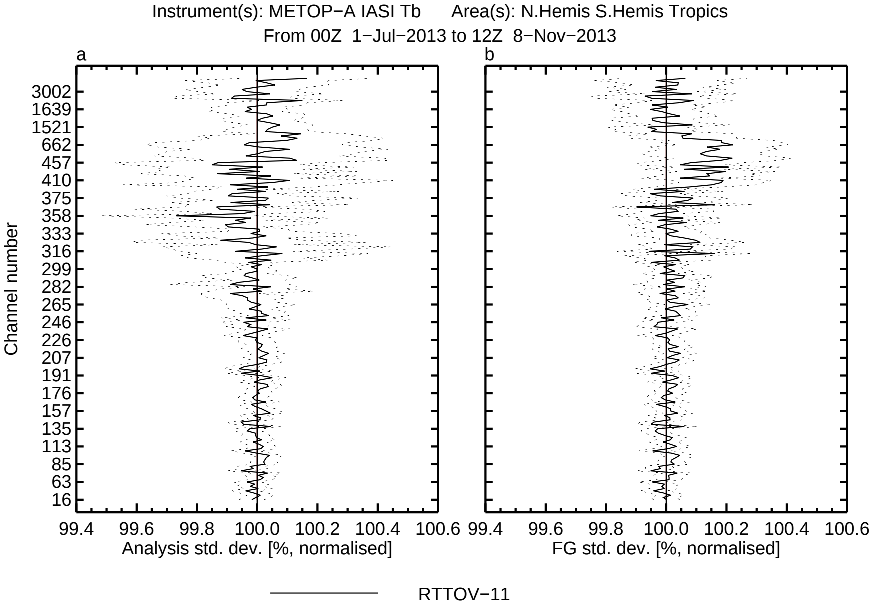


Figure 4: As Fig. 2, but for global IASI on MetOp-A observations.

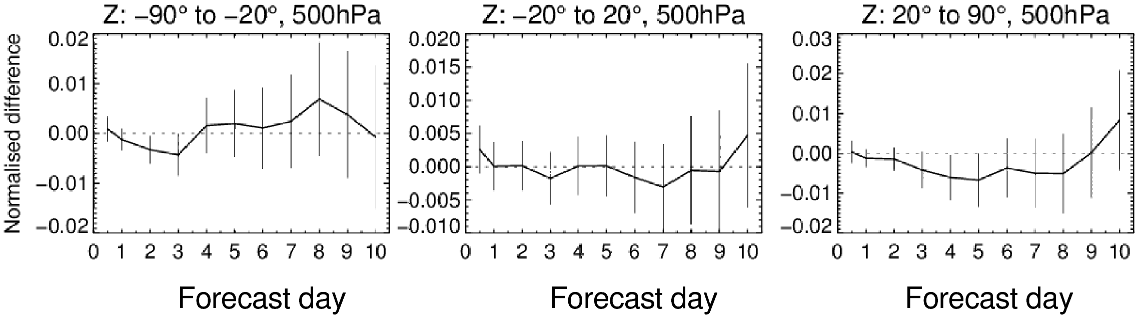


Figure 5: Normalized differences in the root mean square forecast error for the 500 hPa geopotential between the RTTOV-11 and RTTOV-10 experiments for the Northern Hemisphere (left panel), Tropics (middle panel) and Southern Hemisphere (right panel) as a function of forecast range in days (261 cases). Both experiments have been verified against the 'own-analysis' of the experiment. Negative values indicate a reduction in the forecast error for the RTTOV-11 experiment. Error bars indicate confidence intervals at the 95% confidence level.

3 Evaluation of alternative interpolation methods in the RTTOV-11

3.1 Additional options for the internal interpolation

A vertical interpolation scheme is required when the vertical levels of a NWP forecast model differ from those of a fast radiative transfer model. RTTOV-9 introduced an internal interpolator called Rochon interpolator (Saunders *et al.*, 2010), that closely follow what was described by Rochon *et al.* (2007). The Rochon interpolator ensures that all user input levels are appropriately involved in the interpolation and are used in the RTTOV computations. This requirement is needed to provide sensitivity to all model levels and to avoid blind levels in Jacobians.

At ECMWF, the Rochon interpolator was introduced with the RTTOV-9 upgrade in the IFS model cycle 35r2 (Bormann *et al.*, 2009) and remained unchanged through the following RTTOV-10 upgrade (Bormann *et al.*, 2011). With the model cycle 38r2 of the IFS, the number of vertical model levels increased from 91 to 137, which increased the vertical resolution of the model throughout the troposphere and stratosphere. In contrast, the RTTOV regression coefficient files remain specified on 44 fixed-pressure levels for most of the instruments, with few exceptions on 51 fixed-pressure levels for more recent sensors, such as GOES-15, Meteosat-10, CRIS, ATMS and AMSR2.

The way the interpolation option is implemented within RTTOV is detailed in Hocking (2014) and involves two steps: firstly, the input profile is interpolated to the same levels as the coefficient files using the Rochon interpolator. The optical depth calculations are then performed on coefficient levels and interpolated back (using the same Rochon interpolation method) onto the input levels. These interpolated optical depths are used in the integration of the radiative transfer equation to calculate the radiances at the top of the atmosphere, which is done on the input levels, in our case 137 levels.

When the input levels are more densely spaced than the coefficient levels it has been observed that the Rochon interpolation scheme can result in oscillations in the interpolated layer optical depths and subsequently in significant oscillations in the computed temperature Jacobians (Lupu and Geer, 2014). Spiky Jacobians are undesirable, because if not smoothed by the background vertical correlations, they could cause noisy and unphysical temperature increments.

An optional update to the version 11.1, which has later been integrated in the version 11.2 of the RTTOV, implemented alternative options for the internal interpolation. The main aim is to eliminate the oscillations in temperature Jacobians that results when the Rochon interpolator is used to interpolate the optical depths from coefficient to user levels in NWP models. Table 1 show all interpolation modes available in RTTOV v11.2 update. Instead of the Rochon interpolation on optical depths, modes 2 and 3 provide log-linear interpolation on optical depths, while modes 4 and 5 use Rochon and log-linear interpolation, but on weighting function (specifically d(optical_depth)/dp, where p refers to pressure).

Table 1: Interpolation modes available in the RTTOV v11.2.

Interpolation mode	Profile interpolation	Optical depth interpolation
1	Rochon	Rochon on optical depths
2	Log-linear	Log-linear on optical depths
3	Rochon	Log-linear on optical depths
4	Rochon	Rochon on weighting function
5	Rochon	Log-linear on weighting function

The ideas behind the new interpolation modes and a detailed comparison between them for different scenarios of input/coefficient pressure levels in a 1D-Var context are discussed in Hocking (2014) and Hocking *et al.* (2013). The main conclusions from these studies are that no single interpolation mode is optimal for all situations. In general, interpolation modes 4 and 5 allow the calculation of smooth Jacobians when the input levels are more dense than the coefficient levels, with mode 4 being the most computational expensive method. In contrast, mode 2 is not suitable for adjoint and Jacobian calculations and modes 1 and 3 gives better results when the input levels are less dense than the coefficient levels. On the basis of initial comparison and validation results of the interpolation modes in a 1D-Var context, modes 3 and 5 were retained for further evaluation in the IFS.

3.2 Impact of new interpolation modes on temperature Jacobian in the IFS

RTTOV performs the fast computation of the direct radiances but also computes the gradient of the radiances with respect to the state vector variables. Given a state vector, **x**, a radiance vector, y (here brightness temperature TBs), is computed as:

$$\mathbf{y} = H\mathbf{x} + \varepsilon, \tag{1}$$

where H is the non-linear radiative transfer model for calculating the equivalent of the state vector in the observation space (also referred to as the observation operator) and ε is the modelling error.

During the minimisation of the 4D-Var cost function, a small perturbation of the atmospheric state ($\delta\mathbf{x}$) is mapped into the observation space ($\delta\mathbf{y}$) by the tangent linear of the observation operator:

$$\delta\mathbf{y} = \mathbf{H}\delta\mathbf{x}, \tag{2}$$

where **H** is the Jacobian matrix, that is the derivatives of all elements of **y** to perturbations of all elements of **x**.

Likewise, the adjoint model is used to compute the transpose of the Jacobian matrix. The Jacobian matrix is used to produce the gradient of a cost function J with respect to a state vector given the sensitivity of the observations to changes in the state vector:

$$\frac{\partial J}{\partial \mathbf{x}} = \mathbf{H}^T \frac{\partial J}{\partial \mathbf{y}}, \tag{3}$$

The aim of this section is to examine how the choice of the RTTOV interpolation modes affects the temperature Jacobians in a 4D-Var data assimilation context. The jacobians computed by RTTOV-11 using several interpolation modes are illustrated here only for AMSU-A on MetOp-A, looking at individual channels in the 50 GHz oxygen band (channels 5 to 14, but no channel 7 which is broken) with the IFS model cycle 40r1.

Three sets of 8 single cycle/single AMSU-A channel experiments have been performed for each of the interpolation modes 1, 3 and 5. Each of the experiments include only one AMSU-A channel at a time. Due to the large volume of observations, a horizontal thinning is applied to AMSU-A observations, and approximately 500 observations per AMSU-A channel are used in 12-h 4D-Var on 1st January 2013 at 00 UTC analysis. The model resolution is set to T511 (with a 40 km grid) and 137 levels in the vertical. Only one inner loop minimisation is run at the spectral truncation of T255 and the number of iterations is fixed to 1 per minimization. Here, the user input profile on 137 vertical levels is interpolated to the 44 levels specified in the AMSU-A coefficient file to perform the computations of the optical depths. Then, the optical depth are interpolated back onto the user levels. The temperature Jacobians were computed at each grid point for every time step of the integration for each of the interpolation modes 1 (Rochon interpolator), 3 and 5. From eq. 3, if only just one AMSU-A channel is assimilated, the temperature Jacobian $\frac{\partial(TBs)}{\partial T}$ can be recovered dividing the gradient in physical temperature $\frac{\partial J}{\partial T}$ by the gradient in brightness temperature $\frac{\partial J}{\partial(TBs)}$.

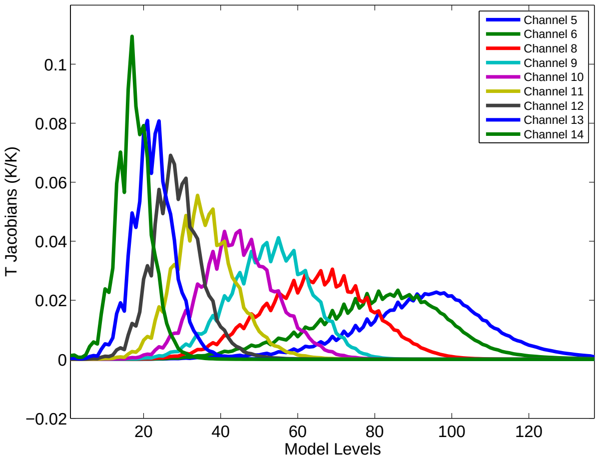
The mean temperature Jacobians for each of the 8 AMSU-A channels are computed using interpolation modes 1, 3 and 5 from the dataset and are illustrated in Figure 6. The x-axes refer to model levels that are adjusted according to surface pressure (at model level 137), for example levels 20, 40, 60, 80, 100 and 120 correspond to 3, 28, 98, 260, 590 and 920 hPa.

In Figure 6(a), artificial oscillations in the temperature Jacobians are noticed when the default Rochon interpolator is used to interpolate the optical depths between the 44 coefficient levels and the 137 IFS model levels. In figure 6(b), interpolation mode 3, which uses log-linear on optical depths interpolation, does not appear to offer much benefit over the Rochon interpolator. Interpolation mode 5 reduces the oscillations in the temperature Jacobians and results in very smooth Jacobians as illustrated in Figure 6(c).

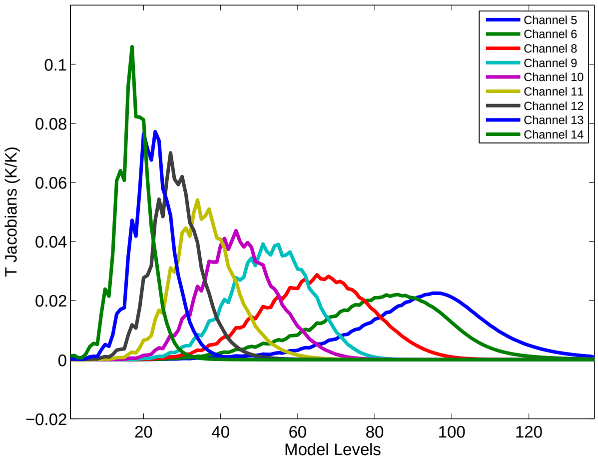
Figure 7 shows the temperature Jacobians obtained using interpolation modes 1, 3 and 5 for AMSU-A channels 6, 9 and 12: channel 6 peaks in the middle troposphere around 400 hPa, channel 9 peaks at 90 hPa and channel 12 peaks at 10 hPa. Both interpolation modes 1 and 3 lead to noisy temperature Jacobians with unrealistic spikes. While there is very little difference between interpolation modes 1 and 3, interpolation mode 5 successfully retains the smooth structure of the temperature Jacobians. The largest differences in temperature Jacobians between interpolation modes 1 and 5 occur for the higher-peaking AMSU-A channels characterised by a sharp peak in their weighting functions. Nevertheless, there are some systematic differences in temperature Jacobians for the lower-peaking AMSU-A channels with overlapping weighting functions that span more vertical levels.

As highlighted in Figure 8, the jagged Jacobians seen in the default interpolation scheme in RTTOV-11 when the input profile levels are more densely-spaced than the coefficient levels have mainly been

(a) 1: Rochon on optical depths



(b) 3: Log−linear on optical depths



(c) 5: Log−linear on weighting functions

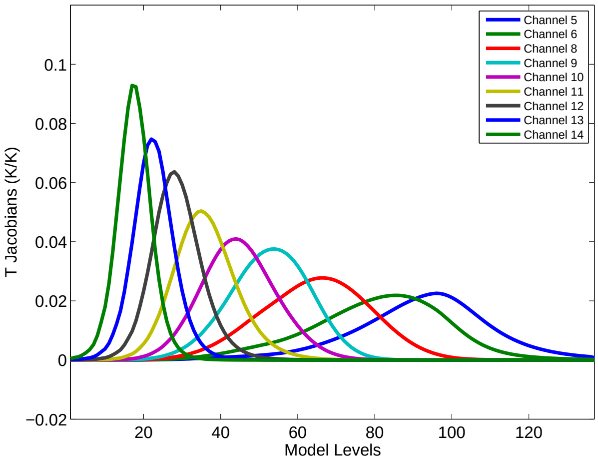
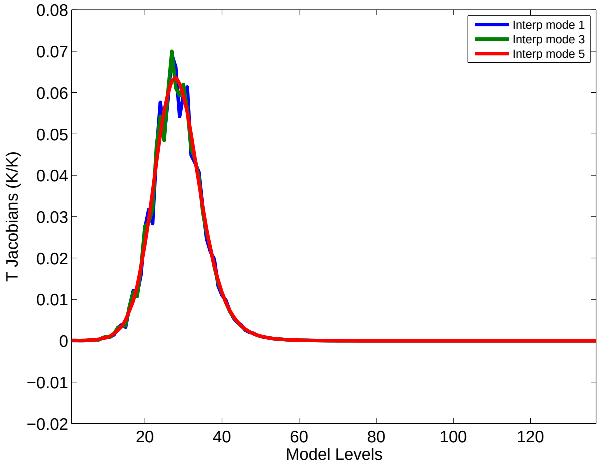
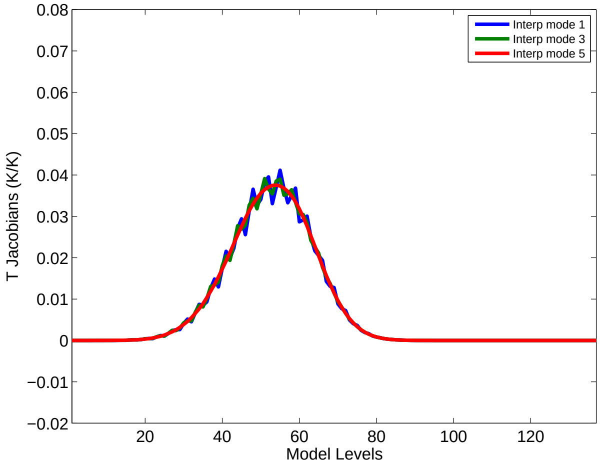


Figure 6: Mean temperature Jacobians for AMSU-A channels 5-14 calculated when mapping from the 44-level RTTOV model to 137 IFS model levels using: a) Rochon interpolator; b) interpolation mode 3; c) interpolation mode 5.

(a) AMSU−A/MetOp−A Channel 12



(b) AMSU−A/MetOp−A Channel 9



(c) AMSU−A/MetOp−A Channel 6

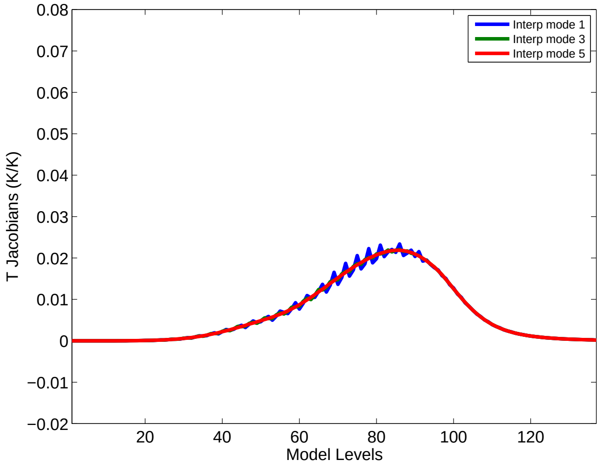


Figure 7: Mean temperature Jacobians for AMSU-A: a) channel 12 peaking at 10hPa, b) channel 9 peaking at 90hPa and c) channel 6 peaking in the middle troposphere at 400 hPa, were compared on 44 RTTOV levels using the Rochon interpolation (blue), interpolation mode 3 (green) and interpolation mode 5 (red).

removed with new interpolation option mode 5. The most notable difference in the temperature Jacobians between mode 5 and modes 1 is in the upper stratosphere, where the 44 AMSU-A RTTOV levels are relatively sparse.

In summary, two of the new proposed interpolation modes 3 and 5 were evaluated in the IFS. Interpolation mode 3 reduces the magnitude of the unphysical features in the Jacobian, but does not eliminate them entirely. Interpolation mode 5 ensures that the unrealistic structures of the Jacobian profiles that may occur using the Rochon interpolator to interpolate the optical depths are avoided. Using interpolation mode 5 has a smoothing effect on the temperature Jacobians and may be considered as alternative to the Rochon interpolator when the input profile levels are more densely-spaced than the coefficient levels.

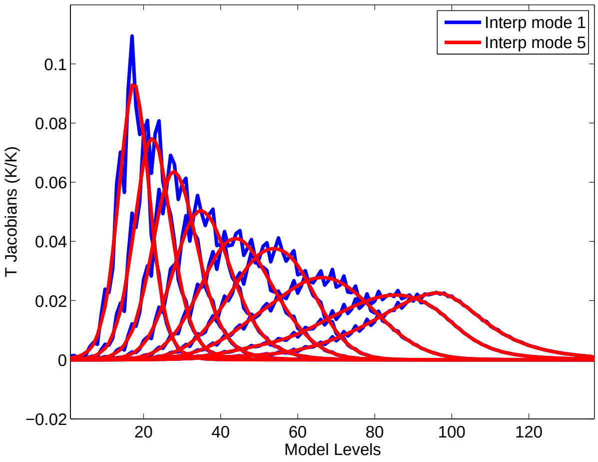


Figure 8: Mean temperature Jacobians for AMSU-A channels on 44 RTTOV levels as obtained using interpolation mode 1 (dashed grey) and mode 5 (solid colours).

3.3 Modifications to RTTOV profile interpolation: impact in the IFS cycle 40r1

The first results in the IFS from using the new proposed interpolation modes have been demonstrated the potential offered by interpolation mode 5 in reducing the inaccuracies in the Jacobians that may occur in mapping user atmospheric profiles to the RTTOV model levels. In this section, the performance of the new interpolation modes 3 and 5 is assessed in the context of a full observing system.

3.3.1 Experiments set-up

Using RTTOV-11 as radiative transfer model, a set of three experiments were run with the full observing system over two periods using the IFS cycle 40r1 at a T511 resolution, 137 vertical levels, and 12-hour 4D-Var. The winter period covers 1st January to 28th February 2013, and the summer period 15th June to 1st September 2013. All the observations assimilated at ECMWF at the time are used, including polar orbiting satellite measurements (AMSU-A, MHS, ATMS, SSMIS, TMI, HIRS, AIRS, IASI, scatterometer wind vectors), geostationary radiances from 5 geostationary satellites, atmospheric motion vectors (AMVs) and GPSRO data, radiosonde temperature, specic humidity and wind measurements, surface pressure data and aircraft temperature reports. For satellite and aircraft data, the variational bias correction (VarBC) is used (Dee, 2005). The first two-weeks at the beginning of each of the experiments were discarded, to allow VarBC to adjust to the bias conditions. The experiments carried out were therefore:

- Interpolation mode 1: uses all satellite and conventional observations and the default RTTOV-11 Rochon interpolator (mode 1).
- Interpolation mode 3: same system configuration, but with the RTTOV-11 interpolation mode 3.
- Interpolation mode 5: same system configuration, but with the RTTOV-11 interpolation mode 5.

3.3.2 Analysis and forecast impact

To evaluate the impact of the new interpolation modes on short range forecasts in the data assimilation experiments, standard deviations of first-guess departures for ‘Interpolation mode 3’ and ‘Interpolation mode 5’ are shown with respect to the ‘Interpolation mode 1’.

Fits to AMSU-A onboard seven satellites (NOAA-15, -16, -18, -19, Metop-A and -B and Aqua), ATMS on S-NPP and MHS on four satellites (MetOp-A and -B, NOAA-18 and -19) are analysed through Figure 9. ATMS channels 6-15 are similar to AMSU-A channels 5-14, and ATMS channels 18, 19, and 22 are similar to MHS channels 5, 4, and 3, respectively. Using interpolation mode 5, the standard deviation of the first-guess departures of AMSU-A stratospheric channels were reduced globally by around 0.1% in channel 11 (which peaks at 25 hPa) and by 0.4% in channel 13 (which peaks at 5 hPa). Consistent with the assimilation of AMSU-A, the standard deviation of the first-guess departures of ATMS equivalent temperature channels were also improved: there is 0.8% improvements in channels 13 and 14 and up to 1.2% in channel 15. Statistically significant improvements around 0.2% were noticed for ATMS lower tropospheric humidity sensitive channel 18 and the equivalent MHS channel 5. Small degradations of up to 0.05% were found in the fits to AMSU-A channel 8 and ATMS channels 8 and 11. There was little impact on background fits when interpolation mode 3 is used.

Background fits to other satellite and conventional observations were not significantly altered compared with the ‘Interpolation mode 1’ experiment. As an example, the standard deviation of background departures for IASI, SSMIS and AMVs are shown in Figure 10. It was found that there was no statistically significant improvement (as measured by the fit of the background to observations) using the new interpolation modes 3 or 5.

Also as a result of changes in the RTTOV interpolation mode, there were small differences in the mean temperature analyses in the stratosphere (not shown). Zonal mean differences were less than 0.3 K above 10 hPa in the ‘Interpolation mode 5’ experiment and less than 0.1 K in the ‘Interpolation mode 3’ experiment.

The impact on the subsequent forecasts has also been assessed. To do so, forecasts have been run from 0 UTC and 12 UTC analyses generated by the ‘Interpolation mode 1’, ‘Interpolation mode 3’ and ‘Interpolation mode 5’ assimilation systems. Forecast scores have been computed as the change in standard deviation forecast errors compared to the ‘Interpolation mode 1’ with the differences normalised by the forecast error of ‘Interpolation mode 1’. Values are averaged over both seasons and compared to own analyses. A negative value of the forecast score means that the use of the new interpolation modes improves forecast accuracy compared to the default Rochon interpolator.

Figure 11 shows results in terms of 500 hPa geopotential height and 100 hPa temperature and wind vector for the extratropical northern and southern hemispheres and for the tropics. In both experiments the impact on 500 hPa geopotential is overall neutral. There is a positive impact at days 2-3 for the

Northern Hemisphere at the very edge of statistical significance. The impact on temperature and wind at 100 hPa are not statistically significant for neither of the experiments.

Zonal means of the standard deviation of forecast error differences for wind vector are shown in Figures 12 and 13 for ‘Interpolation mode 5’ and ‘Interpolation mode 3’ experiments for various forecast times from T+12-h to T+120-h. There is no statistically significant impact in the short to medium range forecast scores from using either of the new interpolation modes 3 and 5.

The computational performance is unaffected by using the new interpolation modes proposed with RTTOV-11. Performance tests indicate that the 4D-Var minimization requires similar computer resources when ‘Interpolation mode 3’ is used and only a modest increase of 0.8% in the elapsed running time when ‘Interpolation mode 5’ is used.

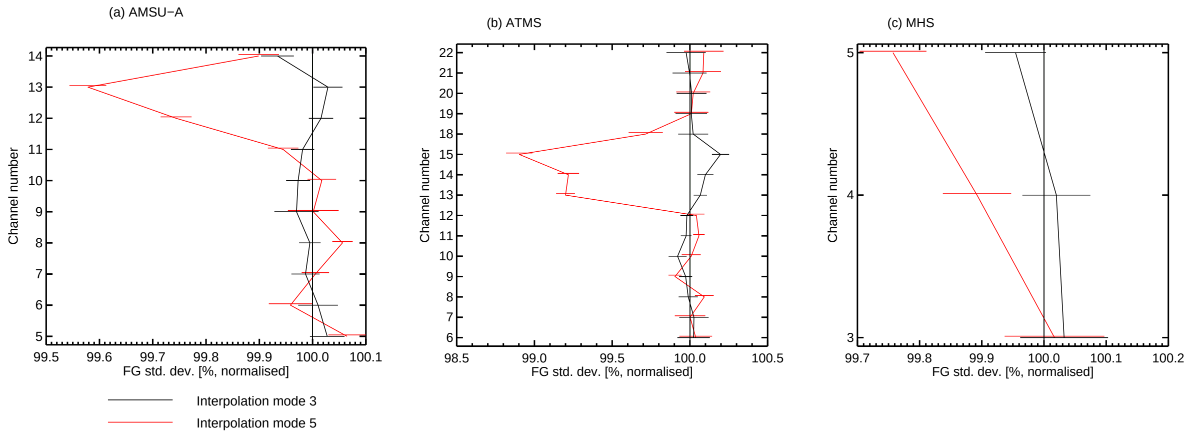


Figure 9: Normalised standard deviation of first-guess departures as a percentage relative to the ‘Interpolation mode 1’ experiment for: a) AMSU-A on seven platforms; b) ATMS on S-NPP; c) MHS on four platforms. The area is global and statistics are based on the combined summer and winter experimentation (15th January to 28th February 2013 and 1st July to 1st September 2013). Error bars indicate the 95% confidence interval. Numbers less than 100% indicate beneficial impact.

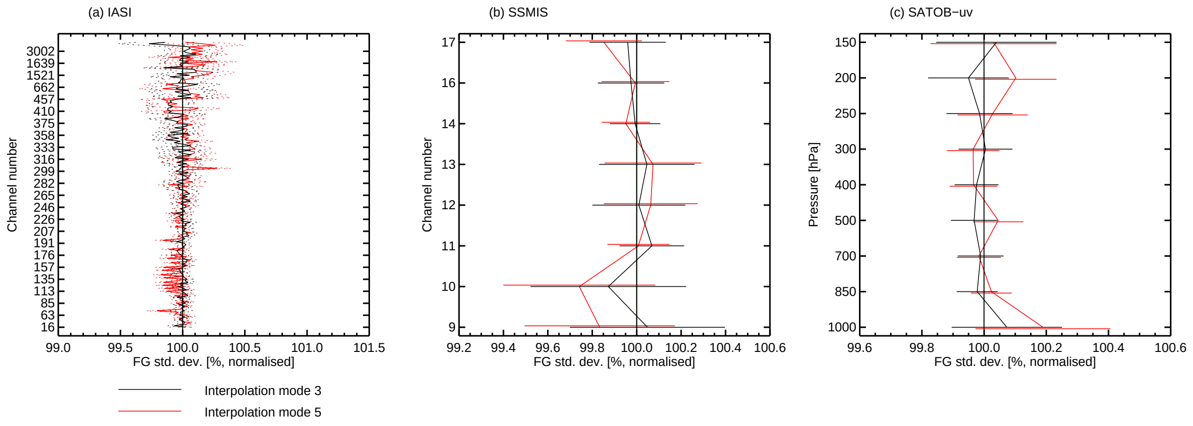


Figure 10: As Figure 9 but for: a) IASI on MetOp-A; b) SSMIS on DMSP-17; c) Atmospheric Motion Vectors (AMVs) combining statistics from u and v wind components.

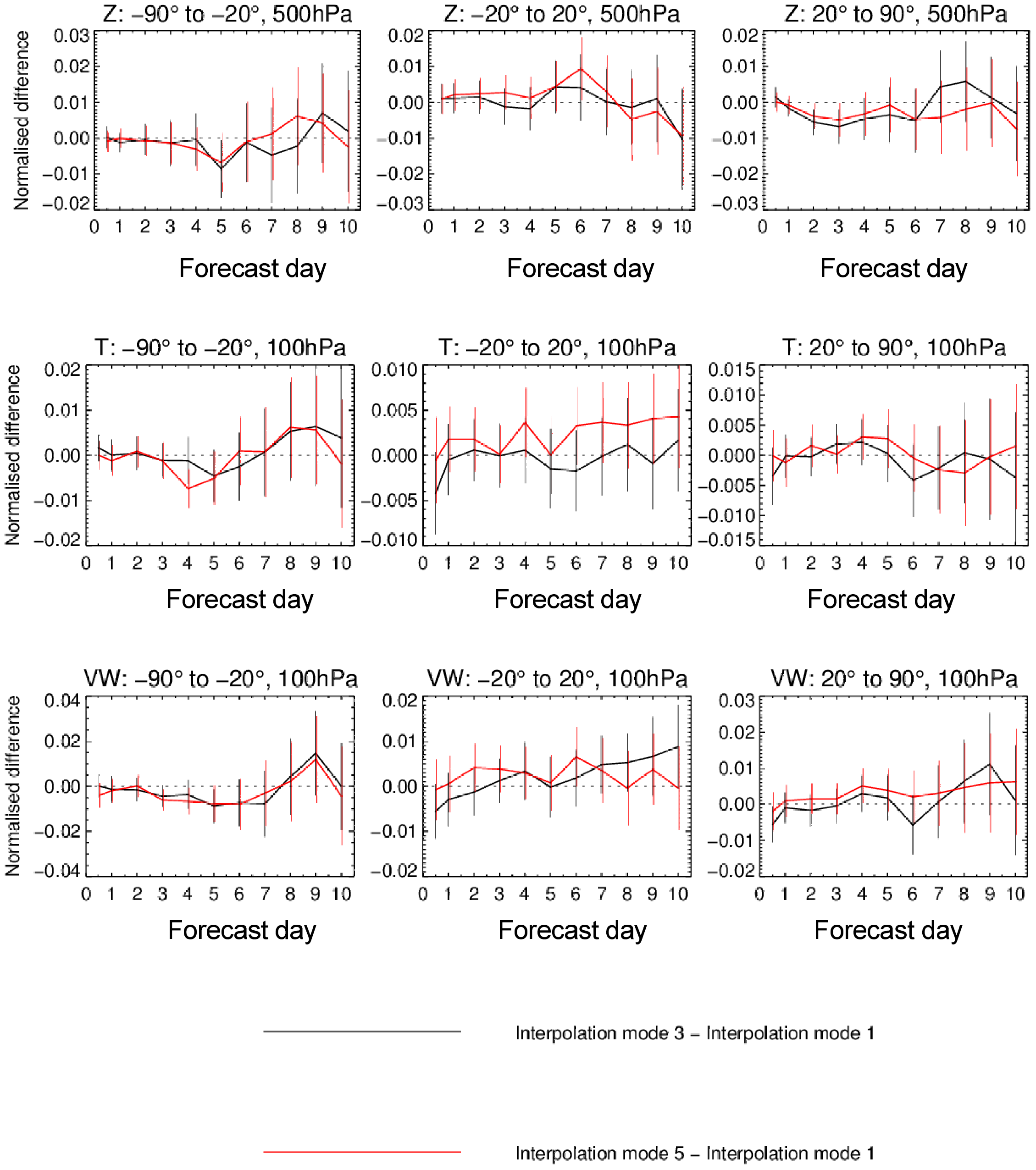


Figure 11: Normalized change in standard deviation of forecast error in geopotential height at 500 hPa (top row),temperature at 100 hPa (middle row) and vector wind at 100 hPa (bottom row). Negative values indicate a reduction in forecast error and hence a beneficial impact on forecasts. Results are based on 176 to 214 forecasts depending on the forecast range for the combined summer and winter experimentation (15th January to 28th February 2013 and 1st July to 1st September 2013). Verification is against own analysis. Error bars give the 95% confidence limits.

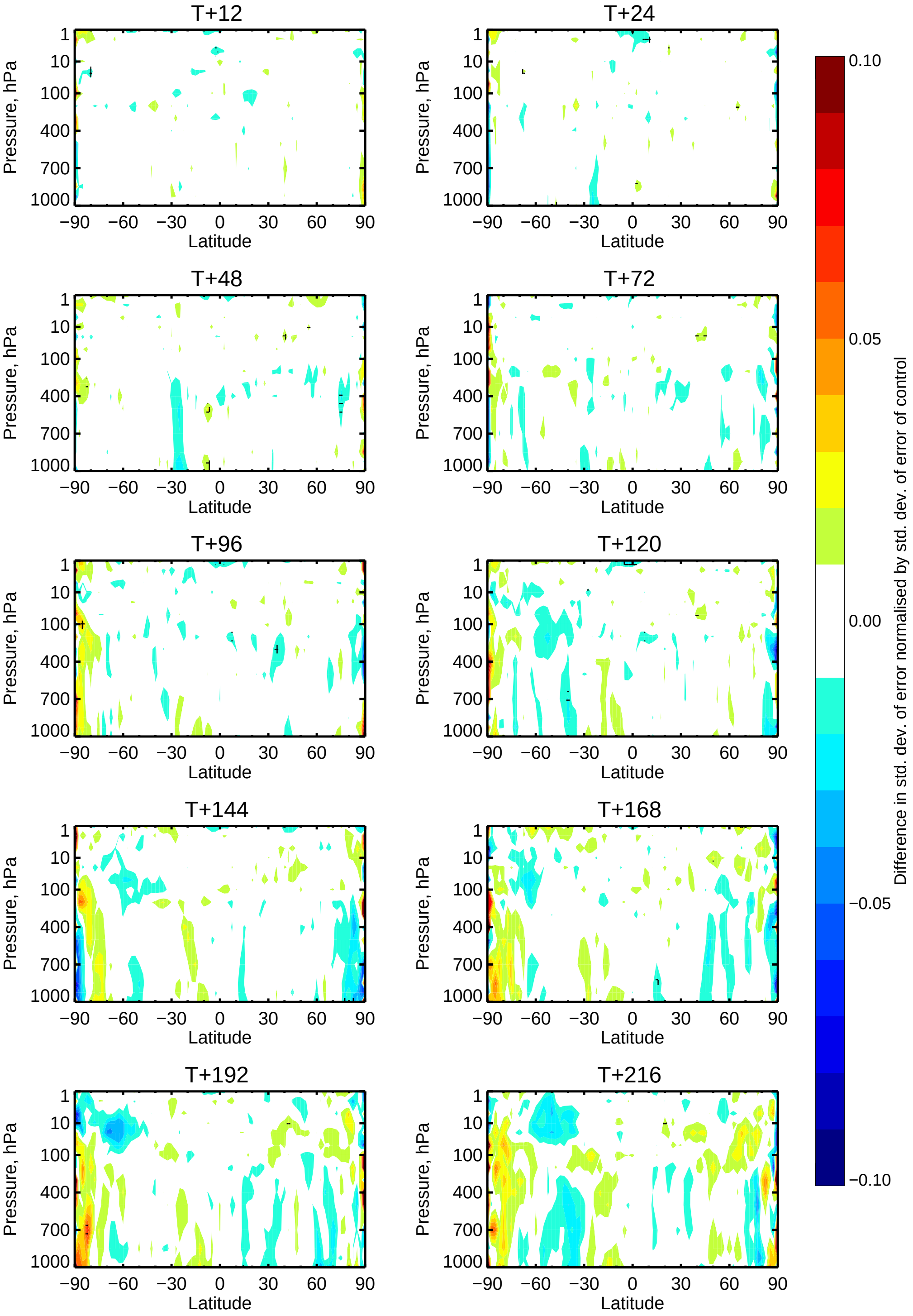


Figure 12: Zonal mean of standard deviation error difference for vector wind from experiment with RTTOV interpolation mode 5. Negative values indicate a reduction in forecast error and are shown in blue. Cross-hatching indicates statistical significance at the 95% confidence level. Results are based on 176 to 214 forecasts depending on the forecast range for the combined summer and winter experimentation (15th January to 28th February 2013 and 1st July to 1st September 2013). Verification is against own analysis.

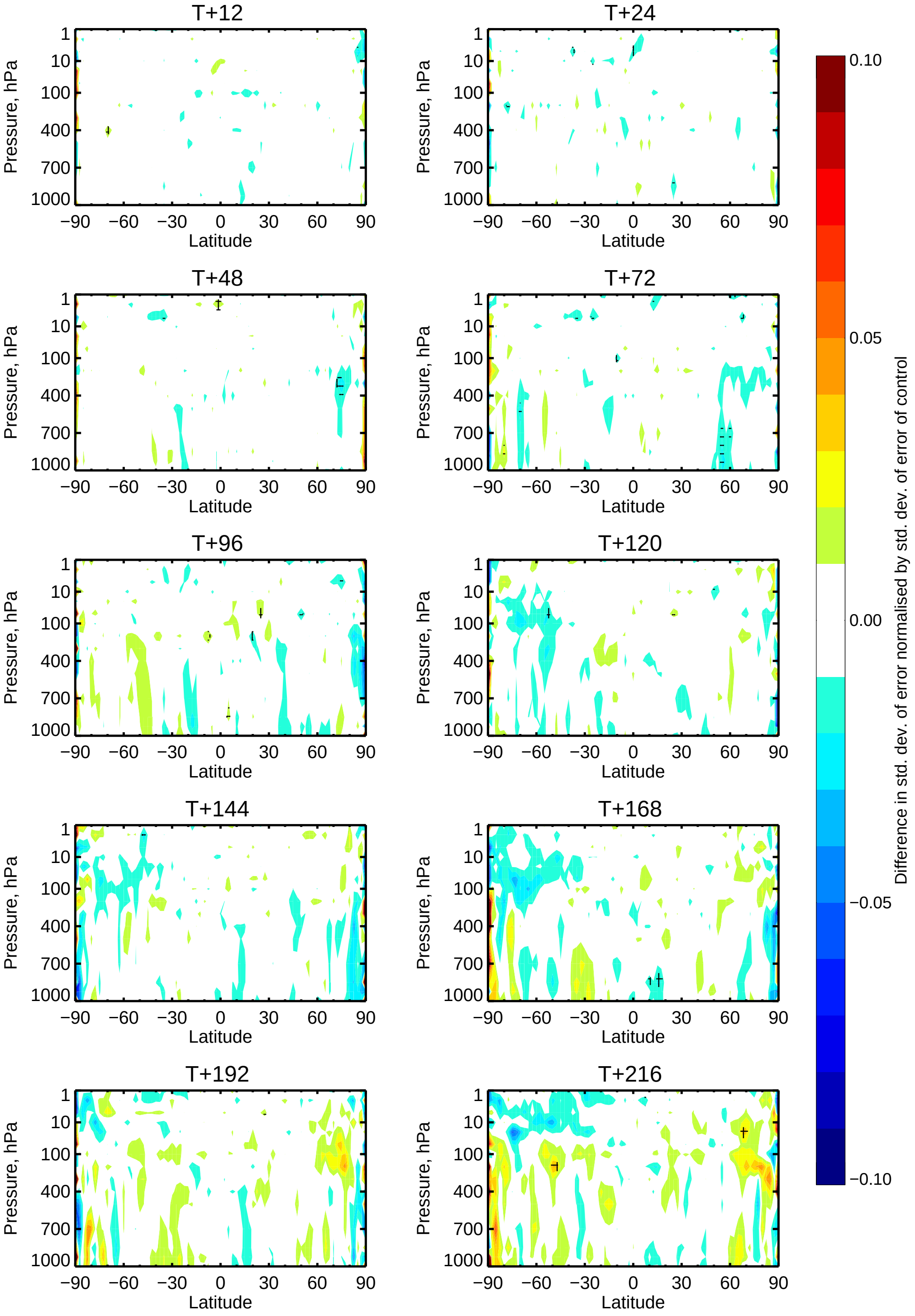


Figure 13: Same as Figure 12 but for the 'Interpolation mode 3' experiment.

4 Conclusions

This memorandum summarises the evaluation of the upgrade of the RTTOV fast radiative transfer model from version 10 to version 11, as was tested in ECMWF's Integrated Forecast System (IFS) cycle 40r1. This was largely a technical implementation to ensure there were no unexpected changes from RTTOV-10. The new RTTOV-11 code was first validated by comparing brightness temperatures simulated from the same first guess profiles with RTTOV-11 and RTTOV-10. When the same profile is provided as input, RTTOV-11 produces identical direct radiance calculations to RTTOV-10 for all IR and MW sensors tested, but the tangent linear and adjoint calculations have slight numerical differences requiring full scientific testing even though no scientific impact is expected.

We have assessed the impact of RTTOV-11 on departure statistics between observed and simulated brightness temperatures for a range of sensors, and compared the results with those obtained with the current operational version 10 of RTTOV. Experiments during the four month period have a neutral impact in term of forecast scores and suggest no significant change to the quality of short range forecast or to the analysis.

The default interpolation option (mode 1) has been observed to introduce oscillations and undesirable noise in the temperature Jacobians. Spiky Jacobians are undesirable, because if not smoothed by the background vertical correlations, they could cause noisy and unphysical temperature increments. RTTOV version 11 allows the possibility to use smoothed Jacobian calculations in the assimilation system. The proposed interpolation modes 3 and 5 have been extensively tested through comparisons of radiative transfer simulations with RTTOV-11 using default Rochon interpolator, and through an analysis of departure characteristics against observations. The impact on forecasts was also investigated through a series of assimilation experiments over a period of 3.5 months. The main findings are:

- Enabling interpolation mode 3 does not appear to offer much benefit over the Rochon interpolator as it does not eliminate the unphysical features in the temperature Jacobians. After bias correction, most first-guess departure statistics for assimilated radiances are overall largely unaltered. The forecast impact is overall neutral.
- Enabling interpolation mode 5 ensures smooth temperature Jacobians and may be considered as alternative to the Rochon interpolator when the input profile levels are more densely-spaced than the coefficient levels. Some small but significant reductions in the size of first-guess departures are noticed for some high-peaking AMSU-A and ATMS channels which benefit from improvements related to the profile interpolation. The verification of forecasts further confirms that there is no loss of skill from using the new interpolation mode 5.
- Performance tests indicate that the 4D-Var minimization requires similar computer resources when the new interpolation modes 3 or 5 are used.

Whilst the vertical correlations in the background error matrix filter out the unrealistic structures in the Jacobians produced by the Rochon interpolator, it is still sensible to use RTTOV interpolation options which eliminate these artefacts. The new interpolation mode 5 will be activated at ECMWF in the next operational cycle 41R1 in May 2015.

The official RTTOV-11 release also provides a new set of radiative transfer coefficient files for various infrared and microwave sounders and imagers based on different or revised spectroscopy and different atmospheric layering (54 rather than 44 or 51 levels). Work is ongoing to investigate the possibility of using these new coefficient files and to evaluate their impact on analyses and forecasts in the ECMWF system (e.g. Lupu *et al.*, 2015). The accuracy of the radiative transfer model underpins the operational radiance assimilation system and continuous efforts are dedicated to ensure that the ECMWF system use the most up-to date version of RTTOV supported by the best spectroscopic data and line-by-line modelling.

Acknowledgements

Cristina Lupu was funded by EUMETSAT via the NWP SAF Programme. Help from Anne Fouilloux and Niels Bormann in debugging and implementing RTTOV-11 in the IFS is gratefully acknowledged, as is support from James Hocking (Met Office). Tony McNally, Marco Matricardi, Stephen English are also thanked for valuable discussions and suggestions throughout the work.

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