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Patterns of precipitation and pollutant deposition in the western Sudete mountains, Poland

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Abstract

The distribution of precipitation and wet deposition of pollutants by rain and snow in the western Sudete mountains in Poland has been investigated both for selected event case studies and for a longer term period of monitoring. The results were compared with a numerical model of two-dimensional airflow and scavenging of cap cloud by precipitation. The results of both modelling and analysis of case studies during north-westerly flow indicate that the first orographic barrier (Stóg Izerski) receives the highest deposition and acts to "shield" downstream hills (Szrenica). The "seeder–feeder effect" typically caused an increase in precipitation at Stóg Izerski of about 50% relative to the upstream lowlands. Ion concentrations in cloud and rime water were consistently higher than those in rain and snow water. Spatial variations in deposition by snow were found by the model not to be as significant as those for rain due to the slow fall speeds of snow crystals and their greater horizontal transport. The monitoring studies showed a maximum in sulphate and nitrate deposition at Stóg Izerski.

Keywords: Acid rain; Snow; Orographic cloud; Pollutant deposition; Izera mountains; Karkonosze; Sudete mountains; Seeder–feeder effect

1. Introduction

The Sudete mountains form the border between Poland and the Czech Republic. During typical westerly wind conditions, these mountains are exposed to highly polluted air from intensive heavy industry and the combustion of sulphur-rich brown coal in the region of the Polish, German and Czech borders. This has caused severe forest destruction, particularly in the altitude range 800–1200 m a.s.l. The aim of the experiments described in this article was to investigate the spatial distribution of precipitation and pollutant deposition in complex terrain for both snow and rain.

Hill cap clouds occur in this area on approximately 240 days in any year as a result of the condensation of rising air (Sobik and Migala, 1993). Although such clouds do not normally rain, they can be washed out by rain from upper level clouds. This mechanism, originally proposed by Bergeron (1965) is known as the "seeder–feeder effect" and can significantly enhance rainfall in hill areas. During winter months the effect may be even more pronounced due to the highly efficient scavenging of cloud droplets by snow crystals, which have a high surface area to volume ratio (Dore et al., 1992b). During the last decade, a number of independent modelling studies have been conducted to investigate the seeder–feeder effect. Richard et al. (1987) made sensitivity studies using cloud droplet distributions representative of both maritime and continental air. The rainfall enhancement was found to

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be insensitive to both the feeder cloud droplet size distribution and the mean seeding raindrop size. However, the physical processes were different for a continental cloud, where the growth of raindrops by accretion of cloud droplets was the predominant process, and a maritime cloud, where the conversion of cloud droplets to rain drops was significant. The modelling studies of Dore and Choularton (1992) and measurements conducted by Blas et al. (1998) dealt with three-dimensional flow over a bell-shaped hill. It was shown that in the presence of an upper inversion layer the flow was suppressed, greatly reducing rainfall enhancement. Chaumerliac et al. (1990) used the two-dimensional version of a meso-scale model, incorporating a quasi-spectral microphysical scheme and aqueous phase oxidation reactions, to study the chemical composition of rainfall over a bell-shaped mountain. Rain was found to be more acid down-wind of the mountain top due to a complex interaction of chemical, microphysical and dynamical processes.

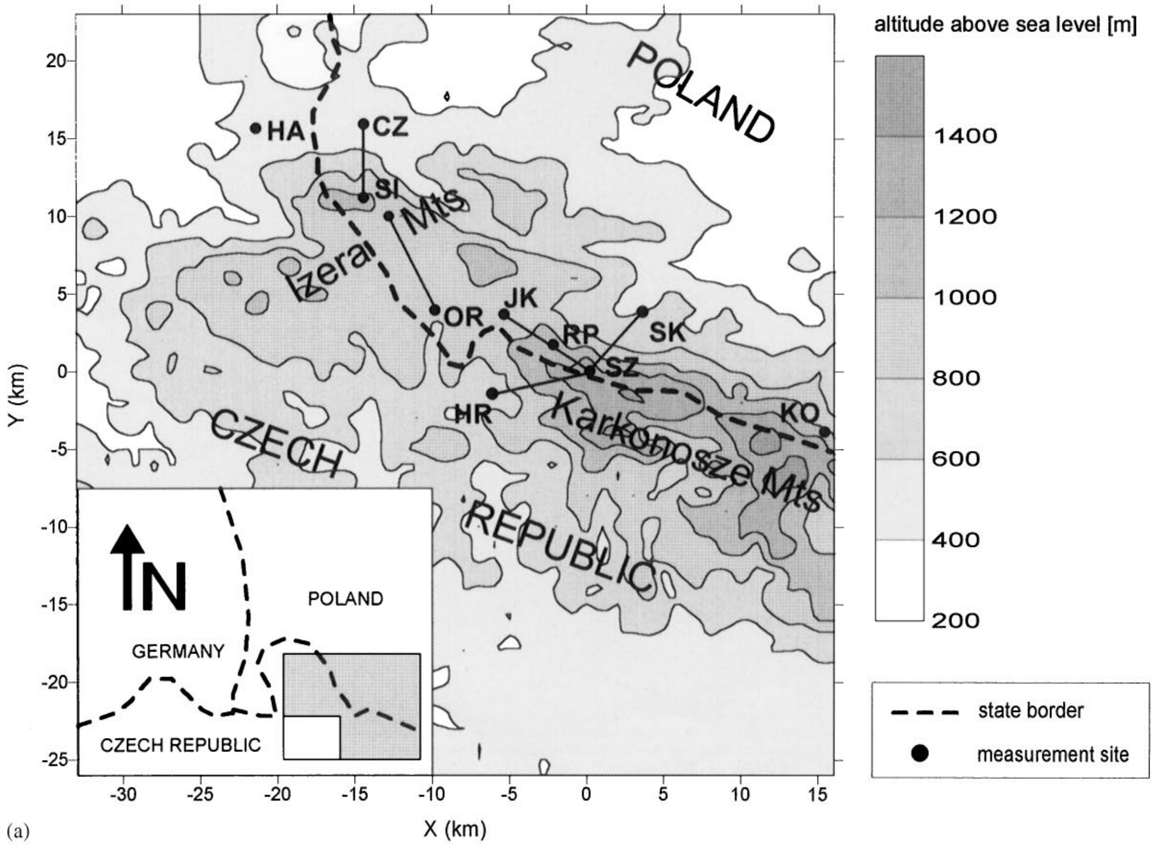
Field studies conducted by Fowler et al. (1988) at a hill site in northern England revealed that a rise in altitude of about 600 m was typically accompanied by a doubling in precipitation volume. Furthermore, concentrations of pollutants in rain samples at the upper site were found to be two or three times greater than those at lower altitude. These observations were adopted as a general trend by Dore et al. (1992a) in making calculations of a wet deposition map of the United Kingdom. Inglis et al. (1995) separated rainfall events in northern England into convective, frontal and mixed events. The seeder–feeder effect was found to occur consistently during frontal rain resulting in significant enhancements of ion concentrations in rain, especially for ions of marine origin. The ion balance of convective rain showed it to be principally of a marine origin whereas frontal rain contained a greater fraction of ions with anthropogenic origins.

The local mountain climate at Szrenica in the Karkonosze Mountains (Fig. 1) is well established on the basis of 30 years of measurements (1961–90) made at the meteorological observatory of the University of Wroclaw situated at altitude 1332 m a.s.l. (Migala et al., 1993). The mean annual temperature is 1.9°C varying from -6.8°C in January to 10.0°C in July. The average relative humidity is 85%, but it frequently reaches 100%. The mean annual number of days with fog is 264 so a relatively large amount of liquid fog deposit and rime is observed at higher altitudes. The annual precipitation is 1430 mm with a minimum of 72 mm during the month of January and a maximum of 180 mm in June. The mean wind velocity is 8 $m\,s^{-1}$, being greater during winter months and less in the summer. South-westerly winds predominate throughout the year, but in spring and summer months north-easterly and north-westerly winds occur more often than during the autumn and winter. The most humid air masses are associated with westerly and north-westerly flow when the occurrence of cap clouds is more probable. For these reasons, and due to the practical restrictions of operating in an area which is divided by a national boundary, precipitation collectors during our projects were aligned in a north-west to south-east direction. Data from Szrenica Observatory during the field experiments were used to select episodes according to air flow direction.

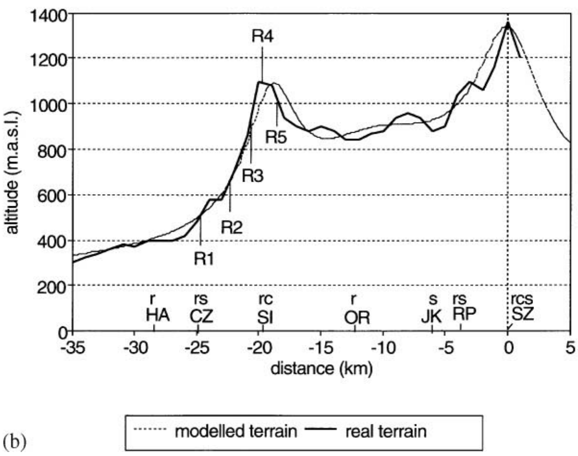
Pollution monitoring studies conducted by Zwozdziak et al. (1993) at Karkonosze between 1988 and 1992 showed that the mean concentration of SO_2 was 6 $\mu g\,m^{-3}$ at Mt. Szrenica and 21 $\mu g\,m^{-3}$ at nearby Mt. Sniezka (1602 m a.s.l.) with a weakly decreasing trend in concentrations apparent during the period of monitoring. The SO_4^{2-} aerosol was found to be the most important pollutant with approximately 80% of SO_2 gas being converted into sulphate aerosol. The highest SO_4^{2-} aerosol concentration (50–200 $\mu g\,m^{-3}$) were associated with westerly and north-westerly airflow and sulphur compounds were generally described as being the main pollutant in this area. The dominant role of the sulphate ion in wet deposition is confirmed by the monitoring studies of Twarowski (1996) in Karkonosze. A survey of forest health in the Czechish Karkonosze mountains (Moravcik and Cerný, 1995) revealed that defoliation was greatest in the western part of the mountains and at sites of high elevation exposed to the wind. A slight improvement in forest health was noted between 1991 and 1993 with mean defoliation falling from 42 to 39%.

2. Field equipment

Two experiments were undertaken in 1994. These were a snow chemistry project during the winter and a rain chemistry project during the spring. In addition, from May till October 1995 a period of precipitation monitoring was undertaken with a more intensive project for events sampling during the autumn. During the snow chemistry project, samples of daily precipitation events were collected between 27 January and 12 February 1994 at four sites. The location of the collectors in relation to the topography of the mountains is shown in a contour plot in Fig. 1a. Fig. 1b shows a cross-section of the terrain in a north-westerly direction passing close to the location of the collectors. The contour map shows the western part of the Sudete massif which comprises the Izera mountains (in the western portion of our map) and the western part of Karkonosze National Park (in the eastern section of our map). Both Karkonosze and the Izera mountains straddle the Polish–Czech border but occupy more terrain in the Czech Republic. Two automatic snow collectors were deployed at Czerniawa (CZ) and Jakuszyce (JK). The collectors (described in detail in Hall et al., 1989) were aerodynamically designed and tested in a wind tunnel to maximise collection efficiency. They



(a)



(b)

Fig. 1. (a) Contour map of the Izera mountains and western Karkonosze with measurement sites for precipitation collections (HA-Hajniste, CZ-Czerniawa, SI-Stóg Izerski , OR-Orle, JK-Jakuszyce, RP-Rozdroze pod Przedzialem, SZ-Szrenica, KO-Kopa) and location of profiles for snow depth measurements (HR-Harrachov, SK-Szklarska Poreba). The origin of the map is located at Szrenica Observatory. (b) Terrain profile through the western Sudete mountains showing a comparison with the modelled hill function. The profile direction is 310° with Szrenica at the origin. Place name symbols are as for Fig. 1a: (R1-5) rain collectors for the 1994 rain project; (r) rain collectors for the 1995 rain project; (c) cloud collectors for the 1995 rain project; (s) snow collectors.

have a circular dish with a thermostatically controlled heating device. Precipitation melts on impact and is collected in a bottle. Additional sample collections were made at Rozdroze pod Przedzialem (RP) and Szrenica (SZ) in buckets installed 60 cm above the snow cover. The collectors were located such that in north-westerly winds, the first collector was upwind of the mountains and consecutive collectors were situated at increasingly higher altitudes. Rime samples were collected on nylon wires at sites RP and SZ. Rain chemistry projects for events analysis took place between 18th May and 4th June 1994 and between 6 August and 30 September 1995. In 1994 five rain collectors (consisting of a simple funnel and bottle arrangement) were installed at different altitudes on the north-west slope of the mountain range, as shown in Fig. 1b. Cloud water was collected at sites R3 and R4 using passive collectors consisting of an array of strung nylon wire and a lid to prevent the capture of raindrops. During the 1995 experiments, seven rain collectors were used to cover an increased range which extended as far as eastern Karkonosze. Collection of rain and cloud water samples and cleaning of the collectors was made on a daily basis and samples were filtered before analysis. Data from detailed meteorological observations, made regularly three times each day, were available from the observatory at Szrenica.

During the snow project, trace metals in the samples were stabilized by the addition of HNO_3 and all ion concentrations were determined using infra-red spectrophotometry. For the rain project, ion concentrations were measured using an automated colorimetric technique. In general the errors in measurements of ion concentrations associated with these techniques can be assumed to be of the order of 10%.

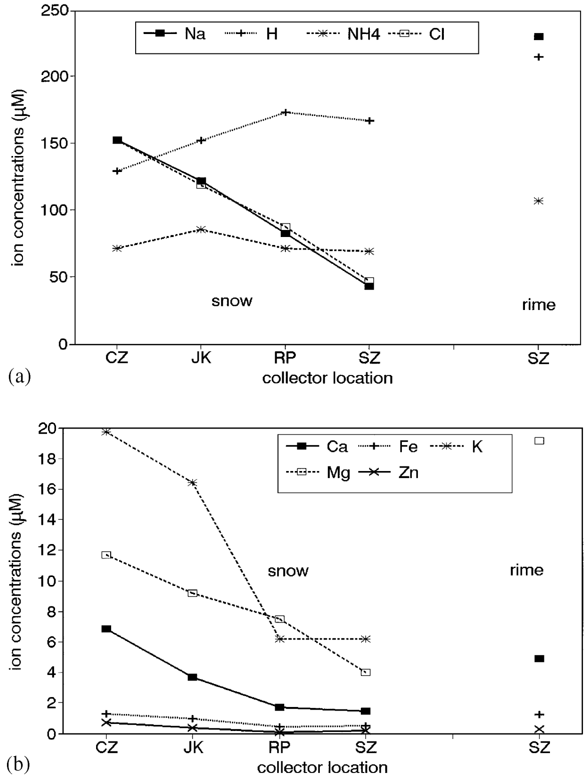


Fig. 2. Ion concentrations in snow and rime, 29 January–1 February 1994.

3. Results

3.1. The snow project

Four days with snowfall occurred in the Sudete mountains between 29 January and 1 February 1994 when the wind was from the north-west. Chemical concentrations of principal ions, averaged over the four days, are presented in Fig. 2. A strong downward trend in ion concentrations with increasing altitude is evident for most ions, with Na^+, Cl^-, Ca^{2+}, Fe^{2+}, K^+, Mg^{2+} and Zn^{2+} decreasing in concentration between sites CZ and SZ by factors of: 3.9, 3.6, 4.7, 2.7, 3.2, 2.9 and 3.5 ($\pm$ 20%), respectively. H^+ concentrations however increase with altitude whilst NH_4^+ reveals no discernible trend. In general, due to the more polluted nature of the boundary layer than the free troposphere, cap cloud water (which is fed by low-level air) tends to contain higher ionic concentrations than precipitation (which is formed in the upper layers). The scavenging of cap cloud particles by precipitation is therefore generally expected to result in an increase in the ion concentration in precipitation. The reverse appears to be the case for this study, despite the fact that measured ion concentrations in rime were found to be higher than those in snow. Two effects might explain this occurrence. Either the cap cloud was efficiently washed out of aerosol over the first hill peak at Stóg Izerski (unfortunately no collections were made at this point) or diffusion could have diluted the chemical concentrations in low-level air as it flowed over the hill (discussed below).

Average chemical concentrations for the entire project duration are presented in Fig. 3. The values were obtained by averaging concentrations over all collection points for each precipitation or fog event and then performing a weighted average over the precipitation events. Weighting was according to the measured depth of fresh snowfall and to the mass of rime accumulated on a standard collector at Szrenica observatory. Approximately 50 cm of snow fell during the project of which 19 cm was contributed by precipitation during the period 29/1–1/2/1994 with north-westerly flow. A period of north-easterly circulation occurred on 11–12/2/1994 with 18 cm of snowfall and the period 3–10/2/1994 was characterized by flow from the south-west with 13 cm of snow. Concentrations of ions in rime are consistently higher than those in snow by factors of 2.9, 1.3, 1.5, 2.2, 2.8, 2.0, 4.1, 2.6, 2.3, 1.8 and 0.43 ($\pm$ 20%) for SO_4^{2-}, H^+, NH_4^+, Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Pb^{2+} and Zn^{2+}, respectively, with Zn^{2+} being the one exception to

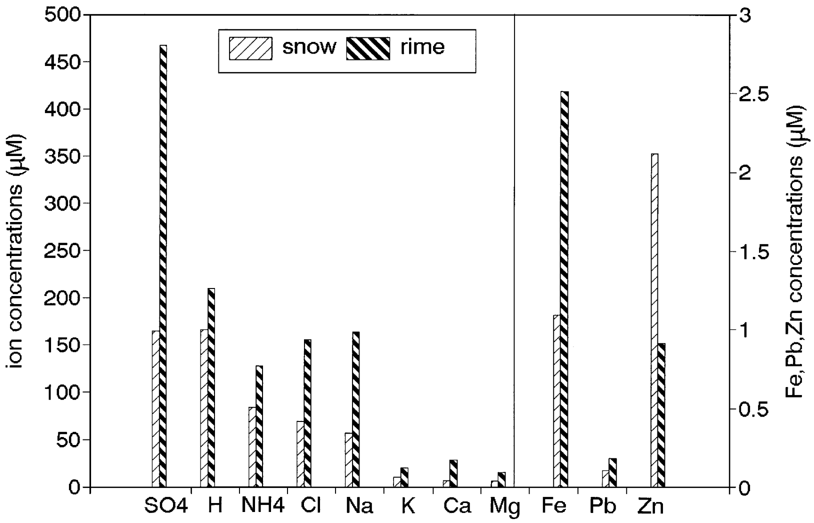


Fig. 3. Average ion concentrations in snow and rime, 27 January–12 February 1994.

the general trend. The relatively close balance between concentrations of Na^+ and Cl^- indicates an absence of industrial contributions to chloride concentrations.

Attempts to measure the amount of precipitation during snowfall apart from during low windspeeds tend to be unsuccessful (Dore et al., 1992b; Sevruk, 1985). This is due to the low terminal velocity of snowflakes which can result in very inefficient capture by a detector. This problem is especially relevant to our experiment where we investigate pollution deposition at sites of different altitude, as the windspeed (and thus the collection efficiency) itself is normally a strong function of altitude. We therefore did not attempt to measure precipitation volume during individual events. Some idea of the distribution of snowfall in the mountains may be obtained by using probes to measure the total depth of the snow in different areas. The depth is a function of the climate of the whole winter period and represents the cumulative total of many precipitation events offset by periods of melting, sublimation and wind drift. Measurement sites were restricted, where possible, to unexposed flat areas normally representing small clearings in the forest.

Fig. 4 shows snow depth as a function of altitude for different trajectories, marked on Fig. 1a. At the highest points of the Sudete mountains, forest cover is sparse and wind exposure is more extreme so that snow cover is often less at high altitude than at sites of intermediate altitude. Despite these complications, a general pattern does emerge from Fig. 4. Trajectories CZ to SI and SI to OR have the lowest values of snow cover so that, for sites of equivalent altitude, the snow depth tends to be greater in the more easterly reaches of the area of measurements. Due to the steep slope and dense forest cover along the

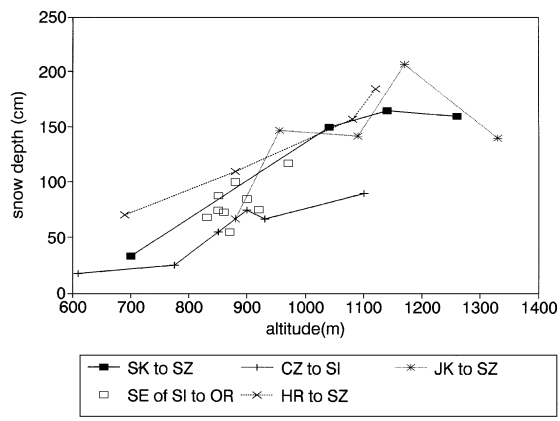


Fig. 4. Snow cover in the Izera and Karkonosze mountains. 4–6 February 1994.

profile between Szklarska Poreba and Szrenica there is a lack of suitable measurement sites hence the gap in data between 700 and 1050 m a.s.l. This area is known to have relatively low snow depth due to melting during föhn winds when flow is from the sector between WSW and SSE. The much greater snow depth at Harrachov than at Szklarska Poreba and Czerniawa is evidence of the influence of föhn winds.

The subject of snow cover in the Izera mountains has been dealt with in greater detail by Mrugasiewicz (1997). The results support our observations in demonstrating a decreasing trend in snow cover towards the west. However, for a given site, the snow cover was found to be more sensitive to other factors such as its local roughness, determined by the surrounding vegetation. As snowfall tends to occur mainly during westerly and north-westerly winds, this tempts us towards two possible explanations: either: precipitation is dominated by the seeder–feeder effect and the heavier precipitation, enriched by scavenging cloud droplets, is carried over distances of a few tens of kilometres by wind drift before settling; or the presence of the massif perturbs upper level flow causing potential instability release and the formation of heavier precipitation systems which fall to ground some distance downstream. In practice the distribution of snow depth measured probably results from a combination of these two effects and the föhn wind.

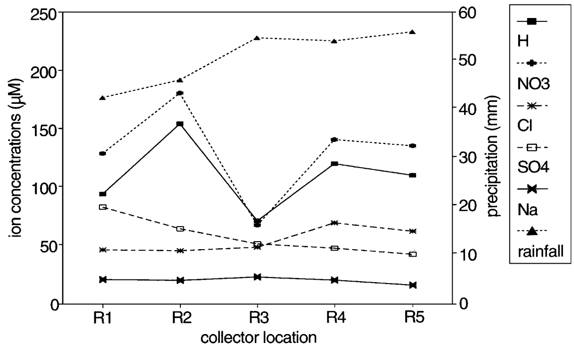


Fig. 5. Precipitation and rain chemistry in the Izera mountains, 27–30 May 1994.

3.2. The rain project

During the first rainfall project a period of four days occurred, from 27 to 30 May 1994, when the wind direction stayed north-westerly and precipitation fell on three days. Samples were taken from five rain collectors on the slope between Czerniawa and Stóg Izerski as shown in Fig. 1b. The total precipitation for the four day period as well as average chemical concentrations in the rain water are presented in Fig. 5 for each collector. A small increase in precipitation with altitude of 31% is evident, probably due to the seeder–feeder effect. As with the snow study, the trend in ion concentrations with altitude appears to be species dependent with no discernible trend in concentrations of H^+, NO_3^- and Cl^- but SO_4^{2-} and Na^+ concentrations showing a slight downward trend. Fig. 6 presents volume-weighted average chemical concentrations in rain and cloud water over the entire monitoring period. Precipitation from the period 27 to 30 May accounted for about half of the 91 mm which fell during the project. A secondary major precipitation event occurred on 19 May contributing 21 mm during easterly wind. The remainder consisted of many small rainfall events, mostly of a convective nature, with various different wind directions. Again cloud water concentrations are significantly higher than those in rain, by factors of 1.3 ($\pm$ 0.3), 1.6 ($\pm$ 0.3), 3.2 ($\pm$ 0.6), 2.7 ($\pm$ 0.5) and 1.4 ($\pm$ 0.3) for H^+, NO_3^-, SO_4^{2+}, Cl^- and K^+, respectively.

During 1995, six rain collectors were employed spanning a much greater distance, as shown in Fig. 1a. Passive cloud water collectors made from strung PTFE wire were installed at Stóg Izerski and Szrenica. Daily collections of rain and cloud water samples were made from May till October and the collectors rinsed with distilled water. The samples were added to a bulk monthly sample for each collector. In addition an intensive field campaign was conducted between 6th August and 30th September when daily samples were stored individually for the analysis of rainfall events. A seventh collector was added at Rozdroze pod Przedzialem during the shorter project. A period of heavy frontal rain during north-westerly winds which occurred between 27 August and 2 September has been selected for analysis. The total precipitation at each site as well as the average volume-weighted

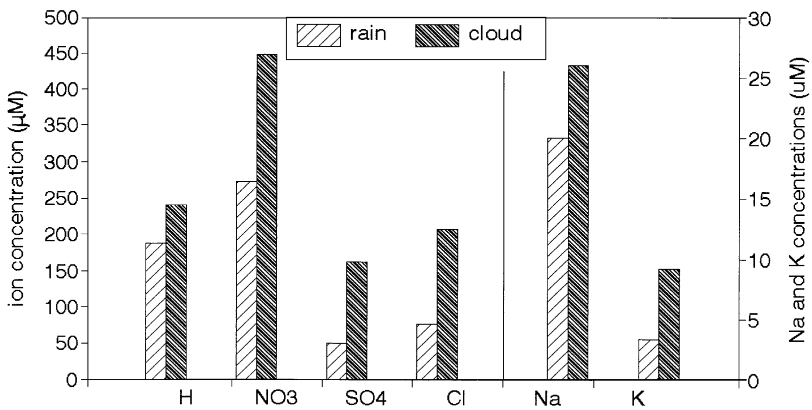


Fig. 6. Average ion concentrations in rain and cloud water, the Izera mountains 18 May–2 June 1994.

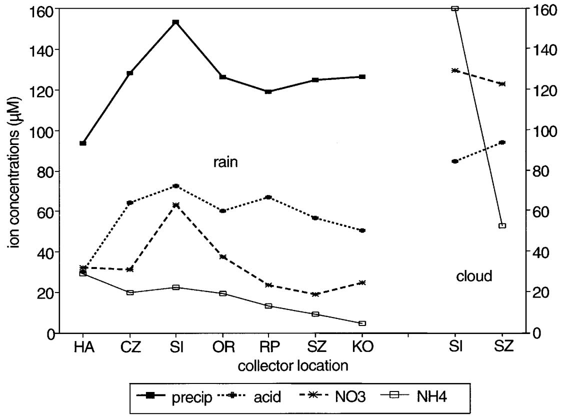


Fig. 7. Precipitation and chemistry of rain and cloud water, 27 August–2 September 1995.

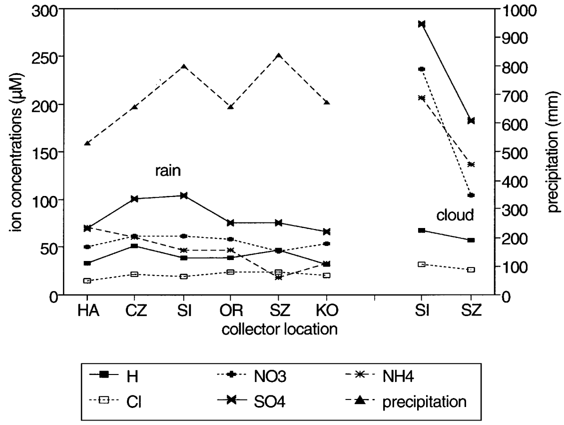


Fig. 8. Monitoring of precipitation and chemistry of rain and cloud water, May–October 1995.

concentrations of ions in rain and cloud water are presented in Fig. 7 (sulphate and chloride analyses are unfortunately missing for this event). Between Hajniste and Stóg Izerski an increase in precipitation of 63% from 94 to 154 mm is evident, with lower precipitation (124 mm) at Szrenica. The concentrations of H^+ and NO_3^- in rain also peak at Stóg Izerski so that this point generally receives the highest pollutant deposition. The NH_4^+ concentration is highest in the upstream collector at Hajniste which may be due to local agriculture sources. The concentrations of ions in cloud water at both Stóg Izerski and Szrenica are significantly higher than those in rain water, on average by factors of 3.8 ($\pm$ 0.8), 3.2 ($\pm$ 0.6) and 1.5 ($\pm$ 0.3) for NO_3^-, NH_4^+ and H^+, respectively. These results suggest the activity of the seeder–feeder effect with polluted cap cloud forming over the first orographic barrier as the air flows from the north west, significantly enhancing precipitation and pollutant deposition in this area.

Total precipitation and volume-weighted average ion concentrations of bulk monthly collections of rain water and cloud water are presented in Fig. 8 for the monitoring period May–October 1995. There is a significant increase in precipitation from Hajniste (530 mm) to the peak at Stóg Izerski (801 mm) of 51% and also high precipitation at Szrenica summit (840 mm). Ion concentrations dissolved in rain water peak at Stóg Izerski for SO_4^{2-} and NO_3^- with Cl^- concentration peaking at Szrenica and H^+ at Czerniawa. As with the case study of 27 August–2 September, NH_4^+ concentrations generally exhibit a decreasing trend from west to east. A notable feature of the graphs is the strong increases in both precipitation and ion concentrations between Hajniste and Czerniawa. These two points are separated by 8 km with only a small difference in altitude from 400 m at the former to 500 m at the latter and small hills of up to 600 m altitude in between. This suggests that even very small hills can have a significant influence on precipitation amount and chemistry. Depending on the wind direction however, precipitation at Czerniawa may be influenced by the Stóg Izerski massif located close to the south. Cloud water concentrations are significantly higher than those in rain, on average by factors of 1.8 ($\pm$ 0.4), 3.1 ($\pm$ 0.6), 3.7 ($\pm$ 0.7), 1.4 ($\pm$ 0.3) and 2.9 ($\pm$ 0.6) for H^+, NO_3^-, NH_4^+, Cl^- and SO_4^{2-}, respectively. All ion species exhibit a marked decrease in concentrations in cloud water between Stóg Izerski and Szrenica.

4. Modelling studies

A number of numerical simulations have been performed to check whether the patterns of pollution deposition measured in the field projects can be explained by the conventional theory of the seeder–feeder effect. A simple two-dimensional linear model (Carruthers and Choularton, 1982) was used to calculate the airflow over the mountains. The terrain was represented by the superposition of four bell-shaped hill functions each with formula:

$$y_i(x) = H_i/(1 + (x - A_i)^2/L_i^2)$$

where $y_i(x)$ is the terrain function for hill i of height H_i, half-width at half height L_i, centred at x-coordinate A_i. The mathematical hill function, as shown in Fig. 1b, follows closely the shape of the real terrain. The transect origin is Szrenica summit and the direction is north-westerly so that the peak at -20 km represents Stóg Izerski at the edge of the Izera mountains.

For the calculations of orographic precipitation, two different models were used. The first is a rainfall model (Carruthers and Choularton, 1983) which simulates the formation of orographic cap cloud due to the condensation of rising air. It incorporates a raindrop size distribution and equations for the terminal velocity, evaporation in undersaturated air and cloud-droplet scavenging of raindrops. The second model, for seeder–feeder snowfall (Choularton and Perry, 1986), is designed on similar principles to the rainfall model but requires more complex equations to describe the microphysics of snow (in this case dendritic crystals).

The input parameters to the model were calculated from data collected from a Szrenica meteorological station, from Wroclaw radiosoundings and chemical analysis of cloud and rain water collections. Analysis of radiosoundings revealed that for both case studies, the atmosphere was best represented by a single stably stratified layer with a value for the Scorer parameter of 0.001. Other meteorological input parameters such as the relative humidity, geostrophic wind speed and vertical temperature profile were also calculated from the radiosoundings. The average precipitation rate at Szrenica observatory was calculated from hourly data from a tipping bucket rain gauge. This precipitation rate, which has been enriched from cloud droplet scavenging, was used to calculate a lower seeding rainfall rate. The model does not included development of the upper level rain field and the seeding rainfall rate is therefore set as a constant over the terrain. Altitude of feeder cloud base and depth of the feeder cloud were calculated from visual observations and analysis of radiosoundings. The concentration of ions in seeding rain was derived from samples of rain water collected at sites upwind of the mountains which were not subject to the influence of the seeder–feeder effect. Ion concentrations in the cap cloud were obtained from cloud water collections on the slope of Stóg Izerski. The cap cloud water ion concentrations were converted into aerosol loadings using knowledge of cloud base and an estimate of the cloud liquid water content. In the model the input bulk aerosol loading is activated entirely and incorporated into the cap cloud water at cloud base.

4.1. *Orographic rainfall simulation for 27/8–2/9/1995*

The rainfall period of 27 August till 2 September 1995 was simulated with the seeder–feeder rainfall model. A seeding precipitation rate of 2.0 mm h^{-1} was used with chemical concentrations in seeding rain of: 30, 32 and 29 μM and aerosol loadings of 0.036, 3.1 and 1.15 μg m^{-3} for H^+, NO_3^- and NH_4^+, respectively. Cloud base was set at 900 m and the geostrophic wind speed was taken to be 13 ms^{-1}. Fig. 9a shows the precipitation rate, which reaches a maximum of 5.4 mm h^{-1} over the summit of Stóg Izerski. A secondary, smaller rainfall peak occurs over Szrenica. At this point the heavy precipitation has significantly depleted the liquid water in the cloud so that the seeder–feeder effect is less prominent. The increase in precipitation at Stóg Izerski is much greater than that measured (63($\pm$ 6)%). The simple two-dimensional model forces the convergence of water vapour above the hill whereas in reality three-dimensional airflow effects should play a role, channelling air to flow around the hills. Fig. 9b shows the concentrations of chemical components in the rain water as a function of position. The highest concentrations occur well upstream of the first hill peak where the rain drops are scavenging cloud which has low liquid water content but high concentrations of pollutants. By contrast the thicker cloud near the summit of the first peak has more dilute chemical concentrations and, although there is intense scavenging and heavy rainfall, the chemical concentrations in rainfall are lower. Combining the precipitation rate and the chemical concentration in rain gives us the chemical deposition rate, which peaks on the upstream side of the first hill peak as shown in Fig. 9c. By the time the air has reached Szrenica, most of the chemicals have been washed out of the cloud and the chemical deposition rate is only slightly greater than that due to the seeding precipitation. The modelled enhancements in deposition of H^+ and NO_3^- between Hajniste and Stóg Izerski (increases by factors of 3.4 ($\pm$ 1.2) and 4.1 ($\pm$ 1.3), respectively) compare favourably with those measured (3.9 ($\pm$ 0.8) and 3.2 ($\pm$ 0.6)). The significant errors associated with the model are due to the fact that a steady state system was modelled to represent a precipitation period spanning several days during which meteorological parameters which effect the deposition (i.e. precipitation rate, windspeed and chemical concentrations) varied considerably.

Two other rainfall simulations were made (27–28 September 1995 and 27–30 May 1994). These are not analysed here in detail but showed similar structure in the graphs of precipitation and ion concentrations in rainfall, with primary peaks near the first hill summit. The 27–30 May 1994 was characterized by a heavy mean seeding precipitation rate of 3.4 mm h^{-1} and a low geostrophic windspeed of 8 m s^{-1}. For this case the cap cloud was slow moving but rapidly scavenged so that the aerosol in the cloud was washed out before the air mass reached Szrenica. The extent to which rainfall and pollutant deposition is concentrated in the area of the first hill is therefore sensitive to the prevailing meteorological conditions. The water content in the cloud, whilst being depleted by scavenging is also replenished by the evaporation of raindrops in undersaturated air between the first and second hills. In reality there is also a source of replenishment for certain chemical species in the cloud due to chemical reactions, for example the oxidation of SO_2 to form $H_2^+SO_4^{2-}$ in cloud. This model does not include chemical reactions and may thus overestimate the rate at which aerosol concentrations decrease due to scavenging.

The results of the modelling studies generally show a decrease in concentrations of chemicals in rain water with altitude. This can be attributed to the nature of the

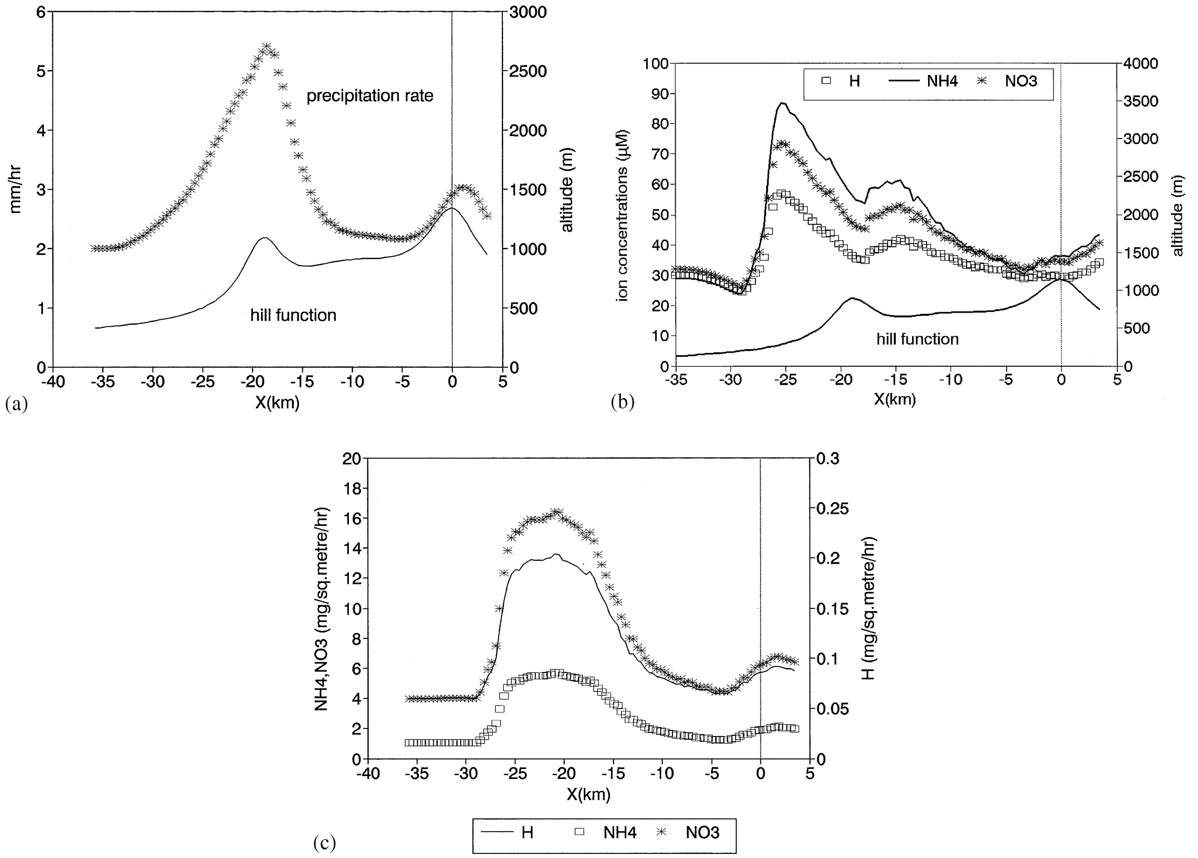


Fig. 9. Model simulation of precipitation and rain chemistry for the episode of 27 August–2 September 1995: (a) precipitation rate, (b) ion concentrations in rain and (c) ion deposition rates.

terrain, the cap cloud forming well upstream of the first hill and much of the aerosol in cloud water being washed out before the cloud reaches the highest point in the mountains (Szrenica). Clearly the variation of chemical concentrations in rainfall due to the seeder–feeder effect is a complex process and depends strongly on both the meteorology and the nature of the terrain. The most important parameter to consider however is the total pollutant deposition. The seeder–feeder effect always results in collection of additional chemical species dissolved in the cloud water and an enhancement of deposition. We note however that the modelling results clearly show that the heaviest pollutant deposition occurs around the area of Stóg Izerski whereas deposition rates at Szrenica are often not much higher than those upstream of the hills.

4.2. Orographic snowfall simulation

A somewhat different pattern emerges from the simulation of the snow event. In this case the geotrophic windspeed was high (29 m s^{-1}). This factor combined with the low terminal velocity of snow crystals means that the snow is transported over large horizontal distances. The precipitation peak (Fig. 10a) over Stóg Izerski is therefore broader than in the case of rain and reaches a maximum several kilometres downstream of the hill summit. A particularly significant result is the transport of pollution over much longer distances than in the case of rain with deposition rates of chemicals at Szrenica being almost as high as over Stóg Izerski (Fig. 10b).

4.3. Discussion of model results

These numerical simulations have shown the seeder–feeder effect in rather a different light from earlier studies. Generally concentrations of chemicals in precipitation seem to be lower at high altitude sites. To a certain extent this is an artifact produced by the simple 2D hill function used in the model, resulting in rainfall concentrations peaking well upwind of the first hill peak. However, the decrease of ion concentrations in precipitation over the

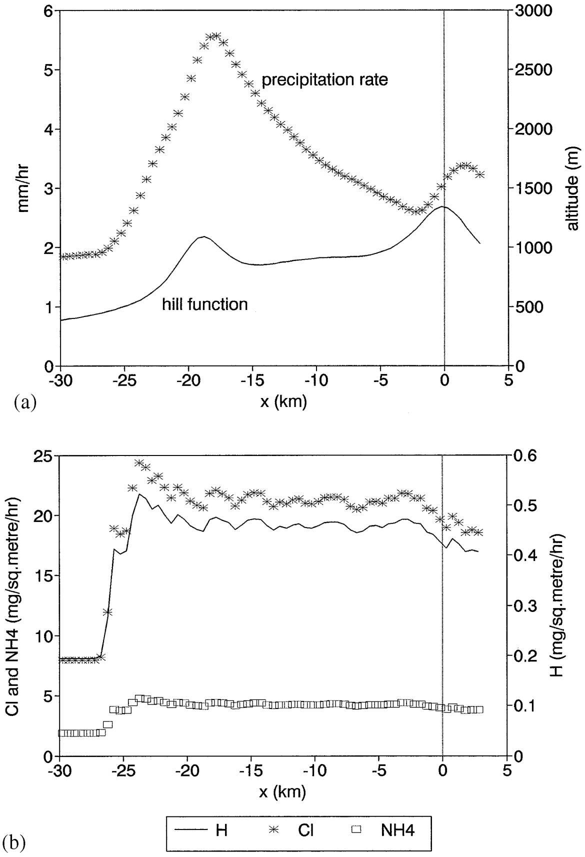


Fig. 10. Model simulation of the snow event of 29 January–1 February 1994: (a) precipitation rate and (b) ion deposition rates.

second, higher peak is a result common to both modelling studies and the measurements programme. The first peak in a chain of hills (in this case, Stóg Izerski in the Izera mountains) tends to take the highest pollutant deposition from rainfall and thus effectively "protects" the successive peaks (such as Szrenica in the Karkonosze massif). For this particular area, considering the importance of Karkonosze National Park as a well-known tourist resort and ski area, this is a significant conclusion. For snowfall however, pollutant deposition is observed to be much more uniformly distributed over the mountains.

The simple two-dimensional linear model used in these studies has indicated a trend in patterns of pollutant deposition in the western Sudete mountains. However the model does have certain major restrictions. The two-dimensional approximation can over-estimate rainfall rates over isolated hill peaks as it does not capture the three-dimensional effects of flow around a hill, as shown by Dore and Choularton (1992) and Blas et al. (1998). For the simulations presented here, the model has calculated much greater rainfall enhancements at Stóg Izerski than those measured. It should also be noted that, depending exactly on the wind direction, a power plant at Turoszow to the north-west of the mountains could be the main source of pollutants. Stóg Izerski is located much closer to Turoszow (about 25 km distant) than Szrenica (about 45 km distant). We would therefore expect concentrations of chemicals in the air to be higher at Stóg Izerski. A future numerical experiment with a three-dimensional model could include the effects of diffusion to investigate how air chemistry varies over the mountain range. On the other hand, if the air mass has not passed over Turoszow power plant, then the main source of pollutants is likely to be a German industrial area, approximately 100 km to the north west of Szrenica. In this case, with the source being further away we would then expect the effects of diffusion to be less significant. The problems of diffusion of air pollution over the western Sudete mountains are currently being dealt with using more sophisticated three-dimensional air flow models.

5. Conclusion

The results of chemical analysis of rain and snow samples collected in the western Sudete mountains have been presented for three case studies and a longer period of monitoring. These data have been compared to a numerical model of the "seeder–feeder effect" whereby hill cap cloud droplets are scavenged by upper level precipitation, a process which can lead to a significant increase with altitude of both precipitation and pollutant deposition in mountainous areas. In the case of the snow experiment we were not able to measure precipitation amount with any degree of confidence. The simple numerical model used was not able to capture the effects of three-dimensional airflow over complex terrain, in-cloud chemical reactions or diffusion of air pollutants, all of which may play an important role. However the combination of both the numerical experiments and the programme of measurements points to some general conclusions.

Ion concentrations in rain were not correlated to altitude in a simple way, due to the complex nature of the terrain, and trends in their distribution seem to depend on the species of ion considered. During frontal precipitation, rainfall at upper level sites could increase by approximately 50% due to the action of the seeder–feeder effect. During winter, analysis of snow chemistry showed that, for some precipitation events, samples were less polluted at higher altitudes. Measurements of total snow depth revealed greater cover in the eastern part of the mountains possibly due to a combination of the seeder–feeder effect and wind-drift of snow crystals in the prevailing westerly winds. Cap cloud water and rime samples were typically two or three times more polluted than precipitation.

Modelling studies predicted that the area of maximum pollutant deposition occurred a few kilometers upstream of the first hill peak with much reduced deposition over the second hill peak. A similar pattern was evident from chemical analysis of rain samples during a prolonged frontal rainfall event. However, the results of a long term chemistry precipitation monitoring programme showed less strong variation in pollutant deposition between the two hill peaks. Sulphate and nitrate deposition were highest over the first hill with chloride deposition peaking over the second hill. Ammonium deposition showed a decreasing trend with distance towards the east. Concentrations of chemical components in cloud water however were consistently higher over the first hill. Evidence is presented to suggest that in a chain of hills in complex terrain, it is the first, most upwind hill peak which receives the bulk of pollutant deposition by rain and cloud water deposition, thus to a certain extent “sheltering” the successive hill peaks downwind.

The motivation for this study was based on the results of research conducted in the maritime climate of the UK (Fowler et al., 1988; Dore et al., 1992a; Inglis et al., 1995) which demonstrated a systematic increase in ion concentrations in precipitation with altitude. In the more continental climate of the Sudete mountains of the Polish–Czechish border, however, the air is on average less humid than in a maritime climate so that we would expect the seeder–feeder effect to be less influential over a long period of time. The results of precipitation monitoring suggest that the increase of precipitation with altitude is less significant in the Sudete mountains than for an equivalent altitude change in a more maritime mid-latitude climate. Fowler et al. (1988) for example quote a doubling in precipitation on the western slope of Great Dun Fell in northern England for a 600 m increase in altitude. For the same increase in altitude in the Izera mountains, monitoring studies revealed only a 50% increase in precipitation. Furthermore, in a more continental climate, convective rainfall makes a more important contribution to total annual rainfall. Convective rainfall is difficult to categorise but it does not generally occur in the presence of cap clouds so that there should be no enhancement of rainfall with altitude due to scavenging. However, reduced evaporation of raindrops in dry air for rain reaching ground at higher altitude sites could lead to an altitude dependence in precipitation amount. For areas of similar latitude, a continental climate will have a greater contribution to total annual precipitation from snow. Snow crystals scavenge atmospheric aerosol more efficiently than rain and are also more influenced by wind drift.

In the case of the Sudete mountains, the extensive forest cover means that direct deposition of cap cloud droplets to vegetation can be an important hydrological and chemical input whereas over grass-covered mountains this factor is less significant. Recent measurements of throughfall at forest stands near Stóg Izerski and Szrenica indicate a much lower cloud base and greater contribution from cloud water deposition at the former. The form of the orography in the western Sudete mountains contributes to the frequent formation of valley cloud along the Karkonosze ridge, particularly on the Czech side, which can last for long periods of up to several weeks. Such low-level clouds occur during anticyclonic circulation with a strong stable atmospheric stratification or low inversion layer and are more common during winter. In these conditions, the upper reaches of the mountains are frequently cloud-free and heavily polluted air is trapped in the lower layer. Although windspeeds are low in such circumstances, deposition of cloud droplets, mainly by sedimentation, may be a significant mechanism of pollutant deposition which has a strong altitude dependence.

These factors suggest that, for mid-latitudes, wet deposition patterns may be more difficult to categorise for continental climates than for maritime climates. In order to produce a wet deposition map of the Sudete mountains it will be necessary to accurately ascertain the relative hydrological and chemical contributions of frontal and convective rain, snow, deposition by cap clouds and valley fog.

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