HIGH RESOLUTION MODELLING OF OROGRAPHIC RAINFALL

Humphrey W Lean* and Peter A Clark
Met Office Joint Centre for Mesoscale Meteorology, Reading, UK

1. INTRODUCTION

Orographic rainfall is an important aspect of the significant weather which a high resolution Numerical Weather Prediction (NWP) model will need to represent. This paper is particularly concerned with the representation of the seeder feeder mechanism which occurs in particular in the warm sectors of depressions and is thought to account for a large proportion of the orographic rainfall in the UK (Bader and Roach 1977, Browning 1980). In this report a simplified analysis of the seeder-feeder mechanism is described leading to a numerical model of the problem and a scale analysis. Results are then presented from the new non-hydrostatic version of the Met Office Unified Model (UM) in cases of orographic enhancement.

2. IDEALISED SEEDER-FEEDER EFFECT

2.1 Seeder-Feeder Effect

The seeder-feeder effect is schematically Illustrated in figure 1.

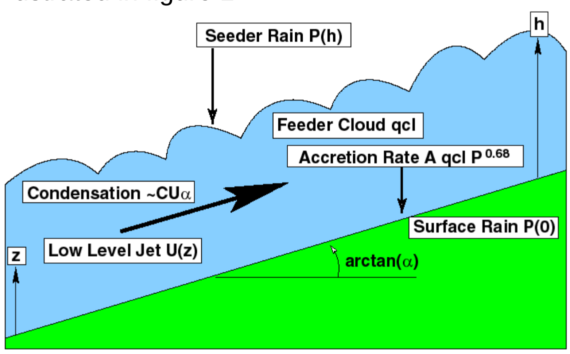

Figure 1. Schematic of seeder-feeder effect.

When air is forced to ascend up a hill the resulting condensation produces low level water cloud. In many cases there is a distinct Low Level Jet (LLJ) which defines the level at which this cloud peaks. On its own this water cloud might be expected to produce rain by autoconversion. The rate of the process, however, is usually too slow to produce significant rain in the time it takes the air to cross the hills. The seeder-feeder mechanism involves some "seeder" rainfall falling into this orographic cloud from above. This "seeder" rain is typically generated by larger scale ascent causing condensation - often of ice by the Bergeron-Findeisen mechanism. This rainfall increases by accretion in the lower level ("feeder") cloud and results in significantly higher rainfall at the ground than would result from either the feeder rain or the seeder rain alone.

This view of the seeder-feeder mechanism is a simplified ideal which will be used for the analysis described here. In practice, however, it is likely to be complicated by a number of factors:

(a) The seeder and the feeder cloud may not be separate

(b) The seeder rainfall may be also enhanced by the orography (by locally enhancing the ascent at the higher levels).

(c) The melting level might be down in the feeder cloud. This will complicate the situation since ice processes will come into play. Advection of snow by the wind is likely to be more significant than the advection of rain due to the difference in fall speed.

(d) Advection of the rain by the wind may be significant. This is discussed below

2.2 Analysis of ideal Seeder-Feeder Effect

The simplified analysis which has been carried out takes account of three processes:

1. The condensation of vapour to form the "feeder" cloud

2. The accretion process by which rain falling from above depletes the cloud and increases itself as it falls.

3. Advection of the feeder cloud

Throughout it is assumed that the temperature is above freezing, i.e. no ice processes are included. Rain is assumed to fall vertically.

The analysis is carried out considering the lower portion of the atmosphere of height h. At the top, z=h, a prescribed, seeder, rainrate is imposed which is assumed to be a constant, P_h, in this section. Assuming the three terms described

Corresponding author: Humphrey W Lean, Met Office JCMM, Meteorology Building, University of Reading, Reading, RG6 6BB, UK

email:humphrey.lean@metoffice.com

above the variation of water cloud, q_{cl} (kg/kg), along a level, is given by

$$U\partial q_{cl} /\partial s = C – A \qquad (1)$$

Where U is the wind velocity at that level, C is the condensation rate and A is the accretion rate.

It is assumed that the air is saturated so that any ascent will cause condensation. Since the air of interest here is relatively close to the ground the ascent is initially represented simply by $U\alpha$ where α is the gradient of the orography (when it comes to matching this model with UM runs the vertical velocity is instead imposed to match that in the model). The condensation term is then simply approximated by $C_0U\alpha$ where C_0 is the condensation per m which the air is lifted. In the cases of interest this can be calculated to have a value $C_0 \approx 1.8x10^{-6}m^{-1}$.

The accretion rate is calculated by making the same assumptions as the UM mixed phase precipitation scheme (Wilson and Ballard 1999) i.e. that the rainfall drop size distribution of the rain entering the top of each level is given by a gamma distribution. Integrating over the distribution gives the simple result that $A=(dq_{cl}/dt)_{acc}=q_{cl}A_0P^{0.68}$ where we have defined $A_0=0.14\ kg^{-0.68}m^{1.36}s^{-0.32}$.

Putting these together with (1) gives

$$\partial q_{cl}/\partial s=\alpha C_0 –(q_{cl} /U)A_0P^{0.68} \qquad (2)$$

which gives the variation of q_{cl} at one level given the precipitation rate at that level, P(s,z). In general both α and P may be functions of s. The second component of the analysis is to link together the different levels by writing down how the rainrate is changed by the accretion. Considering the fluxes of rainfall leads to the following expression for the rate of change of precipitation rate with height

$$\partial P/\partial z = -\rho\, q_{cl}A_0P^{0.68} \qquad (3)$$

where $q_{cl}A_0P^{0.68}$ is the accretion rate as before and ρ is the density of air (~1 kgm^{-3})

For a given $P_h(s)$, $\alpha(s)$, $q_{cl}(0)$ and U(z) one would hope to solve equations (2) and (3) to obtain $q_{cl}(s,z)$, the cloud water distribution, and P(s,0) the surface rainfall rate. In general this has to be done numerically and this is the subject of the next section.

Some useful insight can also be obtained by considering the solution in the special case of $P_h(s)$, $\alpha(s)$ both being independent of s for s>0 – i.e. the ascent up a half infinite long upslope (where the source of moisture never runs out) starting with $q_{cl}(0)$ =0, $U(z)=U_0$. In this case it is expected that the solution will reach a steady state after a certain distance which means that the left hand side of (2) will become zero. This leads immediately to expressions for the limiting values of q_{cl} and P.

$$q_{cl\infty} = U_0\alpha C_0P^{-0.68}/A_0 \qquad (4)$$

For the precipitation rate (3) becomes $\partial P_\infty/\partial z = -U_0\alpha\rho C_0$ which may be integrated trivially to give the result

$$P_\infty(z)= P_h + U_0\alpha\rho C_0(h-z) \qquad (5)$$

In equilibrium all the moisture condensed in the layer between the level z and the top of the model, h, must come out as rainfall. In order to calculate some sample values some typical numbers (for hills in the UK) have been assumed i.e. $U_0=20ms^{-1}$,$P_h=0.5\ mmhr^{-1}$ and also $\alpha=0.02$ which corresponds to a rise of 300m over a distance of about 15km (roughly the slope of the upslope in the case described in section 3). Although the constants etc are given for SI units the quoted rainfall rate values are converted to $mmhr^{-1}$ from $kgm^{-2}s^{-1}$. In this case the equilibrium cloud water value on the top level, $q_{cl\infty}$,works out to $2.1x10^{-3}$ kg/kg. The total enhancement of rainfall from (5) in a depth of 1.5km works out to around 4.0 $mmhr^{-1}$.

2.3 Numerical Model of Ideal Seeder-Feeder Effect.

In order to solve (2) and (3) numerically the hill is divided into a number of points in the s direction (200 in the calculations presented here) and N levels in the vertical (15 at 100m intervals here). The method used is to integrate (2) along the top level (assuming q_{cl} =0 at s=0) using the prescribed values of the precipitation falling into the top of the top level P_N. Then (3) is used at each point along the level to calculate P_{N-1} . These values are then put into (2) to integrate for q_{cl} on level N-1. This procedure is repeated down the model until the surface rainrate is obtained. The model was also run assuming drift of rainfall with the horizontal wind. This results in the rain falling with a trajectory with a slope $V_0P^{0.22}/U$.

Results are shown in figs 2 and 3 for P and q_{cl} against distance using the parameter values quoted in section 2.2. Fig 2 shows the cloud water values. The top curve which is the top of the model appears to be correctly tending towards the equilibrium value described in the last section ($2.1x10^{-3}$ kg/kg). The curves in figs 2 and 3 also illustrate that the effect of including rain drift in the model is to redistribute the rainfall on scales of about 10km.

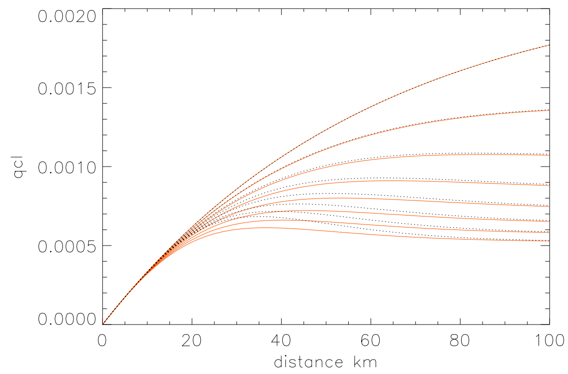

Figure 2. q_{cl} against distance from Ideal seeder-feeder model. The top curve is the values on the top of the model (1.5km) and subsequent ones going down are on the levels of the model at 100m intervals. Solid red curves assume rain falling vertically and black dotted curves are from the model including rain drift

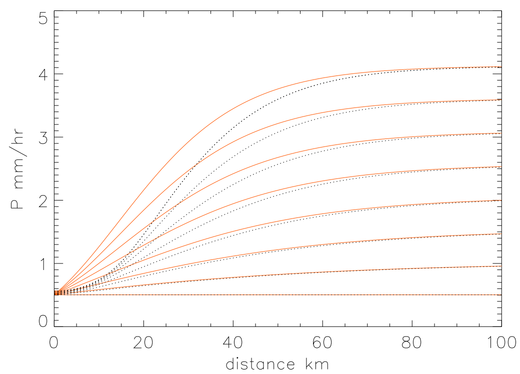

Figure 3. P against distance from Ideal seeder-feeder model. The top curve is the precipitation rates at the surface and subsequent ones going down are on the levels of the model at 100m intervals. The red dotted curves are from the model including rain drift.

It follows that this effect should be included in NWP models which have gridlengths less than this order. The current operational UM (shortest gridlength 12km) does not include rain drift but any higher resolution models in the future would need to. A prognostic rain scheme is currently under development in the Met Office Joint Centre for Mesoscale Meteorology (JCMM) and is expected to be incorporated into high resolution versions of the UM in the future.

2.4 Scale Analysis

The steady state solution for a half infinite slope presented in equations (4) and (5) above raises the issue of scale analysis to see if there is any universality about the curves on various levels. The values of q_{cl} and P may clearly be scaled by the equilibrium values given by (4) and (5). A characteristic distance scale of the problem is the distance, L, in which the condensation term alone would produce the equilibrium amount of q_{cl}. This condition may be written $L\alpha C_0 = q_{cl\infty}$. Substituting (5) into this leads to the result

$$L(z) = (U_0/A_0)P_\infty(z)^{-0.68} \qquad (6)$$

The value of L(z) varies with height. If calculated for the numbers discussed in section 2.2 it is found that L has a value of around 50km for values of the parameters typically found in the UK.

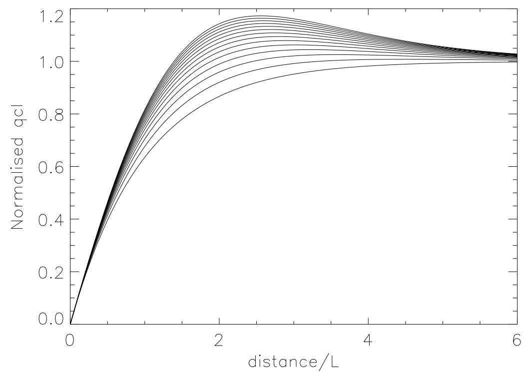

Figure 4 Normalised q curves. Axes are as described in text.

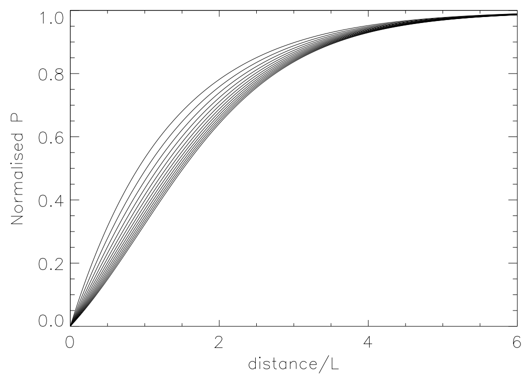

Figure 5 Normalised P curves. Axes are as described in text.

Figures 4 and 5 show q_{cl} and rainrate curves from the model described in the previous section normalised both in value ($q_{cl\infty}$ or $P_\infty(z)$) and distance (L(z)). The normalisation of the q_{cl} values has been carried out by simply dividing by $q_{cl\infty}$. In the case of rainrate there is the complication of the imposed rainrate at the top, P_h, which is added to all the rainrates produced by the seeder-feeder process. Hence the

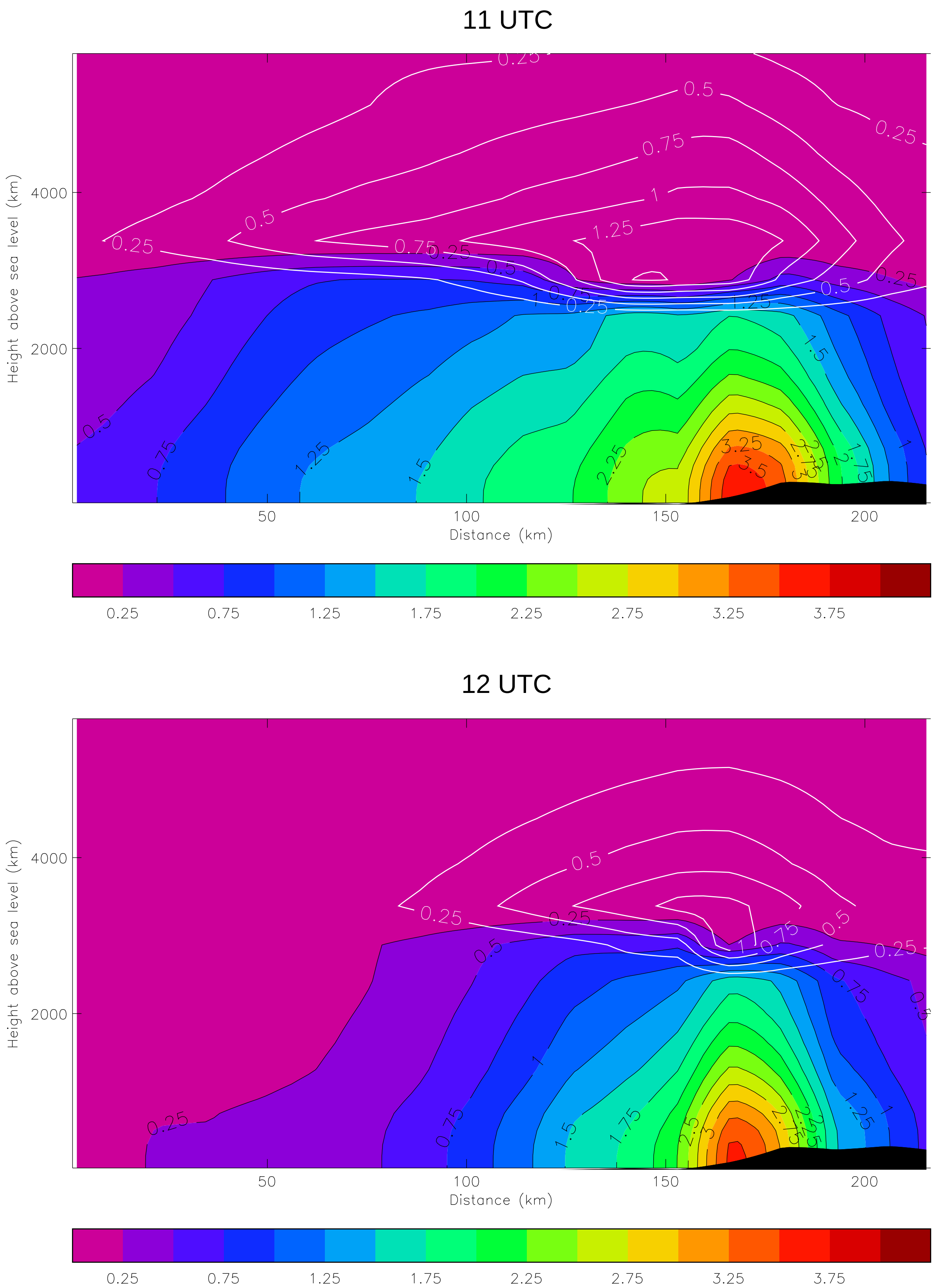

Figure 6 Along wind cross sections of rain rate (colours) and snow rates (contours) an hour apart. The cross section is perpendicular to the range of mountains which can be seen in profile at the bottom right.

normalised P plotted is $(P-P_h)/(P_\infty(z)-P_h)$. The curves which were normalised used the same numbers as previously i.e. as in figure 2 up to 100km but extended to 400km with the same value of $\alpha=0.02$. There are no "universal" curves as such in the sense that the curves don't lie on top of each other. However in all cases the curves approach 1.0 at about the same rate relative to s/L . They are, for example, within 10% of 1.0 by s/L ~3. The distance scale, L, is a useful concept representing a length scale for the seeder-feeder process to reach equilibrium.

In practice it is often of interest to consider the total precipitation produced integrated along the model along a finite upslope of length, l, with total height $l\alpha=H$. In the limit where the upslope is long compared to the equilibration length i.e. l>> L equilibrium is established and integrated rainfall along the slope is proportional to the value of P_∞ which is proportional to α and therefore H, the height of the hill. However in the other limit where l<< L then the solution becomes a linear increase in the case with no rain drift as can be seen in figure 3. The integrated rainfall along the slope then becomes proportional to $l^2\alpha$ i.e. lH which is the *volume* under the hill rather than the height. The case with no rain drift is most relevant to the results from the UM presented in section 3 but the result will be approximately valid if the rearrangement of rain due to the drift of rain is on scales much shorter than L. These two limiting cases l>>L and l<<L are very relevant to the discussion on the effects of smoothing orography in section 3.

3. RESULTS FROM UNIFIED MODEL RUNS IN SEEDER-FEEDER CASES

In this section various aspects of runs of the Met Office non-hydrostatic UM for a seeder-feeder case are briefly presented. The results presented are from a case of orographic enhancement in a warm conveyor belt flow over the South Wales mountains on 29th Nov 2001. This case was chosen because it was a simple to understand seeder-feeder case in the sense that the feeder cloud was all below the melting level so there were no complications from glaciation. (A more typical case where the melting level is down in the feeder cloud is discussed in section 3.5).

Figure 6 shows that although the general area of rain (and the maximum in the upper snowfall rate) is moving east (right in the cross sections) the area of maximum rain on the surface remains locked to the orography confirming that it is due to orographic enhancement.

3.1 Comparison of Ideal Seeder-Feeder effect with UM

In order to check that the rainfall enhancement seen in the 12km UM runs fits with the seeder-feeder effect the output from these runs was compared to output from the ideal seeder-feeder numerical model described in section 2.3. In this case the numerical model was 3km deep with 30 levels and 100 points long. An attempt was made to simulate the enhancement along the cross section taken across the mountains. The rainfall rate at the top of the model was taken from the UM run as was the vertical distribution of U and $q_{cl}(0)$, the value of q_{cl} at the inflow (left) side of the cross section. The vertical velocity was also set up to be as close as possible to that seen in the model by adjusting α taking account of the imposed values of U. This model was therefore simply a test of the enhancement due to the accretion of rainfall in the low level water cloud. The results of this comparison are shown in figure 7. The good agreement seen confirms that the orographic enhancement in the UM is largely due to the seeder-feeder effect.

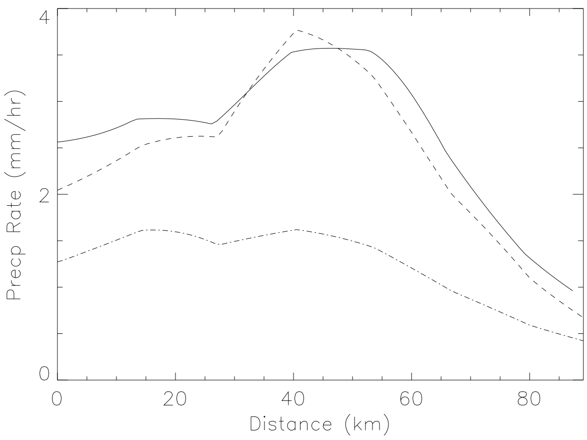

Figure 7. Comparison of UM and ideal seeder-feeder model for South Wales case at 11UTC. The cross section is along the right hand part of the section in figure 6. The solid line is the idealised model solution for the surface rainrate and the upper dotted line is the UM results for the same. The lower dotted line is the rainrate imposed at the top of the model.

3.2 Effect of Smoothing Orography

The operational non-hydrostatic UM uses orography which is smoothed in order to eliminate spurious responses to gridscale structure in the orographic data. The method of smoothing the orography is a Raymond Filter with $\varepsilon=1.0$ There has been interest from forecasters as to whether doing this reduces the amount of orographic rainfall which

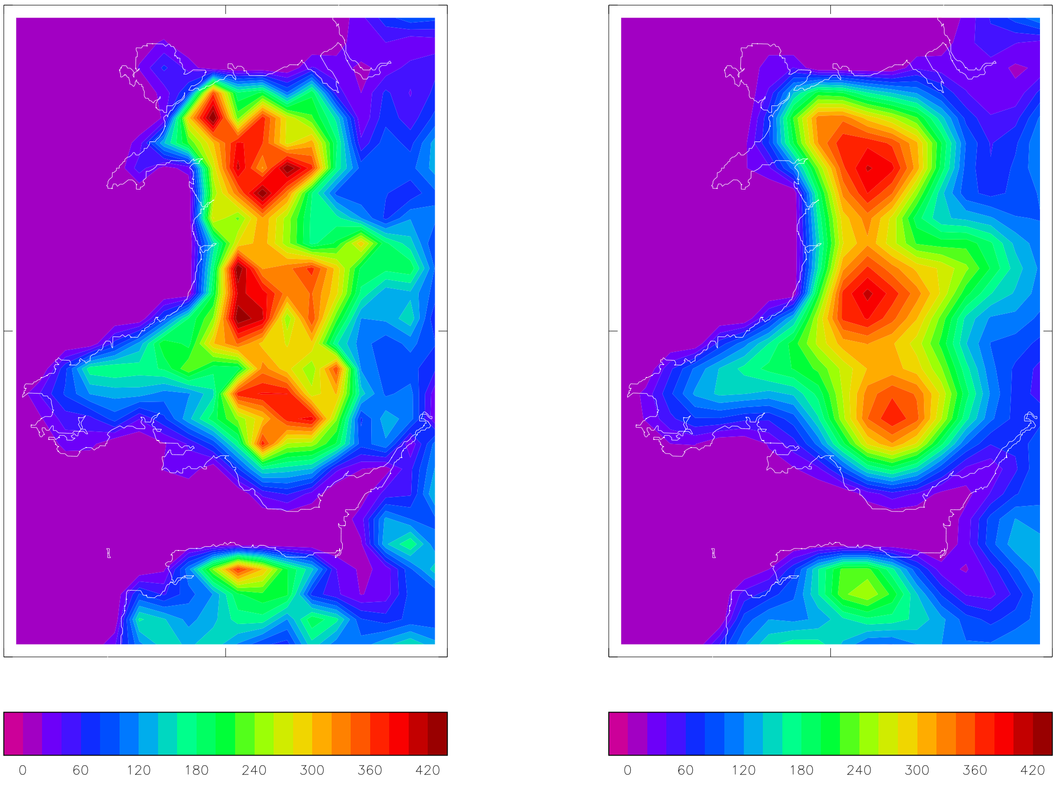

Figure 8. Comparison of unsmoothed (left) and smoothed (right) 12km model orography over Wales.

might be intuitively expected since the smoothed orography produces lower peaks.

The 12km orography over Wales with and without smoothing is shown in figure 8 and to the eye it looks very different. When the rainfall produced by models running with these two orographic datasets is compared (figure 9) it can be seen that there is very little difference between them. The hourly accumulated rainfall in the case shown over the South Wales mountains area changes by only 1.5%. There is, however, some short range redistribution of rainfall.

Similar tests have been carried out with the 60km global version of the UM. These results are not illustrated here but the mountains of South Wales are now barely resolved, being represented by one gridsquare. In this case there *is* a large change in the rainfall seen in the model when the orography is smoothed. These conclusions fit in with the scale analysis discussed in section 2.4. The characteristic length, L, for the seeder-feeder process was shown to be typically 50km. In the 12km model smoothing the orography changes it on scales shorter than L. The rainfall rate integrated along the slope would therefore be expected to be proportional to the volume under the hill which would not be changed very much. In contrast for the 60km model the smoothing will change the orography on scales longer than L and so the total rainrate will be proportional to the maximum height of the hills.

3.3 Comparison with Hydrostatic Model

A comparison has been made between the non-hydrostatic version of the UM which has been used for most of the work described here and the older hydrostatic version (which was the operational model until Aug 2002). It is found that the hydrostatic model produces around 10% less rainfall averaged over the area of the mountains than the non-hydrostatic one and moves the rainfall maximum up the slope. The moving up the slope can be explained with reference to the velocity cross sections shown in figure 10.

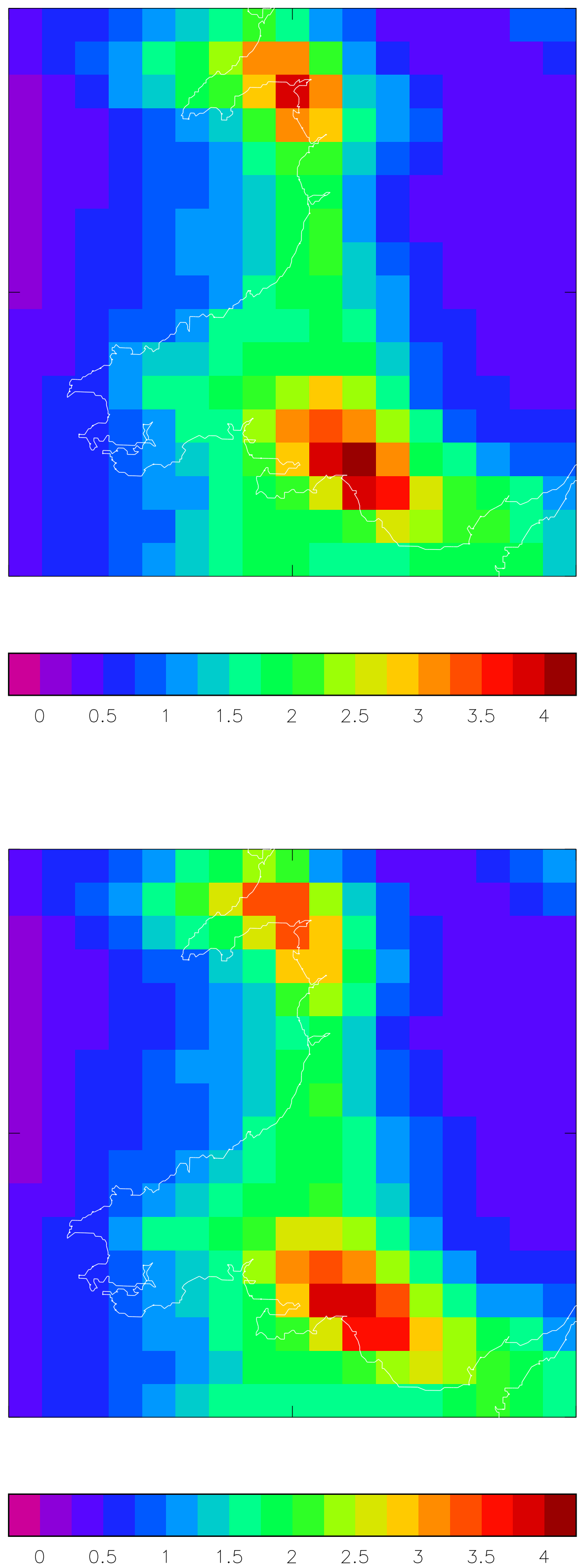

Figure 9 11-12UTC accumulated rainfall from 12km models with unsmoothed orography (top) and smoothed (bottom).

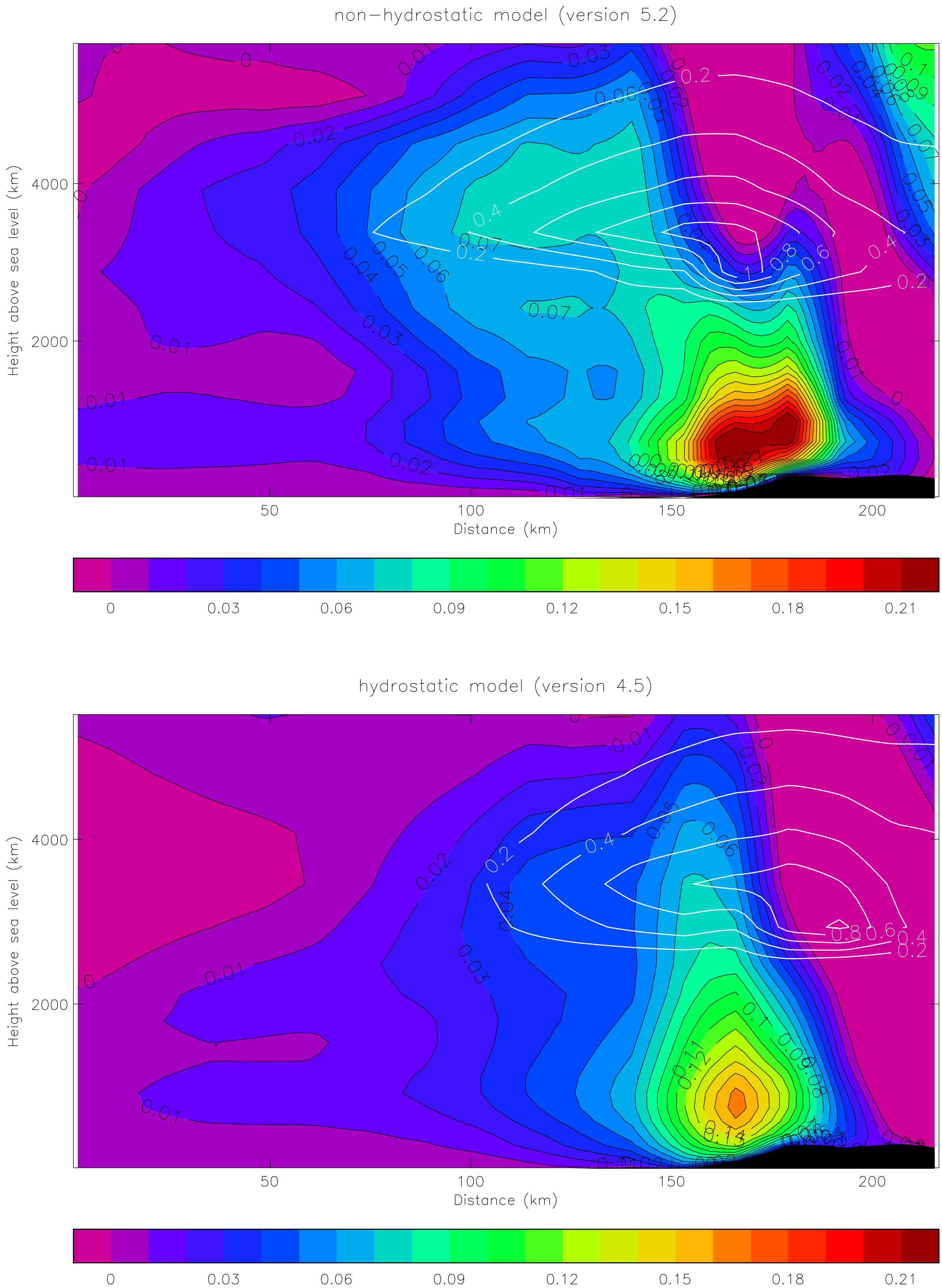

Figure 10 Cross sections of vertical velocity (colours) and snowfall rate (contours) for non-hydrostatic model (top) and hydrostatic model (lower). The cross sections were taken in the same position as in figure 6.

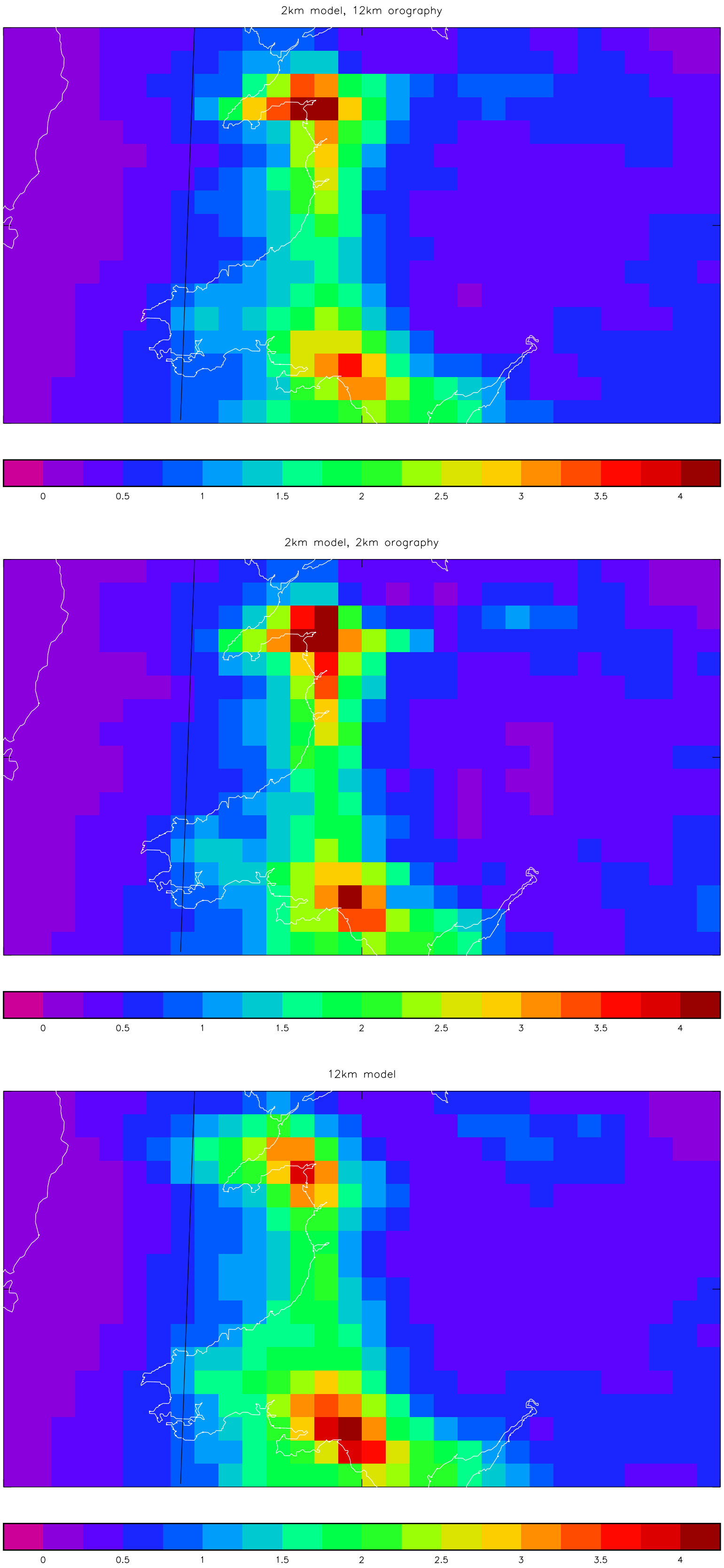

Figure 11. Comparison of 11-12UTC accumulated rainfall for 2km model with 12km orography (top), 2km model with 2km orography (centre) and 12km model (lower). The 2km model fields have been area averaged onto the 12km grid to allow comparison.

In the hydrostatic model the vertical velocity maximum produced by the hill is much less tilted with altitude than in the non-hydrostatic one. This fits in with what would be expected from a hydrostatic wave. This means that the peak in the seeder precipitation at upper levels moves up the hill which produces the shift in the maximum of the surface rainrate in the same direction. The low level rainfall maximum does not move up the hill as far as the upper level maximum due to the enhancing effect of the relatively static lower level feeder cloud. The fact that there is less rain in the hydrostatic model overall seems to be related to the fact that there is less seeder precipitation due to there being less ascent at upper levels. Perhaps unexpectedly there is *more* feeder cloud at low levels in the hydrostatic run, presumably a result of there being less seeder rain to sweep it out.

3.4 Comparison of 12km and 2km models

The work of the group at JCMM is directed towards developing high resolution (order 1km) versions of the UM for future operational NWP use. The South Wales case has been run with the non-hydrostatic model at 2km resolution. This 2km model has been run with both 12km orography and the (unsmoothed) 2km orography. The results are shown in figure 11.

The 2km runs with 12km and 2km orography produce similar results in terms of hourly accumulated rainfall although the model with 2km orography produces less rainfall averaged over the mountain areas. In the region of the South Wales mountains the difference in average rainfall between these runs is around 3%. This is about twice the difference between the runs with unsmoothed and smoothed 12km orography (section 3.2) which is consistent with the greater change in effective resolution of the orography. It should be noted that, even though the rainfall rates are quite similar examination of the vertical velocity fields shows much more wave activity in the model with 2km orography.

The comparison of the 2km and 12km models is more interesting. The 2km model produces significantly less (20%) less rain in the South Wales mountains. Even though it is not the main subject of the current study it is noticeable that the opposite is true in the North Wales mountains (i.e. the 2km model produces *more* rain). It is believed that the difference between the 12km and 2km runs are due to two factors:

1. In the 2km model the low level vertical velocity maximum which is associated with the feeder cloud is larger. This is expected because it is expected that models will attenuate features close to their gridlengths (see for example Lean (2003)). For the 12km model the main upslope of the mountains is closer to gridlength scales and so will be more attenuated. This effect will tend to make more feeder cloud and hence more rain at the surface in the 2km model.

2. In the 12km model there is likely to be some aliasing of the vertical velocity features onto the gridscale. This will tend to give more long wavelength features than in the 2km model which will therefore be expected to extend further upwards resulting in more seeder rain. This effect will therefore tend to make more rain in the 12km model.

These two effects operate in opposite directions and it is not clear what the overall effect will be. Although a detailed analysis has not been carried out it is possible that the steeper slopes in the North Wales mountains favour effect 1. over 2.

3.5 Second Case

Work has been started on a second case of orographic enhancement over Scotland on 5th March 2002. This case is more representative (but harder to analyse) in that the melting level is down in the feeder cloud. This means that in order to understand the model behaviour it is necessary to take into account aspects of the models microphysics. Work on this case is currently ongoing.

4. CONCLUSIONS AND FUTURE WORK

It has been shown that numerical and scale analysis of a simple model of the seeder-feeder effect provides useful insights which are relevant to some aspects of numerical modelling results. Results have been presented on various aspects of modelling an orographic enhancement case over South Wales which appears to be dominated by the seeder-feeder effect.

As stated in section 3.5 work is ongoing on a second case in which the seeder-feeder effect is complicated by glaciation. It is important to understand this case since it is more representative of orographic rainfall in the UK. It is hoped to also use this case to investigate the effect of changing vertical resolution.

It is also intended to start work on verification of the modelling results of orographic rainfall. It is not clear how best to do this but possibilities include climatological rain gauge data and river flow data.

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