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Technical Note: Description and assessment of a nudged version of the new dynamics Unified Model

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Abstract

We present a 'nudged' version of the Met Office general circulation model, the Unified Model. We constrain this global climate model using ERA-40 reanalysis data with the aim of reproducing the observed "weather" over a year from September 1999. Quantitative assessments are made of its performance, focussing on dynamical aspects of nudging and demonstrating that the "weather" is well simulated.

1 Introduction

The ability to mimic the real state of the atmosphere, the "weather", in a climate model is useful for studying processes on short time scales for which monthly means contain only a limited amount of information. Newtonian relaxation or "nudging" is a method that adjusts dynamical variables of general circulation models (GCM) towards meteorological analysis data, providing a realistic representation of the weather.

Jeuken et al. (1996) were the first to consider applying the technique to the validation of GCMs, adding nudging to the ECHAM GCM. This remains the most complete description of a nudged model, though others exist, including the LMDZ (Hauglustaine et al., 2004), GISS (Schmidt et al., 2006) and CCSR/NIES AGCM (Takemura et al., 2000) models. The technique has been widely adopted to study processes where capturing the daily variability of phenomena is important. Examples include examining the behaviour of chemical tracers (van Aalst et al., 2004), and studying the properties of clouds (Dean et al., 2006).

The climate model which we nudge is the Met. Office GCM, the *Unified Model* (henceforth the UM) (Staniforth et al., 2005). There have been applications of the nudging technique in earlier versions of this model, to study clouds (Flowerdew et al., 2007[1]) and to include a realistic quasi biennial oscillation (Pyle et al., 2005). We

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[1]Flowerdew, J., Lawrence, B. N., and Andrews, D.: The use of nudging and feature tracking to evaluate climate model cloud, Climate Physics, submitted, 2007.

describe the first implementation of the nudging technique to the new non-hydrostatic version of the UM, the "New Dynamics" UM, and validate the performance of the system for a 12 month integration starting in September 1999.

After a brief description of the model, we provide a quantitative assessment of its performance with respect to the ERA-40 analysis data. The RMSE, bias and correlations in space and time between the model and the analysis data are calculated, with and without nudging, for variables that are directly adjusted by the nudging and variables adjusted indirectly. After varying a few key parameters we conclude by considering future prospects for the model.

2 Model description

The Model is based upon version 6.1 of the UM (Staniforth et al., 2005). The dynamical prognostic variables adjusted by nudging are potential temperature, θ, zonal wind, u, and meridional wind, v. The configuration used has

– a horizontal resolution of $3.75° \times 2.5°$ in longitude and latitude.

– 60 hybrid height levels in the vertical, from the surface up to a height of 84 km.

– a dynamical time-step of 20 min.

The sea surface temperatures and sea ice coverage are prescribed from the HADISST dataset (Rayner et al., 2002). The version of the model used was known to have temperature biases, the most notable being a warm bias in the lower stratosphere, especially over the poles, and around the tropical tropopause.

To the original model is added a module that reads global analysis data and 'nudges' the model towards it. The analysis data used here is from the ECMWF ERA-40 dataset (ECMWF, 1996; Uppala et al., 2005). Although there are some weaknesses in the ERA-40 analysis, such as an overly strong Brewer-Dobson Circulation (Uppala

et al., 2005), they have been widely used (Jeuken et al., 1996; Hauglustaine et al., 2004) and are adequate to assess the performance of nudging.

2.1 Data assimilated

The ECMWF ERA-40 analysis data is used in the assimilation. It is available at six hourly intervals on a 1˚×1˚ grid. The variables taken for nudging are temperature, T, zonal wind, u, and meridional wind, v.

The analysis data is pre-processed horizontally by bilinearly interpolating on to the model grid. At run-time it is linearly interpolated on to the model time-steps. Previous studies indicate that there is no advantage to using more complex interpolations over these time-scales (Brill et al., 1991). To obtain the UM prognostic variables, T is converted to θ. The variables, u, v and θ, are interpolated linearly in logarithm of pressure, $\ln(P)$, from the ECMWF hybrid pressure levels to the UM hybrid height levels. The different orographies used by the UM and ECMWF models results in errors in regions with complex orography. The base orographic datasets are not dissimilar, but spectral fitting and smoothing creates differences, which can be as large as hundreds of metres over the Andes and Antarctica.

A solution considered was the use of the ECMWF orography in the nudged UM model. However this would create problems; apart from the question of how to interpret a spectral orography in a grid-point model, it could disrupt other aspects of the model such as orographic gravity wave drag. As the errors are predominantly in the lowest few model levels, where nudging is not applied, these disadvantages were felt to make this solution impracticable. Although using the Met Office analysis data (Lorenc et al., 1999) would remove any differences in orography they were not used as they are only available once a day.

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2.2 Set up of the nudging

The analysis data is assimilated into the model by the addition of non physical relaxation terms to the model equations. The rate of change in a variable, X, is obtained from

$$\frac{\delta X}{\delta t} = F_m(X) + G(X_{ana} - X), \tag{1}$$

where F_m is the rate of change in the variable due to all other factors, X_{ana} is the value of the variable in the ECMWF analysis data and G is the relaxation parameter (Jeuken et al., 1996). As we are working in discrete time-steps this equation becomes

$$\Delta X = F_{mt}(X) + (G\Delta t)(X_{ana} - X), \tag{2}$$

where F_{mt} is the change of the variable due to all other factors over the dynamical time-step and Δt is the dynamical time-step size.

The choice of relaxation parameter, although arbitrary, is important, as if it is too small nudging is ineffective, yet too large and the model becomes unstable. The value chosen is the "natural" one of $\frac{1}{6}$ h^{-1}, the time spacing of the analysis data. This also lies within the range of relaxation parameters used by other models (Jeuken et al., 1996; Hauglustaine et al., 2004; Schmidt et al., 2006).

The variation of the relaxation parameter with UM hybrid height level is displayed in Fig. 1. The average ECMWF temperature, as a function of UM hybrid height level, is included for orientation. The temperature is taken from the analysis data in October 1999 and interpolated onto the UM hybrid height levels.

Nudging is not applied to all levels; it is not applied on levels which utilise data from the topmost ECMWF hybrid pressure levels, or in the bottommost levels that constitute the boundary layer. This results in no nudging being applied above level 50 ($\sim$48 km), with a linear increase in G from 0 at level 50 to its full value at level 45 ($\sim$38 km), or below level 12 ($\sim$2.9 km[2]), with a linear increase in G from 0 at level 12 to its full value

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[2]The levels are hybrid height levels and their exact values depend on the orography.

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at level 15 (∼4.5 km). The effect of using different relaxation parameters and vertical ranges is discussed in Sect. 4.

3 Assessment of model performance

The model was run for a year starting from 1 September 1999. From this simulation three periods are selected for more detailed analysis; October, January and July. During these periods a suite of statistical tools is used to determine the size of any differences and correlations between the model and the analysis data.

The main assessment consists of a series of comparisons of variables, including some which are nudged directly (u and θ), and some which are not (surface pressure, P_s, and specific humidity, q). The comparison examines the size and variation of differences between the model and the analysis data. In addition derived quantities, such as precipitation and vertical wind are compared. To establish that nudging does not predominate over the physical tendencies in the model, the effect of nudging and other factors, are studied.

3.1 Comparison of dynamical quantities

The first assessment of the model performance is to compare dynamical quantities between the model and the analysis data. The following variables are studied, the first two are directly adjusted, the latter two not: potential Temperature (θ), zonal wind (u), specific humidity (q) and surface pressure (P_s). This is done using a series of quantitative assessments:

- The root mean squared error (RMSE); obtained by taking the root mean square difference between the model and analysis data. The value on a particular model level is obtained by averaging the differences over time and over all grid-points on that level. It is a measure of the magnitude of differences in the observable.

- Bias; obtained by taking the difference in the monthly mean of the observable between the model and the analysis data. The value on a particular model level is obtained by averaging over all grid-points on that level. It reflects any systematic differences between them.

- Correlation in time (TC); determined by calculating the correlation in time between the observable in the model and the analysis data for each grid-point. The value on a particular model level is obtained by averaging over all grid-points on that level. It is a measure of how well the model represents the variation in time of the analysis data.

- Correlation in space (SC); determined by calculating the spatial correlation between the observable in the model and the analysis data over a model level and averaging over time. It provides a measure of how well the model represents the variation in space of the analysis data.

The variable used to determine the correlation is Pearson's rank coefficient. The time series consisted of one set of values taken every day at midnight UTC. For all variables, excluding surface pressure, the assessments are calculated on levels representing regions of the atmosphere. In the case of surface pressure they are determined for the surface level alone. The chosen levels are

- Level 6, corresponding to a height of around 700 m, representing the boundary layer.

- Level 16, corresponding to a height of around 5 km, representing the free troposphere.

- Level 29, corresponding to a height of around 15 km, which is around the tropopause, as shown in Fig. 1, and the region in the polar stratosphere where polar stratospheric clouds form.

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– Level 35, corresponding to a height of around 20 km, representing the lower stratosphere.

The analysis data is obtained on UM hybrid height levels by interpolating linearly in $\ln P$ for each model time-step.

⁵ The assessments are performed over three time periods, in October, January and July, with and without the nudging module added. The unadjusted results are taken from three separate integrations each initialised at the start of the month from the output of the nudged integration, so that any differences cannot be attributed to starting conditions.

¹⁰ The values for October are given in Table 1 with nudging and Table 2 without. The values from January and July are not significantly different and so are not displayed.

3.1.1 Magnitude of differences

The RMSE represents the magnitude of the difference between the model and the analysis data. The addition of nudging reduces the RMSE in all of the assessments
¹⁵ made, as shown in Tables 1 and 2, evidence that nudging improves the agreement with the analysis data. Figure 2 plots the percentage RMSE of θ between the model with nudging and the analysis data as a function of UM hybrid height level for the three assessment periods. This shows that the RMSE varies little over the height range nudged and over time.
²⁰ The rapid increase in the percentage RMSE towards the top of the model, above the region where nudging is applied, reflects the different treatment of the upper stratosphere between the UM and ECMWF models. The increase in the RMSE towards the bottom of the model has two components. The increase below level 13 ($\sim$3.5 km) is produced by the fading out of nudging. The increase below level 6 ($\sim$700 m) is a result
²⁵ of errors in the vertical interpolation used to obtain the analysis data on the UM hybrid height levels.

This can more clearly be seen in Fig. 3, which plots the absolute RMSE in θ for the

UM hybrid height level closest to the surface (20 m above the surface). The regions where the orography between the two models differ, such as Antarctica, Greenland and the Himalayas, tend to have high values of RMSE. The low values of RMSE over the Oceans close to the surface, as shown in this figure, demonstrate the benefit of prescribing observed climatological sea surface temperatures. The differences over Antarctica are seen in all winter regions where there is snow and ice; in January the RMSE is smaller in Antarctica but larger in the Arctic. These differences probably reflect differences in the heat transfer between the surface and the atmosphere between the UM and ECMWF models.

The RMSE of u shows a similar decrease when nudging is added to the model. The RMSE of q is reduced by nudging, but not so markedly as the RMSE of u or θ. This is to be expected as, though nudging introduces large scale dynamics to the model that are similar to the analysis data, the model physics that determines q is still different. The representation of q in the stratosphere also suffers from unrealistic initial conditions and, as water content varies slowly here, it is unaffected by nudging in this integration. The RMSE of P_s shows a small decrease with the addition of nudging, but as the RMSE is dominated by differences in the orography between the analysis data and the model it is unaffected by nudging.

In general the RMSE arises from a combination of systematic differences and from incorrectly reproducing the temporal variation of the system. These factors are investigated separately by looking at the biases and correlations between the model and the analysis data.

3.1.2 Biases in the model

The biases reflect any systematic differences between the model and the analysis data. They are calculated as monthly mean differences between the analysis data and the model, averaged over each model level.

The most notable biases without nudging in the model are those in θ, which are mostly removed by the addition of nudging (Fig. 4). Nudging removes the biases in

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the upper troposphere and lower stratosphere, corresponding to the smaller biases observed on the three upper levels in Tables 1 and 2. The removal of these biases is crucial to the modelling of phenomena such as polar stratospheric cloud (PSC) formation and dehydration of air passing through the tropopause.

The small bias in level 6 ($\sim$700 m) of the nudged model, located over Antarctica, is attributed to increased cloudiness produced by nudging. The mechanism producing this extra cloudiness is not fully understood. The smaller RMSE with nudging indicates that the addition of nudging still provides a better description of the analysis data. The addition of nudging also reduces biases in u, P_s and, to a lesser degree, q (Tables 1 and 2).

3.1.3 Representing variability

As well as systematic differences there are differences in the variation of the observables over space and time. The ability of the model to produce the same variation as the analysis data is assessed by the TC and the SC. A comparison between Tables 1 and 2 shows that these are improved by the addition of nudging, with the improvement in the TC being more significant.

Figure 5 shows the TC between the model and the analysis data for u, with and without the addition of nudging, as a function of UM hybrid height level. The TC varies smoothly with height both with and without nudging. The addition of nudging greatly increases the correlation, though TC decreases below where nudging is cut-off and declines again near the surface where there are errors in the vertical interpolation of the analysis data. Without nudging the model and the analysis data are very poorly correlated in the troposphere. In the stratosphere the unadjusted model is slightly better at reproducing the variability.

The performance of the model also varies spatially, see for example the TC for θ on UM hybrid height level 6 ($\sim$700 m) (Fig. 6). The TC is high in the extra-tropics, and lower in the tropics, in agreement with Jeuken et al. (1996). The lower TC in this region is not a large problem as the scale of variability is small, as can be seen by the low

values of RMSE in this region in Fig. 3.

A further illustration of the success of the nudged model in reproducing the variation is given in Fig. 7. The large differences in P_s, a variable that is not adjusted, over the Southern Ocean disappear with the addition of nudging. This is a result of the synoptic scale systems being nudged into the same phase as in the analysis data. The differences in orography can also be seen, especially on the edge of Antarctica. These are responsible for the high RMSE for P_s in the model, as seen in Tables 1 and 2 .

The differences in the SC with and without nudging are not as dramatic as those in the TC. This is as a result of the unadjusted model reproducing the spatial variation of quantities such as temperature and pressure reasonably well on a global scale. For a variable, such as u, in which the spatial variation is not reproduced so well in the unadjusted model, the addition of nudging produces significant improvement.

3.2 Comparison of derived quantities

In addition to the variables assessed in Sect. 3.1 two other quantities are examined, precipitation and the vertical wind (defined here as $\omega \equiv \frac{dP}{dt}$). The precipitation is derived differently in both models, so differences are expected due to different treatment of model physics. The vertical wind is a derived quantity in the ECMWF model, but in the UM it is a prognostic quantity, which could result in further differences. In addition the ECMWF analysis data contains some significant biases, most notably an excess of precipitation over tropical oceans (Uppala et al., 2005). In spite of these difficulties these variables are studied as they can be used to confirm that the model is giving an improved description of large scale atmospheric motions.

The vertical wind was studied by comparing ω on the ECMWF fixed pressure levels. This is done by calculating RMSE, TC and SC on pressure levels that approximate to the UM hybrid height levels used in Sect. 3.1, which are displayed in Table 3.

The addition of nudging improves the description of the analysis data, but there are still large differences, which are not unexpected considering the differences between the UM and ECMWF models. Figure 8 shows the TC for ω at a fixed pressure level

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of 500 hPa. The same pattern observed in Fig. 6 is seen, with good agreement in the extra-tropics.

The quantitative assessments used in Sect. 3.1 were applied to the precipitation, as listed in Table 4. To illustrate the improvement produced by the nudging the RMSE between the model and the analysis data is shown in Fig. 9. Improvements can be seen, especially in the extra-tropics. Much of the differences in the tropics can be attributed to errors in the precipitation in the analysis data.

The addition of nudging improves the description of the analysis data by the model, especially in the extra-tropics, though there are still substantial differences, especially in the tropics. The improvement is the effect of synchronising large scale motion, but differences in model physics between the UM and ECMWF models account for much of the remaining differences.

3.3 Effects on the model dynamics

To check that nudging is not unduly affecting the model the tendency due to nudging is compared to that from all other tendencies for θ and u. This is done by calculating the ratio between the magnitude of these two tendencies, as summarised in Table 5. These values are averaged over all grid-points in each UM hybrid height level and over all time-steps in the month.

There is a degree of variability in time and over the height range, but the tendency due to nudging is never larger than the tendency due to other factors. Figure 10 displays this ratio as a function of UM hybrid height levels for θ for the three assessment periods. The ratio tends to increase with height, showing that the UM has to be forced harder at higher altitudes to agree with the analysis data. This agrees with the conclusions drawn from Fig. 2 that the UM and ECMWF models differ most in the upper stratosphere.

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4 Sensitivity to model parameters

The effect of varying some arbitrary nudging parameters is studied here. This is done by the same assessments used on the default nudging parameters in Sect. 3.1, which will now be denoted the *standard assessments*. The sensitivity is tested with respect to varying three key parameters: (i) the magnitude of the relaxation parameter used; (ii) the height above which nudging is turned off; and (iii) the analysis data is interpolated from ECMWF fixed pressure levels rather than the original ECMWF hybrid pressure levels. This is designed to test our sensitivity to the interpolation in height.

The first sensitivity study was to vary the strength of the relaxation parameter (G) used. Month long runs were made in October 1999 with G reduced by a factor of 10, the *weakly nudged* run, and increased by a factor of 10, the *strongly nudged* run. The results of these runs were analysed using the standard assessments. The results are tabulated in Table 6 for the weakly nudged run and Table 7 for the strongly nudged run.

Comparing to Tables 1 and 2, the weakly nudged run produces better agreement than the run without nudging, but not as good agreement as the standard nudging. The strongly nudged run produces better agreement where the variable is being nudged, but there is no evidence of improvement in the variables and regions that are not nudged. The ratios of the tendencies due to nudging and all other factors for the strongly and weakly nudged runs are given in Table 8. The table suggests that, for the strongly nudged run, the nudging becomes the dominant tendency.

The evidence indicates that the relaxation parameter chosen originally is a reasonable choice, producing significant improvement in the description of the analysis data without predominating over the model's physical tendencies.

We apply nudging to as great a height possible, only excluding where the quality of the analysis data becomes doubtful. The ECHAM model[3] has been run in a configuration where the nudging is applied in the troposphere alone and see little difference to the case where nudging is applied to as great as height possible (Lelieveld et al.,

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[3]Version ECHAM5/MESSy1

We perform a similar exercise by turning nudging off above model level 31 (~19 km), above the tropical tropopause. The standard assessments were performed again, producing results very similar to those in Sect. 3.1 in the lowest three assessed levels, but differ on the highest assessed level, level 35 (~20 km), from which the results are tabulated in Table 9, producing slightly worse results, especially in θ. Improvement is observed over the case with no nudging, but not enough to justify using this lower cut-off.

The analysis data is originally produced on hybrid pressure levels but is made available interpolated onto a set of fixed pressure levels. The last study is to take the analysis data on these fixed pressure levels.

A run is made for October 1999 and the standard assessments made. If we compare the model output to the analysis data on fixed pressure levels interpolated on to UM hybrid height levels we see results that are similar to those seen in Sect. 3.1. However if we compare the model output to analysis data on the hybrid pressure levels interpolated on to the UM hybrid height levels we see discrepancies. These differences result from the additional interpolation to produce the analysis data on fixed pressure levels. They are insignificant in the troposphere, but produce significant differences around the tropopause and above, in regions where the gradient is steep, such as the tropical tropopause and just below 20 km above Antarctica. The gentler vertical gradients in u and v result in much smaller differences.

The differences produced by this additional interpolation also give an indication of sensitivity to the interpolation of the analysis data onto the UM hybrid height levels. The small size of the differences throughout most of the atmosphere indicates that the interpolation is not introducing large errors.

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5 Conclusions

We have described a nudged version of the "New Dynamics" Unified Model and demonstrate that it reproduces the ERA-40 analysis data better compared to the model without nudging. This is the first detailed description of the dynamics of a nudged grid-point model and we have noted similar features to those seen in nudged spectral models.

The addition of nudging reduces biases between the model and the analysis data, such as those in θ in the stratosphere (Fig. 4). The variability of the analysis data is demonstrated to be well reproduced (Fig. 5) with the addition of nudging, even in variables not directly adjusted such as q and ω (Figs. 8 and 9). This reflects that the "weather" is reasonably well represented. The strength and height regime of nudging were varied to demonstrate that the parameters chosen are reasonable.

Future work will concentrate on the behaviour of tracers, with the nudged model being used to validate the new UK chemistry and aerosol (UKCA) chemistry climate model (CCM), which is also based on the UM. The removal of biases should aid the modelling of phenomena sensitive to the model dynamics, such as polar stratospheric cloud formation. A reasonable representation of the weather allows episodic data to be used, expanding the available data sets that can be used to validate the model.

In conclusion the addition of nudging improves the correspondence with global meteorological analysis data and will provide a powerful tool for studying aspects of the UM on short time-scales.

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Table 1. Quantitative assessment of model performance in October 1999 with nudging.

	Level	Mean and Bias	RMSE	TC	SC
θ	6	285.5 + 0.5 K	2.5 K	0.75	0.98
	16	306.5+0.0 K	0.6 K	0.94	1.00
	29	416.2+0.0 K	1.1 K	0.98	1.00
	35	607.4–0.1 K	1.9 K	0.95	1.00
u	6	1.22 + 0.19 ms^{-1}	3.47 ms^{-1}	0.78	0.91
	16	6.06+0.00 ms^{-1}	1.45 ms^{-1}	0.98	0.99
	29	12.93–0.03 ms^{-1}	1.17 ms^{-1}	0.98	1.00
	35	10.38+0.00 ms^{-1}	1.37 ms^{-1}	0.98	1.00
q	6	5.8–0.2 g/kg	1.3 g/kg	0.63	0.97
	16	1.0+0.0 g/kg	0.7 g/kg	0.76	0.86
	29	2.4+0.0 mg/kg	0.3 mg/kg	0.26	0.84
	35	2.5–0.1 mg/kg	0.3 mg/kg	−0.12	0.24
P_s	0	963.7 + 0.3 hPa	14.6 hPa	0.92	0.99

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Table 2. Quantitative assessment of model performance in October 1999 without nudging.

	Level	Mean and Bias	RMSE	TC	SC
θ	6	285.0 + 0.1 K	4.5 K	0.26	0.95
	16	305.3–1.2 K	5.3 K	0.20	0.94
	29	420.1+3.4 K	9.9 K	0.23	0.95
	35	608.9+2.2 K	11.0 K	0.26	0.91
u	6	0.75–0.21 ms^{-1}	7.82 ms^{-1}	0.14	0.54
	16	6.01–0.07 ms^{-1}	9.49 ms^{-1}	0.19	0.62
	29	12.32–0.46 ms^{-1}	8.89 ms^{-1}	0.28	0.81
	35	10.12–0.21 ms^{-1}	9.53 ms^{-1}	0.35	0.88
q	6	5.7–0.3 g/kg	1.8 g/kg	0.21	0.94
	16	0.9–0.1 g/kg	1.1 g/kg	0.19	0.63
	29	2.5+0.1 mg/kg	0.4 mg/kg	−0.06	0.81
	35	2.5–0.1 mg/kg	0.3 mg/kg	−0.14	0.28
P_s	0	964.8 + 1.4 hPa	17.6 hPa	0.17	0.98

Table 3. Statistical Assessments for ω with and without nudging.

Level	RMSE		TC		SC	
	with	without	with	without	with	without
925 hPa	$0.10\,\mathrm{Pa\,s}^{-1}$	$0.11\,\mathrm{Pa\,s}^{-1}$	0.38	0.05	0.40	0.10
500 hPa	$0.11\,\mathrm{Pa\,s}^{-1}$	$0.17\,\mathrm{Pa\,s}^{-1}$	0.67	0.06	0.70	0.12
50 hPa	$0.007\,\mathrm{Pa\,s}^{-1}$	$0.009\,\mathrm{Pa\,s}^{-1}$	0.56	0.07	0.67	0.26
10 hPa	$0.003\,\mathrm{Pa\,s}^{-1}$	$0.003\,\mathrm{Pa\,s}^{-1}$	0.52	0.07	0.53	0.19

Table 4. Precipitation in October 1999 with and without nudging.

	Mean and Bias	RMSE	TC	SC
with nudging	2.44–0.14 mm	5.4 mm	0.56	0.59
without nudging	2.45–0.14 mm	7.2 mm	0.26	0.11

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Table 5. Ratio of tendencies in variables between nudging and all other tendencies.

	Level	October	January	July
θ	16 (~5 km)	0.16	0.16	0.15
	29 (~15 km)	0.36	0.47	0.39
	35 (~20 km)	0.30	0.36	0.43
u	16 (~5 km)	0.37	0.39	0.43
	29 (~15 km)	0.29	0.40	0.43
	35 (~20 km)	0.30	0.37	0.43

Table 6. Quantitative assessment of model performance in October 1999 with weak nudging.

	Level	Mean and Bias	RMSE	TC	SC
θ	6	284.9–0.2 K	3.3 K	0.54	0.97
	16	305.8–0.7 K	2.6 K	0.72	0.99
	29	416.7+0.0 K	2.9 K	0.86	0.99
	35	607.9–0.7 K	3.5 K	0.85	0.99
u	6	0.97–0.06 ms^{-1}	5.5 ms^{-1}	0.52	0.77
	16	6.15+0.08 ms^{-1}	5.0 ms^{-1}	0.76	0.90
	29	12.87–0.05 ms^{-1}	3.2 ms^{-1}	0.87	0.97
	35	10.45+0.07 ms^{-1}	2.7 ms^{-1}	0.93	0.99
q	6	5.7–0.3 g/kg	1.5 g/kg	0.40	0.96
	16	0.9+0.0 g/kg	0.9 g/kg	0.49	0.75
	29	2.4+0.0 mg/kg	0.3 mg/kg	0.10	0.85
	35	2.5–0.1 mg/kg	0.3 mg/kg	−0.09	0.19
P_s	0	964.3 + 0.9 hPa	14.6 hPa	0.71	0.99

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Table 7. Quantitative assessment of model performance in October 1999 with strong nudging.

	Level	Mean and Bias	RMSE	TC	SC
θ	6	285.8+0.8 K	2.6 K	0.77	0.98
	16	306.6+0.0 K	0.2 K	0.99	1.00
	29	416.0+0.0 K	0.3 K	1.00	1.00
	35	607.6+0.0 K	0.8 K	0.99	1.00
u	6	1.09+0.06 ms^{-1}	3.09 ms^{-1}	0.82	0.93
	16	6.05–0.01 ms^{-1}	0.40 ms^{-1}	1.00	1.00
	29	12.96+0.01 ms^{-1}	0.46 ms^{-1}	1.00	1.00
	35	10.38+0.01 ms^{-1}	0.59 ms^{-1}	1.00	1.00
q	6	5.8–0.3 g/kg	1.2 g/kg	0.66	0.97
	16	1.0+0.1 g/kg	0.7 g/kg	0.78	0.88
	29	2.4+0.0 mg/kg	0.4 mg/kg	0.30	0.80
	35	2.5–0.1 mg/kg	0.3 mg/kg	−0.12	0.24
P_s	0	963.9 + 0.4 hPa	15.4 hPa	0.93	0.99

Table 8. Ratio of tendencies in variables between nudging and all other tendencies for the strongly and weakly nudged runs.

Level	θ		u	
	strong	weak	strong	weak
16 (~5 km)	0.61	0.09	0.83	0.15
29 (~15 km)	0.92	0.14	1.02	0.18
35 (~20 km)	1.01	0.10	1.11	0.09

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Table 9. Quantitative assessment for model level 35 (~20 km) in October 1999 with "tropospheric only" nudging.

	Mean and Bias	RMSE	TC	SC
θ	606.0–1.0 K	6.6 K	0.69	0.97
u	9.96–0.41 ms^{-1}	3.63 ms^{-1}	0.88	0.98
q	2.5–0.1 mg/kg	0.3 mg/kg	−0.11	0.26

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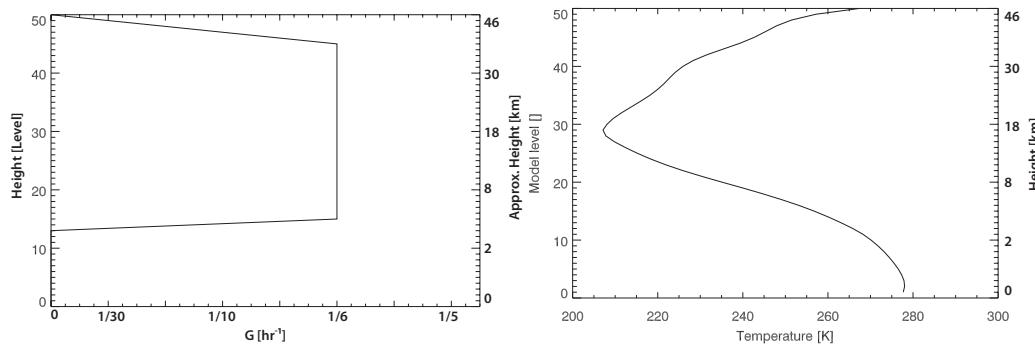
Fig. 1. Relaxation parameter, G, (left) and average temperature (right) as a function of UM hybrid height level.

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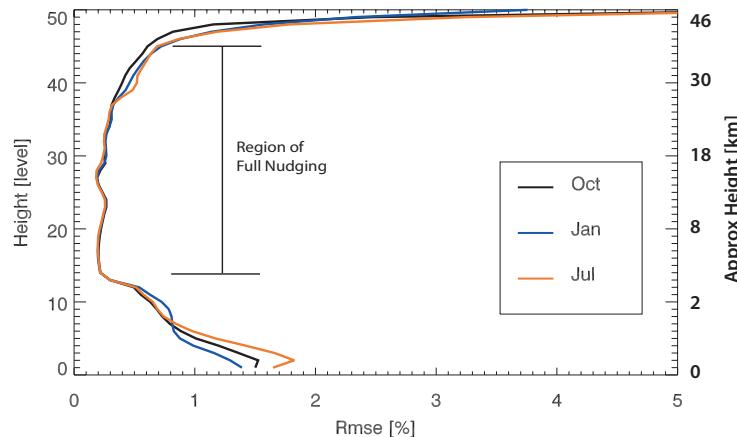
Fig. 2. RMSE in θ between the model, with nudging, and the analysis data as a function of UM hybrid height level for the three periods assessed.

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Fig. 3. RMSE in θ between the model, with nudging, and the analysis data for the lowest UM hybrid height level in July 2000.

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Fig. 4. Zonal mean bias in θ between the model and the analysis data for October 1999. The top plot is with nudging and the bottom without. Isotherms from ERA-40 are included for reference.
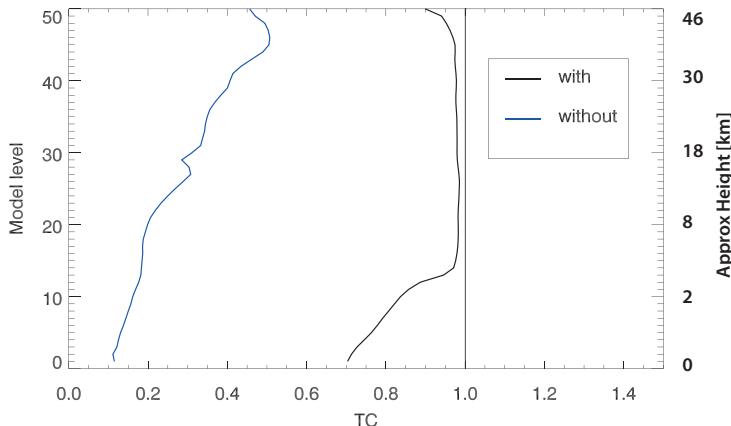
Fig. 5. TC for *u* between the model and the analysis data as a function of UM hybrid height level, with and without nudging, in October 1999. The maximum possible value that TC can take, 1, is shown for reference.

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Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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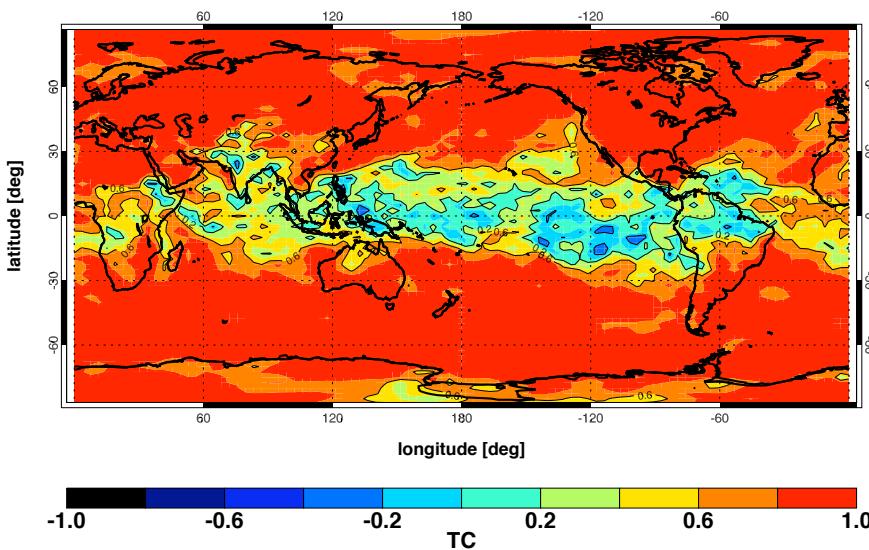
Fig. 6. TC for θ between the model, with nudging, and the analysis data for UM hybrid height level 6 ($\sim$700 m) in October 1999.

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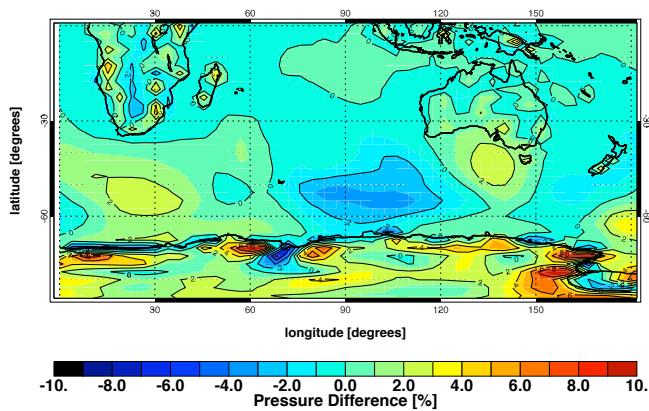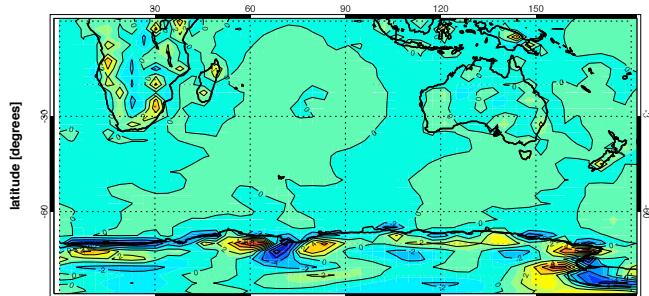
Fig. 7. Difference in surface pressure between the model and the analysis data for a snapshot on 30 October 1999. The top plot shows this with nudging and the bottom without. The region displayed is the eastern half of the Southern Hemisphere.

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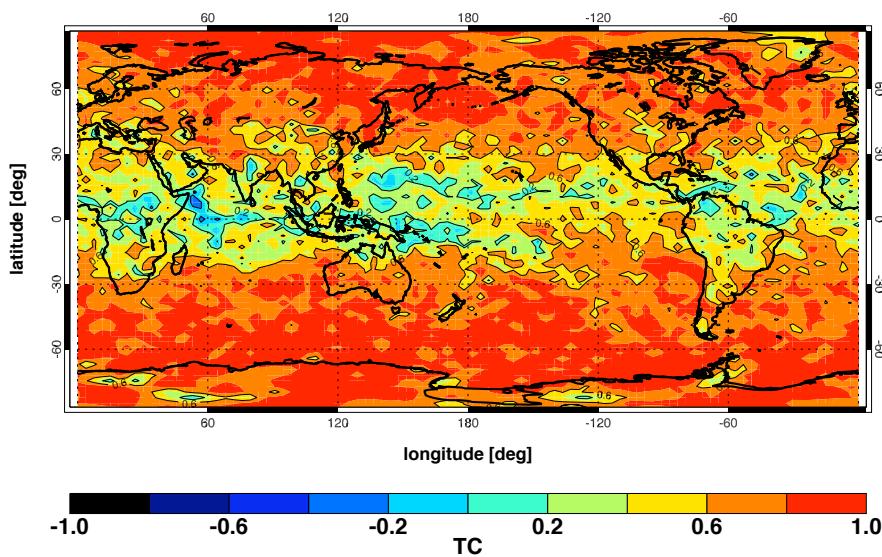
Fig. 8. TC for ω between the model, with nudging, and the analysis data for fixed pressure level of 500 hPa in October 1999.
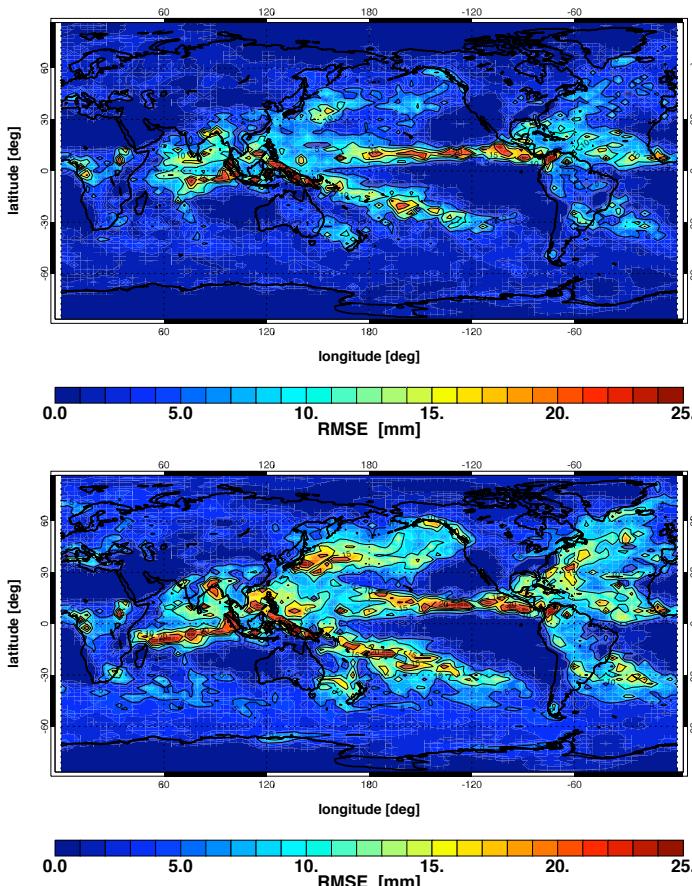
Fig. 9. RMSE for precipitation between the model and the analysis data in October 1999. The top plot is with and the bottom plot without nudging.

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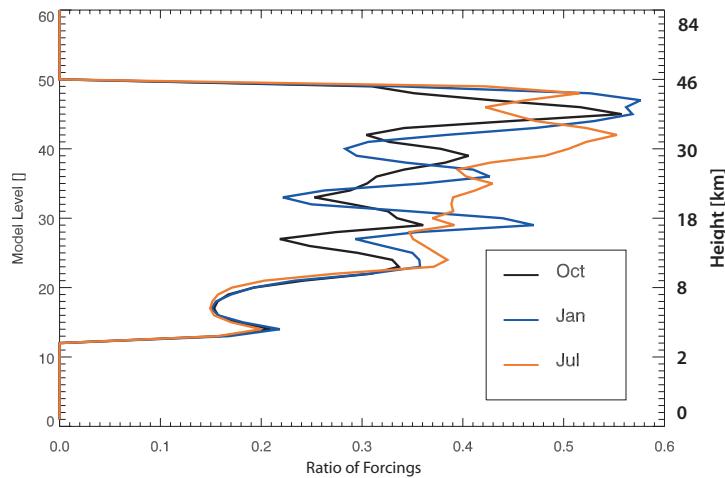
Fig. 10. Ratio of tendency due to nudging to all other tendencies for θ for October 1999 and January and July 2000.

**Nudged version of the UM**

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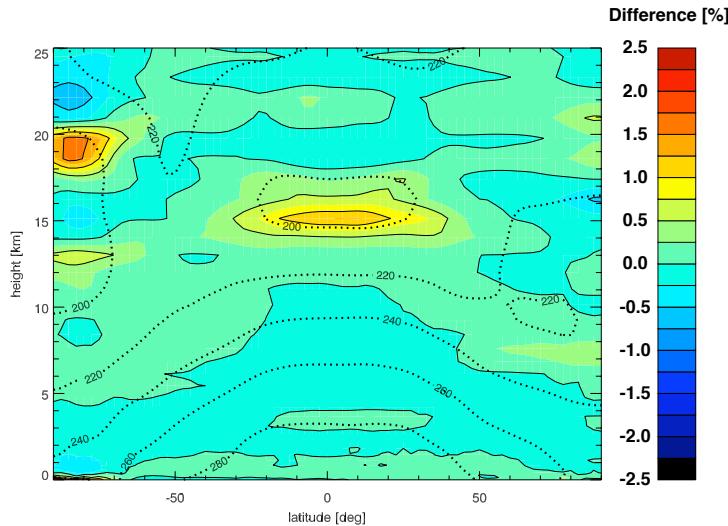
Fig. 11. Zonal mean difference in θ on UM hybrid height levels between analysis data on fixed pressure levels and hybrid pressure levels.