Numerical Weather Prediction

Forcing the Single Column UM from the Mesoscale Model

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by

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Abstract

The Site Specific Forecast Model (SSFM) is based upon the concept of driving a 1D model (primarily concerned with the surface and boundary layer) using output from 3D NWP models, the most appropriate of which is the mesoscale model (MES). The 1D model that has been chosen as a basis is the Single Column version of the UM (SCM) since this will, hopefully, provide maximum compatibility between the forcing data and SSFM and also provide maximum benefits from any improvements in the UM physics.

This report describes the basis of the forcing scheme that has been adopted and tests of the accuracy of the method. The SCM is forced using forcing data derived from MES output which is used in a simplified set of dynamics equations. The system is then tested on how well the SCM set up 'as per MES' can reproduce the MES forecasts.

The system has been tested for two high pressure and two rainfall cases, for the site of Beaufort Park. The SCM set up 'as per MES' with relaxation to the MES profiles ('local advection') can reproduce the MES forecasts very closely with almost negligible differences, with both 5 min and 1 hour forcing data. The rainfall cases show that the SCM with relaxation on can reproduce MES rainfall very closely.

Without relaxation differences appear between the SCM and MES, which are mainly due to inaccuracy in the numerical method of horizontal advection used by the SCM. This could undoubtedly be improved should the need arise, but, at present, there is no requirement to run the model in this way. The method of calculating forcing data using a fixed distance upwind from the site to calculate the horizontal advection was found to be the most accurate.

Contents

Introduction

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This report describes the basis of the forcing scheme that has been adopted and tests of the accuracy of the method. The SCM is forced using forcing data derived from MES output which is used in a simplified set of dynamics equations. The system is then tested on how well the SCM set up 'as per MES' can reproduce the MES forecasts.

Forcing equations

Since the SCM comprises the physics of the full UM, it could clearly simply be forced using the total dynamical tendencies from the large scale model it is being coupled to. However, a constraint we have placed upon ourselves is that the forcing should be capable of running with routinely available NWP output. It is difficult to extract the total large scale dynamical tendencies from the UM even when runs are set up specially for the purpose. It would require considerable modification of the UM to output these tendencies at all required points at every timestep, and the amount of output would be huge. An approximate approach is therefore required capable of following the large scale forcing but also able to introduce realistic local variation. This also has the advantage that the model could also, in principle, be forced using output from other centres. To do this we have developed a simple forcing system based upon the UM dynamics.

Basic Dynamics

The forcing terms are applied to the cloud-conserved variables liquid water potential temperature (θ_L) and total water (q_t) defined by:

$$\theta_L = \theta - (L_c q_c + (L_c+L_f) q_f) / (c_p \Pi) \qquad \textbf{(1)}$$

$$q_t = q + q_c + q_f \qquad \textbf{(2)}$$

where Π is the Exner pressure given by:

$$\Pi = (p/p_0)^{R/c_p} \qquad \textbf{(3)}$$

q_c and q_f are the liquid and frozen cloud, and L_c and L_f are the latent heats of condensation and of freezing.

Since the SCM and UM use hybrid vertical coordinates (η) we have decided to work in the same coordinate system. The full set of dynamical equations is detailed in UM documentation paper 10 (Cullen, et al, 1993, hereafter referred to as UMDP 10). For simplicity, we shall start from the same system but omit the secondary metric and Coriolis terms. In so doing, we can also use horizontal Cartesian coordinates, rather than polar coordinates. These notational changes have no significant impact on the model. The basic system of dynamical equations are as follows:

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\boldsymbol{u}.\nabla_\eta \boldsymbol{u} - f\boldsymbol{k}\times\boldsymbol{u} - \frac{1}{\rho}\nabla_z p + \boldsymbol{F_u} \qquad (4)$$

$$\frac{\partial \theta_L}{\partial t} = -\boldsymbol{u}.\nabla_\eta \theta_L - \frac{1}{\Pi}[(L_c q_c + (L_c + L_f) q_f)/(c_p T)](R T \omega / c_p p) + F_{\theta_L} \qquad (5)$$

$$\frac{\partial q_t}{\partial t} = -\boldsymbol{u}.\nabla_\eta q_t + F_{q_t} \qquad (6)$$

Here, the F terms represent the diabatic terms calculated by the single column model. The last but one term in eq. (5) is a very small correction to allow for the pressure term in the definition of θ_L (as, strictly, it is T_L rather than θ_L that is conserved when cloud forms). The 'vertical velocity' (in pressure terms) ϖ, is given by:

$$\omega = \frac{\partial p}{\partial t} + \boldsymbol{u}.\nabla_\eta p \qquad (7)$$

The advection operator is given by:

$$\boldsymbol{u}.\nabla_\eta = u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + \dot{\eta}\frac{\partial}{\partial \eta} \qquad (8)$$

The horizontal pressure gradient in eq. (4) is the strict horizontal gradient (i.e. at constant geopotential height) rather than on η surfaces and is derived from the model surface data exactly as described in UMDP 10. The current UM dynamics are hydrostatic, and so the surface pressure tendency and $\dot{\eta}$ in the UM are derived from the integral of the horizontal divergence of velocity. Since the surface pressure tendency in the model derived in this way is quite prone to noise, it has been found to be rather dangerous to use this, especially where only hourly forcing data are available. Instead, the surface pressure tendency is derived from the time derivative of the interpolated output surface pressure. This represents the first significant approximation used in the SSFM.

Decomposition to resolved and unresolved terms

The next step is to separate the terms in the above equations into parts derivable from the large scale data and parts which represent local perturbations. The large scale model has a grid size with length scale L, and we can define an operator $\langle\rangle_L$ which performs averaging or filtering on this spatial scale. In other words, the u component of wind, for example, in the large scale model is denoted $\langle u\rangle_L$, and we can define the subgrid deviation, c_s, of any variable c by:

$$c = \langle c\rangle_L + c_s \qquad (9)$$

Using this decomposition we can rewrite equations (4) to (6) as:

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\boldsymbol{u}.\nabla^H_\eta \langle \boldsymbol{u} \rangle_L - \boldsymbol{u}.\nabla^H_\eta \boldsymbol{u_s} - \langle \dot{\eta} \rangle_L \frac{\partial \boldsymbol{u}}{\partial \eta} - \dot{\eta}_s \frac{\partial \boldsymbol{u}}{\partial \eta} - f\boldsymbol{k}\times\boldsymbol{u} - \frac{1}{\rho}\nabla_z \langle p \rangle_L - \frac{1}{\rho}\nabla_z p_s + \boldsymbol{F_u} \tag{10}$$

$$\frac{\partial \theta_L}{\partial t} = -\boldsymbol{u}.\nabla^H_\eta \langle \theta_L \rangle_L - \boldsymbol{u}.\nabla^H_\eta \theta_{L_S} - \langle \dot{\eta} \rangle_L \frac{\partial \theta_L}{\partial \eta} - \dot{\eta}_S \frac{\partial \theta_L}{\partial \eta} - \frac{1}{\Pi}[(L_c q_c + (L_c + L_f) q_f)/(c_p T)](RT\omega/c_p p) + F_{\theta_L} \tag{11}$$

$$\frac{\partial q_t}{\partial t} = -\boldsymbol{u}.\nabla^H_\eta \langle q_t \rangle_L - \boldsymbol{u}.\nabla^H_\eta q_{t_S} - \langle \dot{\eta} \rangle_L \frac{\partial q_t}{\partial \eta} - \dot{\eta}_S \frac{\partial q_t}{\partial \eta} + F_{q_t} \tag{12}$$

The gradient terms are the 'horizontal' (on η surfaces) gradients, as the vertical term is shown explicitly and treated separately. It should be noted that the decomposition here is not complete, in that the local values available in the 1D model are used where possible. Thus, the full local horizontal velocity, u, is used in the advection term, but the gradient is decomposed into large and small scale. The diabatic terms are derived using local parametrizations, as far as possible.

At this stage we shall assume the same orography as the large scale model: treatment of sub-grid orography in the SSFM will be covered in a later publication. We have thus chosen to ignore the subgrid component of the vertical velocity (i.e. $\dot{\eta}_S = 0$) and the subgrid component of the horizontal pressure gradient. Both of these terms arise from sub-grid variations in surface drag and heating. By ignoring them, we are assuming that the main impact of perturbations to the surface characteristics is to change the vertical turbulent fluxes in a way which is balanced by subgrid horizontal advection. We are ignoring situations where these perturbations have a significant impact on vertical motion. Such situations include small scale sea or lake breeze circulations and local triggering of convection. Trying to include the latter explicitly in the dynamics would clearly be extremely dangerous, while impacts of thermally induced convergence will be regarded as a local phenomenon to be considered in the next stage of the project. The surface pressure (and, hence, that at model levels) is simply taken from the large scale model.

The remaining terms involve the following:

1) Variables directly available in the 1D model.
2) Values of the large scale field or the gradients thereof.
3) The horizontal gradient of the local perturbation.

The second of these is derived directly from the output from the large scale model or by numerical differentiation of it, and represents the primary coupling term. The numerical derivation of the gradient terms, which contribute to the large scale horizontal advection terms, will be described below. The last is the only remaining class of terms requiring parametrization.

Local or sub-grid advection

The last term represents local advection, i.e. the advection of the perturbation from the large scale. If we consider a region with different surface characteristics embedded in the larger scale mean, then a simple parametrization of this term is given by:

$$u\frac{\partial c_s}{\partial x} = \alpha \, \|u\| \frac{(c - \langle c \rangle_L)}{l_x} \tag{13}$$

where l_x is the upwind fetch and, for simplicity, we have aligned the x axis with the wind direction. The factor α is an adjustable parameter of order 1. Here, we argue that at the start of the patch with 'local' characteristics, the variable has a value approximately equal to the large scale mean. Parametrizations based on this idea have been tested in 2D and 1D versions of a detailed boundary layer model (BLASIUS) and have been shown to enable the 1D version to give results quite comparable to the 2D model when simulating flow over a surface inhomogeneity (Grant and Best, unpublished). A value of α equal to 1 gives acceptable results, though the best value apparently depends weakly on fetch. Given that, in practice, defining a precise fetch will be difficult (and of only minor importance) we have absorbed α into the fetch specification.

This term, of course, represents a Newtonian relaxation onto the large scale flow. As well as representing the effect of local advection, it ensures that the solution derived from the large scale forcing terms does not stray too far from the large scale model. In practice, we expect our higher resolution simulation to differ from the grid box mean for reasons other than the different local surface. These differences arise from differences in numerical precision, the impact of minor terms in the dynamics which we have neglected, the impact of horizontal diffusion in the NWP solution which we are not using, and different numerical treatment of the advection. These are all (with the possible exception of diffusion) differences which we would wish to minimise if we run the model with a configuration identical to a corresponding mesoscale gridsquare. If we run with a different configuration, then we expect genuine differences arising from, for example, different radiative flux divergence and different turbulent mixing (especially across inversions) because of different resolution. Below the 'diffusion height' in the boundary layer, we expect to see differences arising from the differences in surface characteristics.

To account both model error and genuine physical differences, we have used different effective fetches at different levels. At very high altitude (i.e. stratosphere) the effective fetch is chosen to be short enough to ensure that the single column is essentially identical to the large scale model. (To all intents and purposes, we are simply replacing the SCM profile with the mesoscale). Similarly, in most of the troposphere, a short relaxation timescale of 5 minutes is chosen. In the boundary layer, we have the choice of choosing a relatively long fetch, either representing the real fetch over the surface of interest or the 'gridbox' being simulated, or turning off this term altogether. In the latter case, since we are forcing only with the gradients of the large scale fields, we can derive the maximum impact of both improved model physics and of initial data.

The final model equations are as follows:

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\boldsymbol{u}.\nabla_\eta \langle \boldsymbol{u} \rangle_L - \frac{|\boldsymbol{u}|}{l_\eta}(\boldsymbol{u} - \langle \boldsymbol{u} \rangle_L) - \langle \dot{\eta} \rangle_L \frac{\partial \boldsymbol{u}}{\partial \eta} - f\boldsymbol{k} \times (\boldsymbol{u} - \langle \boldsymbol{u}_G \rangle_L) + \boldsymbol{F_u} \tag{14}$$

$$\frac{\partial \theta_L}{\partial t} = -\boldsymbol{u}.\nabla_\eta \langle \theta_L \rangle_L - \frac{|\boldsymbol{u}|}{l_\eta}(\theta_L - \langle \theta_L \rangle_L) - \langle \dot{\eta} \rangle_L \frac{\partial \theta_L}{\partial \eta} - \frac{1}{\Pi}[(L_c q_c + (L_c + L_f) q_f)/(c_p T)](R T \omega / c_p p) + F_{\theta_L} \tag{15}$$

$$\frac{\partial q_t}{\partial t} = -\boldsymbol{u}.\nabla_\eta \langle q_t \rangle_L - \frac{|\boldsymbol{u}|}{l_\eta}(q_t - \langle q_t \rangle_L) - \langle \dot{\eta} \rangle_L \frac{\partial q_t}{\partial \eta} + F_{q_t} \tag{16}$$

The surface pressure (and, hence, that at model levels) is simply taken from the large scale model. Any local pressure perturbation is ignored. Similarly, the horizontal pressure gradient and large scale vertical velocity are derived directly from the large scale model (in fact, a single adjustment step is run in order to ensure exact comparability and the results bilinearly interpolated to the site of interest).

Numerical treatment of horizontal advection

Horizontal advection is an important consideration in any meteorological model. The accuracy of the numerical treatment can have considerable impact. However, in driving our 1D model we should bear in mind that we already have a solution to the large scale advection problem in the form of the driving data themselves. Thus, we have not attempted to reproduce accurately the full 3D UM advection scheme. Even if we were to derive the large scale advective tendency from forcing data the need for time interpolation would introduce large inaccuracies. Instead, a number of alternative and simpler approaches have been tried.

Before describing these, it is worthwhile considering the interaction of the large scale and 'local' advection terms.

The large scale horizontal advective tendency of any quantity c can be written

$$\left.\frac{\partial \langle c \rangle_L}{\partial t}\right|_{advection} = -\boldsymbol{u}.\nabla^H_\eta \langle c \rangle_L = -|u| \frac{\partial \langle c \rangle_L}{\partial s} \tag{17}$$

where s represents the streamwise direction. The exact solution to this advection equation is, of course, simply to replace c with the 'appropriate' value along the upstream Lagrangian trajectory. Given that we already have the mesoscale solution, the most accurate approach to large scale advection would be to compute accurate upstream trajectories using a high order interpolation scheme to derive the winds and advected quantity at a given point. Implementing this is straightforward in principle but not simple. If we were to do so we could probably make use of code written for the new UM semi-Lagrangian advection scheme. However, to make this worthwhile would imply supplying forcing data for every timestep. A limitation of the mesoscale operational output is that data are only available every hour. Forcing data for intermediate times must be interpolated from these, which ultimately places a limit on the accuracy of the computed advection term. The time resolution of available output can be justified by considering a typical propagation speed at low level of phenomena such as fronts of order 10 ms^{-1}. This implies a traverse of about two grid squares in an hour, which is precisely the shortest wavelength that can be resolved by the model. Thus, the spatial and temporal scale of available information is, at least approximately, compatible, though strictly one might have preferred half hourly data. Given these restrictions on available data, we have elected, at this stage, to implement advection much more simply, with a view to upgrading to a better scheme only if and when the simpler approach proves inadequate. Part of the purpose of this report is to assess the practical impact of the simpler approach.

To first order (i.e. assuming locally uniform velocity), the advected upstream value can be derived numerically from

$$\frac{\partial\langle c(\mathbf{x},t)\rangle_L}{\partial t} = -|\mathbf{u}|\left(\frac{\langle c(\mathbf{x},t)\rangle_L - \langle c(\mathbf{x}-\mathbf{u}\Delta t)\rangle_L}{|\mathbf{u}|\Delta t}\right) \qquad \textbf{(18)}$$

The physical interpretation of this can be understood further by combining with the 'local advection' term and using a simple **implicit** Euler timestep to derive a numerical algorithm for advection:

$$c(t+\Delta t) = c(t) - \left(\langle c(t)\rangle_L - \langle c(t)\rangle_L^{upwind}\right) - \frac{|\mathbf{u}|\Delta t}{l_x}\left(c(t+\Delta t) - \langle c(t+\Delta t\rangle_L\right)$$
$$= \frac{\left(\langle c\rangle_L^{upwind} + \beta\langle c(t+\Delta t)\rangle_L + (c(t) - \langle c(t)\rangle_L)\right)}{(1+\beta)} \qquad \textbf{(19)}$$

where $\beta = |\mathbf{u}|\Delta t / l_x$. This more clearly illustrates the relationship between relaxation and advection; they are essentially the same thing. When the fetch is small compared to the advection distance $u\Delta t$, so β is large, we expect c(t) to equal $\langle c(t)\rangle_L$ (i.e. we are forcing the mesoscale result in very strongly). When the fetch is long, β is small, so we advect in the large scale *upwind* value but maintain any local differences between the SCM and small scale.

From this it is also clear that we could combine the large scale and local advection terms as a single relaxation term onto the upstream value:

$$\begin{aligned}\frac{\partial c}{\partial t}_{advection} &= -|u|\left(\frac{\partial\langle c\rangle_L}{\partial s} + \frac{\partial c_s}{\partial s}\right)\\ &= -|u|\left(\frac{\langle c(x)\rangle_L - \langle c(x-l_x)\rangle_L}{l_x} + \frac{c(x) - \langle c(x)\rangle_L}{l_x}\right) \qquad \textbf{(20)}\\ &= -|u|\left(\frac{c(x) - \langle c(x-l_x)\rangle_L}{l_x}\right)\end{aligned}$$

While we could implement all the advection terms in this way, this has the drawback that our local fetch l_x is quite small compared with the mesoscale resolution so, given the poor temporal resolution of the data, there is a danger that the strongest gradients will be excessively smoothed by doing so. We have elected instead, at this stage, to treat the large scale advection directly in the form of equation (8), using the product of velocity and vector spatial gradient, or equation (17), using an 'along stream' gradient derived over a length scale rather longer than l_x, thereby keeping the large scale and local advection explicitly separate.

In the long run, treating the combined advection by relaxation onto the upstream profile may be much simpler and guarantees a strong compliance with the mesoscale forcing, separating the two terms allows us to consider the large scale and small scale advection as distinct processes.

This separation may, in the absence of the relaxation term, be less accurate and cause a more rapid divergence of the model from the large scale behaviour, but it is judged an advantage to include explicitly the local velocity in the large scale advection, as then any decoupling near the surface will directly feed back on the large scale advection term.

When expressing the advection term in gradient form (eq. (8)) the spatial gradients have been derived using centred finite differencing of first, second or fourth order. To maintain consistency with the pressure gradient, the gradient is derived first on the mesoscale grid then bilinearly interpolated to the site of interest. When expressing it in terms of the upstream difference (eq. (17)) the advective tendency using the 'mesoscale' advection velocity has been used as in eq. (18) but using the velocity in the driving data. The value of Δt was specified in two separate ways; either fixed (equal to half an hour), or depending on windspeed such that the upwind distance is fixed (equal to the diagonal distance across a grid box). The upwind value was derived using simple bilinear interpolation. In the current scheme forcing at intermediate times is derived by simple linear interpolation in time.

It is fully recognised that these algorithms are inaccurate when compared with advection schemes required for advection in a full model, but it is emphasized that we are not trying to solve accurately the advection problem, as the relaxation term should correct small errors generated from low order accurate differencing, but merely to separate the large and small scale advection.

Summary

In summary, five separate algorithms have been used to derive forcing data from mesoscale operational output: centred differncing with accuracy order 1,2 and 4 in grid size, and Lagrangian upwind differencing using either a fixed length or fixed time trajectory. The first order differencing with relaxation turns out to be quite acceptable, but this is mainly because of the relaxation term, so no results with this configuration are included in the following text.

Methodology for testing the forcing scheme

The system described above has been assessed by testing how well the SCM set up 'as per MES' can reproduce the MES forecasts. The SCM was tested for a single site, Beaufort Park, with and without relaxation to the MES profiles, and with forcing data derived from each physics timestep (5 minutes) or the normal MES output frequency (1 hour). It must be remembered in the following that by 'error' we mean deviation from the mesoscale output. Since we are omitting diffusion which is un-physical, a different result is not, necessarily, a less accurate one.

In an operational MES forecast, data assimilation continues for two hours after the analysis time. This cannot be reproduced in the SCM, so a clean comparison with operational output is not possible. Instead for these tests the MES was rerun starting with the operational analysis, without further data assimilation, and fields were output at the end of every (5 minute) timestep. Forcing data was then produced based on either MES output every timestep or every hour, giving 5 minute or 1 hour forcing data. The MES forcing data contains surface pressure, horizontal pressure gradients, and either horizontal gradients or horizontal advection tendencies of temperature, moisture and wind. Etadot was calculated from the MES data by running a single MES adjustment step.

The approximated set of dynamics equations used by the SCM are set out above. The SCM timestepping scheme uses an adjustment step followed by an advection step, both steps use a single forward timestep. The SCM runs a dynamics timestep followed by a physics timestep, the timestep is 5 minutes for all routines except for radiation which is called hourly. If the SCUM is run with a shorter timestep than the forcing data then the forcing data is linearly interpolated in time.

If the SCM is run with relaxation then each timestep the SCM's profiles above the BL are essentially replaced by the MES. Within the diagnosed BL the relaxation has a longer timescale. This timescale has a fixed part (24 hours) and a part obtained from the windspeed and grid box length. Relaxation acts as a correction towards the MES profiles. Ideally no correction would be required, particularly in the BL as this is where the effects of local terrain may be present.

The SCM was set up 'as per MES' with the exactly the same physics routines as the MES (including the rapidly mixing and convection schemes), the same ozone, and the same surface characteristics, and was run from the MES analysis, The only difference in configuration is that the MES is run for MES gridpoints, then the results are interpolated (bilinearly) to the location of Beaufort Park, while the SCM is run for the location of Beaufort Park using forcing data and ozone interpolated to that location (but the grid box surface characteristics). This is likely to result in small differences as the physics and interpolation stages do not commute. Different methods of calculating forcing data were tested. The SCM was run 'as per MES' for Beaufort Park for high pressure, low wind cases and for frontal passages.

Testing

Description of cases.

The model was tested using two light wind 'fog' cases, and two more active 'precipitation' cases.

The nights of 16/17 Oct 96 and 5/6 Dec 96 had fairly clear skies in the evening and formed fog in the morning, and were both high pressure low wind cases. The MES was run for these nights from both 00Z and 12Z analyses. The MES tended to produce more cloud in the evening and less chance of fog in the morning than was observed, although the 00Z run was better in these respects.

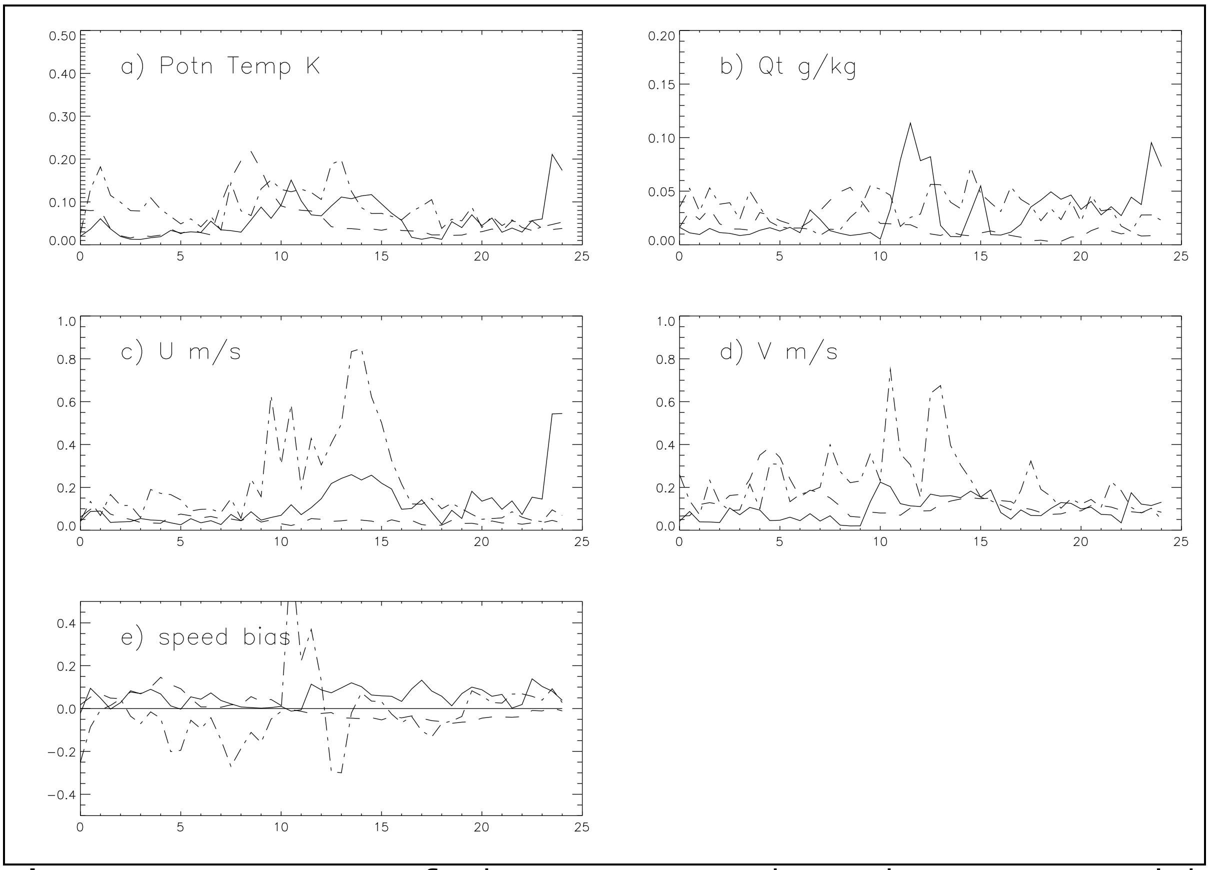

Figure 1 Rms errors of the SCM compared to the MES, SCM with relaxation, 1hr forcing data and distance upwind advection. Full line, 00z/17/10/96 (fog); dashed line 12z/5/12/96 (fog); dash-dot line 00z/19/11/96 (rain).

The MES average geostrophic wind speed estimated over the lowest 2.5 km is given for each run from 00Z to 06Z; for the night 16/17 Oct the 12z run gave 5m/s-4m/s, and the 00z run gave 5m/s-2m/s, for the night 5/6 Dec the 12z run gave 1m/s-3m/s, and the 00z run gave 1m/s-3m/s.

The rainfall cases were 31/10/96 and 19/11/96. The MES was run from 00Z, for both these cases the MES mean geostrophic wind was about 20m/s. On 31/10/96 the MES had a front nearby for most of the day and gave light drizzle, on 19/11/96 the MES had a front and moderate rain (there was some snow this day but this was missed by the MES at this location). The rainfall cases are discussed more in the Rainfall section.

SCM with Relaxation.

The SCM was run with relaxation for all the above cases, for both 1hr and 5min forcing data, and the errors found to be very small. The MES and SCM profiles for theta, q, U and V are

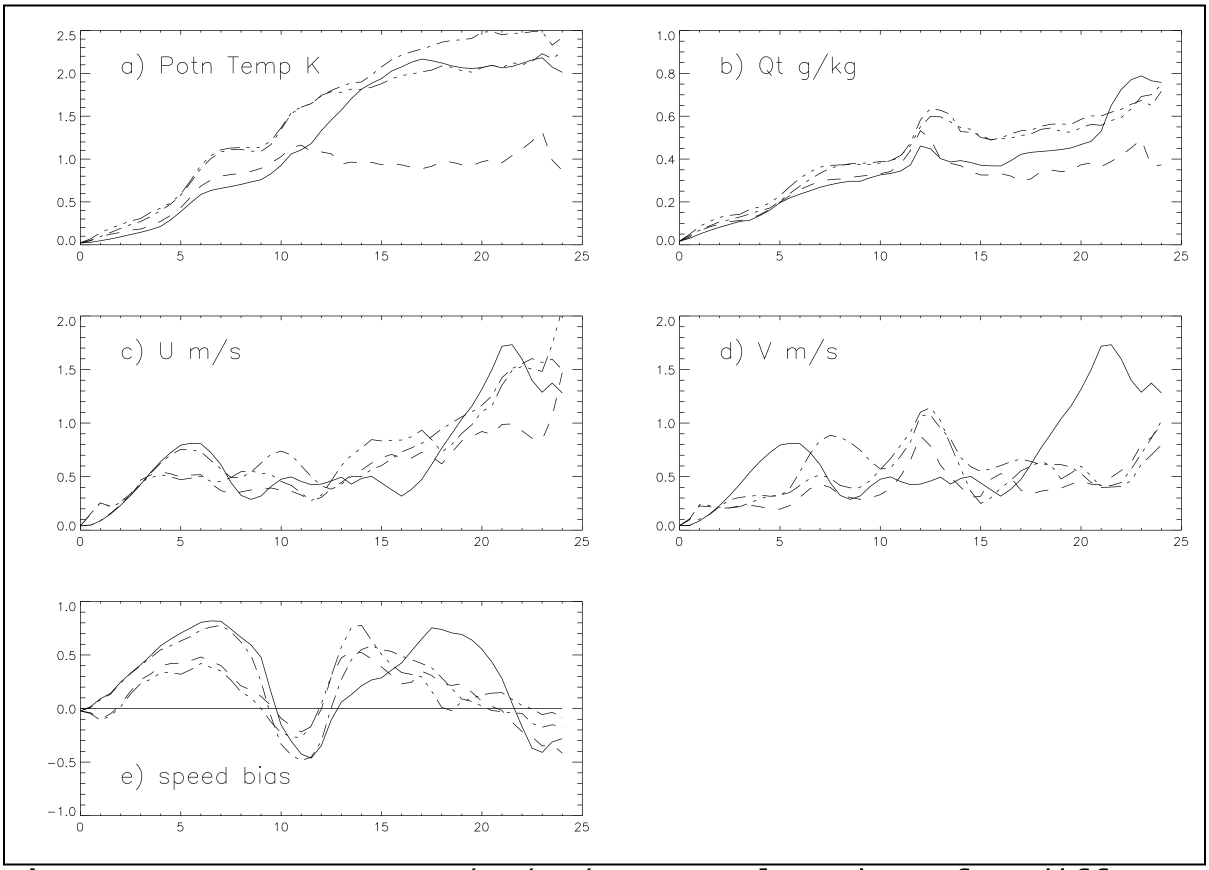

Figure 2 Rms errors 00z/17/10/96 no relaxation, for different forcing data. Full line, 5 min distance upwind (duw); dashed line, 1 hr duw; dash-dot line, 5 min 2nd o gradients (2nd); dash-triple-dot line, 1 hr 2nd. (Note: b) is Q not Qt)

very close to each other, and there is hardly any difference between 1hr and 5min forcing. The SCM was run using upwind forcing data, although forcing data using second order gradients gave nearly the same results.

The rms errors of the SCM compared to the MES, for the SCM with 1 hour forcing and relaxation, are shown in Fig. 1, for the runs starting on 00Z/17/10/96, 12Z/06/12/96 and 00Z/19/11/96. The errors are calculated over the lowest 2.5km (14 model levels), as this is the depth over which the boundary layer scheme operates. Rms errors are shown for potential temperature, specific humidity, and the wind components U and V. The wind speed bias is also shown (the wind speed error at each level averaged over 14 levels). The rms errors and the speed bias remain very small throughout each of the runs. The rms theta errors are less than 0.2^{o}C and generally about 0.1^{o}C, the rms q errors are less than 0.1 g/kg and generally about 0.05 g/kg, and for the high pressure cases the rms U and rms V errors are less than 0.3 m/s. For the rainfall case the rms U and V errors are less than 0.8 m/s which is small compared to the mean BL wind speed of 20m/s.

Method of calculating forcing data.

Forcing data were calculated using either a fixed distance upwind from the site or using gradients from the surrounding grid boxes. For the upwind approach a gridbox diagonal (~24km) upwind is used, and the MES advection is calculated (Umes d/dL). For the gradient approach second order gradients are calculated at surrounding grid points and linearly interpolated to the site. Tests using 1st and 4th order gradients, or taking advection from 1 hour upwind, were found to be less successful and are not shown here.

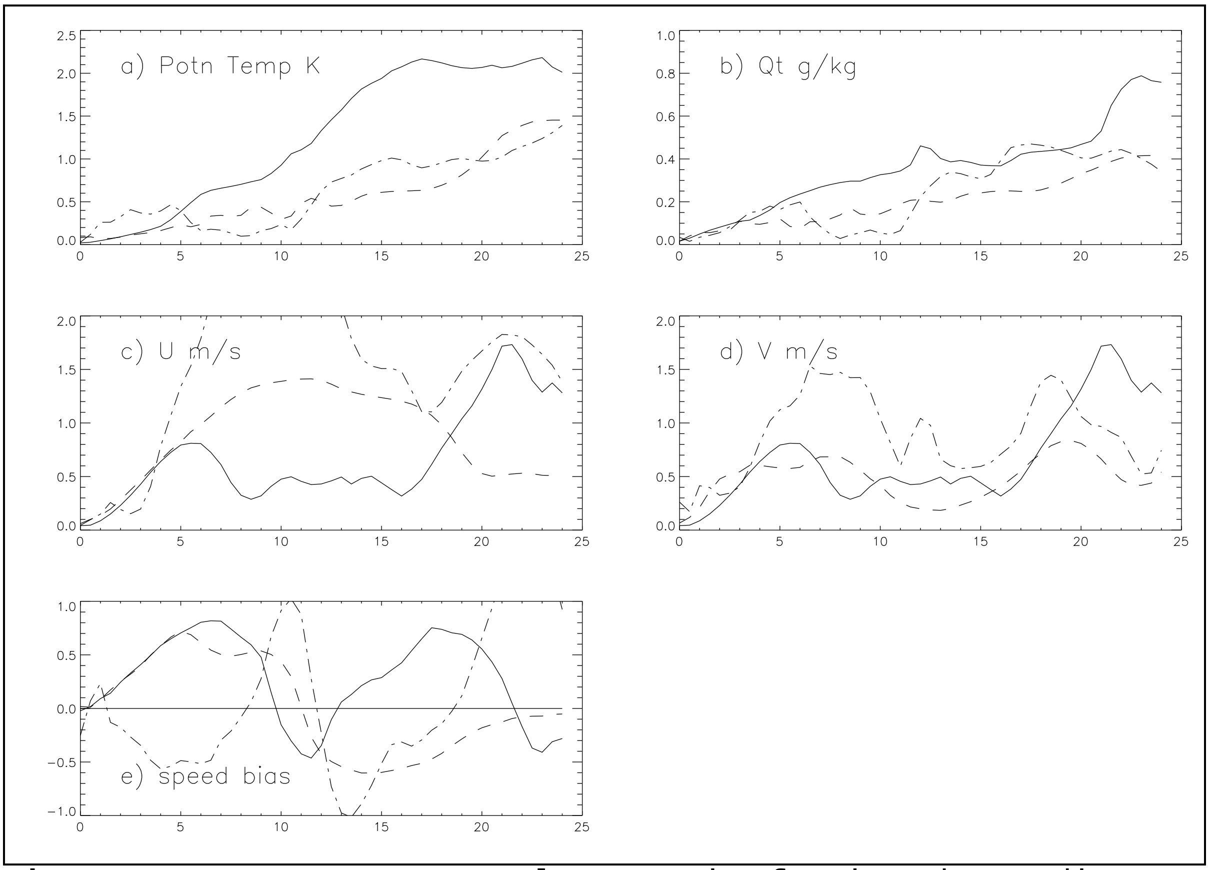

Figure 3 Rms errors, no relax, 5 min forcing data, distance upwind advection. Full line, 00z/17/10/96 (fog); dashed line, 12z/5/12/96 (fog); dash-dot line, 00z/19/11/96 (rain).

Tests were carried out without relaxation, for the two high pressure days 00z/17/10/96, 00z/06/12/96 and for a frontal case 00z/19/11/96. The fixed distance upwind method was compared with 2nd order gradients, using 5 min and 1 hour data, and found to be about the same or slightly better. The comparison was made in terms of rms errors, looking at the mean profiles, and cloud cover and surface fluxes. Fig.2 shows the rms errors for 00z/17/10/96 for the different methods of calculating forcing data. Runs were also made with a reduced timestep of 50 seconds, this made a marginal difference.

Summary of the Runs without relaxation.

Tests were made without relaxation using fixed distance upwind advection terms. The rms errors for two high pressure runs and a frontal case are shown in Fig.3, for 5 min forcing data. The rms theta and q errors grow gradually throughout the runs. The rms U and rms V errors oscillate throughout each run and grow slowly with time. The speed biases also oscillate between over and under prediction.

A summary of the errors in the profiles for each of the runs between 00Z and 09Z is given below. All cases were run with both 5 min and 1 hour forcing data, which gave very much the same results, although the 5 min data generally gave very slightly better results. The results below are for 5 min forcing data, although the same pattern applies for the 1 hour data.

RUN FOR 00Z 17/10/96

For this run, profiles through the lowest 2.5km of atmosphere are shown for θ, q, U and V, in Fig.4, Fig.5, and Fig.6 respectively. The profiles show the MES and SCM at 00Z, 03Z, 06Z and 09Z. The temperature profile shows a stable layer near the surface, above this there is a residual layer which is capped by an inversion. There is some layer cloud at 1.2km. The

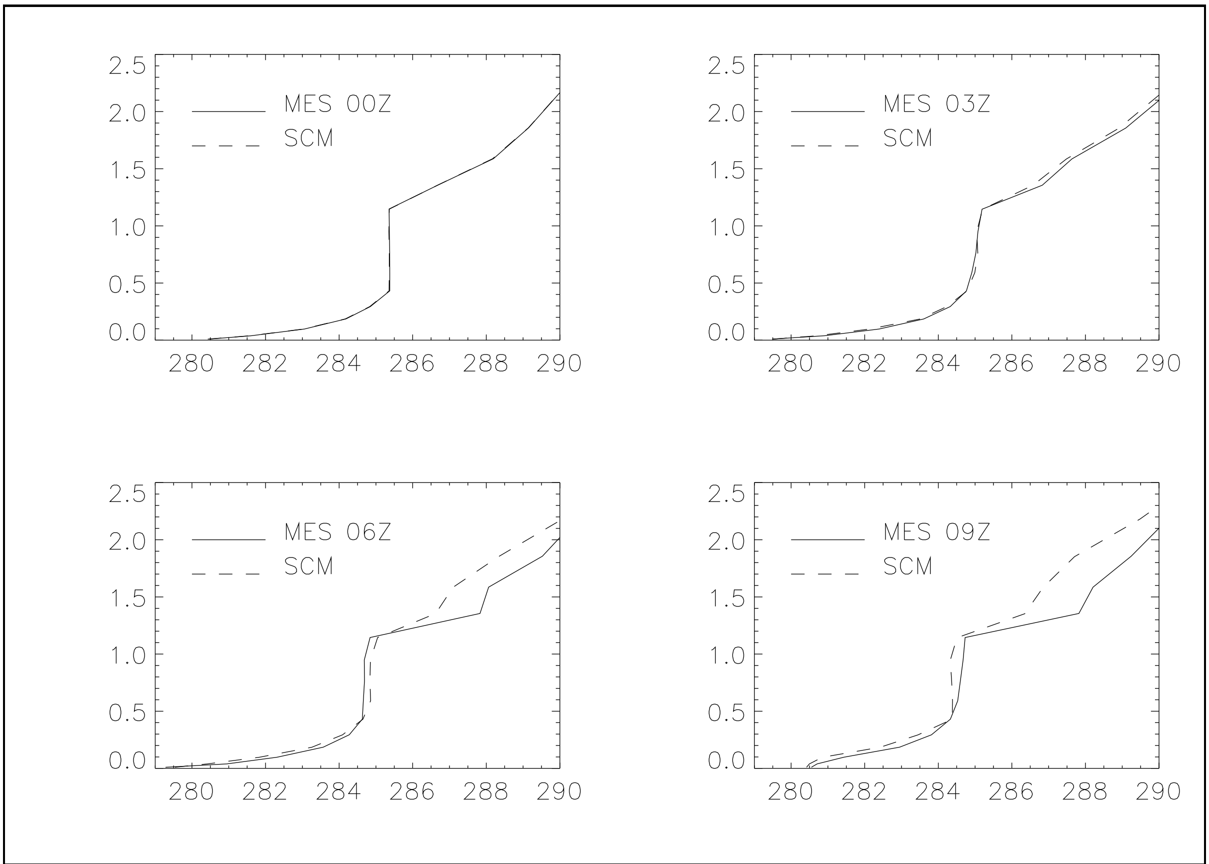

Figure 4 Potential temperature profiles (K) for run 00z 17/10/96, MES compared to SCM with no relax, 5 min data and distance upwind advection.

MES and SCM cool the stable BL and the residual layer about the same, with differences less than 0.2°C. However from 1.2km to 3km the MES stays the same or warms slightly whilst the SCM cools by 1-2° C. Above 3km the MES and SCM θ profiles are about the same. For the q profile the MES dries slowly with time, the SCM only dries slightly so the SCM is moister than the MES. Above 4km the q profiles agree.

The wind profile has a shear layer below 400m, a layer with little shear up to 1.2km, and a shear layer above this. The wind direction is initially from the South, and changes to be from the SE, the NE and from the North by 09Z. The SCM wind profile follows the trend of the MES changes quite well. For the first 8 hours the MES and SCM total cloud and surface fluxes are about the same, later in the run the SCM has more cloud.

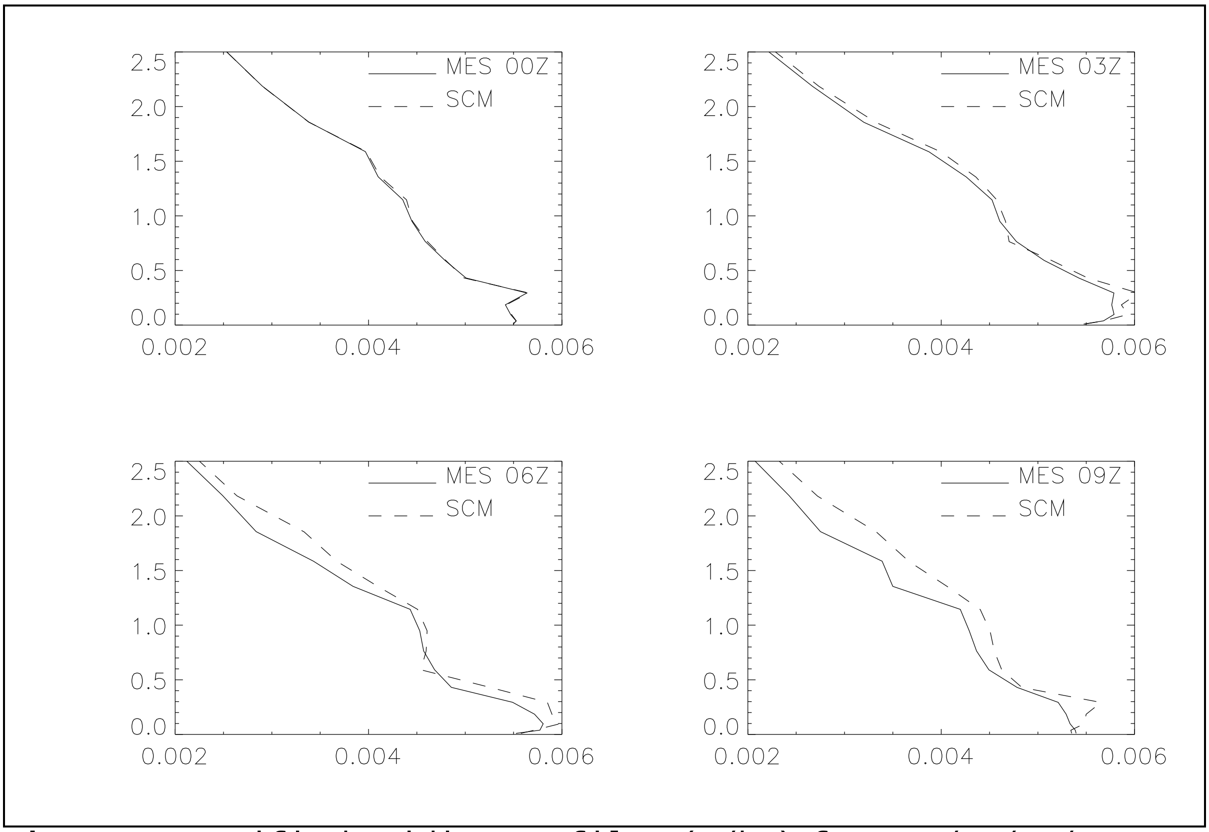

Figure 5 Specific humidity profiles (g/kg) for 00z/17/10/96, MES compared to SCM with no relax, 5 min data and distance upwind advection.

RUN FOR 12Z 16/10/96 (ERRORS FROM 00Z TO 09Z)

By 00Z the MES and SCM profiles are still similar, although the SCM residual layer is about 0.5 warmer (the SCM had less cloud cover during the day). There is cloud at 1.4km, the MES and SCM have comparable cloud cover from 00Z to 09Z. During this period the MES and

SCM θ profiles cool and are about the same in the stable BL and residual layer, but from 1.4km to 5km the SCM is cooler. For the q profile the MES and SCM moisten, but the SCM is slightly moister up to 3km. The MES and SCM wind profiles follow the same trend and are fairly close.

RUN FOR 00Z 6/12/96 (ERRORS FROM 00Z TO 09Z)

For this run the MES forms a cloud layer in the lowest 200m, the SCM does not form as much cloud in this layer. For both the MES and SCM this is the only cloud present. The MES forms a well-mixed temperature profile in the lowest 200m, the SCM has an inversion down to the surface. From 200m to 3km the SCM cools more than the MES, above 3km they are about the same. The MES moisture profile dries out more than the SCM, so that the SCM is moister up to 3km. The MES and SCM winds are fairly close to each other.

RUN FOR 12Z 5/12/96 (ERRORS FROM 00Z TO 09Z)

By 00Z the profiles are still close. From 00Z to 09Z the MES and SCM have almost full cloud cover at 1km, the SCM becomes cooler than the MES from 1km to 3km, and the MES q profile dries more than the SCM. The SCM winds follow the trend of the MES winds.

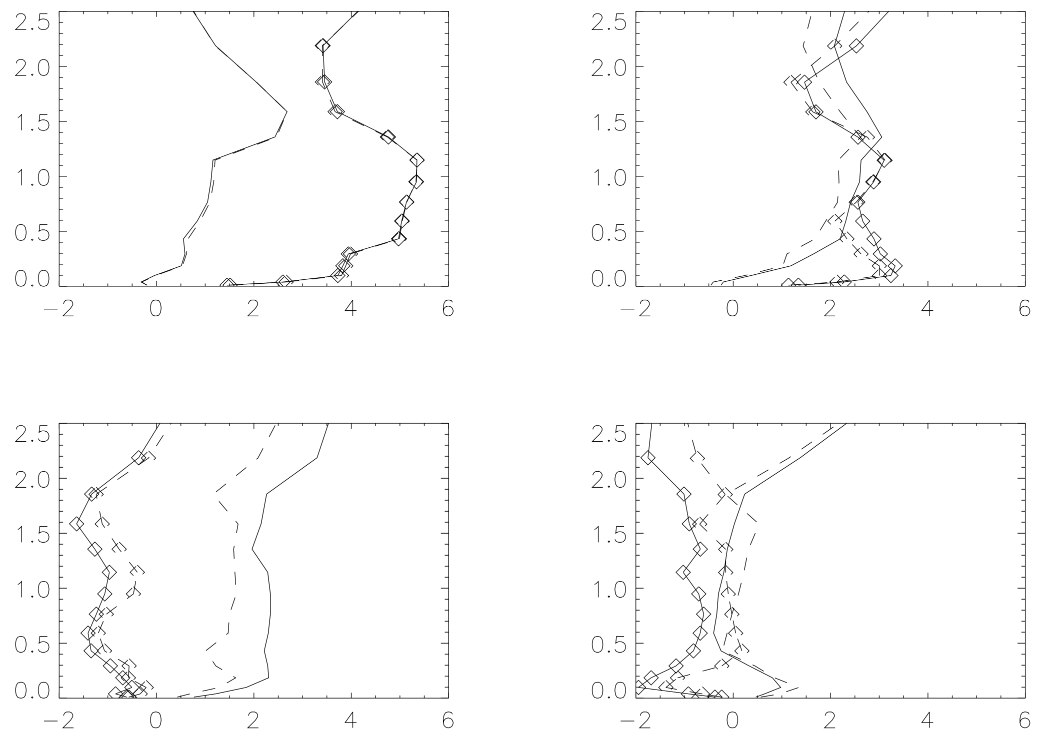

Figure 6 Wind profiles (m/s) for 00z/17/10/96, MES compared to SCM with no relax, 5min data and distance upwind advection. U profiles, plain; V profiles, square symbols. MES, full line, SCM dashed. Profiles 00z to 09z.

RUN FOR 00Z 19/11/96 RAIN

SCM was cooler than the MES below 3km, but warmer above 3km. The SCM was drier than the MES below 3km, and about the same above 3km. Profiles closer than in high pressure cases which had less advection.

RUN FOR 00Z 31/10/96 DRIZZLE

The MES and SCM θ, q, U and V profiles were very close.

Discussion of errors.

This section concerns errors when the SCM is run without relaxation to the MES.

For the high pressure runs the SCM errors formed a pattern, the SCM was cooler than the MES above clouds, and the SCM was moister than the MES in the lowest 3km. However for frontal runs the SCM was closer to the MES, and for 19/11/96 the SCM was both cooler and drier than the MES in the lower 3km. The high pressure and frontal cases taken together dp not suggest any systematic error in the SCM runs.

It was possible that the vertical advection was in error as some missing descent could account for the SCM's cooling and lack of drying, in the high pressure cases considered. The MES was rerun for 17/10/96 to dump etadot, and this was compared with the etadot produced from rerunning one adjustment step, there were slight differences but no systematic differences. The MES etadot was used to calculate the vertical advection using MES 5 min profiles; this was only slightly different to the previous vertical advection, and using the MES etadot gave very slightly more cooling and less drying. (The vertical advection correction term referred to as BRSP in UMDP 10 is included in the SCM code, along with the 'r_s' terms, but their impact is negligible on the timescales being considered.) The vertical advection was not found to have any significant errors.

For 17/10/96 the change in q_t and θ_L over several hours by the MES and by the SCM is shown as profiles in Figs.7, 8, 9, 10, using 5 min forcing data. Also shown is the advective change (horizontal, vertical and total) taken from the 5 min forcing data. Figs.7 and 8 show the changes using the upwind advection scheme, after 1 hour and 9 hours respectively. Figs.9 and 10 show the changes using 2nd order gradients and with U and V relaxed to the MES, so that advection errors were not due to wind errors, also after 1 hour and 9 hours. The advective change taken from the forcing data was either already present in the upwind case for horizontal advection or calculated from the forcing data profiles and gradients, the increments were summed over the appropriate number of hours.

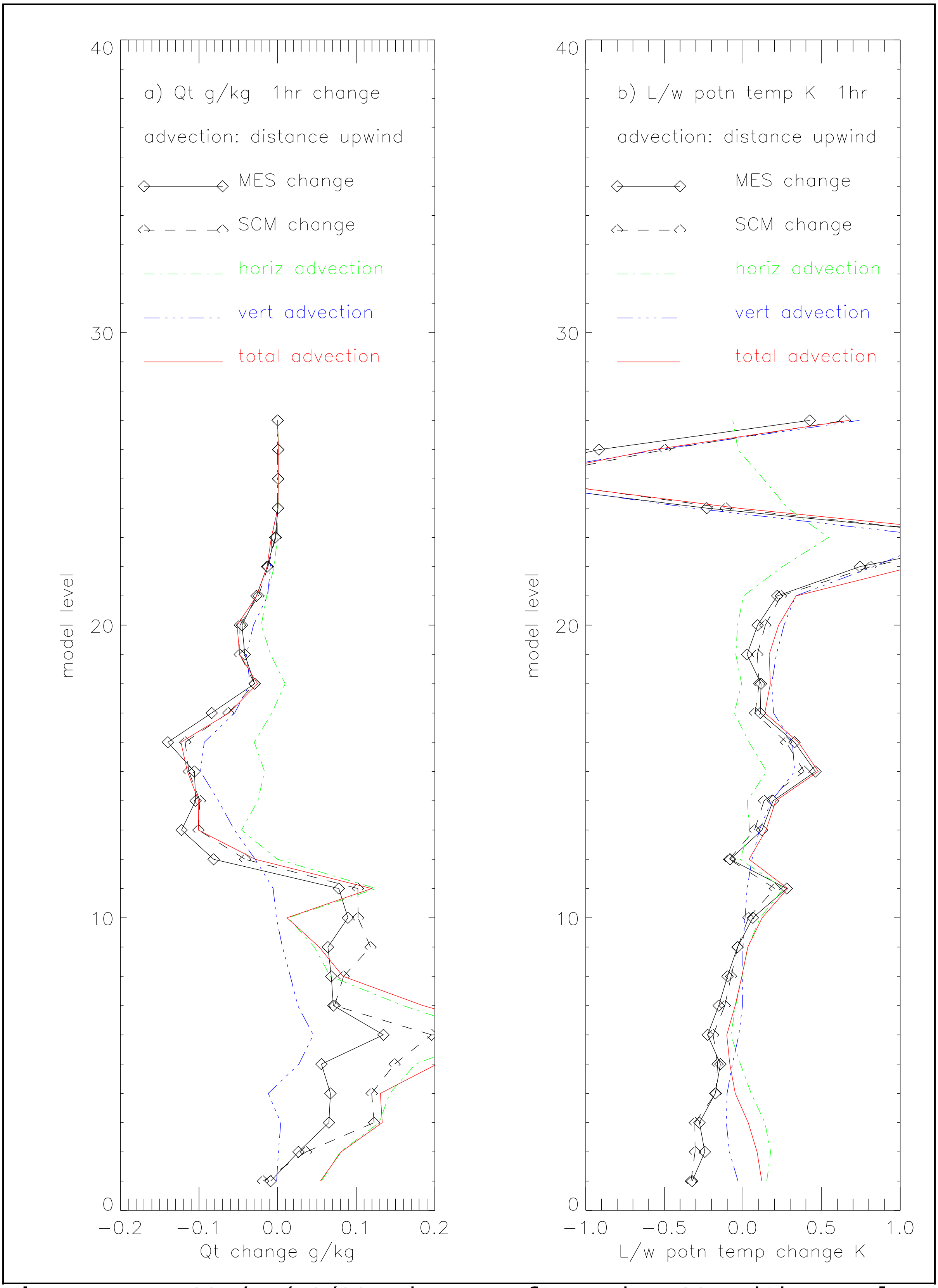

Figure 7 Run 00z/17/10/96, changes after 1 hr. SCM with no relax, 5 min data, distance upwind advection.

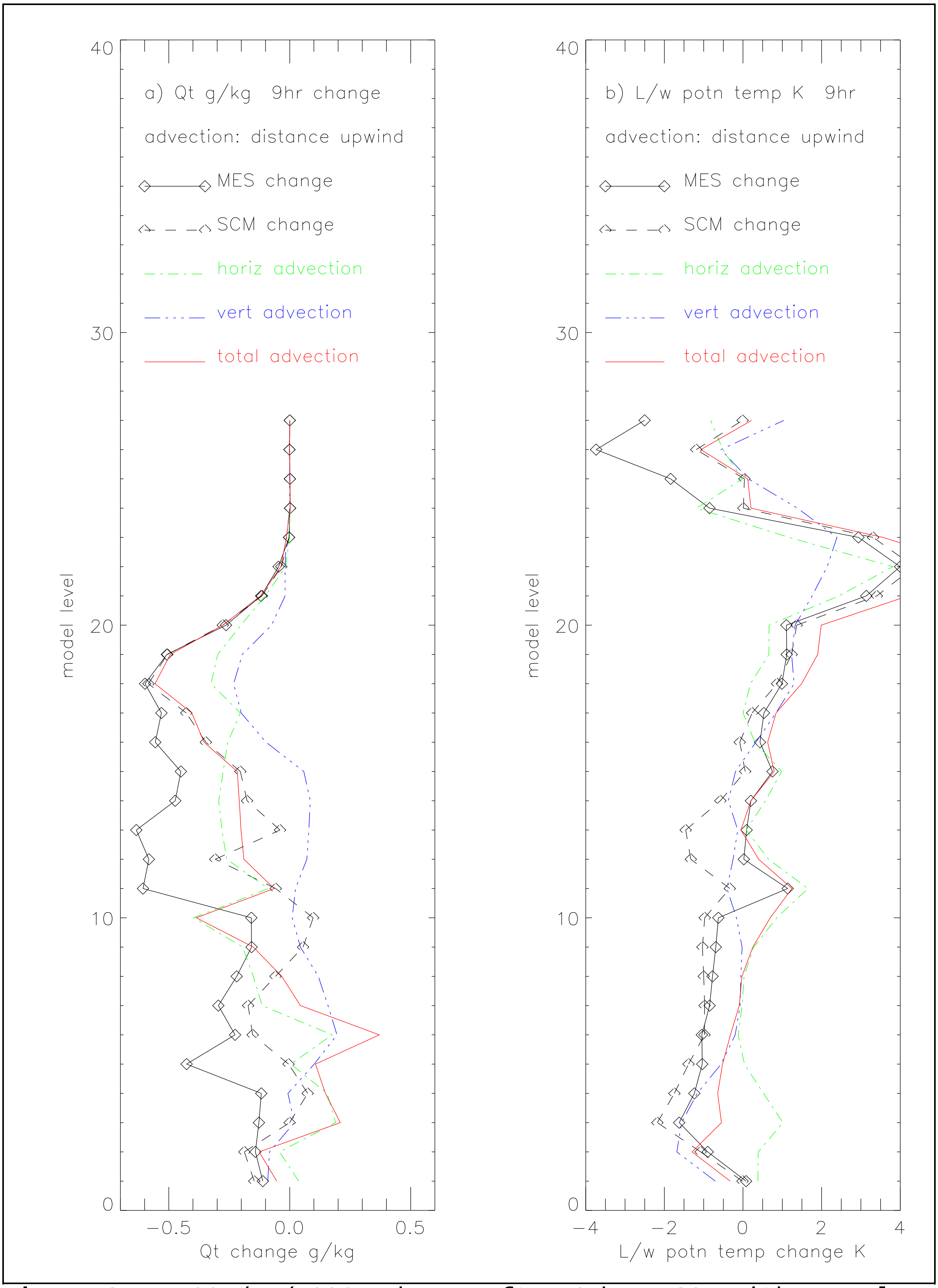

Figure 8 Run 00z/17/1096, change after 9 hrs, SCM with no relax, 5 min data and distance upwind advection.

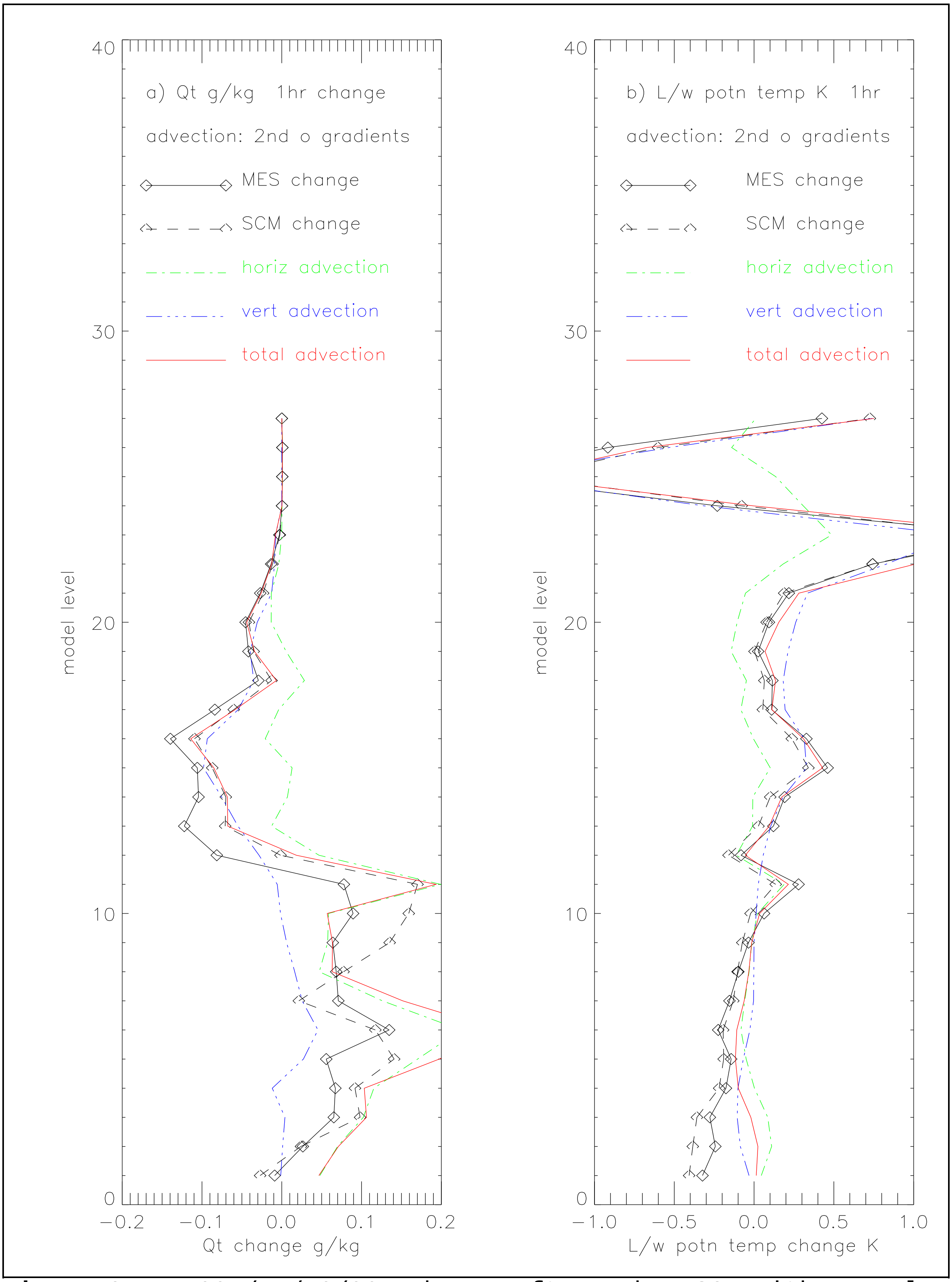

Figure 9 Run 00z/17/10/96, change after 1 hr, SCM with no relax except that U and V are relaxed to MES, 5 min data and 2nd order gradients.

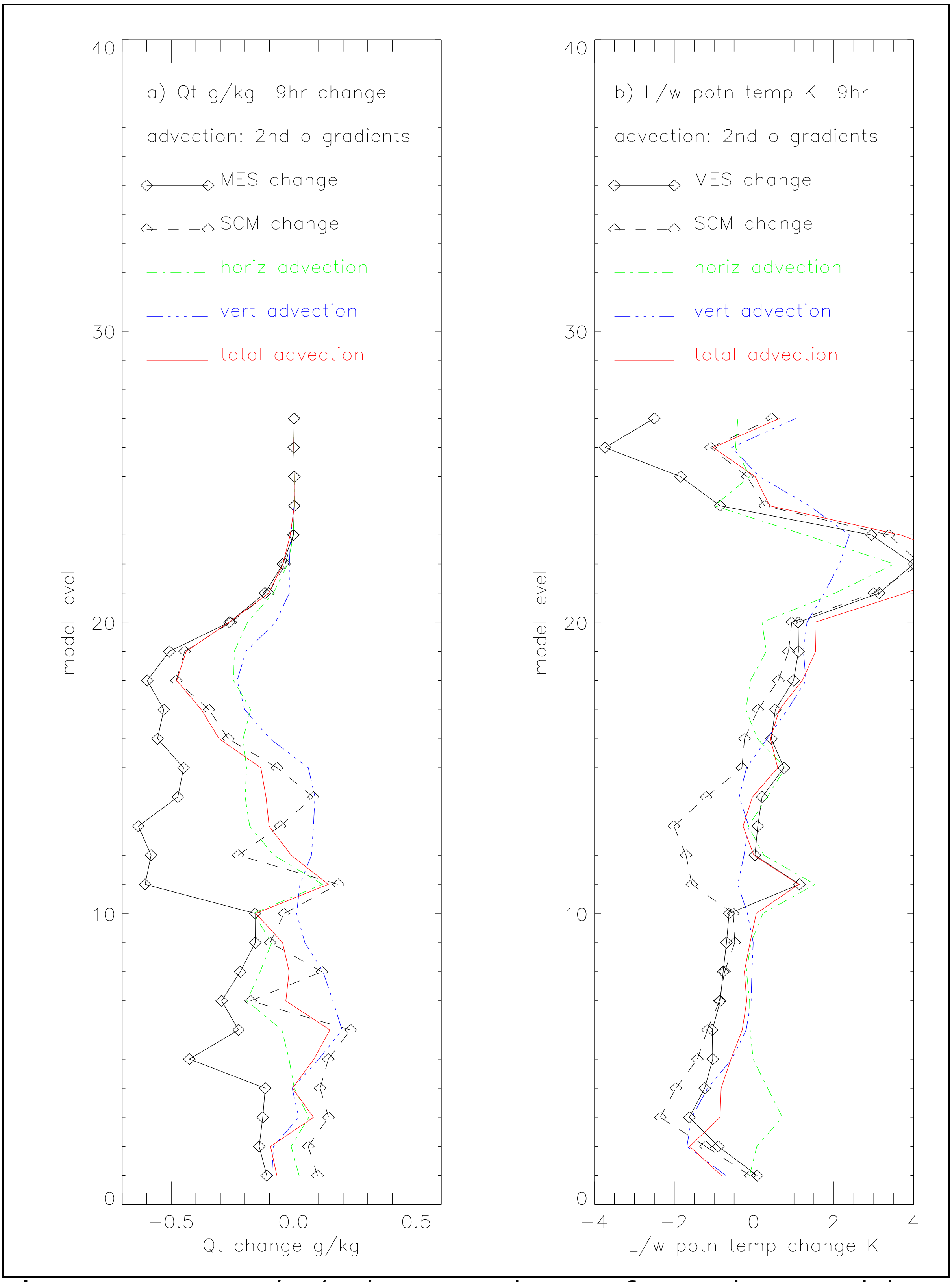

Figure 10 Run 00z/17/10/96, SCM change after 9 hours, with no relax except that U and V are relaxed to MES, 5 min data and 2nd order gradients.

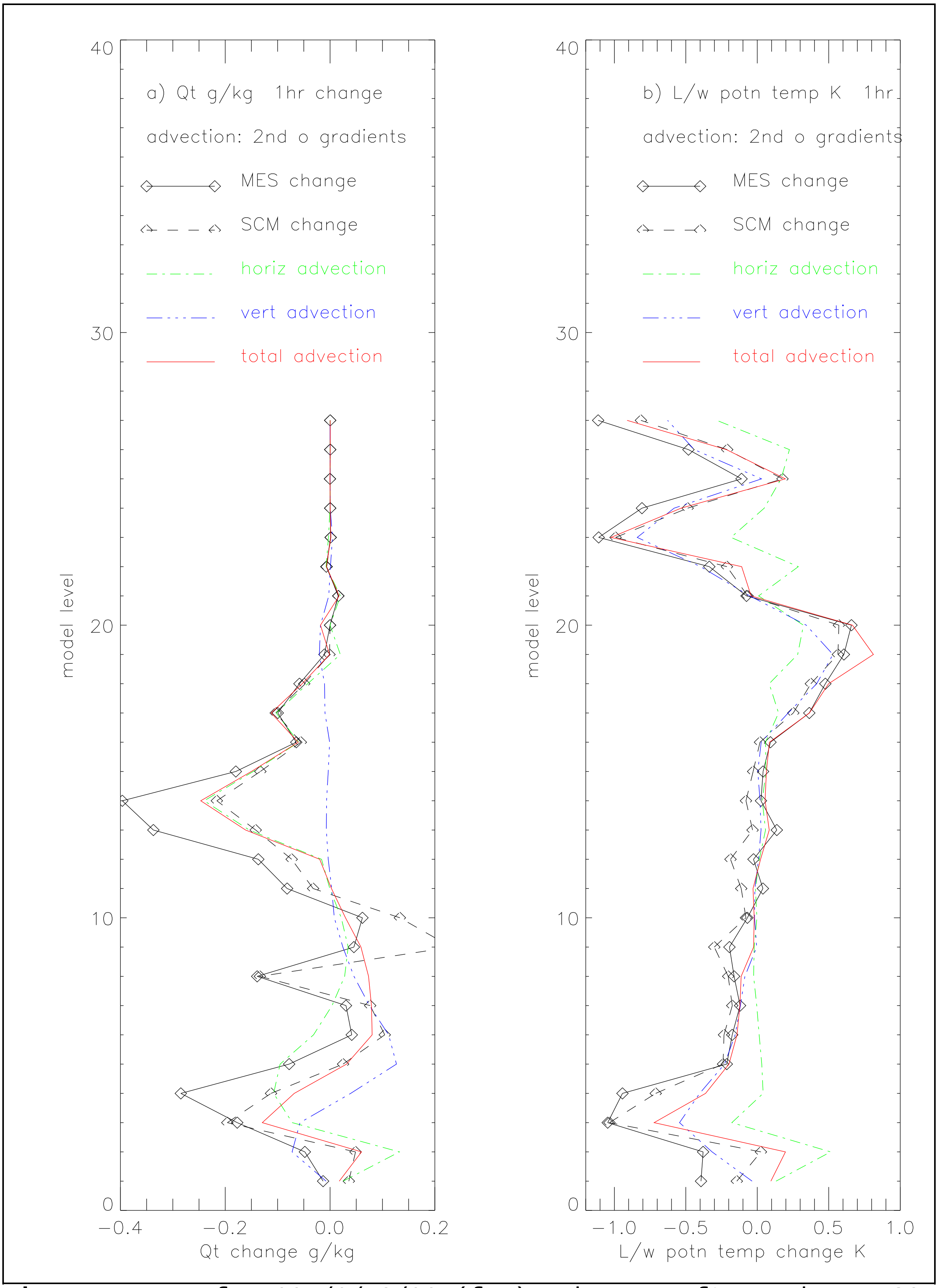

Figure 11 Run for 00z/6/12/96 (fog), changes after 1 hour, SCM with no relax, 5 min data and distance upwind advection.

After 1 hour the change in qt profile (Figs.7 and 9) shows the MES has generally moistened at and below level 11 but dried above this. Model level 10 corresponds to 1.2km, which was the cloud layer in this run. Above level 11 the MES change (drying) is not completely reproduced by the total advective change from the forcing data (red line), for either of the advection methods. Above level 11 the SCM change is very close to the forcing data advective change. As the boundary layer scheme only operates up to level 14, above this for the SCM in the dry case the only process to change qt is advection. After 1 hour, below level 11 the BL scheme has made the SCM change different from the advective change, but above level 11 the BL scheme has as yet made very little difference. Above level 14 only advection changes qt in the SCM, and in this case only advection has changed qt above level 11. As above level 11 the SCM change is very close to the advective change, but both are different from the MES change, this suggests that errors are due to inaccuracies in the horizontal advection, or errors in vertical advection. The vertical advection was not found to be in error (see above), so the errors are from horizontal advection. The MES change is better reproduced by both the SCM change and forcing data change by using the upwind advection method rather than second order gradients, improving the horizontal advection reduces the errors.

The change in qt after 9 hours, shown in Figs. 8 and 10, shows the same pattern as after 1 hour, except that the SCM change and advective change agree above level 14 only, and supports the arguments made above for the one hour profiles.

The change in thetal profiles after 1 hour are shown in Figs.7 and 9, the MES and SCM have both cooled more than the advective change due to LW radiation cooling. The change in thetal after 9 hours are shown in Figs. 8 and 10. After 9 hours the MES cools about 1˚C more than the calculated advective change below level 10, but the MES and advective change agree above this level. It would be expected that the MES would cool more than by advection as there is also radiative cooling, so again there may be errors in advection. The SCM cools about the same as the MES below level 10, but cooled more than the MES by about 2˚C in level 11 reducing to 1˚C more than the MES by level 15. The SCM was also run with Qt, U and V, relaxed onto the MES, this made very little difference to the SCM’s change in thetal, except in levels 11 to 13 the SCM only cooled by 1˚C more than the MES, using the upwind advection method. The SCM’s cooling is mainly due to errors in temperature advection, and only slightly due to errors in the Qt profile.

For 6/12/96 the change in qt and thetal over the first hour for the MES, the SCM, and advection only is shown in Fig. 11. There is cloud in the lowest 6 levels. Again for Qt, above the levels where the boundary layer scheme has had an effect, the SCM change is very close to the advective change but both are different to the MES change, again suggesting that horizontal advection is inaccurate. The fixed distance upwind horizontal advection method was slightly more accurate than the 2nd order gradient method. This was also found for changes over 9 hours.

The 12Z high pressure runs are also affected by different operation of the convection scheme which within the first few timesteps noticeably changes the near surface profiles of the SCM compared to the MES. However the evolution of the SCM and MES over several hours is still similar.

The above two high pressure cases strongly suggest that horizontal advection is the main source of error in the SCM compared to the MES. The fixed distance upwind method is the most accurate for the SCM. The MES has a different timestepping and horizontal advection scheme, which can not be implemented in the SCM. The MES also has diffusion, which is not attempted in the SCM. However the unrelaxed SCM only drifts slowly from the MES, and after 9 hours has thetal errors around 1˚C and qt errors around 0.5 g/kg.

Rainfall.

Although the local SCM is not expected to add much information in frontal cases, it is important that the MES rainfall can be reproduced as errors in rainfall produce errors in soil moisture. It was tested whether the SCM with relaxation on could reproduce rain rates and total accumulation, from 5 min and 1 hr forcing. The SCM again used fixed distance upwind advection terms and results are given below for this, 2nd order gradients gave similar results. As ascent of moist air produces rainfall, does extracting etadot only every hour and interpolating in time lead to too much loss of information to get the right rainfall?

The first case was 31/10/96, which had drizzle for most of the day, around 0.3mm/hr from the MES, a mean wind of 20m/s in the lowest 2km, and full cloud cover for most of the day with a base at 1km. The SCM was run from 00Z. Fig.12a. shows the Large Scale Rain (LSR) rate, for the MES and SCM with relaxation and 5 min and 1 hr forcing, Fig.12b shows this but without relaxation. The total accumulations are shown in Table.1. The LSR rates and total accumulations for the MES and SCUM with 5 min forcing are very close, and only slightly less close with 1 hr forcing. Without relaxation the LSR rates and total accumulations are too large, but occur approximately at the right time.

The other case was 19/11/96, during this day there was a frontal passage, with MES LSR up to 5mm/hr, a mean wind of 20m/s in the lowest 2km, and full cloud cover for most of the day. The SCM was run from 00Z. Fig. . shows the LSR rates, and Table 1 shows the total accumulations for LSR and Convective Rain (CR). With relaxation, the rainfall rates and total accumulations are very close, the SCM LSR total accumulations have less than 10% errors. The MES and SCM theta, q, U and V profiles matched very closely. Without relaxation the LSR occurred about 1/2 hr early, and LSR total accumulation was about 1mm less (with 2nd order gradients LSR total accumulation was about 1mm more). Rainfall rates and total accumulations are adequately reproduced by 1 hour forcing data with relaxation.

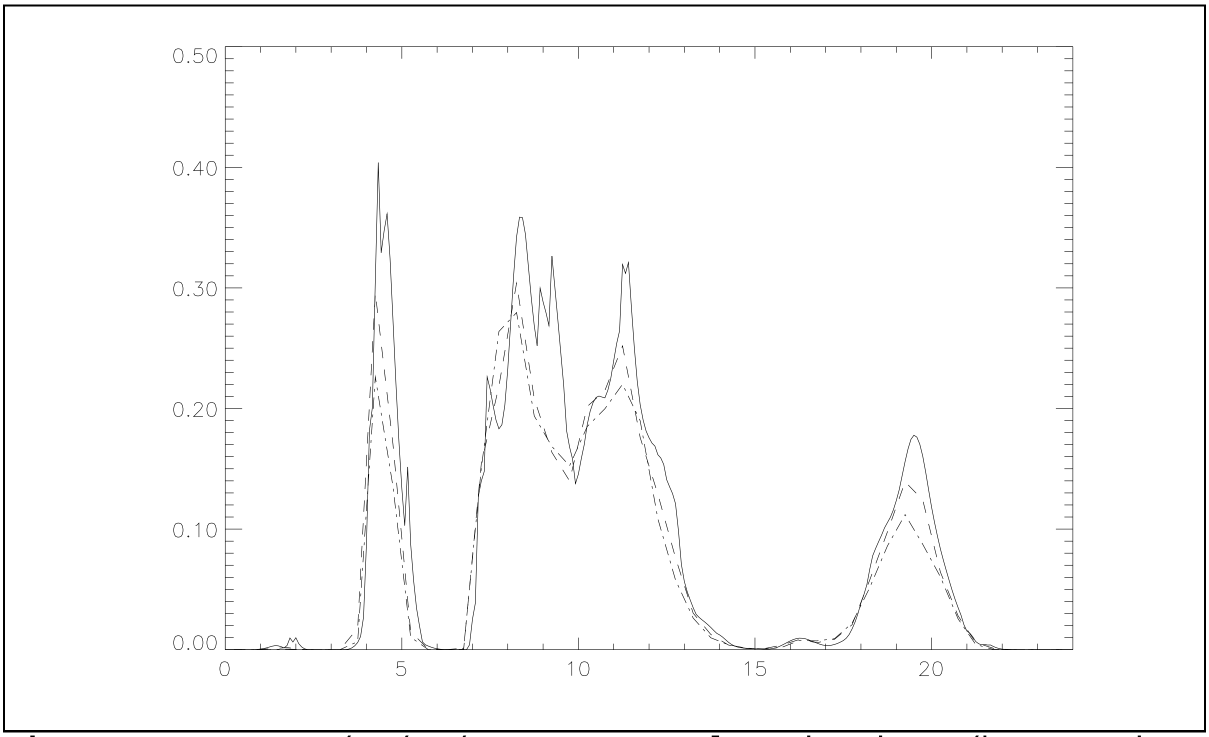

Figure 12a Run 00z/31/10/96, Large scale rain, in mm/hour against hours. SCM with RELAXATION, distance upwind advection. Full line; MES; dashed line, SCM with 5 min data; dash-dot line, SCM with 1 hr data.

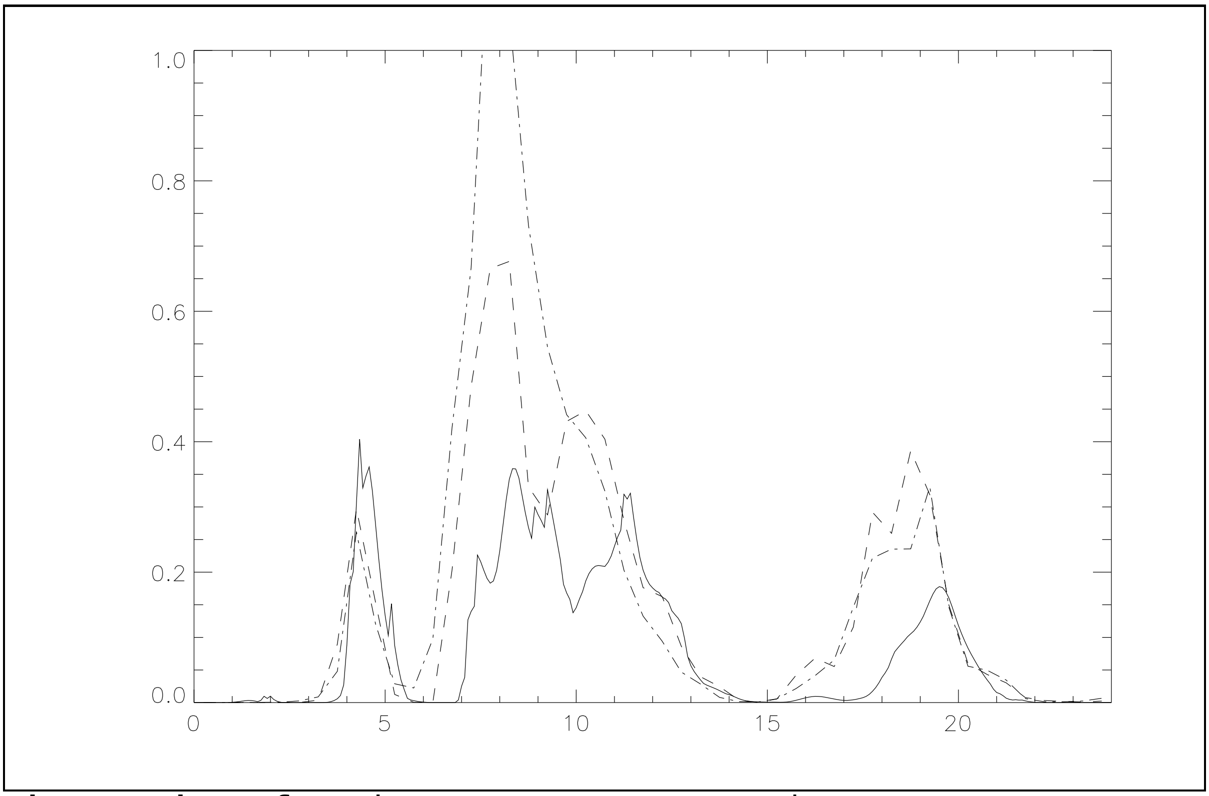

Figure 12b as for Figure 12a, except SCM has no relaxation

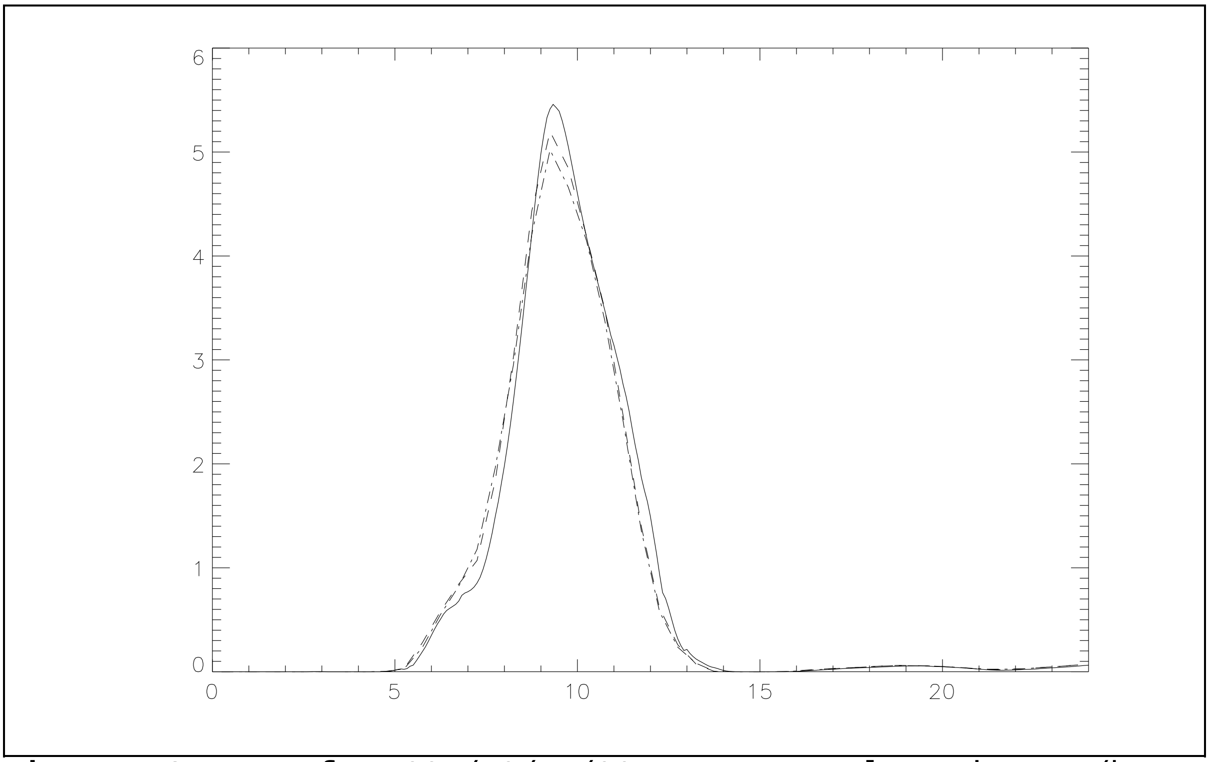

Figure 13a Run for 00z/19/11/96, Large scale rain, mm/hour, against hours. SCM has RELAXATION, distance upwind advection. Full line, MES; dashed line, SCM with 5 min data; dash-dot line, SCM with 1 hr data.

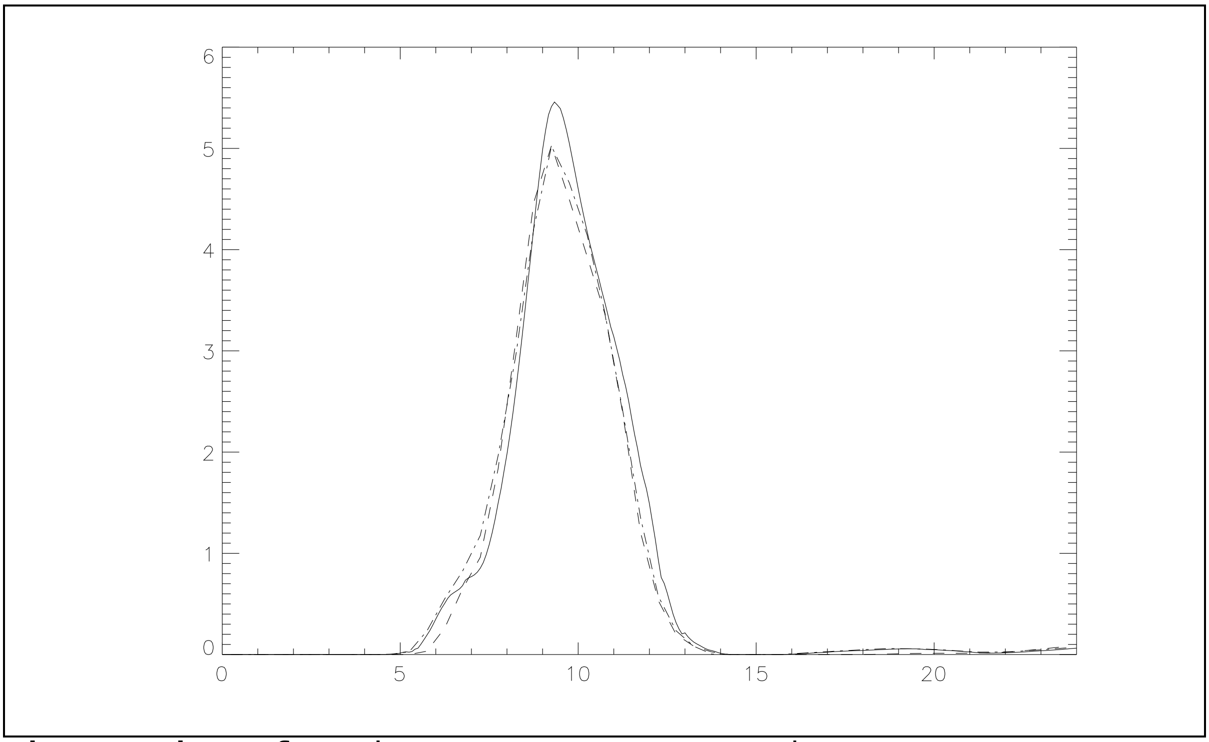

Figure 13b as for Figure 13a, except SCM has no relaxation.

Day		MES	SCM relax 5 min	SCM relax 1 hour	SCM no relax 5 min	SCM no relax 1 hour
31/10/96	Total LSR / mm	2.0	1.7	1.5	3.6	4.3
19/11/96	Total LSR / mm	17.7	17.7	17.2	16.4	16.5
	Total CR / mm	0.3	0.2	0.2	0.5	0.5

Table 1. Rainfall total accumulations over 24hrs for runs starting at 00Z.

Summary

The SCM has been coupled to output from the mesoscale model using approximations to the dynamical terms used in the UM. It has then been tested for two high pressure and two rainfall cases, for the site of Beaufort Park. The SCM set up 'as per MES' with relaxation to the MES profiles can reproduce the MES forecasts very closely with almost negligible differences, with both 5 min and 1 hour forcing data. The rainfall cases show that the SCM with relaxation on can reproduce MES rainfall very closely.

Without relaxation differences appear between the SCM and MES, which are mainly due to inaccuracy in the numerical method of horizontal advection used by the SCM. This could undoubtedly be improved should the need arise, but, at present, there is no requirement to run the model in this way. The method of calculating forcing data using a fixed distance upwind from the site to calculate the horizontal advection was found to be the most accurate.