A three-dimensional model of airflow and orographic rainfall enhancement

By A. J. DORE and T. W. CHoularton

Department of Pure and Applied Physics, University of Manchester Institute of Science and Technology, Manchester M60 1QD

(Received 20 March 1991; revised 28 May 1992)

SUMMARY

A three-dimensional model of airflow over hills has been used in conjunction with a two-dimensional model of orographic rainfall enhancement. This development has allowed the accurate production of rainfall contour maps in areas of complex terrain. A comparison has been made, using a variety of atmospheric stability profiles, between the wind fields and rainfall distributions over a bell-shaped hill and those over a two dimensional ridge of similar height. The results show that, in conditions of either stably stratified air or with an inversion layer aloft, three-dimensional airflow effects can lead to much reduced rainfall over a bell-shaped hill. It is shown that in such situations the use of a two-dimensional approximation can introduce significant errors. An example is presented of the rainfall distribution in complex hill terrain over south Kintyre on the western coast of Scotland.

1. INTRODUCTION

It is well known that hilly or mountainous terrain in maritime regions is commonly shrouded in cloud. In mid-latitude areas, localized hill cap clouds are orographically generated by the forced ascent, and subsequent condensation, of moist low-level air as it flows over hills. The occurrence of cap clouds frequently coincides with the passage of frontal rainfall systems when low-level air tends to have high humidity. In such circumstances it has been observed that rainfall rates over hilly ground are significantly greater than over the surrounding low-level ground. A mechanism to explain this phenomenon was originally proposed by Bergeron (1965). He suggested that 'seeder' rain falling from high altitudes was sweeping out the 'feeder' cap-cloud particles. As the raindrops fell through the cap cloud they grew by accreting cloud drops.

Following Bergeron’s theory a number of numerical experiments were performed to represent the seeder–feeder effect. Storebo (1976) calculated rainfall enhancement by scaling the enhancement from a 100 m vertical cap-cloud layer linearly through the depth of the feeder cloud. This scheme, however, did not account for the variation of rainfall enhancement with height. This occurs partly because of the non-linear variation of saturation vapour pressure with temperature and also because air trajectories at higher altitudes are less perturbed by the presence of hills. The model of Bader and Roach
(1977) was used to calculate orographic rainfall over the hills of south Wales. They assumed that streamlines in the feeder cloud were parallel to the hill surface. This could cause an over-estimate of the updraught near the top of the feeder cloud. In addition it was assumed that raindrops fell vertically. However, in reality, the effects of raindrop wind drift can be very significant. For example a 0.7 mm radius raindrop in a 20 m s⁻¹ wind would drift approximately 8 km horizontally whilst falling through a feeder cloud of depth 2 km. The model of Carruthers and Choularton (1983) was based on a similar approach to that used by Bader and Roach. This avoided detailed microphysical modelling of the feeder cloud but included a number of important improvements. A three-layer model of stratified airflow over hills (Carruthers and Choularton 1982) was used to calculate the wind field. Also the important effects of wind drift were incorporated into the model.

More recently Richard et al. (1987) used a two-dimensional (2-D) mesoscale model with parametrized microphysics to represent the seeder–feeder effect over a hill plateau. The rainfall enhancement was found to be insensitive to both the feeder cloud droplet-size distribution and the mean seeding raindrop size. Alpert and Shafir (1989) used a simple model that incorporated a parametrization of the microphysics and calculated orographic precipitation from the convergence of moisture through the boundary layer. This was found to be adequate to calculate the distribution of annual rainfall over the Judean and Galilean mountains, though it was of limited application for representing individual case studies.

Radar and rain-gauge studies of orographic rain over the hills of south Wales have been conducted by Hill et al. (1981). The results indicated that over 80% of the enhancement occurred in the lowest 1.5 km above the hills. It was found that large rainfall enhancements were associated with strong low-level winds. These results are supported by the model studies of Robichaud and Austin (1988) which included detailed treatment of wind shear. They found that rainfall enhancement was much increased in the presence of a strong low-level jet. Other field studies of the seeder–feeder effect have been conducted by Fowler et al. (1988) and Dore et al. (1990). Fowler et al. collected rainfall samples at a hill site in Cumbria. It was found that a rise in altitude of 600 m, from the base to the summit of the hill, was typically accompanied by a doubling in rainfall.

The models mentioned above are based on a 2-D approximation. The restriction of such methods is that they do not allow the occurrence of airflow around hills. In the case of a ridge-shaped hill, the 2-D approach works very well for modelling rainfall along a trajectory perpendicular to the ridge. However, for conical hills three-dimensional (3-D) airflow around the hill can be important, particularly in the case of low wind speeds and stably stratified air. In such circumstances, a 2-D model is prone to over-estimate the magnitude of the updraughts upwind of the hill summit, leading to an over-prediction of rainfall enhancement. The use of a 3-D model is therefore appropriate for conical hills, and also for producing 2-D maps of ground-level rainfall and pollutant deposition in areas of complex and irregular terrain. A 3-D model of airflow over hills of moderate slope has been used (Carruthers et al. 1989). The orographic-rain-enhancement model of Carruthers and Choularton (1983) was incorporated into the airflow model. Comparisons are presented between the predictions of wind speed, rainfall and ion deposition for the 2-D and 3-D airflow cases. The effect which airflow around hills introduces to rainfall enhancement and wet deposition of pollutants has been analysed. A simple 3-D bell-shaped hill has been used with the rainfall model to produce maps of rainfall rate and ion deposition rate. South Kintyre on the western coast of Scotland has been used as an example of how the model is capable of calculating rainfall over arbitrary terrain.
2. THE MODEL

(a) Airflow model

To calculate a solution for airflow over hills, the airflow model divides the lower atmosphere into three layers: in the inner layer, which is closest to the ground, shear stresses are important. For the surface roughness and hill width used in this study, the depth of the inner layer is approximately 100 m. This layer is, therefore, not relevant to rainfall studies as wind speeds in the model are calculated at higher altitudes. The middle layer is sufficiently high above ground that shear stresses are unimportant. However, in this layer the effects of shear are significant. The upper layer contains the outer part of the turbulent boundary layer and part of the non-turbulent, free atmosphere. In this layer stratification effects are important, but shear and perturbation stresses are not significant. In the upper layer the equations for inviscid stratified flow are solved in three dimensions. The vertical wind speed, \( w \), is calculated from the solution of Eq. (1), using an upper radiative boundary condition. Stratification in the upper layer generates a pressure field which affects flow in the two lower layers. \( N \) is the buoyancy frequency and \( U \) is the horizontal wind velocity.

\[
\frac{\partial^2}{\partial x^2} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) w + \frac{N^2}{U^2} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) w = 0.
\]  

(1)

The unperturbed horizontal wind velocity \( U(z) \) is calculated as a function of height, \( z \), from Eq. (2).

\[
U(z) = \frac{U_*}{k} \ln \left( \frac{z}{z_0} \right)
\]

(2)

where \( k = 0.4 \) and \( U_* \) is the friction velocity, taken to be 0.7 m s\(^{-1}\) for the examples presented here. \( z_0 \) is the roughness length, typically of the order 2 cm over grassland. The model calculates the three components of wind speed at all points on a 3-D grid consisting of 64 grid elements in the \( x \) and \( y \) directions and eight elements in the vertical. Grid points \( x \) and \( y \) were separated by 400 m, with 250 m between \( z \) grid points. Wind velocity was, therefore, calculated up to a height of 2 km, representing the top of the feeder cloud.

The model, by using a method of Fourier transform and numerical inversion, is capable of calculating the airflow regime over any arbitrary topography, provided the hills are of moderate slope (less than approximately 1 in 4). The mathematical methods employed in solving the equations describing airflow are explained in detail by Hunt et al. (1988).

(b) Rainfall model

The model of the seeder-feeder effect is based on the original model of Carruthers and Choularton (1983). This incorporates the Marshall–Palmer raindrop size distribution (Marshall and Palmer 1948) and empirical equations for raindrop terminal velocity and collection efficiency of cloud droplets. A steady-state system is envisaged where the feeder cloud is continually being washed out by constant predetermined rainfall from above. The depletion of liquid water from the feeder cloud is offset by a continual supply of saturated moist air that condenses out when orographic uplift occurs. The feeder cloud was represented by a 2-D grid with a horizontal spacing of 400 m, and typically 250 m (depending on local cloud depth) in the vertical. The model calculates the horizontal drift of raindrops and the evaporation of raindrops in dry air that can occur to the lee of a hill. An aerosol loading of sulphate was put into the model. It is assumed that these
aerosol particles are efficiently nucleation-scavenged when cloud forms. Two-dimensional maps of rainfall rate and sulphate deposition rate were constructed by calculating the rainfall along a series of streamline-following trajectories. By considering the transverse component of wind, the drift of raindrops in a direction perpendicular to the geostrophic wind was calculated. It was, therefore, possible to calculate accurately in three dimensions the trajectory of a raindrop falling to ground through a cap cloud. This contrasts with a 2-D model where wind drift of raindrops is only allowed in the direction of the geostrophic wind. The rainfall-model input parameters, used for all the model calculations presented here, are listed below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of feeder cloud</td>
<td>2000 m</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>10 °C</td>
</tr>
<tr>
<td>Surface pressure</td>
<td>1000 mb</td>
</tr>
<tr>
<td>Seeding rainfall rate</td>
<td>2.0 mm h⁻¹</td>
</tr>
<tr>
<td>Sulphate aerosol loading</td>
<td>3.0 µg m⁻³</td>
</tr>
<tr>
<td>Sulphate concentration of seeder rain</td>
<td>30 µM l⁻¹</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

(a) Comparison between different air stability profiles

To investigate the influence of 3-D airflow on the seeder–feeder effect, the wind field was calculated over a 3-D bell-shaped hill. The hill had a height \( H = 700 \) m and half-width at half height \( L \) of 2.5 km. The hill formula is described by Eq. (3):

\[
z = \frac{H}{1 + \frac{x^2 + y^2}{L^2}}. \tag{3}
\]

For a layer of atmosphere with a potential temperature gradient of \( \frac{d\theta}{dz} \) and mean potential temperature \( \theta_i \), the buoyancy frequency of the air is defined as:

\[
N_i = \left( \frac{g}{\theta_i} \frac{d\theta}{dz} \right)^\frac{1}{2}. \tag{4}
\]

where \( g \) is the gravitational acceleration. The stability of the air is defined by the Scorer parameter:

\[
\mu_i = \frac{N_i}{U_i} \tag{5}
\]

where \( U_i \) is the horizontal wind speed in the layer. For a hill of height \( H \), the surface Froude number may be defined as:

\[
F = \frac{1}{\mu_i H}. \tag{6}
\]

The results of the airflow and rainfall calculations over the bell-shaped hill were compared with those for a 2-D ridge-shaped hill of height 700 m and half-width 2.5 km. Calculations were performed for the two hills using a variety of different atmospheric stability profiles. Firstly, the case of flow with neutral stability was considered. This was compared with conditions of a uniform stable stratification. A buoyancy frequency of \( 6.0 \times 10^{-3} \text{s}^{-1} \), corresponding to a potential temperature gradient of 1 degC km⁻¹, was used. Assuming a surface wind speed of approximately 15 m s⁻¹, with this stability and
for a hill of height 700 m, the surface Froude number is 3.6. The third case involved a lower layer of neutral stability capped by a weak inversion at 1200 m altitude. The inversion consisted of a discontinuity in potential temperature of 3 degC and a uniform stable stratification in the upper layer with a buoyancy frequency of $4.0 \times 10^{-3}$ s$^{-1}$. Such stratification is typical of frontal rainfall conditions. The buoyancy frequencies used in the model for this study are based on the values calculated by Dore et al. (1990, 1992) from radiosonde data in frontal rainfall. Other authors, for example Thorpe and Clough (1991), however, have reported somewhat higher stabilities in conditions of frontal rainfall. The trajectory passing along the central axis of the hill parallel to the wind direction was chosen for analysis.

Figures 1 to 3 show the streamline heights of airflow and the distribution of rainfall across the hill for the six case studies. It is evident from Fig. 1 that flow in the lower layer of the feeder cloud (approximately 200 m above ground) is relatively insensitive to the stability profile. Furthermore, for both the neutral and stably stratified conditions, flow is similar over the two different hills, with air being forced only marginally higher over the 2-D ridge. For the inversion layer there is a significant difference between the flow patterns over the two hills. The inversion suppresses flow over the top of the conical hill, causing significant flow around the hill and a smaller orographic ascent. In the upper layer of the feeder cloud (1125 m above ground), flow patterns reveal a greater dependence on hill shape and stability, as shown in Fig. 2. At the higher altitude, the flow shows a relatively small dependence on hill shape in conditions of neutral stability. With stably stratified air, the ridge-shaped hill forces air at high altitude to rise 100 m more than the conical hill does. This difference is particularly large when the inversion layer is present. Under these conditions, the ridge-shaped hill causes a perturbation of

![Figure 1](image_url)

**Figure 1.** Streamlines of low-level airflow across the central axis of the hill. Curve 1: neutral stability, ridge-shaped hill; 2: neutral stability, bell-shaped hill; 3: stable stratification, ridge-shaped hill; 4: stable stratification, bell-shaped hill; 5: inversion layer, ridge-shaped hill; and 6: inversion layer, bell-shaped hill. (The lower plot represents the hill surface.)
Figure 2. As Fig. 1 but for upper-level airflow.

Figure 3. Rainfall rate across the central axis of the hill. Curves 1–6 as in Fig. 1.
660 m to the streamline altitude whereas the bell-shaped hill results in a rise of only 280 m. Under stably stratified conditions, the strong downdraughts occurring on the lee side of the hill are evidence of supercritical flow. In the event of the occurrence of much higher stabilities than those used in these studies, or of very low wind speeds, conditions may occur when the surface Froude number $F < 1$. In this case, low-level air would be blocked by the presence of a ridge and forced to flow around, rather than over, a conical hill. In both cases, this would suppress the seeder–feeder effect.

To illustrate the dependence of rainfall enhancement on air stability, the model has been used to calculate rainfall under conditions of a single stably stratified layer using a variety of different buoyancy frequencies. Figure 4 shows peak rainfall rate as a function of buoyancy frequency for both the conical hill and the ridge-shaped hill. As expected, rainfall enhancement is consistently higher over the ridge-shaped hill. The difference between rainfall enhancement over the two hills is most significant with higher stabilities, when 3-D airflow effects are more prominent. Both graphs show a peak at a critical buoyancy frequency. For the ridge-shaped hill this occurs at approximately $6 \times 10^{-3}$ s$^{-1}$. Taking the wind speed to be 16 m s$^{-1}$, this gives an air stability of $3.75 \times 10^{-4}$ m$^{-1}$ which corresponds to a stability scale length of $(1/\mu_s)$ equal to 2.7 km. This resonant length is approximately the same as the half-width of the hill, 2.5 km, and represents the critical stability at which air will undergo maximum vertical displacement owing to the presence of a hill with this half-width. The resonant buoyancy frequency for the conical hill is about 10% lower than that for the ridge.

The vertical displacement of air as it flows over a hill determines the liquid water content in a cap cloud formed when orographic ascent occurs. With greater liquid water content, larger cloud droplets are formed and cloud-droplet scavenging by raindrops results in heavier rainfall enhancement. As shown in Fig. 3, the peak rainfall rates are therefore closely tied to the values of vertical displacement of the air induced by the

![Figure 4. Peak rainfall rate as a function of the air buoyancy frequency using a single stably stratified layer.](image-url)
presence of a hill. Thus there is a small difference in peak rainfall for neutral-stability conditions (5.0 mm h\(^{-1}\) for the ridge-shaped and 4.4 mm h\(^{-1}\) for the bell-shaped hill) and a greater difference with stable stratification (7.1 mm h\(^{-1}\) for the ridge-shaped and 5.7 mm h\(^{-1}\) for the bell-shaped hill). With the inversion layer present, the differences between the results for the two different hill shapes are large (6.9 and 4.1 mm h\(^{-1}\)). The strong tendency of the inversion layer to force air to flow around a conical hill is in part due to the inversion itself and in part due to the stable stratification present above the inversion. This can be illustrated by comparison with a case study including an identical inversion but with neutral stability both below and above. This shows less difference in streamline displacement and rainfall enhancement (5.9 mm h\(^{-1}\) and 4.9 mm h\(^{-1}\)) over the two hills. The heavier rainfall enhancement occurring over the ridge-shaped hill also resulted in higher peak values of the sulphate deposition due to rainfall. Peak deposition was higher over the ridge-shaped hill by fractions of 6.0% with neutral stability, 5.6% with stable stratification and 23.8% with the inversion layer.

The strong dependence of airflow and rainfall patterns over a conical hill on the atmospheric stability stratification leads to the question of which scenario is most representative of conditions conducive to rainfall. Examination of UK radiosonde ascents made during rainy conditions reveals that whilst a neutrally stable atmosphere is a rare occurrence, the presence of an inversion layer is a relatively common feature. The effects of potential instability release are not included in this model. In certain conditions, as discussed by Browning \textit{et al.} (1974), the triggering of low-level convection may occur as air flows over a hill. This can result in more pronounced vertical motion of air near the hill summit and cause the formation of new mesoscale precipitation areas in the middle levels.

During prolonged frontal rainfall, the evaporation of raindrops in undersaturated boundary-layer air can result in a cooling and stabilizing of air at low altitudes. However, in conditions of frontal rainfall, strong winds of about 15 to 20 m s\(^{-1}\) are common. Conditions, therefore, in which the surface Froude number (calculated from boundary-layer stability and hill height) is less than unity will be rare. These observations suggest that rainfall is most likely to occur in conditions when 3-D airflow effects will be significant.

\textbf{(b) Case study of airflow and rainfall with a uniform stably stratified atmosphere}

The case of stably stratified air has been selected for a more detailed analysis. Graphs of horizontal and vertical wind speed, sulphate concentration in rain, and sulphate deposition rate for both hills are shown in Figs. 5–8. Similar horizontal wind speeds across the two different hills are evident with slightly greater speed up over the ridge, as shown in Fig. 5. The graphs of wind speed represent flow in the lowest layer (altitude 125 m) and a mid-cloud layer (altitude 1125 m). Because of airflow round the hill, the bell-shaped hill caused less vertical perturbation to the flow than the ridge-shaped hill. This is reflected in the vertical wind velocities (Fig. 6) where the updraughts above the hill summit are lower for the bell-shaped hill in the upper layer. In the lowest layer, however, the airflow is strongly perturbed by the hill and similar updraughts were predicted for both the ridge and the bell-shaped hill. The effect of air flowing around the hill made a significant difference to the generation of the feeder cloud. For the ridge-shaped hill, the forced ascent of air generated a feeder cloud with high liquid water content and the rainfall rate was enhanced to 7.1 mm h\(^{-1}\). For the bell-shaped hill, less liquid water content was generated and the peak rainfall rate was only 5.7 mm h\(^{-1}\). Figure 7 shows the concentration of sulphate in rainfall. The graphs peak significantly upwind of the hill summit owing to the scavenging of highly concentrated cloud droplets that
Figure 5. Horizontal wind speeds at heights 125 m (layer 1) and 1125 m (layer 5) for both the ridge-shaped and bell-shaped hills with a stably stratified atmosphere.

Figure 6. As Fig. 5, but for vertical wind speeds.
Figure 7. Sulphate concentration in rainfall for both the bell-shaped and ridge-shaped hills with a stably stratified atmosphere.

Figure 8. Sulphate deposition rate for both the bell-shaped and ridge-shaped hills with a stably stratified atmosphere.
occur near the cloud base where liquid water content is low. Above the hill summit, liquid water contents are higher and feeder-cloud concentrations lower so rainfall is less polluted at ground level. The ion deposition rate was slightly higher over the ridge-shaped hill, peaking at 22.6 mg m\(^{-2}\) h\(^{-1}\), compared with the bell-shaped hill where the maximum was 21.4 mg m\(^{-2}\) h\(^{-1}\) (Fig. 8). The broad peaks in the sulphate deposition graphs reflect the fact that the peaks in rainfall and sulphate concentration do not coincide.

In this case it has been shown that a 2-D model would over-estimate the peak rainfall rate over a conical hill by 25% and the peak sulphate deposition rate by 6%. However, the discrepancies introduced by the 2-D approximation are clearly a strong function of the hill shape and air stability. The rainfall rates, ion concentrations in rain, and ion deposition rates for the whole of the 3-D hill domain are illustrated by contour plots in Figs. 9 to 11 respectively. It is evident from the rainfall plot that, along trajectories crossing the hill away from the summit, the rainfall rate peaks further downwind than along the central axis. For example, along the y = 0 km axis the maximum occurs at x = 0.6 km whereas for the y = 3.4 km axis the maximum occurs at x = 2.2 km. This illustrates that the gentler hill slopes away from the central x-axis start to generate feeder cloud further downwind than the steep slopes near the central axis. Evaporation of raindrops starts at x = 10.2 km on the central axis of the hill where the rainfall rate falls below 2.0 mm h\(^{-1}\). This is due to the large depletion of liquid water content from the cap cloud as it passes over the hill summit, resulting in drier, unsaturated air on the lee side of the hill. Evaporation does not occur along the trajectories which pass to the side of the hill summit as cloud washout is not sufficient to reduce the relative humidity of the air significantly on the lee side of the hill.

![Rainfall rate contour](image-url)
Figure 10. Sulphate concentration in rainfall (µM L⁻¹) over the bell-shaped hill with a stably stratified atmosphere.

Figure 11. Sulphate deposition rate (mg m⁻² h⁻¹) over the bell-shaped hill with a stably stratified atmosphere.
An interesting feature of Fig. 10 is that the maximum value of ion concentration in rain occurs at \( x = 3.8 \) km, \( y = 6.6 \) km. The peak value is \( 80 \mu \text{M} \text{L}^{-1} \) which compares with a maximum of \( 69 \mu \text{M} \text{L}^{-1} \) along the \( y = 0 \) axis. This is due to the high ion concentration in the thin cloud formed along trajectories passing to the side of the hill summit. The low altitude of the hill along this trajectory means that the cloud liquid water content remains low as air flows over the hill. The steep gradient of ion concentration in the \( y \) direction at \( x = 4 \) km, \( y = 8 \) km signifies that the hill perturbation at this point is only just sufficient to cause formation of a feeder cloud. As shown in Fig. 11, the ion deposition rate peaks at \( 21.4 \text{ mg m}^{-2} \text{h}^{-1} \) \( 2 \) km upwind of the hill summit, an enhancement factor of 3.7 relative to deposition from seeder rain. It was found that the transverse drift of raindrops did not greatly alter the rainfall pattern. Transverse wind speeds were greater in the layers nearer to the ground where the hill causes a greater perturbation to airflow. The transverse wind speeds close to the ground and on the steep part of the hill were generally less than \( 1 \text{ m s}^{-1} \). This contributed to lateral drift of raindrops during their fall to ground, which was not greater than \( 200 \) m.

The primary importance of the 3-D rainfall model is that it may be used to calculate the rainfall distribution over any arbitrary area of terrain and requires only gridded data of the terrain altitude and surface roughness. Because of the restrictions of computer memory storage for an IBM compatible personal computer, the largest grid size which the airflow model may practically use contains about 60 elements in the \( x \) and \( y \) directions. For typical complex hill terrain, the maximum acceptable size of a horizontal grid element is approximately \( 400 \) m. Above this value, errors may be introduced due to inaccurate representation of the hill terrain, and imprecise calculations of horizontal raindrop drift. The model can therefore be used to calculate the rainfall distribution in areas with dimensions of up to approximately \( 25 \) km.

(c) Case study of rainfall distribution over the hills of south Kintyre with a uniform stably stratified atmosphere

Figure 12 shows a contour map of south Kintyre in Scotland. The area is bordered by sea to the west, south and east and contains a range of hills, the tallest of which are about \( 400 \) m and located to the east. The model was run across this terrain with identical input parameters to those used for the previous case studies and the stable stratification profile. The wind direction, along the positive \( x \)-axis, represents a westerly flow which is fairly typical of conditions in this area. The rainfall plot is shown in Fig. 13. As the hills in this area are lower than the bell-shaped hill used above, the cloud liquid water contents generated by orographic uplift are lower and less rainfall enhancement occurred. The areas of highest rainfall are located close to the east coast. Figure 14 shows the plot of the sulphate deposition rate. As with the rainfall plot, peak deposition occurs close to the coast. This suggests that in conditions of higher wind speeds the air pollution captured by the seeder–feeder effect might be blown clear of the land and deposited primarily in the sea.

4. Conclusion

The 3-D airflow model was used with the model of orographic rain enhancement to calculate the rainfall rate and deposition of sulphate over a 3-D hill. A comparison with the 2-D case showed that 3-D airflow effects can be very significant to the seeder–feeder effect. For the cases examined, the 2-D model over-estimated the rainfall rate by \( 14-68\% \) and the ion deposition rate by \( 6-24\% \). This discrepancy will be particularly significant when considering rain enhancement over steep conical hills with low wind speeds and
Figure 12. The hill terrain altitude (m) of south Kintyre.

Figure 13. Rainfall rate (mm h⁻¹) over Kintyre.
highly stable air. It was found that 3-D airflow effects were particularly prominent in the presence of an upper-layer inversion. For high wind speeds and neutrally stable air, however, air tends to flow over hills rather than around them. In such conditions, or for airflow perpendicular to a ridge-shaped hill, a 2-D model is adequate. The results showed that high concentrations of ions in rainfall can occur where air is flowing around the side of a conical hill. In such areas the hill perturbation is small and the feeder cloud generated has low liquid water content and high concentrations of pollutant ions.

The conclusions of this theoretical work cannot easily be tested against observations without access to an extensive rain-gauge network around a conical hill. However, it is worth noting the results of Dore et al. (1992). A 2-D model of airflow and orographic rainfall was compared with rain-gauge data read daily from complex hill terrain in the Lake District and Snowdonia. The results showed that the 2-D model sometimes failed to predict the location of the maximum rainfall. This was attributed to 3-D airflow effects causing air to be channelled through narrow valleys.

ACKNOWLEDGEMENT

This work was supported by the UK Department of the Environment.

REFERENCES


Storebo, P. B. 1976 Small scale topographical influences on precipitation. Tellus, 28, 45–59


---