The effect of model grid length and orographic rainfall ‘efficiency’
on computed surface rainfall

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SUMMARY

Surface rainfall distributions over North and South Wales are derived using a numerical parameterization model. Several different grid lengths are used which allow the dependence on grid length of areal rainfall produced by the model to be examined. It is found that as the grid length increases from one to ten kilometres areal rainfall totals predicted by the model decrease, in some cases quite rapidly. The areal rainfall totals also depend upon the amount of orographic enhancement operating in particular cases owing to cloud physics processes which are not parameterized in the model. A suggestion is offered as to how these processes may be taken into account in the model.

1. INTRODUCTION

The purpose of this paper is to demonstrate how the amount of orographic rainfall enhancement observed over mountainous terrain is related to surface rainfall amounts derived from versions of a numerical parameterization model using different grid lengths. In a previous paper (Collier 1975), the structure of a numerical model aimed at calculating surface rainfall over the Upper Dee area of North Wales was described. It was found, using 'actual' input data, that rainfall over the Dee catchment (≈1000 km²) could be estimated with an accuracy of ±10%; and over sub-catchments (≈100 km²) with an accuracy of about ±20% during the passage of moving baroclinic (frontal) systems for which the orographic enhancement 'efficiency' was approximately 100%. The suggestion was made that forecast input data could be used in the model, perhaps derived from a larger-scale model, such as the Bushby–Timpson 10-level model (Benwell et al. 1971), to forecast surface rainfall on a fine scale over hilly areas.

Harrold (1975) simulated a forecast environment in order to examine the performance of the model described by Collier using forecast input data derived from radio-sonde and radar data. Subsequently the model was re-run using 'actual' data to assess the degree to which various physical processes operating in a hilly area are not included in the model. The use of 'actual' rather than forecast input data was found to have little effect on the rainfall predictions, which on occasions were significantly different from the actual rainfall. These differences can be ascribed to microphysical effects, which we will now discuss.

For orographic rain to occur in any synoptic situation, it is necessary for both 'feeder' and 'seeder' clouds to be present (Bergeron 1965). The feeder clouds, formed over hills at low levels, contribute most water to the total rainfall at the surface (Browning et al. 1975). However, the droplets in these clouds are often small, and are not able to grow quickly enough in the orographic cloud to produce heavy surface rainfall. One of the ways in which orographic cloud can be seeded is from larger droplets from cloud at some higher level. The efficiency of the 'washout' from the feeder cloud depends upon the rate of precipitation from higher level (seeder) cloud, the wind component normal to the hills, and the wet-bulb potential temperature of the low-level flow (Storebo 1976; Bader and Roach 1977).

Browning et al. (1975) pointed out that the model described by Collier assumes that
in the airflow upwind of the hills there is no shortage of seeder cloud which can release precipitation from the low-level orographic feeder cloud. There is therefore no provision in the model to specify what the efficiency of the washout process for a given set of input data is likely to be. Harrold tried to overcome this limitation by linking the various meteorological phases within frontal systems (areas of rain on scales smaller than the frontal system itself) to situations in which seeder cloud was present in varying amounts. This was achieved by comparing the rainfall derived from the model with the actual rainfall over hills upwind of the area of interest. In this way, it was possible to specify the washout efficiency relevant to various meteorological phases and hence derive appropriate 'correction factors'. Identification of the meteorological phases within frontal systems upwind of N Wales (over SW Ireland), enabled correction factors to be advected downwind, and applied to the model calculations over the Upper Dee with encouraging results in a limited number of cases. However, it remains to be demonstrated how conservative these efficiency factors are.

The efficiency of precipitating systems in enhancing rainfall over hilly areas has been examined observationally by Browning et al. (1975) and numerically by Bader and Roach (and by Storebro). We have examined several of the case studies considered by Browning and his co-workers over South Wales using the parameterization model referred to above, with a topographic data set covering the hilly area of South Wales. For these cases, therefore, efficiency factors have been derived independently, ranging from 0·1 to 0·7, and, together with a case for North Wales, they have been used to assess the dependence of model rainfall on efficiency and on grid length.

The efficiency factors are derived using the method described by Browning et al. (1975), that is: efficiency of the orographic rainfall process = \( E_1 E_2 = W/C \), where \( E_1 \) is the true efficiency as influenced by microphysical parameters such as the existence of a sufficient number of suitable seeding particles, and \( E_2 \) is a factor that takes into account any lack of saturation in the initial flow at low levels upwind of the hills. \( W \) is the volume of water reaching the ground per unit time per unit width within sections enclosing the entire mountain area, and is given by

\[
W = \int_{-x_0}^{x=0} R \, dx,
\]

where \( R \) is the orographic component of rainfall, \( x \) is the distance from the mountain crest within the sections considered, and \( x_0 \) is the location where orographic effects first become apparent. \( C \), the orographically induced rate of condensation, is evaluated from \( C = \Sigma C_z = \Sigma U_z H_z \), where the summation is over a number of layers (usually three) in the lower atmosphere within which condensation occurs, up to a height of 3 km. \( C_z \) is the volume of water condensed per unit time per unit width in a layer centred at height \( z \); \( U_z \) is the depth of water condensed, assuming the airflow is initially saturated and follows the average outline of the orography. It is assumed that condensation below 3 km gave rise to most of the rain that reached the ground upwind of the mountain crest (see Browning et al. 1975).

2. Results

Fig. 1 illustrates the dependence of areal rainfall amounts derived from the numerical parameterization model on grid length and efficiency. As the grid length is increased the rainfall derived from the model decreases. A series of curves is shown in the figure for different orographic efficiencies, \( E \).

The low-level vertical velocities generated by flow over steep topography depend
largely upon the strength of the flow and the steepness of the topography. Since the model attempts to estimate the vertical velocity profile over hilly terrain, a change of grid length has the effect of smoothing the topography, resulting in smaller ‘upslope’ motion. Hence as the grid length is decreased the vertical motion is better represented in the model for those cases in which most of the rainfall is of an orographic nature. Therefore for these cases model rainfall amounts become more realistic as the grid length decreases. A point should be reached beyond which the grid length is too small to allow vertical motion to be derived adequately, as the assumption that the airflow follows the average outline of the orography becomes inappropriate. The present results suggest that the minimum grid length is less than one kilometre, and a grid length of one kilometre allows estimates of the vertical motion which enable areal rainfall amounts to be derived quite accurately over North Wales.

For those cases which are inefficient in producing orographic rainfall, vertical motion at low levels may still be large and dependent on the grid length. However, the lack of precipitation from the seeder cloud referred to in section 1 does not enable heavy orographic rainfall to occur. Since the model does not allow for this, areal rainfall totals are overestimated by amounts proportional to the efficiency, if a grid length of one kilometre is
Figure 2. Illustrating (a): the rainfall distribution in mm over North Wales derived using the numerical model with a one-kilometre grid length for 14 August 1974, 1100–1200 z;

Figure 2(b): the same as (a) but using a grid length of two kilometres;
used, for which the vertical velocities are realistically represented. Therefore, using a grid length of one kilometre, it is possible to derive the actual rainfall by multiplying the model rainfall by the efficiency factor as described by Harrold. However, as the grid length is increased this ceases to be possible.

Figure 2(a) gives an example of an hourly rainfall field over North Wales derived using the numerical model with a one-kilometre grid length and actual data. The corresponding rainfall field using a two-kilometre grid length is shown in Fig. 2(b), and in Fig. 2(c) the actual rainfall field observed by the C-band radar at Llandegla (position shown by the letter L in the figure) is given. A one-kilometre grid length gives a rainfall field which is similar to the actual field, whereas the two-kilometre grid length, while retaining certain characteristics of the actual field, is somewhat different. The accuracy of areal radar rainfall measurements calibrated using a small number of raingauges has been compared with the measurements obtained from networks of raingauges with various densities by Collier et al. (1975). Over large areas the calibrated radar measurements were found to be more accurate than measurements obtained using raingauges only, and therefore the actual rainfall has been specified using radar data in the present study.

3. Discussion

The results displayed in Fig. 1 suggest that it may be possible to use the numerical parameterization model discussed by Collier to forecast rainfall over a hilly area, provided that the efficiency of the precipitating system can be specified, and a model grid length of
one kilometre (possibly two kilometres) is used. For this particular model, the rainfall fields derived using larger grid lengths differ markedly from the observed rainfall distributions. However, it is not easy to specify the efficiency of precipitating systems, and much research is required to examine the extent to which this may be done.

Two approaches to the problem of deriving the efficiency are possible: one based on calibration of the rainfall field derived from the model using the actual rainfall field over a hilly area upwind of the area of interest; and the other based on the results of numerical calculations. The former method has been described by Harrold (see section 1), but it depends upon the air moving over the area of interest from a hilly area upwind over which quantitative radar data are available. It also assumes that the correction factors, obtained by comparison of the model-derived rainfall with the radar rainfall upwind of the area of interest, may be associated with the efficiency of the precipitating system. The numerical model would require the rainfall field upwind of the hills to be specified, possibly at different elevations of the radar beam, using a quantitative radar network, but not necessarily over a hilly area. These data would be used in a numerical model of the cloud physics processes involved in the orographic rainfall enhancement mechanism. The rainfall rate from mid-level (seeder) cloud upwind of the hills may then be related to the large-scale topographic gradient, wind speed, wet-bulb potential temperature over the hills and upwind relative humidity, to derive the efficiency as described by Bader and Roach (1977).

The latter method is untested at the present time, although the results described by Bader and Roach are encouraging. A great deal of further work is required to ascertain the extent to which efficiency factors may be predicted and advected with a system's motion. The ability to predict the efficiency of a precipitating system may prove to be the limiting factor in the application of the type of small-scale model referred to in this paper.

4. Conclusion

The numerical parameterization model referred to in this paper may be capable of providing rainfall forecasts over areas of 100 km², if a grid length of one or two kilometres is used, and the ‘efficiency’ of a precipitating system specified. It may prove possible to derive the latter input using a numerical model of the orographic rainfall enhancement process, together with the quantitative rainfall data provided by a network of weather radars.

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