Distribution of precipitation and wet deposition around an island mountain in south-west Poland

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SUMMARY

A comparison has been made between measurements of precipitation intensity and chemical composition and a three-dimensional model of airflow and orographic rainfall enhancement. The ‘seeder–feeder’ effect is shown to be of importance in rainfall distribution, wet deposition of pollutants and the modification of the chemical composition of rainfall over an isolated island mountain. The results show increases in rainfall of between 30% and 83% over the hill, with the smallest increase corresponding to the presence of a strong inversion layer. The peak rainfall enhancement occurred between 0.5 and 2 km downstream of the summit.

The measured concentrations of major ions in the feeder–cloud droplets were greater than those in seeder rain by factors of between two and five. The scavenging of polluted cap cloud by rain drops resulted in an increase in wet-deposition rate by factors of between three and five, with the peak deposition occurring approximately 2 km downstream of the hill summit.

KEYWORDS: Cap cloud Pollutant deposition Precipitation Seeder–feeder effect Sudete mountains

1. INTRODUCTION

In maritime climates, mountainous areas are frequently covered in orographically generated clouds formed by the condensation of humid air forced to rise over the terrain. In the warm sector of a low-pressure system, where there is advection of humid air masses, orographic clouds represent the lowest cloudy layer. In upper layers a frontal cloud can generate precipitation. Rain droplets which fall through the orographic clouds collect cloud droplets and grow by coalescence. This so-called ‘seeder–feeder’ effect was originally proposed by Bergeron (1965), and was later supported by the results of radar studies (Storebo 1976; Bader and Roach 1977; Gocho 1978). The measurements of Hill et al. (1981) showed that over 80% of the rainfall enhancement occurred below 1500 m above sea level.

Measurements made in the UK (Dore et al. 1992a, 1992b) showed that, typically, the seeder–feeder effect was responsible for doubling the precipitation rate. In certain cases it could result in a five- or six-fold increase. Both theoretical considerations and measurements indicate that the seeder–feeder effect is much more efficient in the case of snowfall (Dore et al. 1992c). This is because the large surface-area-to-volume ratio of a snow crystal results in a greater scavenging efficiency of cloud droplets. Dore and Choularton (1992) noted the importance of horizontal wind speed and rain-drop size in determining the distribution of rainfall. A rain drop with radius 0.7 mm, for example, falling through a feeder cloud of depth 2 km with a wind speed of 20 m s⁻¹ would be subjected to a horizontal wind drift of approximately 8 km.

Chemical analysis of ions dissolved in feeder-cloud water show that their concentrations are much higher than those found in rainfall. Recently researchers have shown that aqueous-phase oxidation of SO₂ by H₂O₂ and ozone is responsible for producing most of the sulphate in rainfall (McElroy 1986). This process results in high concentrations of sulphate in cloud water, and in increased wet deposition of sulphate by rain which has scavenged such cloud water. Measurements made in England showed that the average concentrations of Cl⁻, SO₄²⁻, NO₃⁻, H⁺ and NH₄⁺ in rain water at a high-altitude site were

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approximately double those measured at a nearby low-altitude site. The combination of a doubling in rainfall and a doubling of the concentration of ions in rainfall resulted in a four-fold increase in wet deposition at the high-altitude site owing to the seeder–feeder effect (Choularton et al. 1988, Fowler et al. 1988).

Most previous numerical models of the seeder–feeder effect over complex terrain (Robichaud and Austin 1988; Grabowski 1989; Jones and Choularton 1988; Dore et al. 1990; Hill et al. 1987) have employed a two-dimensional approximation. Such models may not be appropriate for calculating the rainfall distribution over terrain which has a complex three-dimensional structure. For an isolated bell-shaped mountain, the two-dimensional approach does not allow for the effects of air flowing around the hill and can overestimate both the displacement of air above the hill and the enhancement in rainfall. This effect is important, especially in the case of an inversion layer with low wind speeds. For bell-shaped hills the employment of a three-dimensional approach is therefore required. Dore and Choularton (1992) made a numerical study using a three-dimensional linear airflow model coupled to a seeder–feeder rainfall model. Their results showed that the two-dimensional approximation, when applied to a bell-shaped hill, resulted in overestimates of between 14 and 68% in the rainfall and between 6 and 24% in the wet deposition.

In the work presented below we employ the model described by Dore and Choularton to make a comparison with measurements of precipitation rate, and of ion concentrations in precipitation, made at an isolated hill near the Sudete mountains in south-west Poland. The aim of this work is to test the influence of atmospheric thermal stratification on precipitation distribution, and to determine the importance of the seeder–feeder effect on rainfall and wet deposition of pollutants over an isolated simple bell-shaped hill.

2. Experimental project

Collections of precipitation were made at Mt. Ślęża, a mountain whose summit rises 560 m above the surrounding lowlands and which approximates well to the classical axi-symmetric bell-shaped hill. Mt. Ślęża is located 35 km from Wroclaw in south-west Poland and forms part of the foothills of the Sudete mountains, but it is sufficiently detached from the massif that in conditions of westerly flow it can be treated as an isolated island mountain. Mt. Ślęża has a humid climate and the summit is frequently enshrouded in orographic cloud. The summit is in cloud for approximately 150 days per year, twice the number for other sites in the Sudete mountains with similar altitudes (Błaś and Sobik 1997); the name of this peak in fact derives from an ancient Slavic word meaning ‘foggy’.

Total precipitation was measured at eight points along an axis oriented west-north-west to east-south-east which passed through the summit of Mt. Ślęża. Standard rain gauges (RGs) were employed for the collection of precipitation. In addition, simple rain collectors (RCs) consisting of a funnel and bottle arrangement mounted 1.5 m above ground were used to collect samples for chemical analysis and to measure total precipitation. Passive cloud-water collectors (CCs) constructed using nylon thread were used to obtain feeder cloud-water samples for chemical analysis. The distribution of the collectors is indicated in Table 1, and a profile of Mt. Ślęża along the selected direction is illustrated in Fig. 1, together with the location of the rain collectors.

Samples of water used for chemical analysis were stored at 4°C. For cloud- and rain-water samples the concentrations of Cl⁻, NO₃⁻, and NH₄⁺ were measured using a potentiometric method, and for SO₄²⁻ Persson’s method (see Tragardh and Granat 1982), was used. Sulphate-aerosol loading was estimated from measurements of sulphate concentration in feeder-cloud water and from visual observations (when available) of the height of
cloud base, under the assumption that the cloud was growing adiabatically. For case-study 2, this gave a value of 8 g m\(^{-3}\) for the aerosol loading of the sulphate ion. For the other case studies measurements of sulphate concentration in cloud water were not available, and so the value 8 g m\(^{-3}\) was used throughout. Data for wind speed and direction, and for humidity and thermal stratification were obtained from radiosoundings taken twice daily at 1100 and 2300 GMT at Wrocław airport, 30 km from Mt. Ślęża. Additional rainfall data were obtained from five stations belonging to the Institute of Meteorology and Water Management (IMGW) in the lowlands surrounding Mt. Ślęża. These were: Mysłaków, Łagiewniki, Borów, Sobótka and Imbramowice (4 km west-south-west, 13 km south-east, 18 km east, 5 km north-east and 14 km north-west of Mt. Ślęża’s summit, respectively). During the collection of the samples visual observations were used to determine the height of the feeder-cloud base and the cloud type (i.e. cap cloud or wave cloud).
3. THE MODEL

The model employed for these calculations has been described in detail by Dore and Choularton (1992). A description of the three-dimensional linear airflow model has been given by Carruthers et al. (1989), and the formulation of the seeder-feeder model has been explained by Carruthers and Choularton (1983). The form of Mt. Ślęża approximates well to that of a classical bell-shaped island hill and was described in the model by the following formula:

$$Z = \frac{H}{1 + \frac{x^2}{L_x^2} + \frac{y^2}{L_y^2}}$$

with the values for the hill height above the surrounding terrain ($H = 568$ m) and the half-width of the hill in the $x$ and $y$ directions ($L_x = 1150$ m and $L_y = 1700$ m) being obtained from best-fit functions to the real terrain (Figs. 2(a) and (b)). The variation of wind speed with altitude was described by the Lajchtmann formula

$$u(z) = \frac{\mu}{\kappa} \ln \left( \frac{z}{z_0} \right)$$
TABLE 2. Input Parameters Used in the Model

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Temperature lapse rate (°C/100 m)</td>
<td>0.66</td>
<td>0.75</td>
<td>0.6</td>
<td>0.38</td>
</tr>
<tr>
<td>Buoyancy frequency (10⁻² s⁻¹)</td>
<td>1.0</td>
<td>0.9</td>
<td>1.12</td>
<td>1.49</td>
</tr>
<tr>
<td>Height of inversion layer (m a.s.l.)</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>1380</td>
</tr>
<tr>
<td>Depth of seeder cloud (m)</td>
<td>1500</td>
<td>2750</td>
<td>3300</td>
<td>2500</td>
</tr>
<tr>
<td>Height of cloud base (m a.s.l.)</td>
<td>550</td>
<td>350</td>
<td>450</td>
<td>700</td>
</tr>
<tr>
<td>Surface pressure (hPa)</td>
<td>985</td>
<td>1010</td>
<td>980</td>
<td>996</td>
</tr>
<tr>
<td>Sulphate concentration in seeder rain (µmol l⁻¹)</td>
<td>120</td>
<td>50</td>
<td>50</td>
<td>–</td>
</tr>
<tr>
<td>Seeding rainfall rate (mm hr⁻¹)</td>
<td>0.6</td>
<td>0.8</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Sulphate-aerosol loading (µg m⁻³)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

a.s.l.: above sea level

(where u* is the friction velocity, κ = 0.4 is the von Kármán constant, and z₀ is the roughness length), and the thermal stratification was represented in the model by an input value for the buoyancy frequency. The option of including an inversion layer was employed where appropriate. The three components of wind velocity were calculated on a grid of size 64 × 64 × 8 using a grid spacing of 250 m in the horizontal and about 300 m in the vertical, depending on the depth of the feeder cloud.

Total rainfall measured during individual precipitation episodes was compared with the results of a model of orographic rainfall enhancement. Calculations of the ascent of humid air over the mountain were used to define the formation of the feeder cloud. In the model the upper-level seeder cloud is separated from the low-level orographic cloud, and the seeder cloud is represented only by the presence of a constant level of seeding precipitation. In reality it was observed that, on some occasions, the seeder and feeder clouds were separated by a layer of clear air whilst on other occasions the top of the feeder cloud protruded into the base of the seeder cloud. The Marshall–Palmer (1948) distribution was used to define the rain-drop size distribution. The rainfall rate at the surface was calculated by integrating, over the depth of the feeder cloud, the effects of rain-drop scavenging of cloud droplets as a function of rain-drop size. The concentration of sulphate in the surface rain was calculated by assuming a constant value for sulphate concentration in the seeding rain above the cloud, and by setting a predefined value for the sulphate-aerosol loading that was incorporated into the feeder cloud at cloud base. Rain drops, therefore, accumulated both water and sulphate during the scavenging process. Equations describing the terminal velocity of the rain drops, and their evaporation in unsaturated air, were also incorporated into the model which was consequently able to capture the effects of the wind drift of rain drops.

4. Results

(a) Case I: 16-18 April 1995

The rainfall which fell on 16 April 1995 was connected with the cold front, and that on 17 April with the warm front, of a depression associated with a polar maritime air mass moving from the north-west. The input parameters for the model (as shown in Table 2) were calculated based on the radiosounding of 2300 GMT on 17 April 1995. The geostrophic wind speed at the 850 hPa level was measured as 13 m s⁻¹, and was taken as the input value for the model.
Figure 3. Streamlines of the modelled airflow pattern (thin lines) across the central axis of Mt. Ślęża (terrain height depicted by the thick line) for 17 April 1995.

Figure 4. Model prediction of rainfall (R) (thick line) over Mt. Ślęża (terrain height depicted by the thin line) for 16–17 April 1995, compared with the measured rainfall totals (stars).

Figure 3 illustrates the model calculations of the deformation of the airflow over the central axis of Mt. Ślęża. A significant vertical displacement of the air on the upwind slope of the hill occurs below the 1500 m altitude level. For a hill of such dimensions, and for a single stably stratified layer, the three-dimensional effects of air flowing around the hill are important.

Data from sites belonging to the IMGW in the lowlands around Mt. Ślęża gave the following precipitation totals: Sobótka 3.1 mm, Łagiewniki 3.4 mm, Borów 3.0 mm, Imbramowice 2.1 mm, Mysłaków 4.0 mm. These values were used to define the seeding-rainfall total used in the model; this was taken to be 3 mm hr⁻¹. Measurements of the total precipitation from the rain gauges in the terrain profile showed that an increase in rainfall started a few kilometres upwind of the hill summit (Fig. 4). The maximum rainfall, measured at Sulistrowiczki (point 6), was 5.5 mm, representing an increase in rainfall of
83% relative to the seeding rate. On the lee side of the hill at points 7 and 8 the rainfall fell below the base rate of 3 mm; this could have been caused by the partial evaporation of rain drops in the dry air to the lee of the hill summit. Thus the precipitation decreased by a factor of almost 3 between points 6 and 8. The field measurements showed good agreement with those of the orographic-rainfall-enhancement model which gave a rainfall enhancement of 77%, the maximum precipitation occuring 1 km downwind of the hill summit. Owing to the limited number of collection points, we cannot specify the location of the precipitation maximum exactly. However, based on the shape of the precipitation curve, a best fit would suggest that the maximum precipitation might have occurred between points 5 and 6, near to the position of the maximum predicted by the model. The two-dimensional surface-precipitation field calculated by the model is illustrated in Fig. 5. The characteristic shape of the precipitation field shows an extension of the areas of high precipitation to the east-north-east and east-south-east. This can be attributed to the high wind velocities on the flanks of the hill, and to the greater horizontal transport of rain drops along these trajectories.

The variation of sulphate concentration in the precipitation along the terrain profile is illustrated in Fig. 6. Both measurements and model calculations show that the point of maximum sulphate concentration in the rainfall occurred at the start of the slope of Mt. Ślęża, about 2 km upwind of the hill summit. Both the measured and modelled concentrations were significantly lower at the hill summit, with a small increase evident on the lee side. This can be explained by the fact that the cloud scavenged at the hill summit had high liquid-water content, and therefore lower concentrations of sulphate. Upwind of the
summit, however, near cloud base the cloud droplets were much smaller and more highly concentrated in sulphate. This effect is particularly noticeable when we examine a graph of the two-dimensional distribution of sulphate concentrations in rain, as predicted by the model (Fig. 7). Two peaks in sulphate concentration (220 μmol l⁻¹) appeared on the sides of the hill where the air trajectory passed over lower orography, and the cap cloud was more tenuously formed, though highly concentrated in sulphate. The rainfall concentration at this point was nearly double that in the seeding rain (120 μmol l⁻¹). A small increase in the sulphate concentrations in rain for both model and measurements appeared on the lee side of the hill (Fig. 6). This represented the area where partial evaporation of rain drops occurred in the drier air downwind of the summit. A similar pattern emerged in the distribution of other ion concentrations in rain water (Cl⁻, NO₃⁻ and NH₄⁺) as shown in Table 3. The product of the precipitation rate and the concentration gives the sulphate-deposition rate, as shown in Fig. 8. The base sulphate-deposition rate in the lowlands was 6 mg m⁻²h⁻¹, with peak values 1.5 km from the hill summit of 19 mg m⁻²h⁻¹. The seeder–feeder effect thus led to a three-fold increase in the wet deposition of pollutants in the highlands.

(b) Case 2: 13–15 April 1995

During the period 13–15 April 1995 rainfall occurred which was associated with an occluded front, with cyclogenesis over the Black Sea. A warm and humid polar air mass passed over Poland with a wind direction between east-north-east and east-south-east. The input parameters for the model (Table 2) were calculated using data from a radiosonde taken at 1130 GMT on 14 April 1995. For this case the cloud base was estimated at 350 m above sea level (a.s.l.) based on visual observations. The geostrophic wind speed was approximately 13 m s⁻¹.

Figure 9 shows stream lines of airflow over the central axis of the hill. The vertical displacement of the air is slightly greater than for case 1. The rainfall totals measured by the IMGW stations were: Sobóśka 11.2 mm, Borów 13.5 mm, Imbramowice 11.5 mm, Łagiewniki 18 mm. The Łagiewniki precipitation total could have been influenced by the proximity of this station to the Niemczan'skie hills (of mean altitude approximately 350 m). Mysłaków (located 4 km west-south-west of the summit of Mt. Śleża) recorded 22 mm, but it was probably within the area of precipitation influenced by Mt. Śleża. The
Figure 7. Model predictions of the distribution of sulphate concentration in rainfall (µmol l⁻¹) over Mt. Ślęża for 16–18 April 1995.

The seeding-rainfall rate for this case was calculated from collections made from rain gauges at points 7 and 8, assumed to be sufficiently upstream of the hill not to be influenced by the cap cloud. The rainfall peak was measured at the summit of Mt. Ślęża as 23.7 mm, which represented an 80% rainfall enhancement (Fig. 10). The model predicted a similar rainfall enhancement, but with the peak located 1.5 km downwind of the hill summit. The concentration of sulphate measured in the rain was quite high for all points in the terrain profile (Fig. 11). Cloud base for this case was particularly low and visual observations indicated the presence of cap-cloud formation at point 7, over the small hill upwind of Mt. Ślęża (see Fig. 1). The high concentrations may therefore be explained by the initiation of the seeder–feeder effect at point 7, where the hill was high enough to have a significant influence on sulphate concentrations in precipitation but not on total precipitation. The model description of the terrain, however, did not include this minor peak, and so the model predicted low sulphate concentrations in the precipitation upstream of Ślęża. Table 3 shows the concentrations of Cl⁻, NO₃⁻, NH₄⁺ and SO₄²⁻ in the collected samples of rain and cloud water. Figure 12 illustrates the sulphate deposition by rainfall as calculated by the model for the whole domain. The maximum deposition rate of 20 mg m⁻²h⁻¹ represents a five-fold increase relative to that due to seeding rain, with peak deposition occurring approximately 2 km upstream of the summit.

(c) Case 3: 26–27 April 1995

The rainfall period of 26–27 April 1995 was associated with an occluded frontal depression which was generated over the Mediterranean sea. The wind direction was
Figure 8. Model predictions of the distribution of sulphate deposition rate (mg m$^{-2}$h$^{-1}$) over Mt. Ślęża for 16-18 April 1995.

Figure 9. As Fig. 3, but for 14 April 1995.
TABLE 3. Measured ion concentrations in rain and feeder-cloud water (μmol L⁻¹)

<table>
<thead>
<tr>
<th>Sites</th>
<th>NO₃⁻</th>
<th>Cl⁻</th>
<th>NH₄⁺</th>
<th>SO₄²⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16–17 April 1995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sady</td>
<td>23</td>
<td>158</td>
<td>67</td>
<td>192</td>
</tr>
<tr>
<td>West-north-west slope</td>
<td>45</td>
<td>56</td>
<td>17</td>
<td>129</td>
</tr>
<tr>
<td>East-south-east slope</td>
<td>39</td>
<td>84</td>
<td>50</td>
<td>123</td>
</tr>
<tr>
<td>Sulistrowiczki</td>
<td>23</td>
<td>56</td>
<td>28</td>
<td>144</td>
</tr>
<tr>
<td>Przemilów</td>
<td>–</td>
<td>113</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Feeder cloud</td>
<td>98</td>
<td>226</td>
<td>177</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>8–15 April 1995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sady</td>
<td>43</td>
<td>42</td>
<td>106</td>
<td>120</td>
</tr>
<tr>
<td>West-north-west slope</td>
<td>61</td>
<td>118</td>
<td>178</td>
<td>178</td>
</tr>
<tr>
<td>East-south-east slope</td>
<td>42</td>
<td>111</td>
<td>118</td>
<td>81</td>
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<tr>
<td>Sulistrowiczki</td>
<td>43</td>
<td>56</td>
<td>50</td>
<td>146</td>
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<td>Przemilów</td>
<td>30</td>
<td>99</td>
<td>72</td>
<td>147</td>
</tr>
<tr>
<td>Feeder cloud</td>
<td>254</td>
<td>528</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>18–28 April 1995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sady</td>
<td>58</td>
<td>90</td>
<td>261</td>
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</tr>
<tr>
<td>West-north-west slope</td>
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<td>145</td>
<td>80</td>
</tr>
<tr>
<td>East-south-east slope</td>
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<td>–</td>
<td>117</td>
<td>71</td>
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<tr>
<td>Sulistrowiczki</td>
<td>34</td>
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<td>122</td>
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<tr>
<td>Przemilów</td>
<td>16</td>
<td>31</td>
<td>89</td>
<td>58</td>
</tr>
<tr>
<td>Feeder cloud</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 10. As Fig. 4, but for 13–15 April 1995.

between east and north-east. The input parameters for the model (Table 2) were calculated from the radiosonde of 2330 GMT on 26 April 1995. The geostrophic wind speed, 11 m s⁻¹, was slightly lower than for the previous cases. The values of total precipitation measured at the IMGW sites were the following: Sobótka 17 mm, Łagiewniki 16 mm, Borów 15 mm and Imbramowice 13 mm. As with case 2, the highest precipitation, 23 mm, was measured at Mysłaków owing to its location to the lee of Mt. Ślęża. The measured total precipitation
along the terrain profile changed from 14.8 mm to 21.2 mm at point 3 on the west-north-west slope of the hill (Fig. 13). This represents a maximum rainfall enhancement of 45%. As with case 2, the peak was located close to the hill summit. The model predicted a slightly larger rainfall enhancement of 60%, with the peak located 1.5 km downwind of the hill summit. The concentrations of sulphate in the rainfall are illustrated in Fig. 14. The highest concentration of 122 μmol l⁻¹ was measured at Sulistrowiczki (point 6), with a significant
Figure 13. As Fig. 4, but for 26–27 April 1995.

Figure 14. As Fig. 6, but for 26–27 April 1995.

decrease in concentration at the hill summit relative to point 6. This pattern of sulphate concentration in rain (peaking upwind of the hill summit) is similar to that observed for case 1. The model showed similar features, though the peak concentration occurred much nearer to the hill summit, and only a small decrease occurred a few hundred metres to the lee.

(d) Case 4: 6–7 April 1995

Two precipitation events occurred during the period of 6–7 April 1995 associated with cyclonic systems and polar-maritime air advected from the north west. The input parameters for the model (Table 2) were calculated using data from the radiosonde at 1100 GMT on 7 April 1995. The geostrophic wind speed, 22 m s\(^{-1}\), was higher than for the previous cases. This rainfall episode was characterized by stable air with a lapse rate of 0.38°C per 100 m in the lower atmosphere, capped by a strong inversion layer. A frontal inversion was present with base at 1380 m a.s.l. and a change in potential temperature of 3.2°C. The airflow model showed that the presence of the inversion layer resulted in a
blockage of the flow over the summit of Mt. Ślęza, with air being strongly restrained to flow around the hill. As shown in Fig. 15, the flow in the upper layers was not greatly perturbed over the hill summit, resulting in the formation of a rather shallow feeder cloud. The total rainfall measured indicated only a very small variation over the hill profile (Fig. 16), with a maximum rainfall enhancement of 30% at point 5, 0.5 km downwind of the hill summit. The model predicted a 20% increase in rainfall, with the peak rainfall occurring 1.5–2 km to the lee of the summit. Figure 17 shows a contour plot of the surface rainfall. For this case an unusual phenomenon is apparent. The presence of the inversion layer partially blocking the flow over the summit meant that the cloud generated on the flanks of the hill was deeper than that at the summit, producing heavier precipitation at these lower-altitude sites.

In certain circumstances, the release of potential instability can be triggered by airflow over a hill releasing precipitation from upper-layer clouds, a process not represented by the simple seeder–feeder model used in this work. However, for the cases presented here it is clear that there was no potential-instability release and the measured changes in precip-
itation resulted purely from the seeder–feeder effect. For this case study, no information on the chemical concentrations in the rainfall was available.

5. Discussion and Conclusion

A number of case studies have been performed to compare the patterns of measured precipitation distribution over a single island mountain with those predicted by a numerical model representing the seeder–feeder effect. The scale of Mt. Ślęza is sufficiently small that, in general, the mountain does not have a significant effect on mesoscale precipitation systems. The local variations in precipitation, for the cases presented, can therefore be assumed to be purely the result of the seeder–feeder effect, an assumption which cannot be so readily applied to rainfall studies over larger massifs. The isolated location of Mt. Ślęza, which is well detached from the main part of the Sudete mountain range located to the south-west, means that for a wide spread of wind directions, an air mass approaching Ślęza can be considered to have been undisturbed by orographic barriers. The shape of the mountain is also particularly convenient for making high-resolution studies of the influence of three-dimensional airflow effects on the local precipitation distribution using a numerical model.

Four case studies have been considered, three representing a stably stratified atmosphere and one with a stably stratified lower atmosphere capped by a strong inversion. The measured increases in precipitation over the hill (83%, 70%, 45% and 30% for the three stably stratified cases and for the inversion layer, respectively) showed good agreement with the model. The location of the peak precipitation occurred between a few hundred
metres and 2 km downwind of the hill summit, with the wind speed being the most important factor in determining the role of the horizontal transport of rain drops. The values of measured rainfall enhancement showed that the influence of three-dimensional airflow effects has an important role in restraining the seeder–feeder effect. This is particularly notable for the case with the inversion layer which produced the smallest rainfall enhancement. For this case the air mass was strongly forced so as to flow around the hill. Flow over the top of the hill was suppressed, causing the formation of a thin cap cloud and only a small increase in rainfall from cloud-droplet scavenging.

Chemical analysis of sulphate concentrations in surface rainfall showed a strong variability with altitude. The points with the highest concentrations of sulphate in rain water were found to occur near the base of the hill’s upwind slope, and were independent of wind direction. This represented the area where cap-cloud formation had just started and the liquid-water content was low. Cloud formation occurred because of the activation of cloud condensation nuclei, which became incorporated into the cloud droplets and contributed to the concentration of ions, such as sulphate, dissolved in the cloud water. The subsequent rapid growth of cloud droplets through further orographic lifting contributed additional water to the droplets, with the result that they were most highly concentrated with sulphate near cloud base. Sulphate concentrations in the rain collected at the summit of the hill were lower than those on the upwind slope because the thicker cloud scavenged here was less highly concentrated in pollutants. The influence of the seeder–feeder effect caused modifications in the rain chemistry which resulted in increases by factors of between two and three in the sulphate concentrations in the rain. Measurements from case 2, with flow from the east-south-east, showed high concentrations of sulphate at a point 5.5 km upstream of the hill summit. This coincided with a small secondary hill peak which protruded 100 m above the surrounding terrain and was sufficient to generate a thin cap cloud and to modify the rainfall concentrations. Table 3 shows the concentrations of Cl⁻, NO₃⁻, NH₄⁺ and SO₄²⁻ in rain and cloud-water samples. Where available, measurements of cloud-water concentrations showed high values, typically four times greater than those in rain. The combination of increases in both precipitation amount and chemical concentrations over Mt. Ślęża resulted in greater deposition of pollutants at higher altitude sites which increased by factors of between 2.3 and 5.0 (depending on the particular precipitation event) relative to lowland deposition rates.

The magnitude of the rainfall enhancement calculated by the model showed good agreement with the measurements. However, the positioning of model features, such as the concentration of the pollutants and the rainfall maxima for events 2 and 3, compared less favourably and appeared further downwind in the model than was evident from observations. This may be explainable by the feeder-cloud depth being too large in the model rainfall enhancement would then start higher up in the atmosphere and be carried downwind by wind drift). The values of the feeder-cloud depth used in the model were quite high (2750 m for 14 April 1995 and 3300 m for 26 April 1995). Cloud depth is an important parameter, but it is not always easy to estimate from tephigrams. The discrepancy might also be explained by the excessively high wind speed in the model; this would make rain drift more significant in the model than in reality.

Measurements from the European network on precipitation chemistry within the European Monitoring and Evaluation Programme (EMEP) indicate a high total deposition of potential acid (SO₃) over a large part of Poland (Erisman and Draaijers 1995), although there is a scarcity of monitoring points in Poland compared with neighbouring countries. The Ślęża massif is situated in an industrial area near the Sudete mountains in south-west Poland where the highest values of deposition in Europe are found (exceeding 4000 mol ha⁻¹ y⁻¹). This is caused by SO₂ emissions from industry and power stations.
The results presented here show that the seeder–feeder effect dominates the enhancement of deposition in frontal–rain events when feeder cloud exists. For convective-rainfall episodes, chemical concentrations in precipitation samples showed no significant variation from site to site. The influence of the seeder–feeder effect on annual precipitation therefore depends on the relative contributions of frontal and convective rainfall. Volume-weighted ion concentrations and measurements of frontal and convective precipitation during the project, together with annual precipitation data in the lowlands, were used to estimate the sulphate-deposition rate for the whole year. The contribution of both kinds of rainfall between 20 March 1995 and 15 April 1995 was similar to the annual average, with the total measured rainfall being 94 mm over Mt. Ślęża and 136 mm over the lowlands. In the lowlands surrounding Mt. Ślęża sulphate deposition was estimated as 374 mol ha\(^{-1}\)y\(^{-1}\), somewhat less than the EMEP results (over 400 mol ha\(^{-1}\)y\(^{-1}\)). Over Mt. Ślęża, the sulphate deposition increased by three times to 1182 mol ha\(^{-1}\)y\(^{-1}\) and was comparable with the highest wet deposition predicted by the EMEP for the Sudete mountains (which form the border between Poland and the Czech Republic, in the so called 'Black Triangle'). On the EMEP map there were no changes through the orographic influence of Ślęża because the effect occurs on a scale smaller than the grid spacing used in the compilation of the EMEP map. The same situation was characteristic for the wet deposition of \(\text{NO}_3\)\(^-\). However, the calculated \(\text{NH}_4\)\(^+\) deposition over Mt. Ślęża (1236 mol ha\(^{-1}\)y\(^{-1}\)) clearly exceeds values presented by EMEP for the Sudete mountains (700–1000 mol ha\(^{-1}\)y\(^{-1}\)). The high estimated deposition is related to seasonal fertilizing of local fields with natural manure during the spring time, an important source of ammonia. The concentrations measured during the project cannot therefore be correctly applied to calculations of annual ammonia deposition.

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