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Deposition in Norwegian Mountain Areas

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Contents

	Page
Summary and conclusions.....	3
Sammendrag og konklusjoner	5
1. Introduction.....	7
2. Precipitation and deposition in Norway	7
2.1 Precipitation climatology	8
2.2 Wet deposition	10
2.3 Dry deposition.....	10
2.4 Deposition patterns	12
3. Deposition of cloud droplets and fog	14
3.1 Cloud and fog droplet formation.....	14
3.2 Cloud and fog droplet chemistry	14
3.3 Orographic cap cloud and seeder-feeder effect	18
3.4 Deposition of cloud and fog droplets	19
4. Cloud and fog droplet deposition in Sweden and Norway	19
4.1 Studies in mountain areas in Sweden.....	19
4.2 Results from Norwegian mountain areas	22
4.2.1 Cloud and fog droplet deposition	22
4.2.2 Seeder-feeder effect	27
5. Seasonal snowcover in Norwegian mountain areas	28
5.1 Snowpack surveys via snow cores	28
5.2 Stationary snow samplers.....	30
6. Exposure to ozone in Norwegian mountain areas.....	31
7. Discussion and recommendations.....	33
7.1.1 Methods to assess pollutant loads in Norway on the regional scale.....	33
7.1.2 Local Investigations of deposition and ozone gradients in Norwegian mountain areas	34
7.1.3 Evaluation of deposition to areas chosen for biodiversity studies.....	35
8. Acknowledgements.....	36
9. References	36

Summary and conclusions

International studies on orographic enhancement of precipitation, cloud and fog droplet deposition and seasonal snow cover have shown that air pollutant deposition to mountain areas may increase strongly with elevation. Since the stations within the Norwegian air pollutant monitoring network are located below the timberline, total deposition to mountain areas may be underestimated.

The objective of this study was to evaluate if the methods used for calculating pollutant deposition on the regional scale (50 x 50 km² grid cells) are precise enough. International scientific literature on deposition to mountain areas was reviewed and discussed together with information on Norwegian topography and climatic conditions. Results from investigations in mountainous regions in Sweden as well as information on cloud droplet composition measured in Norwegian mountain areas were considered.

In Norway pollutant concentrations in precipitation do obviously not increase with elevation. Values decrease with distance from the coast. Thus, the present method of mapping sulfur and nitrogen deposition based on interpolated fields of measured precipitation amounts and mean weighted concentrations is accurate to assess deposition loads on the regional scale. It can be assumed that droplet and rime ice deposition in Norwegian mountain areas contributes with only 10% to total pollutant loads. The principal deposition mechanism for droplets is similar to those for particles (dry deposition). General knowledge about the chemical composition and size typical for fog and cloud droplets at different elevations in mountain areas allows to assess deposition velocities and thus input loads on large scales (e.g., 50 x 50 km grid cells).

Locally, the seeder-feeder effect may lead to an increase in total deposition loads with elevation. In southern, south-western parts of the country, but also close to cities and industrial areas, high episodic pollutant concentrations in fog and cloud droplets may have adverse effects on sensitive plant species. Snow precipitation per area is difficult to measure and assess in Norwegian mountain areas, which may result in an underestimation of total precipitation and pollutant loads.

We recommend to investigate elevational gradients in pollutant concentrations in precipitation, fog and cloud droplet composition, snow cover and ozone at representative sites in Norway. Such studies on the local scale can be used to confirm regional assessment methods for total deposition loads. Investigations should include precipitation, snow cover, cloud droplet and throughfall measurements as well as studies on possible effects on sensitive plant and animal species. The choice of whole catchments within the investigated gradients would allow to apply the watershed mass balance method to quantify total deposition loads.

Generally, ozone concentrations in Norway seem to increase with elevation. Due to relatively low concentrations, this may only have negative effects on vegetation in the south and south-western parts of the country.

Sammendrag og konklusjoner

Internasjonale studier av orografisk økning av nedbør-, sky- og tåkedråpe-deposisjon og av snødekke har vist, at avsetninger av luftforurensninger i fjellområder kan øke betydelig med høyden. Fordi alle stasjoner innen det norske overvåkningsprogrammet er plassert under tregrensen, er det mulig at totale avsetninger til fjellområder blir undervurdert.

Formålet med denne studien er å vurdere om metodene som brukes for å beregne deposisjon av forurensninger på regionale skala (50 x 50 km² ruter) gir tilstrekkelig informasjon også for fjellområde. Internasjonal vitenskapelig litteratur er gjennomgått og diskutert i sammenheng med informasjon om norsk topografi og klimatiske forhold. Det ble også tatt hensyn til resultater fra undersøkelser i svenske fjellområder så vel som informasjon om kjemiske sammensetning av skydråper i norske fjellområder.

Konsentrasjonene av forurensninger i nedbør øker generelt ikke med høyden i Norge. Av den grunn vil interpolerte felter av målte nedbørmengder og midlere veide konsentrasjoner gi gode beskrivelser av tilførsel på den regionale skala. Det kan antas at dråpe- og rimfrostdeposisjon i norske fjellområder bidrar med bare 10% av den totale belastningen. Den prinsipielle deposisjonsmekanismen for dråper er lik som for partikler (tørravsetning). Generell kunnskap om kjemisk sammensetning og mengde typisk for tåke- og skydråper i forskjellige høyde i fjellområder vil gjøre det mulig å vurdere avsetningshastigheter og dermed deposisjonsmengder på større skala. Lokalt kan "seeder-feeder"-effekten føre til en økning av total deposisjon med økende høyde.

I sydlige og sydvestlige deler av landet, men også nær store byer, kan antas at episoder med høye konsentrasjoner av forurensninger i tåke- og skydråper påvirke følsomme plantearter. Snøavsetning pr. areal er vanskelig å måle og vurdere i norske fjellområder, noe som kan føre til en underestimert av total avsetning av forurensninger.

Vi anbefaler å undersøke høydegradienter av forurensningskonsentrasjoner i nedbør, tåke- og skydråper, snødekke og ozon på representative steder i Norge. Slike studier på lokal skala kan brukes til å bekrefte regionale vurderingsmetoder for totalavsetning/eksponering. Undersøkelsene bør omfatte målinger av nedbør, snødekke, skydråper og kronedrypp så vel som studier om mulige effekter på følsomme plante- og dyrearter. Valg av hele vassdrag innen de undersøkte høydegradienter vil gjøre det mulig å anvende massebalansemetoden for den totale vannmengde til å kvantifisere totale avsetninger.

Konsentrasjonene av bakkenær ozon øker med høyden. På grunn av relativ lave konsentrasjoner, er det sannsynligvis bare negative effekter på vegetasjonen i de sydlige og sydvestlige deler av landet.

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

Deposition in Norwegian Mountain Areas

1. Introduction

In Norway wet deposition is the predominant input of acidifying compounds to terrestrial and aquatic ecosystems. Particularly in southern Norway, precipitation originates from air masses that have passed over densely populated and industrialized areas in Europe. Concentrations of sulfate, nitrate and ammonium ions are relatively high and pH values are low. In mountain areas in western and south-western Norway precipitation is strongly enhanced by orographic effects.

In Norway, about 20 % of the total area is located more than 900 m above sea level. Many of these mountainous regions are above the timberline, characterized by thin soils with low base saturation, sparse vegetation and long seasonal snow cover duration. The acid sensitive and mostly nutrient limited terrestrial and aquatic ecosystems in those areas are particularly vulnerable to high acidity and nitrogen concentrations and loads. Additionally, ozone concentrations may increase with elevation.

The major pollutant sources and general deposition processes are well known and understood. Most of the total deposition assessments are based on large-scale models and interpolations of data from single air pollutant measuring sites within monitoring networks. The aim of national and international long-term monitoring of air pollutants is to collect data that are representative for rainfall composition over a larger area, for example within a 50 x 50 km² grid cell. This is why site requirements explicitly exclude locations where complex topographical features may lead to very site specific precipitation samples. However, in mountain areas the chemical pollutant loads through rain, snow, fog and cloud droplets can be much higher compared to surrounding lowland regions.

The aim of this report is to evaluate if mountain areas in Norway are more affected by air pollutant loads than previously assumed. The present understanding of deposition processes and deposition patterns is discussed. International scientific literature on this topic is reviewed and discussed together with information on Norwegian topography and climatic conditions. Results from investigations in Swedish mountain areas close to the Norwegian border are discussed together with information on the chemical composition of cloud droplets in mountainous regions in Norway.

2. Precipitation and deposition in Norway

In Norway precipitation amounts, the chemical composition of cloud, rain or snow water and the total deposition of air pollutants and sea-salts are influenced particularly by the following factors:

- Climate, weather type and meteorological history of the air mass;

- Chemical history of the air mass and chemical transformation during its transport;
- Seasonal variations (e.g., in temperature, photosynthetic activity);
- Orographic enhancement of rainfall or snowfall by mountains;
- Impaction and sedimentation of gases/particles and cloud/fog droplets to vegetation, snow and wet surfaces.

2.1 Precipitation climatology

Precipitation amounts and types in different parts of Norway are strongly influenced by interactions between topography and the cyclonic activity in the North Atlantic. Along the Norwegian west coast precipitation amounts are enhanced by adiabatic cooling of air masses forced over the mountain chains. Westerly and south-westerly winds are predominant, while the inland districts of southern Norway are protected and receive rain mainly with southerly winds. NORDØ and HJORTNÆS (1966) defined precipitation regions based on the relationship between precipitation amounts and indicators of flow and atmospheric pressure (Figure 1).

Region I, the west coast, is characterized by the relatively largest annual rainfall amounts in Norway. Precipitation increases strongly with the elevation above sea level (a.s.l.) where maximum precipitation amounts may reach 4000-5000 mm. Many of the precipitation events are showers combined with strong winds from the north-west and thunderstorms. Monthly amounts are correlated with the pressure gradient along the coast, which is a measure of the on-shore geostrophic wind component (velocity).

Region II, the south-eastern part of Norway, is sheltered by mountains and rarely experiences precipitation with westerly winds. Nevertheless, precipitation amounts are still influenced by cyclonic activity, as demonstrated by the correlation of monthly precipitation amounts with atmospheric pressure. Rainfall amounts are highest in connection with warm-front precipitation when relatively warm and humid air from the south and south is forced over colder residing air. North-east, east, or south-east are the predominant wind directions at ground level during these precipitation events.

The area located between regions I and II in southern Norway is particularly influenced by the deposition of long-range transported air pollutants. It is a transition area where, in the western part, precipitation climatology is similar to those in Region I. However, towards the eastern part it receives progressively more precipitation with winds from the south and south-east. In the mountains of central Norway the transition between the different precipitation regimes is very sharp and weather and climate can change abruptly within a few kilometres.

Region III is relatively similar to Region I, except that the precipitation is more closely connected to winds from the north-west rather than from the south-west. This is also the case for *Region IV*, but the area is also more influenced by continental air masses. Warm front precipitation events may involve air from the east and the south-east. In the southernmost part of Norway precipitation occurs also with westerly and south-westerly winds, but the precipitation amounts are

rather low. Inland areas have a continental climate with very low annual precipitation amounts.

The seasonal distribution of precipitation varies in the different parts of Norway. In coastal areas precipitation amounts are largest in autumn and winter, with a minimum from April to June. Mountain areas in western and northern Norway may experience much snow in winter (see Chapter 5). Inland regions, including the mountain areas in central Norway, receive the largest rainfall amounts in summer, partly in form of convective showers. Precipitation is usually low in some inland valleys surrounded by mountains. At Skjåk and Dovre in Gudbrandsdalen, e.g., rainfall ranges from 300 to 400 mm. The adjacent mountain plateaus receive precipitation amounts of 600 to 800 mm.

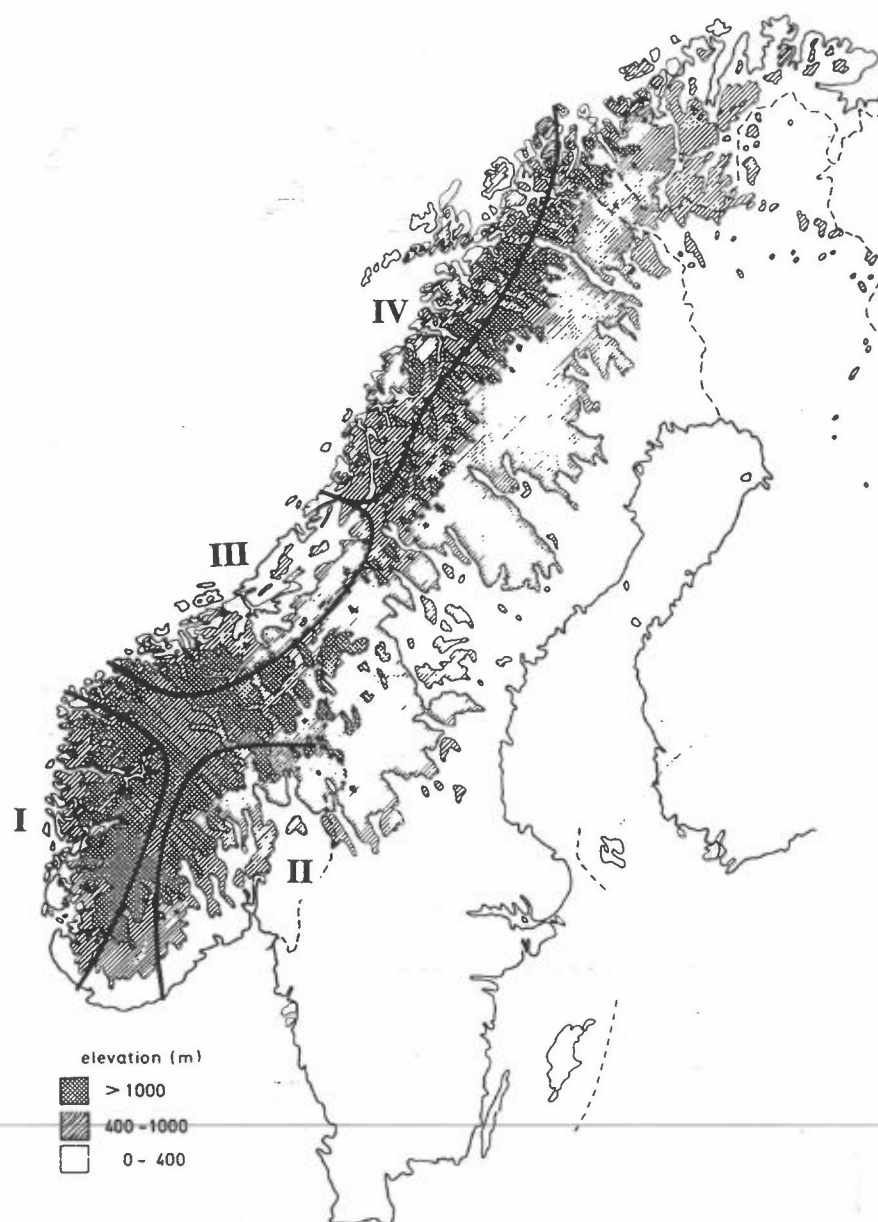


Figure 1: Topographic map of the Scandinavian peninsula showing the precipitation regions I-IV (after Wright and Dovland, 1978).

2.2 Wet deposition

The processes involved in wet deposition have been extensively studied and shall only be summarized in this chapter. Aerosol particles, formed by air pollutants and/or sea-salts, act as condensation nuclei in the formation of cloud droplets. These droplets absorb gases such as nitric acid and sulfur dioxide which are oxidized by hydrogen peroxide (H_2O_2) and ozone (O_3). Both processes are quite efficient, and the concentrations of sulfate (SO_4), nitrate (NO_3) and other ions in the cloud droplets can be predicted from the airborne concentrations and the cloud water content.

The precipitation process is usually initiated by ice crystals which form in the upper part of the cloud at temperatures below -18°C . The crystals grow by accretion of droplets as they fall through the lower layers of the cloud. Most of the rainfall is derived from a range of a few hundred meters (cloud base) to 2000 m meters above ground. Below the cloud base, scavenging of aerosol particles and sulfur dioxide is usually less effective. Nevertheless, highly soluble gases such as nitric acid and ammonia can be absorbed by falling raindrops. There can also be substantial evaporation from the raindrops below the cloud base, particularly when precipitation amounts are small.

2.3 Dry deposition

Gases and aerosol particles can be deposited directly to various surfaces. The most important aerosol particles are sea-salts and ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$). Nitrate can be deposited in form of sodium nitrate (NaNO_3) associated with sea-salt particles, and in some cases as ammonium nitrate (NH_4NO_3) associated with $(\text{NH}_4)_2\text{SO}_4$. The definition "dry deposition" often includes also fog and cloud droplet deposition (= occult deposition). In this report this phenomenon is addressed in Chapter 3.

Depending on the particle size, deposition occurs through diffusion, interception, impaction or sedimentation. Dry deposition of gases is closely related to photosynthetic activity because especially SO_2 , NO_2 and NH_3 are taken up via stomata during the vegetation period. However, wet surfaces, including wet foliage, enhance the adsorption of many gases. Dry deposition is therefore enhanced in coastal regions where humidity is high (Hanson et al., 1989; see also below).

Deposition velocities of particles (and gases) is limited by aerodynamic resistance which decreases with increasing wind velocity and roughness of the underlying surface. While dry deposition to forested areas is high, sparse vegetation and long snow cover duration in Norwegian mountain areas reduce the importance of this deposition process. A number of experimental studies showed that the adsorption of SO_2 and other gases and particles to snow surfaces is low (e.g., Dovland and Hanssen, 1975; Valdez et al., 1987).

Methods to measure and assess dry deposition loads are summarized by Erisman et al. (1993).

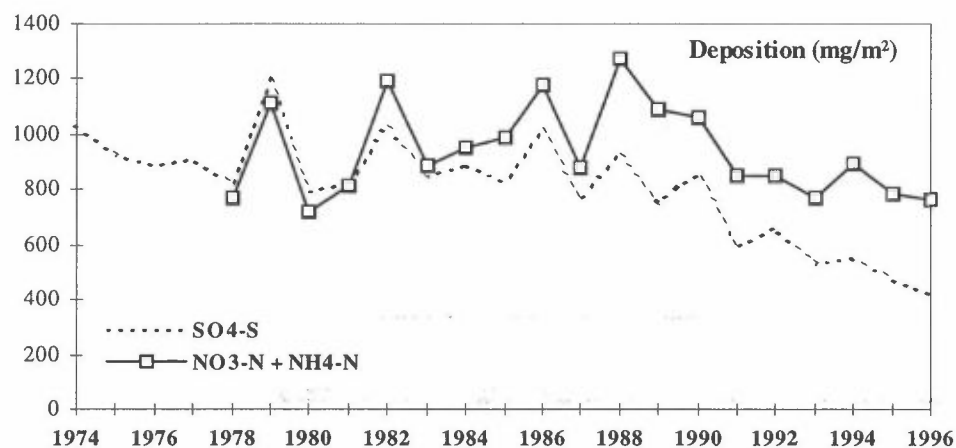
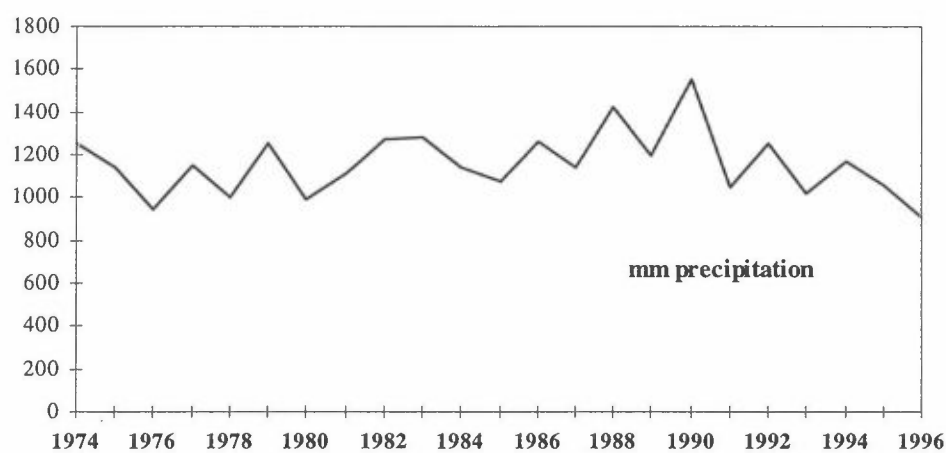
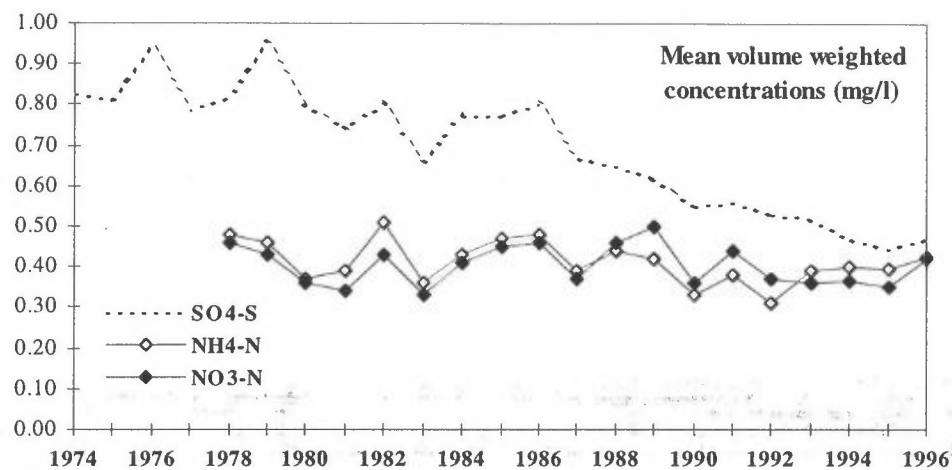


Figure 2: Volume weighted yearly mean concentrations of sulfate (sea-salt corrected), nitrate, ammonium, average yearly precipitation amounts and deposition of SO_4 , sum ($\text{NO}_3 + \text{NH}_4$) for the period 1974–1996 at 7 representative stations in southern and eastern Norway: Birkenes, Lista, Skreådalen, Vatnedalen, Treungen, Gulsvik and Løken (after SFT, 1997).

When discussing the total pollutant loads in different regions in Norway an important fact to be considered is the significant decrease in sulfur (and H^+) in precipitation and deposition over the last 17 years. Since 1980 the volume weighted SO_4 concentrations have decreased by 40 to 60 % in southern Norway, and by 50 to 60 % in northern Norway (Figure 2; SFT, 1997).

2.4 Deposition patterns

Back trajectories allow to identify the origin and history of the air mass in which the precipitating clouds have been formed. In all parts of Norway the maximum concentrations of pollutants in air and precipitation occur with trajectories from the south, i.e., from those areas in Europe where sulfur and nitrogen emissions are largest (Joranger et al., 1980). An exception are some regions in northern Norway where air pollutant deposition is relatively high due to emissions in Russia (e.g., SFT, 1997).

Patterns of precipitation chemistry and pollutant deposition reflect the rainfall regimes in Norway (Figure 3). Areas with no mountain barriers to the south receive the largest amounts of air pollutants. This is especially true for south-eastern Norway, where precipitation occurs predominantly during periods of southerly winds.

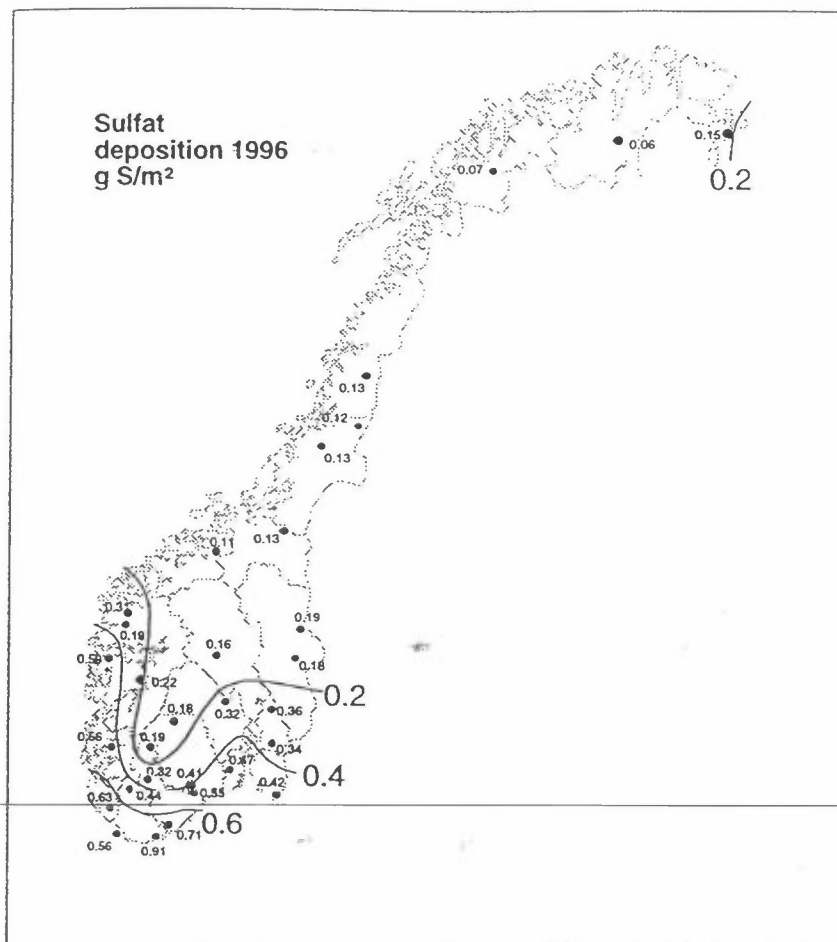


Figure 3: Mean deposition of sulfate (sea-salt corrected) at Norwegian monitoring stations (after SFT, 1997).

Close to the coast, scavenging of sea-salt aerosol droplets results in high deposition loads of sea-salt components in precipitation. This phenomenon occurs episodically, during strong western winds from the North Sea and the North Atlantic (Tørseth and Semb, 1997b). Especially in areas affected by high deposition loads of acidifying pollutants and/or extensive reforestation with spruce, sea-salt events enhance soil and water acidification processes (Hindar et al., 1993).

Within the SNSF project (Acid Precipitation – Effects on Forest and Fish) and, later, within the Norwegian monitoring program on deposition of long-range transported air pollutants a relatively dense network of precipitation sampling sites has been established (Tørseth and Semb, 1995). The measuring results have shown that the concentrations of pollutants and sea-salts in precipitation decrease with distance from the coast. The decrease is particularly strong when precipitation intensity is high due to orographic enhancement. This observation was supported by detailed investigations on the regional variations in precipitation chemistry in western Norway (Fjeld, 1975; Skartveit and Førland, 1976). Additionally, there is a general decrease in concentrations from the southern to the northern part of the country, reflecting the distance from major emission sources.

These findings may be biased because most of the sampling sites are at low elevations compared to those areas where orographic enhancement causes the highest precipitation. However, Wright et al. (1977) found a strong correspondence between the measured concentrations of sulfate in small Norwegian lakes and the estimated weighted mean values of sulfate in precipitation. The SO_4 concentrations in lake water were generally higher than those in the precipitation samples, most pronounced for lakes at relative low altitudes close to the coast, and in areas with relatively little precipitation. Correction for evapotranspiration and the (small) contribution from dry deposition would have improved the correspondence. This encouraged the mapping of sulfur and nitrogen deposition based on interpolated fields of mean weighted concentrations and actual precipitation amounts (Tørseth and Pedersen, 1994; Tørseth and Semb, 1998).

More detailed mapping of deposition at individual catchments was carried out in a mountain area in south-west Norway within the Nitrogen from Mountain to Fjord project (Tørseth and Semb, 1997a). Again, the concentrations decreased with distance from the coast. Nevertheless, since there are strong gradients in precipitation amounts in Norwegian mountain areas, pollutant loads via wet deposition may increase considerably with elevation. The Bjerkeim catchment, for example, is characterized by a coastal climate with strong south-westerly winds from the North Sea. Yearly precipitation ranges from < 1500 mm (low elevation of 160 m a.s.l.) to > 3300 mm (high elevation at 800 m a.s.l.). Assuming that wet deposition at the low elevated site is $7 \text{ kg S ha}^{-1} \text{ yr}^{-1}$ and that there are no elevational changes in air pollutant concentrations in precipitation. Then deposition at the high elevated site becomes $15 \text{ kg S ha}^{-1} \text{ yr}^{-1}$, only due to enhancement of rain- and snowfall.

3. Deposition of cloud droplets and fog

3.1 Cloud and fog droplet formation

Physical and chemical processes in clouds and fogs are very similar. Fog may simply be defined as cloud in contact with the earth's surface. Cloud and fog formation is caused by the condensation of water vapour. At relative humidities above 80%, water-soluble salt particles act as condensation nuclei and start taking up water according to the equilibrium partial pressure of water in the droplet solutions. These particles can be nitrates and sulfates originating from pollutant emissions or sea-salts.

In addition to incorporating the water-soluble aerosol particles, cloud droplets will also take up soluble gases, mainly nitric acid, ammonia and sulfur dioxide. Uptake of sulfur dioxide depends on the oxidation of dissolved bisulphite ions, which is rapid in the presence of hydrogen peroxide. The oxidation rate through ozone at ambient concentrations is slower, particularly at low pH in the aqueous phase (Penkett et al., 1979).

Three different kinds of fog can be distinguished:

- *Radiation fog:*
At night, moist air close to ground is cooled below the dew point. Activation of aerosol particles then produces fog droplets which grow as the cooling proceeds.
- *Advection fog:*
Warm moist air moves over a cold surface, and the cooling that results can produce fog. Most coastal fogs are of this type.
- *Upslope fog or orographic cloud:*
Air that is forced to rise over a topographic barrier (hill or mountain) experiences decreasing atmospheric pressure leading to expansion and cooling of the air.

Radiation fogs often appear at low ground and are closely coupled to local topography and climatology. Fog chemistry may be strongly influenced by local pollution sources.

Fog and cloud droplets can be sampled with passive or active sampling devices (Erisman et al., 1993). Passive sampling methods are usually based on the impaction of wind-driven droplets on cylindrical threads with a diameter close to that of the droplets. Active samplers include a fan to draw the air through a set of impactor stages, or include cyclones to separate the droplets from the air. Rotating impactor-collectors have also been used. Comparisons of fog water samplers were carried out, e.g., by Schell et al. (1992).

3.2 Cloud and fog droplet chemistry

The concentration of pollutants in cloud and fog droplets is mainly a function of:

- the concentration of pollutants in the air mass from which the droplets have been formed;
- the degree by which these pollutants have been incorporated into the cloud droplets;
- the total volume of condensed water in which the pollutants are dissolved.

Water content in precipitating clouds is typically 1-2 g/m³, in non-precipitating clouds it is usually less. Based on aircraft sampling of cloud water in the former USSR, Petrenchuk and Selezneva (1970) concluded that non-precipitating clouds show higher amounts of pollutants than precipitation. The concentrations vary with cloud characteristics and the synoptic situations. Stratus subinversion type clouds of anticyclonic origin, in particular, contain large amounts of contaminants. Due to washout of pollutants below the cloud base, precipitation samples generally contain somewhat higher concentrations of dissolved ions than the droplets in precipitating clouds themselves (Scott, 1978).

The liquid water content of fog droplets is usually much lower than 1 g/m³ so that the pollutant concentrations are relatively high compared to those in snow and rain. This is particularly the case in areas where the ambient air concentrations at ground level are dominated by emission sources within a radius of a few hundred kilometres.

Extensive long-term studies on hill and mountain cloud chemistry in Europe were conducted in Italy (Fuzzi et al., 1992), Germany (Wobrock et al., 1994) and Great Britain (Fuzzi, 1997). The experiments were part of a EUROTRAC sub-project, and the locations chosen were characterized by different climatic and pollution conditions. In the Po Valley in Italy the multiphase system of radiation fog in heavily polluted areas was studied (in 1989). Stratus and strato-cumulus clouds impinging on Kleiner Feldberg, a hill in central Germany, were investigated in 1990. Kleiner Feldberg is characterized by high air pollution conditions, partly due to emissions from the nearby Rhein-Main industrial area. In 1993 the third experiment took place at Great Dun Fell in the UK. The aim was to study cap clouds characterized by high updraught in a "clean" environment. The most important pollutant source identified for Great Dun Fell was long-range transported air mass with continental influence (Swietlicki et al., 1997).

Cloud measurements similar to those in Europe were conducted within the Mountain Cloud Chemistry Project (MCCP) in the USA. The studies included clouds at different sites in Maine, New York, New Hampshire, Virginia, Alaska, Oregon, northern California and North Carolina (e.g., Weathers et al., 1988; Mohnen and Vong, 1993; see also reviews by Lovett and Kinsman, 1990; Fowler et al., 1993).

Some general results of the above mentioned cloud investigations are:

- Chemical composition of cloud water is very site specific.
- Not only cloud chemistry, but also cloud immersion frequency and duration determine the pollutant deposition load in mountain areas.

- Liquid water content of the cloud (droplets) usually increases with height above cloud base, and eventually declines again towards the top of the cloud.
- Pollutant concentrations decrease as liquid water content increases. The closer to the cloud base, the higher are the concentrations.
- Cloud water often contains the major ions in very similar ratios as those typical for precipitation at the same sites.

Whiteface Mountain, a forested area in New York (USA), is a typical example showing how liquid water content (LWC) in non-precipitating clouds increases with elevation while SO_4 concentrations in cloud droplets decrease simultaneously (Figure 4; Mohnen and Vong, 1993). SO_4 values are very high at 1250 m a.s.l., about $700 \mu\text{eq l}^{-1}$, and decrease to ca. $400 \mu\text{eq l}^{-1}$ at the higher elevation (1483 m a.s.l.).

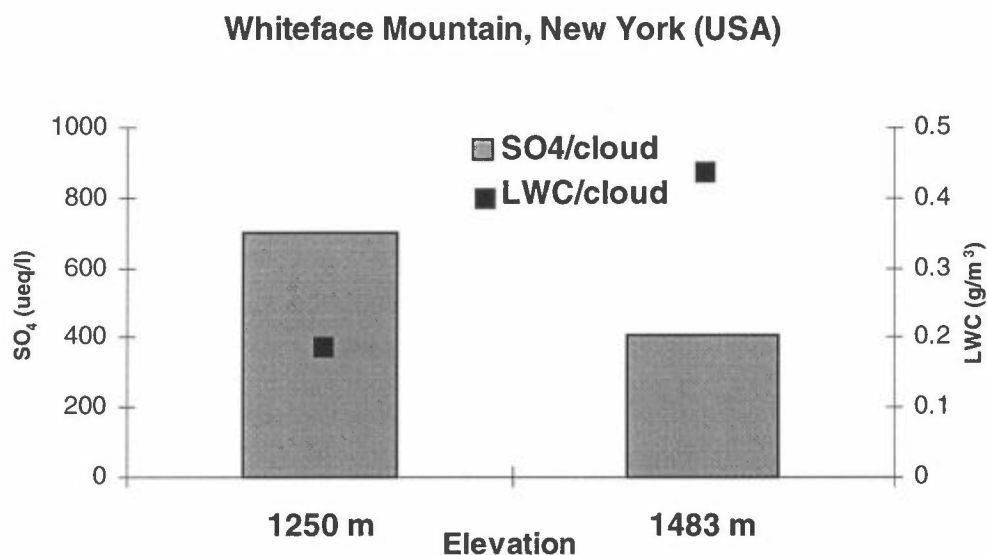


Figure 4: Mean liquid water content (LWC) and sulfate concentrations in cloud water at different elevations at Whiteface Mountain (New York, USA; with numbers from Mohnen and Vong, 1993).

Great Dun Fell is a hill in Northern England (UK) characterized by grassland. Liquid water contents of cloud droplets at low and high elevations are very similar compared to those at Whiteface Mountain (Figure 4 and Figure 5; Fowler et al., 1993). Droplet size increases with elevation (diameter = $7.5 \mu\text{m}$ at 600 m and $10.0 \mu\text{m}$ at 847 m a.s.l.). Sulfate, nitrate and H^+ concentrations in cloud droplets are also comparable to those at the North American site (Table 2), Figure 6 shows a typical frequency distribution diagram of ions in non-precipitating clouds at the White Face summit (New York, USA).

Great Dun Fell, Northern England (UK)

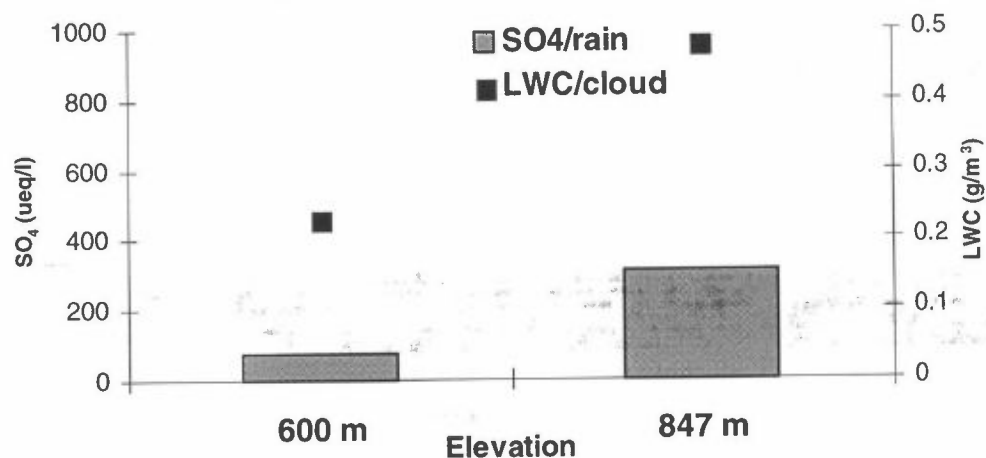


Figure 5: Mean liquid water content (LWC) in cloud water and sulfate concentrations in rain at different elevations at Great Dun Fell (Northern England, UK); with numbers from Fowler et al., 1993)

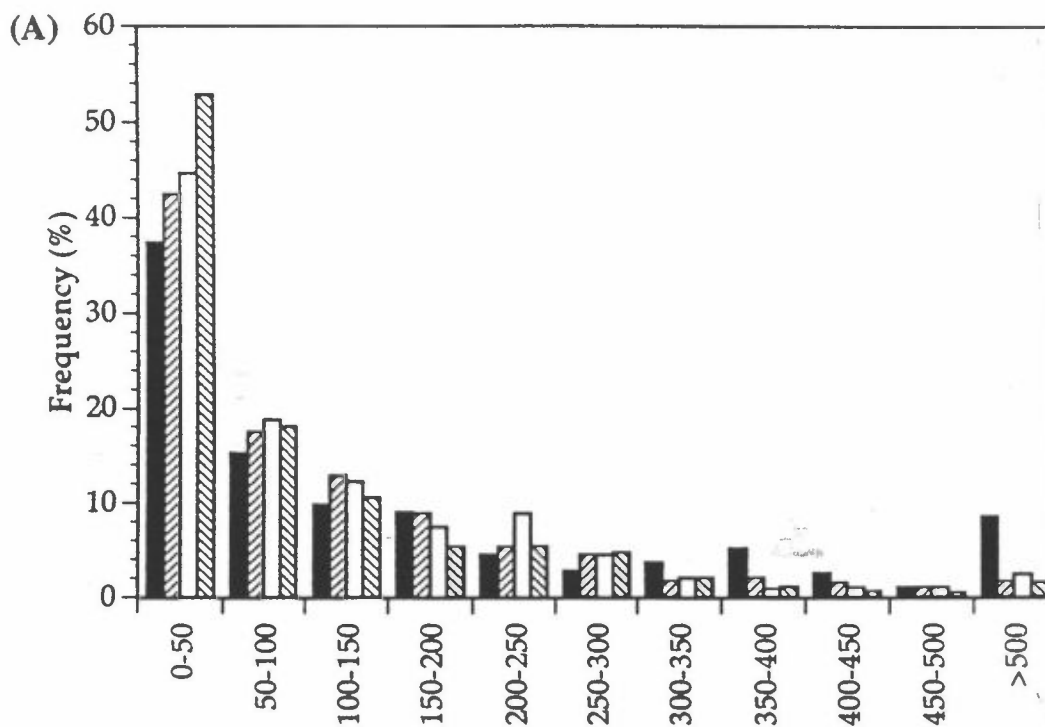


Figure 6: Relative frequency distribution of ions in non-precipitating clouds for Whiteface Mountain summit. Each bar represents one of the major ions (after Mohnen and Vong, 1993).

3.3 Orographic cap cloud and seeder-feeder effect

Orographic cloud can be fed by boundary layer polluted air (Fowler et al., 1993). Since the majority of the ionic content of orographic cloud water is derived from upwind aerosol particles, the composition of the particles provides the best guide to cloud water composition. Above the boundary layer, at very high altitude sites (> 2000 m), the air may be relatively "clean".

For aerodynamic reasons falling rain droplets are not very efficient collectors of submicron aerosol particles, and absorption of sulfur dioxide is not particularly efficient either. However, when aerosol particles are incorporated in cloud droplets, collection efficiencies become much higher. The cloud droplets also increase the deposition of sulfur dioxide: SO₂ is taken up by the droplets and oxidized by hydrogen peroxide and ozone (Hill et al., 1986; Gervat et al., 1988). SO₄ values in precipitation at Great Dun Fell in the UK, though generally much lower than those in cloud droplets, are higher at 847 m than at 600 m elevation (Figure 6). This is caused by the seeder-feeder process: Rain from a high-altitude cloud falls through the cap cloud on the top of the mountain and scavenges cloud droplets with high pollutant concentrations (Fowler et al., 1988).

However, this process is site specific. At Great Dun Fell the seeder-feeder effect is caused by the geographic location of the hill relative to emission sources in combination with moving cyclones and frontal precipitation systems. In the warm-front part of the precipitation system, wind directions change strongly with altitude as relatively warm air from south-west is forced over cold air which changes direction from easterly to south-easterly. This results in cloud and precipitation formation in the bottom layers of the warm airmass, which subsequently replaces the cold air. This situation is then succeeded by a cold front with transport of cold air, usually from north-west, causing vigorous vertical mixing and showers. The seeder-feeder effect is primarily important during warm-front precipitation, where cloud layers are strongly stratified and each layer represents air parcels with different origins and histories. It cannot be expected to occur in cold front precipitation systems, mainly because of the increased vertical mixture which occurs in cold front shower clouds.

Because of the inefficiency of below-cloud scavenging processes, emission sources in the easterly and south-easterly sectors will normally not contribute much to the pollutant concentrations in rain and snow. On the other hand, if orographic lifting causes formation of low clouds in the cold air beneath the warm front, contributions from sources in the south-easterly and easterly directions of the sampling site will increase markedly.

At Great Dun Fell it appears that the main wind direction responsible for lifting air over high ground and leading to the seeder-feeder effect is from south-west. This air mass originates from a wide sector ranging from Belfast to Liverpool. Precipitation from high-altitude clouds, in the absence of a cap cloud, is much less contaminated.

3.4 Deposition of cloud and fog droplets

The definition “dry” deposition often also includes the impaction and sedimentation of fog and cloud droplets to vegetation or other surfaces. Formation of cloud and fog droplets starts when the air becomes supersaturated with respect to water vapour. The droplet size is a function of the liquid water content and the number of activated cloud nuclei. Studies on fog deposition have shown that the deposition rate is mainly determined by the aerodynamic resistance, with typical deposition velocities of several cm/s (Dollard et al., 1983). Dollard et al. (1983) assessed that about 17% of the annual total sulfur deposition at Great Dun Fell (UK) can be attributed to cloud and fog deposition. They based their calculation on cloud and fog frequencies and typical sulfate concentrations in droplet samples. Reviewing investigations on deposition to high-altitude regions at different locations in the USA, Lovett and Kinsman (1990) stated that 15 to 80% of total deposition can be attributed to cloud and fog droplet inputs.

However, in contrary to Great Dun Fell many of the sites investigated in the USA are forested. Due to large surface areas and reduced aerodynamic resistance, especially coniferous trees are very effective in removing particles and droplets from the air. Lovett (1984) concludes that wind speed, cloud/fog frequency and canopy structure are the main parameters controlling cloud water deposition. Thus, mountain tops or hills intruding into a low level cloud deck, are especially affected by droplet impaction. Exposed trees, e.g. at the timberline, receive up to 10 times more cloud water deposition than closed-canopy trees (Hasselrot and Grennfelt, 1987; Dasch, 1987).

4. Cloud and fog droplet deposition in Sweden and Norway

4.1 Studies in mountain areas in Sweden

In a recent Swedish study the influence of elevation on the total deposition of acidifying air pollutants was investigated (Westling and Ferm, 1998). The sites studied over a period of several months were Abisko (close to the Norwegian station Øverbygd), Ammarnäs (close to Tustervatn), Djursvallen and Fulufjället (both close to Valdalen and Osen). Not only wet deposition (rain, snow), but also cloud droplet deposition was measured by passive fog samplers. At four sites the results showed a rise in total deposition of SO_4 , NO_3 and H^+ with increasing altitude (Figure 7, Figure 8). The effect is most pronounced at Ammarnäs and Fulufjället, a mountain area close to Norwegian border in Hedmark county.

Westling and Ferm, 1998 assessed much higher deposition velocities, especially for particles, compared to low elevated sites (Table 1). They attribute the increase in total deposition at high altitudes to high frequencies of fog events and cloud droplet deposition, especially in winter. Additionally, high wind velocities enhance deposition processes. The largest increases were found at southern slopes or southern parts of the investigated mountain areas, indicating long-range transport from southern parts of Sweden or from central Europe. These results are in line with findings of the different cloud experiments mentioned in Chapter 4.1.

SO₄ Deposition at Different Elevations in Swedish Mountains

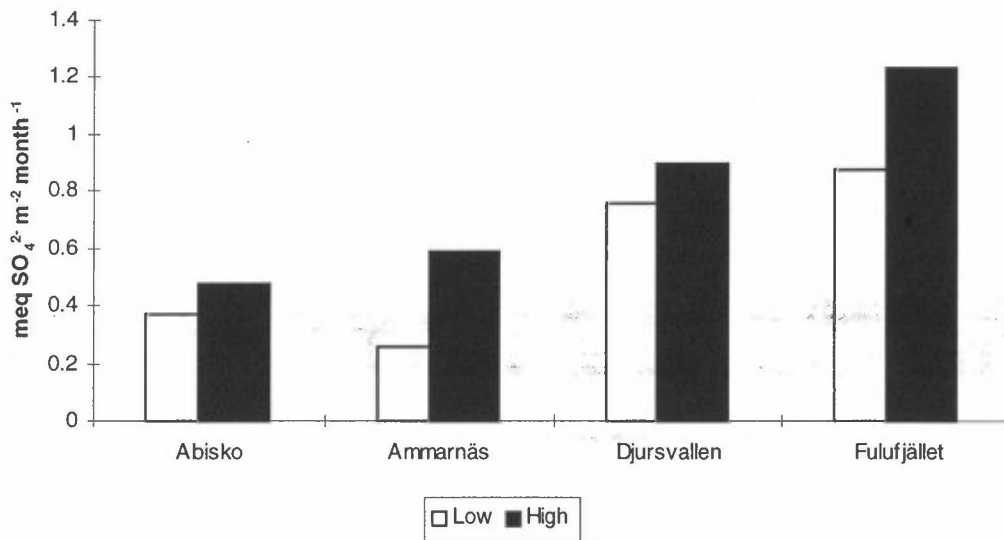


Figure 7: Total sulfate deposition at low and high elevations in Swedish mountain areas (with numbers from Westling and Ferm, 1998).

H⁺ Deposition at Different Elevations in Swedish Mountains

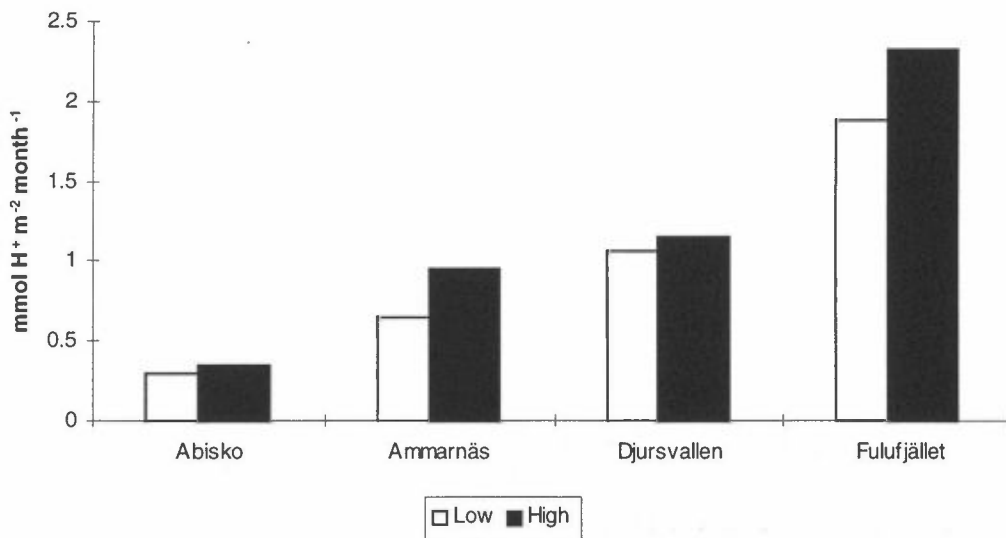


Figure 8: Total H⁺ deposition at low and high elevations in Swedish mountain areas (with numbers from Westling and Ferm, 1998).

Table 1: Assessed deposition velocities and air concentrations in four Swedish mountain areas and calculated (after Westling and Ferm, 1998; for details see there); h.e. = high elevation, l.e. = low elevation

Mountain	Elevation m above sea level	NH ₄ ⁺	SO ₄ ²⁻	SO ₂	tot-NO ₃ ⁻
<i>Deposition velocity Vd mm/s</i>					
Abisko (h.e.)	361	1.5	1.4	1.4	5.0
Ammarnäs (h.e.)	541	1.6	1.3	1.3	4.5
Djursvallen (h.e.)	600	1.1	0.7	0.7	4.7
Fulufjäll (h.e.)	480	0.4	0.7	0.7	0.7
Abisko (l.e.)	1190	3.6	5.3	12	12
Ammarnäs (l.e.)	1068	9.7	7.7	29	29
Djursvallen (l.e.)	900	3.4	2.8	16	16
Fulufjäll (l.e.)	900	3.1	2.6	8	8
<i>Air concentrations nmol m⁻³</i>					
Abisko		15	8	8	4
Ammarnäs		15	9	10	4
Djursvallen		20	10	15	5
Fulufjäll		50	25	30	25

Another important finding of the Swedish study (Westling and Ferm, 1998) was that the highest total deposition loads were calculated for forests at the timberline. In coniferous forests aerodynamic roughness and thus filter capacity for gases, particles, fog and cloud droplets is very high. Throughfall measurements at Fulufjäll at 480 m and 790 m a.s.l showed that considerable amounts of snow were caught by tree canopies during winter so that throughfall concentrations of SO₄ at the high elevated site are lower during this period (Figure 9). The snow melts at mild weather in April–May, when SO₄ shows peak concentrations. Westling and Ferm (1998) conclude that regularly throughfall measurements beneath the canopies are a reliable method to assess total deposition of sulfur at the timberline. Such a conclusion cannot be drawn for nitrogen and nutrient cations (potassium, magnesium, calcium) because their dynamics is strongly influenced by biological cycling, i.e., uptake and canopy leaching processes.

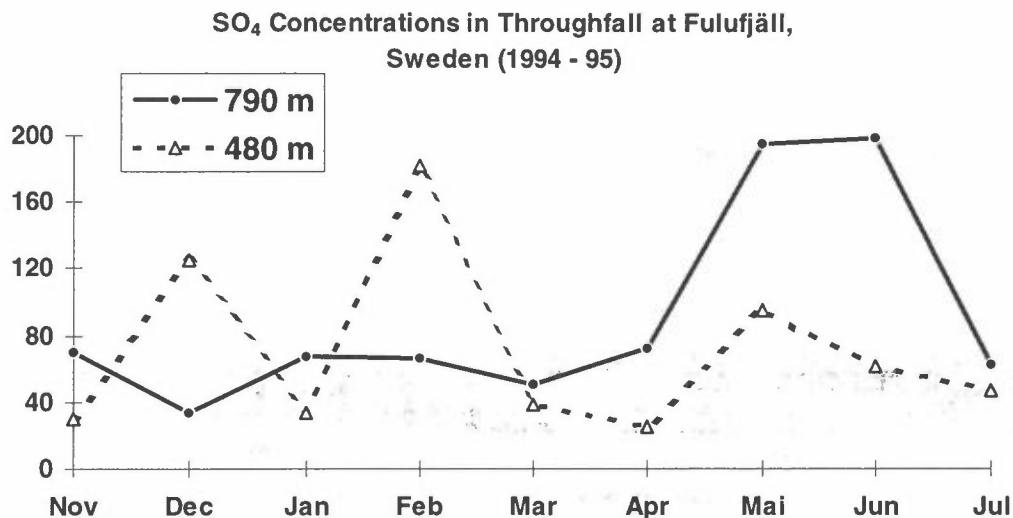


Figure 9: Sulfate concentrations in throughfall at high and low elevations at Fulufjäll, Sweden, 1994–1995 (with numbers from Westling and Ferm, 1998).

4.2 Results from Norwegian mountain areas

4.2.1 Cloud and fog droplet deposition

According to Dannevig (1969) fog frequency is low on the inland mountain plateaus in southern Norway (2 to 3% of the time). Advection fogs occur in autumn and winter. Exceptions are isolated mountains rising above the surrounding area, particularly, if these mountains are freely exposed to the south or south-east. Here fog frequency can be as high as 40-50%. This may be due to both a layer of cloud passing over a mountain or orographic cloud.

Cloud and fog droplet deposition have not been measured in high elevated mountain areas in Norway. Nevertheless, studies on the effects of clean and contaminated snow and ice accretions on high voltage insulators give some information on pollutant concentrations. On transmission lines in inland mountain areas, characterized by high fog frequency, droplets enriched with sea-salts and air pollutants accrete on high voltage isolators. Droplet water evaporates, and rewetting (clouds, fog) leads to electrolyte concentrations that may cause flashovers. During cold seasons the droplets freeze (“rime ice”).

Vegetation surfaces in mountain areas are effected by the same processes. *Locally*, pollutant concentrations in cloud and fog droplets can be very high over longer periods. Several studies have shown that this “acid rain”, often with pH values of 3.0 and less, has direct physiological effects on sensitive plant species, especially mosses. Negative effects on leaves are necrosis, chlorophyll damage, leaching of base cations and a reduced frost resistance. The highest pollutant deposition loads will undoubtedly occur to coniferous trees at the timberline, at isolated hilltops or ridges where fog frequency is high. It is also likely that the vegetation exposed to the polluted canopy throughfall suffers physiological damage.

In 1987 to 1992, 55 ice samples were collected from pylons and isolators at 6 locations in Norway with elevations from 600 to 1800 m a.s.l. (Figure 10; Fikke et al., 1992).

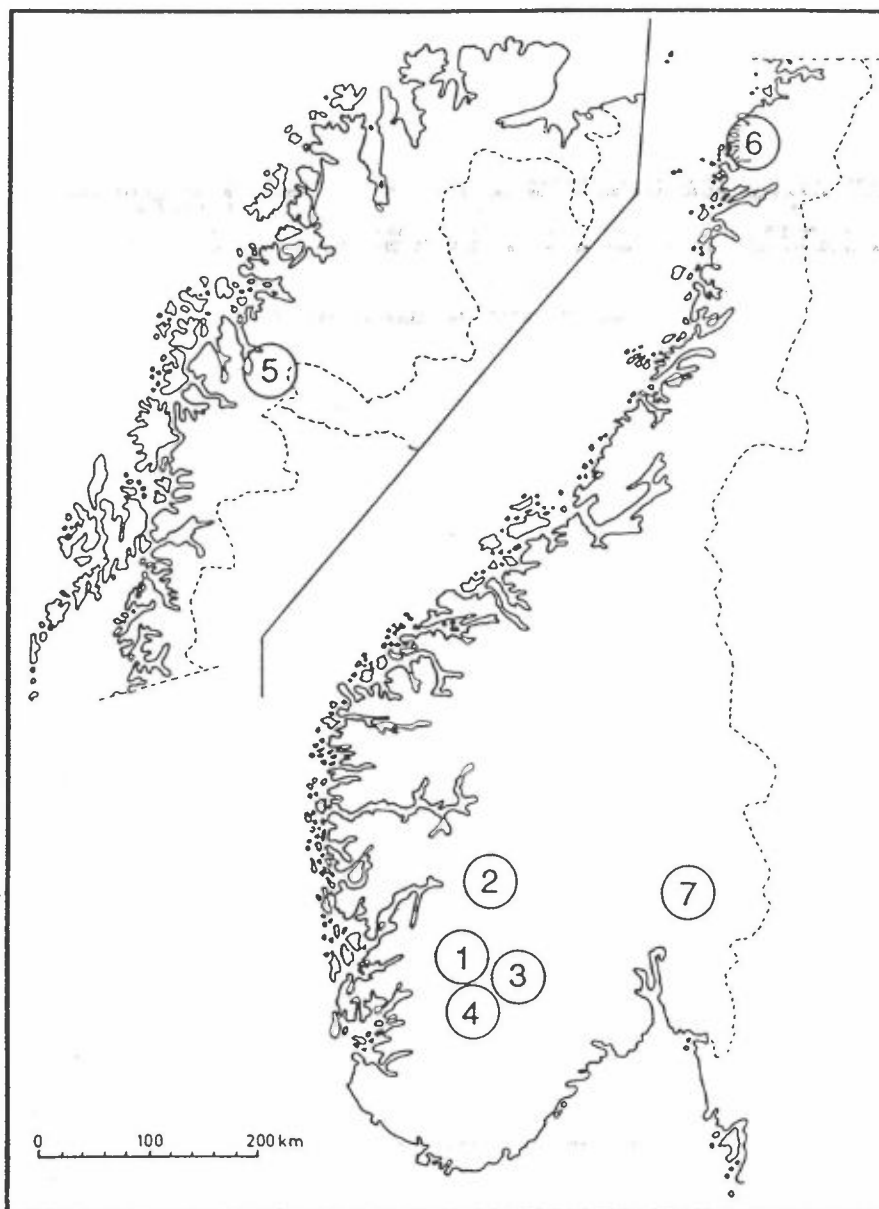


Figure 10: Geographical references for rime ice samples taken in 1987–1991 in Norway (from Fikke et al., 1992).

Sulfate, nitrate and H^+ values in the 55 samples show similar patterns, but there is obviously no relation between high concentrations and elevation (Figure 11). This is not surprising because the samples were taken at very different locations (see Figure 9).

Ion Conc. in Rime Ice from Norwegian Mountain Areas

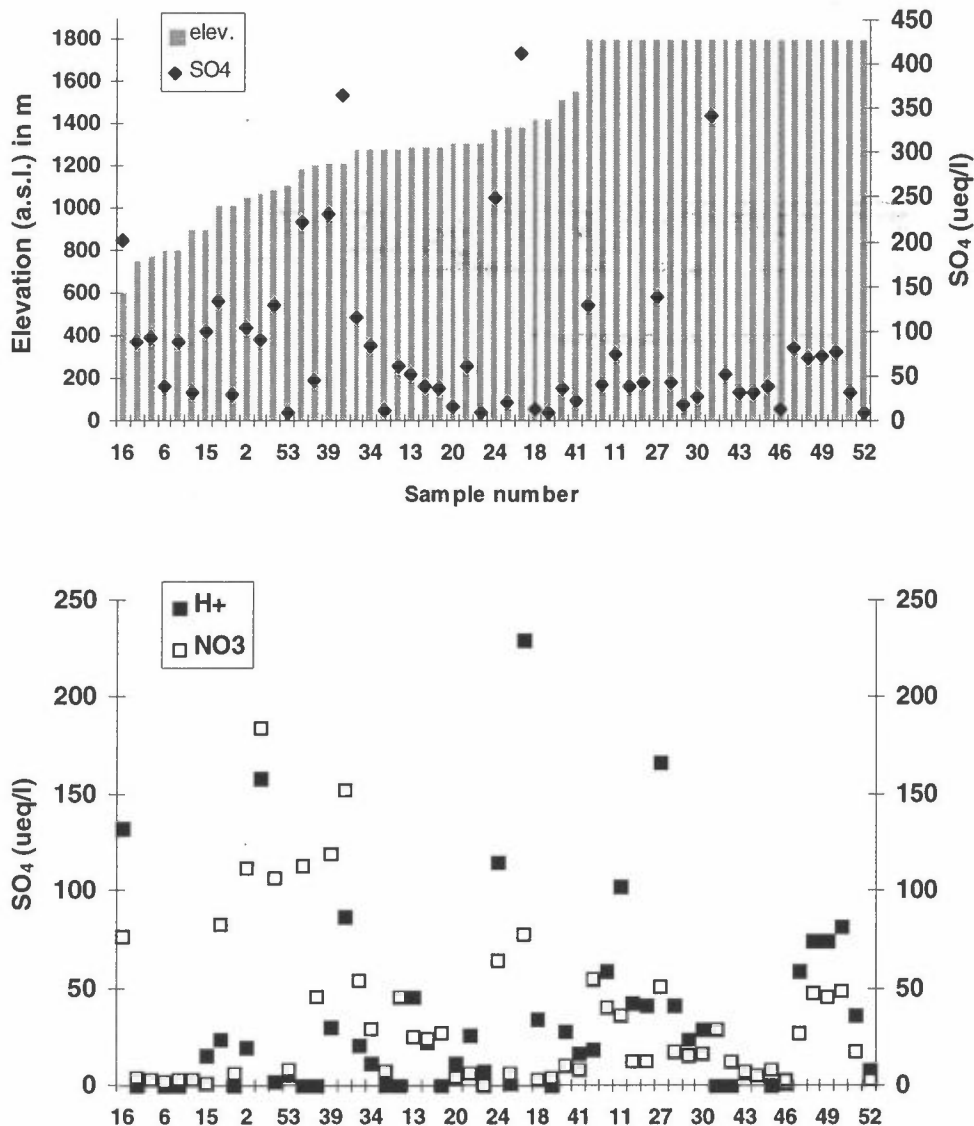


Figure 11: Ion concentrations in rime ice samples taken in 1987–1991 in Norway; upper panel: sampling elevation and sulfate concentrations; lower panel: H⁺ and nitrate concentrations for the same samples (with numbers from Fikke et al., 1992).

Many of the melted samples showed high concentrations of sulfate, nitrate and H⁺ (low pH values). SO₄, NO₃, H⁺ and NH₄ values were on average lower, but nevertheless comparable to those typical for fog and cloud droplets measured in the European and North American cloud experiments (Figure 12; see Figure 6 in Chapter 4.1). However, episodic peak values of > 200 μeq H⁺ l⁻¹ (≅ pH 3.7) during rime ice episodes can have negative effects on vegetation and lichens.

Relative Frequency Distribution of SO₄ Conc. in Rime Ice

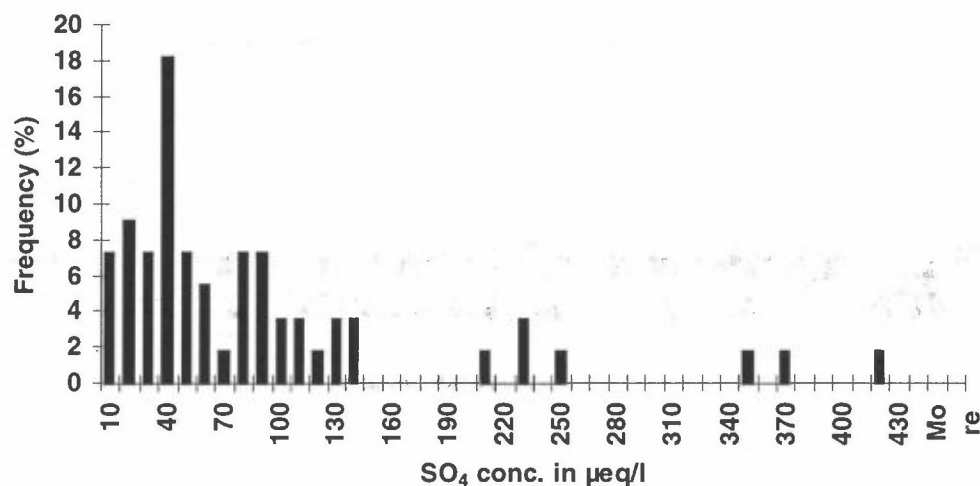


Figure 12: Relative frequency distribution of sulfate and nitrate concentrations in rime ice (1989–1991) in different regions of Norway (with numbers from Fikke et al., 1992).

The results showed three typical solution types, with (Figure 13):

- (1) Very high contents of air pollutants.
- (2) High contents of both sea-salts and anthropogenic air pollutants;
- (3) High contents of sea-salts and low concentrations of anthropogenic air pollutants.

The relations were different for the 7 sampling regions (Figure 10). The relatively highest pollutant values were found in regions 2 (Kvanndal-Songa, Kvilldal-Syilling) and 7 (Fåberg-Røykås; close to Oslo). With sulfate values of up to about 420 µeq l⁻¹ and nitrate values of up to ca. 225 µeq l⁻¹ concentrations in region 2 were the highest measured during the investigation (1987–1992). Moderate pollutant levels and contributions to total concentrations were found at site 4 (most samples from Gaustatoppen) and 5 (close to the monitoring station Øverbygd). At site 5, concentrations are not very high, but sea-salt contribution is almost negligible. Low pollutant contributions were measured for region 1 (close to the monitoring site Voss) and 4 (Holen). At site 6 (at the north-west coast) almost all ions originated from sea-salts (Figure 13).

This pattern reflects nicely the isolines for total sulfur and nitrogen deposition calculated by Tørseth and Pedersen (1992) for the period 1988–1992. The strong sea-salt influence at locations close to the coast could also be confirmed by recent estimates by Tørseth and Semb (1997b) which included also sea-salts and non sea-salt potassium and calcium (period: 1992–1996).

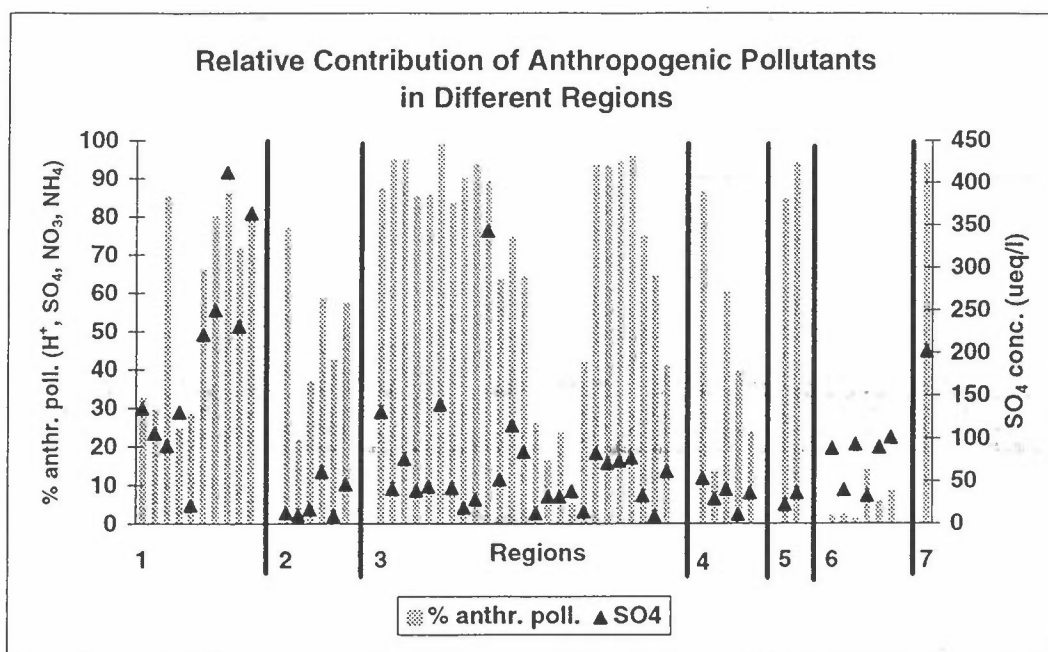


Figure 13: Relative contribution of anthropogenic pollutants in rime ice 1989 to 1991 in different regions in Norway (with numbers from Fikke et al., 1992).

Fog deposition in form of supercooled water droplets (rime ice) was also a severe problem at a radar dome on the summit of Hummelfjell south of Røros (elevation = 1543 m a.s.l.). Here the deposition of ice to different technical installations was studied. In this connection, in 1975 melted rime ice samples were sent to NILU and analyzed. Sulfate values in the analyzed samples were much higher than those measured in precipitation at the nearby monitoring station, Tågmyra in Trysil (Figure 14). Maximum peaks in sea-salt corrected sulfate concentrations were about 400, 600 and 800 $\mu\text{eq l}^{-1}$ (compare to those at Whiteface Mountain and Great Dun Fell).

Due to successful emission reduction measures in Europe, volume weighted sulfate concentrations in Norway have decreased by about 50% since 1977 (e.g., SFT, 1997). This trend is certainly also reflected in cloud/fog droplet and rime ice concentrations. However, peak values during episodes with high air pollutant concentrations and high fog frequencies may still have direct harmful effects on sensitive plant and lichen species, effects that might not be covered by critical loads calculations.

SO₄ conc. in precipitation and fog at Hummelfjell in 1975

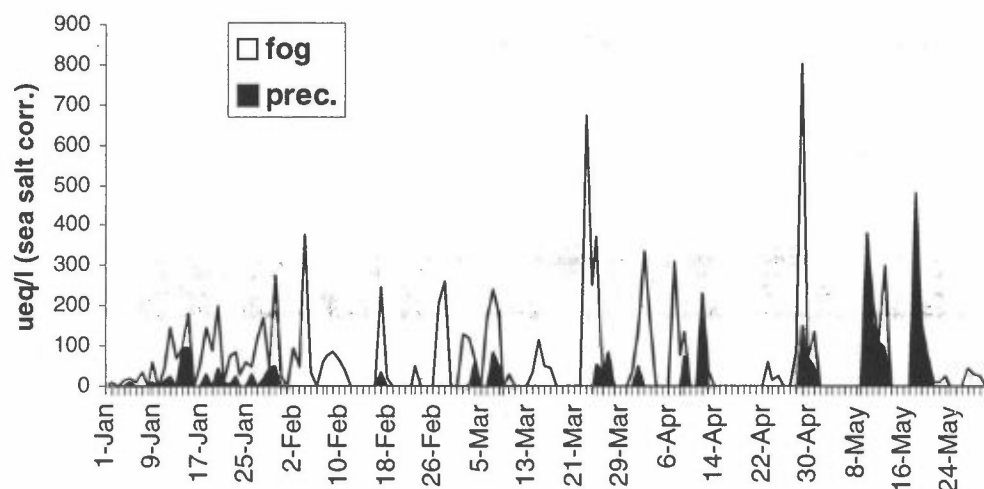


Figure 14: Sulfate concentrations in precipitation and fog water at Hummelfjell, Norway, in 1975.

The interesting question arises: How big is the contribution of cloud and fog droplet input to total deposition loads of air pollutants in Norwegian mountain areas. According to a review by Lovett and Kinsman (1990) cloud water loads in the north-eastern USA can range from 15 to 80% (annual estimates) of total deposition. SO₄, NO₃ and H⁺ loads at high elevated sites (800 to 2000 m a.s.l.) can be 3 to 7 times higher than deposition to nearby lowlands. High cloud water inputs are named as the main cause.

However, due to sparse vegetation and long snow cover duration it can be assumed that droplet and rime ice deposition in Norwegian mountain areas contributes usually not more than 10% to total pollutant loads. At a wind speed of 7 m/s the deposition velocity of fog droplets at Great Dun Fell was calculated to be between 5 and 7 cm/s. Extending these results to a full year on the basis of observed cloud and fog frequencies led to an estimated liquid water deposition of 50 to 130 mm. These numbers may also be realistic for Norwegian mountain tops experiencing high cloud and fog frequencies.

4.2.2 Seeder-feeder effect

The seeder-feeder mechanism is obviously important in Norway, although there is no general increase in air pollutant concentrations in precipitation with increasing altitude. However, highly polluted cap clouds may occur, as indicated by observations at Hummelfjell. Another indication was the fallout of radioactive material observed in connection with the Chernobyl nuclear accident in 1986. Between 28 and 30 April 1986 the radioactive cloud passed over Sweden and Norway with south-easterly winds (Pacyna et al., 1986; Saltbones and Foss, 1986). An occluded front brought precipitation with westerly and south-westerly winds in western and northern Norway and the mixing of these two air masses

caused deposition of radioactive material over the mountain areas in central Norway and further north, mainly to the mountainous areas in Trøndelag. Radioactivity was detected in precipitation samples at Gulsvik, Kårvatn, and Tustervatn, but the largest values were found in mountain areas in central Norway. Soil and vegetation samples were taken subsequently in the Gulsvik area. The analyses showed a steady increase of radioactivity with increasing altitude (Pacyna et al., 1988). Similar observations were also made in the Kongsvoll area. In early May 1986 radioactivity originating from Chernobyl was also deposited in south-western and western Norway.

5. Seasonal snowcover in Norwegian mountain areas

Snow is often the major form of precipitation in Norwegian mountain areas, and snow-cover may last for 8 months. There are two major aspects that have to be considered when measuring or assessing snow precipitation in mountain areas (Delmas et al., 1988; Davies et al., 1988; Westling and Ferm, 1998):

- High spatial variability in complex terrain (areas exposed to bedrock, steep valleys etc.) and post-fall wind redistribution lead to non-uniform deposition fields during snowfall events.
- Partial snow melt may even occur during winter months in mountain areas, resulting in depletion of ions accumulated in the snow pack.

Both factors have a strong influence on the thickness and characteristics of the snow-pack. Attempts to measure snow precipitation amounts and chemical composition in mountain areas help assess total deposition loads at high elevated sites. There are two common ways to measure snow precipitation in mountains: (1) sampling of accumulated snow in spring by using snow cores and (2) precipitation chemistry stations equipped with different kinds of snow samplers.

5.1 Snowpack surveys via snow cores

Systematic chemical analyses of the snowpack in Norway were carried out in 1975 and 1976 (Wright and Dovland, 1978). A 10 x 10 km block was selected at random from each square of a 50-km grid, samples were also taken adjacent to 5 precipitation chemistry stations run by NILU, and a spot with representative snow depth was chosen within an open 100 m² area. 86 sites in southern Norway and 65 sites in northern Norway, Sweden and Finland were included into the survey. Snow samples were taken with snow cores, mostly at high elevated sites. The main findings were:

- (1) There may be large differences in precipitation amount, pollutant concentrations and loads between:
 - (a) replicate snow core samples collected at the same location;
 - (b) snow core samples and precipitation samples from nearby monitoring stations.

- (2) Patterns of precipitation and snowpack chemistry reflect the rainfall regimes in Norway which themselves are influenced by meteorological factors in general, and by orographic effects caused by mountains and hills in particular. The chemical composition of precipitation and snowpack is a result of:
- long-range transported air pollutants (especially in south-eastern Norway);
 - sea water salts (especially Norwegian west and north-west coast).

The study further showed that replicate samples of the snowpack collected at the same site revealed 10-30% differences in the concentrations of major ions. The load (mg m^{-2}) of each chemical component in snowpack varied even more among duplicate samples than did the concentrations. This was due to large variations in snowpack depth and hence meltwater volume, and it reflects the high spatial variability in mountain terrain. Westling and Ferm (1998) mapped different snow types at Hundshögen, a mountain area in Sweden close to Östersund (1371 m above sea level). They found no significant relation between snow type and pollutant concentrations. This finding includes snow profiles at very high elevations which were dominated by deposited rime ice. Nevertheless, the snow mapping method makes it easier to assess total snow precipitation amount for a certain area.

In 1975 and 1976 snow core samples were also taken close to 5 of NILU's precipitation chemistry stations. The results showed that accumulated pollutant loads were often significantly lower than the total deposition loads assessed for snow cover periods at the monitoring stations (Figure 15).

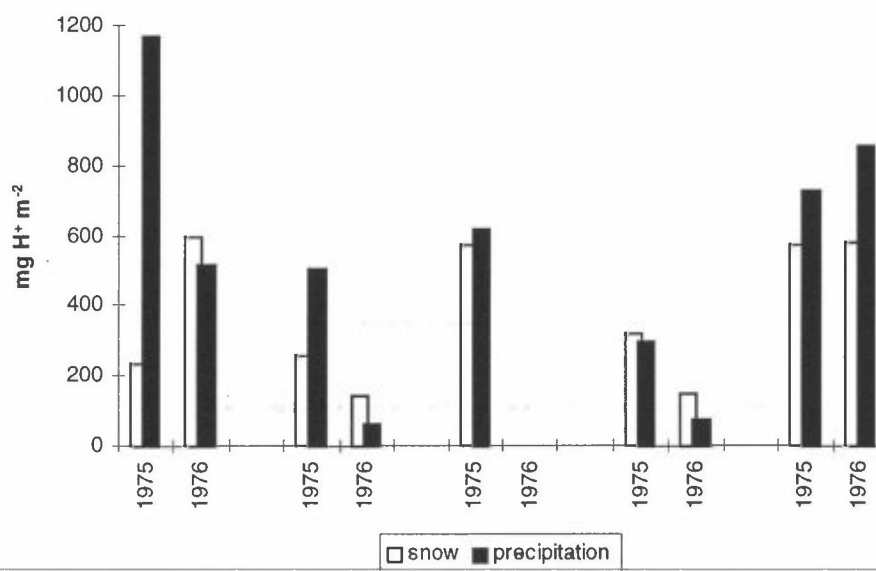


Figure 15: H^+ loads in snow and precipitation (1975, 1976) at different monitoring sites in Norway (with numbers from Wright and Dovland, 1978).

In absence of melting and a significant degree of sublimation the snow should contain greater amounts of pollutants because of fog (and dry) deposition to the snow surface. The explanation for this discrepancy is that mild weather in winter resulted in above-zero temperatures. By late winter, the snowpack in most of the studied areas in 1975 and 1976 had apparently lost some of its chemical load (Wright and Dovland, 1978). Chemical contaminants are preferentially released in the first phases of snowmelt, so that the remaining snow has lower concentrations (Johannessen et al., 1977).

Westling and Ferm (1998) came to the same results when comparing snow sampled in snowbags and snow taken with cores at different mountain sites in Sweden. Snow layers of varying thickness may melt, also at high elevation, during mild periods in winter. Only about half of the precipitation amount and half of the pollutant concentrations were measured in snow core samples compared to snowbag samples. With regard to pollutant deposition loads (concentration times precipitation volume) the difference was even larger.

Thus, in summary, the snow core method is not always a helpful tool to give a measure of total deposition loads of air pollutants in areas with seasonal snow cover. However, snowpack surveys seem to be useful in delineating major precipitation regions. Wright and Dovland (1978) found a clear relationship between precipitation pattern and the pollutant loads (sulfur, nitrogen compounds, H^+ etc.) in south-eastern and south-western Norway and the coastal areas influenced especially by sea-salts (western and northern Norway).

This pattern was confirmed by measurements at 19 NILU monitoring stations in 1973–1976. Assessments of sulfur and nitrogen deposition loads and mapping of the results in form of isoline figures show the same patterns, although pollutant levels of sulfur and lately also oxidized nitrogen compounds have decreased considerably due to successful emission reduction measures in Europe (Tørseth and Semb, 1997b).

5.2 Stationary snow samplers

The influence of different snow samplers on the collecting efficiency at two mountain sites was studied within the SNFS Project (Førland and Joranger, 1980). Dyrdalsvatn (440 m above sea level) is located in a valley surrounded by 600 to 800 m high mountains, ca. 15 km from Bergen. The area is not covered with vegetation. Groset (950 m above sea level) is a rocky plateau, mainly covered with birch trees, close to the monitoring station Møsvatn. One main result was that shielded snow samplers were more efficient in collecting the “real” amount of snow typical for the two mountain sites. But, nevertheless, even the shielded samplers underestimated snow precipitation by up to 20%. At wind velocities of about 4 m/s (at sampler opening) only ca. 40% of the actual snowfall could be collected. At the stations within the Norwegian monitoring network winter precipitation was underestimated by only about 5% (Førland and Joranger, 1980).

The efficiency of snow sampling with different methods was one of the topics of a review by Lovett and Kinsman (1990), concentrating especially on sites in the

USA. The authors conclude that the undercatch at high elevations may reach 20% or more in windy areas.

In a recent study different snow sampling methods were compared in Swedish mountain areas at elevations ranging from 360 to 1190 m above sea level. The methods included snow cores (see Chapter 4.1), wet deposition samplers, snow bags, snow plates, and buried samplers consisting of a funnel and a container (Westling and Ferm, 1998).

Unrealistic low amounts of precipitation were measured with snow cores and wet only samplers (open only when it rains or snows), whereas the buried samplers overestimated the total snow load. Best results could be obtained with snow bags and snow plates. The snow bags are made of plastic (diameter = 195 mm) and meltwater can empty into a container via a funnel that is fastened at the lower end of the bag. During summer funnel and container are used as rain samplers. The snow "plate" is actually a quadratic plastic bowl put onto the soil or snow surface and fastened with four metal sticks. The bowl might be covered with snow but, because of the metal sticks, the snow sample can be cut out with a quadratic box. At snowmelt episodes the water is collected in the bowl and will not leak into the ground.

6. Exposure to ozone in Norwegian mountain areas

A major removal mechanism of ozone from the troposphere is dry deposition to terrestrial surfaces. The dry deposition process is regulated by stomatal uptake by vegetation. Uptake is influenced by light, temperature and humidity and shows strong diurnal and seasonal cycles with daytime and summertime maxima. Ozone damages vegetation directly. Harmful effects are: inhibition of photosynthesis, damage to cell membranes and disturbances in regulation of the stomata.

Mapping of critical levels of ground level ozone was the topic of a recent report (Tørseth et al., 1996). The results are summarized here, considering especially possible effects of ozone on vegetation in Norwegian mountain areas.

Due to the removal mechanisms mentioned above, O₃ concentrations close to the ground can be much lower than at 50–100 m elevation. The vertical stability depends on orographic and micro-meteorological factors and changes over the day. A remote controlled aeroplane was used to measure vertical ozone profiles at Nordmoen, a forested area in Akershus (Tørseth et al., 1996). Results of episodes with high O₃ concentrations showed that values near the ground decreased rapidly during nightly temperature inversions (Figure 16).

As soon as the inversion layer weakens in the morning, ozone from the free troposphere diffuses into the depleted regions. O₃ values above the boundary layer change little during such periods. The influence of vertical ozone profiles is difficult to map on a regional scale, so that concentrations interpolated from existing monitoring sites may underestimate O₃ exposures in elevated areas frequently located above the nocturnal inversion layer. However, uptake of O₃ is negligible due to reduced photosynthetic activity at night.

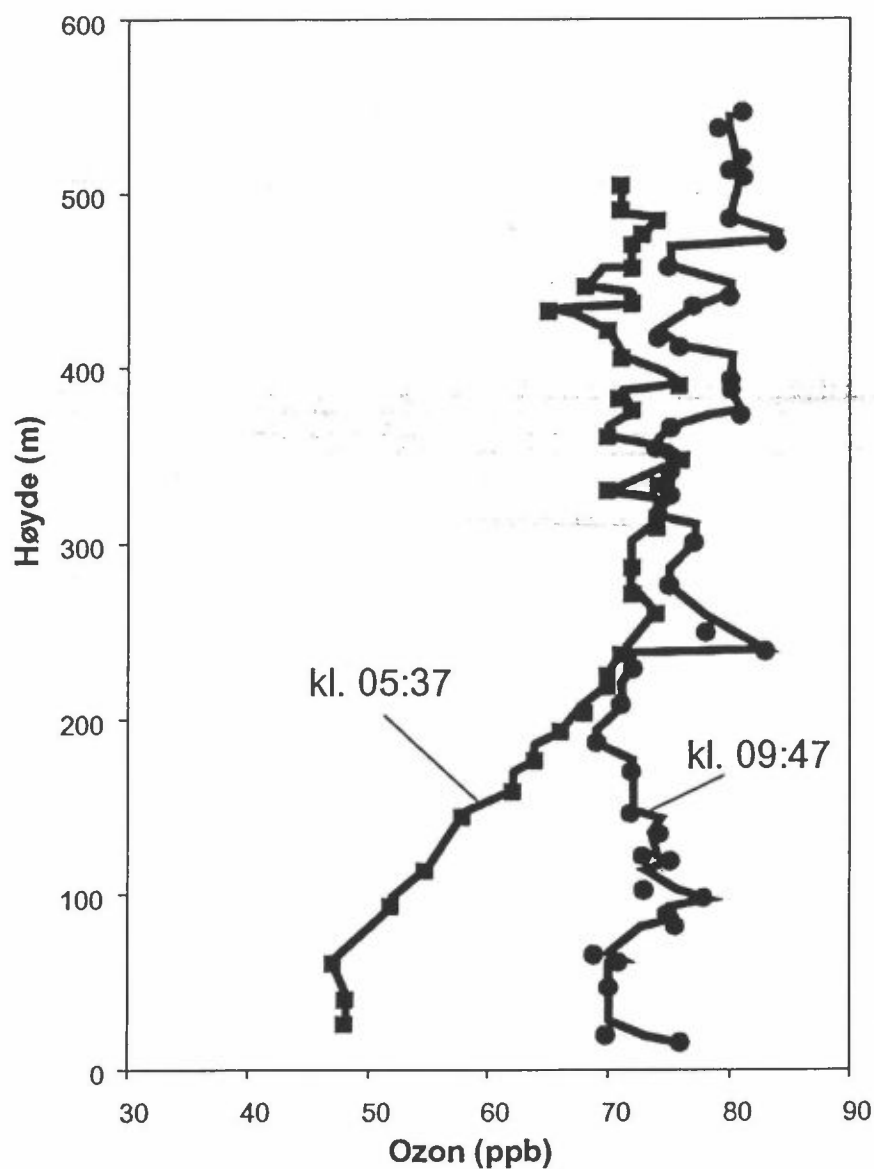


Figure 16: Vertical ozone profile at Nordmoen, July 14 1994 (from TØRSETH et al. 1996).

Within the framework of the UN ECE Convention on Long-range Transboundary Air Pollution (LRTAP) critical levels for ozone have been calculated as the sum of the differences between the hourly ozone concentrations in ppb and the threshold of 40 ppb ($80 \mu\text{g m}^{-3}$) for each hour when the concentration exceeds 40 ppb (so-called AOT40, accumulated exposure over a threshold of 40 ppb). A critical cumulative exposure level is usually set for a 6 months growing season (see, e.g., ECE, 1996).

Ozone is no serious problem in Norwegian mountain areas (Mortensen, 1993, 1994, 1996a,b). O₃ concentrations are relatively low except during episodes in some parts of southernmost Norway. Compared to many crops, mountain plants show very low sensitivities to ozone exposures. The most sensitive species investigated in Norway are birch (*Betula pubescens*) and the grass species *Phleum alpinum*. However, damage to these plants was observed at AOT40 doses of 2.2 to 4.0 ppm-h.

Vegetation is often very sparse in mountain areas and mosses may be a major part of the vegetation cover. Mosses are rather insensitive to O₃. Additionally, the AOT40 critical levels consider a growing season of six months and were developed based on situations in Central Europe. The growing season in Norway, especially in mountain areas, is much shorter (start ca. in June) whereas ozone concentrations are highest in April-May.

7. Discussion and recommendations

7.1.1 *Methods to assess pollutant loads in Norway on the regional scale*

It can be assumed that orographic enhancement of precipitation, cloud/fog droplet deposition and at some locations also the seeder feeder process increase total deposition of air pollutants to Norwegian mountain areas. In addition it is difficult to measure and assess total snowfall amounts to mountainous regions.

Measurements of cloud and fog droplet deposition are technically too difficult and costly to apply them to all mountain areas close to stations of the Norwegian monitoring network. However, as for dry deposition of particles, the principal deposition mechanism is turbulent transport combined with impaction and sedimentation. Therefore droplet deposition can be included into the definition "dry". Estimates on fog and cloud frequency and general knowledge about the chemical composition and size of fog and cloud droplets at different elevations in mountain areas allows to assess deposition velocities and thus input loads on large scales (e.g., 50 x 50 km grid cells).

For the Norwegian background stations (SFT, 1997) and for mapping deposition loads on a regional scale (Tørseth and Semb, 1997b) dry deposition of particles and gases is assessed by multiplying measured mean air concentrations over a certain period with deposition velocities of the various compounds and for different landscape types (for details see Tørseth and Semb, 1997b). The approach is justified because, all in all, the importance of dry compared to wet deposition is relatively low in most parts Norway. Elevation and cloud/fog droplet deposition are indirectly included into the estimations, i.e., relative humidity and snow cover (duration) are considered when assessing "dry" deposition velocities. In summary, the present procedure to assess seasonal dry deposition velocities is appropriate to calculate total deposition loads on a *regional* scale (50 x 50 km² grid cells).

The major constraint of snowfall sampling is simply the problem of collecting *representative* samples in high elevated mountain areas. However, the aim of national and international long-term monitoring of air pollutants is to collect data

that are representative for rainfall composition over a larger area, for example within a 50 x 50 km² grid cell. This is why site requirements explicitly exclude locations where complex topographical features may give rise to updraughts or downdraughts, leading to very site specific precipitation samples (e.g., EMEP, 1995). This is also a main reason why sites within the Norwegian monitoring program are *not* located in complex terrain such as high elevated mountain areas, but at wind-sheltered locations below the timberline. Thus, snowfall and pollutant deposition loads to mountain areas may be underestimated. However, in addition to measurements at the monitoring stations, information on precipitation amounts from 800 DNMI (Norwegian Meteorological Institute) stations is used to assess deposition loads on the regional scale. Many of those stations are located above or close to the timber line.

7.1.2 Local Investigations of deposition and ozone gradients in Norwegian mountain areas

Locations with very high cloud and fog deposition can be especially found in south-eastern Norway at elevations of 500 to 800 m above sea level (e.g., Mistberget, Luksefjell). Enhancement of total pollutant deposition loads can also be expected at isolated mountains and mountain groups facing polluted air masses. Examples are Hummelfjell, Rendalssølen and outcrops of mountains north of Gulsvik.

So far, no specific studies on the variability of snow-cover composition have been made in Norway. The aim of the snow surveys within the SNSF project was to collect representative samples, which proved to be a difficult task. Nevertheless, snow sampling at one or more south-east facing mountain slopes at an elevation of 1200 to 1400 m a.s.l. is of considerable interest. This is particularly true since high variation in snow chemistry was found at Fulufjäll in Sweden, just east of the Norwegian border. However, the time of snow sampling has to be chosen very carefully since partial snow melt during winter may strongly change the chemical composition of the snow-pack.

We recommend to study elevational gradients at one or more representative isolated mountains or mountain chains where snow, fog, orographic cloud and eventually the seeder-feeder process are frequent phenomena. Such local investigations offer also the opportunity to confirm the regional assessments of total deposition loads to mountain areas. They should include precipitation, snow cover, cloud droplet and throughfall measurements as well as studies on the effects on sensitive parts of terrestrial and aquatic ecosystems. Sølénfjellet, Sølénkletten and Rondane are possible locations.

The choice of whole catchments within the investigated gradient would allow to apply the watershed mass balance method to quantify total deposition loads. At Rondane, e.g., extensive studies on river chemistry by Blakar and Borgvang are already available.

Until now there have not been any investigations on changes in ozone concentrations with elevation. In Norway, the values are especially high in the south-western part of the country. Ozone measurements are available for Birkenes and

Karmøy, and exceedances of AOT 40 accumulated doses can be expected at high altitudes. Studies on ozone gradients should be carried out, preferably by the use of passive samplers.

7.1.3 Evaluation of deposition to areas chosen for biodiversity studies

The following regions have been chosen for monitoring biological diversity in mountain areas:

- Sirdalsheiene / Bjerkreim
- Møsvatn area
- Valdals-Femunden
- Dovrefjell
- Børgefjell
- Varangerhalvøya

Sirdalsheiene / Bjerkreim

Bjerkreim (Skreådalen) in south-western Norway represents a region that experiences the largest deposition of long-range transported air pollutants per unit area. Precipitation with south-westerly winds is predominant, but may also occur with southerly and south-easterly winds. The area has been studied extensively, both with respect to deposition of pollutants and effects. Recent investigations concentrated on mountain areas at 500 to 1000 m elevation, located in the municipalities Bjerkreim and Lund (Nitrogen from Mountain to Fjord project). Nitrate and ammonium deposition in these regions can exceed 20 kg N ha⁻¹ yr⁻¹, and thus the critical limit where nitrogen saturation in river and lake catchments must be expected (e.g., Dise and Wright, 1995).

Several studies have proved that there are negative effects on aquatic and terrestrial ecosystems due to acidification and possibly also due to nitrogen saturation. Such effects, e.g. fish deaths, may influence biodiversity studies. Ozone concentrations are also high.

Møsvatn

The Møsvatn area is a typical high-altitude plateau with moderate precipitation amounts. Measurements of rime samples at Gaustadtoppen (1800 m a.s.l.) show moderate pollutant concentrations. Precipitation samples collected at the monitoring station Møsvatn can be regarded as representative for precipitation amounts and air pollutant loads in this area.

Valdals-Femunden

Precipitation amounts at Valdals-Femunden are moderate (500–1000 mm). Concentrations decrease from south to north, and the northern parts receive appreciable amounts of precipitation with north-westerly winds. However, observations at Fulufjäll and Hummelfjell point out that orographic clouds and the seeder-feeder effect cause increased deposition of pollutants on isolated mountains and mountain groups (elevations of about 1400 m a.s.l.). Sølénfjellet, Sølénkletten, and Rondane are examples of areas which should be further

investigated. Due to the quartzite sandstone bedrock, aquatic ecosystems in these areas are extremely sensitive. Ozone exposure is not likely to be high.

Dovre fjell

In the Dovrefjell area precipitation was sampled at Åmotsdal (from October 1992 to May 1994). Monitoring was stopped because of generally low pollutant deposition rates and economical reasons. West of Dovrefjell precipitation amounts increase markedly, and concentrations become similar to those detected at the station Kårvatn, north-west of Dovrefjell.

Børgefjell

The Børgefjell region is relatively well characterized. Precipitation sampling has been carried out at Tustervatn, at Høylandet, and more recently also near Namsvatnet. Chemical composition of precipitation at all these sites was similar, with slightly higher concentrations and precipitation amounts at Høylandet, the site closest to the coast. The pollutant inputs are relatively low.

Varangerhalvøya

Finnmark (north-eastern part of Norway) is strongly influenced by emissions of sulfur dioxide and heavy metals from smelters on the Kola Peninsula. The high emissions are reflected in precipitation samples (Karpdalen, Svanvik), although dry deposition of SO₂ is the main pollutant source. High concentrations of aerosols and SO₂ may also result from long-range transport from the Eurasian continent towards the Arctic, the so-called "Arctic Haze". This phenomenon can mainly be found in winter and is not necessarily associated with precipitation events.

Moss and lichen samples from Varanger area show high concentration levels of copper and nickel, decreasing with distance from the smelters. The Varangerhalvøya is relatively flat, except for some mountains in the middle of the peninsula. These might perhaps be subject to orographically enhanced deposition of pollutants originating from nickel smelters and the Arctic Haze. However, the area affected is relatively small.

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9. References

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