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Assimilation of satellite-derived estimates of tropical convective rainfall

August 2001

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Assimilation of satellite-derived estimates of tropical convective rainfall

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Abstract

At present no attempt is made in the global Unified Model (UM) to assimilate observations of precipitation. Research has been carried out and initial experiments conducted within the Met Office to assimilate satellite-derived estimates of tropical convective rainfall into the global UM using a latent heat nudging technique. This report presents results of extended trials of this assimilation into the operational global UM. Although the overall impact on the model performance is not large, a number of interesting features arose during the extensive verification process, notably a reduction of model convective activity in the assimilation region. The results of these trials will be important in understanding the behaviour of the assimilation under the New Dynamics version of the UM when further tests will be necessary.

Contents

1 Introduction

Convective rainfall in the tropics plays an extremely important role in the tropical circulation through latent heat release. The tropics are hard to represent well in a numerical model, not least because data are sparse in this region, especially over the oceans. There is rarely assimilation of rainfall in global models, due in part to the unavailability of quantitative measurements over large regions. Deriving estimates of surface rainfall from satellites provides a means of obtaining data over a large spatial range. Assimilation of these data by tuning the model latent heating is a potential method of improving the model's representation of the tropics, and possibly even at higher latitudes.

The work presented in this report builds on initial experiments conducted by Ringer (in preparation) to test the impact of assimilating satellite-derived estimates of tropical convective rainfall (TCR) into the global unified model (UM). In his feasibility study Ringer conducted short (3 day) assimilation experiments and found an improvement in the model's representation of convective rainfall in the tropics. He found that the assimilation method was most successful at removing excess model rainfall but that it was much less successful at generating or increasing model rain. This set of experiments aims to give a more detailed analysis of the model's response to these TCR data in order that a decision can be made on whether to proceed with operational implementation. The experiments are therefore carried out in an operational environment, over an extended period. The objectives set out for the proposed work were:

- To produce an end-to-end system to enable the operational assimilation of satellite-derived estimates of TCR from composite, geostationary, infra-red (IR) satellite imagery for use within the numerical weather prediction (NWP) global model, by means of a latent-heat nudging (LHN) technique.
- To conduct assimilation trials and make recommendations regarding operational assimilation of TCR observations under the LHN technique, and further work.

2 Method

2.1 Infra-red (IR) Imagery

The data are taken from a composite IR image, produced by the operational satellite image processing system (Autosat) every 3 hours. The image is made up of the individual full-disk images from the currently operational set of geostationary satellites, and covers the range 60°S to 60°N, 180°E to 180°W. Before compositing, the 55 outermost pixels in each disk are masked, in order to remove from the dataset pixels most affected by limb brightening or by stretching. In areas of overlap, the Autosat software checks the ground location and uses data from the satellite that has its sub-satellite point nearer that location. Occasionally data from one of the contributing satellites does not arrive at Autosat within the 1.25 hour deadline, in which case there are data missing from the composite where the missing disk is not overlapped by other images. At the time of writing, there are five satellites transmitting IR imagery: GOES-East at 75°W, GOES-West at 135°W, Meteosat-7 at 0°, Meteosat-5 (Indoex) at 63°E, and GMS-5 at 140°E.

2.2 Gridded brightness temperatures

The composite image, which is a byte array of 2500 × 835 pixel values, was initially converted to brightness temperatures, within the range 150 K to 350 K, in the following way:

$$\textit{if (binary\_pixel} \geq 0\textit{) then integer\_pixel = binary\_pixel} \qquad (1)$$

$$\textit{if (binary\_pixel} \leq 0\textit{) then integer\_pixel = binary\_pixel + 256} \qquad (2)$$

$$\textit{brightness\_temp} = 150.0 + (200.0/254.0) \times \textit{integer\_pixel} \qquad (3)$$

Since the data consist of an array of more than 2 million elements, it was decided not to treat each element as a point-observation, as occurs with other observation types. Instead, the field of brightness temperatures was encoded as a GRIdded Binary (GRIB) file. GRIB offers a way of encoding geostationary composite IR images as an effective field of observations in which the two-dimensional (2D) spatial relationship is maintained between observations. It leads to a massive reduction in memory required by the Meteorological Database (MetDB) and in the Observation Processing System (OPS) since the grid can be defined in header information and the time is the same for all the observations in one image. Storage of satellite data in GRIB format is a new departure for the Met Office, and uncommon elsewhere. However, having introduced the facility for handling imagery data in this way, opportunities have been opened up for more efficient and suitable handling of similar data in the future. (See OSDP 14 (internal document), GRIB code details for documentation of method). Once converted to GRIB format, the data are transferred to the MetDB from Autosat, via NETLINK.

2.3 Processed rainfall rates

The remainder of the processing of the observational data occurs within the OPS, as with other observation types. In order to make use of the GRIB format data, a new extraction route from the MetDB was constructed, which includes decoding of the data back to a brightness temperature array. These brightness temperatures can then be converted to surface rainfall rates using a chosen conversion method. Data falling outside the tropical bounds of ± 30 degrees were set to "missing data" since only observations within the tropics can be used to derive rainfall rates by the methods employed in this project. There are a number of methods published for the conversion of satellite-derived brightness temperatures to surface rainfall rates, and these are described fully by Ringer (1998). Descriptions in this report are restricted to conversion methods that were used during these experiments.

2.3.i Deep Convective Activity Index (DCA)

$$\mathrm{DCA} = a\,(230 - T_b), \quad \text{if } T_b < 230\ \mathrm{K} \qquad (4)$$

$$\mathrm{DCA} = 0, \quad \text{if } T_b \geq 230\ \mathrm{K} \qquad (5)$$

where:

$a = 0.29\ \mathrm{mmh^{-1}K^{-1}}$

T_b = brightness temperature
[DCA] = mmh^{-1}

This relationship was used in the impact trials conducted by Ringer (in preparation). It is the Deep Convective Activity index of Hendon and Woodberry (1993), based on work by Fu *et al.* (1990). Unlike threshold rainfall estimates, this gives more weight to colder cloud tops since a difference technique is used.

2.3.ii First modified GOES Precipitation Index (GPI1)

GPI1 = bF_ct, if $T_b < 235$ K (6)
GPI1 = 0, if $T_b \leq 235$ K (7)

where:
b = 2 mmh^{-1}
F_c = fractional coverage of cloud colder than 235 K (derived from 0.5° × 0.5° spatial averaging)
t = length of averaging period (h)
[GPI1] = mm; to convert to rain rate, TCR = GPI1/t = 2×F_c

Based on the GPI method of Meisner and Arkin (1987), GPI1 uses an upper bound of 2 mmh^{-1} on the rainfall rate rather than the 3 mmh^{-1} upper rate of unmodified GPI. The First Modified GPI is derived using a spatial scale that is more appropriate for NWP than the unmodified GPI.

2.3.iii Infra-red Power Law Rain Rate (IPR)

IPR = $0.00373\,(267 - T_b)^{1.75} - 0.372$, if $T_b < 253$ K (8)
IPR = 0, if $T_b \geq 253$ K (9)

where:
[IPR] = mmh^{-1}

Goodman *et al.* (1993) developed the IPR based on 3-hourly rainfall rates in the tropics. It has a much warmer threshold temperature (253 K) than the other methods used.

The characteristics of the three different brightness temperature to rain rate conversion methods used are displayed in Figure 1.

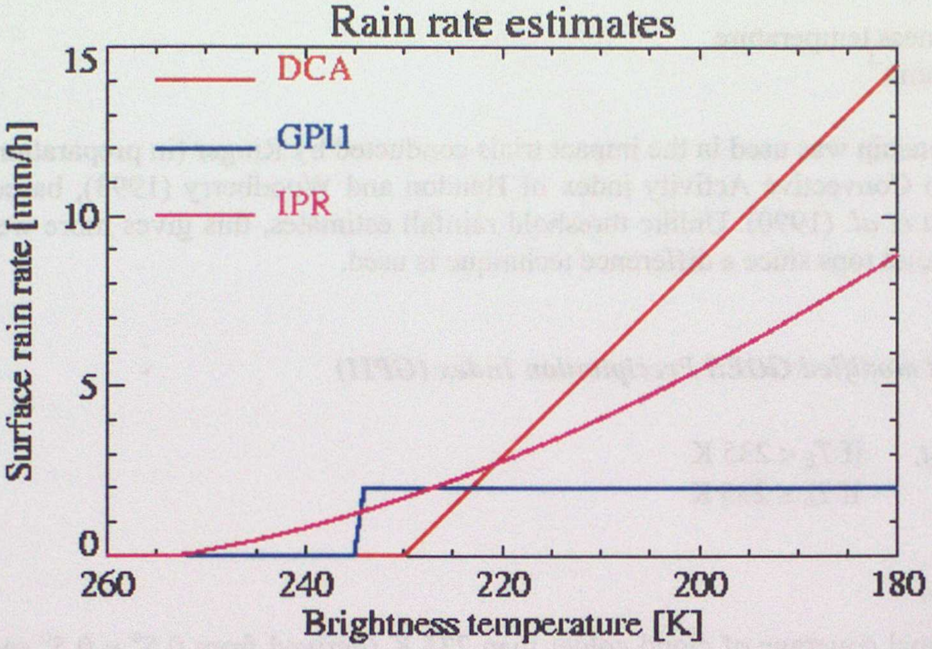


Figure 1: Variation of surface rain rate with brightness temperature for the DCA (red), GPI1 (blue) and IPR (pink) conversion methods.

The final stage in the processing of the brightness temperature data is the preparation of a suitable file (Met Office "ACOBS" file) for assimilation into the global model. Literature on the assimilation of rainfall rate data (*e.g.* Marecal and Mahfouf, 1999; Treadon, 1997) cautions that it is best to produce rainfall rate averages exactly on the model grid, thus avoiding the need for horizontal interpolation. The GRIBbed data fields extracted from the MetDB have a resolution of roughly 15 km at the equator. They are thus superobbed onto the model grid before being presented to the UM in ACOBS format. The rainfall rate unit must finally be converted from mmh^{-1} to $Kgm^{-2}s^{-1}$, which is the unit required for use in the UM (rain rate [$Kgm^{-2}s^{-1}$] = rain rate/3600.0 [mmh^{-1}]).

2.4 Latent Heat Nudging technique

A detailed description of the LHN technique is given in Jones and Macpherson (1997). The technique was first used within the Met Office in the mesoscale model where it is used for the assimilation of both large-scale and convective rain, mainly estimated from radar observations. For these experiments, the LHN technique is employed only to assimilate observations of convective rainfall. Typical modelled area-mean large-scale precipitation rates are negligible compared with convective rain rates between about ± 20°N and very much smaller at ± 30°N (personal communication, S. Milton), and so it is fair to assume that only convective precipitation contributes significantly to the model's latent heating budget in the tropics.

The principle of the technique is to use observed and modelled rainfall rates to derive increments to the potential temperature, within the Analysis Correction (AC) assimilation scheme, which are then applied to the latent heating profiles calculated from the model physics step. Two main assumptions are made: that since most of the water condensing in a cloud is rained out, the vertically integrated latent heating rate is proportional to the net precipitation rate; and that increments to potential temperature due to the convection scheme are from latent heating alone.

The assimilation increment to potential temperature is given by:

$$\Delta\theta_{assim} = \Delta\theta_{fg} \times \left(\frac{\Delta R}{R_{fg}}\right) \tag{10}$$

provided that model rain rates satisfy $\varepsilon R_{obs} < R_{fg} < (1/\alpha) R_{obs}$

where:

$\Delta\theta_{fg}$ = potential temperature increment from convection scheme

ΔR = observed – modelled rain rate $(R_{obs} - R_{fg})$

and in these experiments, ε and α are both set to 1/3

If the model rain rate lies outside the allowed range, then a search is conducted of neighbouring grid-points to find a point where the model rain rate does satisfy these conditions. The assimilation increment to θ for the original point is calculated as:

$$\Delta\theta_{assim} = \left(\Delta\theta_{fg}^{near} - \Delta\theta_{fg}\right)\left(\frac{R_{obs}}{R_{fg}^{near}}\right) \tag{11}$$

If the search is unsuccessful then:

$$\Delta\theta_{assim} / \Delta\theta_{fg} = 1/\varepsilon, \qquad \text{when } \Delta R > 0 \tag{12}$$

$$\Delta\theta_{assim} / \Delta\theta_{fg} = \alpha - 1, \qquad \text{when } \Delta R < 0 \tag{13}$$

The search radius for nearby grid-points satisfying the conditions of equation 10, was set to 4 grid-points. However this and the parameters α and ε are tuneable if required. Finally, the potential temperature increments are smoothed by a recursive filter with a filter scale parameter of one grid length before being added to the model potential temperature field. This is an important step in the mesoscale model assimilation scheme and although it may not be necessary for tropical convective rainfall assimilation, no attempt was made to assess its relevance to this work.

Modifications were made to the LHN code used for mesoscale model precipitation assimilation to enable TCR assimilation within the global model. The potential was maintained to use any of the five different brightness temperature to rain rate conversion methods considered (although only three different methods were actually used). The GPI1 method used gives a maximum observed rain rate of 2 mmh^{-1}. This was accounted for in the LHN modifications in the following way: where the observed rate is equal to the maximum, but the model rate exceeds the maximum, no increment is applied, since there is no information on which to base the increment. A latitudinal dependence of TCR observation weights is also applied at this stage such that the weight given to observed rain rates decreases from unity at a latitude of 25^{o} to zero at the maximum latitude of 30^{o}. This ensures that a smooth transition to the regions in which TCR data is not assimilated is achieved.

3 Ten-day assimilation trials

Initially 7 short 10-day assimilation trials were performed in order to test a number of formulations of the assimilation system. These were run from 1-10 October 2000 at 288 × 217 resolution. Several brightness temperature to rain rate conversion methods were tested to assess whether the choice significantly changed the outcome of the assimilation, and if so, which method gave the most favourable results. There was also the question of whether the TCR data should be assimilated over both land and sea or whether, as suggested by Ringer (in preparation), assimilation over sea only would prove more successful. In all of these assimilation trials, TCR estimates were assimilated into the model every 6 hours. Further work will be necessary to allow use of the data every 3 hours, and will be carried out at a later date.

Since the rationale behind the choice of formulation for each experiment evolved as completed trials were analysed, the trials are discussed fully in turn. The impact of each trial on the NWP index is presented at the end of the section.

3.1 Trial 1: DCA method, land and sea

The first test of the assimilation system was unsuccessful and caused the model dynamics to fail, by exceeding the divergent wind limits at 00Z on 5 October 2000. Close investigation showed that this had occurred at a grid-point in Brazil, very close to the land/sea boundary. Anomalous values of a number of variables were produced, notably maximum and minimum potential temperature values of 1837 K and 80 K at consecutive model levels. Examination of the extreme values and alternation of maxima and minima from level to level at the same point led to the conclusion that a numerically propagated instability had been produced, characteristic of a grid-point storm.

The very high values of vertical velocity (up to 2.7 ms^{-1}) and upper level wind (up to 40 ms^{-1}) indicated the possibility that convection had been initiated to a degree that was unsustainable by the model. This would be a distinct possibility if the LHN technique had incremented the potential temperature in such a way that was inconsistent with the other physical properties of the grid-point. If the satellite-derived rain rate is non-zero at a point, but the point is dry in the model, then the latent heat nudging technique conducts a search of the surrounding grid-points for the nearest wet point, and will use that point's latent heating profile to scale. It is possible therefore that near land/sea boundaries land and sea latent heating profiles may be interchanged and a sea profile used for a land point or vice versa. If a tropical land point was dry in the model and had been clear of cloud for some time, then it could have a very high daytime surface temperature. If a cooler, moist ocean LH profile was then brought in, this could lead to the explosive convection that occurred in this test. In order to test whether this was in fact what happened, the test was re-run turning the "nearest wet grid-point" search off, (see Trial 6).

3.2 Trial 2: DCA method, sea only

Assimilating TCR data over the sea only, the trial ran to completion and no anomalous behaviour was apparent in the region where the previous trial had failed. However, despite rejecting data over land, this trial did produce some very large control–trial temperature differences over central Africa, of up to 14.4 K warmer in the trial at 850 hPa. These occur in a localised region centred around 6th October and are not at all realistic as tropical temperature perturbations. There are also clear perturbations to all the model fields studied, in particular geopotential height, relative humidity, vertical velocity and pressure at mean sea level (pmsl). It appears that the DCA rain rate conversion method is able to produce observed rain rates that are too high for the model to deal with and can cause perturbations to be propagated away from the assimilation region. Despite the concerning behaviour over Africa, this trial did perform well against observations, yielding a +0.46 improvement in the NWP index. The main improvements were made to low level tropical winds and Southern Hemisphere (SH) pmsl. Tropical geopotential heights, however, were degraded and real-time monitoring indicated a degradation in the model comparison with all surface-based observations.

3.3 Trial 3: GPI1 method, land and sea

TCR data were assimilated over both land and sea in this trial and although no grid-point storm occurred over Brazil, as in Trial 1, there were significant perturbations in a number of fields in this region on 4th and 5th October. The constraint on scaling dictated by the maximum GPI1 rain rate of 2 mmh^{-1} prevents the growth of a fatal numerical instability such as that produced by the DCA method. However, it is not desirable to produce perturbations such as these which, although not fatal, are not realistic. The results of this and Trial 1 raise serious doubts about the wisdom of assimilating TCR observations over land. Despite these concerns, this trial produced an NWP index improvement of +0.55, with all tropical and SH winds improved. Northern Hemisphere (NH) pmsl and tropical geopotential heights were both degraded, but real-time monitoring (RTM) statistics showed that surface pressure had been improved overall with respect to observations.

3.4 Trial 4: GPI1 method, sea only

No anomalous behaviour was detected in the model fields for this trial. The GPI1 conversion method allowed smooth and realistic changes to be made to the model variables on assimilation of TCR data. Verification of the results yielded an NWP index increase of 0.42 against observations, and 0.78 against analysis. Assimilation of TCR observations has improved the model forecast significantly, the main improvements being in the forecasts of tropical winds. Geopotential heights are again degraded, especially in the tropics but RTM comparisons with ocean-based surface observations have been improved. Comparisons of wind at station height have been improved considerably over those using the control. This formulation is clearly a strong candidate for the extended trial.

3.5 Trial 5: IPR method, sea only

The IPR brightness temperature to rain rate conversion method gives a smooth variation of rain rate with brightness temperature above the threshold, but does not yield such high rates as the DCA method, and so is of interest if it avoids the problems of assimilating using the DCA method. The IPR method also has a warmer temperature threshold than the other methods, which means rain may be derived over a wider spatial area.

In fact, this trial behaved very similarly to Trial 2, in which anomalous temperature perturbations were produced over central Africa. The warmer threshold for rain meant that the spatial coverage of rain observations assimilated was much greater than previously and corresponded more closely with model background rain rates. However tropical behaviour was significantly degraded in this trial and NWP index only improved by 0.36 against observations, and degraded by 0.55 against analysis. There were improvements in NH variables, especially pmsl, which is encouraging. However, tropical winds were severely degraded, especially at low levels where the results were best in Trial 4. RTM statistics showed a degradation with respect to most surface and sonde observations. Interestingly, in the W. Pacific/S. E. Asia region Trial 5 displayed a reversal in the signals of most model variables studied with respect to Trial 4. The higher temperature threshold of the IPR method has caused much more convective rain to be derived in this region than by the other methods. In response, the behaviour of the model in this region has been significantly altered. This may be a significant factor in the severe degradation of tropical winds with respect to observations.

3.6 Trial 6: DCA method, land and sea, LHN search off

Trial 6 is a repeat of Trial 1 in all but one element. When Trial 1 failed by creating a grid-point storm, investigation suggested that the LHN technique had encountered a dry model grid-point where the derived rain rate was non-zero. In searching surrounding grid-points for a suitable wet latent heating profile, the technique may have used an ocean profile which was considerably different from the original land point profile, and hence introduced an instability into the convection scheme. This trial aims to investigate this hypothesis by repeating the run with this grid-box search disabled.

As suspected, there was no anomalous behaviour apparent over Brazil and the trial continued successfully past the date of the grid-point storm in Trial 1, thus validating the hypothesis. However, a grid-point storm did occur near the end of the run, during the assimilation cycle at 06Z on 9th October, this time near a land/sea boundary in Borneo. Since the LHN search had been deactivated, the model used and nudged the latent heating profile that already existed for this grid-point, and this nudging caused enough convection to destabilise the numerics at this point. It is known that the model often encounters such problems in Indonesia due to the many tiny islands and the maximum in convection in this region. It appears that the potential temperature increment applied through LHN has destabilised a potentially unstable grid-point. The DCA method of rain rate conversion was therefore discounted from further testing and rejection of TCR data over land was deemed the most likely course of action.

3.7 Trial 7: GPI1 method, land and sea, LHN search off

One final short trial was conducted, using the favoured conversion method, but ascertaining whether assimilating over land can be beneficial when land/sea discrepancies, such as occurred in Trials 1 and 3, are prevented. Trial 7 succeeded and showed no evidence of anomalous behaviour over Borneo, but temperature differences between trial and control of 10 K at 850 hPa over the Himalayas on the last day of the trial led to concern. Apart from this anomaly, Trial 7 verified well giving better comparisons against real-time land-based observations than Trial 4. It showed that assimilating over land could potentially be beneficial to the global model forecasts, however the high frequency at which instabilities could be produced dictated that this technique not be used for the extended trial, and that the configuration for Trial 4 be adopted. It is possible that using the LHN technique for convective rainfall assimilation is not viable at such high latitudes and it would be worth investigating, at a later date, whether reducing the tropical bounds from ± 30 degrees to ± 20 degrees allowed data to be more successfully assimilated over land.

Table 1 summarises the configurations of the short trials and their results in terms of impacts on the NWP index.

Trial	*Method*	*Geography*	*LHN search*	*Index vs. Obs*	*Index vs. Anal*
Trial 1	DCA	Land & sea	Yes	Failed 4/10 (Brazil)	
Trial 2	DCA	Sea only	Yes	+ 0.46	– 0.30
Trial 3	GPI1	Land & sea	Yes	+ 0.55	– 0.02
Trial 4	GPI1	Sea only	Yes	+ 0.42	+ 0.78
Trial 5	IPR	Sea only	Yes	+ 0.36	– 0.55
Trial 6	DCA	Land & sea	No	Failed 9/10 (Borneo)	
Trial 7	GPI1	Land & sea	No	+ 0.43	+ 0.60

Table 1: Configuration of the short assimilation trials and their impacts on the NWP index.

3.8 Additional verification of short trials

Tropical cyclone track verification was carried out by J. Heming on Trials 2, 3 and 4 in order to ensure that the assimilation of TCR estimates did not have any serious impacts on the forecasting of tropical cyclones. There were four storms active during the period 1-10 October 2000; Keith (N. Atlantic) and Olivia (N. E. Pacific) were the main storms with smaller contributions from Leslie (N. Atlantic) and 28W (N. W. Pacific).

Table 2 shows the mean percentage forecast track error relative to the control. Positive results thus indicate that experiment errors have been increased and negative results indicate that experiment errors have been reduced.

	T+24	*T+48*	*T+72*	*T+96*	*T+120*	*Weighted mean*
No. of cases	10	5	3	2	1	21
Trial 2	-1.8	+3.7	+6.2	+2.3	-4.4	+0.9
Trial 3	-0.9	+3.2	+4.9	-5.2	-16.0	-0.2
Trial 4	+0.2	+3.7	+1.6	-3.1	-9.6	+1.2

Table 2: Mean percentage forecast track error of trial relative to control, over the whole forecast range. The different cases represent forecasts derived from different analyses on consecutive days, and as such are only partially correlated.

On the basis of these results, tropical cyclone track forecasts have been improved only in Trial 3. However, the sample size is small, especially at long range, where most of the improvements are made, and so care must be taken in analysing these results. The conclusions reached by J. Heming are that no large systematic bias has been introduced into tropical cyclone track forecasts by the assimilation of TCR estimates. Fluctuating positive and negative impacts are to be expected where the changes are small, as shown above, and no solid conclusions as to their meaning can be drawn.

4 The extended trial

An extended trial and control run were performed for the period 1-23 October 2000. As for the short trials, these were performed at 288×217 resolution, and the GPI1 rain rate conversion method was used, over sea only, for the trial. This is the configuration that was used for Trial 4. Since there had been problems with the ATOVS bias corrections used operationally in October, standard updated bias corrections were used for the control run and bias corrections tuned to the trial configuration were used for the trial run. A system was also put in place to enable precipitation verification to be carried out.

From analysis of the results produced, it does not appear that the assimilation of satellite-derived estimates of TCR has had any particularly large impacts on the global model, although an overall small improvement has been made. The table below shows the main impacts when verification is made against observations and against analysis. As would be expected the main impacts are in the tropics, but there are significant impacts made in both Northern and Southern Hemispheres, away from the tropics.

	Observations		*Analysis*	
	Improvements	*Degradations*	*Improvements*	*Degradations*
NH	T50	H100	T50	H100, H50
Tropics	s.r. W, T50	H, l.r. W, T250	W, T500, T50	T850, T250, RH
SH	T50, H50	W100, H250, H100, H700	T100, T50, H50	l.r. H, RH
NWP Index	**+ 0.11**		**– 0.12**	

Table 3: Summary of the main improvements and degradations in the extended trial with respect to both observations and analysis. (s.r.=short range, l.r. = long range, T = temperature, H = geopotential height, W = winds, RH = relative humidity, the number following represents the pressure in hPa.)

The main improvements can be seen in temperature at 50 hPa, at all latitudes and at other selected levels to a lesser extent, tropical winds, and short range pmsl. The main degradations are seen in temperature at selected levels (mainly 250 hPa) and in geopotential heights.

The considerable change in impact between the 10-day Trial 4 and the extended trial (+0.42 to +0.11 against observations, +0.78 to –0.12 against analysis) was attributed to the different ATOVS bias corrections used in the two trials. The short trials all used the ATOVS bias corrections that had been used operationally in October. However, these were far from ideal and did not allow optimum use of ATOVS data in the model. This allowed the assimilation of TCR estimates to contribute a significant improvement to the model in the tropics. Bias corrections had been recalculated after the end of October and these improved bias corrections were used for the extended control. Because TCR assimilation alters the model behaviour in the tropics, ATOVS bias corrections must be recalculated specifically for the trial, using a few days of trial results, in order to take account of the changed model state. With both sets of improved bias corrections ATOVS data are assimilated much more successfully and as a consequence TCR data are no longer able to improve the model state over and above the effect of ATOVS by a significant amount. Although disappointing in terms of TCR assimilation, this does highlight the importance of successful ATOVS assimilation in the tropics and indicates that TCR data have played a part in this improved assimilation of ATOVS through their effect on the tropical mean fields.

4.1 Real Time Monitoring (RTM)

Real-time monitoring of T + 6 background fields with available observations yielded results that complement the standard verification statistics. Changes in the root mean square (RMS) difference between control and trial are generally small and mixed in sign. The main improvements are seen in comparisons with sonde and surface observations. Consistent with detailed verification statistics, there are large improvements in 50 and 850 hPa temperatures and smaller improvements in 700 and 500 hPa temperatures. Most geopotential height and relative humidity comparisons were degraded. Sea-based surface observation comparisons were generally improved more consistently than land-based, with pmsl and Pstar giving the greatest improvements.

4.2 Impact on convective rainfall

An attempt has been made, with this trial, to use a new system for verifying precipitation forecasts in the global model, based on that currently used in the mesoscale model. In addition, comparisons were made between model background (T+6) and GPI1 estimates of convective rainfall rates.

Figure 2 shows the mean control–trial analysis difference field of convective rain rates. There is a small mean decrease in rain rates, and this decrease is particularly apparent along the Inter-Tropical Convergence Zone (ITCZ) where convection is at a maximum.

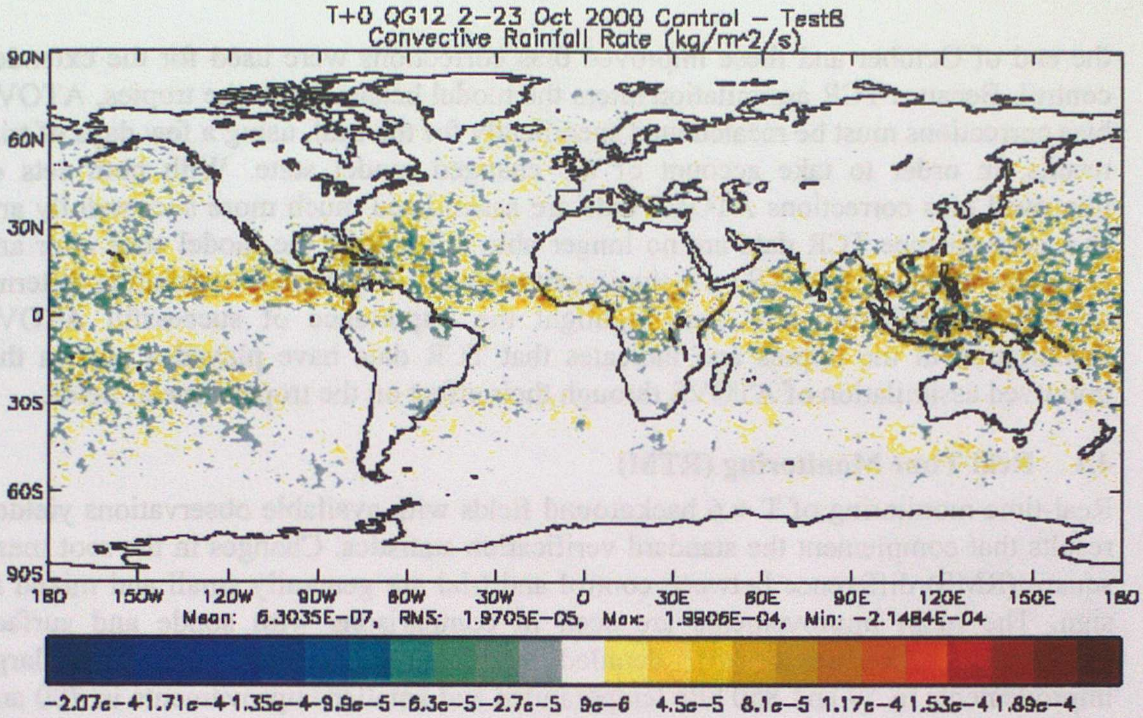


Figure 2: Control–trial difference of convective rainfall rate at analysis, at 12Z, averaged over period 2-23 October 2000.

However, the following section will attempt to draw conclusions as to whether the model representation of tropical convective rainfall has been improved by the assimilation.

In his short assimilation experiments Ringer (in preparation) found that although the method of assimilation employed was fairly successful at removing rain from the model where rates were overestimated, it was not able to add rain where the model was dry but observed rain rates were non-zero. It was hoped that assimilation of TCR estimates in the extended trial would, to some extent, reduce the positional errors in model forecasts of convective rain, by removing from the model some of the rain that was incorrectly located. However, study of the satellite-derived rain rate estimates with respect to the corresponding control and trial background rain rate fields indicates that this is not the case. Figure 3 shows convective rainfall rates from satellite observations (a) and the model control (b) and trial (c) background fields for 9 October 2000 at 12Z.

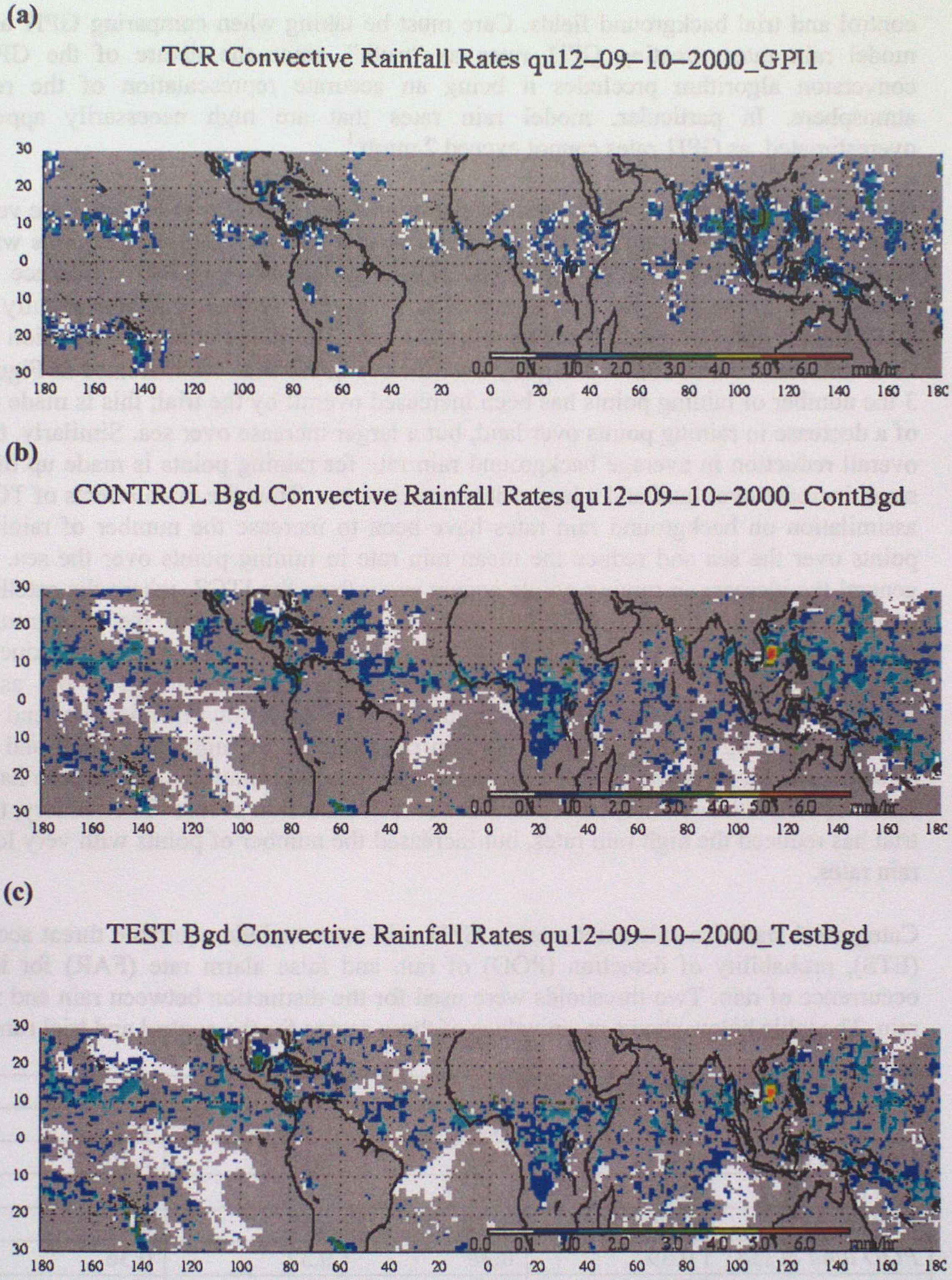


Figure 3: Convective rainfall rates at 12Z on 15 October 2000 (a) derived from satellite observations using the GPI1 conversion method, (b) from the model control background, and (c) from the model trial background.

Figure 3 shows that the coverage by the model of convective rainfall is overestimated with respect to satellite-derived estimates. Whereas GPI1 rain rates are non-zero mainly along the ITCZ and throughout the tropical West Pacific, model rain rates are additionally non-zero over large areas of the tropics either side of the ITCZ in both control and trial background fields. Care must be taking when comparing GPI1 and model rain rates, treating GPI1 rates as "truth", since the nature of the GPI1 conversion algorithm precludes it being an accurate representation of the real atmosphere. In particular, model rain rates that are high necessarily appear overestimated, as GPI1 rates cannot exceed 2 mmh^{-1}.

Differences between control and trial background rain rate fields in Figure 3 are very small and the assimilation of TCR has certainly not removed the large regions with low rain rate either side of the ITCZ. There is an average O–B difference of –0.07 mmh^{-1} throughout the whole control run. The trial reduces this bias slightly to –0.06 mmh^{-1} and this change occurs over the sea. The mean standard deviation of O–B rain rates is also reduced slightly over the sea in the trial. As indicated in Figure 3 the number of raining points has been increased overall by the trial; this is made up of a decrease in raining points over land, but a larger increase over sea. Similarly, the overall reduction in average background rain rate for raining points is made up of a small increase over land and a larger decrease over sea. Thus the main effects of TCR assimilation on background rain rates have been to increase the number of raining points over the sea and reduce the mean rain rate in raining points over the sea. In general the increase in raining points occurs away from the ITCZ, where the satellite imagery does not show a significant amount of cold cloud, but the background produces many points with very low rain rates. These points have not been produced through assimilation of a wet latent heating profile from the imagery, but as a feedback from other effects of the assimilation. The reductions in rain rate tend to occur more along the ITCZ, where the rain rates tend to be high and correspond to areas of cold cloud in the imagery. In these cases, the assimilation does seem to have removed rain/reduced rates, and caused the overall reduction in rate. In summary, the trial has reduced the high rain rates, but increased the number of points with very low rain rates.

Categorical statistics calculated versus GPI1 rain rates include equitable threat score (ETS), probability of detection (POD) of rain and false alarm rate (FAR) for the occurrence of rain. Two thresholds were used for the distinction between rain and no rain. The table below shows mean values of these scores for the control and trial runs.

	0.0 mmh^{-1} threshold		*0.2 mmh^{-1} threshold*	
	Control	*Test*	*Control*	*Test*
ETS land & sea	0.07	0.06	0.10	0.10
ETS land	0.12	0.11	0.10	0.09
ETS sea	0.06	0.04	0.11	0.11
POD land & sea	0.39	0.38	0.37	0.36
POD land	0.28	0.27	0.25	0.25
POD sea	0.44	0.42	0.42	0.41
FAR land & sea	0.77	0.78	0.77	0.77
FAR land	0.62	0.62	0.73	0.73
FAR sea	0.79	0.81	0.78	0.77

Table 4: Mean values of ETS, POD and FAR over land and sea, for control and trial, using rain/no rain thresholds of 0.0 and 0.2 mmh^{-1}.

Although changes in the statistics between control and trial are small, the probability of detection of rainfall has been consistently reduced in the trial, especially over sea, and the false alarm rate has consistently increased. Correspondingly the correlation of background and observed rain rates has decreased slightly over sea. Contrary to expectations, the assimilation of TCR estimates has reduced, rather than improved, the positional accuracy of model convective rainfall over the sea.

There is a known discrepancy between the diurnal cycle of convection in the real atmosphere and that in the UM. In reality the maximum in convection over land occurs in the late afternoon/early evening and the minimum in the early morning. There is sometimes a second nocturnal convection maximum due to night-time cooling of cloud tops. This nocturnal convection maximum is particularly prevalent over the ocean where convection tends to maximise in the early morning and decrease throughout the course of the day. In the global UM, maximum convection occurs at midday over land and sea, when solar heating is at a maximum. The monitoring of background rain rates clearly shows the minimum rates at 0Z and maximum at 12Z, especially over the land. This is the case for both the control and trial, with no noticeable phase difference between the two runs. Examination of the background fields of rain rates corroborates this finding and leads to the conclusion that assimilation of TCR estimates has not made any noticeable difference to the model diurnal cycle discrepancy.

4.2.i Precipitation verification against rain rates

In order to carry out a formal verification of the trial forecasts against rain rates, GPI1 estimates, valid at the forecast time, were again used to represent observed rain rates. Figure 4 shows the mean and RMS forecast errors throughout the forecast range for the control and trial.

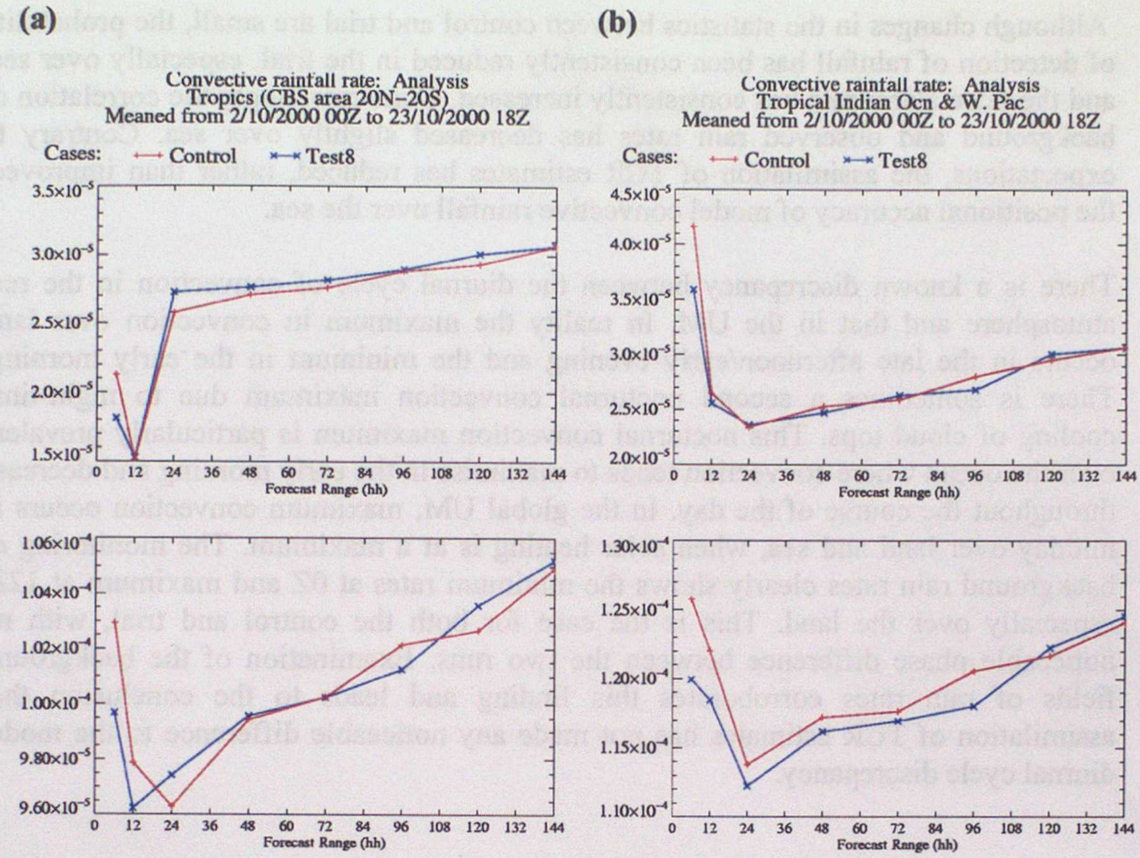


Figure 4: Convective rain rate mean (upper) and RMS (lower) forecast errors (Fc–Obs) throughout the forecast range for (a) the whole tropical region, and (b) the Tropical Indian Ocean and West Pacific. The control is shown in red and the trial is shown in blue.

In general the bias in model tropical rain rates is such that the model rain rates are too high with respect to GPI1 satellite-derived rain rates, as with T+6 comparisons. This is not surprising considering the upper bound on GPI1 rates of 2 mmh^{-1}. Figure 4 shows that the trial tends to increase these rain rates, and thus increase the wet bias, however at short range, the trial reduces the bias by reducing rain rates. In the tropical Indian Ocean and West Pacific, the trial improves the RMS error significantly at all but the longest forecast ranges, by reducing rain rates, and hence appears to give the most favourable results in this region of the tropics.

4.2.ii Precipitation verification against rain accumulations

Rainfall accumulations are reported globally from surface observations and thus provide an independent means of verification for the trial. Accumulation verification is carried out for 6-hour, 12-hour and 24-hour accumulations, however it is important to note that the observations are reported at different times and for different accumulation periods according to geographical location and so for any one time or accumulation amount, the spatial coverage is variable and tends to be continentally localised. Care must be taken to note the number of contributing observations when making accumulation comparisons in different regions of the tropics.

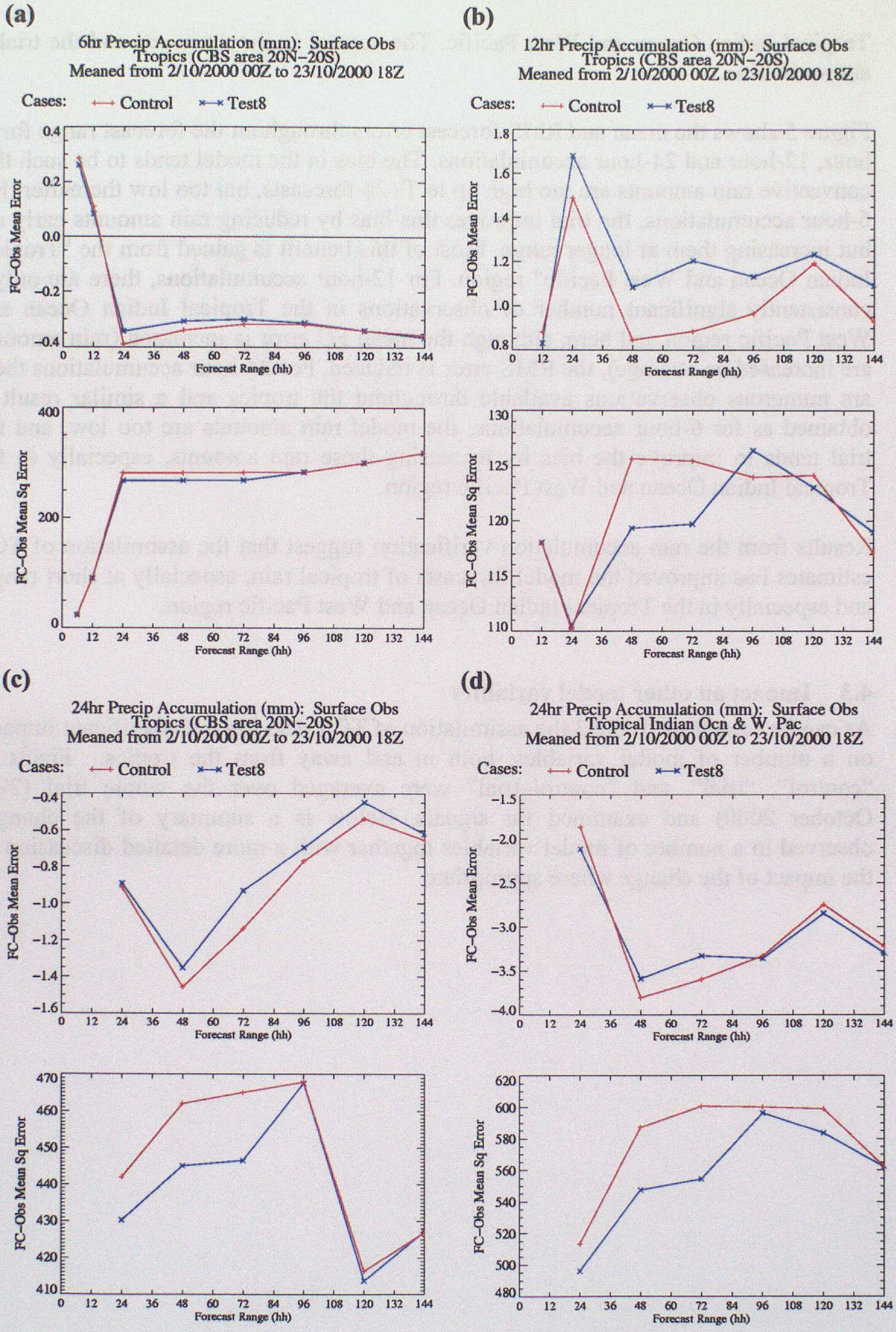


Figure 5: Mean (upper) and RMS (lower) forecast errors (Fc–Obs) throughout the forecast range for (a) 6-hour, (b) 12-hour, and (c) 24-hour accumulations of convective rain in the whole tropical region, and (d) 24-hour accumulations in the

Tropical Indian Ocean and West Pacific. The control is shown in red and the trial is shown in blue.

Figure 5 shows the mean and RMS forecast errors throughout the forecast range for 6-hour, 12-hour and 24-hour accumulations. The bias in the model tends to be such that convective rain amounts are too high up to T+24 forecasts, but too low thereafter. For 6-hour accumulations, the trial improves this bias by reducing rain amounts early on, but increasing them at longer range. Most of this benefit is gained from the "Tropical Indian Ocean and West Pacific" region. For 12-hour accumulations, there are only a consistently significant number of observations in the Tropical Indian Ocean and West Pacific region and here, although the mean FC error is increased (rain amounts are increased on average), the RMS error is reduced. For 24-hour accumulations there are numerous observations available throughout the tropics and a similar result is obtained as for 6-hour accumulations; the model rain amounts are too low, and the trial tends to improve the bias by increasing these rain amounts, especially in the Tropical Indian Ocean and West Pacific region.

Results from the rain accumulation verification suggest that the assimilation of TCR estimates has improved the model forecasts of tropical rain, especially at short range, and especially in the Tropical Indian Ocean and West Pacific region.

4.3 Impact on other model variables

As can be seen from Table 3 the assimilation of TCR data has had significant impacts on a number of model variables, both in and away from the tropics. Fields of “control”, “trial”, and “control–trial” were averaged over the whole trial (2-23 October 2000) and examined for signals. Below is a summary of the changes observed in a number of model variables together with a more detailed discussion of the impact of the change where appropriate.

4.3.i Main diagnostic variables

Pressure at mean sea level (pmsl)

Pmsl is increased overall by an average of 0.32 hPa. Increases have occurred along the ITCZ and decreases in the extra-tropics and mid-latitudes. The tropical low pressure bias in the control forecasts has thus been improved slightly in the trial. The large anomalies seen in the Antarctic region of this and other figures in this section are not uncommon in assimilation impact trials. Since there are almost no observations to constrain the model in this region, the Antarctic model fields are very unrealistic and susceptible to disturbances of the model dynamics. These anomalies are not, however, a cause for concern in these trials. Figure 6 shows mean field differences in pmsl between control and trial averaged over the whole trial period.

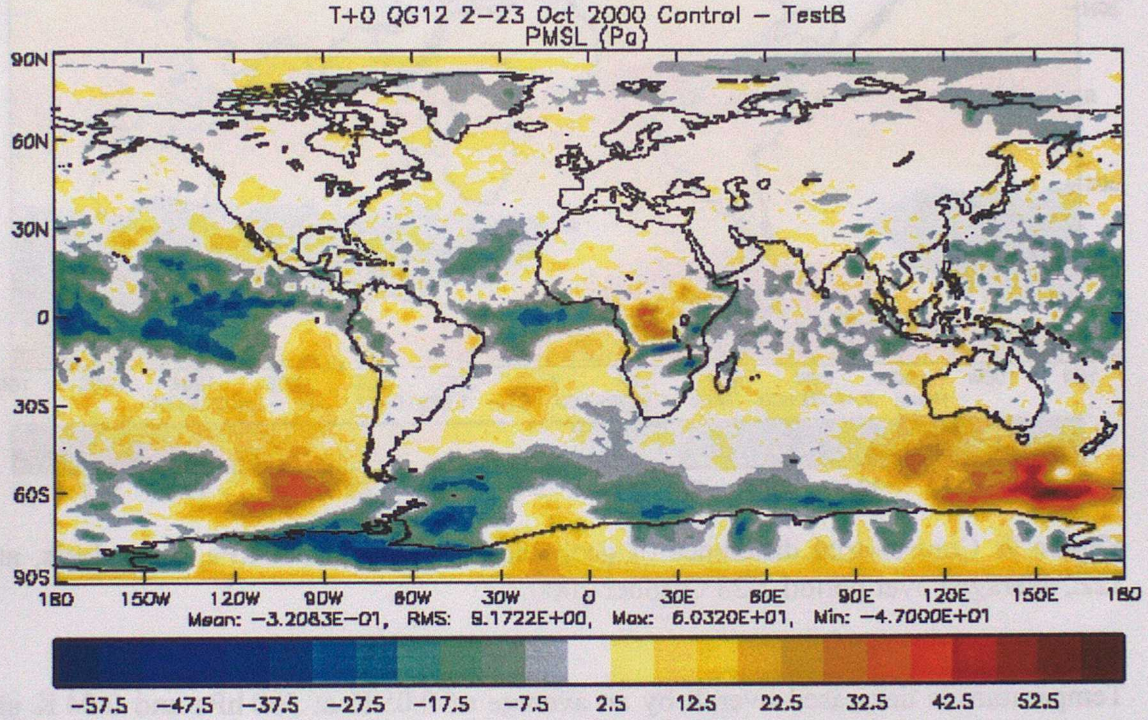


Figure 6: Control–trial difference of pmsl at analysis, at 12Z, averaged over period 2-23 October 2000.

Geopotential height

Geopotential height is decreased overall by an average of 2.48 m at 100 hPa and 0.43 m at 500 hPa. Values are reduced throughout the tropics, especially along the ITCZ, and increased at mid-latitudes. The degradations in geopotential height apparent from standard verification arise because the model tends to underestimate geopotential height in general and the overall reduction in height by the trial has made this low bias worse. Figure 7 shows mean field differences in 100 hPa geopotential height between control and trial averaged over the whole trial period.

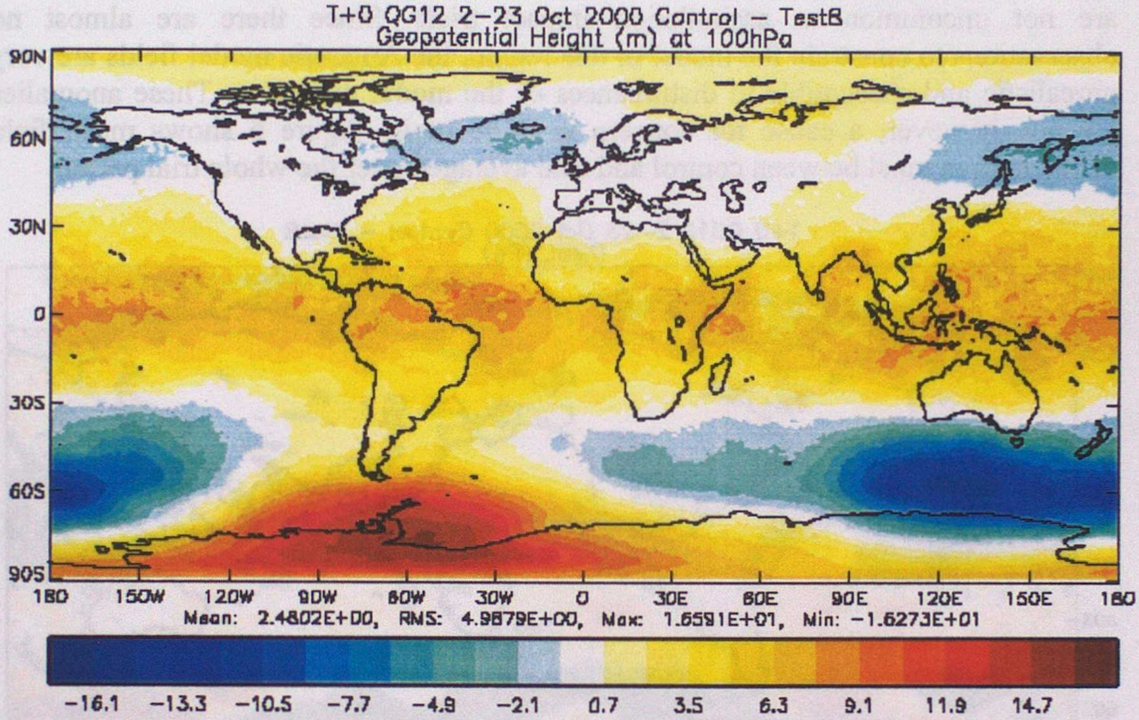


Figure 7: Control–trial difference of geopotential height at 100 hPa, at analysis, at 12Z, averaged over period 2-23 October 2000.

Temperature

Temperature is decreased overall by an average of 0.05 K at 500 hPa and 0.04 K at 750 hPa. At 850 hPa there is cooling along most of the ITCZ, with a maximum reduction of 1.5 K in the mid-Pacific. Warming occurs in the mid-latitudes, particularly in the Southern Hemisphere (SH) and in some isolated regions in the tropics, e.g. parts of the West Pacific. At 500 hPa the pattern is similar, except that the cooling is more widespread throughout the tropics. Figure 8 shows mean field differences in 850 hPa temperature between control and trial averaged over the whole trial period.

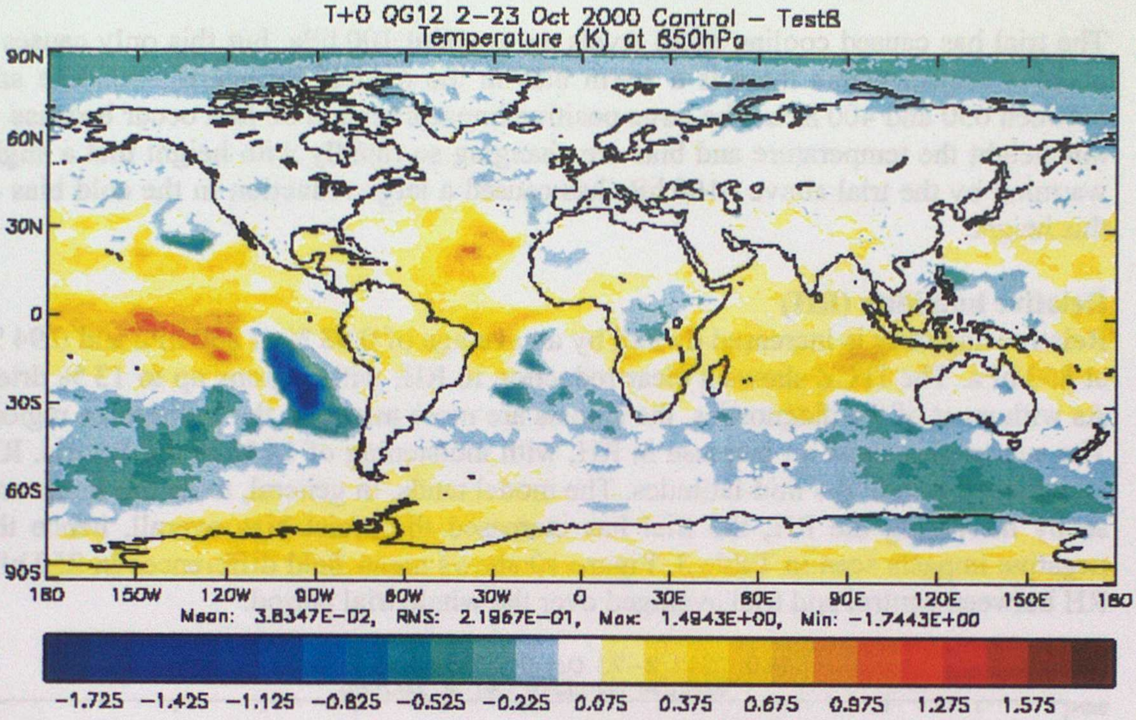


Figure 8: Control–trial difference of temperature at 850 hPa, at analysis, at 12Z, averaged over period 2-23 October 2000.

The impact of these temperature changes on model forecast errors varies depending on vertical level, as seen in Table 3. Figure 9 below shows the vertical profile of mean forecast error in tropical temperature for the control (red) and trial (blue) runs at T+24.

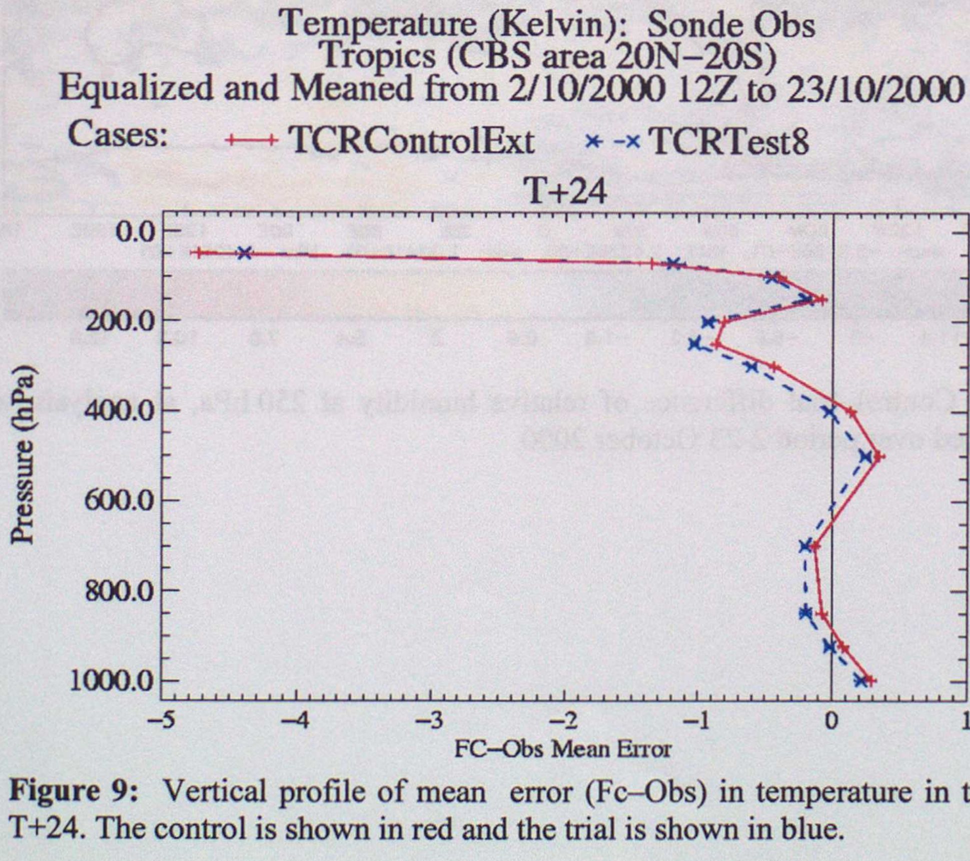


Figure 9: Vertical profile of mean error (Fc–Obs) in temperature in the tropics at T+24. The control is shown in red and the trial is shown in blue.

The trial has caused cooling at all levels up to about 100 hPa, but this only causes a positive impact where there is a warm bias in the model, i.e. below ~900 hPa and between 650 and 400 hPa. The large positive impacts seen at 50 hPa occur because at this height the temperature and bias are changing so rapidly with height that a slight warming by the trial above ~100 hPa has caused a large reduction in the cold bias at this height.

Relative humidity (RH)

Relative humidity is increased overall by an average of 0.98 % at 250 hPa and 0.94 % at 850 hPa. The ITCZ shows a clear reduction in RH, with regions up to 13 % drier. As with most of the diagnostics, the signals are more mixed in the Indonesian region. The sub-tropics show an increase in RH, with moistening of 14 % in the Pacific. RH is reduced again in the mid-latitudes. The model tends, in general, to be too moist and so by increasing the RH, the trial has increased the moist bias overall, hence the negative impacts seen in Table 3. Figure 10 shows mean field differences in 250 hPa RH between control and trial averaged over the whole trial period.

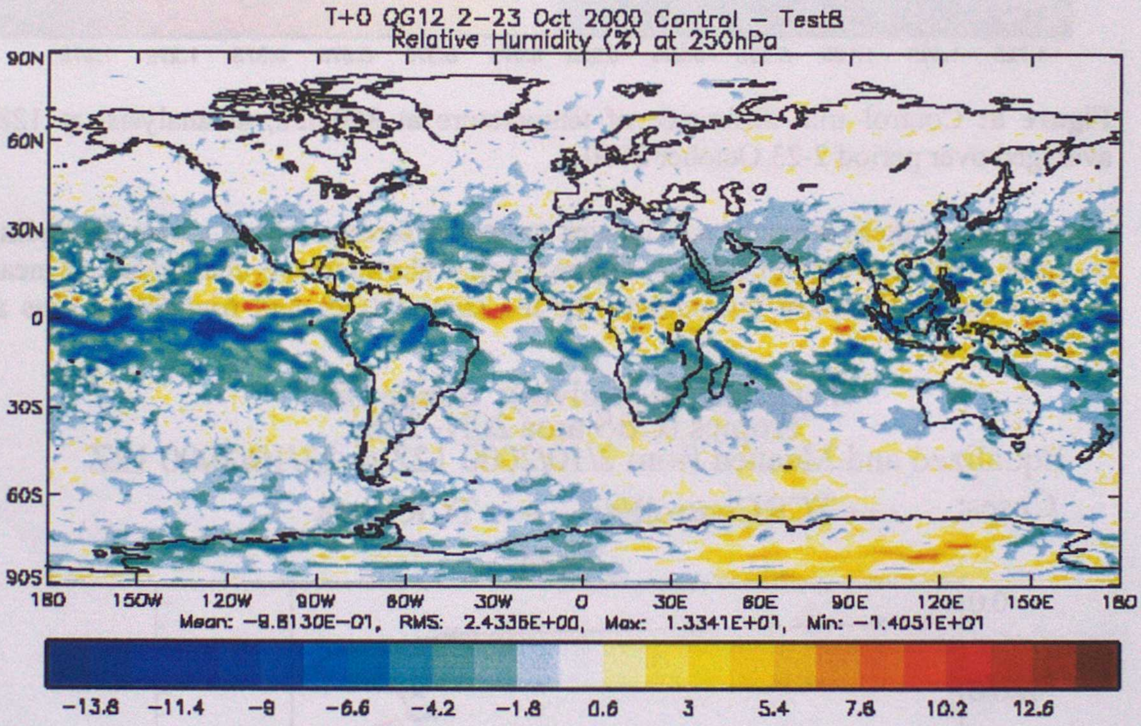


Figure 10: Control–trial difference of relative humidity at 250 hPa, at analysis, at 12Z, averaged over period 2-23 October 2000.

High cloud fraction

The high cloud fraction is increased overall by an average of 0.002. The ITCZ shows a clear decrease in high cloud fraction, of up to 0.3, except over Thailand where an increase of ~0.2 occurs. The main decreases in cloud amount occur to the west of the South American and African continents. Figure 11 shows mean field differences in high cloud fraction between control and trial averaged over the whole trial period.

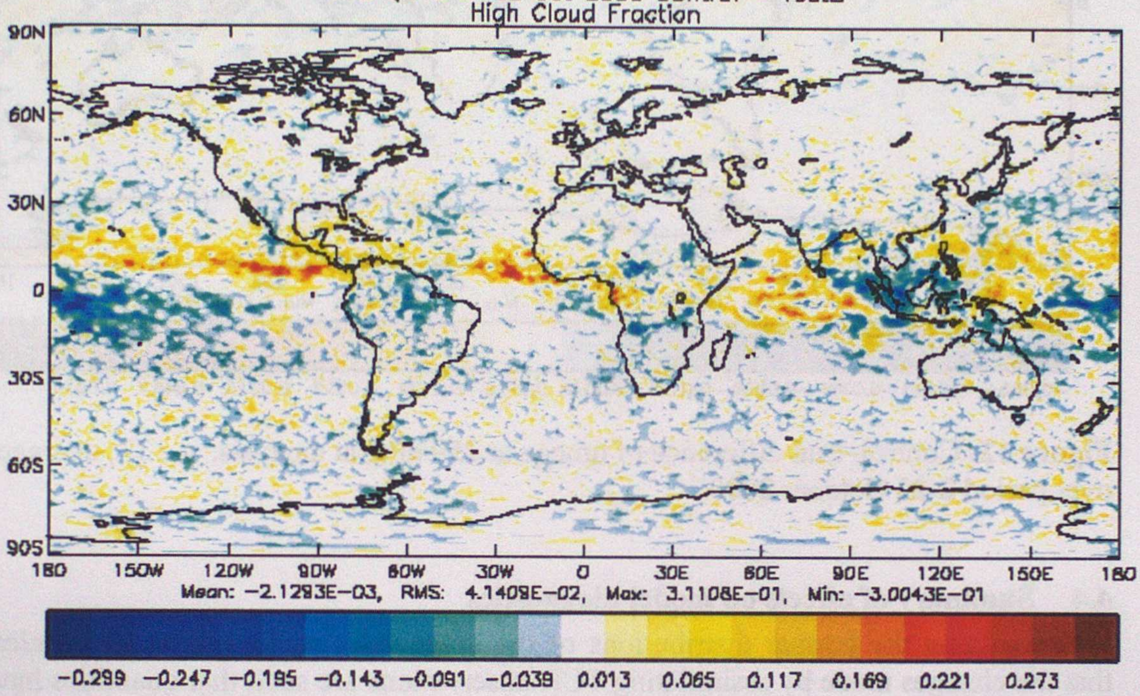


Figure 11: Control–trial difference of high cloud fraction at analysis, at 12Z, averaged over period 2-23 October 2000.

Vertical velocity (Ω)

Since values of Ω are both positive and negative, the RMS change is taken to show what effect the assimilation of TCR data has had. The RMS change in Ω overall is a decrease 0.005 ms^{-1} at 250 hPa and 0.009 ms^{-1} at 850 hPa. Along the ITCZ, where Ω is negative, Ω is made less negative (i.e. the magnitude of upward motion is less), except over Thailand, where upward motion is increased. In the extra-tropics, where Ω is mainly positive, Ω is made less positive (i.e. the magnitude of the downward motion is less). Figure 12 shows mean field differences in 250 hPa Ω between control and trial averaged over the whole trial period.

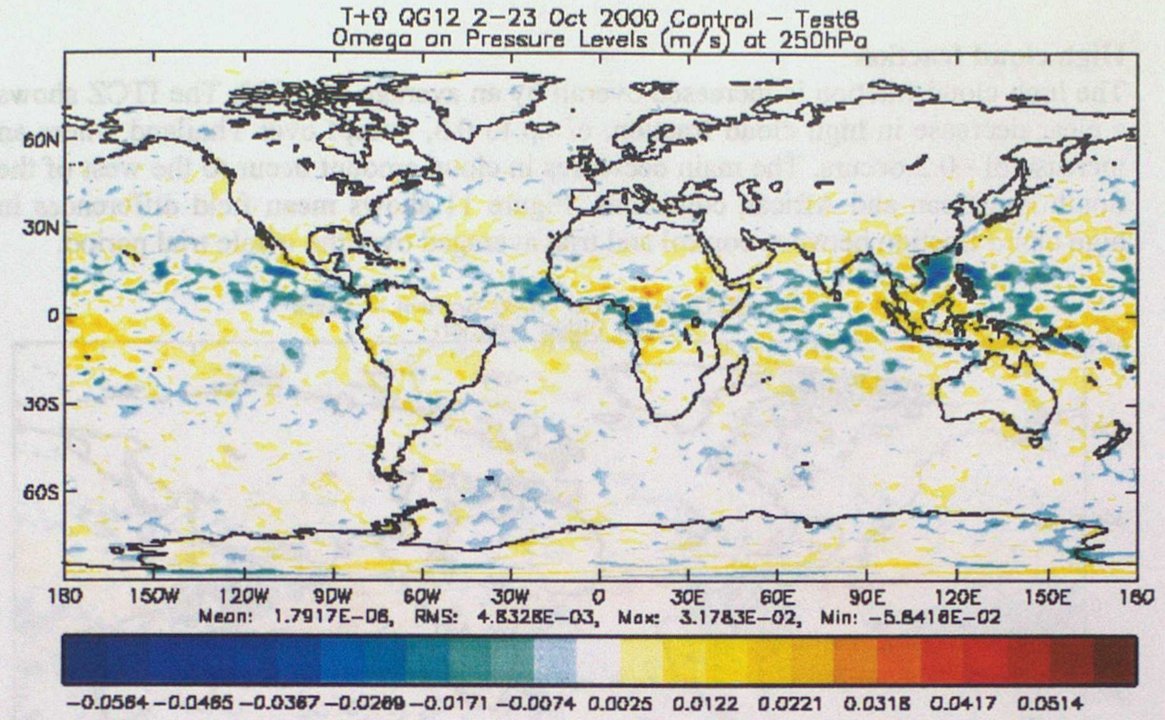


Figure 12: Control–trial difference of omega at 259 hPa, at analysis, at 12Z, averaged over period 2-23 October 2000.

4.4 Summary of effects on model diagnostics

By examining the normal distributions of the diagnostics studied, it becomes clear that the changes made by assimilating TCR observations are such that quantities have been reduced where they are highest and increased where they are lowest, *i.e.* the latitudinal distributions of quantities have been damped. Although the changes are mainly very small, the consistent way in which they have been made means that they do have some significance. The following table shows the direction of changes that have been made to a range of model variables averaged globally, in the region of the ITCZ, and in the sub-tropics.

	Global average	*ITCZ*	*Sub-tropics*
Pmsl	increase	increase	decrease
Temperature	decrease	decrease	increase
Relative humidity	increase	decrease	increase
Geopotential height	decrease	decrease	decrease
High cloud fraction	increase	decrease	increase
Vertical motion	speed decrease	ascent reduced	descent reduced
Convective rain rate	decrease	decrease	increase

Table 5: Qualitative changes in model variables caused by TCR assimilation globally, along the ITCZ and in the sub-tropics.

This would seem to suggest that convection has been reduced along the ITCZ. The reduction in high cloud amount, temperature, relative humidity and convective rain rate are all consistent with reduced ascent from convection, thus less convective cloud formation and less subsequent latent heat release. The region either side of the ITCZ, at about ± 30° where air descends shows evidence of reduced descent and hence of less constraint to convection.

The GPI1 rain rate conversion method only yields rain in the region of maximum tropical convection where cloud tops are sufficiently cold (i.e. ITCZ), and so the slight reduction of convective rainfall in this region in the model would appear to be a direct result of the assimilation. The increase in convective raining points which occurred away from the ITCZ was not a direct consequence of the assimilation, since no sufficiently cold cloud was present in this region, but indirectly through the reduction of descent. Since the descent constraint to convection had been lessened, the model was better able to produce convective motion in this region.

4.5 Monitoring AMSU radiances

In addition to the standard verification and monitoring carried out on this trial, it was also important to ascertain that the model background is not being pulled away from other very reliable observations, on which the model relies heavily, by the assimilation of TCR estimates. For this reason, the effect of the TCR assimilation on AMSU O–B radiance standard deviations was assessed by D. Jones. It was not expected that these could be significantly improved by the trial, but it was important to ascertain that there were no significant degradations in the comparison between background and observed AMSU radiances.

Monitoring statistics from both channels 5 and 6 were examined, as these channels correspond to the lower part of the atmosphere which is most likely to be affected by TCR assimilation. Figure 13 below shows the zonal mean standard deviation OB for AMSU channel 5, using uncorrected observed radiances.

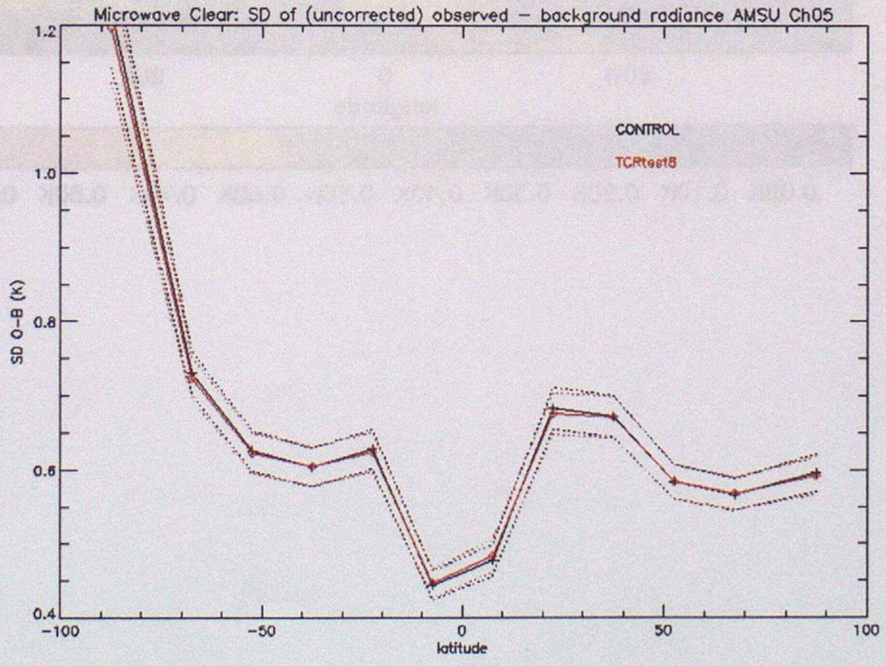


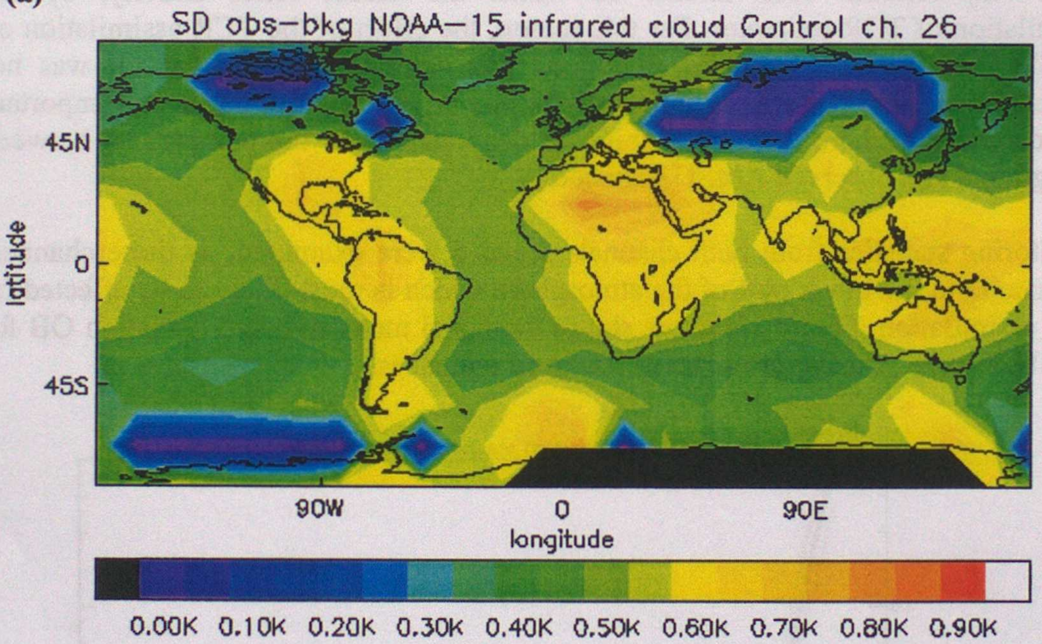
Figure 13: Zonal mean standard deviation of uncorrected observed–background radiance for AMSU channel 5; microwave clear. The control is shown in black, and

the trial in red. Limits of standard error are given by the dotted lines and the zonal mean standard deviation is given by the solid lines.

Assimilating TCR estimates has clearly made very little difference to the standard deviation of O–B channel 5 AMSU radiances, and all changes occur within the limits of standard error. This behaviour is very similar for bias corrected (O–B) statistics. These results lead to the conclusion that the assimilation of TCR estimates has not in any way degraded the model representation of AMSU radiances. It is worth noting that, although not of major concern, the TCR assimilation does have a more detrimental effect on channel 18 O–B statistics. This represents a degradation in model relative humidity errors.

In addition, the standard deviation of O–B was plotted on maps for AMSU channel 6 in order to examine the effect of TCR assimilation on areas of known model error with respect to AMSU observations. Figure 14 shows these maps for the control background (a) and the trial background (b).

(a)



(b)

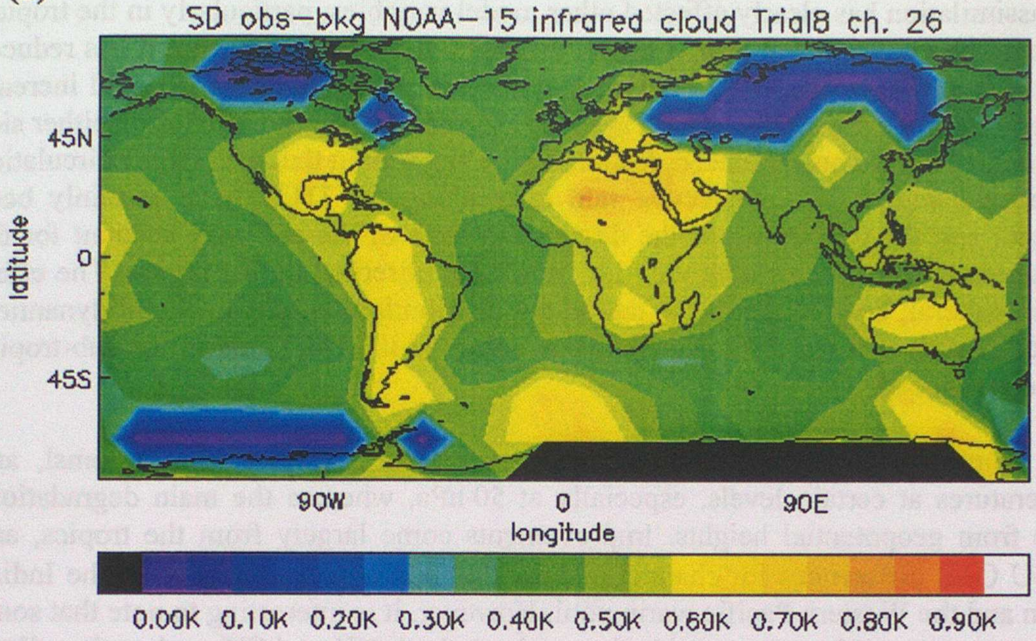


Figure 14: Standard deviation of O–B for AMSU channel 6 radiances for (a) the control and (b) the trial.

It is clear that the standard deviation has not been increased in any way by the assimilation of TCR estimates (no increase in (b) over (a)). There is no reason for concern, therefore, that the model is being pulled further away from the "truth". However, the standard deviation does appear to have been reduced in a number of regions in (b), suggesting that the TCR assimilation may actually be reducing known model errors to some extent. The main areas of improvement are in the tropics near land/sea borders and in the Indian Ocean and West Pacific, where the standard deviation (SD) O–B is reduced by up to 0.1 K over large areas. This improvement in model error is important since the "warm pool" in the tropical Western Pacific is a known systematic error. There is no obvious difference between control and trial in the NH outside the tropics, but there are small improvements in the Southern Hemisphere, notably in the S. Pacific Ocean and S. Indian Ocean/Southern Ocean. It should be stressed that although these results are encouraging, the changes involved differ between AMSU channels and should not be awarded too much significance. For channel 5 the same area is degraded slightly in the trial relative to the control.

5 Conclusions

Although only small, the assimilation of satellite-derived estimates of TCR into the global model has produced an improvement in the NWP index with respect to observations. The effect of the assimilation on model tropical convective rainfall has not been great, and no improvement has been made in diurnal errors or positional accuracy of the model rainfall. However, the verification suggests that rain rate and amount forecasts have been improved by reducing short range rainfall and increasing it at longer range, hence slightly improving the model spin-up and subsequent drop-off of convective rainfall.

The assimilation has clearly affected other model variables, particularly in the tropics, as would be expected, but also at higher latitudes. It would appear that it has reduced tropical convection, causing a cooling, lowering of geopotential height, and increase in pmsl. Both the ascending motion at the ITCZ and the descending motion either side (~30 degrees) have been reduced, leading to the suggestion that the Hadley circulation has been damped. The convective rain rates along the ITCZ have certainly been reduced, and the weakening of the descending limb of the cell may account for the increase in raining points with very low rain rates observed in this region. The effect has, in general, been to damp the latitudinal distributions of physical and dynamical quantities such that the difference between values at the ITCZ and in the sub-tropics has been reduced.

Main improvements to the forecast are to be seen in tropical winds, pmsl, and temperatures at certain levels, especially at 50 hPa, whereas the main degradations come from geopotential heights. Improvements come largely from the tropics, and AMSU O–B differences for channel 6 show that this is particularly so in the Indian Ocean and the Western Pacific warm pool. However, it is interesting to note that some improvements are also seen outside the tropics in both NH and SH, and so the effects of the assimilation have propagated out of the region of assimilation.

These trials do not give sufficiently positive results to recommend operational assimilation at this point. However, they are sufficiently encouraging to warrant further investigation in additional trials to be undertaken when the New Dynamics formulation of the UM is operationally available.

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