Some Aspects of High Resolution NWP at the Met. Office

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1 Introduction

We discuss two particular aspects of high resolution modelling. In the following section we discuss the general validity of the equation sets used. This is followed by a section outlining some of the high resolution modelling experiences at the Met. Office. The final section summarises some of the outstanding issues for high resolution NWP.

2 Equations

The hydrostatic primitive equations are widely used in operational weather forecasting and climate modelling. It is generally accepted that they are the appropriate set of equations for synoptic scales in NWP and climate modelling but they are sometimes applied to shorter scales where some of the assumptions and approximations are open to question.

Consider the fully-compressible Navier-Stokes equations in a spherical polar coordinate system rotating with angular velocity Ω.

$$\frac{D_{\boxed{r}}u}{Dt} - \frac{uv\tan\phi}{\boxed{r}} - 2\Omega v\sin\phi + \frac{1}{\rho\boxed{r}\cos\phi}\frac{\partial p}{\partial\lambda} = -\left\{\frac{uw}{\boxed{r}} + 2\Omega w\cos\phi\right\} + F_u \quad (1)$$

$$\frac{D_{\boxed{r}}v}{Dt} + \frac{u^2\tan\phi}{\boxed{r}} + 2\Omega u\sin\phi + \frac{1}{\rho\boxed{r}}\frac{\partial p}{\partial\phi} = -\left\{\frac{vw}{\boxed{r}}\right\} + F_v \quad (2)$$

$$\delta_V\frac{D_{\boxed{r}}w}{Dt} + \frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{\partial\Phi}{\partial r} = \left\{\frac{(u^2+v^2)}{\boxed{r}} + 2\Omega u\cos\phi\right\} + \delta_V F_w \quad (3)$$

$$\frac{D_{\boxed{r}}\rho}{Dt} + \rho\nabla_{\boxed{r}}\cdot\mathbf{u} = \mathbf{0} \quad (4)$$

$$\frac{D_{\boxed{r}}\theta}{Dt} = F_\theta \quad (5)$$

$$p = \rho R T \tag{6}$$

where

$$\frac{D_{\boxed{r}}}{Dt} \equiv \frac{\partial}{\partial t} + \frac{u}{\boxed{r}\cos\phi}\frac{\partial}{\partial \lambda} + \frac{v}{\boxed{r}}\frac{\partial}{\partial \phi} + w\frac{\partial}{\partial r} \tag{7}$$

$$\nabla_{\boxed{r}} \cdot \mathbf{u} \equiv \frac{\mathbf{1}}{\boxed{r}\cos\phi}\left(\frac{\partial \mathbf{u}}{\partial \lambda} + \frac{\partial\left(\mathbf{v}\cos\phi\right)}{\partial \phi}\right) + \frac{\mathbf{1}}{\boxed{r}^2}\frac{\partial\left(\boxed{r}^2\mathbf{w}\right)}{\partial \mathbf{r}} \tag{8}$$

$\mathbf{u} = (\mathbf{u}, \mathbf{v}, \mathbf{w})$, and $\theta = (p/p_0)^{-R/c_p}T$.

In writing the equations in this form we have assumed the geoid is approximated by a sphere (see Phillips (1973) for a discussion) but this could be relaxed by allowing gravity to vary both horizontally and vertically. We have introduced a so-called "hydrostatic switch" δ_V in the vertical momentum.

The equation set admits the following conservation principles, White (1999):

$$\frac{D_{\boxed{r}}}{Dt}\left[\left(u + \Omega\boxed{r}\cos\phi\right)\boxed{r}\cos\phi\right] = F_u\boxed{r}\cos\phi - \frac{1}{\rho}\frac{\partial p}{\partial \lambda} \tag{9}$$

$$\frac{D_{\boxed{r}}}{Dt}\left[\frac{1}{2}\left(u^2 + v^2\right) + \frac{\delta_V}{2}w^2 + \Phi\right] = \mathbf{u}\cdot\mathbf{F_u} - \frac{\mathbf{1}}{\rho}\mathbf{u}\cdot\nabla_{\boxed{r}}\mathbf{p} \tag{10}$$

where $\mathbf{F_u} = (\mathbf{F_u}, \mathbf{F_v}, \mathbf{F_w})$,

$$\rho\frac{D_{\boxed{r}}}{Dt}\left[\frac{\mathbf{Z}_{\boxed{r}}\cdot\nabla_{\boxed{r}}\theta}{\rho}\right] = \nabla_{\boxed{r}}\cdot\left[F_\theta\mathbf{Z}_{\boxed{r}} + \theta\nabla_{\boxed{r}}\times\mathbf{F_u}\right] \tag{11}$$

where

$$\begin{aligned}
\mathbf{Z}_{\boxed{r}} &\equiv 2\underline{\Omega} + \nabla_{\boxed{r}}\times\mathbf{u} = \textbf{absolute vorticity} \\
&= \Bigg[-\frac{1}{\boxed{r}}\frac{\partial}{\partial r}\left(\boxed{r}v\right) + \frac{\delta_V}{\boxed{r}}\frac{\partial w}{\partial \phi}, \{2\Omega\cos\phi\} + \frac{1}{\boxed{r}}\frac{\partial}{\partial r}(ru) - \frac{\delta_V}{\boxed{r}\cos\phi}\frac{\partial w}{\partial \lambda}, \\
&\qquad 2\Omega\sin\phi + \frac{1}{\boxed{r}\cos\phi}\left(\frac{\partial v}{\partial \lambda} - \frac{\partial\left(u\cos\phi\right)}{\partial \phi}\right)\Bigg].
\end{aligned}$$

Setting $r = a + z$ (where z is the height above the Earth's surface and a is the (constant) radius of the Earth) we note that $z << a$; the depth of the atmosphere is of order 100km compared with the Earth's radius of 6371km. Neglecting z so that $r = a$ is the shallow atmosphere approximation which of course simplifies the spherical operators since we now have a constant radius. As noted by Phillips(1973) and White and Bromley (1995), to obtain conservation principles analogous to (9)-(12) requires the neglect of the curly-bracketed terms in (1)-(3). The curly-bracketed terms involving Ω are the horizontal components of the Coriolis terms which are considered to be smaller than the vertical component. However, White and Bromley (1995) argue that for both planetary-scale motion and diabatically driven synoptic-scale motion in the tropics, scale analysis suggests that these terms may attain magnitudes of 10% of the key terms so their neglect may not be justified. The metric terms, however, can be safely neglected.

There are four consistent combinations of the hydrostatic/non-hydrostatic and shallow/deep assumptions which satisfy the conservation principles. These are summarised in the following table.

	Deep	Shallow
Non-hydrostatic ($\delta_V = 1$)	Fully-compressible Navier-Stokes	Non-hydrostatic Primitive
Hydrostatic ($\delta_V = 0$)	Quasi-hydrostatic	Hydrostatic Primitive

Table 1: Valid Compressible Equation Sets

The hydrostatic primitive equations are obtained by making the shallow atmosphere approximations, setting $\delta_V = 0$ and $\Phi = gr$. This set is used by most global NWP and climate models.

The non-hydrostatic primitive equations (Tanguay et al. 1990) differ only in having $\delta_V = 1$. These equations are used in the non-hydrostatic models at Météo France (Bubnova et al, 1995) and Environment Canada (Yeh et al, 1999) and are based upon the "hydrostatic pressure" coordinate of Laprise (1992). Draghici (1987, 1989) argues that the $2\Omega u cos\phi$ term in the vertical momentum equation may dominate $\frac{Dw}{Dt}$ for some non-hydrostatic mesoscale motions so this may limit the applicability of these equations.

Following on from the shallow atmosphere discussion above, White and Bromley (1995) proposed the quasi-hydrostatic equations by setting $\delta_V = 0$. The neglect of the vertical acceleration term $\frac{Dw}{Dt}$ filters out the acoustic modes but now the spherical operators have variable r. A pressure-based coordinate version of these equations is used in the current Met. Office Unified Model (UM, Cullen 1993).

The fully-compressible Navier-Stokes equations retain the vertical acceleration terms and are valid for non-hydrostatic flows and for deep atmospheres. These equations are being used in the new dynamics for the Met. Office UM (Cullen et al 1997, Davies et al 1999).

Whilst it is clear that non-hydrostatic equations are essential for modelling non-hydrostatic flows there is no clear evidence that the consistent neglect of other terms described above is detrimental in NWP and climate modelling. It is likely that where the effect of neglecting these terms is important other approximations, such as physics parametrizations, may make it difficult to establish conclusive evidence to prove the hypothesis.

3 High resolution NWP

At the Met. Office, we have over 25 years experience in running high resolution limited-area models (LAM) operationally. Since 1993, the same formulation, the Unified Model (UM, Cullen, 1993), has been used for all operational configurations. The UM operational suite until 1998 consisted of a global model (approx. 100km horizontal resolution, 19 levels), a LAM (approx. 50km, 19 levels covering Europe and North Atlantic) and a mesoscale model (17km, 31 levels covering the British Isles). In 1998 the global model resolution was increased (60km, 30 levels), the LAM was removed, the mesoscale resolution increased (12km, 38 levels) and its domain made four times bigger.

The higher resolution LAMs provide more detail to structures such as fronts and the gradients around depressions. This can be verified objectively but verification scores may be compromised by the treatment of lateral boundaries (contemporaneity, proximity/remoteness, orography, ratio of driving model resolution to LAM), from differences in analyses or from differences due to the tuning of physics. The operational performance of the LAM before 1998 meant that we were confident that a higher resolution (60km) global model would result in a significant improvement over the 90km version. Parallel trial results reported by Milton et al. (1998) showed an overall reduction in errors with particular improvements in Northern hemisphere PMSL at all forecast ranges. See figure 1 (Figure 30 from their report) where the top panel Northern hemisphere comparison shows the lower RMS error (upper pair of lines) for nearly all the high resolution forecasts (dashed lines) compared with the control (full line). Figure 2 shows a typical example of the improvements in the forecasting of central pressure and the pressure gradients by running at higher resolution. The top panels are verifying analyses, the middle panels the control at T+72 and T+96 and the lower panels are from the higher resolution forecasts.

The desire to improve short-range (0 to 36 hours) forecasting of weather elements is driving many modelling groups towards running mesoscale models at resolutions below 10km. The improvement in the structure of the precipitation may be gauged by comparing figures 3 and 4. These are 24 hour accumulated precipitation from the December 1998 forecast from both the LAM (60km) and the mesoscale model (12km). The orographic enhancement in the mesoscale model can be clearly seen as can the tendency for the LAM to over-emphasise the rain-shadow effect.

Verification of precipitation by calculating threat scores does not show as clear a benefit as do the climatological plots. Figure 5 shows the 12 months up to April 1999 and April 2000 threat scores (upper panel) from both the global model (60km) and mesoscale model (12km). Both models show improvements from 1999 to 2000 except at the highest rates for the global model. At low rainfall rates the global model scores better but above 2.4mm/6hr the mesoscale model is better. The biases (lower panel) show the tendency of the mesoscale model to overforecast particularly for smaller rates whereas the global model underforecasts the larger rainfall rates.

Experimentation at high resolution is continuing. The JCMM (Joint Centre for Mesoscale Meteorology) are using the FASTEX observational campaign to help in evaluating the performance of both the current UM and the new dynamics at high resolution. In experiments with the UM, worthwhile impact is achieved by increasing resolution from 50km to 25km but improvements overall at still higher resolutions are generally smaller. Some small-scale structures (which have short predictability timescales) are better captured at the higher resolutions and some of these structures can be seen in observations (taking into account timing and position errors). Cases are currently being run with the new dynamics at 4km horizontal resolution.

Experience has also been gained with the current UM by running the COMPARE typhoon Flo case in a comparison organised by the JMA (Japan Meteorological Agency)(Culverwell and Wilson, 2000). The results in forecasting both the depth and track show a significant improvement from increasing horizontal resolution (50km to 20km). Increasing resolution still further gave smaller impacts. At the higher resolutions (10km and 5km) there is certainly more structure in the precipitation. These cannot be compared with observations but it is unlikely they would match as there appears to be a lack of (numerical) convergence at the highest resolutions. Experiments changing the closure assumptions in the

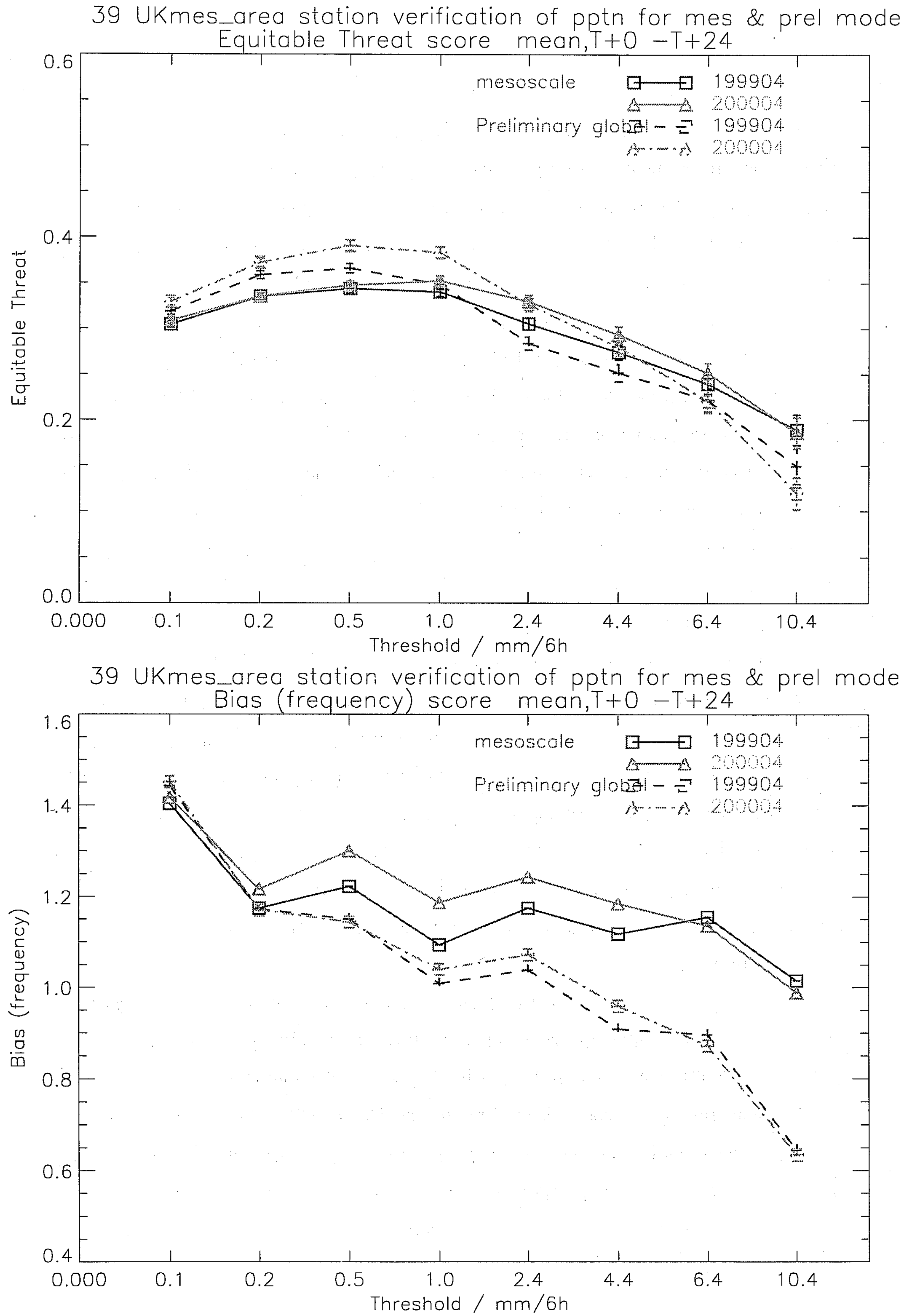

Figure 5: Precipitation verification comparing Global (dashed lines) and Mesoscale (full

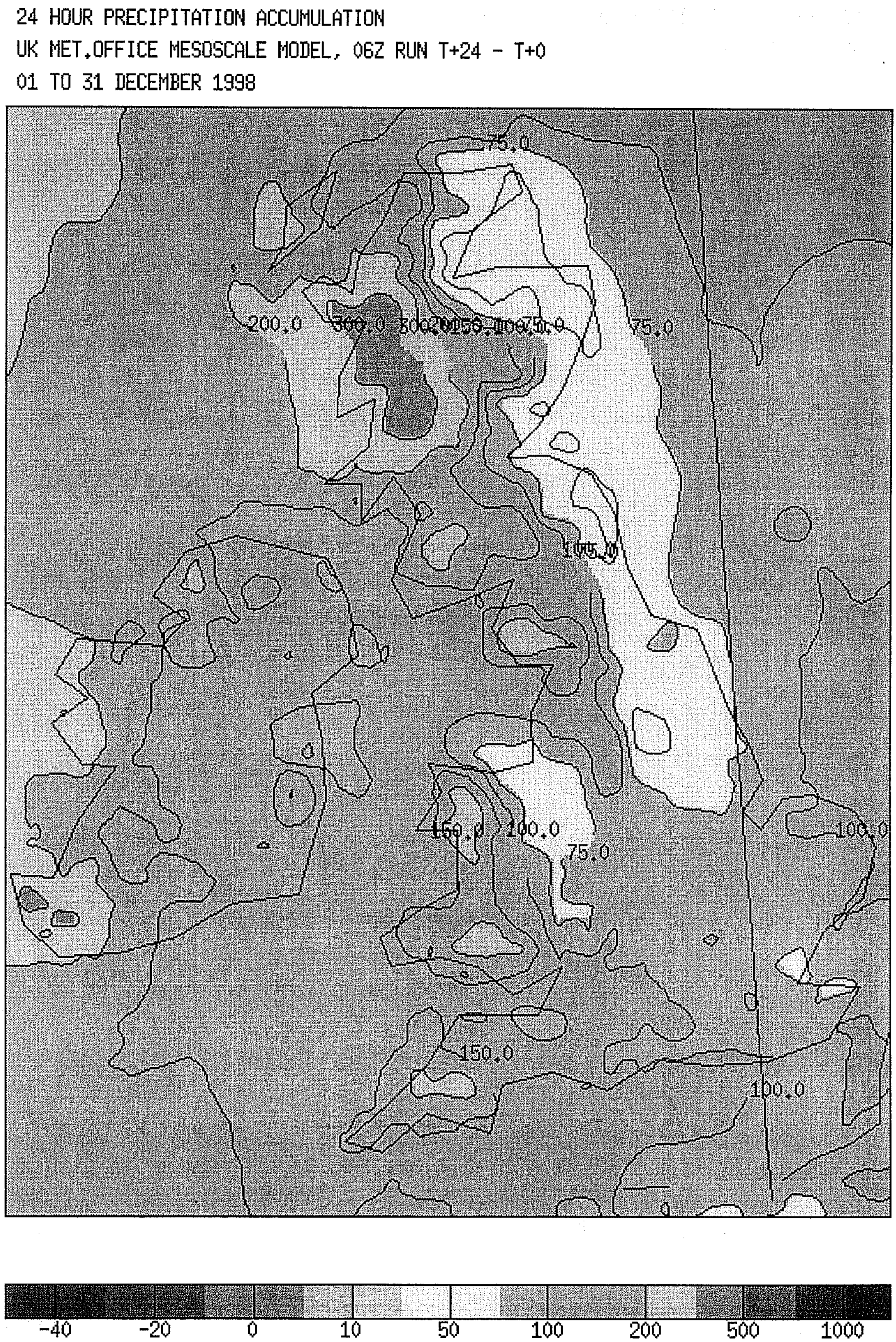

Figure 4: 24 hour accumulated rainfall from Mesoscale model forecasts for December 1998

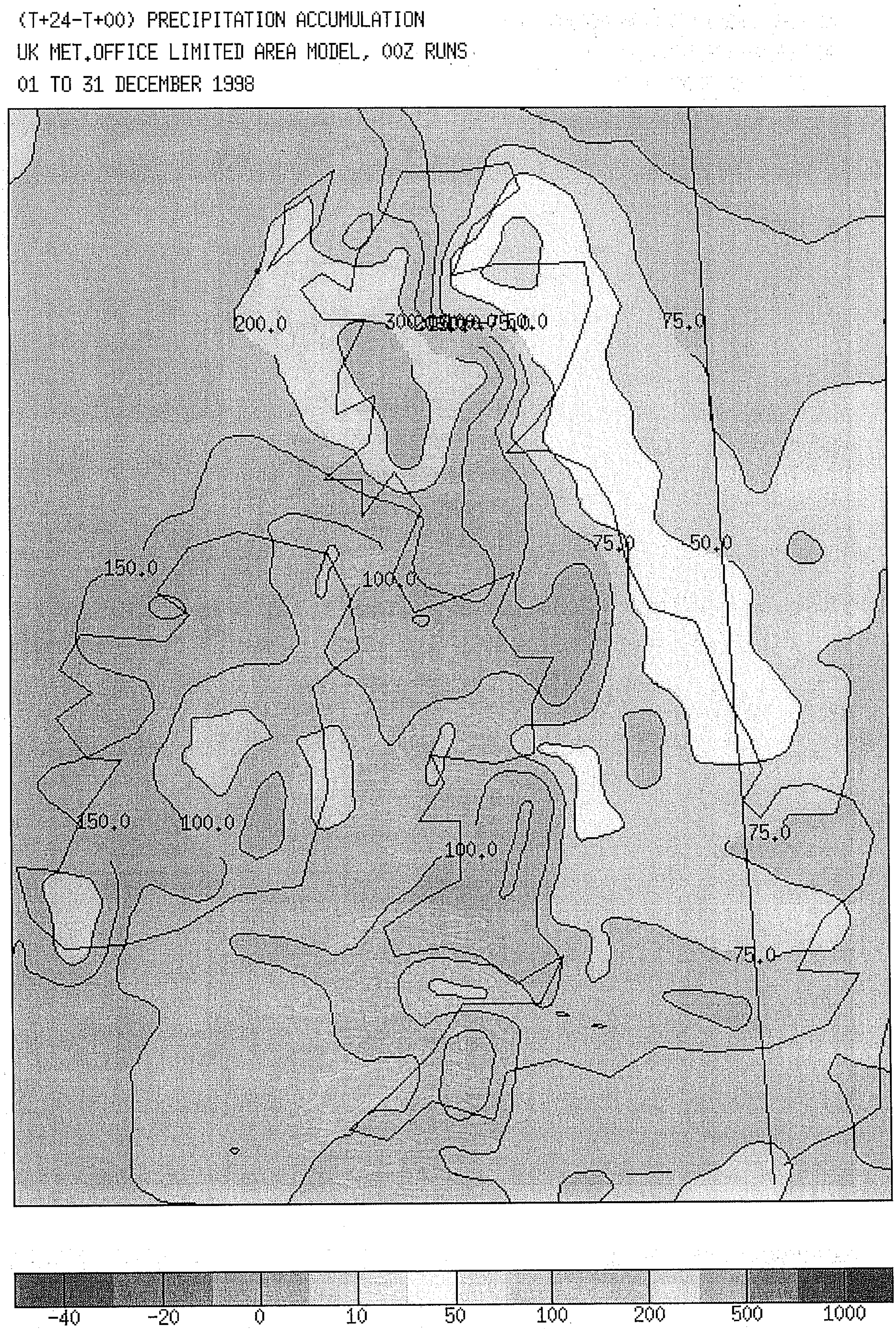

Figure 3: 24 hour accumulated rainfall from LAM forecasts for December 1998

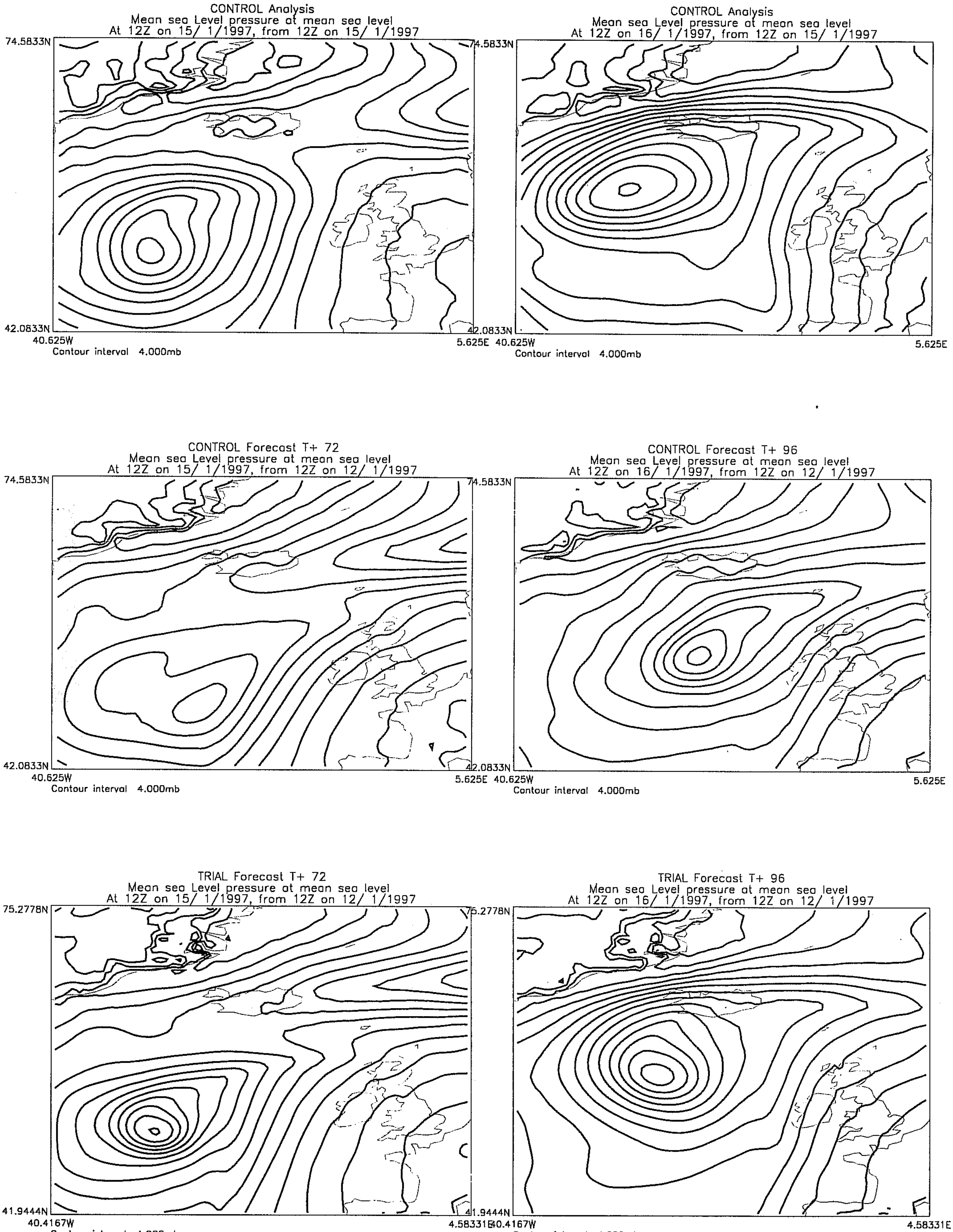

Figure 2: PMSL verification from high resolution global model trial

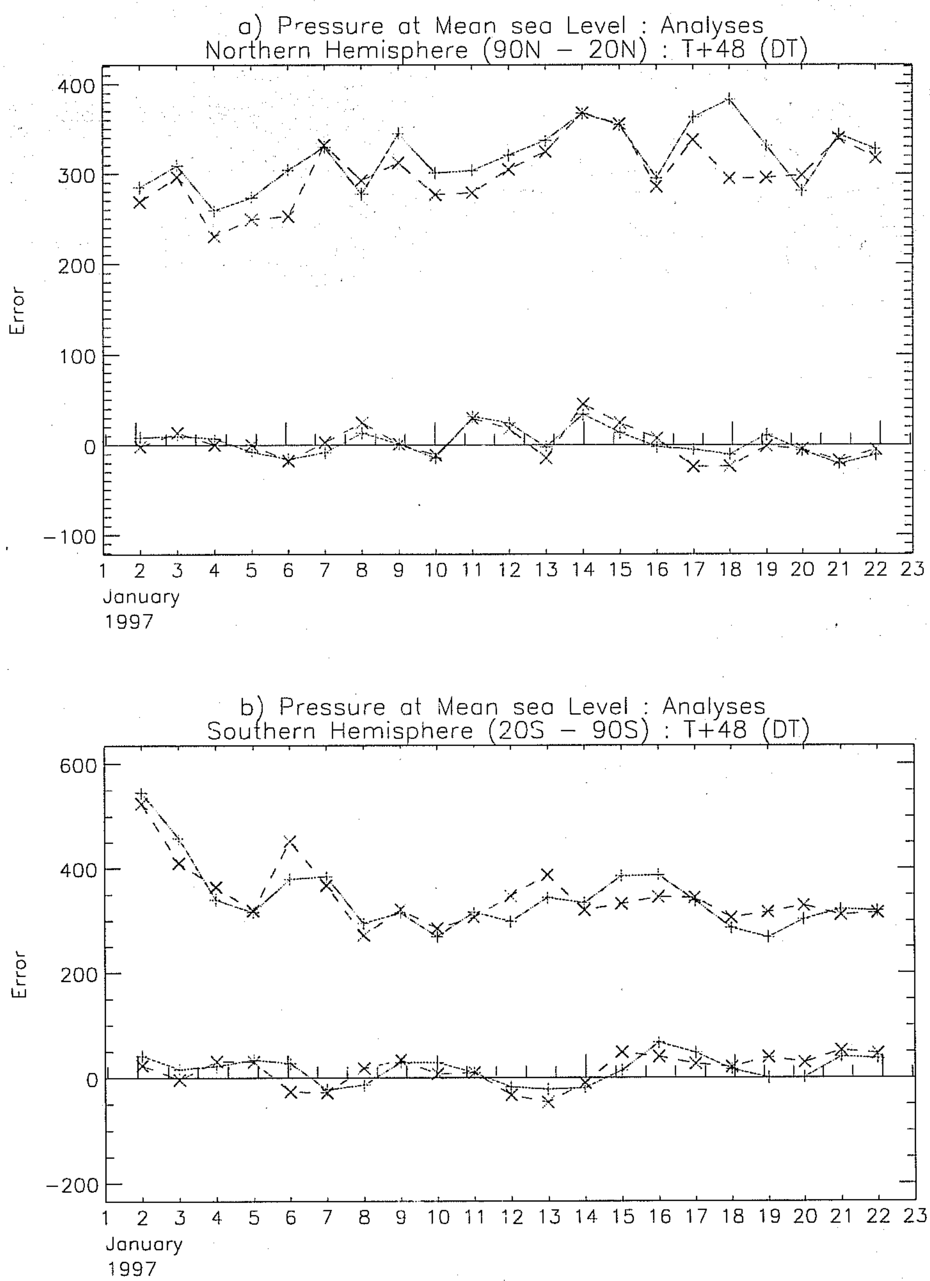

Figure 30: The T+48 MSLP RMS errors for verification of individual forecasts against model analyses during January 1997 trial for (a) Northern Hemisphere, (b) Southern Hemisphere. The solid line is the CONTROL and the dashed line is the HIRES model.

Figure 1: PMSL verification from high resolution global model trial

convective parametrization (CAPE timescale, CMT) showed significant sensitivity in the precipitation details and partitioning between large-scale and convective precipitation.

4 Discussion

In general, experience with running high resolution LAMs and mesoscale models have showed worthwhile improvements when using horizontal resolutions down to around 20km. Below that improvements are not universal. One particular problem with the higher resolutions is that the smaller domain usually needed to make them affordable means that lateral boundary effects affect the results more so than with more remote boundaries used at lower resolution. However, problems are not confined to the lateral bounday effects. As resolutions tend towards 10km or lower:

1. Non-hydrostatic effects become more important and may no longer be safely neglected.

2. The behaviour of the convective parametrization is less predictable. The underlying assumption that there are an ensemble of plumes in the convective parametrization cannot be supported and the rate of stabilisation produced by the scheme may have to be reduced unrealistically.

3. The ratio by which number of grid-points exceeds the number of observations increases (i.e. the analysis problem becomes more undetermined).

4. Small-scale structures which have short predictability timescales have poor predictability on longer timescales.

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