1M.5 **TRIALS OF HIGH RESOLUTION VERSIONS OF THE UNIFIED MODEL FOR SHORT RANGE FORECASTING OF CONVECTIVE EVENTS.**

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1. INTRODUCTION

The Met Office is moving towards higher resolution models for short range weather forecasting applications. The main motivation for this is to provide improved forecasts of hazardous weather and in particular severe convective events. With the availability of more computer power and the advent of the non-hydrostatic version of the Unified Model (UM) (Davies et al 2005) high resolution models are becoming more feasible. Until early 2005 the highest resolution model being run operationally was the 12km mesoscale model covering the UK. This is currently being replaced by a 4km gridlength UK model. Whilst it is expected that the 4km model will lead to improvements in the forecasting of convective events, it is hoped that, in due course, moving to a 1km gridlength model will bring further improvements.

This paper describes trials which have been carried out on a suite of 12km, 4km and 1km models in order to evaluate the potential benefits of the 4km and 1km models. These trials have focused on short range forecasting (out to T+7) of convective events. Key aspects of the model configuration are described in section 2. Section 3 presents some results from the trials.

2. MODEL CONFIGURATION

Most of the model configuration for the 1km and 4km gridlength models has been taken over from the 12km model. The full list of changes is shown in the table at Annex A. In this section some of the key aspects which have been changed are discussed.

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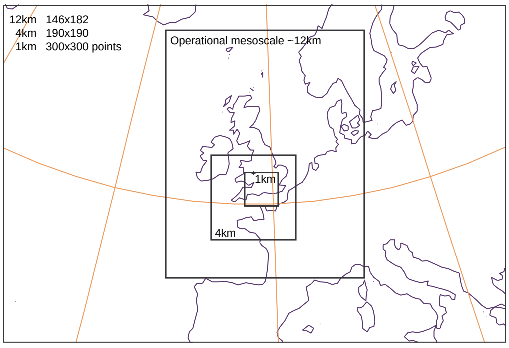

Figure 1 Domains used for the 12km, 4km and 1km models

2.1 *Domain*

The domains which have been used are shown in figure 1. The outer domain shown is the operational 12km model. This model was run for comparison purposes and also to provide boundaries (one way nested) for the 4km model. The 4km and 1km models were both run on square domains which were approximimately centered on the Chilbolton Radar in central southern England. This meant that the 4km model extended south to include a good part of northern France. This was considered advantageous in order to capture situations where storms move north from the south. The 4km model discussed here is smaller than full UK domain being used for the 4km model currently being implemented operationally.

The 1km domain was 300x300 gridpoints which was the largest which it was thought practical to run with available computer resources. This model used lateral boundary conditions from the 4km model.

The 4km model used the same 38 levels in the vertical as used in the operational 12km model. The

1km model used 76 levels which were the 38 levels doubled.

2.2 *Convection*

A key issue in these models is the convective parameterisation. The 12km gridlength operational Unified Model uses a mass flux convection scheme with Convectively Available Potential Energy (CAPE) closure (Gregory and Rowntree 1990). This scheme is designed on the assumption that there are many coluds per gridbox, an assumption which is already marginal at 12km but even more questionable at higher resolutions. The 4km model is found not to produce satisfactory results either with no convective parameterisation or with the standard one included. With no convective parameterisation the large gridlength (relative to the typical cloud size) means that the model tends to produce too few, too heavy and too widely spaced showers in strongly forced situations and nothing at all in weakly forced ones. With the standard convective parameterisation the model misses organisation of showers which sometimes means grossly underestimating the amount of rain. For this reason the 4km model uses a modified version of the convection scheme in which the CAPE closure timescale is a function of CAPE so as to limit the mass flux from the scheme if the CAPE is large (Roberts 2003). The rationale behind this is to encourage the model to produce convection explicitly when there is strongly forced, deep convection but to allow the convection scheme to produce weaker convection which would otherwise be missed. This solution is not satisfactory – there is no single tuning of the modified scheme which produces good results for all situations.

In contrast the 1km model has a small enough gridlength to represent better many situations without a convection scheme and generally produces better results when run in this way. The above points are illustrated by figure 2 which shows the 1km domain area averaged rainfall rate against time for a case from 3rd May 2002.

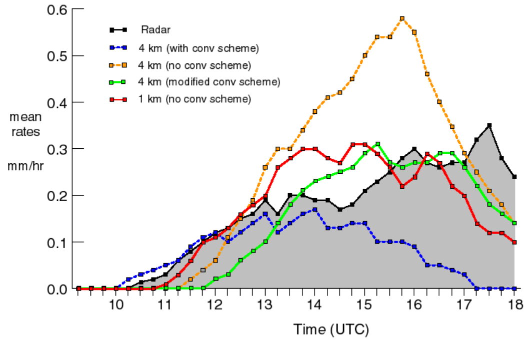

Figure 2 Domain averaged rain rates against time for the 3rd May 2003 case.

The 3rd May 2002 was a case of scattered showers breaking out fairly uniformly over sourthern England and later becoming more organised. The 4km model with convection scheme initially does well but fails to reproduce the organisation later in the period resulting in gross underestimates of rainfall. Without a convection scheme the 4km model has delayed initiation but later produces around a factor of two too much rain. The 4km model with modified convection scheme generally does well but suffers from an even larger delay in the initiation. (It is possible to reduce this delay by modifying the parameters of the scheme but at a cost of making the representation later less satisfactory). The 1km model with no convection scheme produces a generally good representation in that the delay in initiation is less than in the 4km model and the later phases are captured reasonably well.

2.3 *Prognostic Rain*

In the operational 12km model the rainfall rate on each level is diagnosed on each timestep according to the sources and sinks and including a flux from the layer above and to the layer below (Wilson and Ballard 1999). No account is taken of advection by either horizontal or vertical winds. With typical horizontal wind speeds and rain fall velocities it would be expected that the advection of rain in the horizontal would be on scales of around 10km. For this reason rain has been included as a prognostic which is advected by horizontal and vertical winds in the 4km and 1km models. (Ice is already included as a prognostic in the standard version of the model). Prognostic rain has been shown to improve forecasts in cases of orographic rainfall. It is hoped that prognostic rain might improve the representation of convection because the rain is less likely to fall back down into the updraft.

2.4 *Assimilation*

For short range forecast applications it is assumed that it will be essential to use an assimilation system to initiate high resolution models. The alternative of starting from a low resolution analysis suffers from the forecast not being useable for the first few hours while the high resolution structure spins up.

The operational 12km model uses 3D-Var (Lorenc et al 2000) running in a 3 hour cycle. This produces a set of increments which are nudged into the model using an Incremental Analysis Update (IAU) scheme for an hour on each side of the nominal analysis time. The 3D-Var includes surface temperature, humidity, pressure, winds and visibility, radiosonde, pilot and dropsonde data, satellite atmospheric motion winds, ATOVS radiances and wind profiler data. In addition cloud and surface precipitation data are nudged into the model via the Moisture Observations Processing system (MOPS) and latent head nudging (LHN) (Jones and Macpherson 1997) respectively. These data are used at 15km resolution with a time resoltuion of 3 hours for the cloud data and 1 hour for the precipitation data. This assimilation set up (both 3D-Var and nudging) is taken over largely unchanged to the 4km model.

The 3D-Var set up, however has been changed to take account of the relatively small domain of the 4km model. Analysis increments from the larger 12km model could contain additional and useful information for the 4km model (i.e. these contain increments from observations from outside the 4km domain). In order to address this a scale selective 3D-Var system in used in which the analysis is carried out in the following steps: (a) Spectrally filter the 12km increments to obtain "long waves" increments based on an appropriate cut-off wavelength (180km); (b) Add "long waves" to the 4km background; (c) Analyse the "short waves" not retained by the filtered increment added to the background in the 4km 3D-Var; (d) form the new analysis by adding in both the long wave and the short wave increments via the IAU. The 4km model uses MOPS and LHN nudging of cloud and precipitation data taken over unchanged from the 12km.

For the 1km model it was not thought desirable to run 3D-Var both because of the cost and because the size of the domain in physical terms is only a few times longer than the correlation length which would lead to problems related to the boundaries. This will be a subject of future developments but currently the model is being run using the 3D-Var increments resulting from the 4km analysis. Due to the smallness of the domain the 1km model is very dominated by the boundaries. A test running the 1km model without any VAR increments (i.e. just forced by the boundaries) gave very similar results to the model including increments.

The 1km model does include nudging of cloud and precipitation data which is taken over almost unchanged from the 12km model (a number of changes had to be made to the code to take account of the lack of a convection scheme). For both the 4km and 1km models the radar data is used at the same temporal and special resolution as in the 12km model. The LHN search radius (the radius over which the model searches for a model profile which results in the same amount of rain as seen in the radar) was kept at 72km in the 4km and 1km models (as in the 12km model). There is clearly a lot of scope for tuning the parameters of the 4km and1km LHN/MOPS schemes and, as discussed in section 3 there is evidence that the current configuration is causing problems.

Both the 4km and 1km models are currently being run with a 3 hour cycle length. This is for convenience since the 12km assimilation system on which this is based has 3 hour cycles. It is recognised that a short range forecast system based on a 1km model will need more frequent cycles and this will be addressed in the future.

3. MODEL TRIALS

3.1 *Description*

These models have been run on a number of cases from the summers of 2003 and 2004 (see table at Annex B). The cases were mostly convective and ranged from very heavy organised storms to light, scattered showers. For each case four forecasts were run at three hour intervals covering the period of interest. All three models were run out for 6 hours after the end of the assimilation period at T+1. For comparison purposes for each case two suites of models were run. The first was a suite with assimilation in the 4km and 1km models (as described in section 2.4). The second was a suite with the 4km and 1km models initialising each forecast from the corresponding 12km T+1 analysis.

3.2 *Subjective Analysis*

In this section examples are shown in order to illustrate the comparison between the three different resolution models. Figure 3 shows some fields from the 9 UTC run for the 1st July case at 14 UTC. This was a case of bands of failrly heavy convective rain moving south. The 12km model did produce evidence of the bands of rain although the peak values were too light and the rain was spread over too large an area.

The 4km model produces stronger evidence of the rain band but suffers from the typical behaviour of producing a number of discrete, large and heavy cells rather than a continuous band. This rain is all explicit (since the convection scheme is limited). The discrete cells are caused by the 4km gridlength being too long compared to the features which it is trying to represent. In contrast the 1km model is producing a relatively good representation of the band variablility on approximately the correct spatial scales.

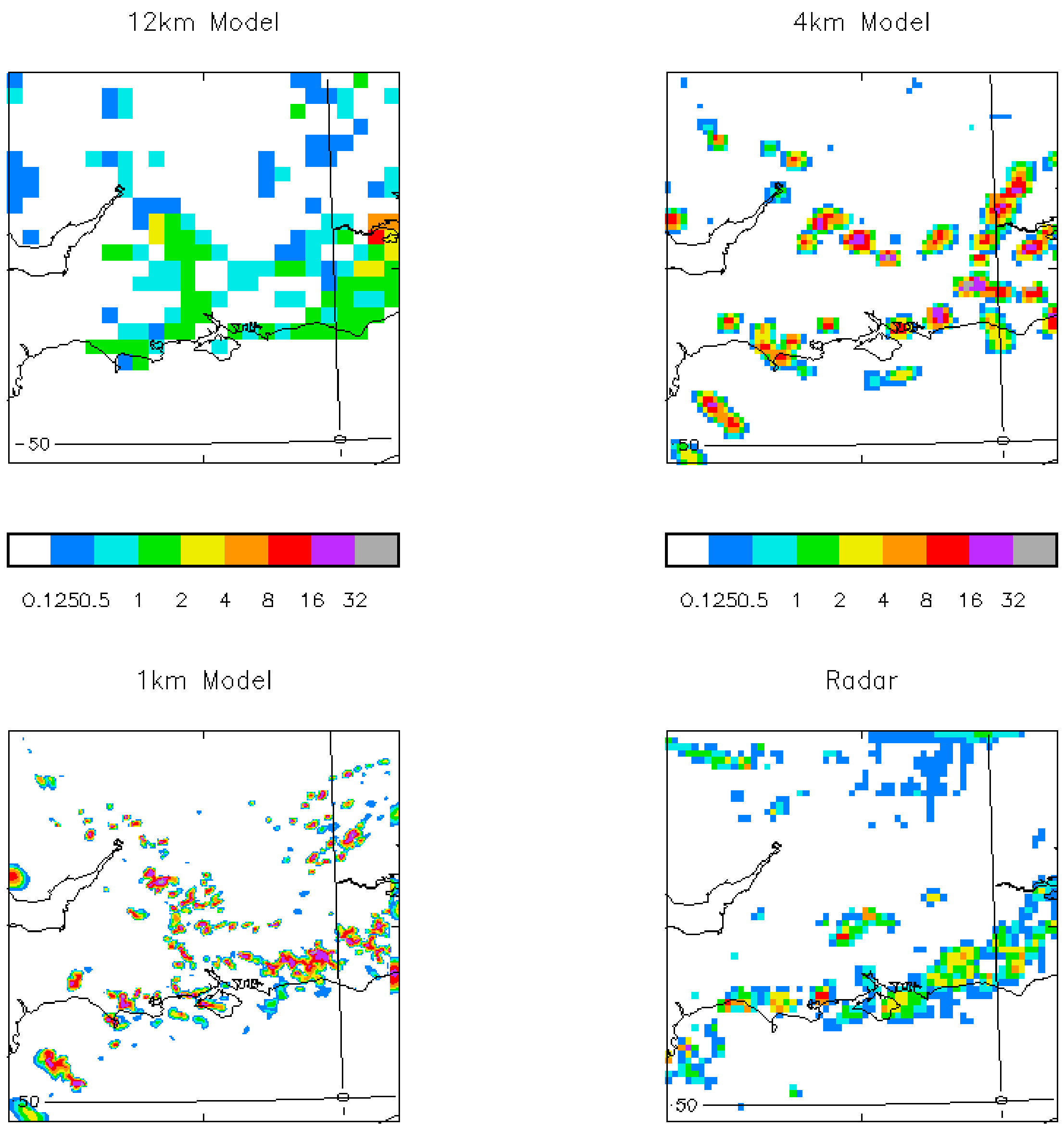

Figure 3 Instantaneous rain rates for 14 UTC 1st July 2003 from 9 UTC forecasts. The radar data is on 5km grid.

It is noticable from this example that the 4km and 1km models both are producing too much rain overall. If the domain averaged rainrates are calculated the 12km model produces about the correct amount of rain but the 4km and 1km produce around a factor of 2 too much. Despite this failing it is clear that the 1km model produces a better indication of the spatial distribution.

A second example of the performance of these models is shown in figure 4. This was from the 3rd August 2004 thunderstorms case which was notable because it produced some high rainfall totals and significant flooding in parts of west London. The figure shows total rainfall over a 6 hour period. The 12km model produced a reasonable forecast overall with an indication of high rainfall totals. However the area of heaviest rain (>32mm per hour in the figure) is too far west and therefore does not indicate the high totals over the London area. Analysis of this case has shown that all the models are suffering from an absence of an upper level mesoscale vortex which, in reality, significantly modified the precipitation distribution.

The 4km model produces a number of areas of heavy rainfall distributed over most of the land area shown in the figure. However, again, there is no indication of large accumulations over the London area. In contrast the 1km model does produce a strong indication of large accumulations over the London area although it does overdo the amount of rain elsewhere.

The third example is taken from the 16th August 2004 which was a notable flood event in Boscastle on the north Cornwall coast. This case was not included in the trials described in the rest of the paper because Boscastle is outside the standard 1km domain. It is included here because it was a good example of the benefits of high resolution models.

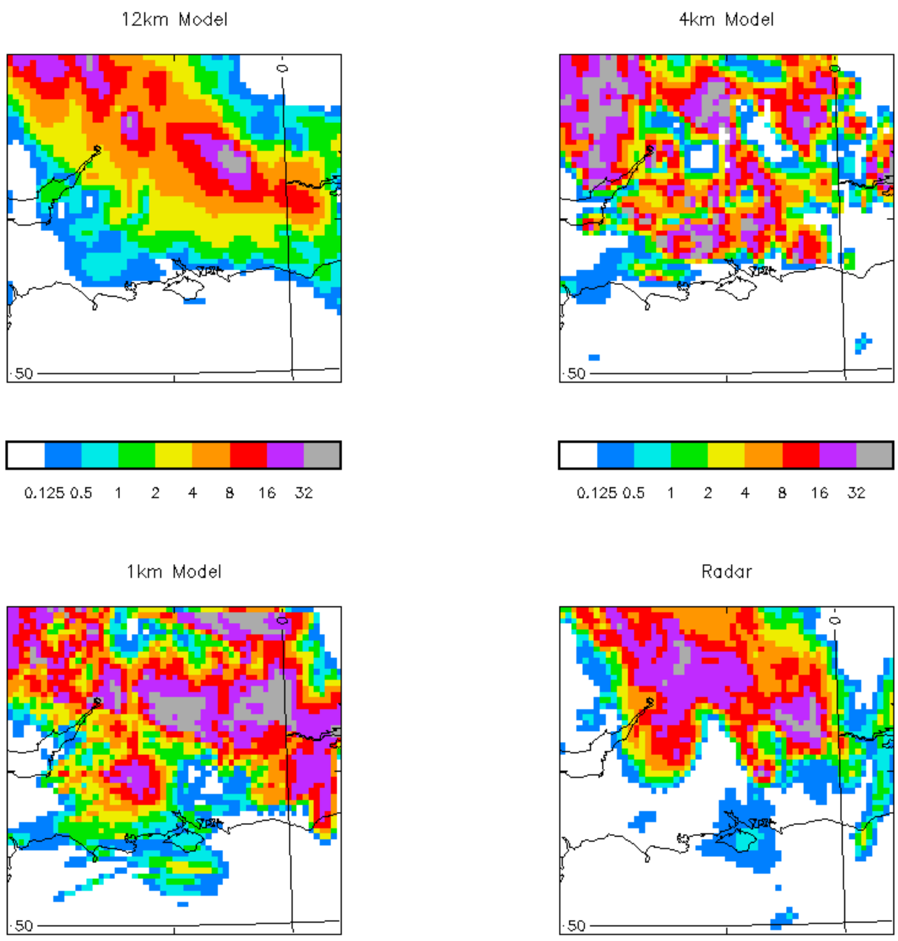

Figure 4. Accumulated precipitation from 13-19 UTC on 3rd August 2004 from 12 UTC forecasts. For clean comparison all fields have been interpolated/aggregated onto a 5km grid.

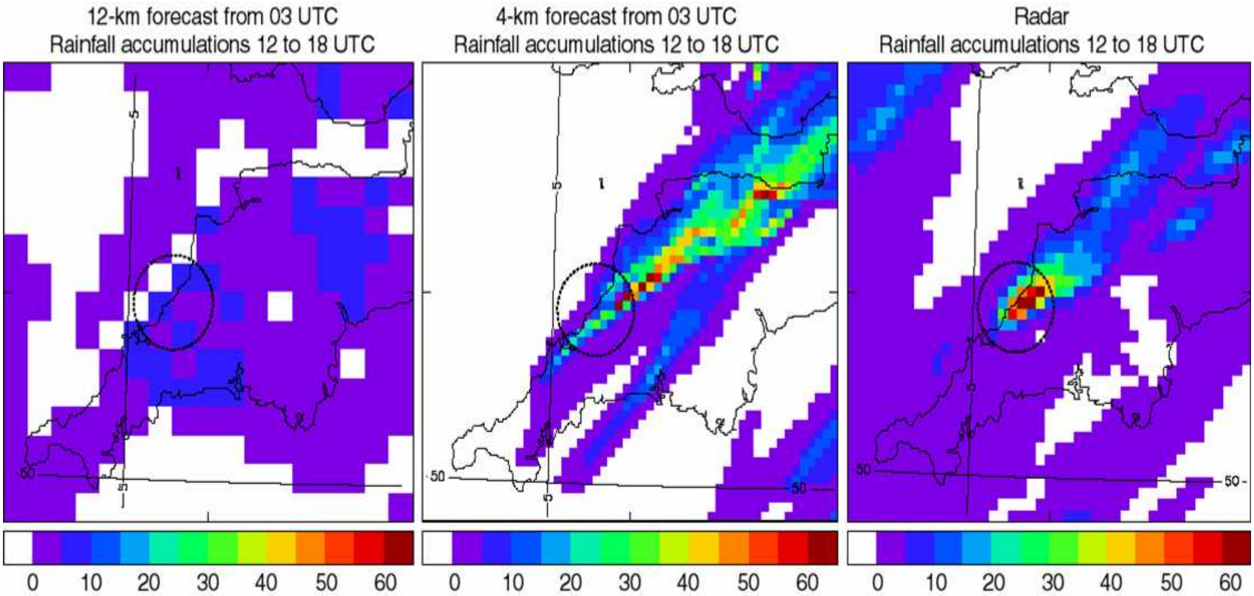

Figure 5. Accumulated precipitation for 12-18UTC on 16th August 2004. The circles on each plot are drawn at a radius of 20km from Boscastle.

Figure 5 shows the accumulated precipitation over the period of the flood (12-18 UTC). The radar data shows a strong peak in the accumulation in the area of Boscastle (marked by a circle on the figure). The 12km model completely fails to pick up this feature giving light rain over the whole area –although there is a hint of slightly heavier rain over the north Cornwall coast. In contrast the 4km model, although not perfect, correctly produces the line of very heavy rain and would have given a good indication of the possibility of high accumulations in the area. The 4km does better because it is able to more correctly generate a convergence line along the coast and represent the advection of showers in a line initiating to the SW of Boscastle.

A 1km model has been run for this case on a non-standard domain and shows somewhat lower intensities of precipitation but better positioning of the maximum accumulation (i.e. further SW). More details of this case and 1km model runs are given by Golding et al (2005).

3.3 *Averaged Rain rates*

In this and the next section we show data which is combined from a number of forecasts. These statistics are aggregated over all 4 runs of each of the 7 cases from summer 2004 (i.e. 28 forecasts).

The first measure we consider is the area averaged rainfall rates as a function of time. This was calculated over the area of the 1km domain. Figure 6 shows the domain averaged rainrate plotted against time after the analysis time averaged over all the forecasts. The equivalent radar data is also shown. It is important to remember that the radar estimate may have significant errors associated with it. The 12km model produces approximately the correct amount of rain overall.

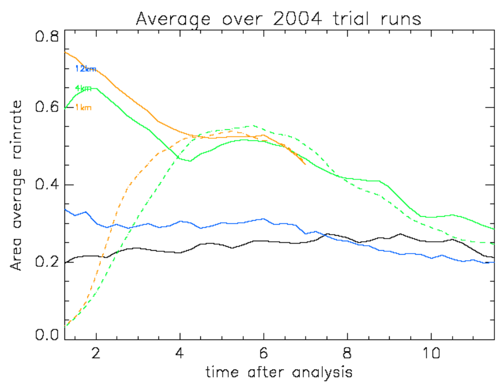

Figure 6 Domain averaged rain rates against time since forecast time for 7 cases of the 2004 trial. Black line is radar data, blue 12km model, green 4km and red 1km. Solid lines are assimilation models and dashed models starting from 12km analyses.

Looking first at the 4km and 1km runs starting from low resolution analyses (dotted lines on the figure) there is very little rain at the start due to the finite amount of time required to spin up the explicit convection. As the convection spins up the rain rate overshoots and produces a maximum at around T+6. Analysis suggests that this behaviour is due to Convectively Available Potential Energy (CAPE) building up unrealistically while there is no rainfall and then being released by producing high rain rates.

The implication of this is that forecasts spinning up from 12km analyses should not be used for at least 6 hours after the analysis time and are not likely to be useful for short range forecasting applications.

In contrast the solid lines show that the runs including assimilation are producing far too much rain in the first few hours after the analysis time although the rates do diminish rapidly as the time after analysis increases. It seems likely that much of this spurious rain is due to the behaviour of the MOPS/LHN assimilation of cloud and moisture data and work is now being carried out to address this.

It is also noticable that both the 12km and 4km rain rates appear to tend to much closer to the radar value by T+12. This appears to imply that the problems with excess rain are mostly due to initialisation problems rather than model bias. However other work with these models has contradicted this conclusion. Data from a 4km model running for 24 hours each day from 0 UTC shows that the domain averaged rainfall rate tends to exceed the radar by an amount proportional to the amount of rain falling. This implies that there is a significant bias in the model as well as the initialisation.

3.4 *Precipitation Statistics*

The precipitation fields from the summer 2004 runs have been analysed with a scale dependent verfication method. For details of this analysis technique the reader is referred to Roberts (2003). The method works on precipitation accumulation fields because that is the quantity of most interest in forecasting severe flooding. The precipitation accumulation fields from the 3 models are interpolated or aggregated onto the same 5km grid which the radar data are on. Skill scores are then calculated for a given precipitation threshold. The threshold may either be an absolute threshold (eg 4mm/hr) or a relative one (eg top 10% of points in the domain) . A relative threshold allows an overall bias in the amount of precipitation to be neglected scoring only the spatial distribution. The scores are calculated by sampling a number of points around each point (the number determined by the sampling radius). The scores therefore provide a method of filtering out errors on scales less than the sampling radius.. This allows small spatial errors due to either fronts, convergence lines etc being missplaced or due to individual cells not being predictable to be ignored. The skill score plotted here is a fraction skill score which has a value 1.0 for a perfect forecast and 0.0 for a forecast with no skill.

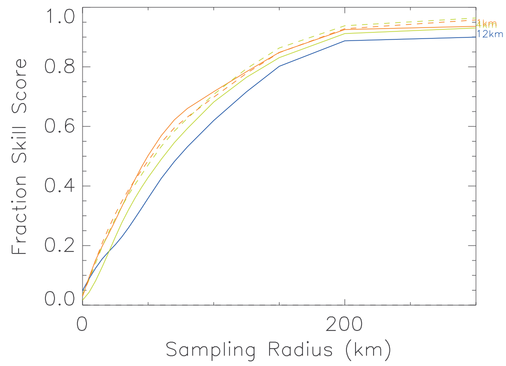

Figure 7 Aggregated fraction skill score as a function of radius for a 6 hour accumulation threshold for top 1% of points**.** The colour and line type key is the same as in figure 5.

Figure 7 shows that the aggregated 6 hour accumulation skill scores for a relative threshold is better for the 1km and 4km models than for the 12km. This confrims the impression from the subjective analysis that the spatial distribution is better for 6 hour accumulations despite the prediction of too much rain overall. It is noticable that, although the differences are not large, the 1km model outperforms the 4km model for sampling radii between about 40 and 120km. If an absolute threshold is instead used for calculating the scores the 4km and 1km models do somewhat worse than the 12km model but this simply reflects the overall excess in precipitation as shown in figure 6.

Figure 8 shows the skill scores for an hourly accumulation threshold of 4mm. These are plotted as a function of time after analysis time for a fixed sampling radius. The sampling radius was chosen to be 50km for this plot (choosing a lower value makes all the skill score values lower but does not change the relative positions of the curves). By this measure the assimilation 4km and 1km models are clearly better than the 12km after about T+3 with the 1km model doing best. The high resolution models do better when shorter accumulation periods are considered because they then have more information than the 12km model which tends to produce relatively uniform rain over the area of convection. Earlier on the 12km is better due to the initiation problems referred to in section 3.3. The runs without assimilation are significantly worse since at the start of the forecast they usually have very little rain until it spins up. Despite this these forecasts are still better than the 12km forecast after about T+5.

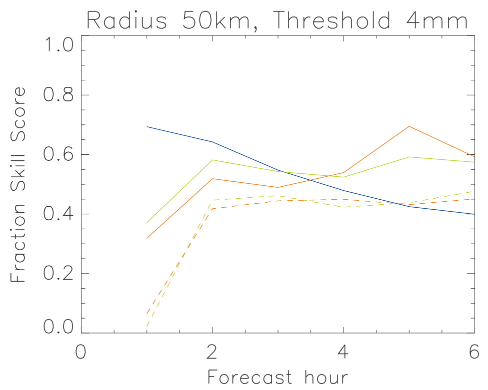

Figure 8 Aggregated fraction skill scores for an hourly accumulation threshold of 4mm/hr as a function of time after analysis time. Colour/line type key as in previous figures.

Figure 9 shows a similar plot of hourly fraction skill score against time for a relative threshold. Now the 4km and 1km model forecasts are better than the 12km at all times after T+1. This confirms that the poorer scores in the first half of the forecast in figure 7 were due to the over prediction of rain. When only spatial distribution is considered the high resolution forecasts are better except at the very start with the 1km model once again being the best.

By this measure the forecasts initialised from the low resolution analyses are closer to the assimilation ones and in the case of the 4km model are better at all times except at the ends of the forecasts. It is also noticable that the forecast skill decays significantly more slowly with time in the 4km and 1km models than in the 12km model.

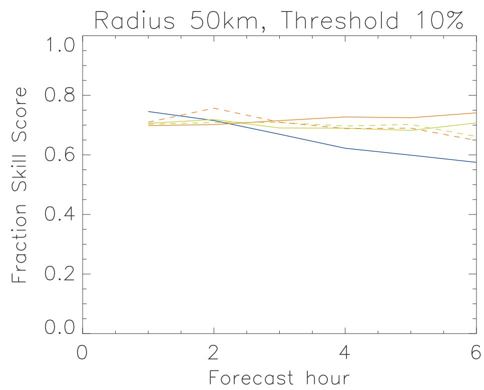

Figure 9 As figure 7 but for a relative accumulation threshold of 10%

4. CONCLUSIONS AND FUTURE WORK

We have described an experimental configuration of the UM at 4km and 1km resolutions. These models have been run for a number of convective cases from summer 2003 and 2004 in a suite of models which also included the 12km model (for comparison and in order to provide boundary conditions).

The subjective conclusion from examining fields from these forecasts is that the 4km and 1km models can produce better results than the 12km models. They have an advantage over the 12km model in that the use of the convection scheme in the 12km model often produces quite uniform rain over the area of convection which misses organization and the heaviest rain. The 4km model tends to produce too large, too widely spaced and heavy showers as a result of attempting to represent the convection explicitly on a relatively coarse grid. The 1km model doesn't suffer from this problem in many cases.

The average precipitation rate data, along with the precipitation statistics show that, although there is an issue with the over prediction of precipitation overall, the 1km and 4km models produce better spatial distribution of rainfall than the 12km when 6 hour accumulations are considered. When 1 hour accumulations are considered the 1km model is best, even including the rainfall over prediction, except near the start of the forecasts.

Both the subjective and objective analysis therefore lend weight to the conclusion that the 4km and 1km models have the potential to provide improved forecasts. The 1km model represents a further improvement over the 4km in the representation of convection.

The 4km model is now running as part of the Met Office operational suite. This model runs on a larger domain than described here covering the whole UK but the configuration is otherwise the same. It is currently running twice a day with the forecasts initialized from 12km analyses. It will, however, shortly be implemented with a full assimilation system.

It is clear from this work that an assimilation system will be essential at 1km if short range forecasts are required. A future operational system will need to use a shorter cycle length than the 3 hours in the current work. Numerous other developments to the assimilation system are planned and some of these are described by Ballard et al (2005).

It is hoped that it will be possible to reduce the over prediction of rain partly by addressing some issues with the assimilation system. There will also be work to reduce the bias in the model by addressing some aspects of the diffusion, convection and microphysics configuration.

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Annex A – Table Summarising differences in configuration between 4km and 1km models and the current operational 12km model.

	12km	4km	1km
Horizontal Domain			
Approximate Gridlength (km)	12	4	1
Gridlength (deg)	0.11	0.036	0.009
lat BLC		-5.45	-2.630
lon BLC		356.6	359.3
grid size	146x182	190x190	300x300
pole lat	37.5	37.5	37.5
pole lon	177.5	177.5	177.5
Vertical Levels			
No levels	38	38	76
Top of model (m)	approx. 40000	approx. 40000	approx. 40000
BL levels	13	13	26
ozone levels	11	24	48
LBC issues			
Driving model	Global	12km	4km
Rimwidth	8	8	8
Time frequency	60 min	30 min	15 min
Aerosol Boundary values from	UKmes boundary model	12km	4km
Timings			
Timestep	5 mins	100s	30s
Radiation timestep	60 min	15 min	5 min
Parameterisations			
Convection	4A scheme (previously known as CMODS). CAPE closure timescale 1800s	3C scheme with CAPE dependent CAPE closure settings 1 for 4km i.e. function with t=1200s, c=0.5	No convection scheme
Microphysics	3B dual phase including iterative melting.	3C dual phase No iterative melting but with prognostic rain.	3C dual phase. No iterative melting but with prognostic rain.
Gravity Wave Drag	On	Off	Off
Boundary Layer	13 levels	13 levels	26 levels
Other			
(Max del-4 diffn for stability		3.3e4	4.2e3)
Horizontal Diffusion	None	del-4, 8 min i.e. 1.14e4 (5.1/6.1) 8.53e3 (5.1.1/6.1.1)	del-4, 8 tsteps i.e. 1.43e3
RHcrit	0.85 above boundary layer	As 12km	As 12km

Annex B. Table of cases investigated from summer 2003 and 2004.

Date	**Model Runs**	**Description**
13th May 2003	6,9,12,15	Line of thunderstorms develops around 15 UTC
25th May 2003	6,9,12,15	Scattered convection
1st July 2003	6,9,12,15	Line of convection
28th August 2003	6,9,12,15	Bands of convective rain
27th April,2004	9,12,15,18	Heavy storms initiating over London at about 15:30 UTC and subsequently moving west.
8th July,2004	3,6,9,12	Bands of rain around a cyclone in the Channel.
10th July, 2004	3,6,9,12	Gust fronts initiating showers downstream from initial development over S Wales at 06 UTC.
20th July,2004	6,9,12,15	Showers initiated at around 13 UTC in sourtherly flow.
22nd July,2004	6,9,12,15	Showers initiate around 13 UTC over Somerset subsequently move north and develop.
3rd August,2004	6,9,12,15	Showers initiating along S coast at around 12:30 UTC moved N and developed into line of V heavy rain with lightning and hail by around 15UTC.
20th August,2004	3,6,9,12	Bands of heavy showers moving east.