Forecasting Research

Forecasting Research Division
Technical Report No. 203

Assessment of the single column UM for use as a local forecasting tool: suitability and recommended configuration

by

P A Clark, W P Hopwood, M J Best, C C Dunlop and P E Maisey

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Abstract

A project is currently under way to build a Site Specific Forecast Model (SSFM) using the single column version of the UM as a basis, driven by output from 3D NWP models. Stage 1 of the project was to assess the suitability of the model for this application. This report contains the end of stage project report, and summarises conclusions regarding the suitability of the model physical parametrizations for this application.

Deficiencies in the UM schemes have been identified as follows:

- The omission of a vegetation canopy in the surface heat budget is potentially very important, and is recognised as an area requiring effort in the UM development as a whole.

- The surface exchange coefficients in the UM appear inappropriate for **local** use, though the errors resulting from using them may be small.

- The soil scheme may need to be run at higher resolution, which will require some re-coding.

- The local boundary layer mixing scheme seems adequate as far as a first order scheme can be, but the rapidly mixing and convection schemes lead to unrealistic boundary layer behaviour.

- Cloud top entrainment is important for dissipation of fog and cloud, and is not treated at all in the present UM (though a scheme is under development).

- The treatment of large scale precipitation is either inappropriate or will need modification for use in the SSFM.

However, most of these deficiencies can be addressed relatively simply and some have been as part of this investigation. Given this, investigation of the UM system for use in the SSFM has generally been encouraging. By far the most significant finding has been the impact of the treatment of surface vegetation, which can lead to changes in forecast minimum temperatures of several degrees on radiation nights. A number of other factors, such as soil moisture, resolution of the soil scheme and the importance of vertical resolution in fog simulation, show that running a 1D version of the UM configured specifically for a location of interest can result in changes in evolution of a similar magnitude to the representativity errors currently identified in the larger scale model.

As a final note of caution, while we have found that the UM has generally acceptable properties, and that improvements in formulation and configuration can lead to physically sensible changes in forecasts that are significant compared with current errors, this does not, in itself, guarantee that such improvements will be achieved in practice, as the factors changed may not be those which dominate the real errors at particular sites.

Assessment of the single column UM for use as a local forecasting tool: suitability and recommended configuration.

1. Introduction.

The purpose of the Site Specific Forecast Model (SSFM) development project is to develop a relatively simple model which takes gridscale data from NWP forecasts and adds some local or site-specific detail based upon a physical simulation which is more representative of the locality. It is envisaged that the model will be a 1D (vertical) model using higher resolution, local surface conditions and forced using dynamical forcing terms derived from the 3D NWP product, modified in a simple way to take account of some effects of upwind fetch. Description of the coupling technique is beyond the scope of this report, and, indeed, requires development work to define the technique in detail, but it is envisaged that the coupling will make use of the horizontal pressure gradient, vertical velocity and horizontal advective gradients from the NWP output. Any accumulating errors above the boundary layer will be corrected by forcing in the large scale profiles, while, within the boundary layer, the affects of local advection over differing surfaces will be model using simple relaxation terms forced by the large scale field.

It is proposed that the single column version of the Unified Model (UM) be used as a basis for this model, in order to make full use of parametrization developments. However, it is recognised that the UM physics was not developed with this application in mind and, indeed, has largely been developed to provide a good representation of processes in a coarse horizontal and vertical grid. It is not obvious, therefore, that features of the model design will not prevent its successful use in the SSFM project. Stage 1 of the project has thus concentrated on establishing the suitability of the model for our purposes.

Before assessing the model, certain assumptions have been made. In particular, it is assumed that the major processes that produce systematic subgrid variability are associated with the surface and boundary layer. Systematic sub-grid effects on dynamic cloud and precipitation above the boundary layer result mainly from the 3D effects of orography and are regarded as beyond the scope of the project. There may be systematic sub-grid effects on deep convection but these arise either from the effect local surface and boundary layer processes have on triggering or from similar dynamical processes as those affecting dynamic cloud and precipitation. As the model is developed, some benefits should arise from making use of local data and local corrections to forcing data such as winds. It is assumed that the main benefits arising from the model formulation itself will be produced as follows:

- by using surface data representative of the site rather than the gridbox mean, to give a better representation of fluxes of momentum, heat and moisture.

- by using higher vertical resolution in the boundary layer, to give a better representation of inversions, fog, cloud etc. near the surface.

Work has thus concentrated on the soil temperature, hydrology, surface exchange and boundary layer schemes, though other aspects of the model will be discussed briefly.

The schemes have been assessed from two viewpoints. The first is purely in terms of the physical formulation as compared with state of the art knowledge that would ordinarily be used in the formulation of a **local** (as opposed to coarse grid) 1D model. In this way we hope to distinguish between deficiencies which arise naturally as a consequence of simplifying the description to 1D or simply from our lack of knowledge, and those which arise because the UM was designed explicitly to deal with large gridbox averages, not local effects. There is little that we can do within the scope of the project to rectify deficiencies of the first type, whereas those of the second type represent a potential source of avoidable error.

The second viewpoint is to look specifically for those areas which might lead to significant systematic differences between the gridbox mean and small scale forecasts. Since we are not considering specific sites (at this stage) , no judgement has been made regarding the sign of these changes. The primary consideration, when considering the viability of the project as a whole, is whether the factors that are under our control can lead to substantial differences in behaviour when varied over the sort of range that might be encountered within a gridbox.

It should be emphasised that this report is not meant to represent an in-depth critique of the UM physics schemes, but merely meant to identify potential weaknesses in the context of the SSFM development. Since we are looking for gross problems, assessment has been confined to a narrow and well defined set of conditions of the sort where we might expect to have a good understanding of expected behaviour. A small number of cases have been used, with initial thermodynamic profile taken from mesoscale analyses. This has been done in order to ensure realistic vertical profiles, rather than to simulate particular events. Forcing conditions have been kept constant through each run, with a constant (both vertical and in time) horizontal pressure gradient to simulate the geostrophic wind. The initial wind profile at mesoscale resolution is brought into quasi-equilibrium by iterating the boundary layer scheme and geostrophic forcing terms (i.e. pressure gradient and Coriolis force), resetting all variables apart from the wind to the initial values after each call of the boundary layer scheme until no significant change occurs over a step. This profile is then interpolated to other resolutions in the same way as the other variables.

The soil/surface/surface exchange system is clearly of great importance for near surface temperatures, and is the area where local impact is expected to be most amenable to improvement within the model. It is therefore considered first. Next, the boundary layer as a whole is considered. The impact of unstable, stable and fog conditions have been considered in some detail. Clearly, there are some conditions which will not be covered, but in most cases these represent transition boundary layers which we are unlikely to be able to treat well in any 1D model.

The main issue with unstable layers is which of the schemes in the UM to use, and what errors are likely to result. It is acknowledged that we are very unlikely to get improved simulation using higher vertical resolution, as the main spatial scales of importance are quite large compared with the grid, except, perhaps, from improved representation of any capping inversion, so the main question regarding the impact of higher resolution in unstable conditions is whether the existing schemes can cope numerically.

In stable conditions, the radiative flux divergence near the surface, and any subsequent fog formation, is very poorly resolved by the mesoscale model, so improvements should be expected from the use of higher resolution: the issue here is whether the UM physics behave properly when run with higher resolution.

2. Performance of the Soil/Surface/Surface Exchange Schemes

2.1 Method of Assessment

The surface exchange within the single column UM has been divided into four areas:

1. Parametrization of the surface temperature - The surface temperature has been investigated with regard to its behaviour over a diurnal cycle, with emphasis being given to nighttime temperatures since it is during the night that fog is most commonly formed. The *surface only* version of the single column UM has been used to compare the current UM physics with some data obtained from a grass surface site at the Met. Research Unit (MRU), Cardington.

2. Soil temperature parametrization - This determines the amount of energy that is stored in the ground during the day and subsequently released at night. For the site-specific model, it is important that this stored heat is accurate over the forecast period, which is likely to be a diurnal cycle. Unfortunately, the soil temperature information is not easily obtained, so it would be an advantage for the soil temperature to `free wheel' within the model. This requires an accurate parametrization of the heat storage over longer periods. As it is the ground flux that determines the flux of energy that enters or leaves the ground at any time, it is an important component in the surface energy balance, especially at night when it becomes a large component. The ground flux will not be directly compared with observations here, but the influence of changing the soil temperature parametrization on the surface temperature and turbulent fluxes will be assessed.

3. Surface exchange coefficients - Together with the surface temperature, the exchange coefficients determine the magnitude and sign of the turbulent heat fluxes. The *surface only* version of the single column UM has been used, along with observational data from MRU, Cardington, to determine the effects of changing the parametrization of the surface exchange coefficients.

4. Parametrization of the hydrology - The hydrology determines the control of moisture exchange between the surface and the atmosphere, as well as parametrizing the movement of water within the soil.

2.2 Surface Temperature Parametrization

This model uses the surface exchange and soil components from the Unified Model and is driven by observed air temperature, humidity, wind speed and radiation. There are five days worth of data from these observations, although two days suffer from instrumentation problems. Figure 1 shows a plot for a typical day from this data, the other days give similar results. It is evident from these results that the surface temperature given by the parametrization in the single column

UM does not cool far enough during the night (Figure 1a). In fact, the modelled surface temperature does not fall far below the air temperature (Figure 1b). This behaviour is typical of a concrete slab and not of a grass surface which commonly cools as far as five degrees centigrade below the air temperature (Forecaster's Reference Book) and sometimes as much as 10 or so degrees. The most likely explanation for the behaviour of the single column UM parametrization is that the ground flux during the night acts as a source of heat which prevents the model from cooling far enough. It should be noted that in spite of the incorrect surface temperatures, the turbulent fluxes are reasonably well estimated. So the impact of these errors on the large scale flow may be less noticeable.

A possible solution is to introduce a vegetation canopy scheme to the surface temperature parametrization, which removes the ground flux from the energy balance equation from which the surface temperature is calculated. Figure 2 shows a representative diagram of such a canopy scheme whereby the canopy is linked to the substrate by radiation and turbulent fluxes and is not directly affected by the ground flux. Figure 3 shows a similar plot to Figure 1 except that the canopy scheme has been added to the surface parametrization within the UM. It can be seen from Figure 3a that the surface temperature predicted by the canopy scheme is in much better agreement with the observations and is capable of cooling sufficiently below the air temperature (Figure 3b). Table 1 shows the mean errors and the root mean square errors for all five days of the Cardington data, with the current UM parametrization and with the canopy scheme.

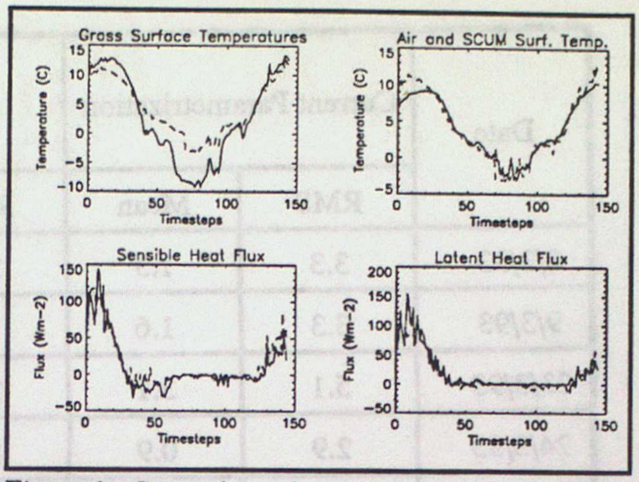

Figure 1 - Comparison of modelled output with current surface temperature parametrization (dashed line) against observations at Cardington (solid line). (a) Surface temperature, (b) Modelled temperature and observed air temperature, (c) Turbulent heat flux, (d) Turbulent moisture flux.

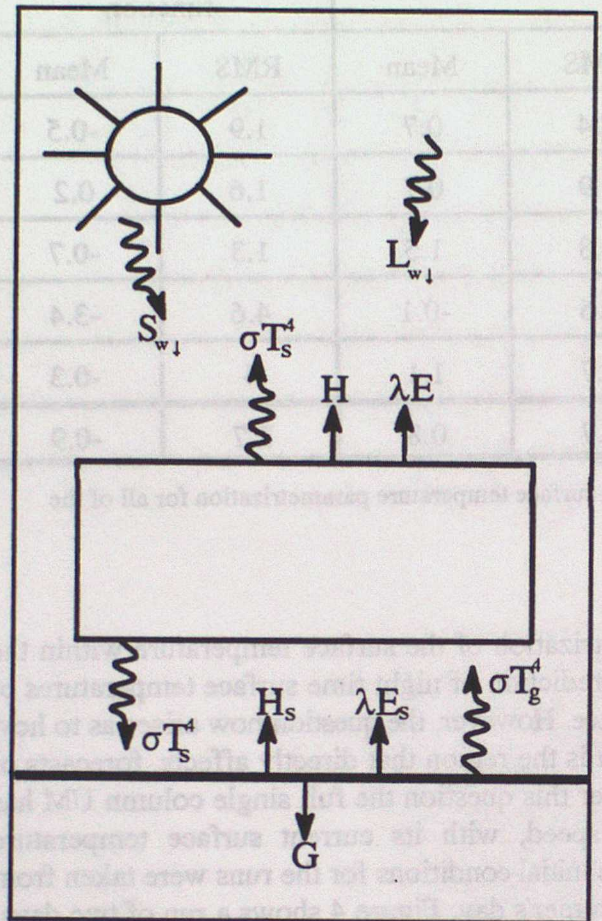

Figure 2 - Diagram showing the additional interactions involved in introducing a vegetation canopy scheme to the surface temperature parametrization.

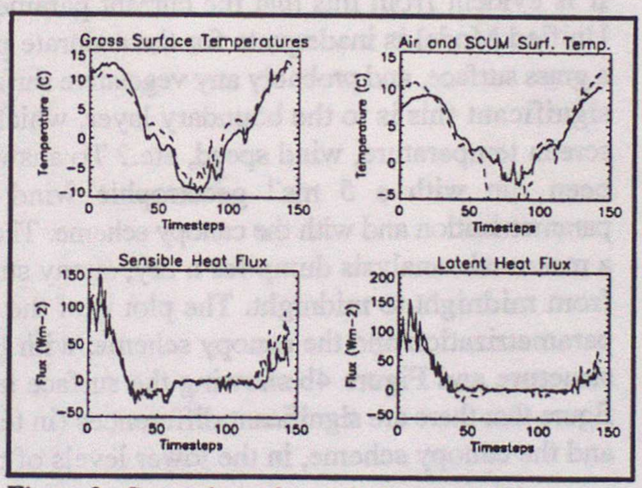

Figure 3 - Comparison of modelled output with a canopy scheme (dashed line) against observations at Cardington (solid line). (a) Surface temperature, (b) Modelled surface temperature and observed air temperature, (c) Turbulent heat flux, (d) Turbulent moisture flux.

Date	Current Parametrization		Canopy Scheme		Canopy Scheme with Beljaars and Holtslag function	
	RMS	Mean	RMS	Mean	RMS	Mean
8/3/93	3.3	1.3	2.4	0.7	1.9	-0.5
9/3/93	3.3	1.6	1.9	0.7	1.6	0.2
23/3/93	5.1	3.1	2.8	1.5	1.3	-0.7
24/3/93	2.9	0.9	1.6	-0.1	4.6	-3.4
25/3/93	6.2	3.2	4.7	1.1	4	-0.3
Average	4.2	2	2.7	0.8	2.7	-0.9

Table 1. Mean and root mean square errors with each surface temperature parametrization for all of the Cardington data.

It is evident from this that the current parametrization of the surface temperature within the Unified Model is inadequate for the accurate prediction of night time surface temperatures of a grass surface, and probably any vegetative surface. However, the question now arises as to how significant this is to the boundary layer, which is the region that directly affects forecasts of screen temperature, wind speed, etc.? To answer this question the full single column UM has been run with a 5 ms^{-1} geostrophic wind speed, with its current surface temperature parametrization and with the canopy scheme. The initial conditions for the runs were taken from a mesoscale analysis dump for a dry, sunny summer's day. Figure 4 shows a run of two days, from midnight to midnight. The plot is of the difference in temperatures between the current parametrization and the canopy scheme, with Figure 4a showing the atmospheric temperature structure and Figure 4b showing the surface temperature difference. It can be seen from this figure that there are significant differences (in temperature between the current parametrization and the canopy scheme, in the lower levels of the model at night.

Figure 5 shows the differences in the current parametrization and the canopy scheme for (a) longwave radiation heating rates and (b) the heating rates due to the turbulent flux of heat, for the same single column UM runs as for Figure 4. It can be seen that, although the longwave radiation heating rates are different at night, due to the colder underlying surface of the canopy

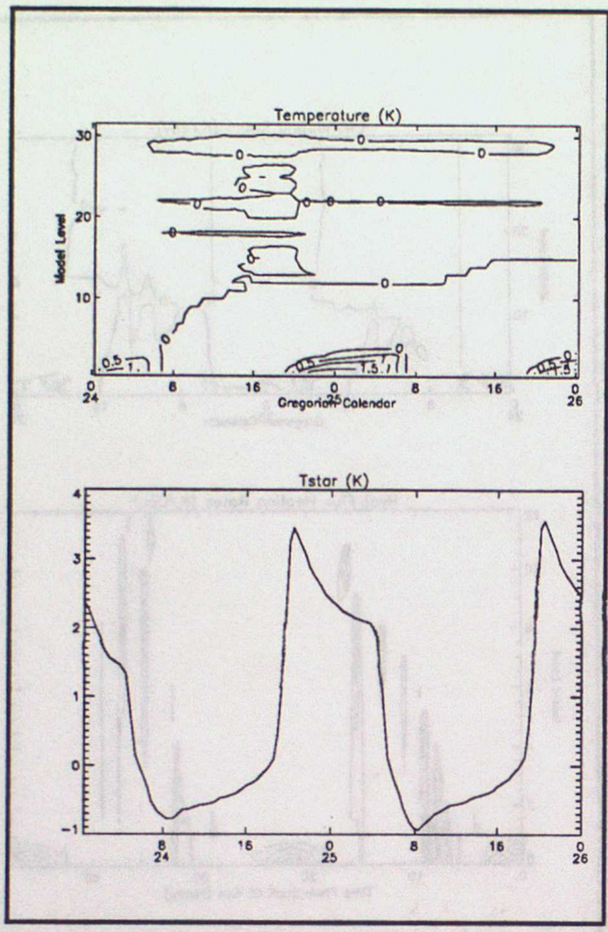

Figure 4 - Difference between current single column UM surface temperature parametrization and canopy scheme for a 5 ms^{-1} geostrophic windspeed. (a) Temperature structure of the atmosphere, (b) Surface temperature.

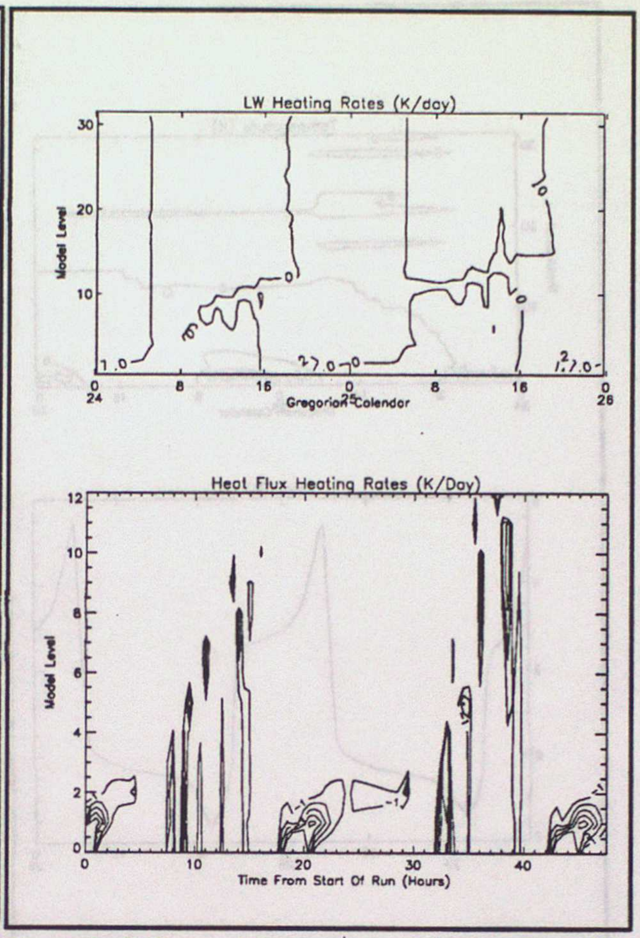

Figure 5 - Difference between current single column UM surface temperature parametrization and canopy scheme for a 5 ms^{-1} geostrophic windspeed. (a) Longwave radiation heating rates, (b) Turbulent heat flux heating rates.

scheme, the greatest difference in the heating rates at night comes from the turbulent heat flux. Hence the difference in temperature in the lower levels on the model at night, between the current model and the canopy scheme, for a 5 ms^{-1} geostrophic wind speed, is mainly due to the cooling of these levels by the downward turbulent heat flux, which can be sustained during the early part of the night.

Figure 6 shows the temperature differences between the current parametrization and the canopy scheme for similar runs to those described above, except with a 2 ms^{-1} geostrophic wind speed. It can be seen from this plot that there is still significant differences in the temperatures between the two parametrizations, but Figure 7, which shows the heating rates of longwave radiation and turbulent heat flux for this run, shows that the differences in these temperatures now comes largely from the longwave radiation heating rates, which is caused by the colder underlying surface of the canopy scheme.

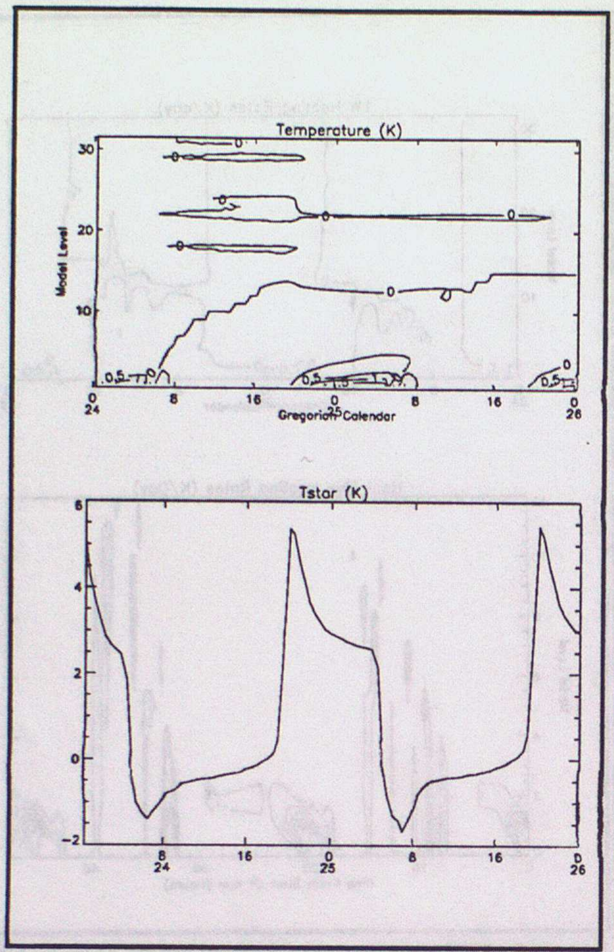

Figure 6 - Difference between current single column UM surface temperature parametrization and canopy scheme for a 2 ms^{-1} geostrophic windspeed. (a) Temperature structure of the atmosphere, (b) Surface temperature.

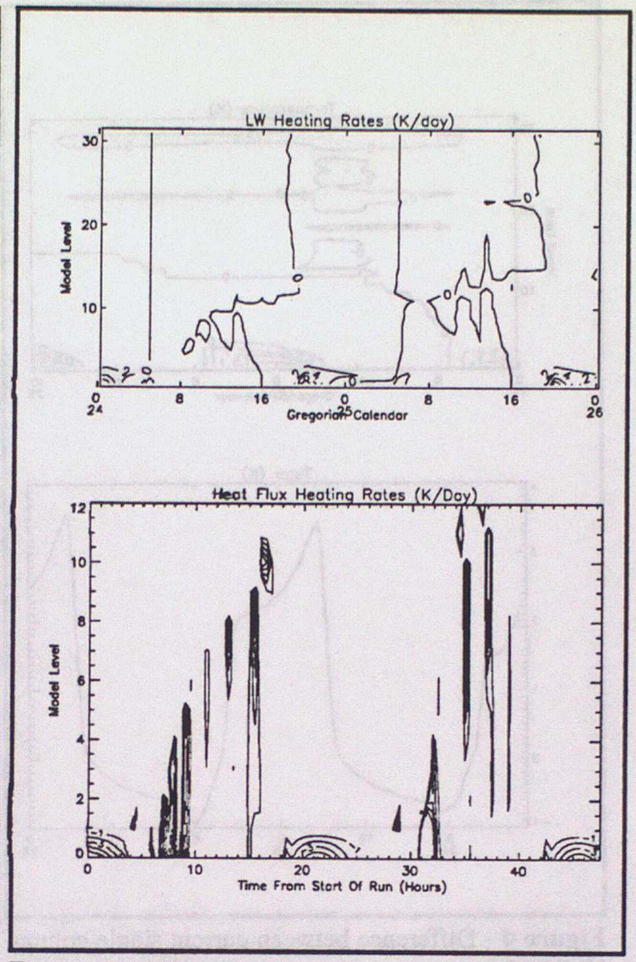

Figure 7 - Difference between current single column UM surface temperature parametrization and canopy scheme for a 2 ms^{-1} geostrophic windspeed. (a) Longwave radiation heating rates, (b) Turbulent heat flux heating rates.

Considering the inaccuracies in the current surface temperature parametrization and the warm bias in the screen temperature at night shown by the Unified Model, it is therefore suggested that the surface temperature parametrization should be replaced with one which involves a vegetation canopy, similar to the one used in these tests.

2.3 Soil Temperature Parametrization

The current Unified Model has a four level soil temperature parametrization, which has the temperature levels at a depth of 1.0 Z_0, 2.3 Z_0, 6.9 Z_0 and 24.15 Z_0, where $Z_0=\sqrt{(2\lambda/\omega_1 C_s)}$, λ is the thermal conductivity of the soil (typically $=1.5Wm^{-1}K^{-1}$), C_s is the thermal capacity of the soil (typically $=2.0\times10^6 Jm^{-3}K^{-1}$) and $\omega_1=1.45\times10^{-4}$. The typical values above imply physical depths at approximately 0.1, 0.23, 0.7 and 2.46m.

Tests with the single column UM were carried out to compare the accuracy of this parametrization with a nine level parametrization. This nine level parametrization has temperature levels at depths of $0.105v_d$, $0.357v_d$, $0.693v_d$, $1.204v_d$, $2.303v_d$, $0.357v_a$, $0.693v_a$, 1.204ν_a, 3.218ν_a, where ν_d is the e-folding depth of the diurnal temperature wave in the soil (= $\sqrt{(\lambda\tau_d/\pi C_s)}$, τ_d =86400s) and ν_a is the e-folding depth of the annual temperature wave in the soil (=$\sqrt{(\lambda\tau_a/\pi C_s)}$, τ_a=365x86400s). The typical soil characteristics above imply physical depths at 0.015, 0.05, 0.01, 0.17, 0.33, 0.98, 1.9, 3.30 and 8.83 m. Due to the increased resolution near the surface of the nine soil level scheme, this parametrization requires an implicit implementation when run with timesteps appropriate to the mesoscale model or longer, though when run with timesteps of order 10 s, appropriate to the vertical resolution of the atmosphere model envisaged, the explicit scheme will probably be satisfactory.

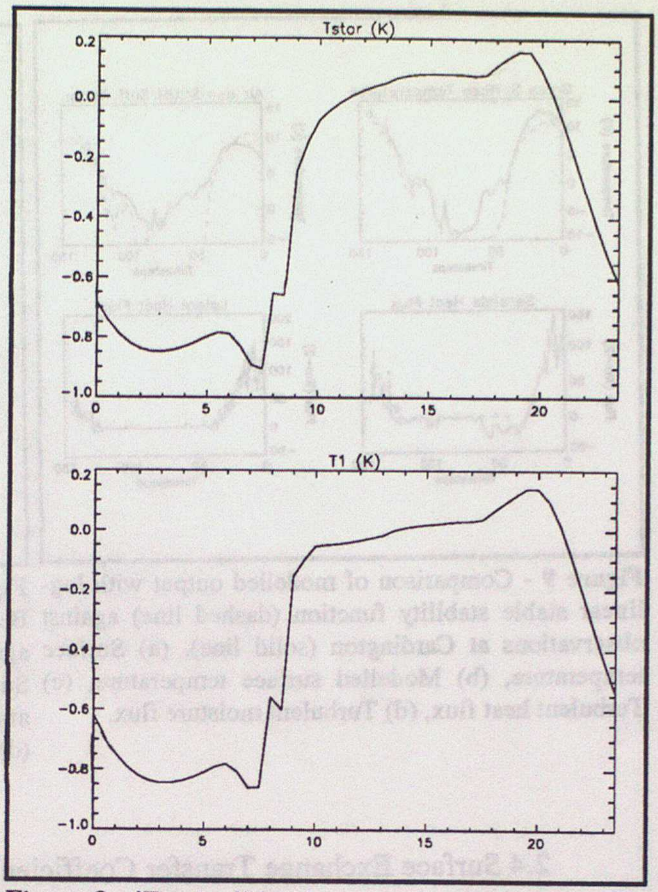

Figure 8 - 'Four' soil level parametrization minus 'nine' soil level parametrization for, (a) Surface temperature, (b) First model level (10 m).

The results presented here all have the canopy scheme. Figure 8 shows the differences between the four level parametrization and the nine level parametrization, for a typical day from a thirty day integration. Figure 8a shows the differences in the surface temperature, whereas Figure 8b shows the influence that this difference has on the first model level temperature. It is evident from this plot that the magnitude of the differences in temperature between the four and nine soil level parametrizations is of the same order of magnitude as the difference in the temperatures between the current surface temperature parametrization and the canopy scheme. Therefore, the differences in temperature between the four and nine soil level parametrizations is significant. The nine soil level parametrization is, however, more computationally expensive, since it has to be an implicit parametrization due to the high resolution near the surface. It is recommended that if this extra computation is acceptable, then the nine level soil scheme should be tested in practice. This would mean a change in the method of solution for the soil temperature profile, but the physics is essentially the same.

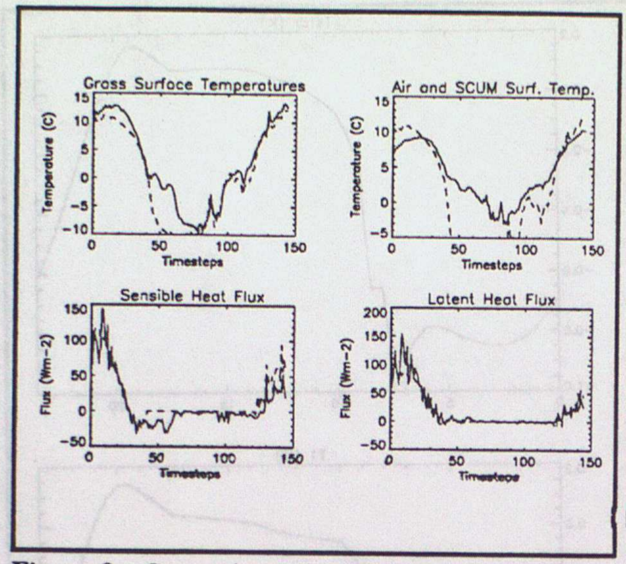

Figure 9 - Comparison of modelled output with log-linear stable stability function (dashed line) against observations at Cardington (solid line). (a) Surface temperature, (b) Modelled surface temperature, (c) Turbulent heat flux, (d) Turbulent moisture flux.

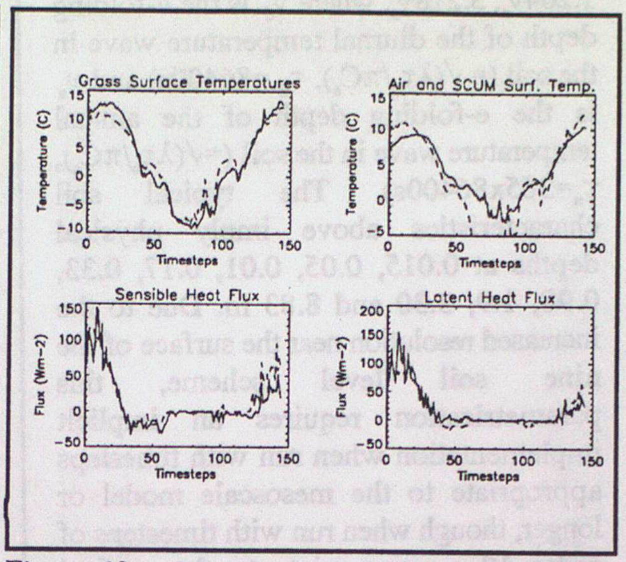

Figure 10 - Comparison of modelled output with Beljaars and Holtslag stability functions (dashed line) against observations at Cardington (solid line). (a) Surface temperature, (b) Modelled surface temperature and observed air temperature, (c) Turbulent heat flux, (d) Turbulent moisture flux.

2.4 Surface Exchange Transfer Coefficients

The transfer coefficients that are currently used within the Unified Model do not have a cut-off region in stable conditions. This does not seem appropriate for a site specific model as observations demonstrate that such a cut-off exists in reality. Therefore, the surface only version of the single column UM was run with the current stability functions and with Monin-Obukhov similarity theory, using the Businger and Dyer function for unstable conditions (Dyer 1974) and a log linear function for stable conditions. Figures 3 and 9 show the results of the model run with the canopy scheme, compared to the observational data from Cardington, with the current stability functions and the Monin-Obukhov similarity functions respectively. It can be seen that introducing the cut-off in the stability functions made the results of the surface temperature much worse and stopped the turbulent heat flux too quickly. Similar results are obtained by using the current transfer coefficients used in the Unified Model, but with the HETGEN parameter set to a value of 1.0. The HETGEN parameter ranges between 0.0 and 1.0 and represents the degree of heterogeneity of the surface, with 1.0 representing a homogeneous surface. By giving the HETGEN parameter a non-zero value, a cut-off in the stability functions, depending on the Richardson number, is possible. To test the cut-off functions further, the log linear function was replaced with the Beljaars and Holtslag function for stable conditions (Beljaars and Holtslag 1991). The results with this function are shown in Figure 10. It can be seen from this figure that the turbulent fluxes now agree well with the observations again. Also, there is an improvement in the surface temperature over the current transfer coefficients used in the model, without the cut-off. Table 1 shows the mean and root mean square errors of the surface temperature, using the canopy scheme with this function for the stable stability, for all of the Cardington data. It can be seen that there is improvement in all but one case. The one case that is worse seems to have some suspicious observations and so should be given less weighting when comparing the parametrizations in Table 1. Therefore it is suggested that the transfer coefficients that are currently used within the Unified Model should be replaced with Monin-Obukhov similarity theory, with the stability function of Beljaars and Holtslag taken for stable conditions, though it is acknowledged that the model behaviour can be very sensitive to the specification of these functions. It should be emphasized that it is not only the presence of a cutoff which lead to improved results in the tests: the *shape* of the stability functions is of primary significance.

2.5 Hydrology Parametrization

The new MOSES system for the Unified Model was not available for testing at the time of writing this report. However, the MOSES system has all of the features that are desirable in a hydrology parametrization. The most important of these features is that of the interactive stomatal resistance, which is the mechanism that controls transpiration, especially during the night. The hydrology parametrizations in the Unified Model before MOSES did not contain such features, hence no testing has been done on them, in anticipation of the MOSES scheme. It is not expected, however, that any changes will have to be made to the MOSES scheme and it is therefore suggested that this scheme be used as it is.

3. Performance of the Boundary Layer Scheme

3.1 Method of Assessment.

As stated in the introduction, the main issues concerning the UM boundary layer scheme are:

1. Can the scheme run successfully at high resolution in unstable conditions?
2. Which unstable formulation should be used?
3. Do we obtain better performance with high resolution in stable conditions?

Assessment was largely performed by running experiments using initial conditions taken from the mesoscale model from cases exhibiting fairly simple and ideal behaviour (e.g. light wind, cloud-free hot summer day with a strong capping inversion for unstable conditions) and constant geostrophic forcing. Results are described below starting with some general comments on impact of higher resolution followed by assessment in unstable, and stable, clear sky or fog conditions. The importance of fog cannot be understated, however it is closely linked to the occurrence of strong stable stratification so the two are considered together. A total of four cases have been used in this assessment.

3.2 Assessment at high resolution.

As has been mentioned in the Project Initiation Document (Clark, 1996) the UM code*was not designed for site specific use, therefore the suitability of the UM physics to perform well at the high resolutions demanded for local forecasting tasks cannot be assumed. Indeed although remaining within the UM framework is desirable, a significant factor in the decision to do so rests with whether the UM code can support the high vertical resolutions required.

The method of resolution enhancement chosen and recommended for future use, relies on the assumption that the local effects (*e.g.* site surface characteristics, upwind surface characteristics, local topography) that perturb forecast variables away from the gridbox mean of the large scale forecast model are confined to the boundary layer. The model resolution was increased to ×2 and ×4 the number of levels in the mesoscale model boundary layer and compared to the mesoscale model for two cases, one in unstable and one in stable, clear sky conditions. As a guide the mesoscale model has 14 levels treated by the boundary layer scheme (up to about 2.5 km) with a lowest level set at 10 m. Multiplying this by four gives 53 levels within the same layer and a lowest model level set at 2.5 m.

A number of issues are raised when the vertical resolution is increased to such an extent. The vertical transport in the boundary layer is dominated by local diffusion. To maintain numerical stability, the timestep must be reduced in proportion to the square of the vertical grid spacing. The `correct' timestep depends upon conditions. At mesoscale resolution, 100 s is found to be short enough for all circumstances, though, in practice, 300 s has been found to be acceptable despite some additional noise. Therefore a ×4 increase in resolution requires a timestep of about 100/16=6 s. For convenience a timestep of 10 s has been used here though the exact timestep threshold beyond which the diffusion terms are too large remains unresolved. Some problems have been encountered using this timestep with larger surface roughness lengths, so further work is being conducted to deduce this threshold as unnecessary model timesteps could be a significant cost at model runtime when the model goes operational. To this end unnecessary runtime cost can be incurred by those physics routines *e.g.* radiation, that are not dependent upon diffusive timescales. In addition the radiation scheme is the most computationally expensive scheme within the single column model. The timescale for radiative transfers is dominated by changes in the local cloud cover which is of the order of 600-1800 s. Hence it is only necessary to run the radiation scheme every 60, 10 s physics timesteps. This has been tested for fog and low cloud and no significant impact found.

One additional problem was found running at higher resolution: the UM uses a relationship to derive the Exner pressure at a model full level from that at the level boundaries which is a finite difference form of the identity

$$\Pi = \frac{1}{(1+\kappa)} \frac{\partial(\Pi p)}{\partial p}$$

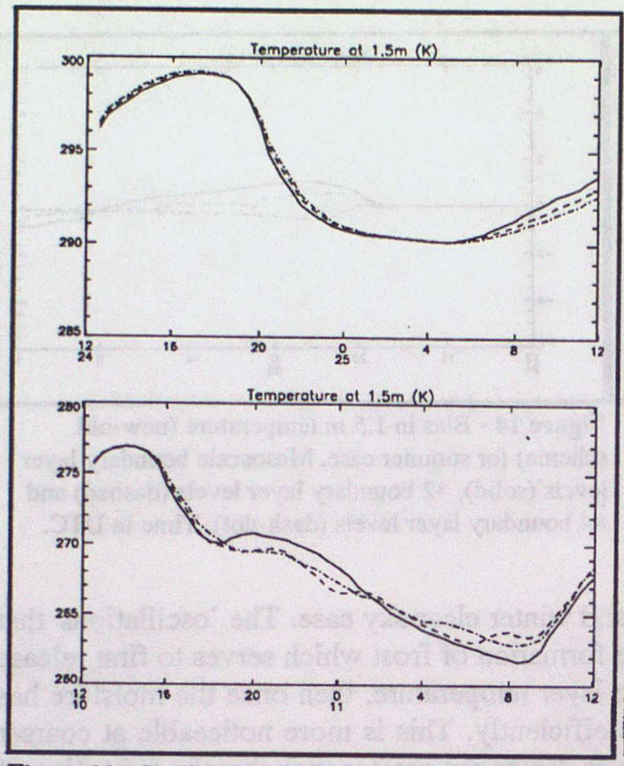

Figure 11 - Cooling curves with resolution. - Mesoscale boundary layer levels (solid), ×2 boundary layer levels (dashed) and ×4 boundary layer levels (dash-dot). Time in UTC. a) Summer case, b) Winter case.

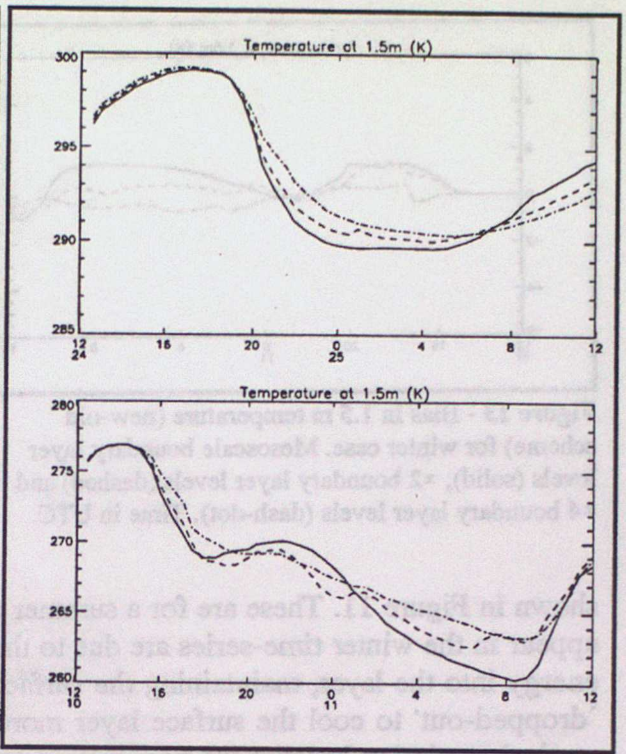

Figure 12 - Cooling curves with resolution for new surface exchange scheme - Mesoscale boundary layer levels (solid), ×2 boundary layer levels (dashed) and ×4 boundary layer levels (dash-dot). Time in UTC. a) Summer case, b) Winter case.

so

$$\Pi_k = \frac{1}{(1+\kappa)} \frac{\Pi_{k+\frac{1}{2}} p_{k+\frac{1}{2}} - \Pi_{k-\frac{1}{2}} p_{k-\frac{1}{2}}}{p_{k+\frac{1}{2}} - p_{k-\frac{1}{2}}}$$

This is used for consistency with the hydrostatic relation. Unfortunately, at the 32 bit precision used this difference form is highly inaccurate at high resolution (actually leading to a **negative** height of level 1). To overcome this, the simpler and alternative formulation:

$$\Pi_k = \frac{\Pi_{k+\frac{1}{2}} + \Pi_{k-\frac{1}{2}}}{2}$$

has been used. This has negligible impact on results, but is mentioned as it is a feature of the UM in general, not just the single column version. Running at 64 bit precision (e.g. on the Cray) should not have this problem.

The performance at higher resolution can be initially assessed from the 1.5 m cooling curves

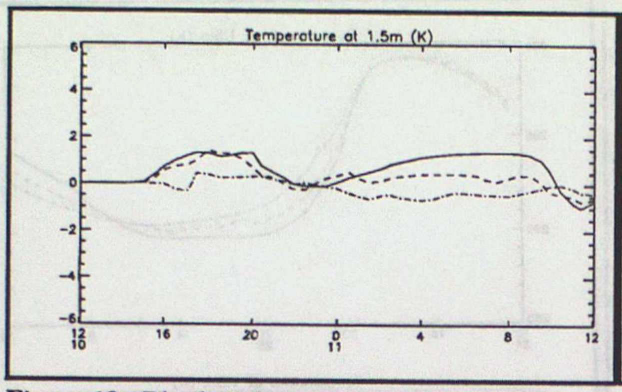

Figure 13 - Bias in 1.5 m temperature (new-old scheme) for winter case. Mesoscale boundary layer levels (solid), ×2 boundary layer levels (dashed) and ×4 boundary layer levels (dash-dot). Time in UTC.

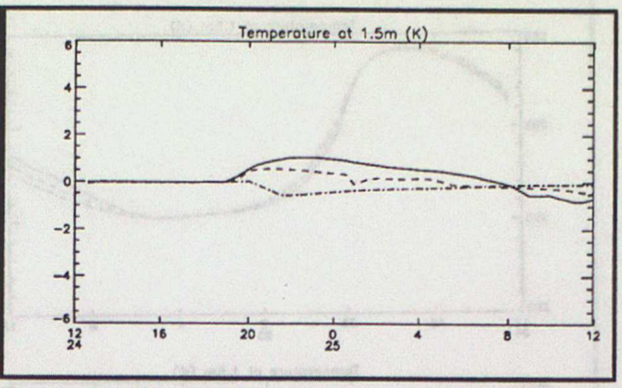

Figure 14 - Bias in 1.5 m temperature (new-old scheme) for summer case. Mesoscale boundary layer levels (solid), ×2 boundary layer levels (dashed) and ×4 boundary layer levels (dash-dot). Time in UTC.

shown in Figure 11. These are for a summer and winter clear sky case. The `oscillations' that appear in the winter time-series are due to the formation of frost which serves to first release energy into the layer, maintaining the surface layer temperature, then once the moisture has `dropped-out' to cool the surface layer more efficiently. This is more noticeable at coarser vertical resolution because the near surface layer depths are greater such that the formation of frost within a `thick' layer extracts more total water than from a thin one. Despite this both cases show that with the current model configuration the surface layer temperature is not too sensitive to resolution. Indeed, it is expected that under nocturnal conditions where the surface exchange is dominated by the soil flux and long wave cooling, then the cooling rate determined by the existing scheme will not vary if the model resolution is changed. However, the results from sections 2.2 and 2.4 where the surface temperature parametrization and formulation of the surface exchange coefficients were assessed, support the inclusion of a scheme to represent a vegetative canopy, with a formulation for the surface exchange coefficients that is based upon Monin-Obukhov similarity and possessing a turbulent `cut-off' in stable conditions. The current UM scheme for calculating the bulk surface exchange coefficients is an explicit one and uses a number of tunable parameters making it reliant on the model set-up. In particular, it is written in terms of the surface layer bulk Richardson number, which is grid-dependent. The implementation of this scheme on the same cases as shown in Figure 11, is shown in Figure 12. This results in a cold bias in the surface layer temperature when comparing the existing scheme with the Monin-Obukhov scheme, the magnitude of which is inversely proportional to resolution increase. The 1.5 m temperature bias is shown in Figure 13 for the winter case and Figure 14 for the summer case. At the mesoscale resolution the cold bias is as much as 1.5 K, whereas at high resolution (53 boundary layer levels) the bias is a net warm one of about 0.3 K.

In summary, the advantage the Monin-Obukhov formulation of surface exchange coefficients brings, is grid independence and better performance for lower values of z/z_0. Further benefits of the increased resolution (not shown here) include the nighttime stable boundary layer inversion being more accurately resolved in terms of height and extent. Also the evolution of the morning boundary layer growth is smoother and quicker leading to less propagation of stress and heat flux perturbations throughout the boundary layer.

3.3 Assessment of the Convective Boundary Layer.

The surface exchange formulation does have some impact on unstable conditions, and, as is shown below, the current scheme has difficulty correctly representing different ratios of roughness length for heat and momentum, which must be considered a site-specific characteristic. However, assessment of the performance of the single column UM code under unstable conditions has concentrated on how the boundary layer mixing is described within the UM boundary layer scheme. Observations by Kaimal *et al.* (1976) have shown that the convective boundary layer (CBL) is expected to have mean profiles that are well mixed in the bulk of the boundary layer, with large surface layer gradients. However Garratt (1992) has been one of many to comment that first order mixing models cannot reproduce these mixed layers as they require fluxes to be down gradient.

The boundary layer scheme in the UM is a first order closure mixing length scheme where the eddy diffusivities depend upon local stability through function of the gradient Richardson number, Ri. This makes the eddy diffusivities increase with increasing instability. In the UM this local mixing is insufficient to produce a fully mixed boundary layer at its coarse vertical resolution, therefore the mixing is enhanced in unstable conditions via a `rapidly mixing scheme'. This scheme firstly calculates the local fluxes as before, then it adds on a linear flux profile for liquid/frozen water temperature and total water content using the appropriate surface and top of boundary layer flux. It should be noted that momentum is transported by the local scheme only.

To assess the suitability of these schemes at high resolution the single column UM was tested with and without the `rapidly mixing scheme' under clear sky summer conditions and at mesoscale and high (53 boundary layer levels) resolution. The model was initialised with data from the mesoscale model analysis for midnight on 24/7/95 from the nearest gridpoint to Beaufort Park. In the cases considered, deep convection should not have been occurring, but to avoid any confusion or competition, the convection scheme was disabled in all experiments described.

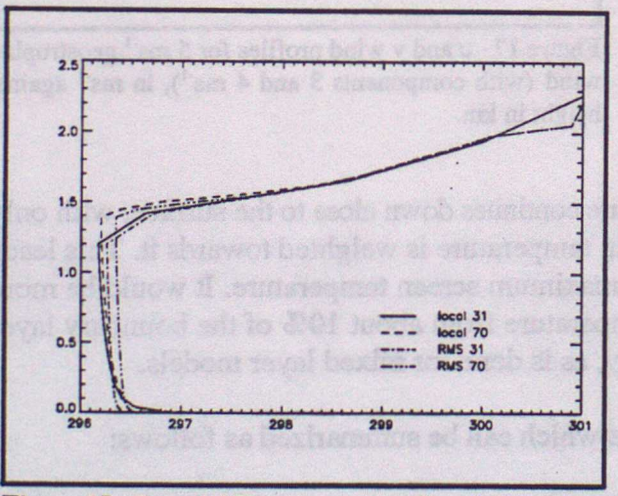

Figure 15 - Potential Temperature profiles, in K against height in km.

The results of comparing the local mixing scheme (LMS) and the `rapidly mixing scheme' (RMS) for temperature, humidity and wind are described at 17:00 UTC, the time representative of each scheme's afternoon CBL profiles. Figure 15 show the potential temperature profiles of both schemes for mesoscale (14 boundary layer levels) and high resolution (53 boundary layer levels).

The results may be summarized as:

1) Potential temperature for the LMS decreases with height in the boundary layer and has large gradients near the surface.

2) The boundary layer with the RMS is warmer by 0.1-0.2 K, the potential temperature profile has a gradient close to zero which continues closer to the surface than is the case with the LMS, and there is a small near-surface gradient.

3) The screen temperature, diagnosed at 1.5 m was 1 K cooler with the RMS rather than with the LMS for mesoscale resolution. For high resolution this difference increased to 1.5 K.

4) The screen temperature at high resolution is slightly warmer than mesoscale resolution with the LMS, but slightly cooler with the RMS.

5) The maximum screen temperature with the LMS is at 16:30 UTC, whereas for the RMS it is at 17:00 and 17:30 UTC for mesoscale and high resolution respectively.

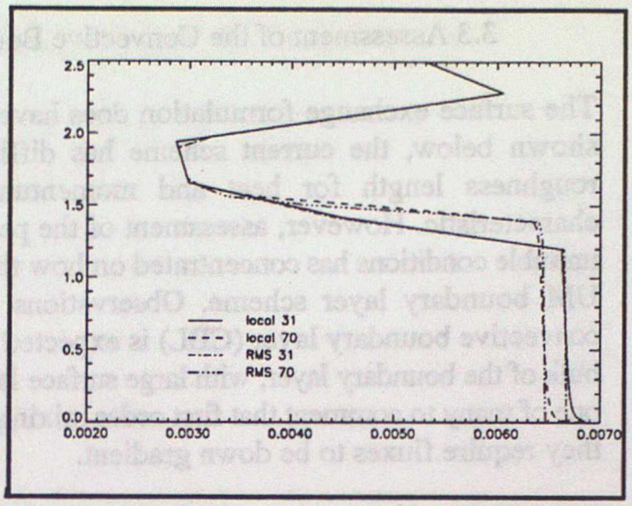

Figure 16 - Specific humidity profiles, in Kg/Kg against height in km.

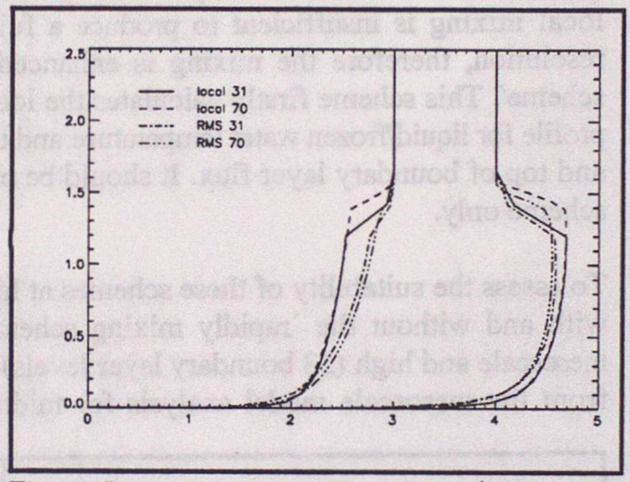

Figure 17 - u and v wind profiles for 5 ms^{-1} geostrophic wind (with components 3 and 4 ms^{-1}), in ms^{-1} against height in km.

6) For the RMS, the mixed layer temperature continues down close to the surface, with only a small super-adiabat, so that the screen temperature is weighted towards it. This leads to a lag in the time of occurrence of the maximum screen temperature. It would be more appropriate to diagnose the screen temperature from about 10% of the boundary layer depth using Monin-Obukhov similarity, as is done for mixed layer models.

Figure 16 shows the specific humidity profiles which can be summarized as follows:

1) The LMS gives a small humidity gradient that increases in the surface layer.
2) The RMS gives a smaller, near constant humidity gradient all the way down to the surface, thereby reducing the near-surface dew points.
3) The boundary layer depth influences the mixed layer humidity as shown in the comparison between mesoscale and high resolution runs. This is important because at nocturnal transition the mixed layer humidity will remain throughout the night.

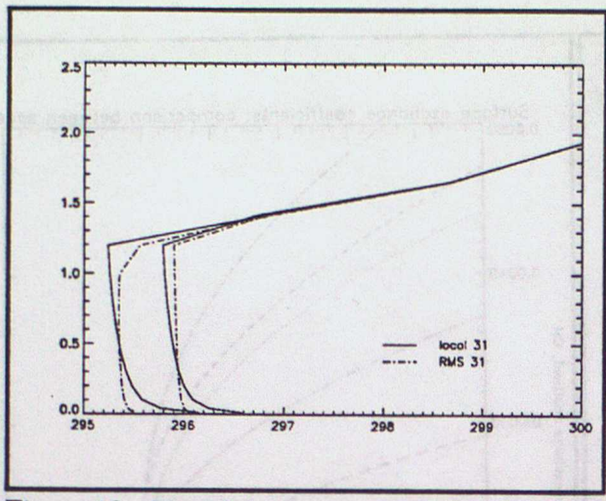

Figure 18 - Potential temperature profiles for 15:00 (left) and 16:00 UTC (right).

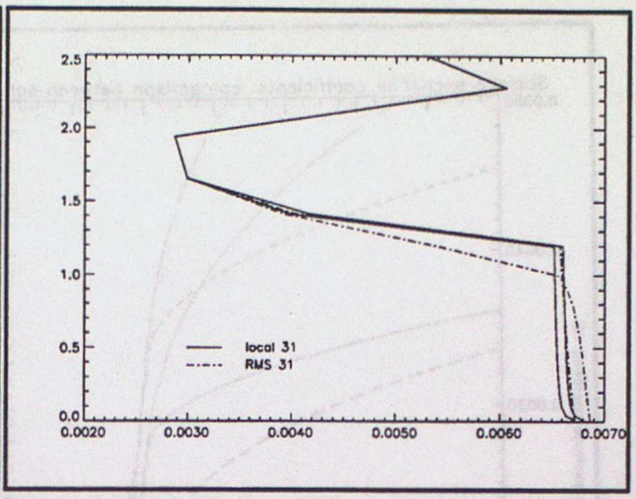

Figure 19 - Specific humidity profiles for 15:00 (outer curves) and 16:00 UTC (centre curves)

Figure 17 shows the zonal and meridional wind profiles. The LMS produces a wind profile that is fairly well mixed throughout the boundary layer with a large shear across the boundary layer top. In contrast the RMS produces a wind profile with more shear within the boundary layer and less shear across the capping inversion. Within the CBL there is a large difference in surface stress, diagnosed via the friction velocity u_*, between the two schemes. During the afternoon the u_* diagnosed from the LMS is about 18% larger than that diagnosed from the RMS. Associated with this there is a corresponding difference in the 10 m winds.

It should be noted that errors in u_* will cause errors in the surface layer temperature profile, even if the surface layer temperature gradient starts at a realistic height. If u_* is too small then, for a given surface heat flux, the temperature gradient will be too large and take longer to decay. This causes the maximum screen temperature to occur later. The wind profile and u_* generated by the RMS suggest that it is providing insufficient mixing of momentum. As the RMS temperature profile is only slightly unstable this makes the Ri's less negative and so reduces the eddy diffusivities for momentum.

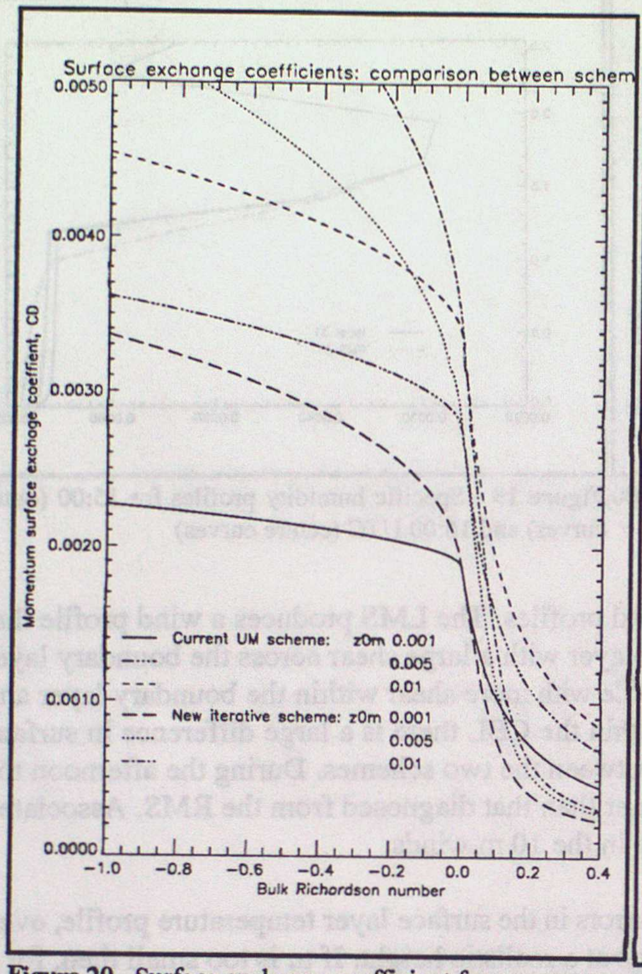

Figure 20 - Surface exchange coefficient for momentum, C_D, for a range of roughness lengths, z_0, calculated using the original UM scheme and the proposed high resolution scheme. In each case, $z_{0h} = 0.1\ z_0$.

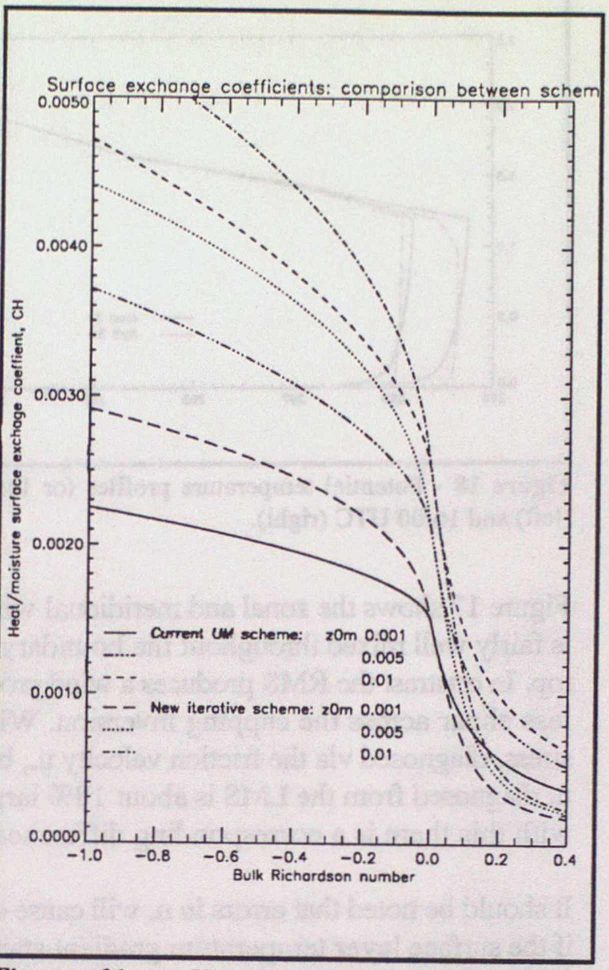

Figure 21 - Heat/moisture surface exchange coefficient, C_H, for a range of z_0 calculated using the original UM scheme and the proposed iterative, high resolution scheme. In each case, $z_{0h} = 0.1\ z_0$.

At the top of the boundary layer there are temporary differences in temperature and humidity between the two schemes. This can be seen in Figures 18 and 19 which show potential temperature and specific humidity profiles at 15:00 and 16:00 UTC for the mesoscale resolution. At the boundary layer top the wind shear across the inversion affects the local stability; the smaller shear observed with the RMS increases the stability and therefore reduces the downward heat flux and upward moisture flux across the boundary layer top, compared the what is observed with the LMS. As a result the temperature and moisture profiles generated by the RMS take longer to become well mixed to the same depth as the profiles generated by the LMS. Although this occurs in less than an hour of real time, for a short period the specific humidity profile from the RMS may be moister. This slower mixing across the boundary layer top is more pronounced for mesoscale resolution rather than high resolution. This is because at high resolution the model layer depth (*i.e.* distance between model levels) is smaller and the finite difference form of Ri depends upon the layer depth.

In summary, provided a short enough timestep is used, the UM unstable BL parametrization gives similar results at high resolution to 'mesoscale' resolution, and the differences are probably not significant. There is little to recommend the RMS for site-specific use: its wind profile is less acceptable, it probably leads to an underestimate of screen temperature, and appears at least partly responsible for the known tendency of the UM to produce maximum temperatures too late in the day. (Ironically, these features can be ascribed to the 'Rapidly Mixing' scheme actually mixing the unstable boundary layer less rapidly).

3.4 Assessment of the Nocturnal Boundary Layer.

Assessment of the performance of the single column UM under stable conditions is weighted towards the performance of the surface exchange scheme within the single column UM, which has already been discussed in some detail in section 2. The results of experiments with the high resolution version of the single column model in statically stable conditions are important as local surface characteristics provide significant forcing to modify the overall flow regime. As has been mentioned in section 2 the current UM surface exchange coefficients are calculated using a scheme that is explicit and non-similar. It is therefore reliant upon the current model set-up. In order to cope with the proposed inclusion of a vegetative canopy scheme within the surface temperature parametrization and a turbulence `cut-off' in section 2, a replacement iterative scheme has been developed and is proposed for further use. This scheme is based upon Monin-Obukhov similarity and as such is not tuned to any particular model configuration or conditions. The scheme works by:

i) Calculating the initial value for the Monin-Obukhov length for neutral conditions using the bulk Richardson number, Ri_B calculated in the *surface exchange* routine;

ii) Determining the choice of stability functions from the value of Ri_B (*i.e.* stable or unstable);

iii) Iterating to obtain a value for the Monin-Obukhov length to a predetermined accuracy and, subsequently, calculating the bulk surface exchange coefficients which are then returned to the *surface exchange* routine.

Being iterative the above proposed scheme has to run to a specified accuracy, currently set to 0.1%, and/or a limiting number of iterations which if exceeded sets the transfer coefficients to zero. The detrimental effects of this tolerance have yet to be assessed and an iteration limit justified. However, in most cases the scheme converges in about 5 iterations, the limiting iterations only being approached when turbulence cuts off or is close to doing so, in which case the accuracy lost by limiting the number of iterations is unlikely to be of significance. When short timesteps are used, the scheme could probably be made more efficient by saving the Monin-Obukhov length from one step to the next, to act as a first guess.

Figures 20 and 21 show comparisons of the surface exchange coefficients derived from the current UM scheme and the proposed high resolution scheme for the case where the roughness length for heat is one tenth that for momentum as recommended by Garratt (1978) and Hopwood (1995). In the proposed scheme the surface exchange coefficients are increased in unstable conditions and reduced in stable conditions. The UM currently sets $z_{oh} = 0.1 \times z_o$, though this can be varied, and will be for site specific use. The two schemes are much more similar on the unstable side when these two roughness lengths are made equal, as expected, since this is assuming the transfer efficiencies of heat and momentum are the same under stability conditions where momentum transfer by bluff processes is minimized.

3.4.1 Clear sky conditions, no fog observed.

The sensitivity of the single column UM under stable conditions to changes in geostrophic forcing, initial specific humidity profile and formulation of the surface exchange coefficients, has been investigated for a winter, clear sky scenario where, in reality, no fog was observed. The

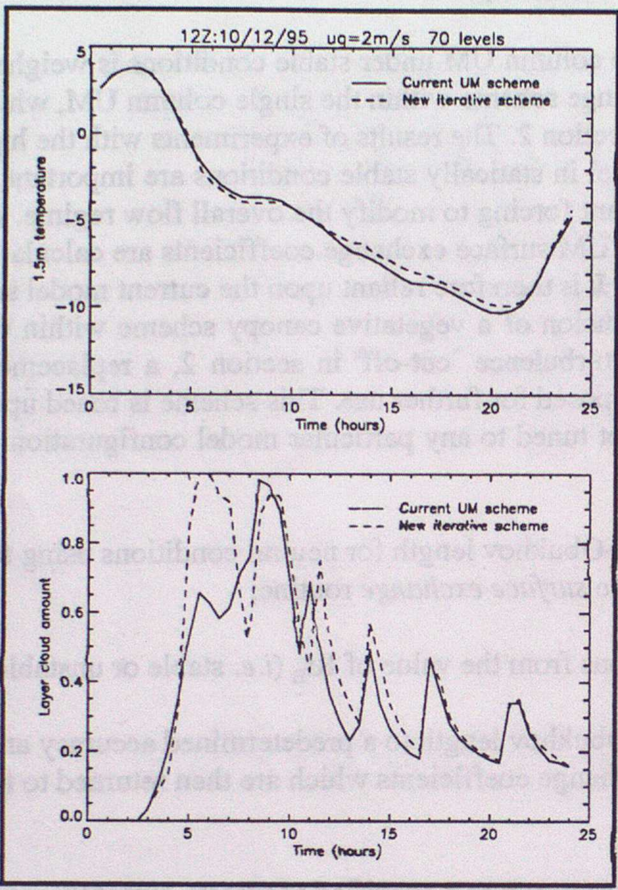

Figure 22 - 1.5 m temperature and bottom model level layer cloud amount - `fog' - for winter, clear sky conditions with the UM and Monin-Obukhov formulations for the surface exchange coefficients.

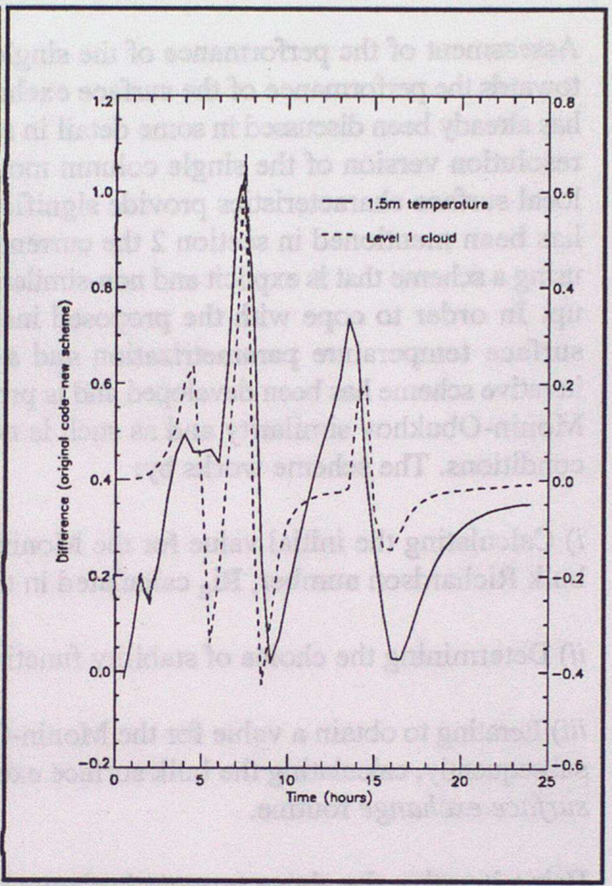

Figure 23 - Differences between 1.5m temperatures and the layer cloud amounts produced with the UM and Monin-Obukhov formulations for the surface exchange coefficients.

model was initialized with mesoscale analysis data at 12Z on 10/12/95, from the nearest gridpoint to Beaufort Park. The effects can be seen by comparing Tables 2 and 3 which show the fog formation/dissipation times and 1.5 m minimum temperatures with (Table 3) and without (Table 2) the Monin-Obukhov scheme for determining the surface exchange coefficients. Times given are times into the run, so, for example, fog from 6-11 signify 18Z to 23 Z. The experiments were conducted with geostrophic forcing of 2, 5, 8, 10, 12 and 15 ms^{-1} (geostrophic windspeed in the initial analysis was approximately 14 ms^{-1} in the boundary layer), and column specific humidity profiles of 90%, 95%, 100%, 105% and 110% of the initial analysis profile within the boundary layer only.

Although no fog was observed in the case considered (as would be expected given the analysed geostrophic wind), fog is eventually formed in the model in all the conditions considered. As would be expected, however, `thick' fog, defined for the purposes of this assessment as ≥20% cloud cover in the lowest model level, is only formed in the low windspeed cases *i.e.* 2 ms^{-1} and

5 ms^{-1}. Higher windspeeds produce a thin layer of low cloud as a consequence of the enhanced mechanical turbulence. This layer thickens with integration time due, in part, to the increase of total moisture in the model atmosphere from the soil moisture and, primarily, from continued long wave cooling of the model as a whole in the absence of external thermal forcing. Decreasing/increasing the boundary layer specific humidity serves to delay/hasten the onset of fog by 1-2 hours for a 10% change in initial specific humidity. As expected there is a close correlation between the formation and amount of fog and the magnitude of the 1.5 m temperature, as can be seen in Figures 22 and 23. (The oscillations visible in these figures are discussed later in this report).

UM cdch		Time of fog formation (hours after start of run)					1.5 m minimum temperature (°C)				
Levels	q×	0.9	0.95	1.0	1.05	1.1	0.9	0.95	1.0	1.05	1.1
	Wind/ ms^{-1}										
31	2	5	4	4	3	0	-11.5	-11.5	-11.3	-10.8	-9.2
	5	6	5	4	3	3	-9.5	-9.3	-8.3	-7.4	-7.3
	8	13	12	11	10	9	-7.5	-7.1	-6.7	-6.3	-5.8
	10	18	17	16	15	14	-6.6	-6.4	-6.2	-5.9	-5.6
	12	-	-	-	21	20	-5.9	-5.7	-5.5	-5.3	-5.2
	15	-	-	-	-	-	-4.7	-4.6	-4.4	-4.2	-4.1
70	2	3	3	3	2	2	-10.9	-10.3	-10.2	-9.7	-9.3
	5	5	4	3	2	2	-9.3	-9.0	-8.5	-8.0	-7.7
	8	11	10	9	7	0	-7.4	-7.2	-7.0	-6.8	-6.6
	10	16	15	14	13	0	-6.5	-6.3	-6.2	-6.0	-5.8
	12	-	20	19	18	17	-5.8	-5.6	-5.5	-5.3	-5.1
	15	-	-	-	-	-	-4.9	-4.7	-4.5	-4.4	-4.2

Table 2 - Fog formation time and 1.5 m minimum temperatures for "case A", using the current UM surface exchange coefficient scheme. The fog formation time was determined as the time at which the layer cloud amount exceeded 0.05 in the lowest model layer. A dash (-) indicates that this criterion was not reached. The 1.5 m minimum temperature is that which occurred nocturnally (between sunset and sunrise; 4:00 pm until 8:00 am).

New cdch		Time of fog formation (hours after start of run)					1.5 m minimum temperature (°C)				
Levels	q× / Wind/ ms^{-1}	0.9	0.95	1.0	1.05	1.1	0.9	0.95	1.0	1.05	1.1
31	2	5	5	4	3	0	-12.7	-12.8	-12.6	-12.1	-10.5
	5	6	6	5	4	3	-10.2	-9.9	-9.4	-7.4	-7.4
	8	13	12	11	10	9	-7.7	-7.3	-6.9	-6.3	-5.9
	10	18	17	16	16	15	-6.7	-6.5	-6.2	-6.0	-5.7
	12	-	-	-	21	20	-5.9	-5.7	-5.6	-5.4	-5.2
	15	-	-	-	-	-	-4.7	-4.6	-4.4	-4.2	-4.1
70	2	4	3	3	2	2	-10.4	-10.0	-9.8	-9.3	-9.0
	5	5	4	3	2	2	-9.3	-9.0	-8.5	-8.0	-7.7
	8	11	10	9	8	0	-7.4	-7.2	-7.0	-6.8	-6.6
	10	17	15	14	13	0	-6.5	-6.4	-6.2	-6.0	-5.8
	12	-	-	19	18	17	-5.8	-5.6	-5.5	-5.3	-5.1
	15	-	-	-	-	-	-4.9	-4.7	-4.5	-4.4	-4.2

Table 3 - As table 1; case B, using the new iterative surface exchange coefficient scheme.

To summarise the above findings, after windspeed the dominating factor in the control of fog formation restricted to statically-stable conditions is the magnitude of the initial moisture profile. This fog formation is further modified by the formulation of the surface exchange coefficients, in particular the presence of a turbulent `cut-off'.

3.4.2 Clear sky conditions, fog.

The results of experiments with the high resolution version of the single column UM in the prediction of fog where fog was observed show that it is reasonably good at predicting its occurrence, but a number of areas have been found where deficiencies in the model formulation impact on its development and subsequent dissipation. The most notable impacts, apart from those discussed in section 3.4.1, are in the time of dissipation, the diagnosed fog depth and the cooling within the fog. Here the model was initialized with mesoscale analysis data at 12Z on 16/1/96, from the nearest gridpoint to MRU, Cardington in Bedford. The following describes the most important mechanisms where deficiencies in the model have been found.

i) Influence of Surface exchange coefficients.

The potential influence of surface exchange coefficients is well illustrated by the results shown in Fig. 24. This is taken from the same 11/12/95 case as used above, but with the relative humidity in the boundary layer reduced to 80% in the initial conditions, a very light (1 ms^{-1}) geostrophic wind, and the initial soil temperatures set equal to the surface temperature at all levels. This is to ensure maximum comparability between schemes. The results come from a 70 level configuration, with the precipitation scheme disabled to avoid the complications discussed below.

The main, solid, line uses the Monin-Obukhov surface exchange coefficients, and the vegetation canopy model, which requires the Penman-Monteith (PM) formulation of surface exchange and soil temperature. This shows the expected rapid cooling after sunset. This may be compared with the dashed line, which is the same formulation but without the vegetation canopy. In the second case, the soil heat flux is generally greater (more negative) and the moisture lost by dewfall (latent heat flux) rather less as the surface temperature is higher. In spite of this, as a result of higher screen temperatures, fog formation is delayed by 2-3 hours, as shown by the total cloud curve (which includes about 2/8 cirrus). The other two curves show the same results with the original, non-Penman-Monteith , surface scheme. This is characterized by a different treatment of the soil temperature, especially the top soil level. This has greater thermal inertia, and is able to supply more heat to the surface during the afternoon and evening, thus preventing the moisture loss seen in the PM scheme and bringing fog formation forward to shortly after dusk. The influence of the surface exchange coefficients themselves, in this case, is small, although there is still an impact from a period of cutoff turbulence during the night which persists until fog formation, when cooling at fog top promotes turbulent transport again.

These results do not, in themselves, show one scheme to be right, or wrong, but rather highlight that one of the most important phenomena for the correct forecasting of fog formation is the correct simulation of the amount of heat and moisture lost from the air near the surface when it cools by radiation. This determines whether dew or fog or both are likely to form. For the fog cases chosen the impact of using the existing formulation of the surface exchange coefficients, used in the mesoscale model, compared to the Monin-Obukhov formulation described above is to delay the formation of fog by between 30 minutes to 1 hour, as discovered in the `clear sky, no fog' case. Adding the impact of vegetation, or different model soil characteristics, can have a more dramatic impact of 2-3 hours delay, and, undoubtedly, conditions could be found in which the difference was critical for the formation of fog at all. Once the fog has formed there is no significant evolutionary difference between the different schemes as the surface exchange is dominated by the turbulence generated at fog top.

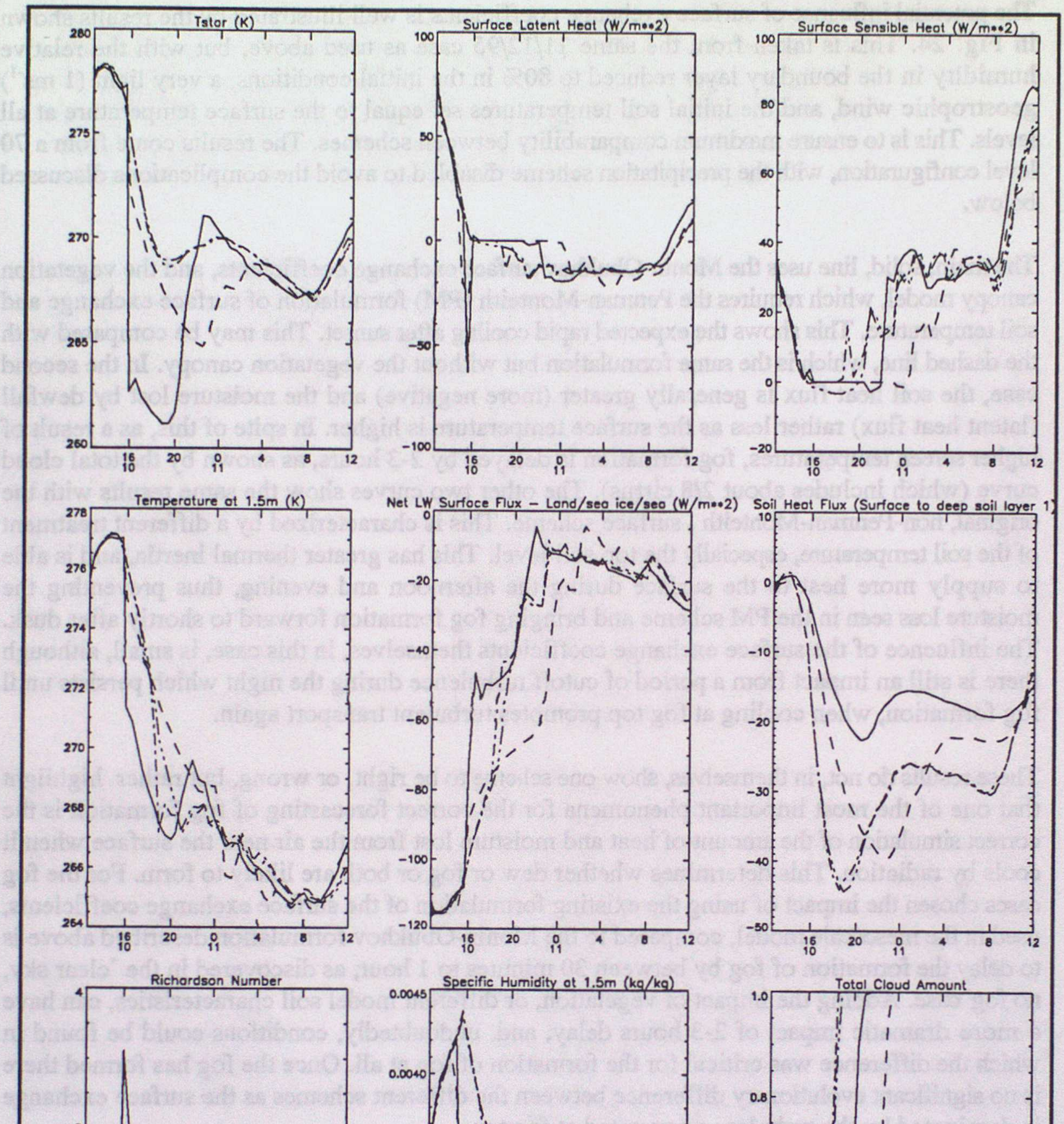

Figure 24 Comparison of evolution using different surface schemes: PM+Veg+MO (solid), PM+MO (dashed), Original+ MO (dash/dot), Original (dash/dot/dot).See text for key.

ii) Influence of Fog droplet settling.

Cloud droplets fall slowly, and under most conditions, their settling can be ignored. However, when close to the ground and particularly in stable conditions, where turbulence is low or absent, the downward flux of moisture can have a significant affect on the water budget. This is not currently treated within the UM and will have to be addressed.

iii) Influence of Boundary layer top entrainment.

When a fog has developed to a substantial depth, the main cooling is radiative and from the top of the fog layer. This layer can then become unstable. The instability formed generates turbulence that mixes up the fog layer and entrains potentially warmer air from aloft into the fog. Although the first of the mechanisms is described in the UM, the second is not and since the fog top inversion is very stable, little transport can occur across it. The impact of this missing process on the single column version of the UM is, that without any advection terms present, once a deep fog has formed the layer as a whole cools to a greater degree than is seen in reality. This can be seen in Figure 25a in comparison to the observed temperature profile at MRU, Cardington, at 07:00 UTC via the `Balthum' tethered balloon program. The `Balthum' observations show that the model fog layer is approximately 5K colder than what was observed. It is also very difficult to dissipate. This can be seen in Figure 25b where the `Balthum' observations indicate that entrainment from aloft is warming out the fog from the top, creating the instability that will lift and dissipate the fog via turbulence. This gives a false forecast for the following daytime. This is less of a problem in the UM (global, LAM, mesoscale) as they are all 3D models so that any fog has a horizontal extent and can be dissipated from the edges via advection and diffusion. Therefore it would be reasonable to assume that coupling the single column model to the mesoscale forcing terms would aide fog dissipation via advection. However, for conditions where advection is small the deficiency in the entrainment has to be addressed. A separate parametrization is under development in APR/MP to treat it which should hopefully be ready for inclusion in the UM by the end of the year.

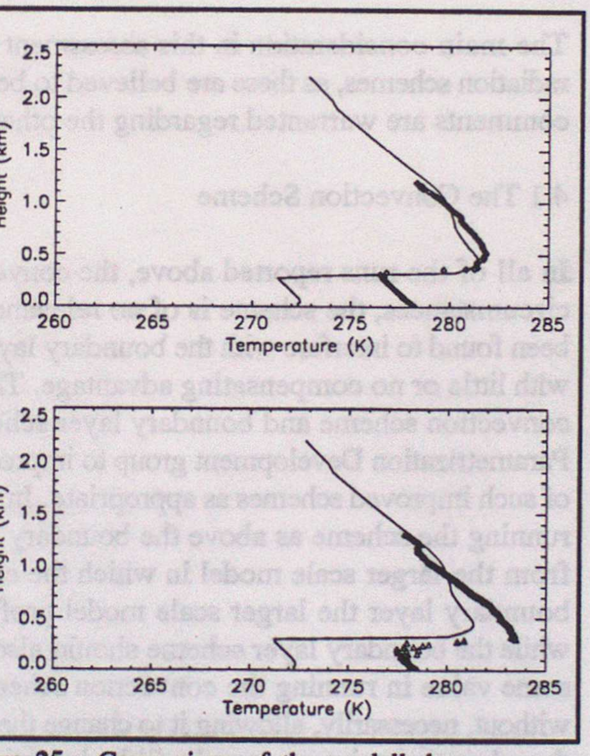

Figure 25 - **Comparison of the modelled temperature profiles with: the UM formulation for surface exchange coefficients (solid); Monin-Obukhov formulation for surface exchange coefficients; `Balthum' observations (triangles). (a) 07:00 UTC, (b) 11:00 UTC.**

iv) Influence of the Initial temperature and humidity profile.

The initial conditions the single column version of the UM is provided with, have only a secondary effect upon whether the formation of fog will or will not occur, as the relative humidity change as temperature falls is much greater than the uncertainty in the near surface relative humidity. Initial conditions derived from the larger scale models, particularly the mesoscale model, may be good enough for defining the near surface humidity, though additional local information may improve the forecast of the onset of fog by an hour or two. Uncertainties in the humidity and temperature **profiles** have a much greater impact on the near surface stability and the eventual fog depth. In particular, if a shallow mixed layer has formed in the mesoscale model, this will be defined exactly by one of the available levels - fog therefore tends to be either 40 m, 100 m, 190 m or 300 m deep. This is a disadvantage of initialising discrete runs with a mesoscale model vertical profiles. There is clear advantage from using locally observed vertical profiles when available, but the findings also suggest that running with higher resolution and forcing with horizontal pressure and advective **gradients** from the larger scale model might improve the simulation of fog depth, and ultimately clearance.

4. Other Parametrization Schemes

The main consideration in this assessment has been the boundary layer and (by implication) radiation schemes, as these are believed to be most important for our purposes. However, some comments are warranted regarding the other schemes in the single column model.

4.1 The Convection Scheme

In all of the runs reported above, the convection scheme has been disabled. Clearly, in many circumstances, the scheme is of no relevance. In shallow unstable conditions, the scheme has been found to interfere with the boundary layer scheme and produce highly unrealistic profiles, with little or no compensating advantage. This problem of unrealistic interactions between the convection scheme and boundary layer scheme is well known and work is planned in the UM Parametrization Development group to improve the schemes. When available, use will be made of such improved schemes as appropriate. In the meantime, it is felt that little will be gained by running the scheme as above the boundary layer, the model will be forced back to the profile from the larger scale model in which the convection scheme has already been run. Inside the boundary layer the larger scale model profile will still have an influence through advection, while the boundary layer scheme should also act to remove instability. However, there may be some value in running the convection scheme for diagnostic purposes and radiation purposes, without, necessarily, allowing it to change the model evolution. The question of what to do with the scheme remains open and will be investigated as part of the next stage of the project where the impact of real, time varying, forcing will be investigated.

4.2 The Large Scale Precipitation Scheme

The large scale, or dynamic, precipitation scheme is a fairly simple diagnostic scheme which works reasonably well for large grid boxes. Some deficiencies have been found when running at high resolution to look at boundary layer cloud and fog.

Above freezing, the model is dominated by the autoconversion term, which tends to turn on quite suddenly and remove liquid water rather efficiently. However, this could probably be tuned by adjusting the parameters that allow for the typical droplet size to take into account the fact that boundary layer cloud is likely to have a very large number of small drops. Thus, while some tuning work will be required, no major changes to the scheme should be needed.

Below freezing, the situation is much less satisfactory, as the current scheme tends to produce snow very rapidly as soon as temperatures drop low enough. This snow grows and falls out very rapidly, depleting the cloud water and ice throughout the layer. Fresh cloud water or ice forms as soon as the fog layer reaches the next model level, and is then rapidly removed. This 'pulsing' behaviour occurs at all resolutions, and is responsible for the spikes in the layer cloud amount shown in Fig. 22 and the differences in Fig. 23. Higher resolution smooths the behaviour somewhat, but is not a solution. The new mixed phase precipitation scheme, currently under development for the UM, has a separate ice variable, and thereby a mechanism for controlling the formation of snow. This may help with these oscillatory problems, but this has yet to be tested. It should be noted that the behaviour is fundamental to the UM, not particular to the single column version, though it is clearly more noticeable with constant forcing.

These problems are not insurmountable, and are common to all UM formulations. For the most part, behaviour in a high resolution version should be no worse but probably no better than in the driving model. There is clearly scope for improving the microphysical treatment in the single column, perhaps using the UM scheme above the boundary layer and a more sophisticated treatment designed more for boundary layer cloud within it. This would also deal with the fog droplet settling issue. While this would be a departure from the UM scheme, it would be compatible so might have positive impact in the 3D configurations. At this stage, however, it might be better simply to attempt to tune the existing scheme(s) to produce more realistic behaviour.

4.3 The Radiation Scheme

All tests have been run with the old, currently operational, radiation scheme, called every 5 minutes. At some stage, the new Slingo-Edwards scheme will come into use. There is no suggestion that this will in any way be inadequate, indeed, it is more likely that it is more sophisticated than is required for our purposes. Work will be required, however, to configure it appropriately.

While the scheme itself should more than meet our needs, it does not directly address issues that are of more direct interest to the SSFM. One example of this is the penetration of radiation into and through stratocumulus. This remains an unsolved problem, and the SSFM is likely to be a valuable testbed for studying it.

5. Recommendations

5.1 For the Surface Exchange in the SSFM

i) The surface temperature parametrization should include a canopy scheme which will enable the surface temperature to cool more correctly during the night.

ii) If the additional computation time is acceptable, then an implicit nine soil level parametrization, which has very high resolution near the surface, should be used to calculate the temperature structure of the soil.

iii) It would be desirable to use transfer coefficients derived from Monin-Obukhov similarity theory. These behave better for a range of roughness lengths, are more appropriate at high resolution, and have a cut-off in stable conditions. However, care must be taken in ensuring that the appropriate stability functions are used in stable conditions. The Beljaars and Holtslag function works well for the data obtained at Cardington.

iv) The MOSES hydrology scheme should be used, but no changes are expected to it.

5.2 For the Boundary Layer in the SSFM

i) Remain within the UM framework for the parametrization schemes at least. Although not discussed some of the general control code is not appropriate for SSFM use and should be re-written.

ii) Enhance boundary layer resolution to ×4 mesoscale resolution with associated lower bottom model level. It is unlikely that much would be gained by running at even higher resolution without a significant change to the formulation of boundary layer mixing. However the choice of the height of the bottom level remains undecided, as there may be some advantage in making small adjustments in order to facilitate derivation of some diagnostics. Work is therefore encouraged to investigate the influence of the height of the lowest model layer.

iii) Timestep for diffusive processes to be 10 s or smaller, the exact magnitude to be investigated further in light of possible runtime cost saving.

iv) Timestep for radiation schemes to remain at 600 s in line with timescales for the change in cloud amount.

v) At the high resolution required of the SSFM the 'rapidly mixing' unstable boundary layer formulation has several disadvantages: The mixed layer temperature and humidity gradients are followed until near the surface, leading to 1.5 m temperatures and near surface dew points that are too low and temperature maxima that occur too late. However, the greatest drawback of the 'rapidly mixing scheme' is in its influence over the wind profile. It is responsible for producing more shear in the bulk of the boundary layer yet less shear across the boundary layer top and in the surface layer. This is due to insufficient momentum mixing as a result of a slightly unstable temperature profile and the local stability dependence of the momentum fluxes. Hence 10 m winds and surface stresses are considerably lower which subsequently feedback into the surface fluxes, surface layer gradients and timing of the maximum screen temperature. These disadvantages lead to the recommendation that the `rapidly mixing scheme' should not be used with the high resolution SSFM.

vi) Address the problem of fog droplet settling with a simple `fall-out' solution or modify the existing or new large scale precipitation scheme to treat the boundary layer and fog more accurately.

vii) Incorporate a boundary layer top entrainment scheme to aid fog dissipation and boundary layer growth.

viii) Disable the convection scheme but investigate possible uses in diagnostic mode.

6. Concluding Remarks

Investigation of the UM system for use in the SSFM has generally been encouraging. By far the most significant finding has been the impact of the treatment of surface vegetation, but a number of other factors, such as the soil scheme and the importance of vertical resolution in fog simulation, show that running a 1D version of the UM configured specifically for a location of interest can result in changes in evolution of a similar magnitude to the representativity errors currently identified in the larger scale model. Other factors have not been discussed but are well known: for example, soil moisture can have a marked effect on screen temperature and humidity, so making use of local energy balances and local rainfall can significantly affect evolution. This has been demonstrated already in the UM, so was not repeated here, but again gives hope that improved forecasts should be derivable by using the SSFM.

Deficiencies in the UM schemes have been identified. The omission of a vegetation canopy in the surface heat budget is potentially very important, and is recognised as an area requiring effort in the UM development as a whole. The surface exchange coefficients in the UM appear inappropriate for local use, though the errors resulting from using them may be small. The treatment of large scale precipitation is either inappropriate or will need modification for use in the SSFM.

As a final note of caution, while we have found that the UM has generally acceptable properties, and that improvements in formulation and configuration can lead to physically sensible changes in forecasts that are significant compared with current errors, this does not, in itself, guarantee that such improvements will be achieved in practice, as the factors changed may not be those which dominate the real errors at particular sites.

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