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Overview of acid rain
The summer of 1990



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An overview of the acid rain problem

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Summary

The formation, transport and deposition of acid-rain species, as well as their effect on the environment, is described. Ways of mitigating the effects are briefly presented.

1. Acid rain

Acid rain is a very general term which has grown in popular usage to include the deposition of all atmospheric pollutants which are acidic, or have the potential for being naturally transformed into acidic species, whether they be deposited in rain or snow or by dry-deposition processes. The major species contributing to acid rain are, or have been derived from, the so-called emitted primary pollutants, namely sulphur dioxide (SO₂), the nitrogen oxides (NO_x), ammonia (NH₃) and the various volatile organic compounds (VOCs). All these species are subject to chemical transformation within the air, sometimes involving oxidation which is often most rapid within cloud, or in the presence of sunlight, to form secondary more acidic species like sulphuric and nitric acids.

The pH of rainwater is a measure of its acidity and is directly related to the logarithm of the hydrogen ion concentration by:

$$\text{pH} = -\log_{10}(\text{H}^+).$$

Because the scale is logarithmic a change of one pH unit represents a tenfold change in real acidity. Table I shows typical values.

In 1987, at European stations that monitor daily average values of pH in rain and snow, the overall median value was 4.73. However the lowest daily values during the year ranged from pH 5.6 at a Romanian

Table I. Typical values of pH

Condition	pH
Extremely alkaline	14
Pure water	7
Pure water in presence of carbon dioxide gas	5.6
Rain in remote temperate areas of the world	4.5-5.6
Coffee	5
Annual average rain over Europe and the USA	4.1-5.1
Annual average rain over the United Kingdom	4.4-5.1
Average mountain-cloud water in north-east USA	3.5
Wine	3.5
Urban fogs	2.2-3.3
Lemon juice	2.0
Battery acid	1.0

station down to one extreme value of pH 1.96 at a northern Italian station (a reading which may be suspect since a pH just below 3 is more usual). The median value of these minima was close to pH 3.8, nearly a whole unit below the median of the means.

2. The effect of acid rain on the environment

Considerable uncertainty still persists on the extent to which acid rain damages the environment. The reasons for this are twofold. Firstly, whilst damage is often evident, it is not always certain how important acid rain

is in creating this damage relative to damage from other possible causes like drought and disease. Secondly, once the rain reaches the surface the acidity and character of the rainwater is frequently modified, sometimes to an extreme degree. Soils, and in particular the near-surface humus layer, have the ability to modify dramatically the pH of water seeping through them. Almost all soils are in a state of long-term acidification by natural means, and this process can be accelerated or retarded not only by acid rain, but also often more importantly by ploughing, liming, the application of fertilizers, by soil erosion, by afforestation and deforestation, as well as by changes in climate. However, whenever the soil has reached a critically acidic state and the resident ecosystem is in a stressed state, the input of acidic rain can have a relatively rapid effect. Thus there are many parts of Scandinavia and upland Great Britain with underlying rocks which have a slow release rate of buffering minerals by weathering where the input of acidic pollution in rain, and in particular sulphate, is the main cause of acidification of their lakes and rivers and the elimination of fish and other organisms which once inhabited them.

2.1 The effect on fish

The strong acids not only affect the fish directly but have two other effects. The first is to release toxic aluminium from its 'locked-in' state within the soil. Secondly, acid rain has, over many years, depleted the soil of much of its available calcium so that water entering the rivers is deficient in it, and this has an adverse effect on the fish. As a result the fish suffer from one or more of the following afflictions:

- (a) mucus clogging of the gills inhibiting effective oxygen uptake,
- (b) difficulty in ridding the body of waste salts,
- (c) a breakdown in the normal mechanism by which young fry can develop and escape from their egg sacs,
- (d) a significant depletion of the food supply, the abundance of which may also be adversely affected by acidity, and
- (e) an increased likelihood of being affected by disease.

2.2 The effect on trees

The situation appears to be more complicated still with regard to trees. Trees collect not only acidic species in rain but also enhance dry deposition by scouring the air of aerosols and particles some 20 times faster than over barren land. Jaenicke (1989) explains this enhancement, not through increased impaction (since wind velocities are generally too small), but through coagulation and settling of the particles and the typically long residence time within the forest allowing these processes to be of importance. In consequence the pH of rainwater may be significantly lowered as it passes through the canopy. A forest is a complex ecosystem which can be extremely sensitive to the stresses imposed upon it.

These stresses include:

- (a) Strong winds — damage to branches and roots which can lead to the onset of wet rot and fungal diseases.
- (b) Drought — the 1975/76 drought severely affected trees, especially those on chalklands (e.g. beech and yew) and on sandy soils (e.g. pine). Weakened trees are subsequently prone to attack by disease and pests. Many such trees are still very evident in parts of southern Great Britain.
- (c) Cold — extreme cold in winter or unseasonable cold after the sap has begun rising in springtime can cause cell damage and death of foliage.
- (d) Disease, fungi, insect infestation, etc. — can seriously damage trees.
- (e) Atmospheric ozone — ozone is a very reactive gas and can damage leaves causing visible markings. It can also damage the stomata by which the leaves 'breathe'.
- (f) Acid rain — various hypotheses exist as to how acid rain affects trees, and each may have some validity in different conditions. Five of these are: (i) Ulrich's hypothesis in which acid rain acidifies the soil and releases toxic aluminium ions. These may damage the fine roots of the trees and result in insufficient or unbalanced uptake of nutrients, (ii) acidification of the soil may result in the fine-root system being confined to the upper layers of the soil, making the trees much more susceptible to periods of water-stress (Eichhorn 1989), (iii) acid rain leaches essential nutrients from the leaves; an effect which is increasingly probable if the stomata have been damaged by ozone and cannot open and close as efficiently as they should, (iv) very acidic fogs can cause damage to the coating leaf-waxes and this may result in a lower water-holding capacity of the trees; a result particularly serious in times of drought (Hogrebe and Mengel 1989), and (v) nitrates and ammonium in the rain can promote excessive and early growth which can make the tree more susceptible to damage from other stresses.

The problem with interpreting symptoms of stress is that different causes create very similar symptoms. Similarly, trends in damage over time have been difficult to ascertain since detailed surveys were not generally carried out until fairly recently, and an understanding of how to classify damage has developed only gradually since then.

Turning to trees in Britain, some are not in particularly good health at present and in some respects their state is comparable to the state in Germany, where so much public concern has been expressed. It is possible that the causes of the problem may be completely different and proper comparisons are difficult, if not impossible, because of the different environments and average tree-ages. Beeches appear to be most affected in the United Kingdom, but decline

seems to be restricted to certain areas only. Generally, beech stands, as distinct from more isolated specimens, are in better health than many stands in southern Germany. Where there is visible deterioration, this may be linked in some way to the fact that England is on the tree's northern geographical limit and also to the slow recovery many of the trees are making, or trying to make, from the damage caused by the prolonged 1975/76 drought.

Spruce also show some pockets of damage, but not always in areas of significant pollution. The reasons may again lie with climatic variations and other 'natural' causes.

Generally then, little evidence is available of serious damage to British woodlands which can be clearly attributed to acid rain. The situation in some parts of the continent is rather different. For example, some pine

woods in the The Netherlands are being seriously affected and the damage appears to be linked to the large emissions of ammonia associated with intensive livestock production in that country (Table II). Ammonia tends to neutralize sulphuric acid in cloud droplets and can lead to increased sulphate formation (see later). Rain falling from such clouds is therefore high in ammonium sulphate. The ground then experiences an enhanced sulphate intake and the effective acidity is markedly increased as some of the ammonia is released back into the atmosphere, increasing the stress on the trees.

Fig. 1 shows the increasing damage to silver fir in east Bavaria from 1978 to 1986. Other conifers have suffered in a similar but usually less dramatic manner. Such decline is not always monotonic however and some evidence suggests individual trees can show partial recovery.

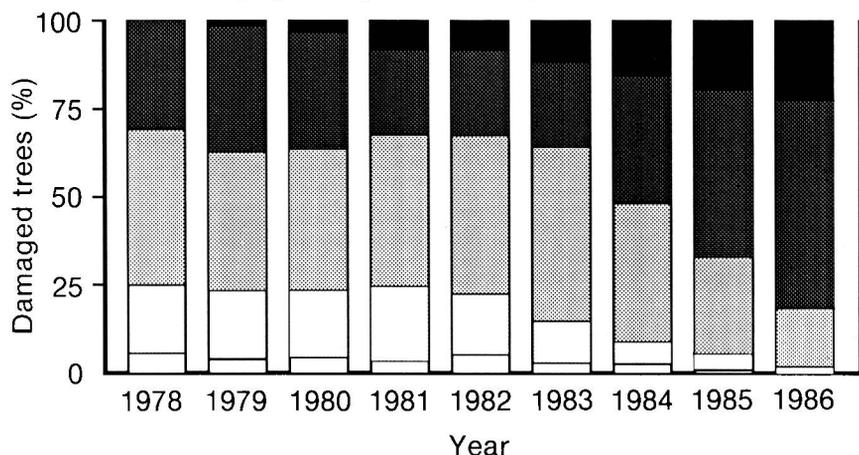


Figure 1. The decline in silver fir in eastern Bavaria (from Hoerteis and Schmidt (1986)). The stippling from white to black represents the percentage of trees from undamaged to dead.

Table II. Forest damage assessment in four European countries 1984-86 (from Innes 1987). The table gives needle or leaf loss as a percentage.

	0-10%			11-25%			26-60%			61-100%		
	84	85	86	84	85	86	84	85	86	84	85	86
United Kingdom												
Sitka spruce	65	83	45	28	12	39	6	5	15	1	0	1
Norway spruce	71	84	32	26	15	36	3	1	31	1	0	1
Scots pine	49	74	25	29	18	41	16	7	32	5	1	3
Germany												
Norway spruce	49	48	46	31	28	32	19	21	20	2	3	2
Scots pine	41	43	46	38	41	40	20	15	13	1	2	1
Silver fir	13	13	18	29	21	22	45	50	49	13	16	11
Beech	50	46	40	39	40	41	11	13	18	1	1	1
Switzerland												
Norway spruce	65	63	50	28	29	36	6	6	12	1	2	2
Scots pine	50	35	34	31	47	43	16	13	19	1	5	4
Silver fir	62	60	47	27	28	36	9	8	13	2	4	4
Beech	74	69	52	23	27	40	3	3	7	0	1	1
The Netherlands												
Norway spruce	62	48	49	28	41	34	7	9	12	3	2	4
Scots pine	34	48	50	51	36	33	12	14	13	2	2	3
Corsican pine	57	40	19	34	42	29	8	15	40	1	3	12
Beech	71	72	68	24	21	26	4	6	5	1	1	2

2.3 Damage to buildings

Air pollution, and principally sulphur dioxide, accelerates an otherwise natural process of degradation of building materials. In spite of a marked decline in the levels of urban smoke and sulphur dioxide in the United Kingdom over the last 30 years since the introduction of the Clean Air Acts, damage still continues at a high rate and this may be because the initial crucial damage occurred when levels of sulphur dioxide were still relatively high. Against this, however, damage to coverings made of zinc, which has a comparatively short 'memory' also continues unabated. This suggests that nitrogen oxides whose concentrations have remained much more static, because of the increase in vehicular emissions balancing reductions elsewhere, may play an

important role, either on their own or synergistically with the sulphur dioxide.

Additionally, salt blown on the wind from the sea or applied to the roads in freezing weather together with surface cracking of the stonework by frost may also play an important role in the United Kingdom in causing damage, which is especially costly when it happens to historic architectural gems.

Even modern buildings do not escape. Many of the earlier reinforced concrete structures have shown considerable problems of corrosion in recent years. This is largely due to the inadequate understanding of the devastation acid rain could have on the form of concrete used at that time.

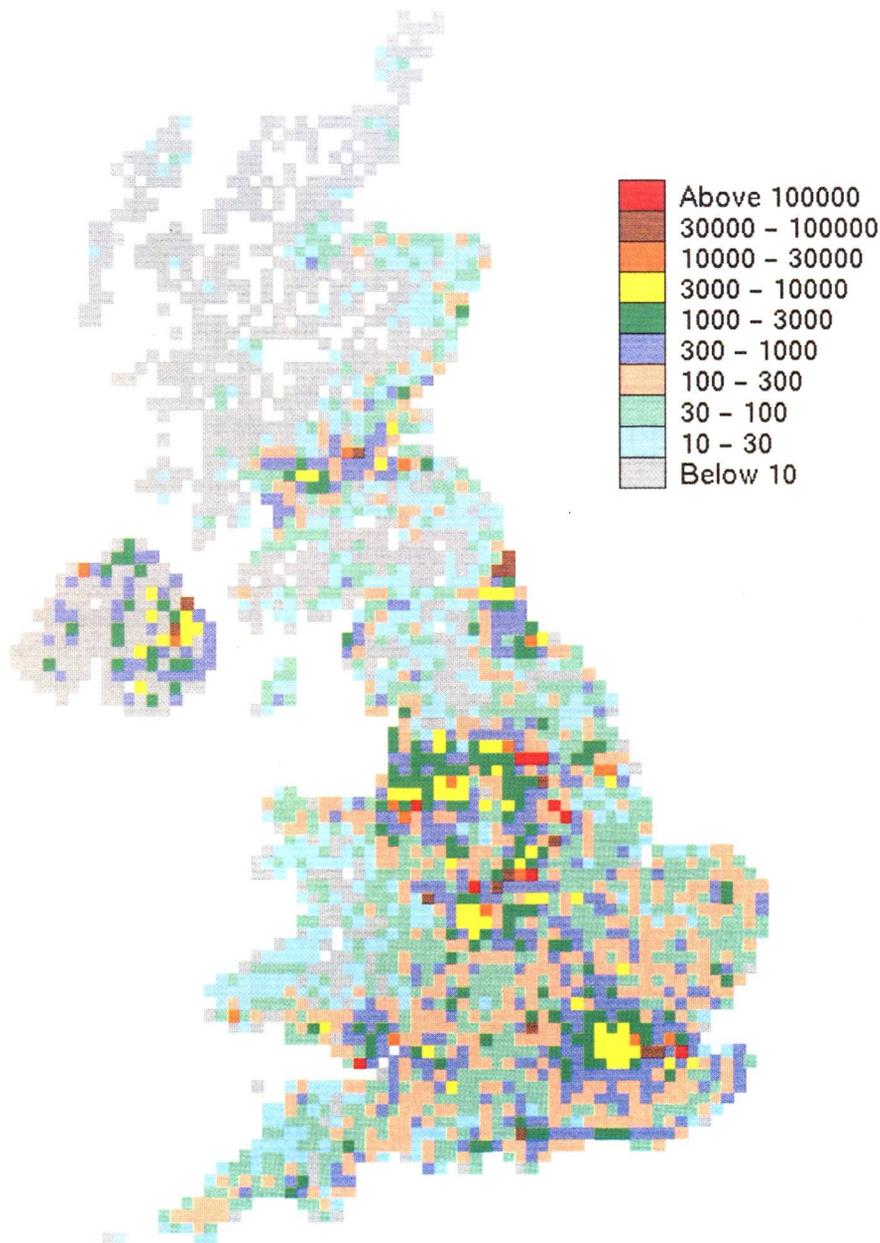


Figure 2. Total sulphur dioxide emissions (metric tonnes) within the United Kingdom for 1987. (Warren Spring Laboratory, 1989, personal communication.)

3. Emissions

Most countries in western Europe make an analysis of the emissions of the common air-pollutants, like sulphur dioxide and the nitrogen oxides, from a wide range of sources within their own country. In the United Kingdom, Warren Spring Laboratory in Stevenage derive annual maps of the emissions of SO₂ and NO_x in 10 km × 10 km Ordnance Survey grid squares. An example is shown in Fig. 2 for 1987. The national total was 3.867 million tonnes of SO₂, showing that after a substantial decrease from the 1970s values the UK emissions are creeping upwards again.

In Europe at least three series of emission maps are prepared on a much coarser grid. One is made by the European Monitoring and Evaluation Programme (EMEP) Western Centre at the Norwegian Meteorological Institute, Oslo, and these maps cover all of Europe on a 150 km × 150 km grid. The second series have been produced in the PHOXA photochemical oxidant project (Klug *et al.*, 1988). Their maps cover a more limited area of western and central Europe. The third series is from the OECD (1989) which covers only those countries in the OECD itself. On a national basis the emissions generally agree to within a few per cent but, on a grid-square basis, differences can be up to 50% or more, especially in east European countries where much less detailed source data are readily available. Note however that since some of the basic input data are common to all these maps, the magnitude of these differences may underestimate the real uncertainties. Figs 3–5 show a section of the latest EMEP maps for

SO₂, NO_x and NH₃ for 1985. The largest grid-values tend to lie in a belt extending from central England across Germany into southern Poland and Czechoslovakia,

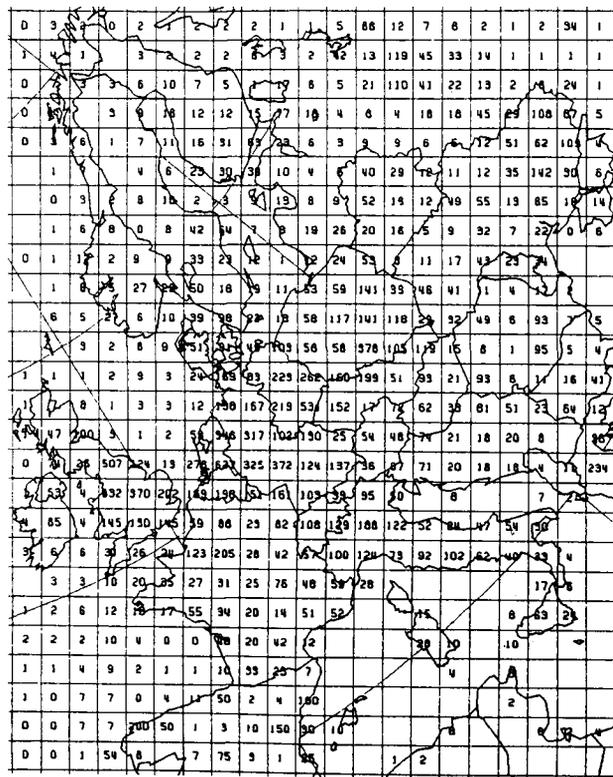


Figure 4. EMEP 1988 emission values (kt a⁻¹) for nitrogen dioxide expressed as equivalent nitrogen (EMEP MSC-W, 1990).

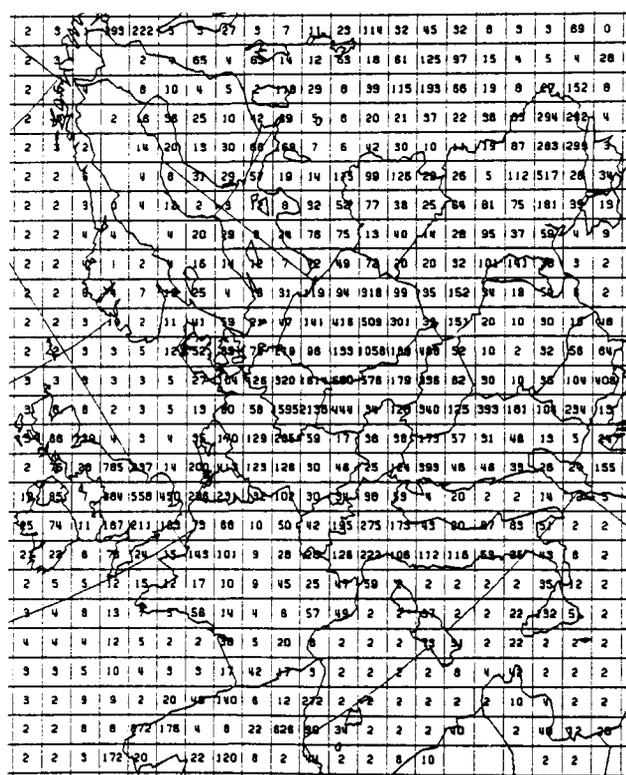


Figure 3. EMEP 1988 emission values (kt a⁻¹) for sulphur dioxide expressed as equivalent sulphur (EMEP MSC-W, 1990).

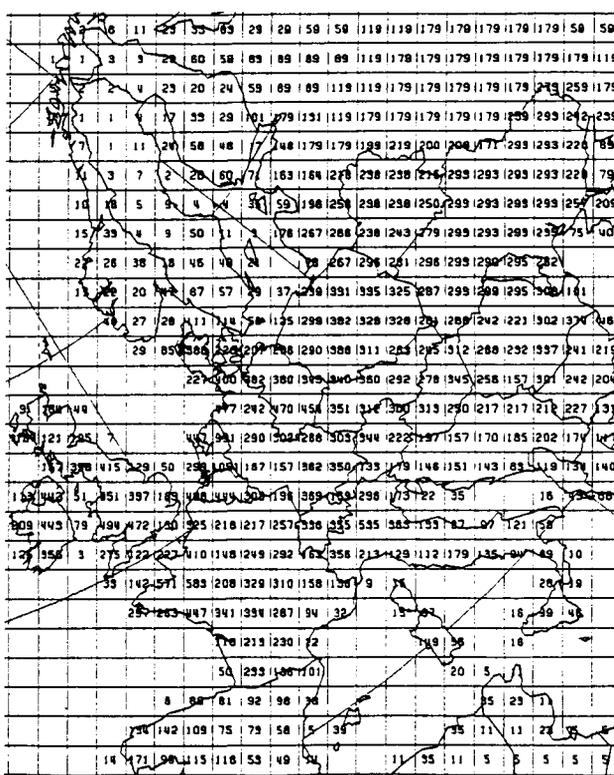


Figure 5. EMEP 1988 emission values (100 t a⁻¹) for ammonia (EMEP MSC-W, 1990).

with other pockets around Rostov in the USSR, northern Spain and in northern Italy.

National emissions of SO₂, NO_x, NH₃, and VOC (volatile organic compounds, which are important in the generation of ozone) are given in Table III in units of kt a⁻¹. In the United Kingdom, roughly 70% of the sulphur emissions are from fossil-fuel power stations. The remainder are from industrial and domestic sources. In the region as a whole, anthropogenic sources dominate, but in late spring and early summer significant amounts of dimethyl sulphide (DMS), and other related sulphur-containing species, are emitted by plankton in the sea, and these are readily oxidized to sulphate. During this period these natural emissions are believed to represent about 30% of the total sulphur depositions in Scandinavia, and are therefore quite significant. Not shown in Table III is that sulphur dioxide emissions peaked in about 1980 and have fallen since then at least in western Europe.

Nitrogen oxide emissions arise mainly from vehicles (typically about 40% of the total in western Europe) and from fossil-fuel power stations. Emissions have risen

over the last decade very slowly due to the increase in the number of vehicles.

Ammonia emissions have increased by over 50% since 1950 due to more intensive livestock farming and fertilizer application to crops which then release ammonia in significant amounts during the growing season.

4. Chemical transformations in the atmosphere

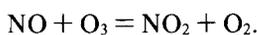
Many of the primary pollutants associated with acid rain are subject to chemical transformations in the atmosphere, forming secondary pollutants. Sulphuric acid and nitric acid are formed by oxidants such as ozone, hydroxyl radicals and hydrogen peroxide.

4.1 Formation of oxidants

Ozone occurs naturally, being formed in the stratosphere by ultraviolet light and transported downwards by complex vertical circulations. However, ozone can also be produced within the lower, polluted layers of the atmosphere. Two reactions are principally involved:

Table III. Total national emissions of SO₂ as S, NO_x as N, NH₃ as N and VOC in units of kt a⁻¹, in 1985 (except for the VOC which refer to 1980), taken from Eliassen *et al.* (1988). The last three columns are as follows: emissions of SO₂ in kt a⁻¹ per head of population, the position in a table when these emissions per head are ordered in magnitude, and the percentage change in emissions of SO₂ between 1980 and 1985.

Country 1985	SO ₂	NO _x	NH ₃	VOC	S/hd	Pos.	%
Albania (AL)	25	3	20	—	9	25	0
Austria (AT)	85	66	70	391	11	23	-52
Belgium (BE)	234	117	78	374	24	11	-41
Bulgaria (BG)	570	46	121	—	63	4	+11
Czechoslovakia (CS)	1575	373	165	—	102	2	+2
Denmark (DK)	163	72	109	197	32	8	-26
Finland (FI)	185	73	42	685	39	7	-36
France (FR)	923	515	693	2971	17	18	-48
Germany (East) (DD)	2500	291	200	—	148	1	+25
Germany (West) (DE)	1200	882	361	2724	19	16	-27
Greece (GR)	180	46	93	260	18	17	-10
Hungary (HU)	710	91	125	—	66	3	+2
Iceland (IS)	3	4	2	—	12	22	0
Ireland (IR)	69	21	114	94	20	14	-35
Italy (IT)	1252	485	351	2116	22	12	-35
Luxembourg (LU)	7	7	5	17	19	15	-39
The Netherlands (NL)	138	163	140	534	10	24	-41
Norway (NO)	50	68	34	319	12	21	-29
Poland (PL)	2150	457	394	—	59	5	+4
Portugal (PT)	134	58	45	436	13	20	0
Romania (RO)	100	119	288	—	4	27	0
Spain (ES)	1603	289	224	1786	42	6	-2
Sweden (SE)	135	92	51	1201	16	19	-45
Switzerland (CH)	48	65	51	361	7	26	-30
Turkey (TR)	161	53	575	—	3	28	0
USSR (SU)	5550	892	2619	—	21	13	-13
United Kingdom (GB)	1780	560	394	1746	32	9	-24
Yugoslavia (YU)	588	58	194	—	26	10	0

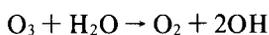


This reaction takes place in sunlight. An equilibrium is established between the two sides of the reaction equation. The second reaction involves reactive hydrocarbons (RH) and forms further NO₂ which disturbs the equilibrium formed in the first reaction and results in a net production of ozone. The second reaction (which strictly is a multi-stage reaction) is as follows:



The carbonyl compounds formed then tend to break down in the presence of sunlight to form hydroperoxyl HO₂ radicals and carbon monoxide.

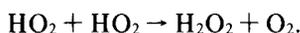
In the generation of hydroxyl radicals (OHs), two pathways dominate. The first involves ozone and water



and requires sunlight; the second involves the HO₂ formed by the reaction described above and NO:



For the generation of hydrogen peroxide (H₂O₂), some of the hydroperoxyl radicals can recombine to form hydrogen peroxide and oxygen:



4.2 Oxidation of SO₂ and NO₂

4.2.1 Outside clouds



Typically this converts SO₂ to sulphate at an average rate of about 1% per hour.

During the day



converting NO₂ at about 9% per hour.

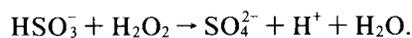
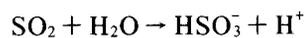
At night or during the day, conversion is via a multi-stage reaction:



These two processes dominate nitric acid formation.

4.2.2 In clouds

SO₂ and hydrogen peroxide are both very soluble and form sulphuric acid at a rapid rate independent of the pH:



Two other routes exist which may be important if and when the available hydrogen peroxide has been depleted or is otherwise scarce. The first is through a reaction with less-soluble ozone at a rate which decreases rapidly with decreasing pH, and hence on the presence of other acidic species, like hydrochloric acid, or on alkaline species like ammonia dissolved within the cloud droplets.

The second route is by oxygen (O₂) which may become a significant process due to catalytic iron and manganese ions present after passing sources in major industrial areas.

5. Deposition processes

5.1 Dry deposition

The direct take-up of airborne gaseous or particulate material present in the lowest layers of the atmosphere to the surface or to vegetation by processes of absorption, impaction or sedimentation is called dry deposition, to distinguish it from deposition by precipitation, even though at times dew, cloud droplets or surface water may be involved.

Dry deposition on natural surfaces is very difficult to measure directly, certainly in any routine operational manner. The supposition is usually made that the rate of deposition, or flux (*F*), is proportional to the concentration in the air just below the surface of height *z*:

$$F = -v_d C(z).$$

The coefficient *v_d* has the dimensions of a velocity and is therefore called the deposition velocity. *v_d* is a slowly varying function of height *z*, and depends rather critically on the stability of the air. Normally we may assume that *v_d* is independent of the magnitude of *C(z)* although the deposition rate of an acidic species on to a damp surface decreases as more of the species (and other acidic species) accumulate in the film.

The deposition velocity for sulphur dioxide has an overall average value of about 0.4 cm s⁻¹ whereas that for sulphate aerosol is much smaller at about 0.05 cm s⁻¹.

5.2 Removal by rain and snow

Precipitation tends to be very efficient at removing most acidic species. Moderate rain will often remove more in one hour than dry deposition will over two or more days. Of course rain is a very sporadic event. In the lowlands of England it rains only about 3-4% of the time, and even in wet areas like north-west Scotland it rains only some 8-10% of the time. However wet deposition is usually comparable in importance to dry deposition and in the United Kingdom is typically

responsible for 70–80% of the total deposition of sulphate, for example.

Aerosols and particles can get into precipitation elements either:

- (a) by being swept out as the element falls through the air, or
- (b) by becoming cloud condensation nuclei for developing cloud droplets which subsequently turn into precipitation elements by coalescence, or
- (c) by so-called phoretic effects in which various forces, like electrical forces, act on the particles pushing them towards the droplet.

Finally, particles can enter droplets by

- (d) Brownian capture — when the particles are sufficiently small ($\ll 0.1 \mu\text{m}$) that they are moved by molecular bombardment and can collide with, and be captured by, larger cloud droplets.

Chemical changes may also be important. For example SO_2 , which whilst it is to some extent absorbed directly into raindrops and reaches the ground as SO_2 , can undergo oxidation to sulphate (which is a fine aerosol) either before or after being incorporated into rain, as just described. This increases the efficiency of the removal process. The oxidation rate depends not only on the availability of suitable oxidants (like ozone) but also on the relative humidity (or the amount of cloud).

Removal in-cloud is generally called ‘rain-out’ (even though the precipitation may be in the form of snow), whereas below-cloud removal is usually called ‘wash-out’. Rain-out is more efficient than wash-out if the concentration is the same in and below cloud.

If the removal process affects the concentration uniformly over the plume volume, then the concentration decreases according to

$$C_a(t) = C_a(0)\exp(-\Lambda_w t).$$

The resulting concentration in the rain may be expressed in terms of a coefficient ω :

$$C_r = \omega C_a$$

where C_r is the resulting concentration in the rain. If C_a and C_r are expressed in g m^{-3} then ω is usually of the order of 10^5 for wash-out and 5×10^5 for rain-out. If, however, C_r is expressed in g l^{-1} then ω is three orders of magnitude less. Note that ω for wash-out depends on the total depth of the polluted column through which the rain falls. The values quoted refer to a depth of the order of 1000 metres.

5.3 Wet deposition

The resulting wet deposition, D_w , in g m^{-2} is obtained by multiplying the concentration in the rain, in terms of g l^{-1} , by the rainfall R in millimetres.

$$D_w = C_r \times R = \omega C_a R.$$

The wash-out ratio can also be used to define a wet deposition velocity by analogy to the dry deposition velocity (see later).

$$v_w = \frac{dD_w}{dt} / C_a = \omega \frac{dR}{dt}$$

where t is here time, and the units of v_w are here in m s^{-1} . With light rain falling at a rate of 1 mm h^{-1} and a value of ω of 100, v_w is about 3 cm s^{-1} , which is of the order of a 1000 times greater than the corresponding dry deposition velocity.

Wash-out ratios for snow tend to be severalfold higher than for rain although R for snow is usually less than for rain due to the lower temperatures involved.

Λ is related to ω through the relations:

$$\Lambda = \frac{\omega}{h} \frac{dR}{dt}$$

where h is the depth of the polluted layer through which the rain is falling, R is in mm , and t , the time, is in seconds. Assuming $\omega = 100$, $h = 1000 \text{ m}$, then Λ is approximately $3 \times 10^{-5} R'$ for wash-out and $1.5 \times 10^{-4} R'$ for rain-out, where R' is the rainfall rate in mm h^{-1} . A value of Λ between 3×10^{-5} and 3×10^{-4} has been suggested, consistent with our estimate when both wash-out and rain-out are included and when we allow for heavier rainfall rates.

Note that we have assumed a linear relation between Λ and R . However, some theories and experimental evidence have pointed to a dependence:

$$\Lambda = aR'^b$$

where b is not 1 but lies in the range 0.7 to 0.9.

6. Topography

In many maritime regions, the tops of hills are immersed in a capping cloud for a high percentage of the time. This cloud is formed as boundary-layer air is forced up over the hill and the moisture it carries condenses. The cloud usually evaporates again on the downwind side of the hill, so the cloud appears to be stationary although in reality it is in a constant state of regeneration. The concentrations of the major acidifying ions in the cloud droplets are frequently much higher than are typical in normal rain. These droplets, blown by the wind, are rather readily deposited on any trees or vegetation in their path and can contribute significantly to the overall deposition of ions to the ground. This form of deposition is commonly called ‘occult’ deposition.

Rain also tends to increase with ground elevation so that the rainfall map for the United Kingdom is qualitatively very similar to the physical map showing contours of height above mean sea level, when viewed

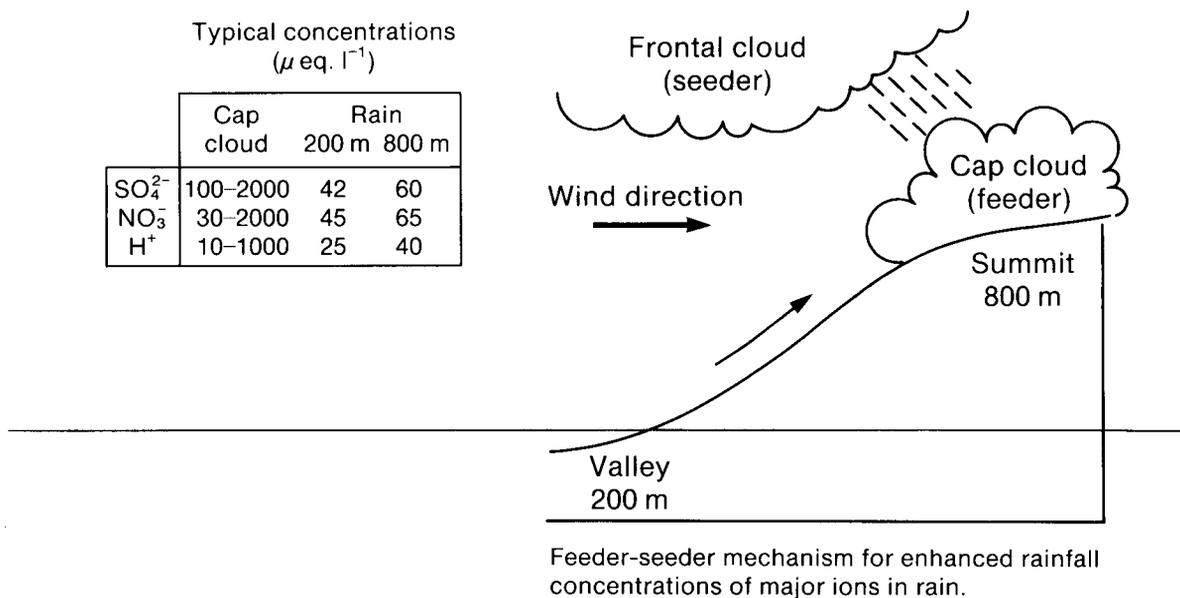


Figure 6. The influence of hills on the concentration in rain of three of the common ions. Results from the Great Dun Fell study in Cumbria carried out on behalf of the UK Dept of the Environment.

on a large scale. When rain falls from upper cloud (often called the seeder cloud in this context) through the capping cloud beneath (then called the feeder cloud), the rainfall rate is not only increased but the concentration of the acidifying ions also increases. At Great Dun Fell in Cumbria, this effect is being actively studied by several research teams under contract from the UK Department of the Environment. Fig. 6 summarizes some of their earlier findings.

At higher elevations more of the precipitation is in the form of snow. This has an effect on the average pH. Grosch and Georgii (1989) have studied the enrichment of trace elements in snow relative to rain. Anions, like sulphate, are typically increased by some 10-80%, with an observable increase with ground elevation. The enrichment is thought to be due to more efficient below-cloud scavenging by snow resulting from a slower descent rate and a longer residence time, and the filigree structure of snowflakes permitting better scavenging.

7. Concentrations in the air and depositions to the surface

7.1 Monitoring

For Europe, the most complete picture of concentrations and depositions on a day-to-day basis comes from the monitoring station network of the 'Cooperative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe' — the full title of the EMEP programme described earlier. The programme started in 1977 and is still active today. It replaced an earlier smaller programme covering much of western Europe under the auspices of the OECD. In 1987, 97 stations were participating across 24 countries at which some or all of the species summarized in Table IV were measured (see Schaugh *et al.* 1989).

The samples are analysed within the station's own

country, but are checked and collated at the Norwegian Institute for Air Research (NILU).

7.2 Modelling studies

Acid rain is concerned with the transport of material typically over distances out to a few thousand kilometres at average speeds of about a thousand kilometres per day. These large time- and space-scales complicate the description of transport considerably. However, models of various levels of complexity can be used to simulate the transport, dispersion, transformation and deposition processes involved. Unlike the monitored data, such models can provide information on the contribution one area of sources makes to the deposition in another country or region.

Determination of the transport of pollution requires a knowledge of wind fields. Most pollution is injected into the boundary layer, the layer of the atmosphere which is closest to the ground and is under its direct influence. The layer is typically several hundred metres deep, but varies considerably from place to place and from one time to another, usually being deepest during the day, especially on a hot sunny day, and being least at night when the air is nearly calm. Many of the earlier models, and many of the simplest models, assume the pollution remains within this well-mixed boundary layer and so can be carried by a single wind which varies only from

Table IV. EMEP's measurement programme in 1987

Gas	SO_2 , NO_2 , O_3
Particles	SO_4^{2-}
Precipitation	SO_4^{2-} , pH/ H^+ , NO_3^- , NH_4^+ , Ca^{2+} , K^+ , Cl^- , Na^+ , Mg^{2+} , conductivity

one location to another, and with time. In reality some of the pollution escapes from the boundary layer into the so-called free troposphere where it may be carried with winds that differ substantially from those in the boundary layer. The most complete models have to take into account the 3-dimensional nature of the wind and do so by using the output of numerical weather prediction models, whether from the analysed fields or from the forecast fields.

Models can use various techniques to follow the pollution. These have been described in, for example, Pasquill and Smith (1983). Eulerian, Lagrangian, spectral and multi-particle stochastic methods have all been employed and details should be sought from the above reference. A further division can be made; models can be statistical, operational on a day-by-day basis, or complex, designed to study special events. Statistical models use statistics of wind, boundary-layer depth and precipitation. They are very simple and their results only have validity over long times — a year or longer. Best results are obtained when the sporadic nature of rain is incorporated using simple statistical techniques. Operational models, like that operated within the EMEP programme, use winds at a single level and interpolated data on precipitation and boundary-layer depths. Usually other properties like the rate of dry deposition

are parametrized. Their results compare reasonably well with measured data when averaged over several weeks. Complex models are essentially mesoscale models working with quite fine grids which supplement the actual observed data by generating physically plausible data through the 3-dimensional equations of motion and heat and moisture, taking into account the effects of the known local topography. These complex models require a large computing facility and are intended to gain a greater understanding of the nature and importance of some of the difficult processes involved.

One of very simplest of the statistical models which can yield estimates of the deposition one country makes to another is as follows (the form given is specifically for sulphur species, but can be modified for other species):

- (1) The average deposition within a country due to its own emissions is:

$$\text{total deposition} = 25E/\sqrt{A} \text{ gS m}^{-2} \text{ a}^{-1}$$

where roughly 56% comes from dry deposition and 44% from wet deposition. E is the annual emission of SO_2 in Mt a^{-1} and A is the area of the country in thousands of square kilometres.

- (2) The total average deposition in country 1 due to emissions E_2 in country 2 is given by:

Table V. Sulphur budget (kt a^{-1}) for Europe for 1986 from the EMEP model (Eliassen *et al.* 1989). See Table III for explanation of lettering. 'IND' is explained in the text, and 'RE' means residual and 'SUM' is total.

		Emitter countries																															
		AL	AT	BE	BG	CS	DK	FI	FR	DD	DE	GR	HU	IS	IE	IT	LU	NL	NO	PL	PT	RO	ES	SE	CH	TR	SU	GB	YU	RE	IND	SUM	
Receiver countries	AL	6	0	0	4	0	0	0	0	0	2	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	7	27	
	AT	0	21	1	2	27	0	0	3	15	10	0	22	0	0	18	0	0	0	17	0	0	0	0	1	0	1	3	15	0	24	185	
	BE	0	0	49	0	3	0	0	16	5	12	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	3	115	
	BG	0	0	0	153	2	0	0	0	1	0	1	2	0	0	1	0	0	0	3	0	3	0	0	0	0	1	12	0	4	0	18	206
	CS	0	5	2	2	394	0	0	5	90	18	0	47	0	0	6	0	1	0	89	0	1	0	0	0	0	0	3	6	11	0	29	713
	DK	0	0	1	0	2	31	0	1	11	7	0	0	0	0	0	1	0	4	0	0	0	0	0	0	0	1	9	0	0	9	81	
	FI	0	0	0	0	6	1	52	1	13	3	0	2	0	0	0	0	0	0	12	0	0	0	4	0	0	55	5	0	0	67	227	
	FR	0	2	19	1	22	0	0	330	36	42	0	7	0	1	38	0	4	0	14	1	0	47	0	4	0	1	40	7	1	150	768	
	DD	0	0	5	0	79	3	0	8	678	51	0	3	0	0	2	0	3	0	35	0	0	0	0	0	0	2	15	2	0	25	915	
	DE	0	4	22	1	62	3	0	46	137	331	0	10	0	0	14	1	12	0	36	0	0	2	0	2	0	2	47	5	0	71	813	
	GR	0	0	0	19	0	0	0	0	0	0	45	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3	4	0	1	0	25	106
	HU	0	3	0	5	21	0	0	0	7	2	0	190	0	0	7	0	0	0	14	0	2	0	0	0	0	0	3	1	28	0	16	303
	IS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	16
	IE	0	0	0	0	1	0	0	1	2	1	0	0	0	18	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	25	62
	IT	0	3	0	4	8	0	0	11	8	5	2	9	0	0	394	0	0	0	5	0	0	5	0	0	2	0	1	3	19	1	83	569
	LU	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7
	NL	0	0	11	0	3	0	0	8	9	30	0	0	0	0	0	0	29	0	1	0	0	0	0	0	0	0	20	0	0	10	127	
	NO	0	0	2	0	5	4	1	3	14	10	0	0	0	0	0	0	1	9	7	0	0	0	2	0	0	9	22	0	0	100	193	
	PL	0	3	4	2	142	4	0	8	235	35	0	30	0	0	6	0	2	0	743	0	1	1	1	0	0	20	15	10	0	50	1317	
	PT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	18	0	0	0	0	0	1	0	0	20	75
	RO	0	0	0	0	21	17	0	0	1	11	2	0	31	0	0	5	0	0	0	23	0	35	0	0	0	1	32	1	26	0	41	250
	ES	0	0	1	0	3	0	0	19	5	4	0	1	0	0	6	0	0	0	2	7	0	510	0	0	0	0	5	0	2	85	655	
	SE	0	0	2	0	18	13	6	3	50	16	0	2	0	0	1	0	2	3	30	0	0	0	40	0	0	17	20	1	0	103	331	
	CH	0	0	1	0	4	0	0	7	4	5	0	2	0	0	17	0	0	0	3	0	0	1	0	8	0	0	2	2	0	15	77	
	TR	0	0	0	10	1	0	0	1	1	0	4	1	0	0	3	0	0	0	1	0	0	0	0	0	0	53	14	0	1	0	83	178
	SU	0	3	4	14	103	8	22	7	155	34	1	57	0	0	8	0	3	1	265	0	11	1	8	0	221	143	29	22	0	412	3319	
	GB	0	0	5	0	6	1	0	11	14	11	0	1	0	5	1	0	3	0	6	0	0	2	0	0	0	1	517	1	0	66	655	
	YU	1	2	0	54	11	0	0	2	6	2	3	30	0	0	32	0	0	0	11	0	3	1	0	0	1	6	1	200	0	71	445	
RE	4	4	34	40	86	36	18	112	222	122	24	25	0	15	221	0	26	5	145	10	4	203	19	2	21	184	431	32	9	932	2991		
SUM	14	54	166	338	1029	109	101	613	1734	763	86	478	0	45	794	5	95	2014	74	51	65	801	78	22	862	514	1218	392	162	564	15728		

$$\text{deposition over the whole country} = 125A_1E_2 \exp(-x/1000)/x$$

in units of thousands of tonnes of sulphur per annum. The distance in kilometres between the centres of the two countries is given by x .

The results of these simple relationships can be compared with the results of the EMEP model. Table V gives a sulphur budget for countries in Europe from the EMEP model only for the year 1986. If the comparison is made then agreement is generally within a factor of 2, which is surprisingly good. Presumably the EMEP results are better than those of the simple model, but even so are still not in perfect agreement with the monitored data when averaged over a year. Fig. 7 shows the measure of the scatter for 1985. Some of this scatter must arise from the inadequacies of the model, but errors in measurement and analysis cannot be ruled out either.

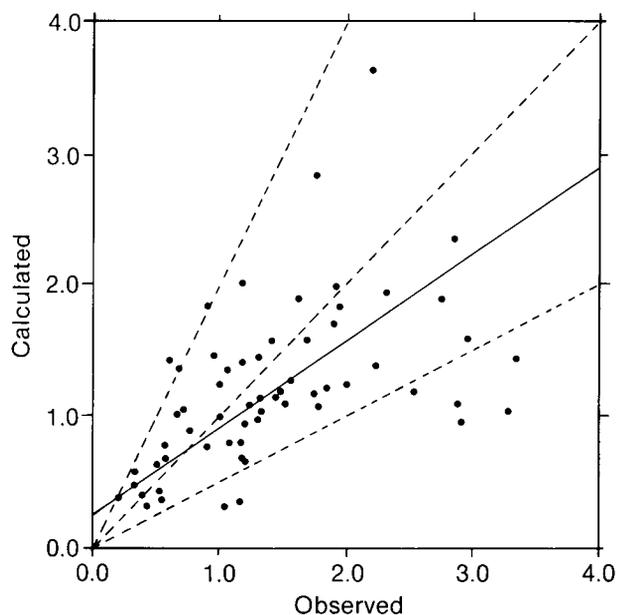


Figure 7. A comparison between observed and calculated sulphate concentrations in precipitation at EMEP monitoring stations for 1985. The pecked lines correspond to a line of perfect fit and 'within a factor of 2' agreement. The continuous line is the best-fit linear regression line.

8. The background or indeterminate contribution

The penultimate column in Table V is labelled 'IND' for indeterminate. This is the contribution from an imposed additional small background concentration of sulphate in rain that has to be added in all rain events in order to get a broad agreement over all of Europe between annual model and observed depositions. It is argued that the origins of this component are threefold:

- Sulphur is only tracked for 96 hours in the model and is then lost.
- Sulphur that is transported outside the model area is lost but in reality some of it may return and be deposited within the area. Studies of arctic haze have confirmed that this consists in part of acidic species that have reached this remote area along a favoured route that has passed over Europe and has then been advected northwards over Novaya Zemlya in northern USSR with one return path out of the Arctic again near Greenland and back towards Europe. Because of the extreme stability of the air and the low precipitation rates in the Arctic, relatively little of the sulphate load is lost on this long journey.
- Sources outside Europe will include natural emissions of dimethyl sulphide, and other sulphur compounds, emitted from plankton in the sea. These emissions are subsequently oxidized to sulphate.

Other sources are man's activities in North America. However it has been estimated in a preliminary study (Iversen *et al.* 1989) that approximately 10% or less of the indeterminate contribution in north-west Europe is of North American origin.

9. Sector analysis

It is to be expected that the highest mean concentrations of the acidic species will often be found at a receptor when the air trajectories have earlier crossed major sources of the corresponding primary pollutants. This is verified by so-called sector analyses in which concentrations at the receptor are related to the direction of the track the air has taken in reaching the receptor. Fig. 8 gives two examples of these averaged concentrations as a 'rose' (akin to a wind-rose). One is for Birknes in southern Norway, the other is for Eskdalemuir in

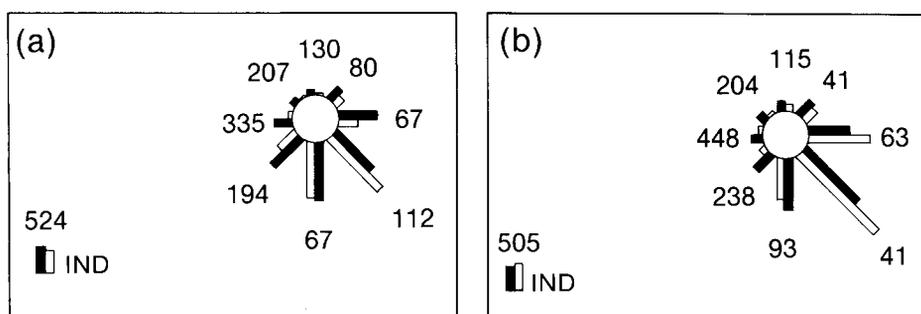


Figure 8. Concentration roses for sulphate in air at (a) Birknes in southern Norway and (b) Eskdalemuir in southern Scotland, showing how air travelling from major European source areas is likely to have the highest concentrations.

southern Scotland. At Birknes the highest concentrations of airborne sulphate are in flows coming from within 45° southerly and south-easterly sectors, that is from continental European areas. Similarly Eskdalemuir experiences its highest concentrations in the south-easterly sector. Annual deposition roses on the other hand show peak contributions in westerly and south-westerly sectors, implying that by far most of the rain comes in these directions and that even though the concentration of sulphate may be small the overall contribution to the deposition is dominant.

10. Episodes

Fish are an example of one part of the environment which can respond dramatically to episodes of acid rain, or more exactly, to acidic flushes of water into their habitat. These flushes usually reflect acid rain although conditions have to be right for this to occur. Three causes are common:

- when acidic rain is not modified by soil ion-exchange processes but runs straight off into the streams and lakes because of rocky slopes or frozen ground,
- in northern regions when winter snow begins to melt in springtime the first melt-water often carries off most of the acidic species trapped in the snow and runs directly into the streams since the ground is still frozen, and
- after a long dry spell rain takes up the accumulation of dry deposited acidic material on the vegetation and soil surface, and produces a highly acidic surge.

Furthermore even the most cursory examination of daily average concentrations or depositions at any monitoring site reveals the large variability in the magnitudes. Indeed, taking wet-deposition data as an example, if the values over a specified period like a year are listed in order of magnitude then the first few values have great importance to the year's total deposition. Smith and Hunt (1979) defined these days with the highest wet depositions which, when summed, account for 30% of the total annual wet deposition as episode-days, and 'episodicity' at that site as the ratio of the number of episode-days to the total number of rainfall days, expressed as a percentage. Fig. 9 gives an example of the definition for a site in eastern England.

The episodicity in Europe usually varies from about 3% to 15%. Confusingly the smaller the episodicity defined this way the more episodic is the character of the depositions. Smith and Hunt define sites as being 'highly episodic' if the episodicity is less than 5% and 'weakly episodic' if it is greater than 10%.

The episodicity shows some continuity between neighbouring sites so that maps can be drawn showing regions of high, medium and weak episodicity. The reasons for this continuity are obviously related to the location of the sites in relation to major source areas and

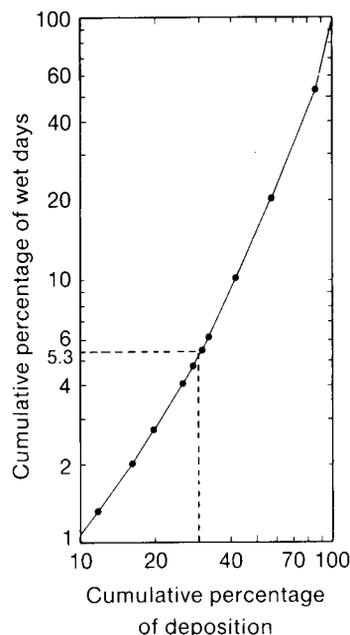


Figure 9. The cumulative percentage of deposition plotted against cumulative percentage of wet days, plotted on logarithmic scales, for Cottered in the eastern Midlands of the United Kingdom for 1974.

the main directions of rain-bearing winds. The episodicity regions do appear to change slowly however in time due to normal fluctuations in climate on a time-scale of several years or decades.

Episodes in concentration at any one site are often associated with similar synoptic situations. Examples are given in Fig. 10 for two of the EMEP monitoring stations. The synoptic situations shown are representative of conditions in approximately half the episodes experienced.

11. Remedial strategies

11.1 Sulphur dioxide

Probably marked changes in emissions can only come about through political legislation resulting from national and international accord, although hand-in-hand with such legislation have to go consideration of the economics, technological advances and perhaps the availability of alternative energy sources. A description of the progress on the political side up to the present time, and possible progress in the future, is beyond the scope of this paper, but an excellent summary is to be found in the Report of the Watt Committee on Energy (1988).

Two main options are available. One is to burn 'sulphur-free' natural gas (mainly methane) instead of coal in new power stations, and perhaps even in some existing stations after conversion. This appears to be the current intent of the Government. The obvious advantage of this policy is that it reduces SO₂ emissions more or less pro rata, the disadvantages are that it both consumes a valuable limited resource which might be

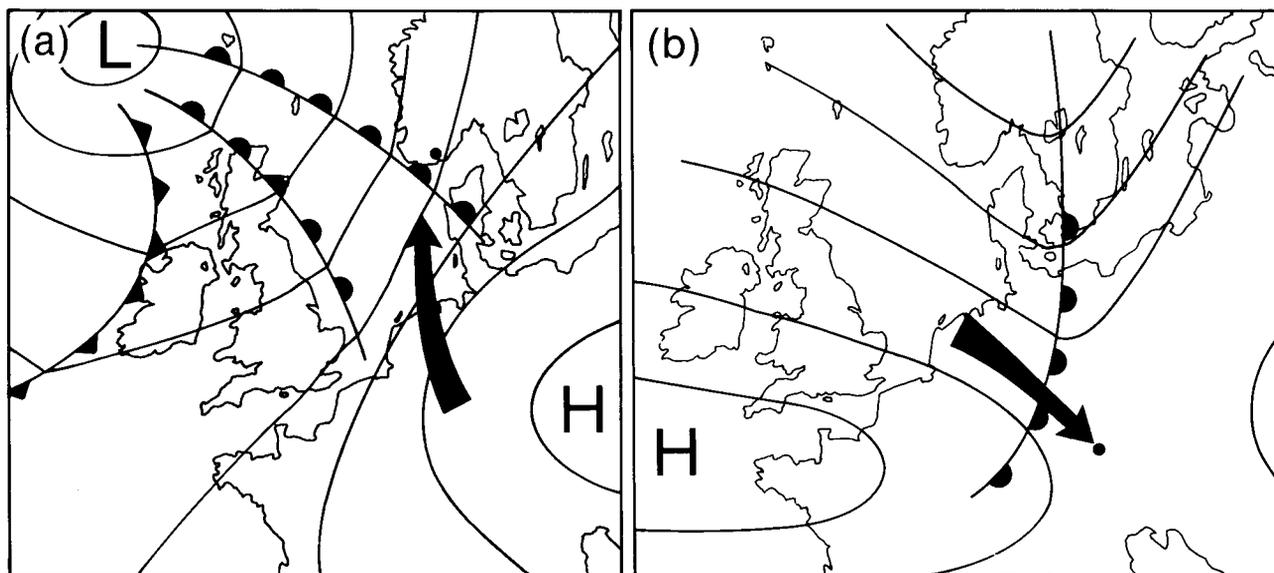


Figure 10. The commonest synoptic situations giving rise to episodes of concentration of sulphate in precipitation in (a) southern Norway and (b) Germany (Smith 1983).

better used, and that it gives a more uncertain future to the coal industry. The second option is to stay with coal as the main fuel and reduce emissions by fitting flue-gas desulphurization (FGD) systems, especially to all new power stations and to some existing large modern stations like Drax in South Yorkshire.

Two FGD systems are under consideration. The first uses lime or limestone and produces gypsum as a byproduct which can be used in the construction industry in the manufacture of cement and wall-board. The second method uses the British Wellman-Lord system which produces sulphur or sulphuric acid which also can be used by industry. This system has the added attraction of being able to reduce emissions of nitrogen oxides as well. The gases are absorbed by activated carbon which can subsequently be made to release the sulphur and nitrogen compounds and be used again.

11.2 Neutralizing additives

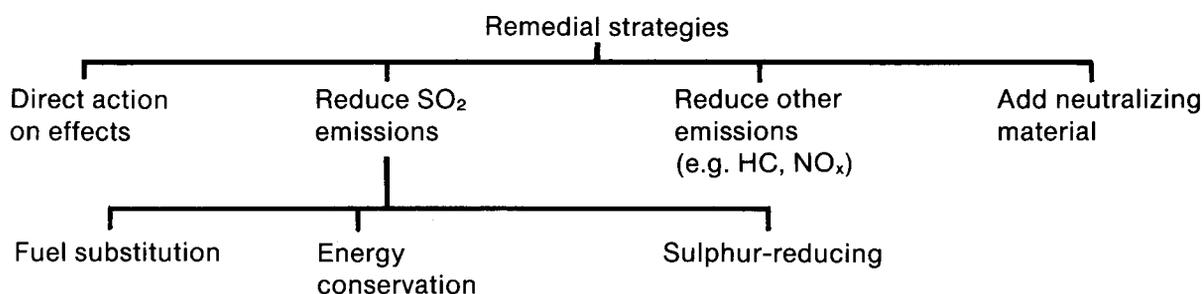
A novel suggestion by Dr Byron Lees, a fuel technology consultant, has yet to find full favour in the power-generation industry, although it seems to offer a relatively cheap alternative to FGD if thorny political 'side-effects' could be overcome. His suggestion involves the release of fine magnesium hydroxide powder (about $3\ \mu\text{m}$ average diameter) into the flue gases whenever the airstream is expected to travel towards ecologically

sensitive areas, and especially if rainfall is anticipated in those areas on arrival. The Meteorological Office believes, on the basis of preliminary tests, that it could successfully forecast such conditions on an acceptably high fraction of occasions. The magnesium hydroxide can be, and indeed is, produced commercially in the United Kingdom from seawater at a competitive cost of some £240 per tonne. It is very reactive, convenient to handle and non-hygroscopic. Being such a fine powder, little is lost by dry deposition from the atmosphere but it is effectively washed out when precipitation occurs where it can react with its companion sulphuric and nitric acids on the ground. The annual cost for a large power station is estimated to be in the range £10M to £30M, very significantly less than for other systems. It also has the advantage that it could help to correct the depleted levels of natural magnesium often found in many soils in areas badly affected by acid rain, thereby improving the balance of nutrients available to the vegetation.

11.3 Nitrogen oxides

Emissions from large combustion plants can be reduced in one or more of four ways:

- (a) burn less fuel through economies,
- (b) use less-polluting fuels,
- (c) prevent NO_x being formed during combustion.



The source of the nitrogen which goes into the NO_x may be partially from within the fuel and partially of atmospheric origin. Keeping combustion temperatures down can reduce the formation of the NO_x, and (d) remove any nitrogen oxides before the waste gases are released into the atmosphere. In-furnace control technologies can also have a very important impact and much productive research has gone on in this area.

Nitric oxide is also emitted from spark-ignition engined vehicles, along with carbon monoxide, carbon dioxide and unburnt hydrocarbons. In the United Kingdom vehicles contribute roughly 40% of the NO_x emissions and 35% of the volatile organic compounds (the hydrocarbons), some of which are released by evaporation from the fuel tanks, or during refuelling at petrol stations. Solvents and gas leakages are responsible for most of the remaining VOC emissions. Reduction of vehicular emissions is possible by either or both of two approaches:

- (a) Catalytic converters which oxidize the combustion products to 'harmless' substances. New EEC regulations will require converters to be fitted to 2-litre engines and above.
- (b) Reduced-temperature combustion (RTC) systems. Generally these result in a loss of efficiency.

Lean-burn engines endeavour to reduce emissions through burning weak mixtures of fuel in air in which good mixing has taken place and this leads to a reduction of NO_x formation without a loss in efficiency. However there appear to be limitations to these methods and attempts to overcome them have led to active research into stratified charge engines. One disadvantage of the RTC system is that in reducing NO_x emissions, hydrocarbon emissions are increased and this may tend to enhance the production of ozone in the atmosphere. The addition of a catalytic converter can substantially correct this defect however.

Emissions of nitrogen oxides and hydrocarbons from large diesel engines can be reduced by retarding the injection timing which reduces the combustion temperature at the expense of some loss in efficiency. A second approach involves exhaust-gas recirculation which reduces temperature by increasing the specific heat of the fuel mix.

11.4 Liming

Liming badly affected lakes to correct acidification has been successfully practised in Scandinavia for some years. However many lakes are very inaccessible for application using land-vehicles, especially in the high mountains, and this demands spraying from helicopters — a more costly process. Many have objected, saying the concept runs contrary to the principle of 'polluter pays' taken in its most general sense, and that it is the responsibility of the polluting nations to remove the

nuisance. Such views in part reflect the feeling that liming is a possible substitute for emission-reduction. In fact, as Dr Peter Chester (National Power) has argued, liming is not a substitute; both are necessary to restore freshwater vitality. This claim has been supported not only by logical argument but also by a 5-year study at Loch Fleet in Galloway in south-west Scotland carried out by the (as was) Central Electricity Generating Board, the South of Scotland Electricity Board, the North of Scotland Hydro Electric Board and British Coal, with the scientific support of various university and research organizations.

The loch underwent acute acidification in the early 1970s and became fishless, it is believed, in 1975. The study set out amongst other things to discover the response of the lake and its catchment area to various forms of lime treatment. As mentioned earlier in section 2.1, acidity and calcium content of the water are of paramount importance to fish health. If concentrations are expressed in micro-equivalents per litre, then if

$$K = Ca^{2+} - 3H^+$$

(an approximate relation) is positive then brown trout will thrive; if negative they may disappear (see Fig. 11). If initially a lake has negative K but the acidifying emissions are substantially reduced, H⁺ concentrations will fall but so will the leaching of Ca²⁺ and the lake may remain with negative K and unable to support fish for many years. If however, sufficient calcium is also added to the catchment area then K will become positive and reintroduced fish have a reasonable chance of persistent survival.

First liming around Loch Fleet was carried out in April 1986 with further liming in other parts of the catchment in 1987. As Fig. 12 shows, the pH and the calcium and inorganic aluminium concentrations all responded beneficially in a very short time and these improvements have persisted. Fish were reintroduced in May 1987. These thrived and spread throughout the

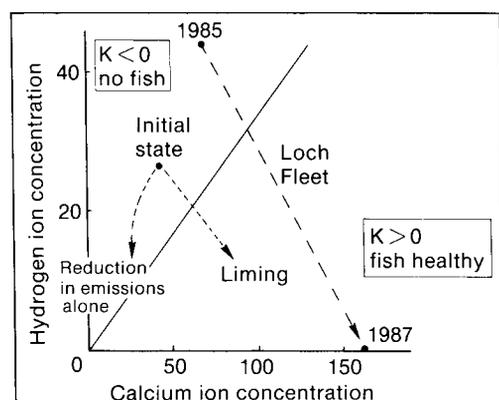


Figure 11. Fish health depends on the hydrogen ion and calcium ion concentrations in the water. Above the diagonal line fish stocks are threatened, below the line they are likely to remain healthy. The arrows show the response of the ions to three scenarios: to a reduction in emissions, to liming, and at Loch Fleet following liming in 1986.

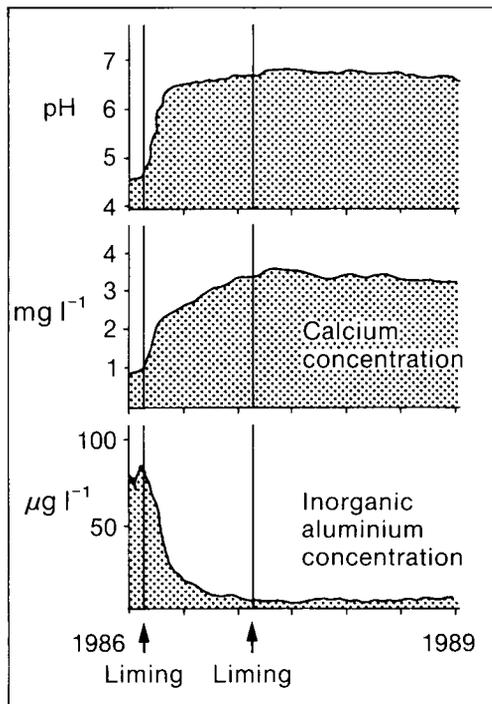


Figure 12. Time response of the concentration of major ions in tributary water at Loch Fleet following liming of the surrounding catchment area (CEGB *et al.* 1989).

lake and downstream. Subsequently trial catches were made in September 1988 and the fish were in excellent condition.

Experience from the project indicates that liming should be applied, preferably at a rate in excess of five tonnes per hectare, and that emphasis should be placed on liming areas that are boggy or have springs, and ensuring that a significant proportion of the dominant run-off water is intercepted. Best results are obtained with fine powder or pelleted limestone or chalk. The cost of liming is not cheap, varying in terms of overall cost between £20 and £70 per tonne, or at least £100–£350 per hectare, for lasting effects. The catchment area of Loch Fleet is some 110 hectares although not all of it need be limed to get excellent results. Assuming that some 200 other lochs in Scotland could also benefit from liming, some with much larger catchment areas, one can see that several million pounds are involved, but this is only a very small addition indeed to the money likely to be needed for desulphurization of emissions in the next 10 years in the United Kingdom.

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The summer of 1990 in the United Kingdom

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Summary

Despite a somewhat cool, dull and wet period during June and the first half of July, the summer as a whole turned out to be warmer and drier than normal over England and Wales and eastern Scotland, although wetter than usual in the rest of Scotland.

1. The summer as a whole

The summer was warmer than average over the whole United Kingdom, with temperatures ranging from near average in parts of the north-west to 1.5 °C above average in the Midlands. Summer rainfall amounts were below average nearly everywhere in England and Wales, parts of the Border Region, eastern Scotland and the

central Highlands, but above average elsewhere in Scotland and in Northern Ireland, ranging from 143% of average at Cape Wrath, Highland Region to less than half the average in some central and south-eastern areas of England. Despite the dull June the summer as a whole was sunnier than average nearly everywhere, and sunshine totals ranged from 83% of average in Shetland

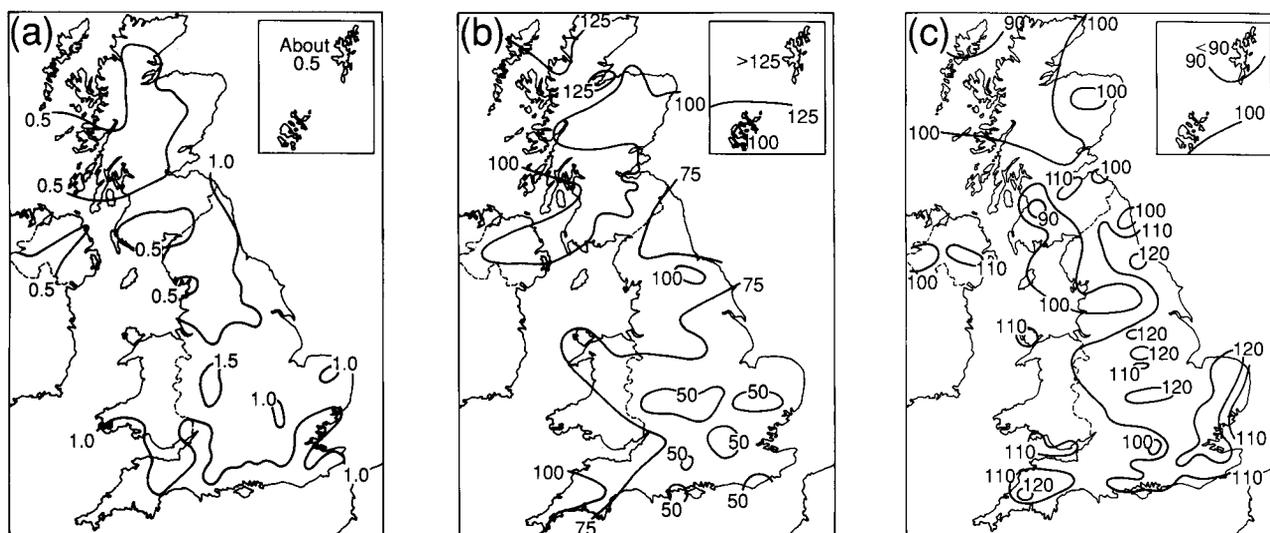


Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for summer, 1990 (June–August) relative to 1951–80 averages.

Table 1. District values for the period June–August 1990, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.6	+1	106	101
Eastern Scotland	+0.6	-1	96	102
Eastern and north-east England	+1.0	-1	78	115
East Anglia	+1.1	-3	58	118
Midland counties	+1.2	-3	64	111
South-east and central southern England	+1.2	-3	59	114
Western Scotland	+0.4	-3	106	100
North-west England and North Wales	+0.9	-1	78	105
South-west England and South Wales	+1.0	0	87	110
Northern Ireland	+0.7	+2	113	108
Scotland	+0.5	+1	104	101
England and Wales	+1.1	-2	72	112

Highest maximum: 37.1 °C in Midland counties in August.

Lowest minimum: 0.3 °C in northern and eastern Scotland in June.

to more than 120% of average in some, mainly eastern, areas of England.

Information about the temperature, rainfall and sunshine during the period from June 1990 to August 1990 is given in Fig. 1 and Table I.

2. The individual months

June. Mean monthly temperatures were below normal nearly everywhere, apart from the far north of Scotland, the Western Isles, Orkney, Shetland, the Channel Islands, and one or two places on the east coast, where temperatures were just above normal. Temperatures ranged from 0.6 °C above normal at Whitby, North Yorkshire to 1.3 °C below normal at Alice Holt and Martyr Worthy both in mid Hampshire. Monthly rainfall totals were above normal nearly everywhere, except in parts of western Scotland, East Anglia, north Devon and east Kent where amounts were below normal, and ranged from more than 280% at Edinburgh to 56% at Cambridge. At the Royal Observatory, Edinburgh, where records go back to 1896, the total of 127 mm was the highest since 1928 and the second highest on record. Monthly sunshine amounts were below average everywhere, except at Tiree, Strathclyde Region where it was just average, and ranged from 100% at Tiree to as little as 51% at Reading, Berkshire.

The month was generally unsettled, with rain at times followed by showers, and thundery outbreaks in most areas, but with a more settled spell from the 11th to 17th, after which unsettled weather returned, although rain fell mainly in northern areas. On the 6th parts of Scotland had the first substantial amount of rainfall for some time. During the night of the 6th/7th rain was very heavy in the Inverness area: at Carrbridge part of the railway embankment was washed away by a swollen burn and the Inverness to London morning express narrowly avoided derailment when it crossed the gaps. Later, on the 21st, there were thundery outbreaks over the Moray Firth, the Firth of Forth and Tynemouth, and on the 22nd over East Anglia, Kent, the south Midlands and the Firth of Forth. On the 23rd a group of thunderstorms in the unstable westerly airstream crossed from Merseyside to East Anglia, but amounts of rainfall were small everywhere. Late on the 27th thundery outbreaks came to much of northern England and the north Midlands; a severe thunderstorm occurred 3 km to the north of Keyworth, Nottinghamshire and there were reports of large hailstones, structural damage caused by lightning, and flooding. On the 30th severe thunderstorms caused cuts in power supplies in a wide area of north-west England, including the Lake District, and the National Garden Festival at Gateshead was hit by a freak thunderstorm.

July. Mean monthly temperatures were above normal everywhere except for one or two locations in the south-east, and ranged from 1.7 °C above normal at places in western Wales to 0.1 °C below normal at

Folkestone, Kent. Monthly rainfall amounts were below normal in all areas except the far north-west of Scotland and the Isle of Man, with as little as 8% of normal at Eastbourne, East Sussex, compared with a rainfall amount more than 150% of normal at Stornoway, Western Isles. Southern parts of England and Wales had no significant rain from the 7th for the rest of the month, including Odiham and Farnborough, Hampshire, Easthampstead, Berkshire and Charing, Kent. Monthly sunshine amounts were above average everywhere and ranged from 168% at Aldergrove, Co. Antrim to 107% at Lerwick, Shetland.

The month began with a period of somewhat unsettled weather in northern areas, but more settled weather in southern areas. Early on the 5th an unstable north-westerly airstream covered all areas, with strong winds and some rain in most areas during the day, although amounts were mainly light. Rain fell in many places from the Midlands northwards on the 15th, but it became warm and sunny on the 16th, and southern areas remained so for the rest of the month. However, western and northern areas of Scotland had very small amounts of rain on the 18th, and on the 19th there was a little light rain or showers in western areas. On the 27th it became unsettled in most areas although remaining warm. The month was remarkable for the infrequency of thunder, although some outbreaks did occur, sometimes with hail in places.

August. Mean monthly temperatures were above normal nearly everywhere in the United Kingdom, ranging from 0.1 °C below normal at Dall, Tayside Region to 3.4 °C above normal in Cambridgeshire. The mean minimum temperature at Valley, Gwynedd was the highest there since records began in 1941 and equals the highest minimum values measured at nearby Holyhead in 1911 and 1933. Temperatures reached 32 °C in parts of the Home Counties on the 1st, and on the 3rd a temperature of 37.1 °C was measured at Cheltenham, Gloucestershire, the highest temperature recorded at an officially accredited station since records began. On the night of the 3rd/4th a minimum temperature of 24 °C was recorded at Brighton, East Sussex and in central London. Monthly rainfall totals were below normal everywhere except for parts of Northern Ireland and western and northern areas of Scotland, where they were above normal, and ranged from 153% at Lerwick, Shetland to as little as 20% at Guernsey, Channel Islands. During the late afternoon of the 6th a moderate shower gave 16.5 mm of rain at Wilsden, West Yorkshire. Most places had some rain on the 14th: for some places in southern England this rain ended a period of 38 days with no significant rainfall, the last having been recorded on 6 July. Monthly sunshine amounts were generally above average over most of England and Wales, but below average over most of Scotland and Northern Ireland, ranging from 154% at Monks' Wood, Cambridgeshire to 65% at Fort

Augustus, Highland Region. Brooms Barn, Suffolk reported the sunniest August at the station for over 40 years.

After four very hot days at the beginning of the month it became cooler with patchy rain from time to time in northern areas, but remained very warm in parts of East Anglia and south-east England until the 14th, when it became generally cooler and unsettled, with rain at times and a good deal of thundery activity. Thunderstorms occurred at Wick, Highland Region on the 14th, over the Midlands and East Anglia on the 15th, over

much of central and south-eastern England and East Anglia on the 16th, and over East Anglia on the 19th. Further thunderstorms developed over North Wales and northern England on the 24th, with isolated thundery showers over central and southern England, and over the Channel Islands and parts of eastern Wales and Somerset later. Thundery outbreaks occurred in parts of south-east England and East Anglia on the 25th and 26th, and more extensively in eastern areas of England on the 29th.

Satellite and radar photographs — 8 March 1991

During 7 March 1991, cyclogenesis occurred over Iberia, resulting in a deep low which gradually moved northwards towards the British Isles. Fig. 1(a) shows this low pressure system as seen on the AVHRR visible image taken at 0749 UTC on 8 March, when a distinctive spiral cloud pattern was centred just north of Brittany. The surface analysis for 0600 UTC (inset) confirms the position of the

low centre. The low sun angle reveals a great deal of detail in the image through shadow and highlight effects. For example, the high cirrus cloud at W can be seen to have a wispy texture, contrasting with the lumpy texture of the cloud at B to the north and east, which is more convective in nature. Near the centre of the system, where the air is most unstable, the edges of cumulonimbus clouds can be seen lit

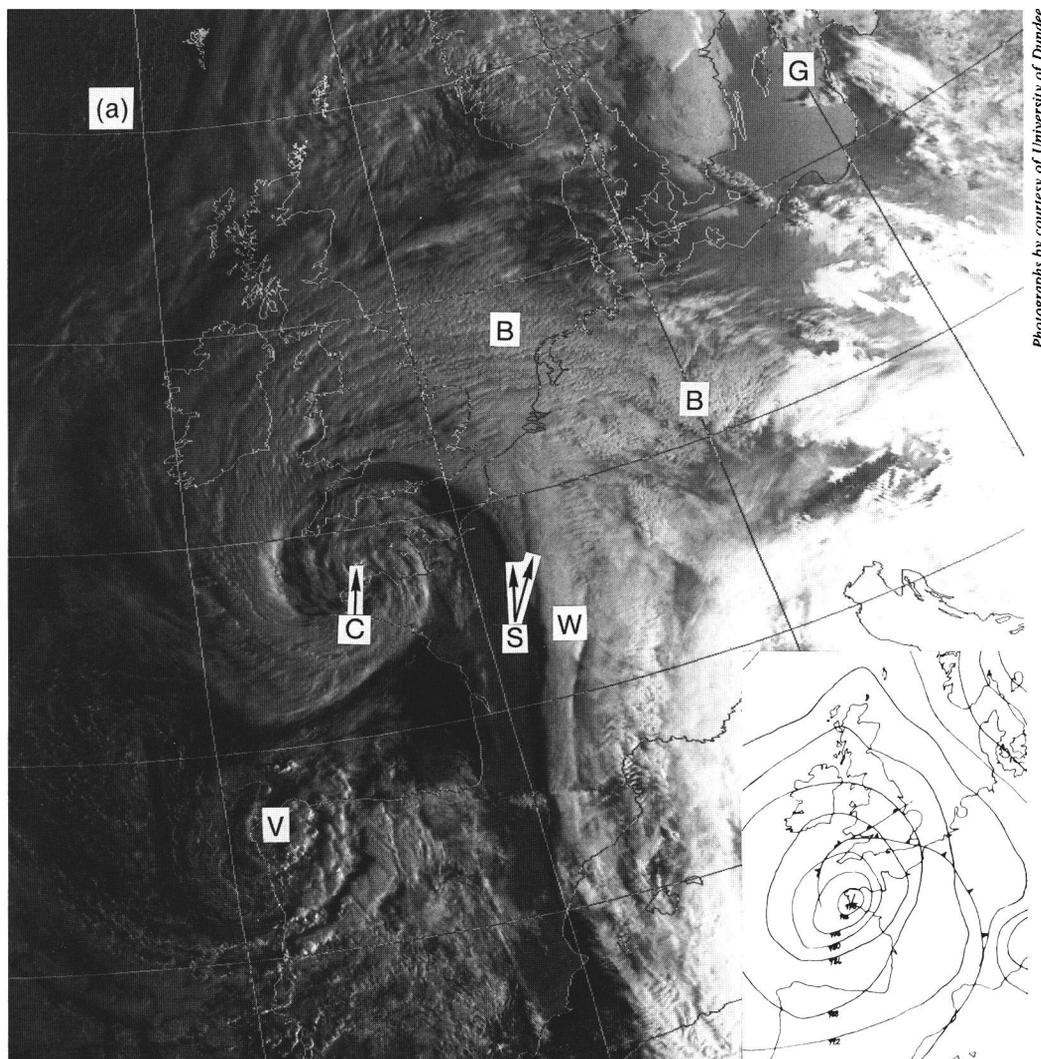
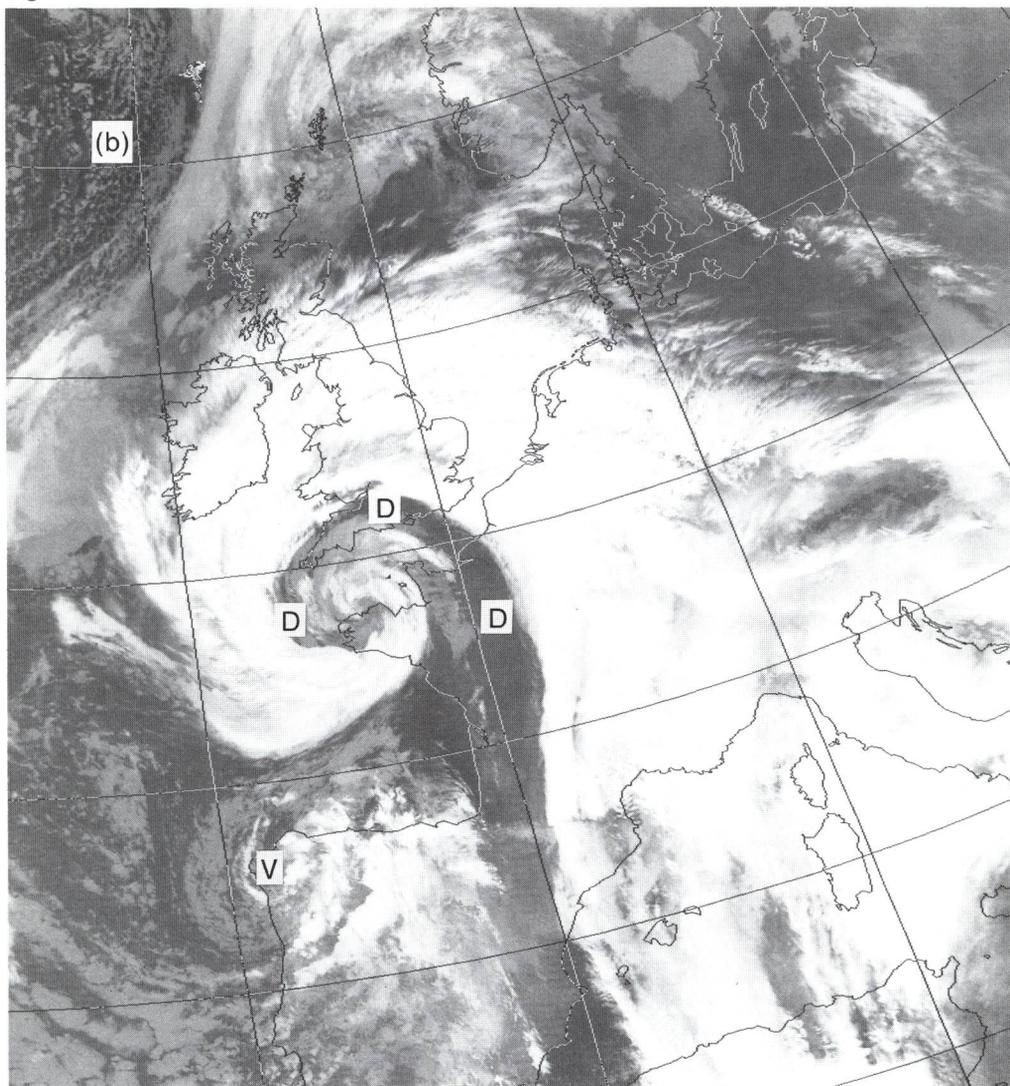


Figure 1. AVHRR images from the NOAA-10 satellite at 0749 UTC on 8 March 1991, (a) visible, and (b) infra-red. See text for explanation of lettering. The surface analysis for 0600 UTC is inset.

Figure 1. Continued.



up at C. Note the two lines of shadow at S, both where the high cloud casts a shadow on lower mid-level cloud and again where the mid-level cloud casts a shadow on the ground. The sharpness of the cloud edge near these shadows can be seen better on the infra-red image for the same time, Fig. 1(b); west of the cloud edge is a mostly cloud-free slot D-D-D which spirals right in to the centre of the system.

The COST-73 European radar rainfall composite picture for 0600 UTC is shown in Fig. 2. The rainfall pattern shows the same spiral shape as the satellite pictures, and the shape of the rainband mirrors the shape of the high cloud just outside the dry slot, although the rainband is further forward than the high cloud edge. Note the high gradient of rainfall rate of the inner edge of the rainband, especially near A where rainfall rates above 10 mm h^{-1} are recorded.

Other features of interest on the images shown here include the loosely-ordered vortex of convective cloud V centred over Cape Finisterre at 0749 UTC (Fig. 1) which has moved to north-eastern Spain by 1428 UTC (Fig. 3). Notice also the area of diffuse sun glint at G on Fig. 1(a), where light from the low sun reflects brightly off the relatively calm waters of the Baltic Sea.

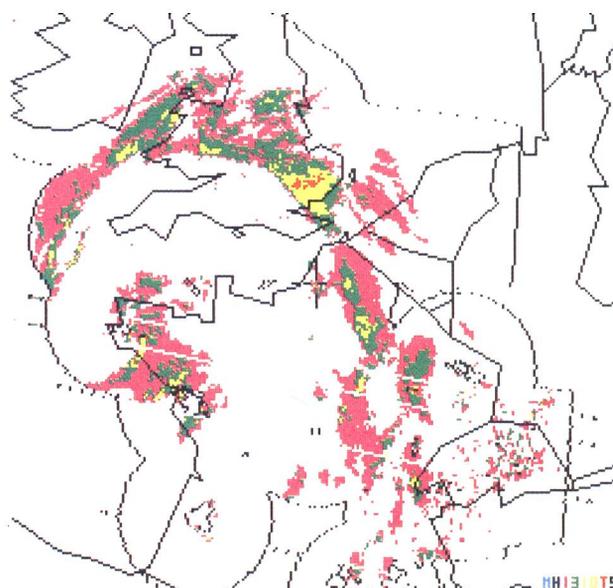


Figure 2. COST-73 European radar composite picture for 0600 UTC on 8 March 1991. Rainfall rates (mm h^{-1}) shown are: pink 0.3-1, green 1-3, yellow 3-10, red 10-30, black > 30. See text for explanation of lettering.

Photograph by courtesy of University of Dundee

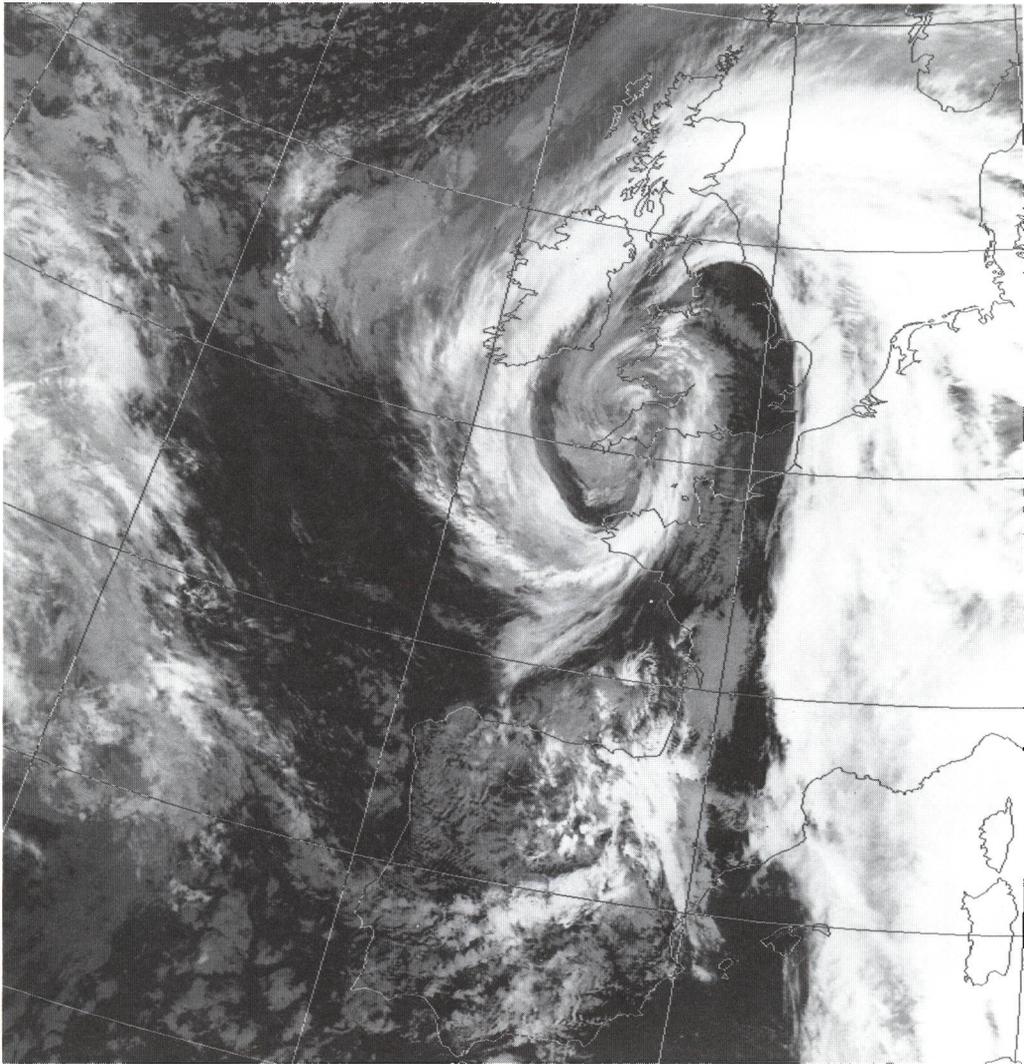


Figure 3. AVHRR infra-red image from the NOAA-11 satellite at 1428 UTC on 8 March 1991.

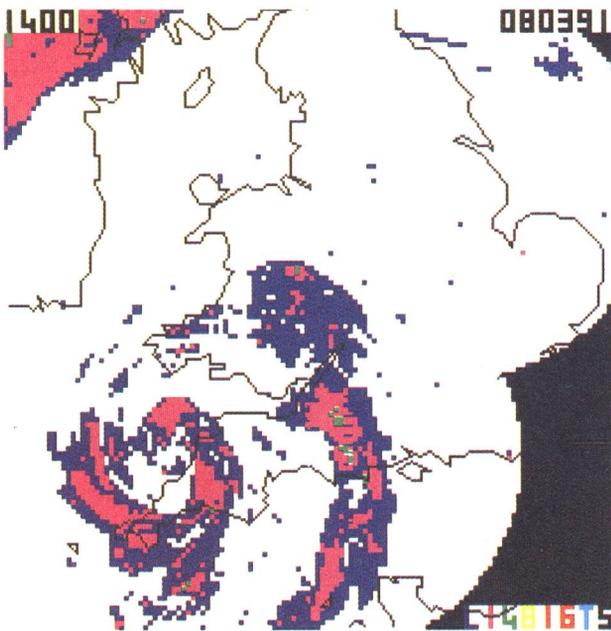


Figure 4. UK radar composite picture for 1400 UTC on 8 March 1991. Rainfall rates (mm h^{-1}) shown are: dark blue 0.1-1, pink 1-4, green 4-8.

The system continued to move northwards during 8 March, tracking across Cornwall and gradually filling. Fig. 3 shows the AVHRR infra-red image for 1428 UTC, by which time the low is centred in the Bristol Channel to the north of the Cornish coast. Surface observations for 1500 UTC suggest that the low has started to fill, but there is still a clear spiral shape to the cloud around the centre of the system. The UK radar rainfall composite picture for 1400 UTC, Fig. 4, shows the rainband also spiralling around the low centre, although the rain is somewhat lighter (mostly below 4 mm h^{-1}). At about this time, severe gales on the south-eastern flank of the system affected parts of south-west England; mean winds of 55 kn were recorded at Torquay at 1200 UTC, with 40 kn still being recorded at 1500 UTC.

R.B.E. Lilley

GUIDE TO AUTHORS

Content

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