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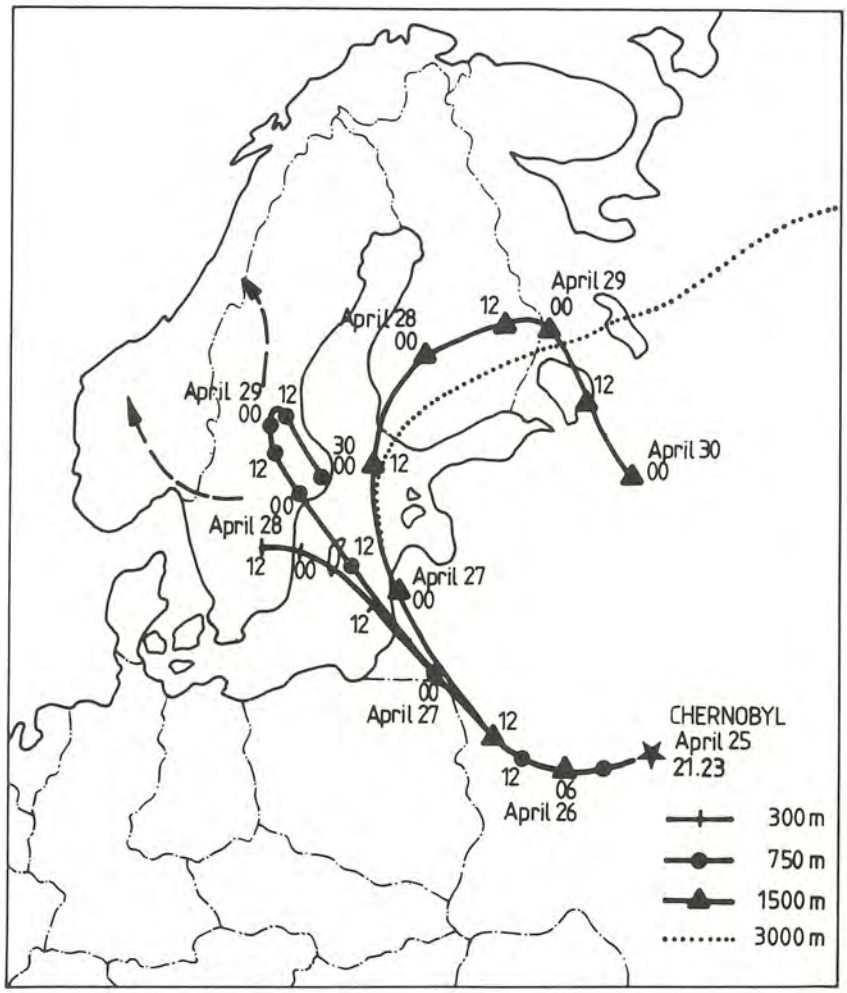

THE CHERNOBYL ACCIDENT

A meteorological analysis of how radionuclides reached Sweden

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Title (and Subtitle)

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Abstract

The atmospheric transport to Sweden and the deposition there of radioactive material following the Chernobyl accident have been described on the basis of radiological and meteorological data and theoretical calculations of despersion. The radioactive cloud created by the explosion at 01.23 local time on 26 April 1986 was transported north-west and north over the Baltic Sea. An extensive long-distance transport of radionuclides to Scandinavia and Finland took place. Sweden was affected by dry deposition, including fairly large hot particles and also by wet deposition. Wet deposition occurred in connection with precipitation over eastern Sweden on 28 April, which further affected parts of northern Sweden until 30 April. Deposition of caesium mainly occurred through wet deposition. In the case of certain other radionuclides, including ^{95}Zr and ^{239}Np, a considerable part of the deposition occurred in the form of dry deposition. The study has attempted to estimate the probability of Sweden being affected to a similar extent following a major nuclear accident outside the country's borders.

Key words

Chernobyl accident, atmospheric transport, deposition, iodine-131, caesium-134, caesium-137, hot particles, particle sizes, probability

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CONTENTS

SUMMARY

The atmospheric transport to Sweden and the deposition there of radioactive material following the Chernobyl accident have been described on the basis of radiological and meteorological data and theoretical calculations of dispersion. The radioactive cloud created by the explosion at 01.23 local time on 26 April 1986 was transported north-west and north over the Baltic Sea. An extensive long-distance transport of radionuclides to Scandinavia and Finland took place, with the first probably reaching south-east Sweden early on 27 April. In eastern Svealand, high concentrations of radionuclides began to appear on the evening of the same day.

Sweden was affected by dry deposition, including fairly large hot particles and also by wet deposition. Wet deposition occurred in connection with precipitation over eastern Sweden on 28 April, which further affected parts of northern Sweden until 30 April. The deposition of radionuclides over the country has been mapped in detail, principally through measurements of gamma radiation using aircraft. Deposition of caesium mainly occurred through wet deposition. In the case of certain other radionuclides, including ^{95}Zr and ^{239}Np, a considerable part of the deposition occurred in the form of dry deposition.

An integration of the total caesium deposition shows that as much as about 10% of the total quantity of caesium released may have been deposited over Sweden. The study has attempted to estimate the probability of Sweden being affected to a similar extent following a major nuclear accident outside the country's borders.

1. INTRODUCTION

The purpose of this study is to describe the atmospheric transport to Sweden and the deposition there of radioactive material as a result of the reactor accident at Chernobyl ($51^{o}17'N$, $30^{o}15'E$), USSR, on 25 April at 21.23 UTC (26 April, 01.23 local time) 1986. The basis for the analysis consisted of radiological measurements and theoretical calculations of transport and dispersion. In Sweden, a total of about 40 different radionuclides have been detected in the emissions from Chernobyl. Since the composition differs both in time and space, the comparison between the purely meteorological analysis and radiological measurements has concentrated on iodine (in the form of ^{131}I) and caesium (in the form of ^{134}Cs and ^{137}Cs), the two most significant radioactive elements (i.e. those which were most frequent, contributed most to the total dose and were most extensively measured).

Calculations of air transports with the aid of meteorological data can provide supplementary information where radiological information is insufficient. Such calculations are especially valuable in the acute stage of an accident, since they can be performed in real-time and even give certain predictive information. In the Chernobyl accident, calculation routines produced by the Swedish Meteorological and Hydrological Institute (SMHI) were implemented at an early stage. In fact, routine calculations of receptor-oriented trajectories had been calculated by SMHI even before the accident was made known. These were sent by telex to the National Defence Research Institute (FOA), Section for Nuclear Detection. A trajectory describes the transport path of a certain air parcel and can be used to trace sources of contaminated air. In January 1985, a cooperative programme between SMHI and FOA was introduced, with SMHI making daily calculations of trajectories to the FOA's air filtering stations.

Figure 1 contains the trajectories showing the origin of the air at 02 (Swedish time) on 28 April at an air filtering station just south of Stockholm. At 13.00 on 28 April, only 45 minutes after receiving an alarm from the National Institute for Radiation Protection (SSI), FOA was able to announce on the basis of these trajectories and a directly analysed air filter, that the detected radionuclides originated most probably from a reactor accident in the south-east part of the USSR. SMHI then performed further calculations and in the evening of 28 April, after the exact location of the accident was made known, calculations were started on source-oriented trajectories for describing the transport of the radioactive emissions from Chernobyl.

The primary reason for doing this was to support the work of the National Institute for Radiation Protection. The information produced by SMHI, describing the dispersion of the radionuclides over Europe, was also used by the World Health Organization (WHO) in its first survey of the situation on 6 May, when data was still very sparse. Table 1, which, apart from point 6, is included in the WHO report (World Health Organization, 1986) from 6 May, contains an approximate description of the areas of Europe most affected by increased levels of radionuclides.

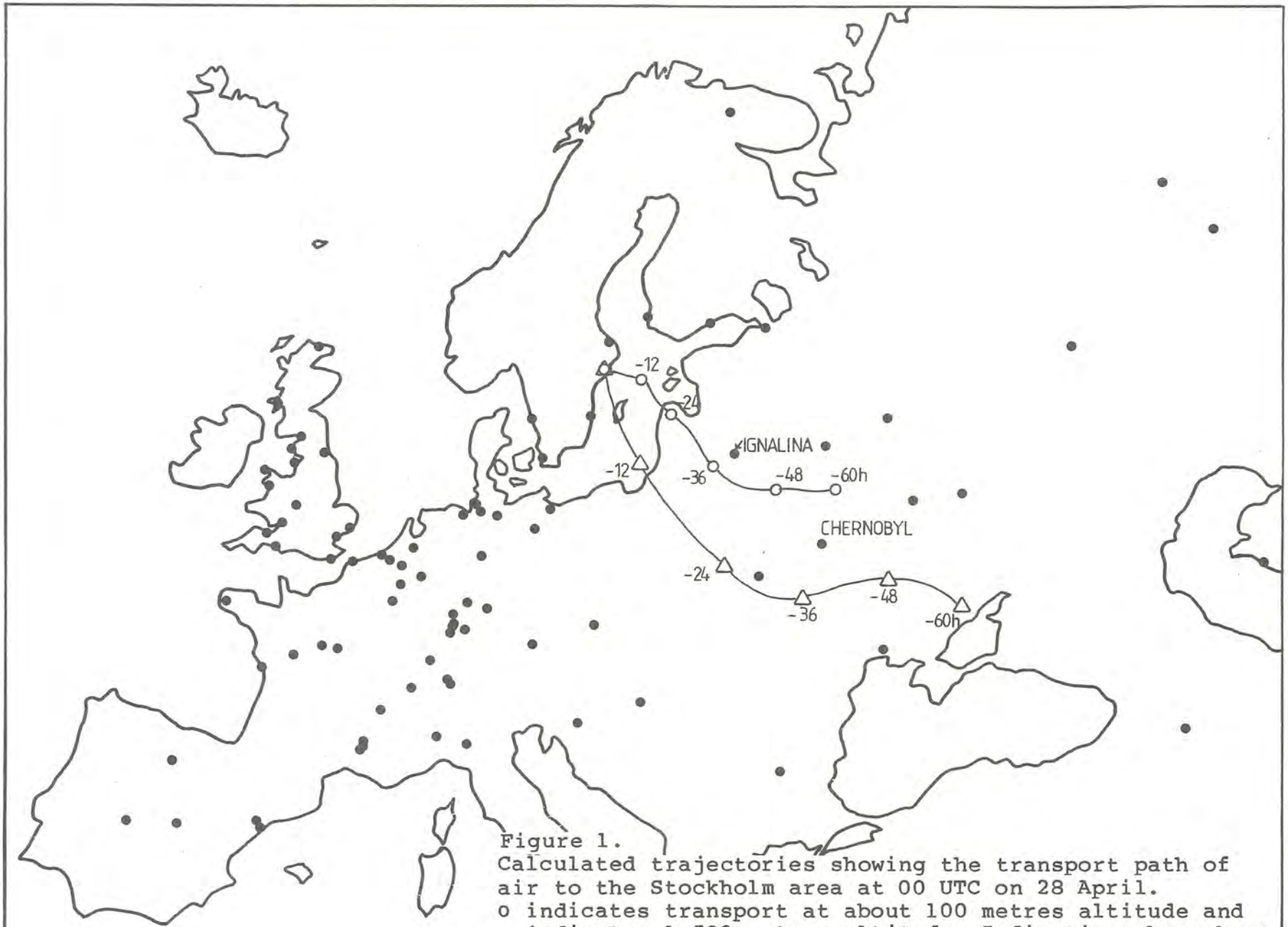


Figure 1.
Calculated trajectories showing the transport path of air to the Stockholm area at 00 UTC on 28 April.
o indicates transport at about 100 metres altitude and
▵ indicates 1,500 metres altitude. Indications have been entered for every 12 hours. The figure also contains the positions of all the European nuclear power plants.

TABLE 1

1.	Area:	Baltic states, Scandinavia, Finland
	Emission:	26 April, arrived 27 - 30 April
2.	Area:	Eastern central Europe, southern Germany, Italy, Yugoslavia
	Emission:	27 April, arrived 28 April - 2 May
3.	Area:	Ukraine and eastwards
	Emission:	28 - 29 April, arrived 28 April - 2 May
4.	Area:	Rumania, Bulgaria, Baltic states
	Emission:	29 - 30 April, arrived 1 - 4 May
5.	Area:	Black Sea, Turkey
	Emission:	1 - 4 May, arrived 2 - 7 May
6.	Area:	Central Europe, Scandinavia, Finland
	Emission:	5 May; arrived 6 - 9 May

This study concentrates on describing the first period, although period 6, when transport again turned in the direction of Sweden, is also dealt with.

2. THE WEATHER SITUATION

At the time of the reactor explosion, the weather in Europe was dominated by an extensive ridge of high pressure with its centre over north-west Russia and a weak trough of low pressure reaching from Spain across central Europe to southern Scandinavia. Warm air moved at lower altitudes with a south-easterly wind towards the Baltic, which has a very low surface water temperature at this time of the year. On the night the explosion occurred, the area around Chernobyl was almost still and free of cloud. A temperature inversion reached from the ground up to an altitude of 400 - 500 m. The temperature within this inversion increased about 2 - 4^{o}C with altitude. Above the inversion there was, at least at the radio sounding stations north and north-west of Chernobyl, a band of strong east to south-east wind with a speed of 12 - 14 m/s. Higher up, the wind decreased somewhat, and at 1,500 m altitude it was south-east 8 - 12 m/s.

The Soviet report (USSR State Committee, 1986) to the IAEA Accident Review Meeting confirms this picture in all essential details. The report states that on 26 April the power plant was in a relatively constant pressure zone with a light wind of varying direction. At an altitude of 700 - 800 m to 1.5 km, the area lay on the south-west edge of a high-pressure ridge with south-easterly winds of 5 - 10 m/s. The differences found in the description seem to be due to the fact that the Soviet report uses information based on the radio sounding stations south of Chernobyl, while we regarded radio soundings north-west and north of Chernobyl, towards which the plume was travelling, as most relevant. These radio soundings were made 2.5 hours after the explosion.
Figure 2 describes the weather over Europe during the period 25 April - 9 May in the form of a series of simplified weather maps. It can be seen that the warm air from the south-east penetrated

south-east Sweden on 27 April behind a warm front, travelling over inner Svealand and south-east Norrland on 28 April. An area of rain in connection with the warm front and a cold front from the west formed over central Scandinavia on 28 April. The rain moved northwards over Sweden and affected central Norrland the following day. Winds were light. On 30 April, a weak cold front entered over southern Scandinavia and air from the west moved in. On 1 May, a ridge of high pressure formed over southern Scandinavia and the weak westerly wind remained over southern and central Sweden. The high pressure ridge moved slowly north-east and on 3 May south-easterly winds again began to blow over the country. In the Chernobyl area, however, winds were still strong and northerly. On 5 - 6 May, a low pressure trough over the British Isles and a high-pressure ridge over the Baltic caused air from the Chernobyl area again to stream up towards Scandinavia. On 8 May, a large part of Sweden was covered by warm air from the south-east. A cold front through Denmark and Norway moved eastwards over the country and brought rain in south-west areas. Behind the cold front, colder air flowed in over Sweden from the west. On the evening of 9 May, the air from the west had reached in over southern and central Sweden, moving on to northern Sweden by the following day. After this, Sweden was not affected by any further appreciable releases of radionuclides from the Chernobyl accident. As shown in Figure 3, the variation in the level of radionuclides in the Stockholm air illustrates the significance of weather changes during this period, although of course the variation in the emission is also influential on the caesium level.

3. EMISSION CONDITIONS

The destroyed reactor, Chernobyl 4, had a thermal output of 3,200 MW and delivered 1,000 MW of electric power. It was a graphite moderated reactor of the channel boiler type. Before the accident, there were 12 of these in operation in the Soviet Union, of which one was operated, and is still operated, at 50 % higher output (Ignalina in Lithuania). Chernobyl 4 had been in operation since December 1983 and was being operated at a mean burnout of 10.3 MWd/kg, or about half the maximum capacity. 75 % of the fuel rod bundles had been in the core since the reactor was first started and were burned to between 12 and 15 MWd/kg. The pool for spent fuel was not involved in the accident.

In the report to IAEA (USSR State Committee, 1986), the Soviets made estimates of the volume of emissions from the reactor during the explosion and the subsequent period. In the immediate explosion and during the first 24 hours, it was calculated that about 0.80 EBq (1EBq = 10^{18} Bq) was released, excluding the inert gases. Figure 4 describes how the emissions varied, as a total and for ^{137}Cs, between 26 April and 6 May (local time). On 26 April, the emissions were dominated by the explosion sequence. A start was then made on covering the open core with 5,000 tons of boron, dolomite, sand, clay and lead, which succeeded in limiting the emissions during the last days of April. However, the residual power of the fuel heated the material to over 2,000^{o}C, so that the emissions again began to increase on 2 May and by 5 May were up to a third of the level of 26 April. On 6 May, workers succeeded in cooling the core and almost stopping the emissions.

Note: The three regions of Sweden - Götaland, Svealand and Norrland are indicated in Figure 20.

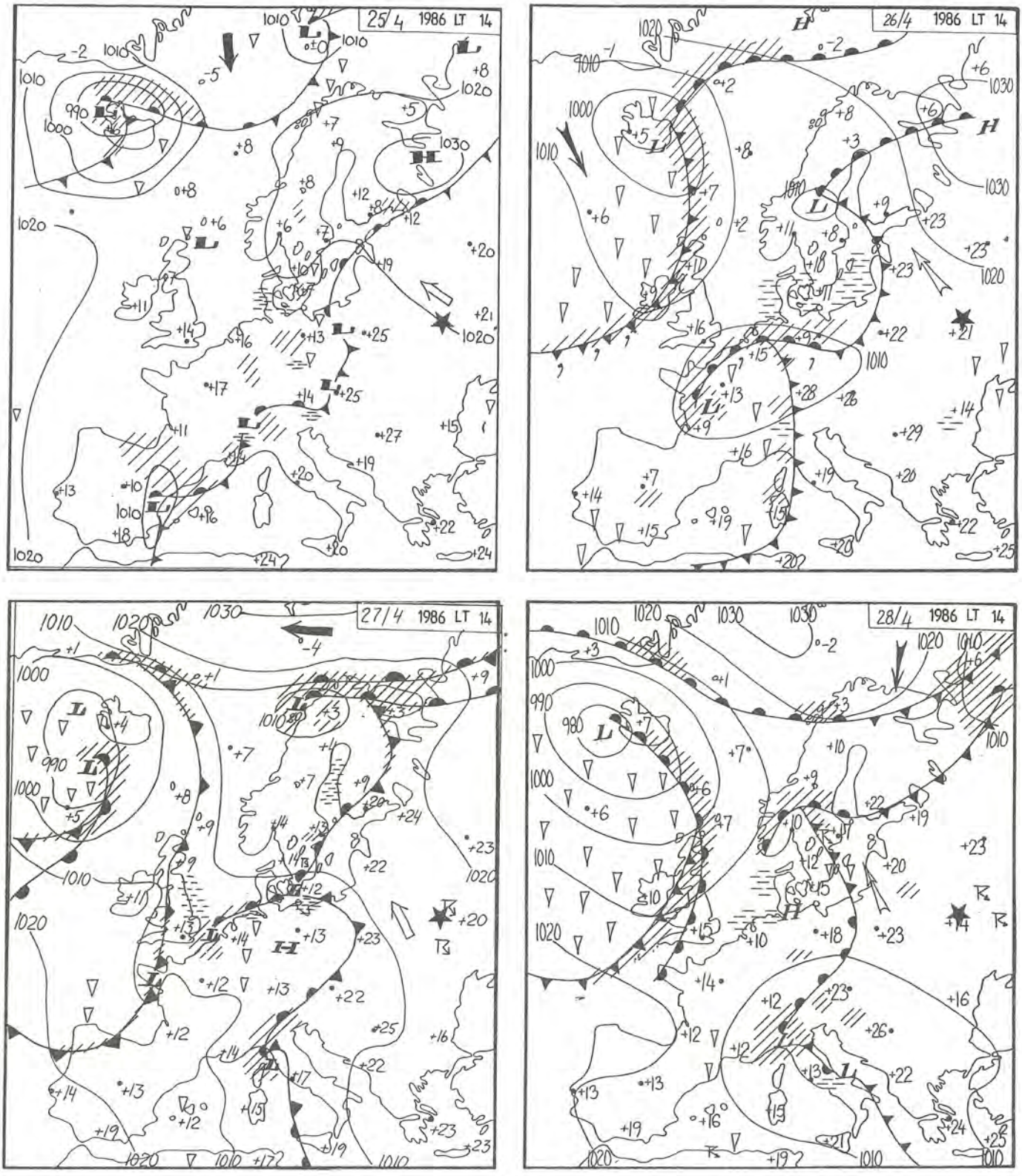
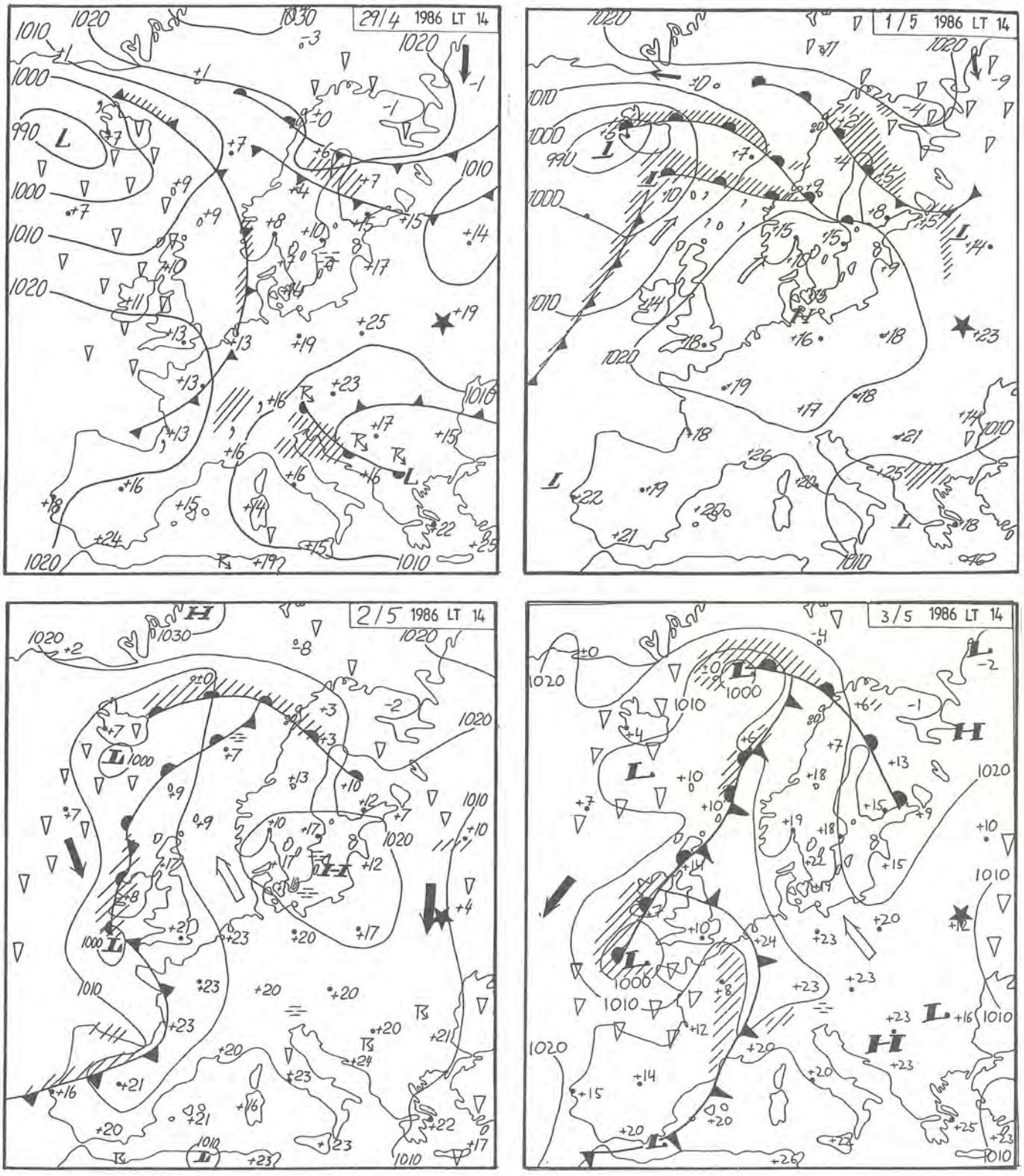


Figure 2. A selection of simplified weather charts for the period 25 April - 9 May, showing general weather development over Europe.



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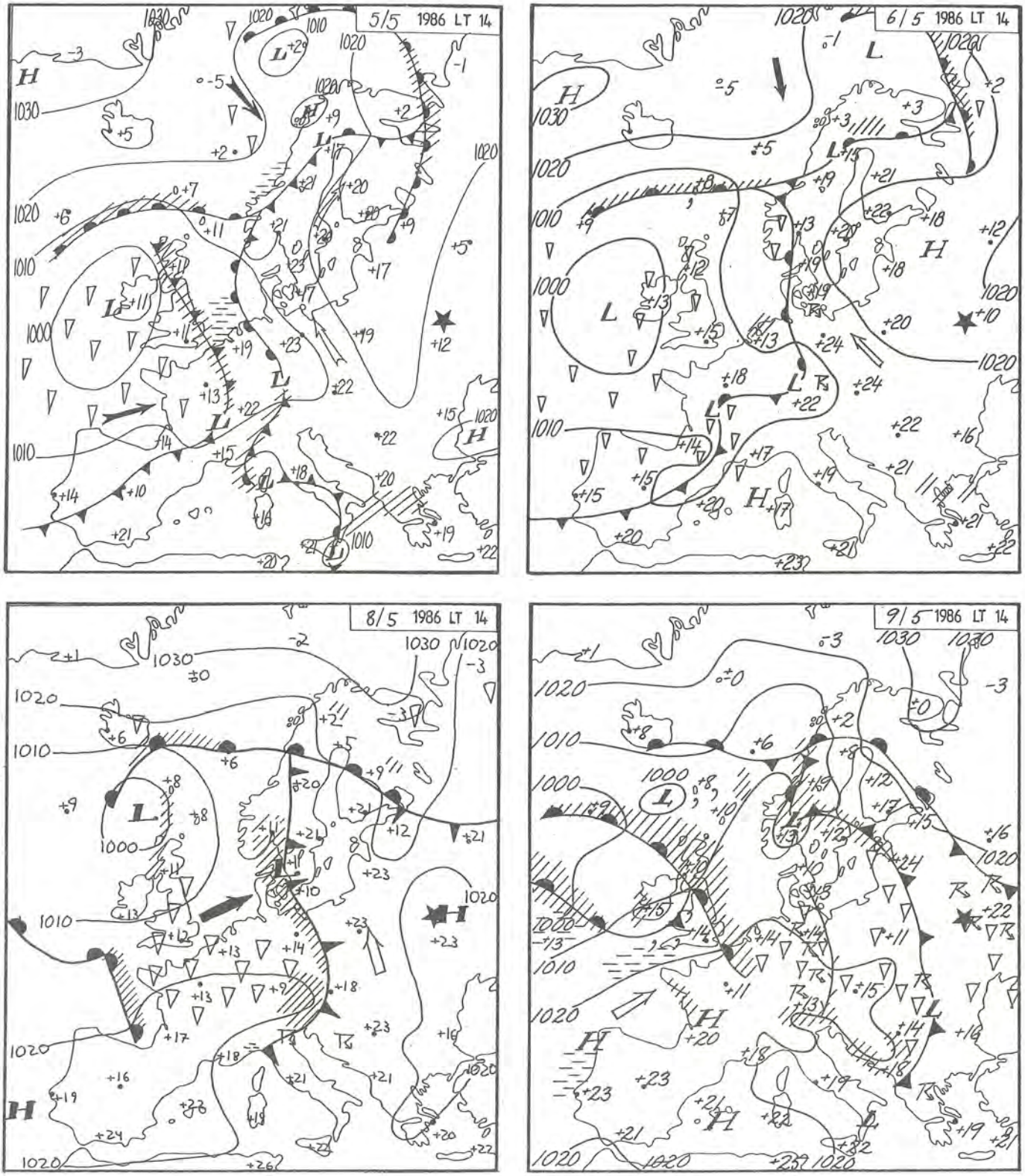


Figure 2. Cont

Table 2 lists the total emissions (26 April - 5 May) divided according to the most important radionuclides as stated in the Soviet report to IAEA. However, the values have been converted from MCi to EBq and are related to 26 April instead of 6 May. The estimates are based only on measurements of what was deposited within the Soviet Union and the accuracy is put at ±50%. The estimates are therefore probably on the low side. This applies especially to the volatile substances I, Cs and Te. Volatile substances are designated as such if they are volatile at the temperatures occurring in the accident. Non-volatile substances are termed refractory. Table 2 also shows values for the core inventory of 26 April, partly as calculated from the Soviet report and also on the basis of a calculation for an RBMK-1000 reactor with the code ORIGEN (Markoff, 1986). Correspondence is good for most radionuclides, but differs by a factor of 2 or more in the case of ^{106}Ru, ^{239}Np, ^{239}Pu and ^{242}Cm. The activity ratio $^{134}Cs/^{137}Cs$ is about 0.57 in the deposition in Sweden, which agrees relatively well with the Soviet figure (0.68) but not with the ORIGEN calculation (1.3).

The explosion itself and the subsequent fire, which developed a great amount of heat, caused a rise of the emitted plume. The Soviet figures on the altitude reached by the emission are imprecise. However, it is stated that radiation was detected in the altitude range 0.7 - 1.5 km on 26 April. It is also stated that aircraft measurements showed that the plume reached over 1.200 m altitude on 27 April moving north-west at a distance of 30 km. Subsequently, the initial plume never exceeded an altitude of 400 m. Chapter 5 discusses theoretical calculations of the plume rise and how this is supposed to have varied according to meteorological conditions.

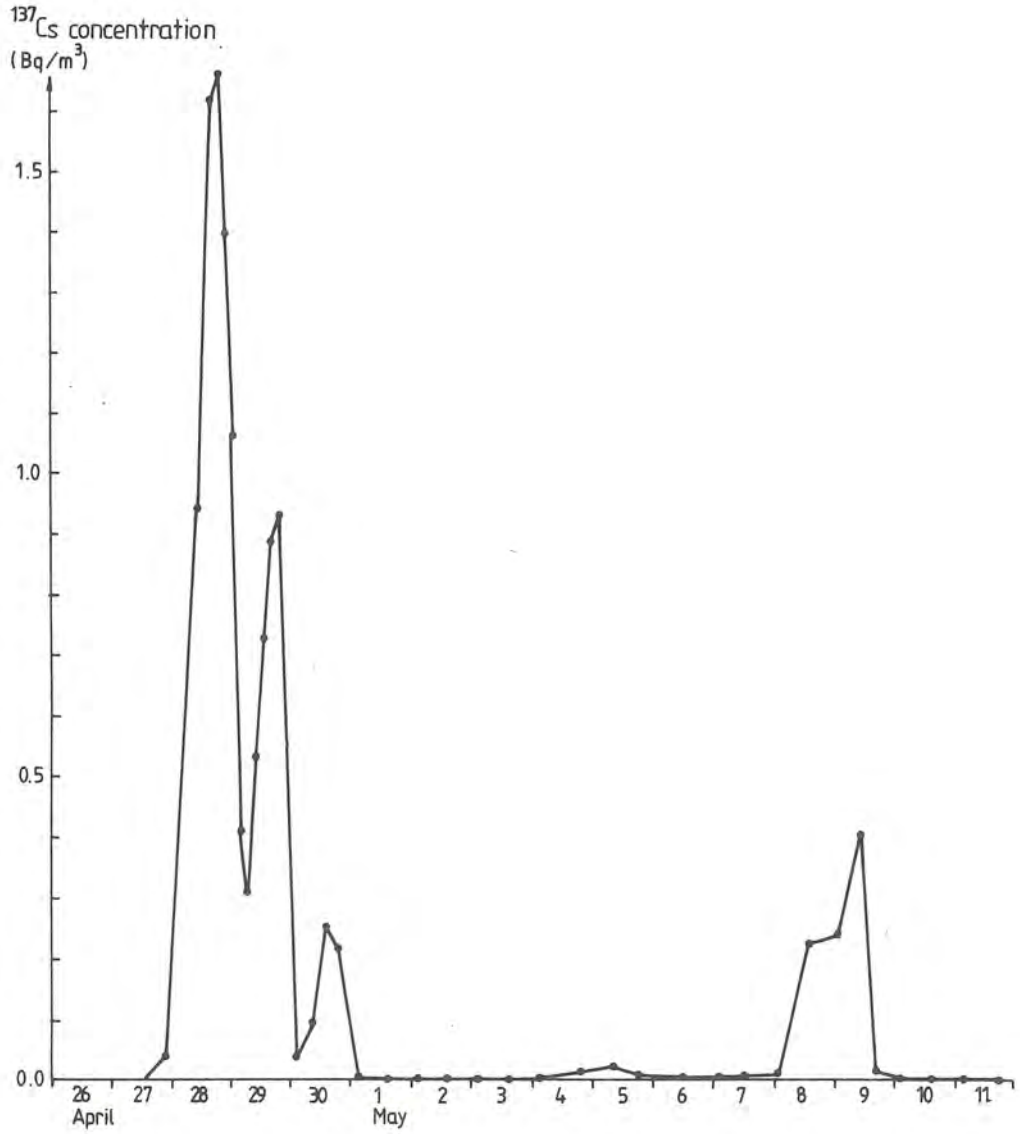


Figure 3. Air concentration of ^{137}Cs at ground level at FOA's measuring station in Stockholm during the period 26 April - 11 May 1986.

Table 2. Total emissions of the most significant radionuclides (column 3) from Chernobyl 4 according to the Soviet report to IAEA. Column 4 gives the Soviet values for the proportion of the inventory released. Column 5 gives the values of the inventory derived from the two previous columns, while column 6 gives the inventory according to an American ORIGEN calculation (for 780 days' operation) (Markoff 1986). All activity values relate to 26 April 1986.

Radio-nuclide	Half-life	Total emission EBq	% of in-ventory	Derived inventory EBq	Inventory according to ORIGEN EBq
^{89}Sr	50.5 d	0.094	4.0	2.4	3.1
^{90}Sr	29 år	0.0081	4.0	0.20	0.20
^{95}Zr	64.0 d	0.16	3.2	5.0	5.1
^{99}Mo	2.75 d	0.16*	2.3	7.0	6.0
^{103}Ru	39.4 d	0.14	2.9	4.8	5.0
^{106}Ru	372 d	0.059	2.9	2.0	1.0
^{131}I	8.04 d	0.67	20	3.3	3.2
^{132}Te	3.26 d	0.45	15	3.0	4.6
^{134}Cs	2.06 år	0.019	10	0.19	0.34
^{137}Cs	30.2 år	0.037	13	0.28	0.27
^{140}Ba	12.7 d	0.28	5.6	5.0	5.8
^{141}Ce	32.5 d	0.13	2.3	5.6	5.4
^{144}Ce	285 d	0.088	2.8	3.1	2.5
^{239}Np	2.36 d	0.97	3.2	30	76
^{238}Pu	87.7 år	3.0×10^{-5}	3	1.0×10^{-3}	1.1×10^{-3}
^{239}Pu	24 110 år	2.6×10^{-5}	3	8.7×10^{-4}	2.0×10^{-3}
^{240}Pu	6 560 år	3.7×10^{-5}	3	1.2×10^{-3}	1.9×10^{-3}
^{242}Cm	163 d	7.8×10^{-4}	3	2.6×10^{-2}	8.9×10^{-2}

* The report states 3 MCi but this is assumed to be a typing error which should read 0.3 MCi.

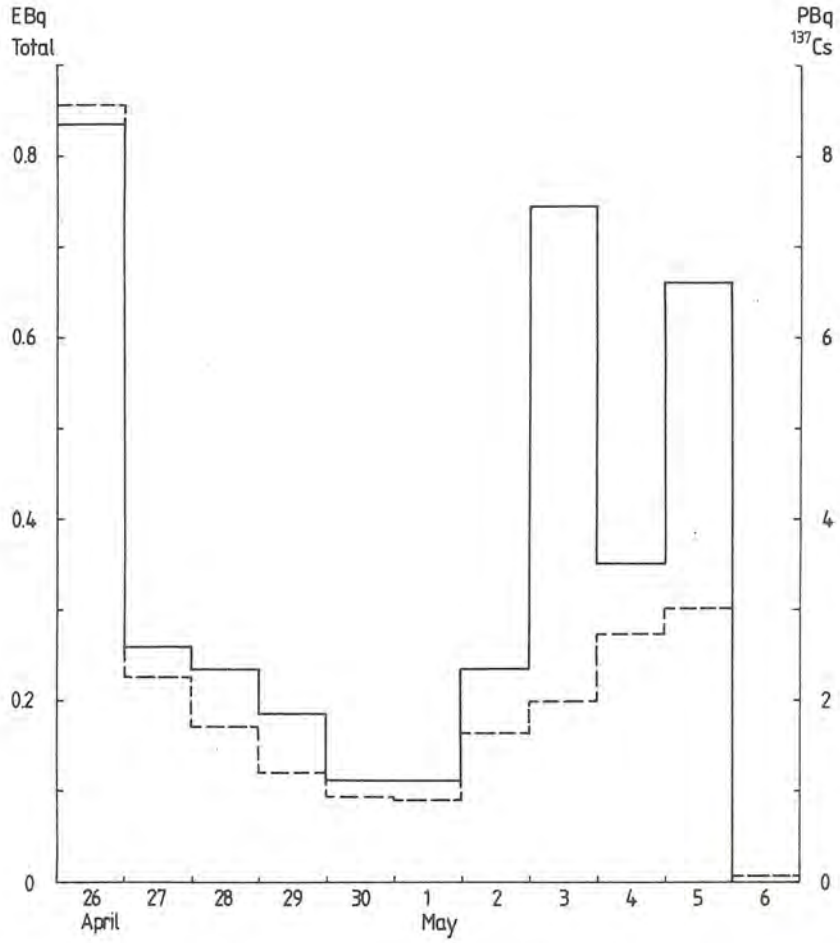


Figure 4. Daily emissions from Chernobyl 4 according to the Soviet report to IAEA. The broken line indicates the total activity excluding inert gases (left-hand scale) while the solid line indicates the emissions of ^{137}Cs (right-hand scale). (PBq = 10^{15}Bq).

4. RADIOLOGICAL DATA

High resolution measurement in both time and space is essential when using radiological data to describe transport in the atmosphere, dispersion and deposition on the ground. The sequence in ground air is best described by the FOA's seven permanent stations and measurements at the Swedish reactors. These give air concentrations of a large number of radionuclides for varying periods of time (De Geer et al, 1986). Owing to insufficient resources, however, analyses could not be made with the same high frequency for all the FOA's stations during the first days when Sweden was affected. The 25 ion chamber stations of the National Institute for Radiation Protection give no concentration values but only indicate approximate changes in the total occurrence of radioactive substances at ground level at the stations. It is especially during the deposition of radioactivity that indications are obtained. These stations have been used for information on when the radioactive substances have arrived at these locations (Kjelle, 1986).

At higher altitudes, FOA and the Swedish Air Force made daily samplings using J32 Lansen aircraft during the period of interest, so that a number of cross-sections of the plume could be produced. Similar measurements were also made in Finland (STUK-B-VAL O 44, 1986) and a number of these were used for comparison.

The deposited activity was mapped very thoroughly by the Swedish Geological Company (SGAB) with aircraft measurements. These were combined with the FOA in situ measurements to produce deposition charts for specific radionuclides.

5. TRANSPORT, DISPERSION AND DEPOSITION OF RADIONUCLIDES

Several general theoretical descriptions of how the radioactive emissions were dispersed over Europe have already been produced. The WHO report of 6 May (World Health Organization, 1986) describes SMHI's first calculations of the areas primarily affected and the periods for this. The study was based on trajectory calculations and gives no quantitive information on contents in the air or deposition on the ground. Later, several other trajectory studies have been described from the Finnish, Norwegian, Dutch and French meteorological institutes as well as from the European Centre for Medium Range Weather Forecasts (ECMWF). The Swedish and most of the other calculations assume that transport takes place in certain pressure surfaces in the atmosphere (isobaric transport) e.g. 925 hPa corresponds to about 750 m altitude (height varying somewhat) while 850 hPa corresponds to about 1,500 m. The calculations from ECMWF, however, are based on wind analyses where the vertical component of the wind is included, allowing more realistic calculations of 3-dimensional trajectories. ECMWF also has somewhat better resolution of the analysed wind field near the ground compared to SMHI. The latter is of special importance for calculating transports the first night after the explosion, when a strong windband appeared at about 500 m. Both SMHI and ECMWF use a trajectory model developed by Källberg (1984).

Several dispersion models have also recently been described where contents in the air and deposition on the ground of certain radionuclides have been calculated. Lawrence Livermore Laboratory (LLL), USA, has made calculations covering large parts of the northern hemisphere, while Dutch (Leeuw et al, 1986) and English (ApSimon and Wilson, 1986) model calculations have been made mainly for central Europe. The LLL calculations give only a very schematic deposition field over Scandinavia without regard to the true precipitation. The English model omits the episode over Finland and eastern Sweden and is therefore of no interest here. Furthermore, the English model uses only the pressure zone at the ground surface and certain assumptions on changes in wind direction for the transport calculations, which creates considerable uncertainty in episode studies. However, the Dutch variant uses a 2-dimensional wind field based on true wind observations. The wind field has been obtained from analyses at ECMWF, but since the model only includes southernmost Sweden, it is of little interest.

A description of the transport and dispersion of radionuclides to Finland has been made by the Finnish Meteorological Institute (Savolainen et al, 1986).

5.1 Transport path

The transport path of the emitted radionuclides is determined by the wind conditions above the ground where the released cloud is located and the way in which the wind varies geographically and with time. During transport, a turbulent dispersion of the cloud both horizontally and vertically occurs and part of the radionuclides is deposited on the ground or sea surface over which the cloud passes. The magnitude of both the turbulent dispersion and the deposition depends largely on the prevailing weather conditions.

Theoretically, the transport path of the emitted radioactive cloud can be calculated with the aid of trajectories. In order for such calculations to provide a correct result it is necessary both to have correct information on the horizontal wind field and to determine the vertical motion of the emitted cloud. In this context, the heat from the explosion and fire in the reactor is especially important. The explosion itself also caused a dispersion of radionuclides to higher altitudes. During the first night after the explosion, a ground inversion limited the rising of the plume. Just above the inversion, at about 500 m altitude, there were fairly strong winds which also restricted the rise. Very large quantities of energy may have been imparted to the plume immediately after the explosion and, according to theoretical calculations made by SMHI, temporarily caused the plume to rise by 1,500 - 2,000 m. The theoretical calculations indicate, however, that the major part of the emission was transported at 1,000 m altitude or lower during the first night. The recently published Soviet report to IAEA provides certain indications concerning the plume rise, for example, on 27 April, the plume reached 1,200 m altitude. This value probably relates to daytime, when the meteorological conditions were favourable for the plume rise.

The radioactive decay taking place continuously in the plume, produced a small amount of heat which purely theoretically may have caused a successive plume rise. However, calculations show that the quantity of heat was quite insufficient to exert any significant influence. Larger particles (diameter > 5 µm) have a gravitational fall velocity that is significant. Deposition of radionuclides through falling particles is greatest in the immediate vicinity around Chernobyl but may be of some importance also at greater distances. It is possible, for example, to state that the dry deposition occurring in Sweden during 27 - 28 April consisted to a relatively large extent of hot particles. An important type of vertical motion is caused by the atmosphere's own upward and downward winds. As there are no direct observations of these, they must be determined indirectly from other meteorological information.

In our theoretical calculations of the transport path of the radionuclides first emitted, we have made use of trajectories from both SMHI and ECMWF. The strong windband at about 500 m altitude during the first night is better described by the more detailed wind analysis made at ECMWF. The ECMWF trajectory at the 750 m level has therefore been used for the time from the explosion up to 06 UTC on 26 April. For practical reasons, our calculations are subsequently based on trajectories from SMHI.

On the morning of 26 April, the initially emitted cloud reached a convective boundary layer over western White Russia. The weather there was bright and sunny. As the ground surface warmed up, stratification became increasingly unstable near the ground, with increased mixing up to just over 2,000 m. A certain amount of radionuclides was also lifted higher in connection with the formation of cumulus clouds, which covered up to one quarter of the the surface. Owing to the vertical mixing, we performed transport calculations for 750 m, 1,500 m and 3,000 m altitude, starting at 06 UTC on 26 April. From 00 UTC on 27 April, calculations were also made for 300 m altitude. Figure 5 shows the trajectory calculations for the radionuclides first emitted, and covers a period of about 4.5 days. The trajectory for 300 m altitude, i.e. the layer closest to the ground, passed over southern Götaland, while the trajectory for 750 m reached Sweden somewhat further north, stopping over eastern Svealand and the southern part of Norrland for about 2 days. It then turned slowly back. The trajectories for higher levels moved towards Finland. During transport, the radioactive cloud expanded successively and, according to the deposition data, a part must have been transported further north and west than indicated in the diagram. The generally weak winds prevailing in this area, together with strong vertical motions in the atmosphere, caused great difficulty in following the transport with the trajectory calculations available at SMHI. Available foreign calculations also had difficulty in describing the transport in this area. On this occasion, a frontal zone also passed over the area. It is well-known from earlier studies, such as Hobbs and Persson (1983), that relatively small-scale windbands may then appear, which are seldom revealed in the sparse and infrequent network of routine upper wind observations.

On the evening of 28 April, a vertical profile of the cloud was measured over the Baltic between Stockholm and Gotland with the aid of a helicopter and it was found that the centre of the cloud was probably at an altitude of about 750 m, which supports the picture of the transport to Sweden as shown in Figure 5. Another observation of interest in describing the transport is that northern Gotland (unlike southern Gotland) had a fallout pattern that agrees well with south-eastern Svealand, i.e. a relatively high proportion of refractory elements associated with hot particles.

The trajectories shown in Figure 5 have a somewhat later arrival in the Helsinki area and the inner parts of southern Finland (about 00 UTC on 28 April) than shown by the first observations from the area (about 12 UTC on 27 April). This indicates that part of the emission initially had a higher plume rise than we have indicated for most of the plume and reached 1,000 - 2,000 m altitude over the Chernobyl area. The transport for this portion may be illustrated by trajectories for 1,500 m all the way from Chernobyl, as indicated in Figure 6. The arrival time for this portion in the Helsinki area agrees well with the first observations of radionuclides there. Increased concentrations appeared there in a fumigation situation, i.e. radionuclides mixed downwards from higher altitudes and were also deposited somewhat later in connection with a rain shower.

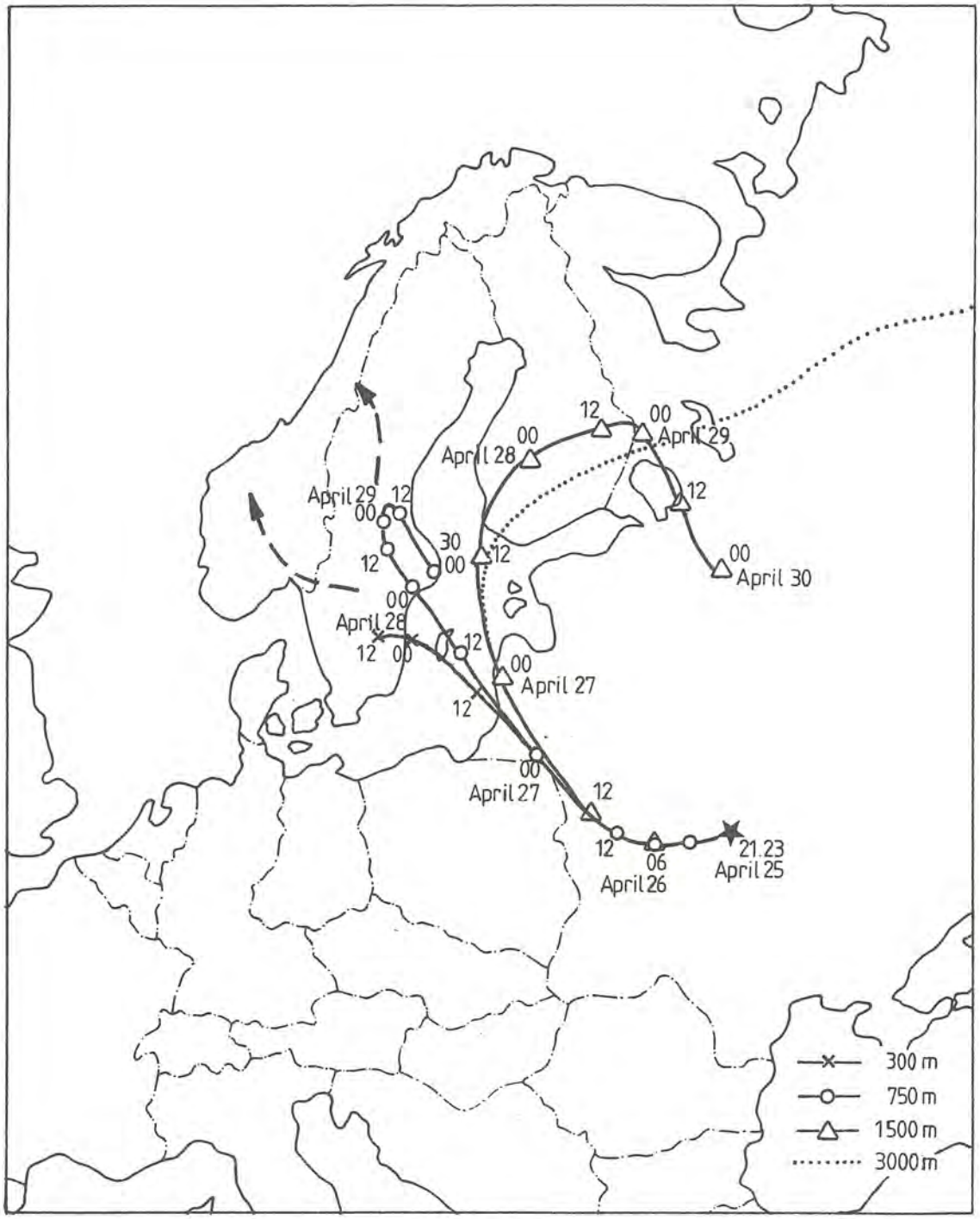


Figure 5. The calculated transport path and position at various times of the radioactive cloud first emitted. For the first 9 hours, the calculations refer to 750 m altitude. Different altitudes are then given. After 12.00 UTC on 28 April, the trajectory for 300 m turns east again. Trajectory calculations made at SMHI and to some extent ECMWF have been used. The broken arrows indicate probable further transport paths for various parts of the cloud.

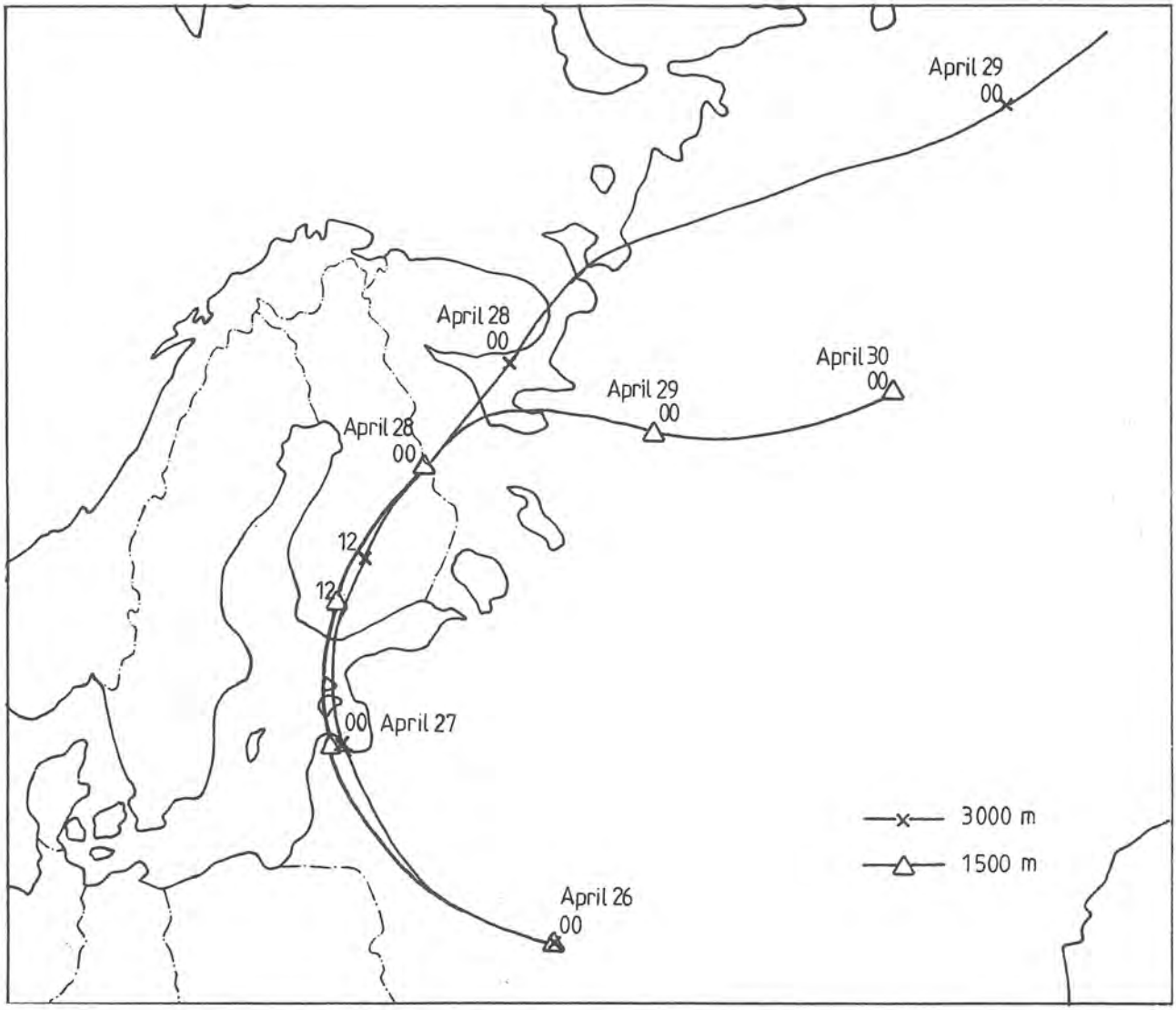


Figure 6. Trajectories from Chernobyl at 00 UTC on 26 April at the 1,500 m and 3,000 m levels.

It is interesting to note that the first emitted radioactive cloud reached large parts of Scandinavia and Finland almost simultaneously, even though the turbulent dispersion during most of the transport was very small. The reason for this was that the radionuclides were dispersed in a fairly deep layer of the atmosphere, mainly through convection over White Russia and that the variation with altitude of the transport direction then led to considerable horizontal dispersion.

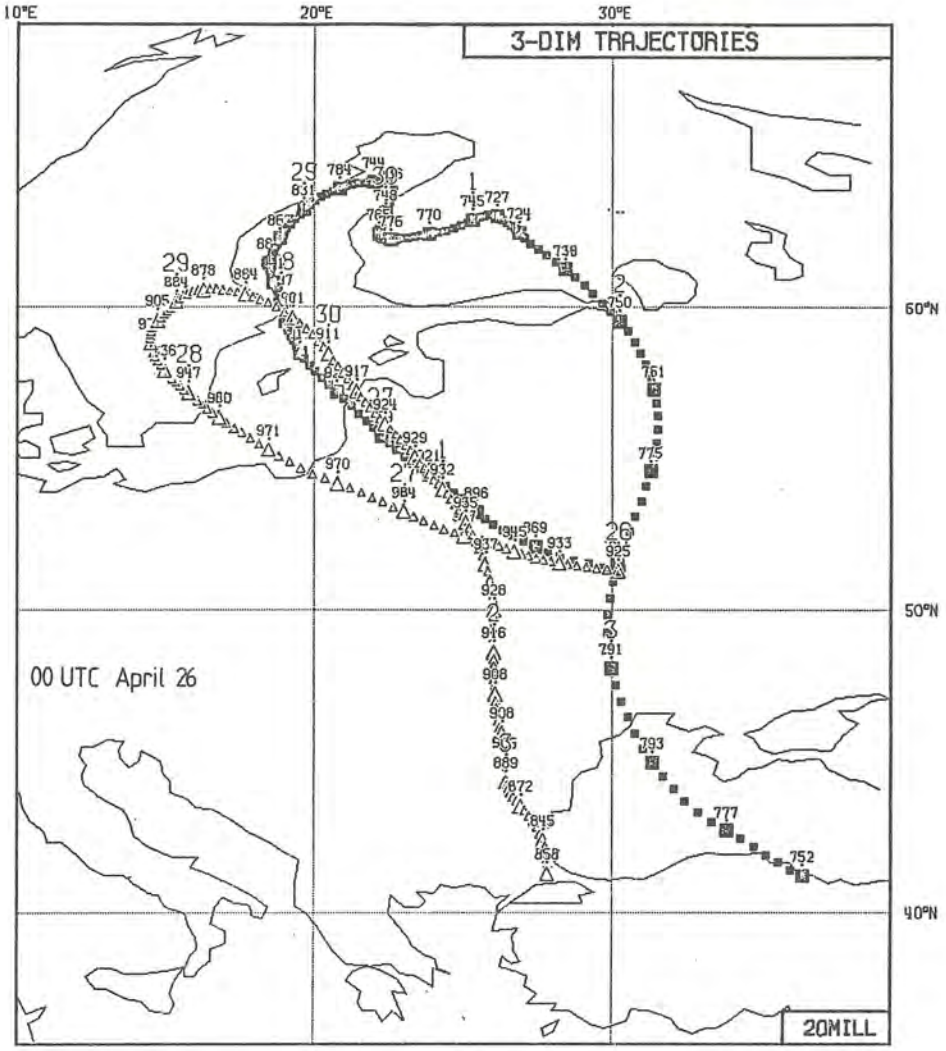


Figure 7. Calculated 3-dimensional trajectories from ECMWF starting at pressure levels 925 hPa (approx. 750 m), indicated by open triangles, and 850 hPa (approx. 1,500m), indicated by filled squares. The trajectories start at Chernobyl at 00 UTC on 26 April and are followed until 00 UTC on 4 May. Altitudes are given in the form of pressure values (hPa). At these levels, a pressure difference of 100 hPa corresponds approximately to a difference in height of 1,000 m. Time is indicated at date and a larger position indication for every 6th hour.

The significance of the vertical motions in the atmosphere for the calculated trajectories is illustrated by a comparison between Figures 6 and 7. Figure 7 shows 3-dimensional trajectories from ECMWF, while Figure 6 indicates the SMHI isobaric trajectories for the same time. There are certain important differences between the results of the calculations. From a comparison with radiological data, however, no clear conclusions can be drawn regarding which of the calculations best describes the transport to Scandinavia and Finland. For practical reasons, we have therefore primarily made use of the SMHI trajectories.

The weather during the atmospheric transport remained relatively unchanged for the emissions that occurred between the explosion and 12 UTC on 26 April. After this, a change in the transport path began as illustrated in the series of maps in Figure 8. In the figure, 5 trajectories (covering 4 days) have been calculated for each occasion and each level - 1 trajectory from Chernobyl and 4 at about 100 km around Chernobyl. We can see that the change of direction started at a lower level (750 m), where a transport towards the southern part of West Germany and the Alps started. At a higher level (1,500 m) the transport stopped for several days over north-eastern Poland and then also moved towards the Alps.

Figure 8 illustrates the uncertainty in the transport calculations and the way in which these may vary from one time to another. In the case of the emission at 12 UTC on 26 April, the trajectories at 1,500 m altitude moved very cohesively, indicating that uncertainty in calculating trajectories at this level is relatively low. At a higher level, 750 m, 4 trajectories moved towards the northern Baltic, while the fifth moved towards the Alps, which indicates uncertainty. In the case of the emission at 00 UTC on 27 April at the 1,500 m level, uncertainty is very high after a few days.

During the period 1 - 7 May, no significant transport of radionuclides into Sweden occurred. On 8 - 10 May, however, the country was again affected by a direct transport of emitted radionuclides from the Chernobyl reactor. The trajectory calculations made at SMHI, shown for the 300 - 500 m level in Figure 9, indicate that it was the emission during 5 May that reached Sweden and that the transport mainly occurred at levels of 750 m and lower. Because of the turbulent dispersion, the emission had broadened so that the whole of southern and central Sweden was affected. Both the trajectories and FOA's data, exemplified by ^{131}I in Figure 10, show that southern Sweden was affected first and that about 12 hours later the radionuclides reached the Stockholm area. In Stockholm, the concentration of ^{131}I in the air was about 1/5 of the maximum values during the period 28 - 30 April, while the concentration of ^{103}Ru, for example, was five times higher than during the first period. The comparatively higher concentrations of ruthenium in the later phase of the emissions were probably due to the formation of volatile oxides. In elementary form, ruthenium is refractive.

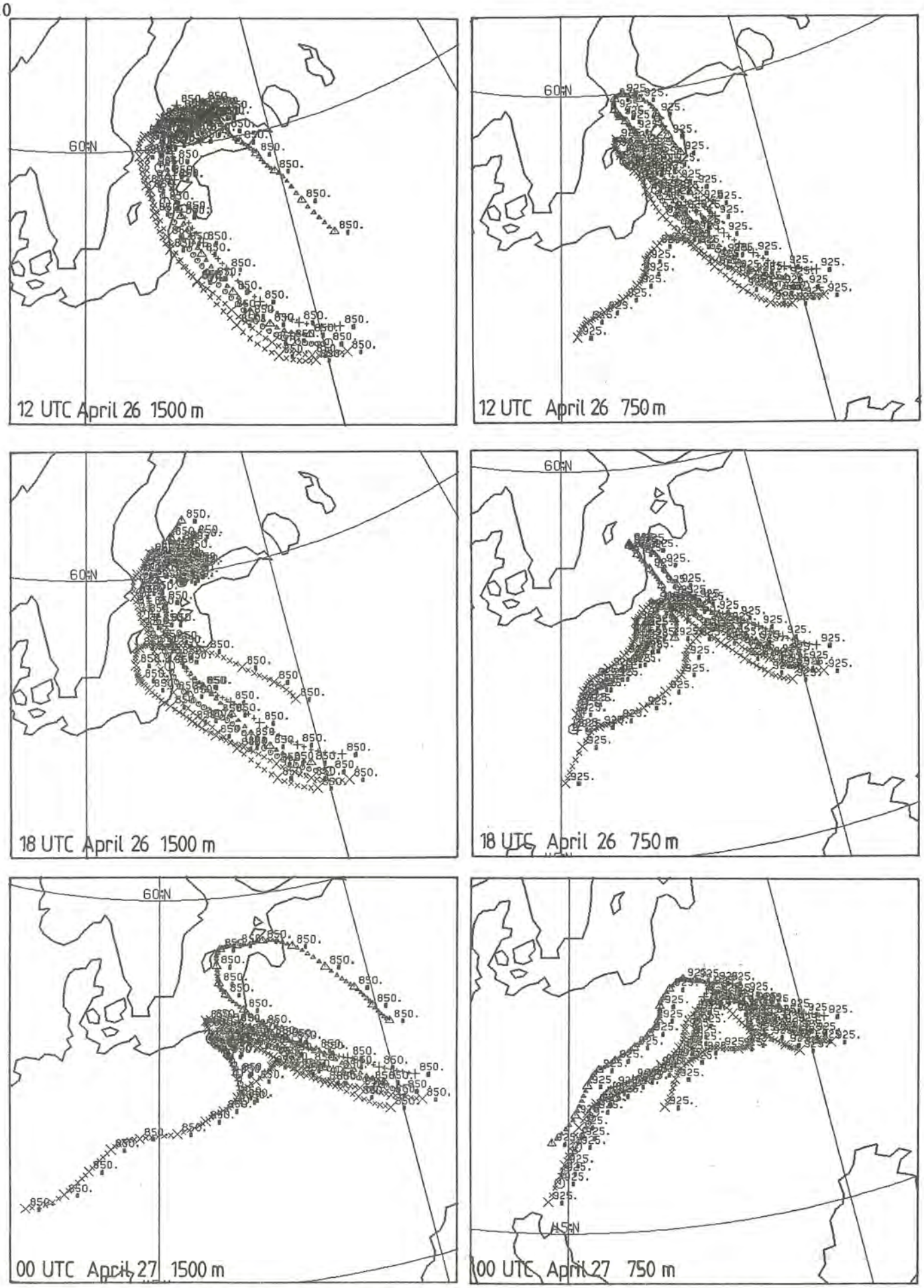


Figure 8. Five calculated trajectories from the Chernobyl area at altitudes of 1,500 m and 750 m shown for various times during 26 - 27 April. The trajectories were followed for three days. One trajectory begins at the reactor site, while the remaining four begin at about 100 km around the site.

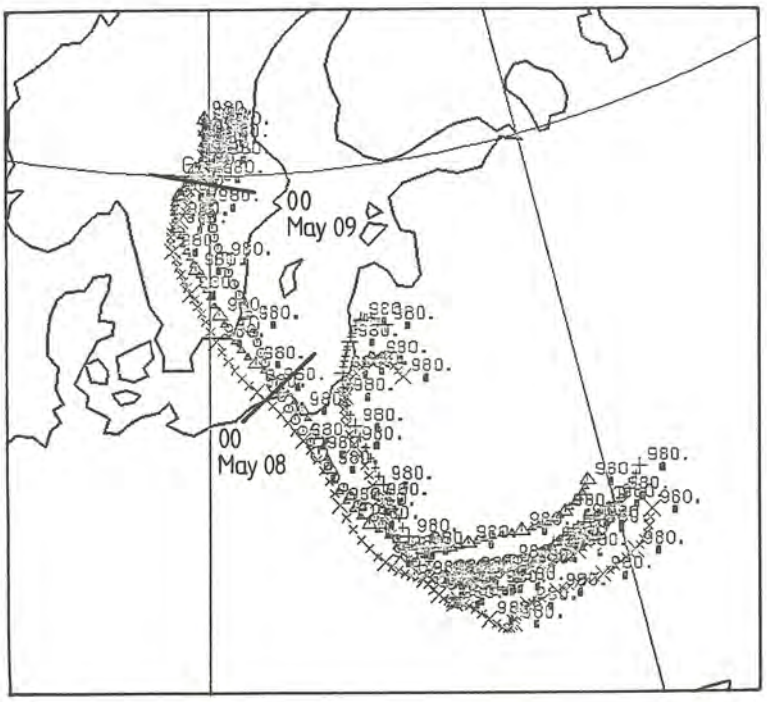


Figure 9. Trajectories calculated by SMHI for 300 - 500 m altitude beginning in the Chernobyl area. The trajectories commence at 18 UTC on 5 May and continue until 18 UTC on 9 May. One trajectory begins at the reactor site and the other four at a distance of about 100 km.

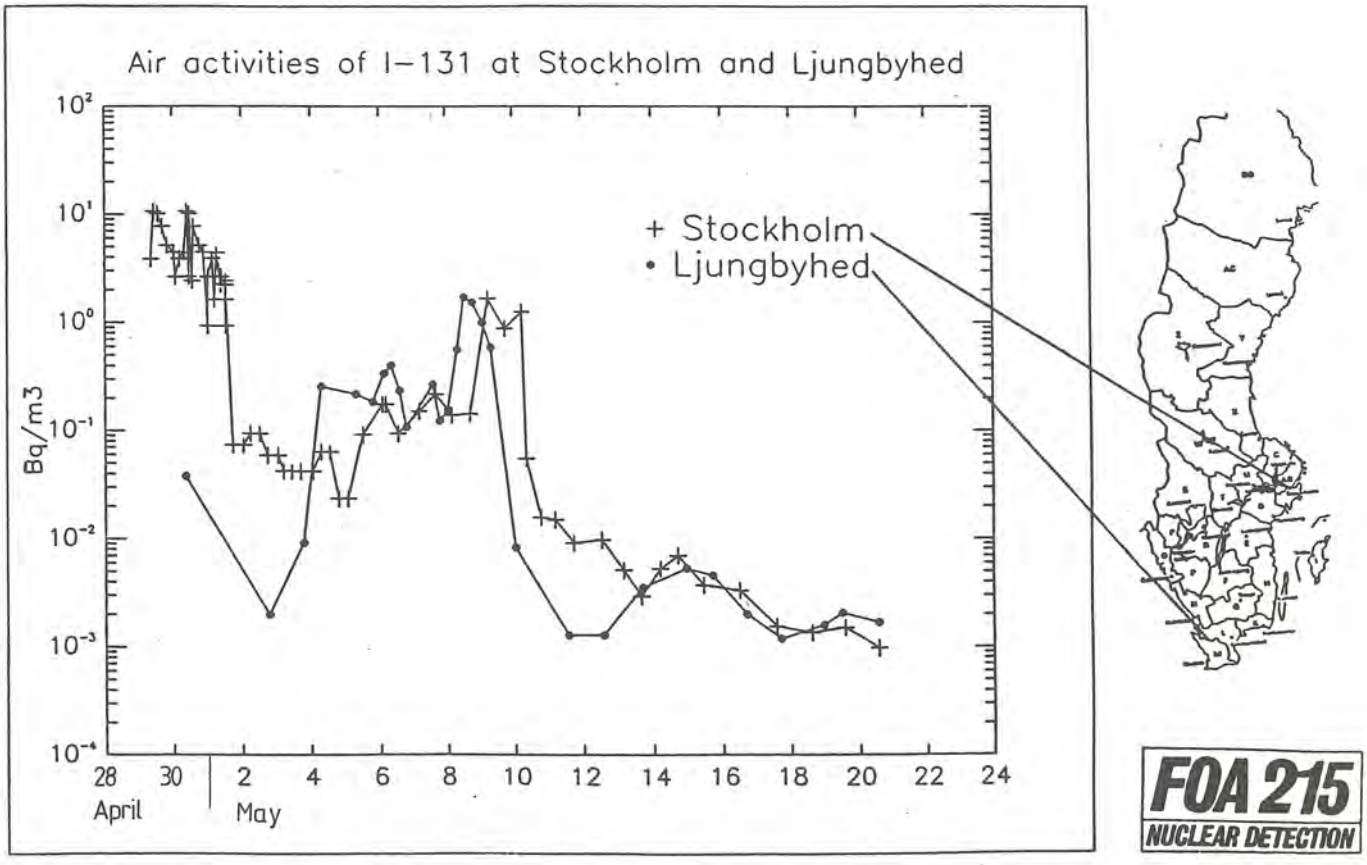


Figure 10. Measured concentrations of particulate ^{131}I in the air at FOA's measuring stations at Stockholm and Ljungbyhed.

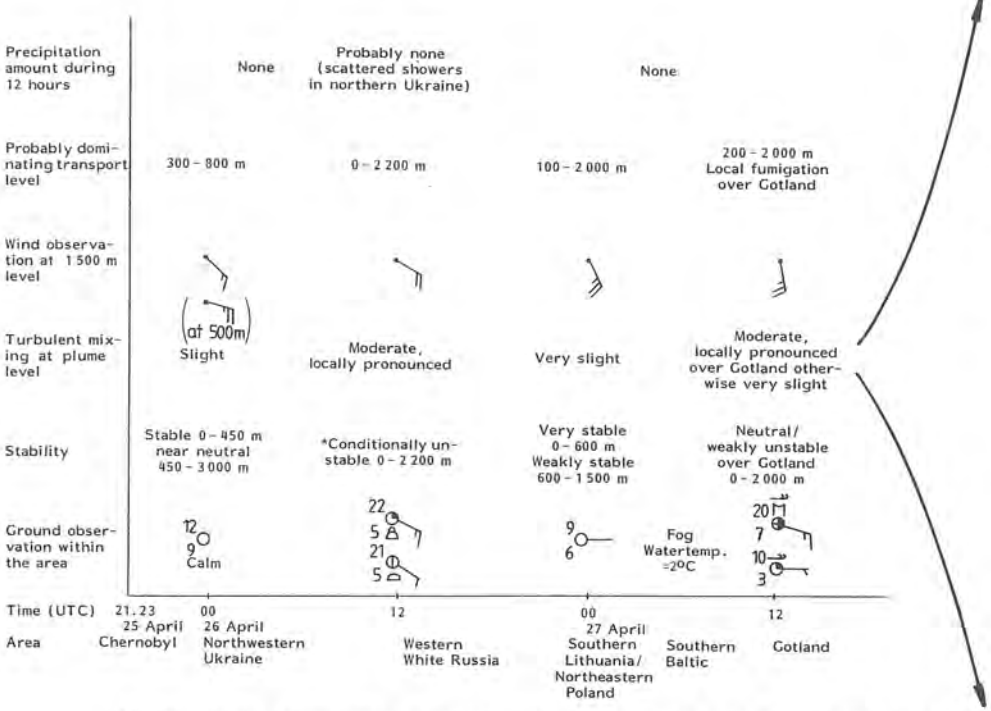
5.2 Weather and dispersion along the transport path

Using data on the general weather situation as described in Chapter 2, this section describes the weather in greater detail and the way in which it affected dispersion. In the case of the first emission, we have chosen a presentation in diagrammatic form, see Figure 11. This describes how the various weather parameters of interest in this context varies along the transport path of the emitted cloud. The transport path and indicated times are based on the calculated trajectories in Figure 5.

During the night of the explosion and the following nights, the weather in the Chernobyl area was clear. During daytime, convective clouds formed. Occasional rain showers appeared in northern Ukraine on 26 April and thunder showers on 27 April. These showers may have caused local deposition if they coincided with the plume from the reactor. Otherwise, there was no precipitation that could purge the air of radionuclides before the transport reached eastern Sweden.

The radionuclides that were first registered clearly in Sweden appeared in eastern Svealand on 27 April at 12 UTC. They had probably been transported over the Baltic at high altitude, approximately 1,500 m (cf Figure 5), and reached the ground through fumigation over the most easterly parts of Svealand. In a fumigation process, a smoke plume transported coherently in a stable layer at some height in the atmosphere comes into contact with an unstable layer, creating a mixed boundary layer where parts of the plume rapidly descended to ground level. During daytime on 27 April, stratification was very stable over the Baltic, whose surface temperature was only $+2^{\circ}C$. Over Stockholm, stratification was unstable nearest the ground with a boundary layer not quite reaching 1,000 m, where an inversion began. Consequently, there were excellent conditions for fumigation. The stratification curve for Stockholm for 27 April is shown in Figure 12.

Early on 27 April, along the Baltic coast, a "division" of the radioactive cloud appears to have occurred. At a lower level, air flowed towards the east coast of southern Sweden, while at higher levels, the cloud continued northwards and later eastwards, passing over southern Finland (cf Figure 5). Over eastern Sweden, convergence took place, i.e. air flowed in from the sides and an associated upward motion occurred. According to calculations by ECMWF, the average ascending motion was approximately 700 m during 28 April. During this process, precipitation was created over parts of eastern Sweden. In south-eastern Norrland, up to 27 mm of rain fell during the 24-hour period, causing considerable deposition of radionuclides. Over southern Finland, where part of the radioactive cloud was also blown, there were only small amounts of local precipitation.



*Conditionally unstable means unstable in connection with condensation i.e. cloud formation otherwise neutral or weak stable

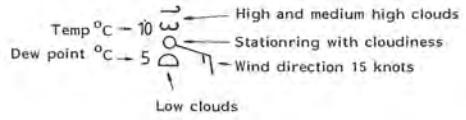
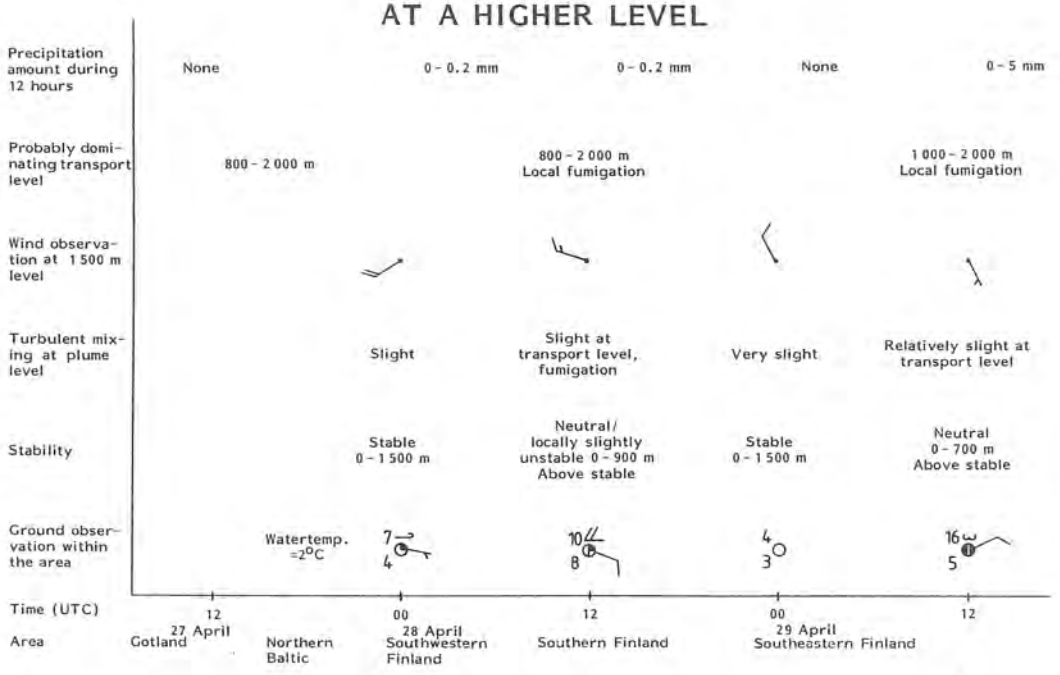
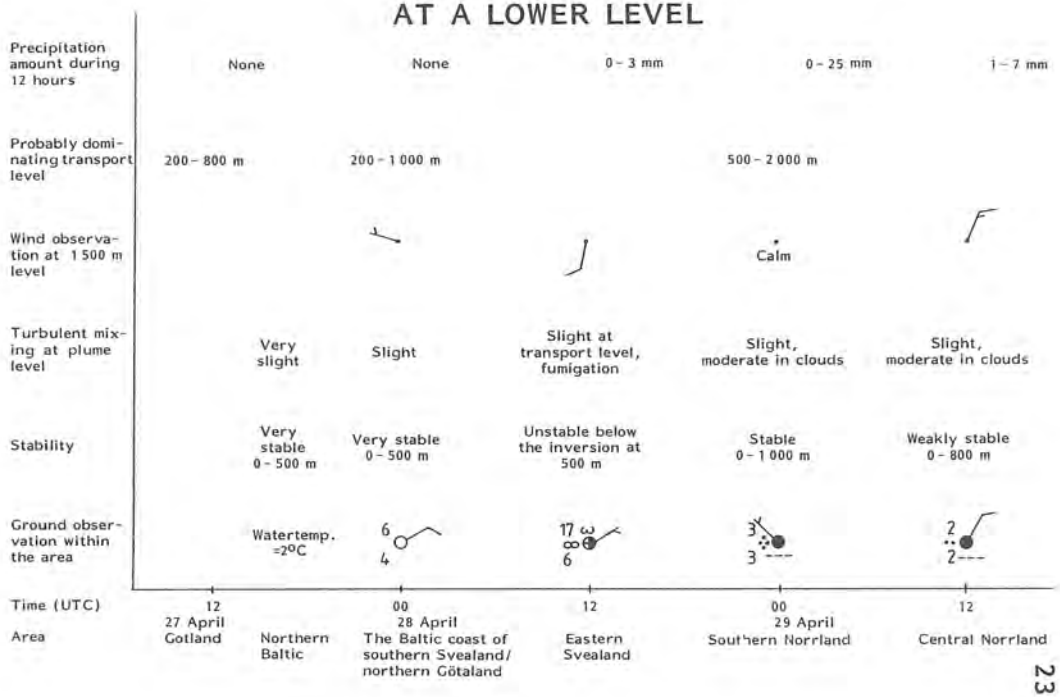


Figure 11.
The weather during the transport (cf Figure 5) for the major part of the first emitted radioactive cloud. (Wind direction shown against the station ring).





It is interesting to note that the transport of the radioactive cloud to Sweden largely occurred in a stable or very stable air mass with limited dispersion and dilution. It was only during daytime on 26 April, when the cloud passed over White Russia, that a greater degree of mixing took place. The boundary layer over White Russia then reached just over 2000 m and the general temperature stratification was almost neutral. During condensation in connection with cloud formation, stratification was unstable (conditionally unstable stratification). The reported cloudiness was 1/8 - 2/8, with small or medium-size cumulus clouds. This means that mixing over the area was generally moderate to good, with a certain amount of large vertical transports in connection with clouds. It is probable that in this area a large part of the plume mixed relatively well in the layer from ground level up to just over 2,000 m. A certain mixing took place at higher altitudes, particularly in connection with clouds. However, some smaller parts of the plume may have passed over with only limited dilution.

The dilution occurring over White Russia was very probably of great significance for the concentrations and depositions of radionuclides that occurred. Without this passage over a relatively well-mixed area, the plume could have reached Scandinavia in a far greater concentration.

The stratification over the Baltic was very stable, as shown by the Visby sounding from 28 April, 12 UTC. The temperature at an altitude of a few hundred metres was +17°C, while the surface water temperature in the Baltic and thereby the air temperature nearest the surface, was +2°C.

In Figure 13, we have attempted to make a qualitative summary of the vertical dilution of the first emitted cloud during the transport to northern Sweden.

Sweden was also affected by a heavy increase in airborne radionuclides during a second episode occurring on 8 - 10 May. This involved emissions from the reactor on 5 May, which first moved towards Poland and then north over Scandinavia and Finland. As in the first episode, the weather situation was dominated by high pressure in the western parts of the Soviet Union. The transport occurred in warm air, streaming north towards Scandinavia from the south-east. During daytime, the ground was warmed by solar radiation and stratification was instable up to 500 - 1,500 m, with accompanying extensive mixing and dilution in that layer. No precipitation occurred before the radioactive emission reached Scandinavia, where a cold front with rain approached from the west during 8 - 10 May.

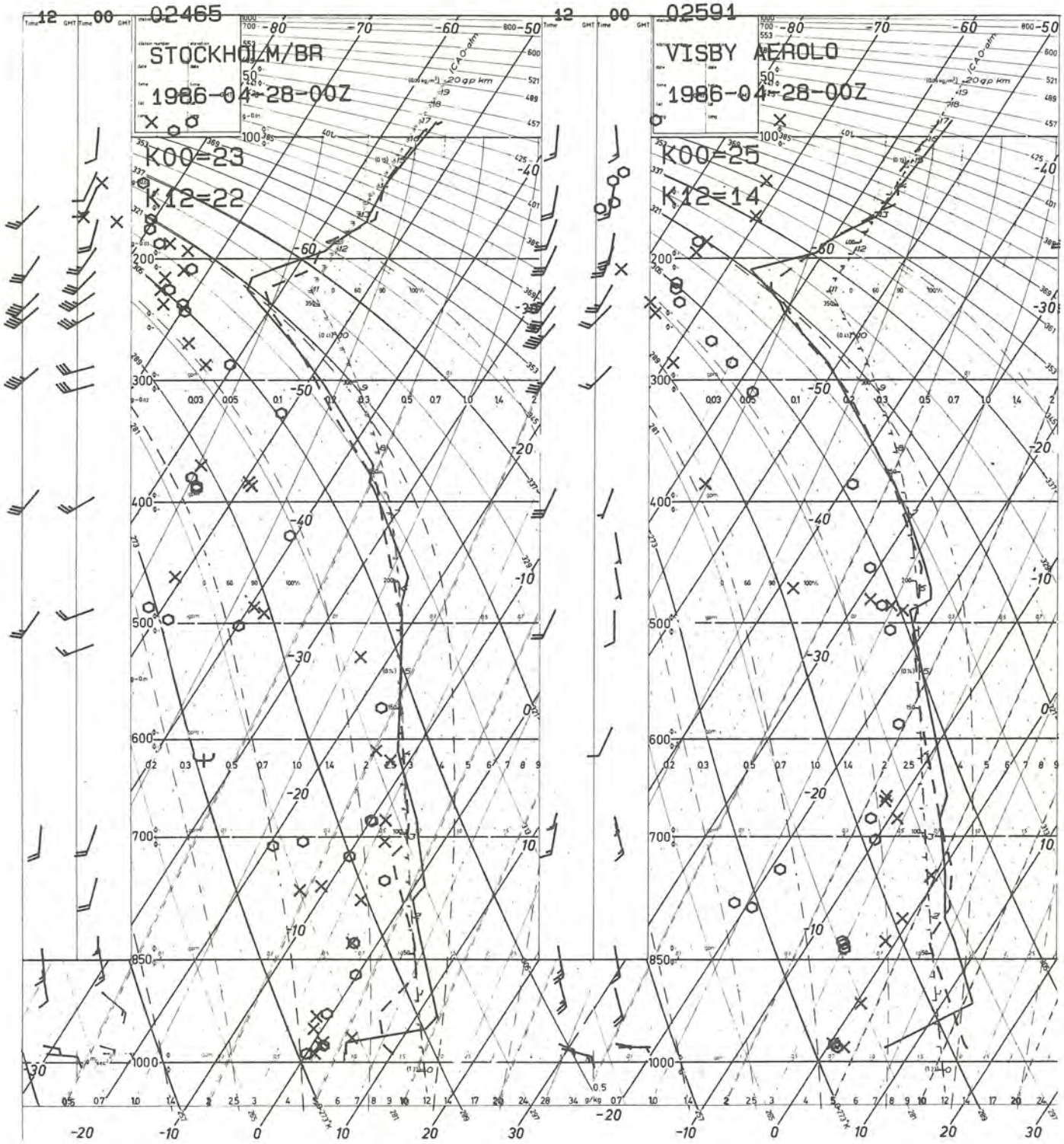


Figure 12. Temperature soundings entered in a sounding diagram from Stockholm and Visby for 27 April 12 UTC, 28 April 00 and 12 UTC and 29 April 00 UTC. The solid curve shows temperature soundings for the time indicated in the diagram, while the broken curve shows soundings 12 hours earlier. Wind information. shown at the left in the diagram, is illustrated in the same way as in Figure 11.

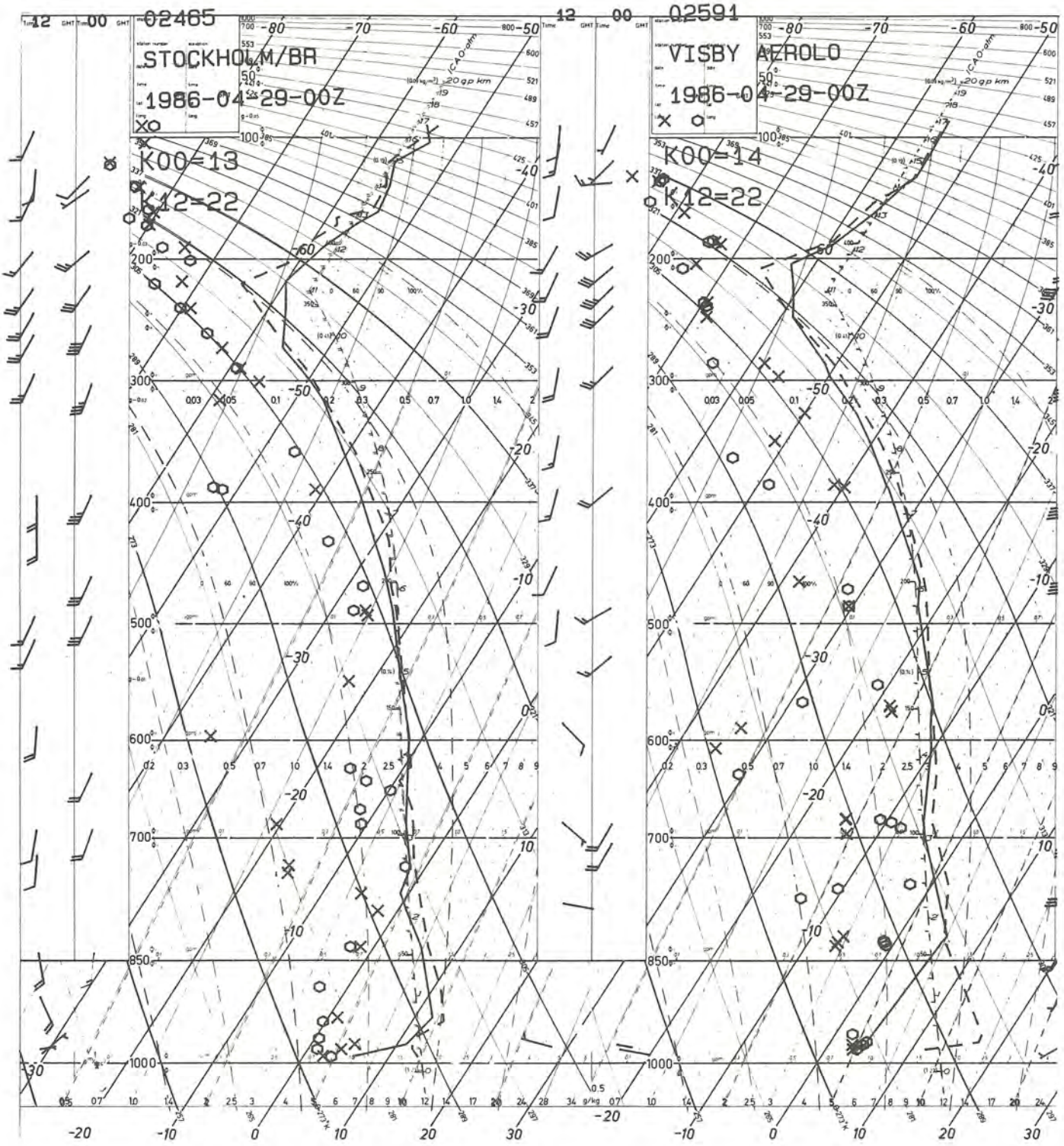


Figure 12. Cont.

5.3 Successive dispersion of radionuclides over Sweden

Using principally radiological data for the period 27-30 April, we have attempted to make a day-by-day geographical survey of the dispersion of the radionuclides at ground level. It is desirable to base such a survey on measured concentrations in the air, such as ^{137}Cs. However, there are only a few locations with such measurements and we have been obliged also to use values for total gamma radiation as indirect information on concentrations in the air. Increased gamma radiation values can be obtained both through increased concentrations of airborne radionuclides and through depositions of radionuclides on the ground. Radionuclides deposited on the ground remained there and continued to contribute to increased gamma radiation, even after the contaminated air had blown away. In the survey shown in Figure 14, we have therefore marked the stations which had a higher level of gamma radiation compared to the previous day. The values have only been indicated in a qualitative way. Since an incoming transport of airborne radionuclides may occur even if gamma radiation decreases somewhat, data from the stations must be interpreted with caution. Figure 14 provides a schematic diagram of the areas with increased concentrations of ^{137}Cs in the air at ground level. Norwegian measurements (Pacyna et al, 1986) have also been included, since these radionuclides were transported over Sweden.

During the afternoon and evening of 27 April, the eastern parts of Götaland and Svealand were affected by heavily increased levels of airborne radionuclides. In Svealand, the level began to increase slowly at 14 - 15 hrs in the afternoon, at the same time as the warm front from the south-east arrived (see Figure 2). The deposition that occurred was characterized by a relatively high proportion of refractory elements (^{239}Np, $^{95}Zr/Nb$, ^{141}Ce, ^{144}Ce etc) carried by relatively large particles with a high deposition rate. Already on the morning of 27 April, warm air from the south-east had arrived over south-eastern Götaland, including the Baltic islands of Öland and Gotland. It was probably at this early point that the first radionuclides reached Sweden (Kjelle 1986).

The warm air also affected southern Götaland and Zealand for a short period at mid-day on 27 April. In connection with this, a very weak increase in radionuclides was noted at Risö in Denmark. In eastern parts of Götaland, the concentration of radionuclides in the air rose heavily at 18 - 19 hrs in the evening, probably with a higher proportion of volatile elements (iodine, tellurium and caesium isotopes) in these parts of the moving cloud. The FOA station at Ljungbyhed recorded 0.8 Bq/m^3 of ^{137}Cs.

The plume then lay over central Sweden during Monday 27 April, turning more to the north. The highest concentration in the air was recorded at Oskarshamn. During the evening, the concentration was greater over the coast of Northern Svealand than on Gotland (according to aircraft measurements at 300 m). The proportion of volatile radionuclides in the cloud was greatly increased. When rain later during the night fell through the cloud, it caused a considerable deposition in parts of eastern Svealand and southern and central Norrland.

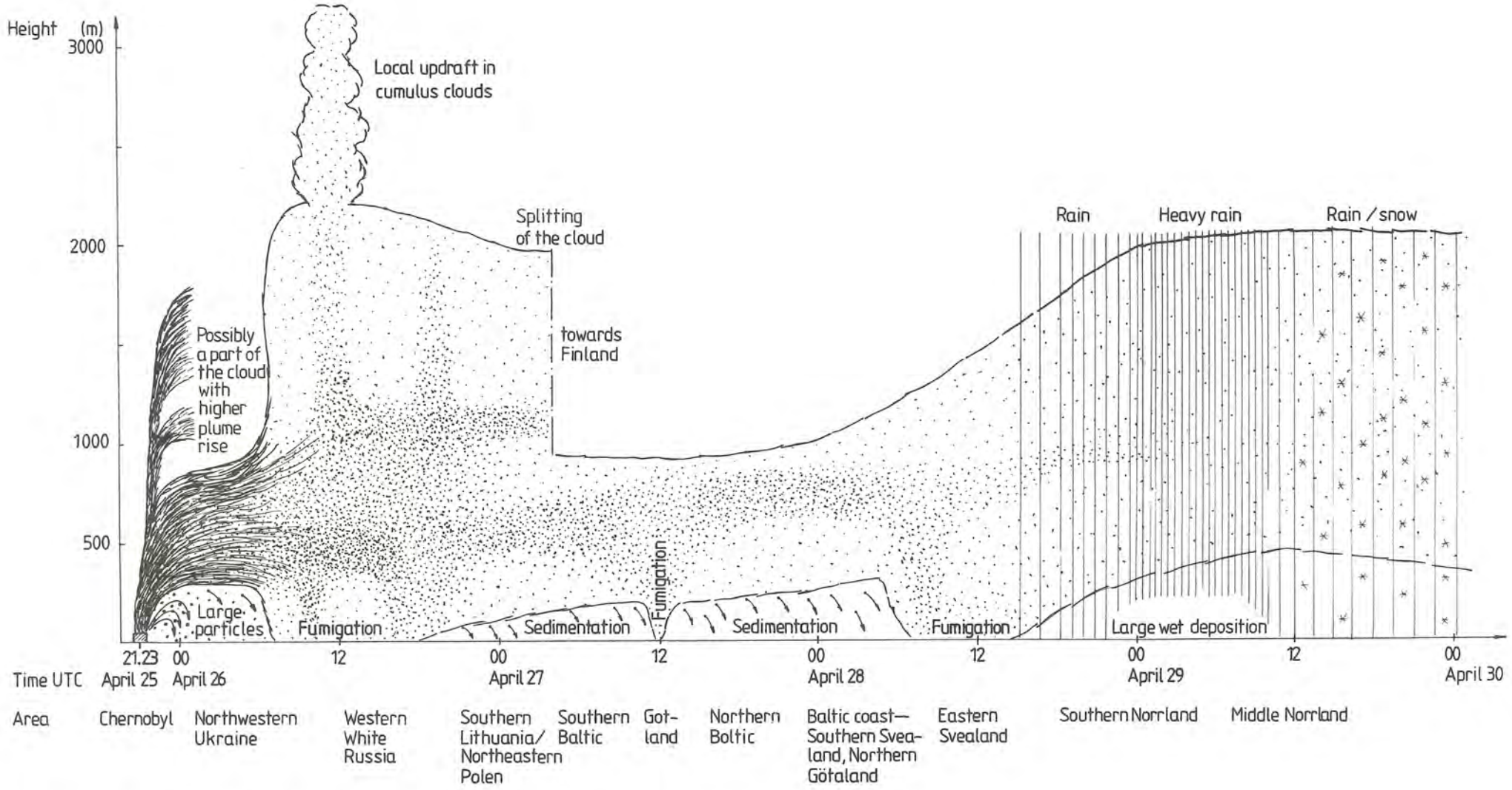


Figure 13. Qualitative description of the transport path and dispersion of the first emitted cloud of radionuclides.

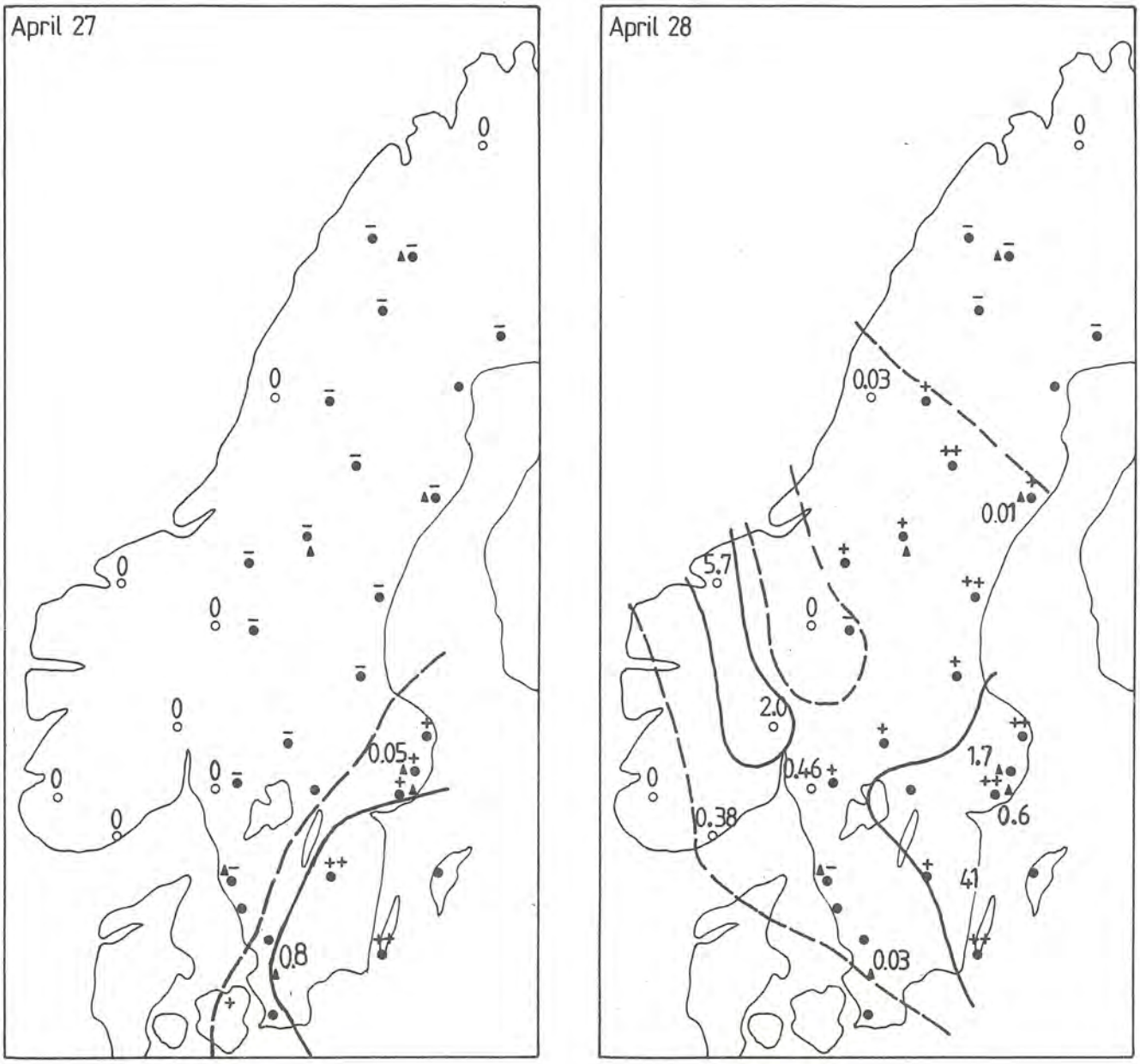


Figure 14. Schematic chart of ^{137}Cs air concentration near the ground. Available measured concentrations (Bq/m^3) are marked. In addition, the gamma radiation at the SSI stations marked with a solid circle is indicated as follows:

\- = no change or a reduction since the preceding day
\+ = slight increase since the preceding day
++ = large increase since the preceding day

The FOA's stations are marked with a solid triangle. The values for the Norwegian stations, marked with a circle, have been taken from Pacyna et al (1986).

In the outline chart, --- indicates "slightly increased" concentration of ^{137}Cs and ___ "higher" concentration. The survey covers the period 27 - 30 April.

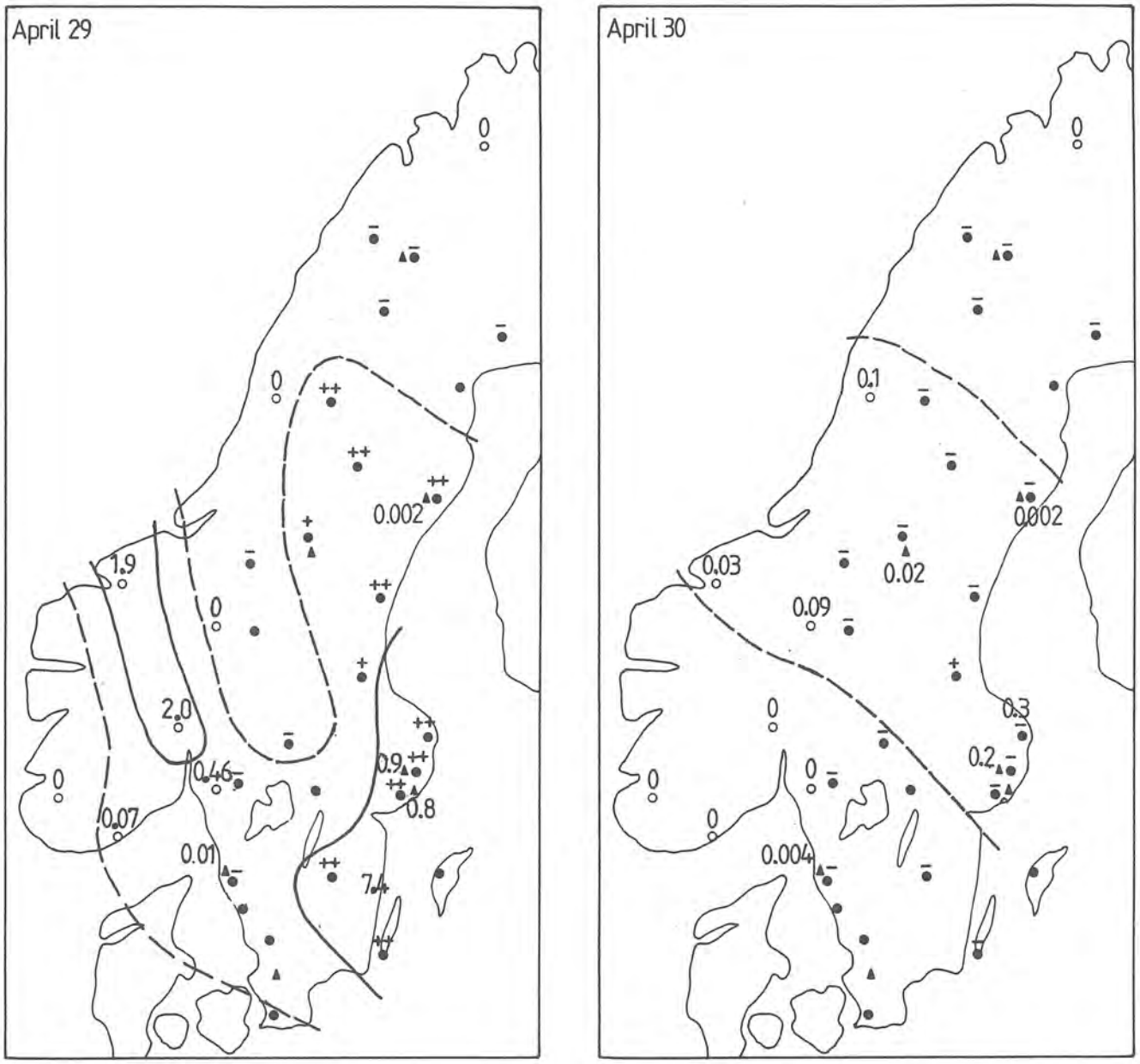


Figure 14. Cont.

On 28 April, a portion of the radionuclides drifted over northern Götaland and Svealand towards southern Norway, where the concentrations in the air rose at a number of stations, with radionuclides primarily being deposited in the mountain areas. However, the gamma radiation values on the ground rose very little in western Sweden. On 29 April, the concentrations in air were still at a higher level, although lower than on 28 April. A slight increase was also measured at Ringhals in south-west Sweden. On 30 April, the concentrations in the air fell at the few recording stations that registered measurements.

During the period 8 - 10 May, the concentrations initially increased in southern Sweden. The increased levels of radionuclides then moved towards the north-east (cf Figures 9 and 10) and clean air entered from the west behind the cold front.

From 28 April onwards, FOA performed daily samplings at various altitudes with the aid of the Air Force Target Division F13M at Linköping. During 28 - 30 April, sampling took place along the same route between the east coast of northern Svealand and east of Gotland. Six samples were taken during each flight. Figure 15 shows the results of these for ^{137}Cs. The aircraft measurements made in Finland during the same period generally show lower concentrations at both lower and higher altitudes. However, one measurement, made on 29 April at 1,500 m altitude east of Helsinki, showed a level as high as 155 Bq/m^3 of ^{137}Cs (STUK-B-VALO 44, 1986).

5.4 Particle sizes

It has not been possible to obtain any reliable data on particle sizes of the radioactive aerosol particles during the period 27 - 30 April. At several sites in eastern Svealand and in southern Finland, observations have been made of relatively large particles with a diameter of about 5 µm or more, with a high level of radiation. Measurements have been made by FOA at several locations and Ingemansson (1986) contributes a report from Forsmark. Generally, the most radioactive particles have proved to contain only molybdenum and ruthenium isotopes as active components. It is known that during operation, particles such as these are formed in the reactor fuel (d'Annunni et al, 1977). A number of particles found in Stockholm and Uppsala proved to contain up to 10 kBq ^{99}Mo, 30 kBq ^{103}Ru and 5 kBq ^{106}Ru, all this activity being attributed to the emission on 26 April.

General calculations can be performed to determine the likelihood of larger particles being transported to eastern Svealand. If we assume that particles have a density of between 5×10^3 and 10^4 kg/m^3 and are completely spherical, approximately the following plume rise would be required at Chernobyl, and an upward transport through convection over White Russia during daytime on 26 April:

Particle diameter (µm)	Initial plume rise greater than (m)	Least upward transport over White Russia (m)
2.5	30 - 60	150 - 300
5	120 - 240	600 - 1,200
10	500 - 1,000	2,500 - 5,000
20	2,000 - 4,000	10,000 - 20,000

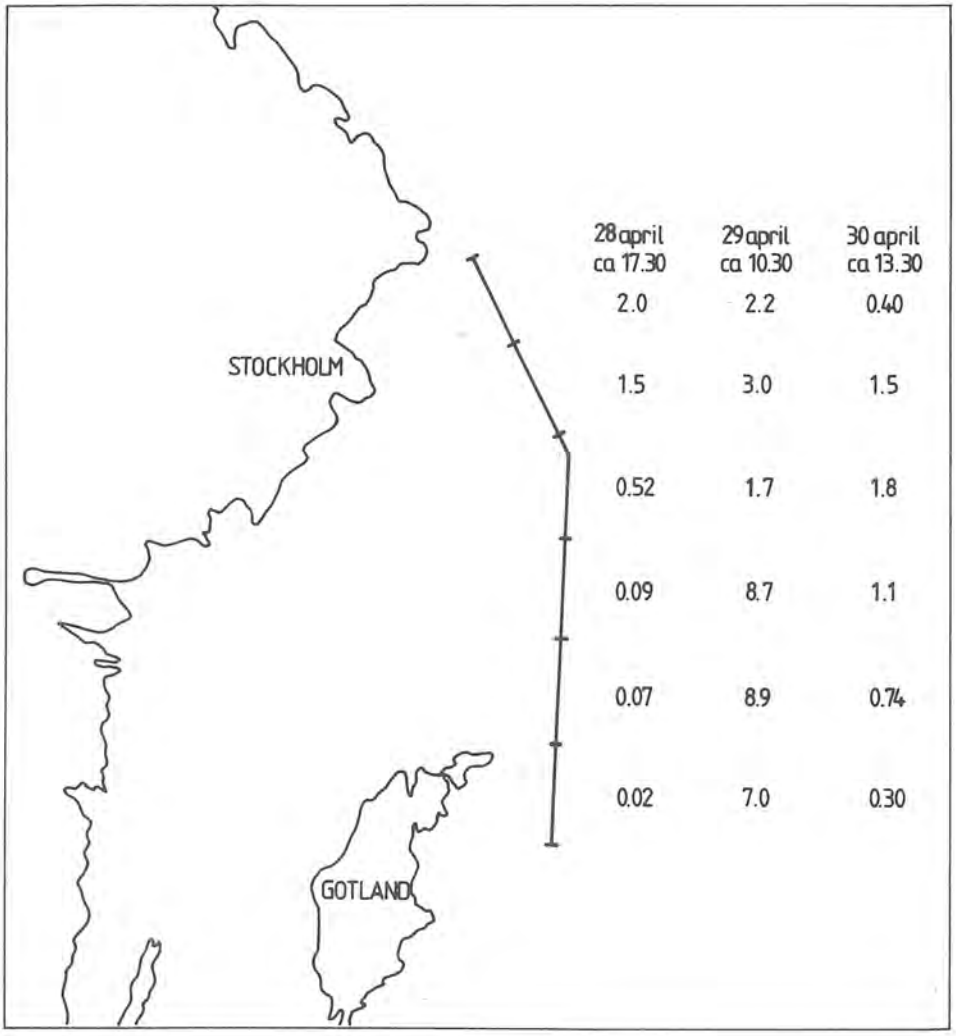


Figure 15. Concentration in air of ^{137}Cs (Bq/m^3) at 300 m altitude over the Baltic on 28 - 30 April 1986.

If we make a comparison with the qualitative picture of the plume's dispersion as in Figure 13, it will be seen that spherical particles with a diameter of up to 10 µm may very well have been transported to Sweden, reaching eastern Svealand on 28 April. The probability of reaching Sweden then decreases rapidly with increasing particle size.

For the episode of 8 - 9 May, Studsvik Energiteknik has made measurements of particle size with the aid of a cascade impactor (Chyssler, 1986). The measurements, 70 km south-east of Stockholm show that the radiation was borne solely by particles with a diameter of less than 3 µm. For ^{137}Cs, all radiation occurred in the range 0 - 2.1 µm and was dominated by particles of less than 1 µm.

Unlike caesium, iodine occurs both in the particle and gas phase. The ratio of particle phase to gas phase depends on the age of the plume and the weather. Measurements at Studsvik (Devell et al, 1986) indicate that 60 - 80% of the ^{131}I occurred in the gas phase

when the plume reached Sweden. The particle phase of the ^{131}I occurred during 7 - 9 May on aerosol particles with a radius of less than 0.7 µm (Chyssler, 1986). The photochemistry which is of significance for the occurrence of iodine has recently been discussed by Jenkins et al (1985).

5.5 Deposition

Several processes contribute to the deposition of radionuclides:

- wet deposition with precipitation
- dry deposition through sedimentation of large particles (diameter > 5 µm)
- dry deposition through small particles and gases adhering to vegetation and the ground surface.

In the immediate area of Chernobyl, "hot spots" have been detected where the ground within an area of one or more kilometres has a very much higher concentration of radionuclides, up to 1,000 times higher, that that observed in the surrounding area. This can be seen to some extent in the deposition maps in the Soviet report delivered to IAEA. Further verbal information on this was given by the Soviet representative at the WHO meeting in Holland on 25 - 27 June. "Hot spots" have been found both close to the reactor and at distances of hundreds of kilometres. No explanation for these was offered, but it is possible that local rain showers during the first two days may have caused part of the "hot spots". Streaks of greatly increased deposition may have occurred through the emission of large particles which descended rapidly.

The deposition over Sweden has been surveyed by the Swedish Geological Company, Uppsala (SGAB) with the aid of aircraft measurements of gamma radiation. Figure 16 shows the deposition pattern for ^{137}Cs. The values are based on measurements of ^{134}Cs and a constant conversion factor (1.75). Independent control measurements of ^{134}Cs and ^{137}Cs in-situ at a number of locations have been used to calibrate the aircraft measurements. There is primarily uncertainty in the case of areas with low deposition in southern Sweden. This survey, which took place during the period 1 - 23 May, covered all the deposition from Chernobyl that occurred up to the time of measurement. A comparison with the SMHI precipitation chart for the period 08 on 28 April to 08 on 30 April (see Figure 17) i.e. the two days when the air over Sweden was most affected by radionuclides, shows very great similarities between the pattern of caesium deposition and amount of precipitation.

In order to make a closer study of wet deposition during this period, we have calculated the correlation between the precipitation amount during the period and the total caesium deposition as shown in Figure 16. Approximately 300 points have been distributed evenly over Sweden and the correlation calculated for the whole country, with the exception of northern Lapland, where very little caesium was deposited, is as high as 0.8. This shows that wet deposition during the period 28 - 29 April played a large part in the total deposition

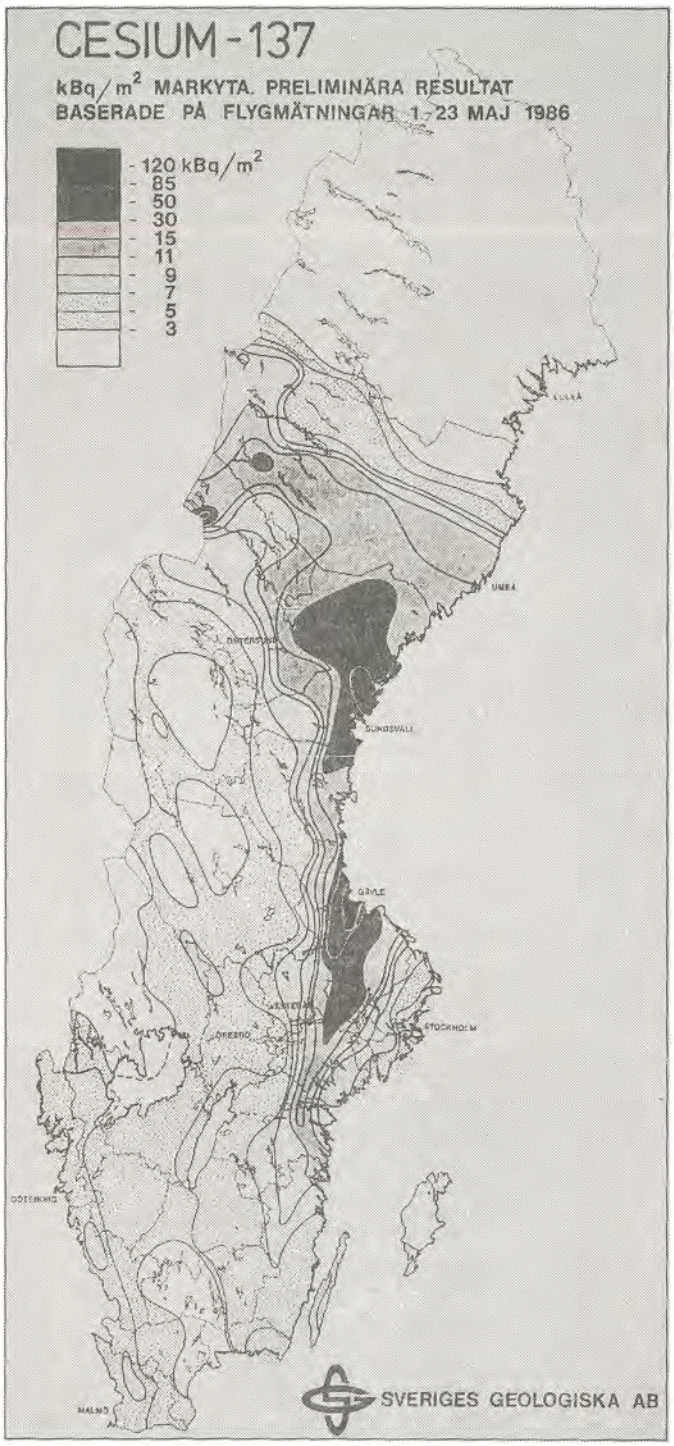


Figure 16. Recorded deposition of ^{137}Cs over Sweden. Measurements made by the Swedish Geological Company.

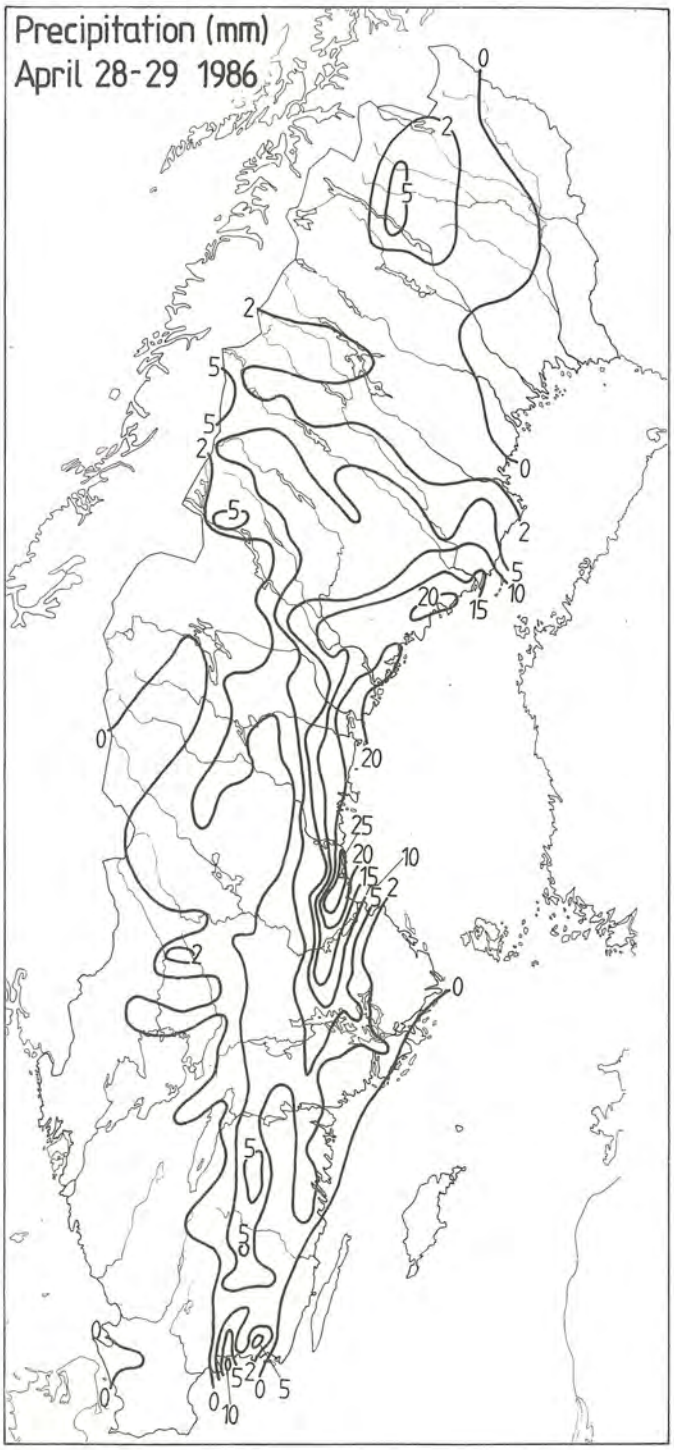


Figure 17. Recorded amounts of precipitation (mm) over Sweden for the period 28 April 06 UTC to 30 April 06 UTC.

of caesium. The correlation is high despite the fact that certain parts of Sweden, not directly affected by the radioactive plume, have also been included in the correlation calculation. In addition, south-west Sweden received considerable additions to the total caesium deposition in connection with precipitation during the period 8 - 10 May, which also reduces the correlation. If a corresponding calculation of correlation is made for the total volume of precipitation during the 3 days 28 - 30 April, correlation falls to below 0.7. This is explained by the fact that during the third day, it was mainly the county of Västerbotten and the coast of the Gulf of Bothnia that received the added deposition of radionuclides (cf Figure 14), while precipitation also affects other areas. Figure 18 shows a survey of precipitation over Sweden, day by day, for the periods 27 - 30 April and 8 - 9 May.

In order to investigate the extent to which direct measurements of radionuclides in precipitation can quantitatively explain the observed total deposition of ^{137}Cs, we have measured the concentration of radionuclides in a large number of precipitation samples.

Measurements of precipitation have been made through:

i) Monthly samples collected during April from 40 stations distributed throughout Sweden as in Figure 19 (Department of Meteorology, University of Stockholm). However, all activity is attributed to precipitation during 28 - 30 April.

ii) Daily samples from Bredkälen in northern Jämtland on 26, 29 and 30 April and 11 May (IVL, Gothenburg), Rörvik outside Gothenburg on 10 May (IVL), Hoburg (Gotland) on 10 May (IVL) and Studsvik outside Nyköping on 28 May (SNV).

iii) Samples collected in Uppsala on the morning of 29 April (Department of Hydrology, University of Uppsala), Östhammar on the morning of 29 April) (Ingemansson, 1986) and Barsebäck on 8 May.

The total wet deposition of ^{137}Cs during April (up to the morning of 1 May) based on the monthly samples is shown in Figure 19. The deposition is calculated from the measured concentrations and takes into account the volumes of precipitation collected at the same time. The values in brackets in Figure 19 indicate the ratio (in per cent) between the measured wet deposition and the total deposition measured as in Figure 16.

The highest measured wet depositions occurred at the stations south-west of Umeå (43 kBq/m^2), near Örnsköldsvik (34 kBq/m^2), west of Umeå (25 kBq/m^2) and south-west of Gävle (26 kBq/m^2). The measurements were made on precipitation samples taken for purposes other than radionuclide measurement. This means that part of the caesium was not dissolved in the water. We have attempted to introduce a correction for this but the uncertainty in these data appears to remain at a factor of about 2.

In view of the doubt regarding the values for deposition through precipitation, the agreement between these and the completely independent values for total deposition must be considered good.

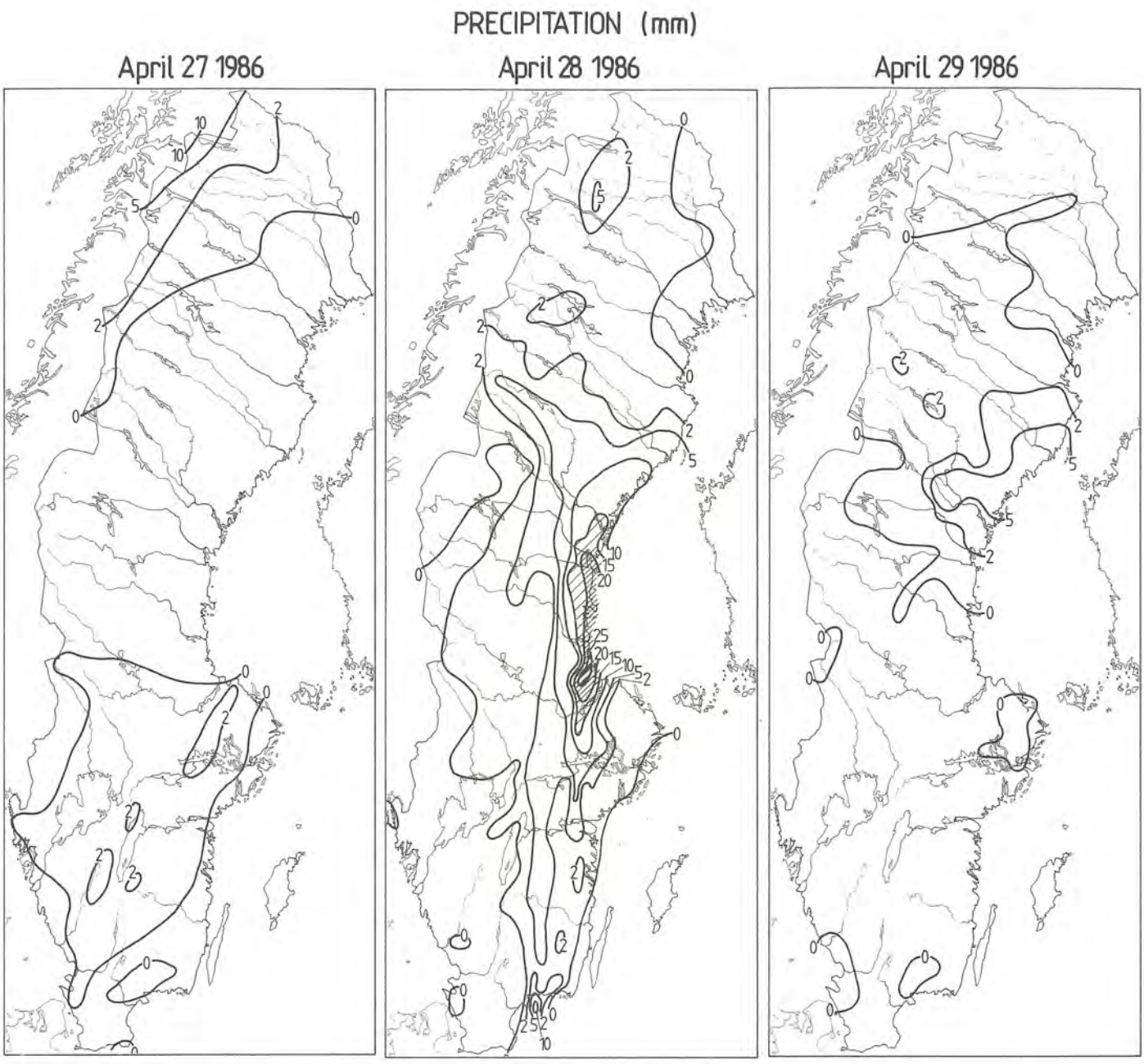


Figure 18. Precipitation charts for 27 - 30 April and 8 and 9 May. Measurements performed from 06 UTC each day to 06 UTC the following day.

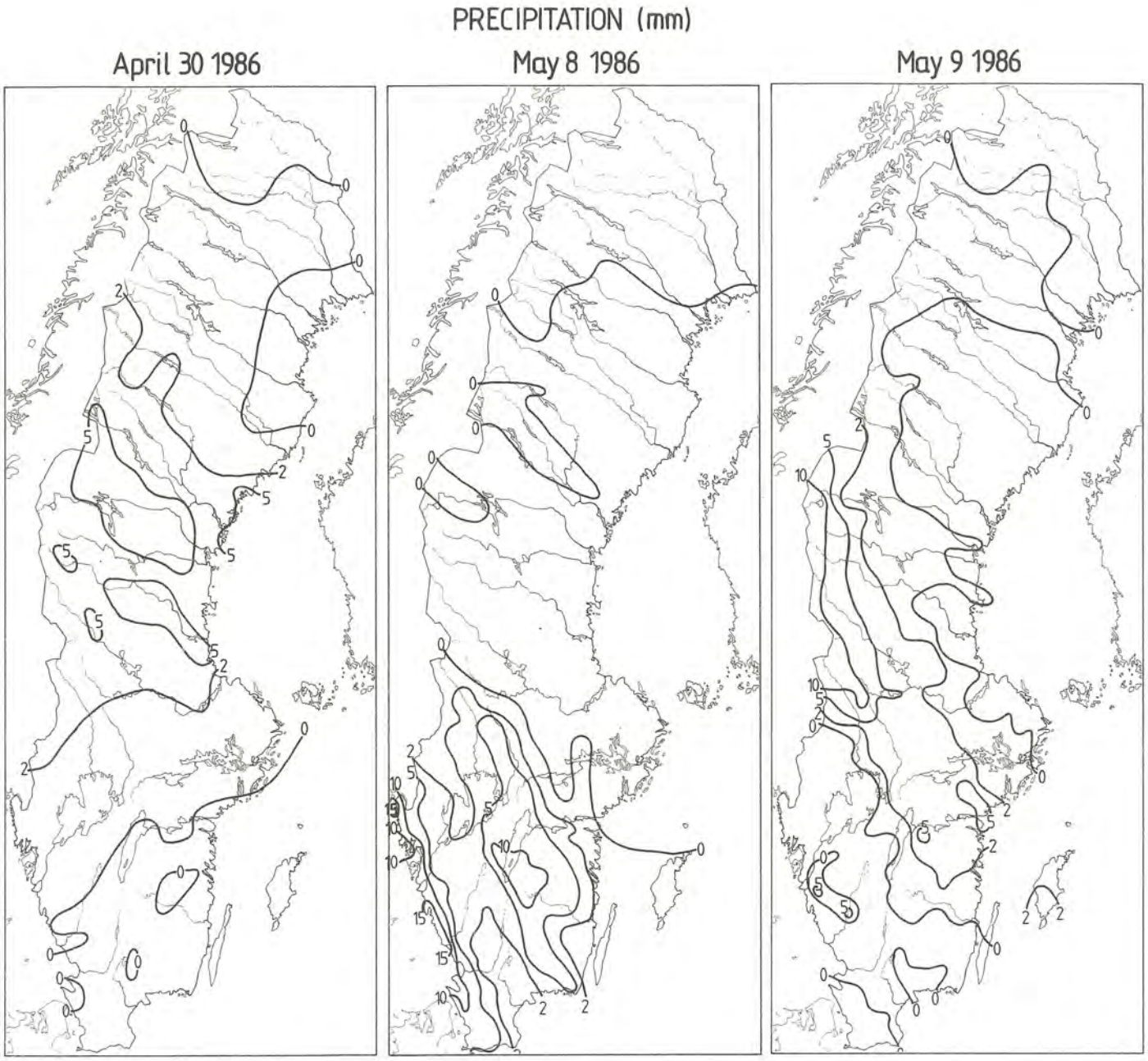


Figure 18. Cont.

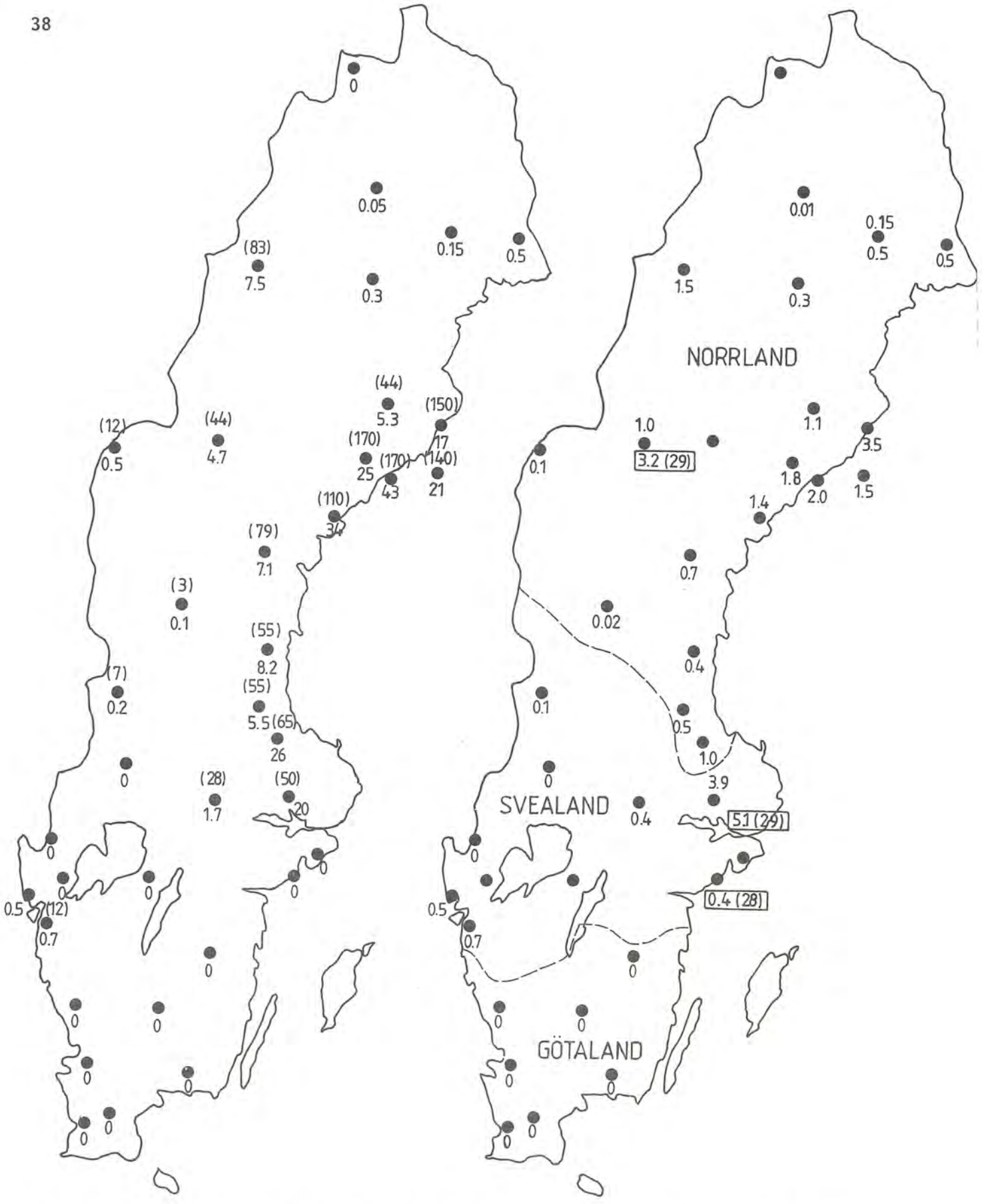


Figure 19. Measured deposition of ^{137}Cs through precipitation in April 1986 (kBq/m^2). Values in brackets show the ratio between deposition through precipitation and the total deposition (in per cent).

Figure 20. Measured mean concentration of ^{137}Cs in precipitation (kBq/l) for the period 28 - 30 April 1986. Measured daily values given in rectangles, with the day in brackets.

In every case where the deposition through precipitation exceeds 10 kBq/m^2, the ratio between this and the total deposition is within the range 50 - 170 %.

At the stations where deposition through precipitation was less than 10 kBq/m^2, the total deposition was consistently greater than the wet deposition during April. This is probably the result of a considerable part of the deposition at these locations occurring through precipitation during 8 - 9 May or in the form of dry fallout. A contributory cause is that aircraft measurements appear to have overestimated the deposition by a factor of as much as 2 within the areas with low deposition (Anders Linden, SGAB).

The activity in the precipitation falling during the relevant period has been estimated by dividing the total activity in the monthly samples by the volume of precipitation falling during the period 28 - 30 April. The volumes of precipitation are taken from analyses of SMHI data. The values for ^{137}Cs obtained in this way are given in Figure 20. The figure also contains data from the short-term samples collected during the same period. The highest activity (approximately 5 kBq ^{137}Cs per litre) was measured in the sample from Uppsala on 29 April.

It is interesting to compare the measured and calculated precipitation concentrations with corresponding concentrations in the air in order to obtain an idea of the efficiency of the scavenging processes. Those cases where approximately simultaneous measurements were made of air and precipitation concentrations are collected in Table 3. The ratio between the concentration in precipitation and that in the air (the washout ratio) varies between 0.3 x 10^6 and approximately 5 x 10^6. The lower values (0.3 to 0.4 x 10^6) agree well with previously reported values for substances borne by particles with a diameter of about 1 µm (Slinn et al, 1978). The higher values indicate the presence of larger particles (or that the indicated concentrations are not representative).

Table 3. Comparison between precipitation concentrations and air concentrations of ^{137}Cs.

Location	Date	Concentration in precipitation (Bq/m^3)	Concentration in air (Bq/m^3)	Washout ratio
Studsvik	28/4	0.4 x 10^6 (a)	1.4 (b)	0.3 x 10^6
Östhammar	29/4	6.4 x 10^6 (c)	1 - 2 (d)	(3 - 6) x 10^6
Uppsala	29/4	5.1 x 10^6 (e)	1 - 2 (d)	(2.5 - 5) x 10^6
Barsebäck	8/5	0.2 x 10^6 (f)	1 - 2 (f)	0.4 x 10^6

(a) Precipitation samples from IVL, Gothenburg
(b) Filter samples from SNV, Studsvik
(c) Ingemansson, 1986. The sample may contain a considerable proportion of dry deposition.
(d) Estimated mean
(e) Precipitation sample from the Department of Hydrology, University of Uppsala
(f) Data from the Barsebäck nuclear power plant

These comparisons between total deposition and measured wet deposition show clearly that the major proportion of the caesium deposited in north-eastern Götaland, eastern Svealand and Norrland arrived through wet deposition between 08 on 28 April and 08 on 30 April (in parts of Norrland, there was also some deposition later on 30 April). The fact that ^{137}Cs was almost exclusively wet-deposited and that this occurred during a well-defined period of time facilitates detailed study of the geographical variation in the caesium concentration in precipitation during this period. In Figure 21, a survey has been made of the mean concentration of ^{137}Cs in the precipitation under the assumption that the values measured by SGAB are caused wholly by wet deposition during 28 - 29 April. The concentration values have thus been obtained by dividing the measured total deposition by the precipitation volume during the period. Only the areas with a precipitation of 1 mm or more have been included. The calculated caesium concentrations in the precipitation varied considerably, being highest in the eastermost parts of the precipitation area over eastern Götaland and eastern Svealand. In the western parts of the precipitation area, the concentrations decrease rapidly (by a factor of as much as 10). However, there is an exception in the case of northern Jämtland, where the calculated caesium concentrations are high. If precipitation from 30 April is included, the pattern is not notably altered, although the calculated concentrations decrease somewhat.

The higher calculated values in north-eastern Götaland and eastern Svealand are mainly the result of the radioactive plume having its centre area east of the precipitation area. In the horizontal inflow that occurred in connection with the precipitation, air was sucked in from both the east and the west. Larger amounts of radionuclides were thus included in the rain that fell in the easternmost parts compared with the situation further west. In this way, cloud processes came to reinforce the horizontal differences in activity. This is also indicated by the detailed survey in Figure 22 of the fallout in the Gävle area, together with the precipitation data from the SMHI stations. The $^{134}Cs/^{137}Cs$ ratio is very constant in the fallout from Chernobyl, so that the corresponding ^{137}Cs chart appears similar, but with values 1.75 times higher. It is evident that the concentrations of caesium were much higher immediately east and south-east of Gävle than to the west. The calculated caesium concentration in the precipitation varies by a factor of 10 within a distance of 40 km.

During 29 - 30 April, part of the precipitation in the northernmost parts fell in the form of snow. However, no significant differences in, for example, estimated caesium concentrations in precipitation were found in this area.

During 8 - 9 May, when the activity values in the air over Sweden began to increase again, rain fell, mainly in south-western Götaland, see Figure 18. This resulted in increased values for caesium fallout. Previously, the area had hardly been affected by any wet deposition. The secondary maximum on the west coast shown by the deposition chart (Figure 16) is thus a result of washout in connection with the passage of the cold front on 8 - 9 May.

Figure 21. Concentration of ^{137}Cs in precipitation (kBq/l), calculated according to the assumptions mentioned in the text, for the period 28 - 29 April. --- differentiates areas where the amount of precipitation was less than 1 mm or where caesium data are unavailable.

The dry deposition rates are difficult to determine owing to the lack of more detailed data for concentrations in air. Over Öland and Gotland and in the Stockholm archipelago, there was no rain during the period 27 - 30 April and only small amounts during the period up to 10 May, so the caesium deposition recorded there was mainly dry deposition. This applies also to the relatively large levels of iodine found on southern and central Gotland. It was over these areas that the most concentrated plume was transported. In Stockholm, which is on the periphery of this area, FOA made simultaneous measurements of concentration in air as well as deposition after 29 April, the latter measurements being made with a field gamma spectrometer on the lawn outside the laboratory. These measurements show that during the first days, caesium had a dry deposition velocity of about 0.5 cm/s. Refractory radionuclides such as ^{95}Zr, ^{95}Nb, ^{103}Ru and ^{239}Np were deposited with a considerably higher velocity, 2 - 3 cm/s, which shows that at an early stage these were enriched in larger particles.

These values of the deposition velocity agree well with the view that ^{137}Cs mainly occurred in particles with a diameter of less than about 2 µm, while ^{103}Ru and other refractory radionuclides occurred in larger particles.

Using the deposition velocities mentioned above and measured or estimated dry deposition, a rough estimate can be made of the concentration in air where no air measurements have been obtained. In areas with no precipitation during the particular period, the estimated dry deposition should agree with the measured total deposition. On Gotland, where there was no precipitation during the period 27 April - 7 May and only a few millimetres during 8 - 9 May, the total deposition of ^{137}Cs according to Figure 16 was 5 - 10 kBq/m^2. To explain these values as being due to dry deposition, the concentrations of ^{137}Cs at ground level must have been an average of 10 - 30 Bq/m^3 during the two days when the plume affected Gotland. These are considerably higher concentrations than those observed in eastern Svealand. However, in view of the concentrations observed by aircraft in southern Finland on 29 April (155 Bq/m^3) and at ground level in Oskarshamn on 28 - 29 April (7 - 41 Bq/m^3), they are not unreasonably high. It is also possible that the measured total deposition is somewhat overestimated (cf above).

The deposition charts for ^{134}Cs and ^{137}Cs have also been utilized to calculate the extent of total deposition over Swedish territory. The total deposition in Sweden from Chernobyl is 2.2 x 10^{15}Bq of ^{134}Cs and 3.8 x 10^{15} Bq of ^{137}Cs. This constitutes about 10% of the total caesium emission as estimated in the Soviet report to IAEA. Since the caesium deposition over Sweden may be overestimated and the Soviet figure for the caesium is probably underestimated, the true figure ought to be somewhat lower. Our analysis above shows that a dominating part of the fallout in Sweden took place during the period 28 - 30 April and that this fallout originated from the emission of 26 April. If a comparison is made between the total deposition of ^{137}Cs in Sweden and the reported emission during 26 April alone (cf Figure 4), the proportion is as high as about 40%. However, it is improbable that the true level was of this magnitude.

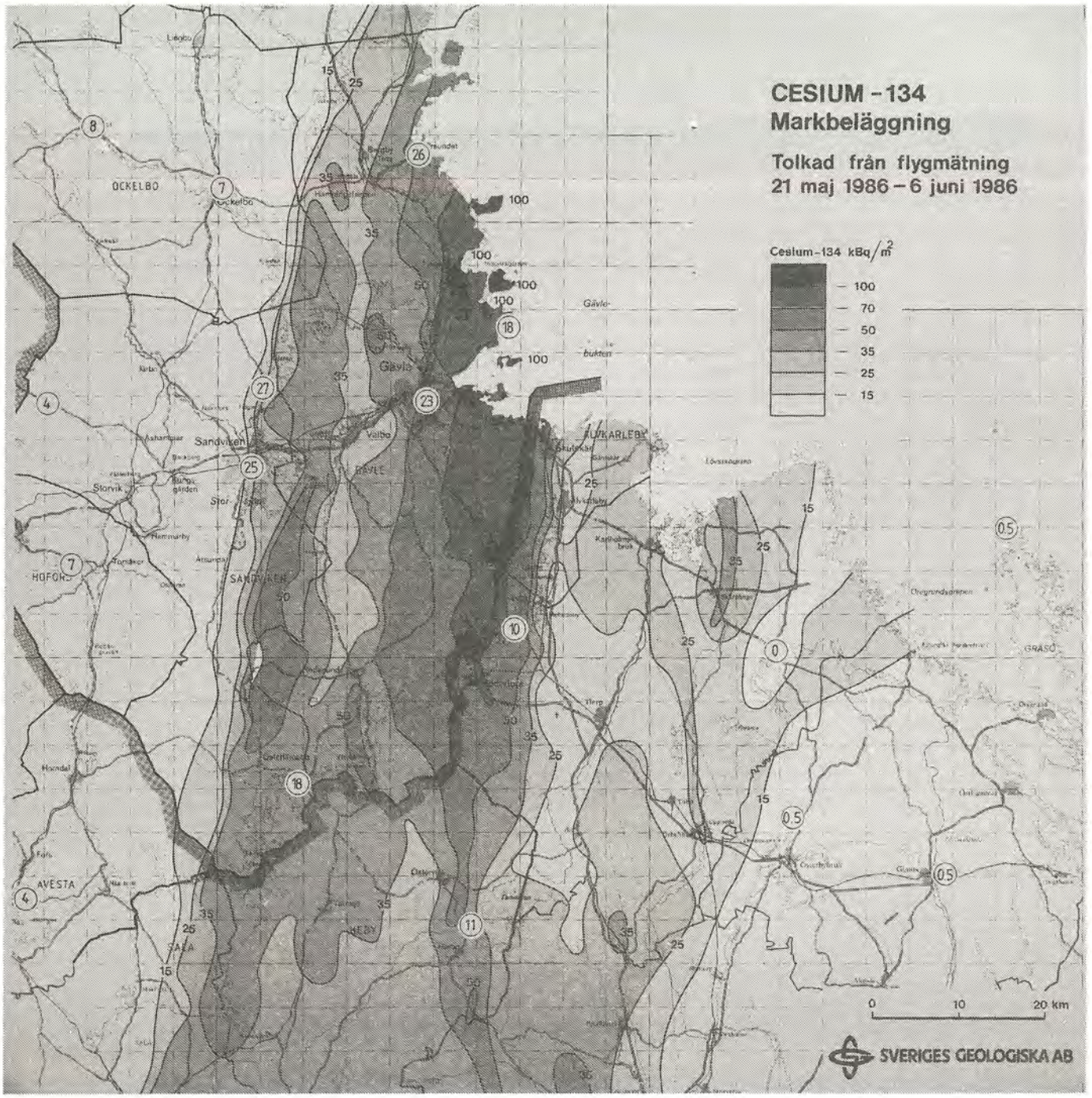


Figure 22. Measured deposition of ^{134}Cs in the Gävle area. The measurements were made by the Swedish Geological Company. Volumes of precipitation (mm) during the period 28 April 06 UTC to 30 April 06 UTC at SMHI precipitation stations in the area have also been marked. The indicated precipitation values are circled.

6. THE RISK OF SWEDEN BEING AFFECTED BY A NUCLEAR POWER ACCIDENT AT LONG DISTANCE - SOME METEOROLOGICAL ASPECTS

This chapter takes up information of a more general nature and makes a number of general calculations. The following discussion may provide a basis for planning a more detailed study of the risks occurring in connection with emissions of radionuclides outside Sweden.

6.1 The probability of a high deposition over Sweden

Figure 1 indicates the locations of all the nuclear power plants in Europe. Bearing in mind this picture, we have made a rough quantitive estimate of the risk of a large deposition of radionuclides over Sweden following a nuclear power plant accident outside the Swedish borders.

Let P* indicate the probability of a "high" deposition over Sweden (of the type that occurred in the Gävle area) assuming that a major accident occurred outside the country. If we regard events 1, 2 and 3 as mutually independent, as is reasonable in this general calculation, we can write:

$P^* = P_1 \times P_2 \times P_3$ where

P_1 = the probability of the trajectory from the accident site passing Sweden within 5 days of the emission (after longer transport times, the major part of the emission has usually been deposited). P_1 decreases rapidly with the distance of the source from Sweden and is somewhat higher for western Europe than for eastern Europe. The following values can be estimated from Rodhe (1972):

Great Britain	about 25%
West Germany	about 15%
Eastern Europe at the same distance	about 10%

P_2 = the probability that the vertical temperature stratification in the atmosphere is stable near the ground, so that the plume remains relatively concentrated. This depends on the season, whether the transport occurs over land or sea and the transport time. The longer the transport time, the greater will be the possibility that the plume at some point (especially in daytime) becomes well-diluted. In transports over the Baltic during spring and early summer, the probability of very stable stratification is high, owing to the low water temperature. No simple estimate of P_2 can be made, partly because of the "gradual scale" and also large variations according to land/sea, season, and time of day. In our rough approximation, the value 20% may be considered reasonable if the definition "stable" includes a short period with somewhat better mixed conditions (as in the case of the Chernobyl accident). The value for transports from southern Europe should be higher than for those from western Europe.

P_3 = the probability of precipitation in the plume when this affects Sweden. From Persson och Kindell (1981) the following estimate can be made:

In transports from W Europe to SW Sweden	- 20%
In transports from W Europe to central Sweden	- 15%
In transports from E Europe to SE and E Sweden	- 15%
In transports from E Europe to N Sweden (coast + inland)	- 25%

If there is also a condition that no significant precipitation should involve the plume before it reaches Sweden, these figures should be reduced by a factor of at least 2.

By entering the indicated values and calculating P*, we can obtain a rough estimate of the probability of a high deposition over Sweden following a major accident in Europe. We calculate the values both for Great Britain, West Germany and eastern Wurope at the same distance as 0.002 - 0.005. The difference between the values for western Europe and eastern Europe is probably quite small. This may seem surprising since Sweden is dominated by winds from the south-west. However, the difference is largely compensated by an increased probability of stable stratification in transports from the south-east and a relatively high frequency of precipitation over north-east Sweden (as occurred after the Chernobyl accident).

If large emissions continue for several days, the probability of Sweden being affected at some period naturally increases. Generally, the weather situation can be taken to change every 24 hours. This means that the P* of an emission lasting longer than 5 days will be about 5 times higher than the values given above. In the Chernobyl accident, a large part of the emission occurred during three days (the first, eighth and tenth). Given an emission lasting three days, the probability of a high deposition anywhere in Sweden is therefore of the order of 1%.

In the case of nuclear power plants near the Baltic, the P values are somewhat higher. During spring and early summer, almost all transports from these countries north over the Baltic would occur under very stable conditions, with little dilution of the plume throughout the transport to Sweden. We estimate that the maximum deposition of caesium and iodine could then be 10 times higher than in the Chernobyl accident. This assumes that emissions and weather conditions over the whole area are the same as in the case of Chernobyl. In unfavourable conditions, the fallout of certain radionuclides, especially those associated with larger particles, could be considerably more than 10 times the levels following Chernobyl. This means that the total fallout of radionuclides could also be over 10 times higher.

6.2 Deposition values in Sweden following the Chernobyl accident compared to a "statistical" mean

A "statistical mean" for deposition over Sweden in connection with nuclear accidents in other countries may be roughly estimated from a number of simple assumptions. The "statistical mean" is defined as the deposition value that would be obtained in the case of a long-term emission over 1 year or more.

We assume an isotropic windfield, i.e. that the wind has the same velocity distribution and frequency in all directions everywhere, and that precipitation occurs with the same frequency everywhere for all wind directions. We also assume a mean passage of radionuclides in the atmosphere (τ_0) of 7 days, which is a reasonable value for substances associated with small particles. The deposition per unit of time and area at a distance r from the emission can be calculated from the expression (Rodhe 1972):

$$d(r) = \frac{A}{r} e^{-r/r_0}$$

where r_0 = mean transport velocity $\times \tau_0$

$$A = \frac{Q_0}{2\pi r_0}$$

and

Q_0 = emission per unit of time.

Using this simple calculation method, the total deposition over Sweden would be about 0.7% of the emission, which in this case corresponds to a mean of about 0.6 kBq/m^2 for ^{137}Cs.

The maximum values of 150 - 200 kBq/m^2 for ^{137}Cs deposition in Sweden which were observed after the Chernobyl accident, are therefore about 300 times higher than the calculated "statistical mean", while the measured mean deposition within the country is about 10 times higher.

7. CONCLUSIONS

From the analysis of meteorological and radiological data made in the aftermath of the Chernobyl accident, we draw the following conclusions:

- Sweden was affected primarily by emissions of radionuclides occurring during the first and tenth days after the explosion. This radiation affected the country during the periods 27 - 30 April and 8 - 10 May.

- The transport of radionuclides from Chernobyl to Sweden during the above periods may be described quite satisfactorily with available meteorological data. On the other hand, it is not possible to make a detailed determination from these data of the variation in concentrations in the air over the country. Measurements of radionuclides in ground-level air provide some information in this respect, while data from air at higher levels are very incomplete.

- The deposition of radionuclides over the country is well-mapped, especially through measurements of gamma radiation using aircraft, (cf Figure 16).

- The deposition of caesium over Sweden occurred mainly through wet deposition. This took place over eastern and northern Sweden in connection with precipitation on 28 - 29 April (over northern Sweden also on 30 April) and for south-west Sweden on 8 - 9 May. In the case of certain other radionuclides, including ^{95}Zr and ^{239}Np, a considerable part of the deposition occurred in the form of dry deposition. Iodine occupies an intermediate placing. Considerable dry deposition of iodine was observed in areas without rain, while wet deposition completely dominates in areas with heavy rain.

- An integration of the total caesium deposition shows that as much as 10% of the total emission of causium may have been deposited over Sweden.

- Had the accident occurred in the countries around the Baltic under similar meteorological conditions, the maximum deposition values of caesium and iodine could have been about 10 times greater.

Experience from the Chernobyl accident shows extremely clearly that dispersion and fallout of radionuclides are not limited to areas within a short distance of the site of the emissions. Very high fallout may occur at distances of thousands of kilometres in connection with precipitation. The dispersion sequence is influenced both by local meteorological conditions up to a few kilometres altitude and by the general weather situation during the following days. The results of our study provide a basis for further discussion regarding the planning of safety precautions in the event of a nuclear power accident.

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