ministerie van verkeer en waterstaat

koninklijk nederlands meteorologisch instituut

verification of an objective analysis scheme

meteorological analyses after the Chernobyl disaster verified by trajectories of radioactive air masses.

G. J. Cats, B. J. de Haan and L. M. Hafkenscheid

scientific reports WR 87-4

wetenschappelijke rapporten WR 87-4

de bilt, 1987

METEOROLOGICAL ANALYSES AND THEIR VERIFICATION BY TRAJECTORIES OF RADIOACTIVE AIR MASSES DURING THE CHERNOBYL DISASTER

G.J. Cats, B.J. de Haan and L.M. Hafkenscheid

Royal Netherlands Meteorological Institute
De Bilt, The Netherlands

January, 1987

Abstract

An intermittent data assimilation scheme has been used to produce wind and precipitation fields during the 10 days after the explosion at the Chernobyl nuclear power plant on 25 April 1986. The wind fields are analyses, the precipitation fields have been generated by the forecast model part of the scheme. The precipitation fields are of fair quality. The quality of the wind fields has been monitored by the ensuing trajectories. These were found to describe the arrival times of radioactive air in good agreement with most observational data, taken all over Europe. The wind analyses are therefore considered to be reliable.

1. INTRODUCTION

Meteorological information is an essential input to air pollution dispersion models. Many investigators use the analyses routinely produced by some meteorological centre (e.g. Savolainen et al., 1986). Especially ECMWF products found wide application (Reiff et al., 1985; Kolb et al., 1986). These analyses are quality assured by the monitoring of the quality of the ensuing weather forecasts. Also, they have the advantage of their ready availability "off-the-shelf". On the other hand, they suffer from low resolution (in the order of 150 km in the horizontal, one or two pressure levels in the boundary layer, 6 hours in time). Some centres, including ECMWF, do not use surface wind data over land. As a consequence, the boundary layer wind is not well analysed over land. Precisely this parameter is the most important meteorological input to dispersion models.

In this paper we report on the generation of reliable meteorological fields at a higher spatial and temporal resolution. Through a recent mischief we have been provided with an extensive data set to verify the produced analyses directly, without reference to the quality of weather forecasts.

Late in the evening of 25 April 1986 (GMT) one of the nuclear reactors in Chernobyl (51°15' N, 30°15' E) went out of control. During the following few weeks, large amounts of radioactivity were released and deposited over many parts of Europe. Throughout this area and this period many measurements of radioactivity in the air, in precipitation, in crops etc. were taken.

Quite a few researchers have afterwards attempted to simulate these measurements, using a range of representations of the atmospheric situation and air pollution dispersion models (Van Egmond and Wirth, Apsimon and Wilson, Van der Auwera and Vanlierde, Gudiksen and Lange, all 1986). In this study we will concentrate on the meteorological fields required by dispersion models, and not discuss any such models.

The meteorological fields in the 10 days following the Chernobyl disaster have been analysed with an analysis scheme developed at KNMI. This scheme is a 3 hour intermittent data assimilation system, consisting of optimum interpolation (OI) (Cats, 1984a), initialisation (Bijlsma and Hafkenscheid, 1986), and a 3 hour forecast with the KNMI fine mesh limited area model. In section 2, a brief description of this scheme is given.

The scheme has proven its usefulness to simulate episodes of severe storms (Cats, 1984b) and storm surges (Peeck, 1985). The OI step formed part of a system to simulate episodes of photochemical smog (Cats et al., 1985). The full scheme has not been applied before to air pollution episodes. To provide an immediately verifiable form of model output, independent of an air pollution dispersion model, a simple trajectory module was added to the forecast step. With this module puffs, released at 3 hourly intervals at Chernobyl, were traced through the subsequent series of analysis cycles, using full model resolution in time (7½ minutes), in the horizontal (ca. 61 km, Fig. 1) and in the vertical (4 sigma layers below 2500 m).

We used the scheme to generate wind and precipitation fields; the trajectory module aids in the verification of the wind fields. The results are given in section 3; they are discussed in section 4. There also the results of the verification against observational data are given.

2. MAIN CHARACTERISTICS OF THE DATA ASSIMILATION SCHEME

a. The structure of the scheme

The data assimilation system consists of a series of repeated 3 hour cycles; each cycle comprises an analysis and a 3 hours forecast from that analysis. The analysis makes use of the meteorological data collected over the 3 hours centered at the analysis time, and of a first-guess field. This field is the result of the 3 hours forecast from the previous cycle. It represents the best available description of the state of the atmosphere at analysis time, just before the observations became available.

The whole series of cycles is started from an ECMWF analysis as first-guess, interpolated to the higher resolution grid. To generate high resolution information in the first-guess to the first analysis of the episode, 4 "warming-up" analysis cycles were run before the start of the episode. The first of these four was valid at 12 GMT on 25 April 1986; the episode started at 00 GMT on 26 April, and we stopped the simulation at 00 GMT on 6 May.

b. The meteorological data

Use is made of reported mean sea level pressure, geopotential height and wind components of synoptic surface and upper air observations. Most of the area being over land, these conventional data types provide a good data coverage. Therefore we excluded other data, such as satellite temperature profiles, although the analysis scheme is able to handle those as well. The data are subjected to checks on coding, gross error, deviation from the first-guess and on multivariate (mainly geostrophic) and three-dimensional consistency.

c. The analysis scheme

The data that have passed all checks enter a multivariate, three-dimensional optimum interpolation (OI) scheme (Lorenc, 1981). This scheme produces an analysis of geopotential height and horizontal wind at 10 standard pressure levels (1000, 850, 700 .... 100 mb). Also, it generates a crude estimate of the accuracy of those fields.

The analysed fields are vertically interpolated to the levels of the first-guess model, with a technique called "interpolation of increments" (Talagrand, 1980, private communication; Baker et al., 1984). This technique has the advantage that it preserves the details of the boundary layer structure of the first-guess.

Analysed fields at arbitrary levels are available from those at sigma levels through vertical interpolation. For wind components, this interpolation uses a logprofile below the lowest model level, which is at approximately 70 m.

d. The model

The first-guess field is obtained by running a predictive model from the previous analysis, during 3 hours.

The model runs on sigma levels. It contains an extensive package of parameterisations of physical processes in the atmosphere. Many of these are from the ECMWF global model (Louis, 1979), but radiative and convective processes have been changed. Also, several parameters, such as rate of horizontal diffusion, have been adapted to the higher resolution and the limited area (hence the acronym LAM, limited area model) of the present application.

To avoid the growth of high frequency waves, excited by imbalances in the analysed fields, these fields are initialised by the bounded derivative technique (Bijlsma and Hafkenscheid, 1986). The initialised fields serve as initial conditions for the model integration. Lateral boundary conditions are taken from ECMWF analyses. Surface boundary conditions (sea surface temperature, soil moisture etc.) follow from climatology. The orography was interpolated from the one in operational use at ECMWF in 1979. Because of its low resolution (1.875°) the orography is very smooth (Fig. 1).

Several physical processes generate precipitation during the model integration. This precipitation is accumulated over the 3 hours of the integration. We present this model precipitation as estimate of the real precipitation over those 3 hours. Comparison with observations show that this estimate provides a fair indication of precipitation areas and duration. The intensity, however, may in circumstances, such as showers, be in error by a factor of 3. We did not include a precipitation analysis based on precipitation data in this study because of many yet unresolved difficulties, e.g. in distributing 12 hourly accumulated observations over 3 hours periods, and in treating the data void sea areas. Furthermore, there are indications that wash-out and similar wet removal processes depend less on precipitation intensity than on duration (Georgii, 1965). It is of interest to note that a future precipitation analysis scheme may make use of the present model output as a first-guess, e.g. to supplement the data over sea.

Our contestation that the model precipitation in the first three hours is reasonable, deviates from experience with many other models, which suffer from a "spin-up" problem. We propose the following explanations of the fact that in the present study the spin-up problem is less manifest.

a. The problem is most apparent in the tropics, thus outside our area (Heckley, 1982).

b. Over land, the analysis increments are generally small, because the first-guess is a very short-range forecast (3 hours) with a sophisticated model, from an analysis which, being over a data dense area, is of high quality. The initial humidity field is taken from the ECMWF analyses at 6 hourly intervals, and directly from the first-guess at intermediate hours. Therefore, especially at the intermediate hours, the initial fields of mass, wind and humidity contain small imbalances only. The spin-up problem originates from imbalances, and will therefore be small as well (Hollingsworth, 1986).

During the model run, the three wind components are available at the full four dimensional model resolution. These wind fields are very suitable for trajectory calculations because of their high resolution and their consistency, both amongst each other, and with other model fields (e.g. stability, orography). We present trajectories, obtained this way, as implicit verification of the analysed wind fields.

In principle, the physical parameterisations within the model make it possible to generate an extensive set of meteorological fields that are of interest to air pollution modellers (e.g. atmospheric stability). For practical purposes we limited ourselves to the production of the meteorological fields required by one specific dispersion model (Van Egmond and Kesseboom, 1983); these are analysed horizontal wind components at the height of 10 m and at the 850 mb level, and model precipitation. For manual diagnostics, we added analysed mean sea level pressure. All of these fields were stored at 3 hourly intervals, at full horizontal model resolution.

3. RESULTS

The results of the present simulation of the meteorologcal conditions in the episode after the Chernobyl disaster fall into three categories:

a. Analyses of wind fields, to be used directly in air pollution dispersion models.
b. Estimates of areas and amounts of precipitation. These fields can be used directly in dispersion models, but preferably they would be used in conjunction with precipitation observations.
c. Trajectory calculations, based on the wind fields as available in the consecutive 3 hour model integrations. The trajectories can be used in Lagrangian air pollution models; their direct usage is to aid in the manual assessment of the movement of contaminated air masses.

At the time of the disaster, winds were weak and variable in the Chernobyl area (Fig. 2). A high pressure area caused the nighttime boundary layer to be stable. During the daytime, the mixing depth became about 2500 m. Winds remained generally weak because of a low pressure gradient (Fig. 3). The daytime releases of radioactivity were almost instantaneously mixed over this layer. We will assume this also for the nighttime releases. Strictly speaking, they first moved unmixed away from their source. Because of the low night time wind speeds, they did not move far before they were mixed in the next daytime mixing layer. The assumption of instantaneous mixing is therefore justified except within a few tens of kilometers from the source. With this instantaneous mixing, the dispersion of radioactive air is insensitive to the actually occurring plume rise.

Based on these considerations, we decided to run the trajectory module for releases from Chernobyl at the heights of 600 and 1600 m. At the higher of these levels, the wind is to a high degree representative for transports within the daytime mixing layer. The lower one has been added to give an indication of the nighttime, and lower mixing layer daytime transport. In the rest of this paper we will refer to the trajectories by their release level, which, through possible vertical motion, is not necessarily equal to the actual height at some time after the release.

Trajectories were started in Chernobyl at intervals of 3 hours. For a full description of the movement of radioactive clouds one would have to start a new trajectory at every point where horizontal or vertical mixing takes such a form, that the mixing cannot be described by simple (gaussian) diffusion around a centre of gravity. This is expecially the case at every transition from day to nighttime, because after such a transition, the flow in the nocturnal boundary layer may become decoupled from that at higher levels. We did not go into this complication, because the trajectories are secondary output only, added to verify the primary wind fields. For the same reason, we did not attempt to model dispersion around the calculated trajectory position.

We present the results of the trajectory calculations in two ways; in the form of trajectories and in the form of "plumes". The plume at a certain moment consists of the set of positions, at that moment, of all releases up to that moment. This plume would show on a photograph from space as a common plume from a chimney, if the radioactivity would be visible.

The horizontal distance between two successive releases, 3 hours apart, after some time, is a crude measure of dilution along the plume axis. To visualise this effect, we plot the plumes by connecting the positions of consecutive releases by a line, whose thickness decreases with its length, until it breaks if it would become too thin (this way of plotting is similar to the behaviour of a piece of chewing gum, when it is stretched).

The plume at a certain moment is plotted in a map of model precipitation in the preceding 3 hours. Whenever the plume is in or near a precipitation area, the model suggests radioactive rainfall. Because the main radioactive contamination of soil and crops was through precipitation, the combined plots of plumes and precipitation reveal the economically most affected areas at a glance, without complicated concentration and deposition calculations.

In Fig. 4 one such plot is shown. It depicts the situation in the morning of 28 April 1986, two and a half days after the explosion. The forward edge of the 1600 m plume has reached the Stockholm area, in an area of model precipitation. The parts of that plume with later release times take a more westerly course, as does the 600 m plume.

For a synopsis of the developments during the subsequent days, we present Figs. 5 to 9 which display the position of the plume at several instances within the episode.

The 1600 m plume is seen to split into several parts. The first remains over Northern Scandinavia for a long time, while "washing-out" through precipitation. The second part moves to Western Europe, taking tracks to the North and the South of the Alps. Poland, Germany, Austria, Italy, France and the U.K. are among the affected countries. Later parts move to the east and to the south (e.g. Greece). Also substantial parts of the 600 m plume moved over Western and Southern Europe.

Calculated trajectories are shown in Figs. 10, 11 and 12. As an example, Fig. 10 displays the trajectory of the 1600 m release at 18 GMT on 26 April 1986. The air travelled over Poland to the Munich area, where it bended north, remaining North of the Alps. It reached The Netherlands at noon on 2 May, at a height of 500 m. Of course, vertical diffusion would have brought radioactivity to other levels as well.

A compilation of all calculated 1600 and 600 m trajectories is given in Figs. 11 and 12 resp. They show clearly that some areas were more affected than others. Because trajectories and plumes are just alternative ways of presenting the same information, one would be able to identify release and travel times of the trajectories by matching positions in Figs. 4 to 9. The distinct parts of the plumes show up in Figs. 11 and 12 as bunches of trajectories, travelling in a certain direction . Especially clearly is seen how many trajectories follow the Po valley (south of the Alps) and the Rhone valley (between the Alps and the Massif Central).

4. DISCUSSION

a. Observations and trajectories

In this section we will compare the calculated radioactive plumes with observational data. We have taken the data from two WHO reports (Beninson, 1986, referred to as WHO-1, and Van Egmond and Wirth, 1986, referred to as

WHO-2).

The situation at the time that increased levels of radioactivity in precipitation were observed first in Sweden, is described by Fig. 4. This situation caused the Swedish Radiation Protection Institute to raise an alarm internationally (WHO-1). The earlier report of increased radioactivity at Kajaani, Finland (64° N, 28° W) on 27 April, is not described by the present calculations.

The observed arrival in the Munich area in the afternoon of 30 April (WHO-1 and -2) in rainy conditions is accurately described. We find, however, that the release time of the relevant radioactivity was in the evening of 26 April (Figs. 5 and 10), as opposed to 27 April, as stated in WHO-1.

In WHO-2 some time series of Iodide-131 observations throughout Europe are quoted. Most of these confirm our calculations: Marcoule (South France), from 30 April onwards (Fig. 5), Paris from 1 May (Figs. 6, 7), Bilthoven (The Netherlands) (Figs. 7, 10), Harwell (South England) in the morning of 2 May (Fig. 7), Varese (Northern Italy) (Figs. 5, 6), Stockholm from 28 April, Vienna from 30 April.

Over The Netherlands the model generated precipitation from 3 May, 18 GMT. In reality precipitation was observed a few hours earlier, with an isolated shower already on 2 May, 18 GMT. The arrival time of the radioactive cloud was well diagnosed.

The observation at Risø (Denmark) of raised levels of I-131 radioactivity on 27 April is not present in our calculations, but later observations are (around 5 May).

b. Trajectories and precipitation

Fig. 8 and the situation over Sweden around 28 April show an interesting phenomenon. There is a tendency for the plume to be within a precipitation area. This is explained physically by the fact that large scale precipitation is often connected to large areas of rising motion, which forces convergence in the lower layers of the atmosphere. The plume is thus "sucked" into the precipitation area. It is exactly by the use of a full, internally consistent model for the atmospheric circulation that this phenomenon can reliably be diagnosed in the Figures. The phenomenon is important because of the economic consequences (e.g. for food production) of coincidence of precipitation and radioactivity.

Many of the areas for which restrictions on food production and consumption were imposed, are indeed indicated by our calculations, in the form of areas with coinciding precipitation and radioactivity at some time during the episode. Into this category fall parts of the UK (Fig. 9), Northern Sweden, Northern Italy (Fig. 8) and The Netherlands (Fig. 8).

c. Error discussion

There are a number of uncertainties in both the calculated and observed data. The levels of observed radioactivity depend strongly on the observation method. With our trajectory data we do not try to predict those; only the presence of radioactivity and radioactive rain can be described. But even those quantities are often not well observed. E.g. arrival times are often blurred by the sampling periods of up to 24 hours.

There are two main sources of errors in the calculated trajectories. The first is the integration method. Because we integrate the trajectories at full model resolution, this error is negligible. In fact, trajectories calculated this way have been used as "truth", to benchmark less accurate methods (Kuo et al., 1985). The second source is found in errors in the wind field, due to errors in the analysis method and in the forecast model.

The theory of optimum interpolation provides an estimate of the RMS analysis error. In our case this estimate amounts to 1.5 to 2 m/s in the u and v components, over land, with somewhat smaller values at the lower levels because of the high availability of 10 m wind observations. The same value for the error estimate is derived from the fit of the analysis to the observational data. In view of the many assumptions to follow, we decided to stay on the safe side, by taking the high end of the quoted range (2 m/s) for the estimate of the RMS error in the analysed wind components.

During the subsequent 3 hour forecast, the error will presumably decrease at first (Hollingsworth et al., 1985) because the atmospheric model achieves a better consistency of the field than the analysis; later in the forecast the error will tend to grow because of the errors in the model formulation. We assume here that the wind errors remain constant throughout the 3 hours forecast, and 100% correlated with the initial error. After one analysis cycle, the position of the trajectory will then be in error by 20 km (RMS). If we further would assume that the wind errors in consecutive analysis cycles are uncorrelated, we would find an RMS error of 140 km after 6 days.

In this estimate we have neglected the fact, that if the position of the trajectory is in error at a certain timestep, the position at the next timestep will be calculated with the wind vector at a wrong position. The estimate is therefore only correct in situations with a constant and homogeneous wind field, or if the position error is small enough to make variations in the wind field negligible. In our case with a high pressure area over Europe during much of the episode, the wind field is fairly homogeneous and constant, so the RMS position error will not be orders of magnitude in excess of the value of 140 km found above. We will try to substantiate this following another line of thought.

In non-homogeneous wind conditions the position error may be thousands of kilometers after a few days (Sykes and Hatton, 1976). In the present case the good agreement between the calculated trajectories and observed levels of radioactivity proves that substantial error compensation must have occurred. We expect this to happen in areas of confluence, and we have seen that many trajectories indeed are in such areas. The error estimate will therefore depend strongly on the meteorological situation. The best way to obtain the error estimate would be via Monte Carlo simulations. Without actually going through this expensive procedure we get an impression of its likely outcome by considering the ensemble of trajectories (Figs. 11 and 12). The fact that they follow a limited number of "paths" suggests that the individual trajectories are in error by something like the path width, say a few hundreds of kilometers. This number does indeed agree with the earlier estimate of "not much in excess of 140 km". We conclude that the RMS error in the trajectory position is a few hundreds of kilometers after some days. Much larger values are found if the trajectory passed an area with diffluent flow.

Taking account of this error estimate, of the uncertainty in the position of the edge of the radioactive cloud due to diffusion and of the uncertainty in the observational data, we conclude that the model describes the arrival times as observed with the exception of the early arrivals in Kajaani and Risö. The good fit of the trajectory results to the observed data confirms the reliability of the analysed wind fields.

d. Orography

We think that the factor that contributes most to uncertainties in the output fields, is the weak representation of orography in the model. Fig. 13

shows a map of mean orography at a higher resolution (61 km). Comparison with Figs. 11 and 12 shows that the trajectories cross high terrain only very occasionally. The use of a higher resolution orography will therefore not change the trajectories by much. This is explained, of course, by the use of the wind observations, which are consistent with the real orography.

However, model generated rainfall may change drastically by the use of high resolution orography. This change is not necessarily an improvement; e.g. through generation of standing gravity waves spurious precipitation should be expected (Bougeault, 1983). We plan to rerun (part of) the episode with the orography shown in Fig. 13 to investigate this.

5. CONCLUSIONS AND OUTLOOK

For simulations of air pollution episodes with dispersion models it is essential to have good meteorological input fields available. The fields should be at sufficient spatial and temporal resolution, and be mutually consistent.

In this paper we reported on a method to generate a set of meteorological input fields. The produced fields were of good consistency, which was nicely demonstrated by the confluence of trajectories in precipitation zones. The resolution was sufficient to have orographically forced flow, even though the model representation of the orography was at a very low resolution. The generated wind fields led to trajectories that described the outflow of radioactive air over Europe in good agreement with available observational data. We are therefore confident that the wind fields are of sufficient quality to serve a wide range of air pollution dispersion models.

The precipitation fields, however, are less reliable. They indicate roughly where, and even more roughly how much precipitation occurred. Improvement of the precipitation analysis may be achieved by using observational data in addition to the presented model output. The impact of higher resolution orography on the precipitation will be one of the subjects of our future investigations.

The presented method is based on analysis forecast cycles. The forecast model can, however, also be run for longer forecast periods. In fact, it has been developed for 24 to 36 hours forecasts. With its short execution time on modern computers (a 24 hours forecast takes 90 s on a CRAY-XMP), it may be part of a short term prediction procedure in case of a calamity.

We have been discussing the meteorological input for an air pollution model only. To complete the simulation or prediction of an air pollution episode, also some model for the behaviour of air pollution is needed, comprising e.g. dilution, chemical reactions and nuclear decay. Meteorological data, generated and processed by limited area models may be a valuable input for such air pollution modelling.

Acknowledgements

We acknowledge gratefully the valuable contributions, through discussions, of A. van Ulden, H. van Dop and J. Reiff.

References

Apsimon, H.M., and J.J. Wilson, 1986: Preliminary analysis of dispersion of the Chernobyl release. Paper given at the Nuclear Inspectorate, 20 May 1986. London, U.K.

Baker, W.E., R. Atlas, M. Halem and J. Susskind, 1984: A case study of forecast sensitivity to data and data analysis techniques. Mon. Wea. Rev. 112, 1544-1561.

Beninson, D. (rapporteur), 1986: Report of a consultation, 6 May 1986, WHO report DOC 7246E, pp. 38. WHO Regional Office, Copenhagen, Denmark

Bijlsma, S.J. and L.M. Hafkenscheid, 1986: Initialisation of a limited area model: A comparison between the nonlinear normal mode and bounded derivative methods. Mon. Wea. Rev. 114, 1445-1455.

Bougeault, S., 1983: A non reflective upper boundary condition for limited height hydrostatic models. Mon. Wea. Rev. 111, 420-429.

Cats, G.J., 1984a: A scheme for mass and wind analysis on a limited area using multivariate threedimensional optimum interpolation. KNMI Techn. Rep. TR46, pp. 53. KNMI, De Bilt, The Netherlands.

Cats, G.J., 1984b: A mesoscale analysis scheme. In: LAM Newsletter 9. European working group on limited area modelling. Available from Det Norske Meteorologiske Institut, Oslo, Norway.

Cats, G.J., J. Reiff and C.A. Engeldal, 1985: Procedures used in the boundary layer height and wind analysis for the PHOXA project. KNMI Techn. Rep. TR64, pp. 26. KNMI, De Bilt, The Netherlands.

Georgii, H.W., 1965: Untersuchungen über Ausregnen und Auswaschen atmosphärischer Spurenstoffe durch Wolken und Niederschlag. Berichte des Deutschen Wetterdienstes, Nr. 100, pp.23.

Gudiksen, P.M., and R. Lange, 1986: Atmospheric dispersion modeling of radioactivity releases from the Chernobyl event. Lawrence Livermore National Laboratory, pp. 18. P.O. Box 808, Livermore, CA, U.S.A.

Heckley, W.A., 1982: Adjustment in numerical weather prediction models in the tropics. In: ECMWF Workshop on current problems in data assimilation, 8-10 November 1982, 299-343. ECMWF, Reading, U.K.

Hollingsworth, A., 1986: Objective analysis for numerical weather prediction. In: Proceedings of the WMO symposium on NWP, Tokyo, August 1986.

Hollingsworth, A., A.C. Lorenc, M.S. Tracton, K. Arpe, G. Cats, S. Uppala and P. Kallberg, 1985: The response of numerical weather prediction systems to FGGE level II b data. Part I: Analyses. Quart. J. Roy. Meteorol. Soc. 111, 1-66.

Kolb, H., G. Mahringer, P. Seibert, W. Sobitschka, P. Steinhauser and V. Zwatz-Meise, 1986: Diskussion meteorologischer Aspekte der radioaktiven Belastung in Österreich durch den Reaktorunfall in Tschernobyl. Publ. nr. 309, Zentralanstalt für Meteorologie und Geodynamik in Wien, pp. 59.

Kuo, I., M. Skumanich, P.L. Haagenson and J.S. Chang, 1985: The accuracy of trajectory models as revealed by the observing system simulation experiments. Mon. Wea. Rev. 113, 1852-1867.

Louis, J.F. (editor), 1979: ECMWF forecast model documentation manual, Volume 1. ECMWF research paper. ECMWF, Reading, U.K.

Peeck, H.H., 1985: Interim report on a comparison of storm surge models. Internal KNMI memorandum 85-19, pp. 24. KNMI, De Bilt, The Netherlands (unpublished manuscript).

Reiff, J., G.S. Forbes, F.Th.M. Spieksma and J.J. Reynders, 1986: African dust reaching Northwestern Europe: A case study to verify trajectory calculations. J. of Climate and Appl. Meteorol. 25, 1543-1567.

Savolainen, A.L., T. Hopeakoski, J. Kilpinen, P. Kukkonen, A.Kulmala and J. Valkama, 1986: Dispersion of radioactive releases following the Chernobyl nuclear power plant accident. Finnish Meteorological Institute, report nr 1986: 2.

Sykes, R.I. and L. Hatton, 1976: Computation of horizontal trajectories based on the surface geostrophic wind. Atm. Env. 10, 925-934.

Van der Auwera, L. and R. Vanlierde, 1986: Application of a trajectory model on the Tsjernobyl accident. Koninklijk Meteorologisch Instituut van België, Publ. Series B, nr. 124, pp. 39. Uccle, Belgium.

Van Egmond, N.D. and H. Kesseboom, 1983: Mesoscale air pollution dispersion models-I. Eulerian grid model. Atm. Env. 17, 257-265.

Van Egmond, N.D. and E. Wirth, 1986: Report of the WHO working group on assessment of radiation dose commitment in Europe due to the Chernobyl accident. Bilthoven, 25-27 June, 1986. RIVM, Bilthoven, The Netherlands.

WHO-1: Viz. Beninson, 1986.

WHO-2: Viz. Van Egmond and Wirth, 1986.

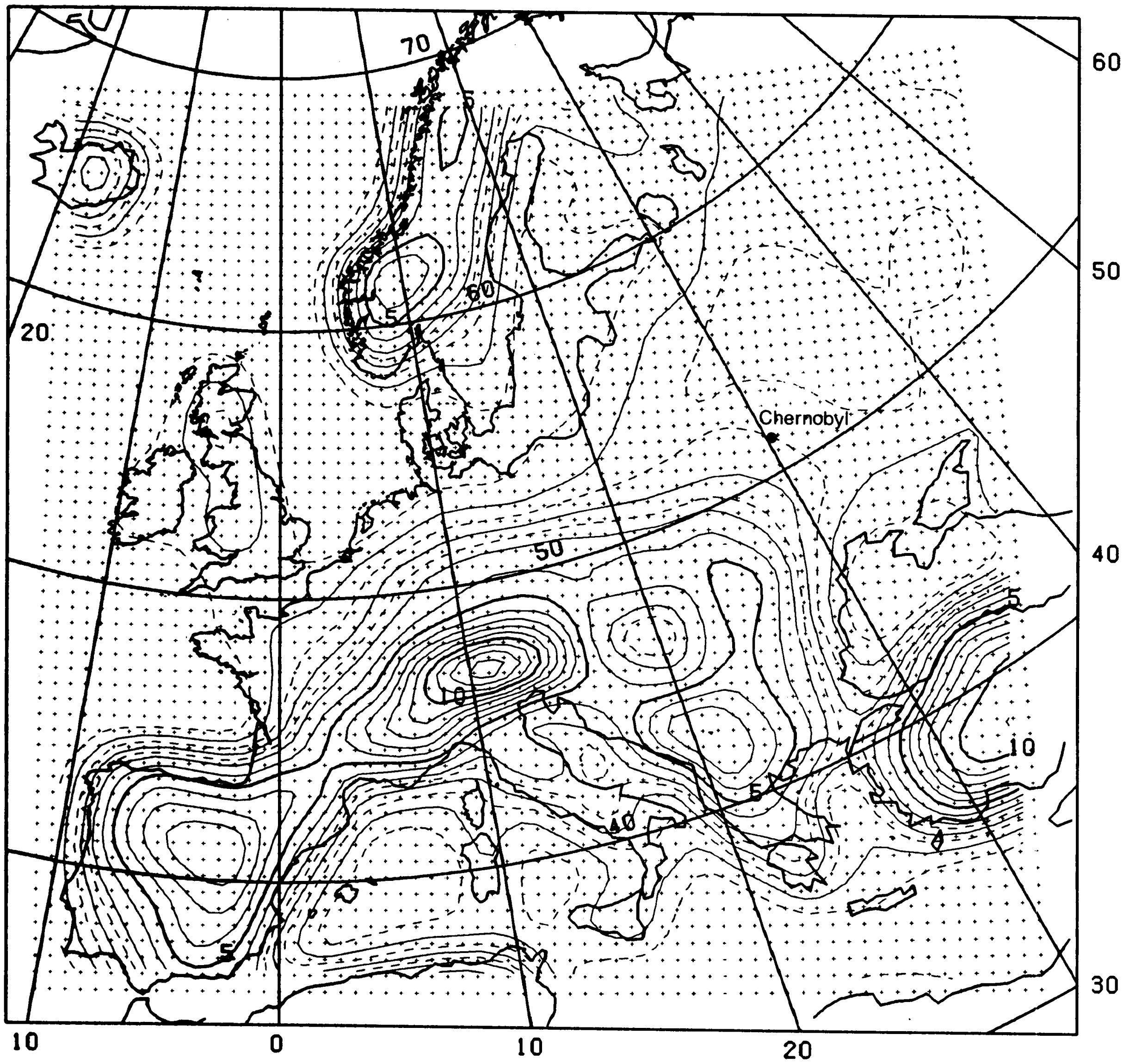

Fig. 1 The gridpoints of the used data assimilation system and the orography representation within the forecast model. Contour interval is 100 m (full lines), 50, 150 and 250 m contours dotted.

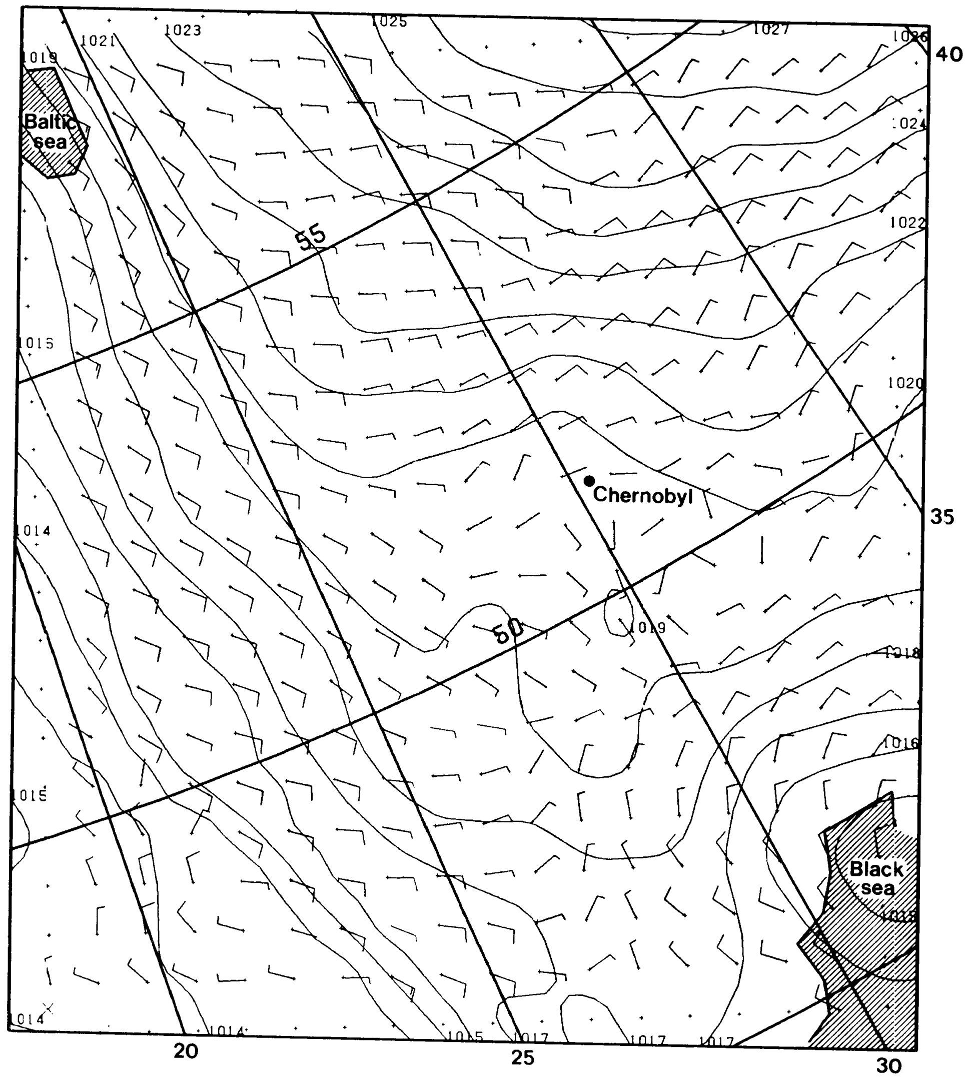

Fig. 2 Analysis of wind and mean sea level pressure in the area around Chernobyl at the time of the explosion.

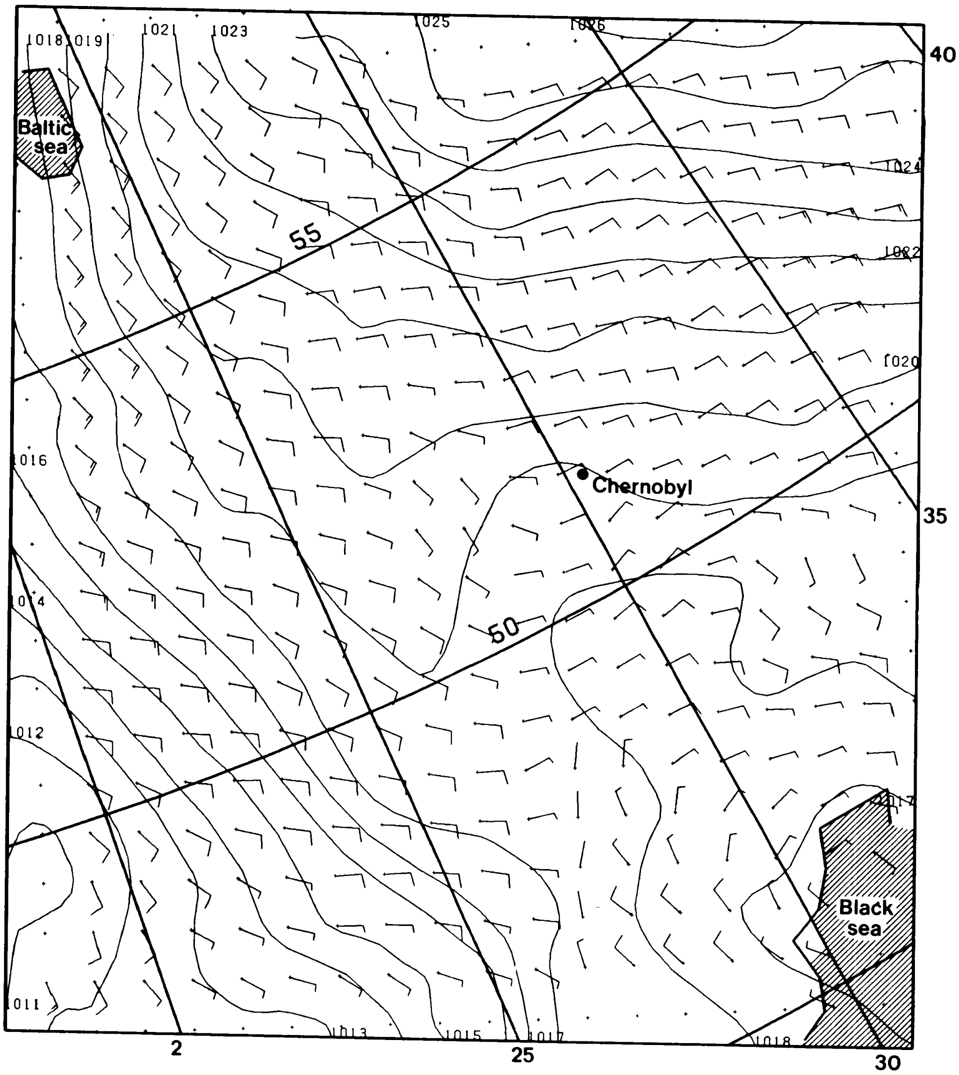

Fig. 3 As Fig. 2, for the afternoon after the explosion.

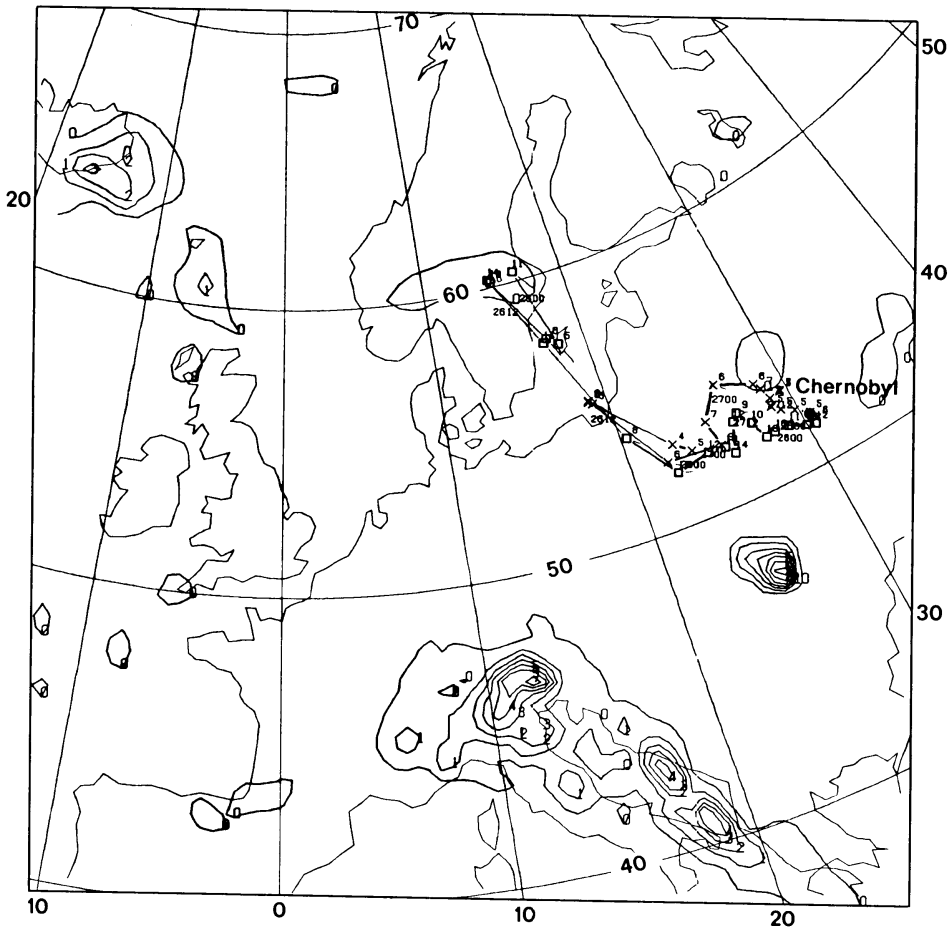

Fig. 4 Precipitation (mm), accumulated during the forecast from 6 GMT to 9 GMT on 28 April 1986; and the plumes released at 1600 m (□) and at 600 m (X). The Height of the plume is plotted to the top right of the symbol (in 100 m); the release time is plotted at 12 hours intervals, in the format DDHH, DD = day of month (April/May 1986), HH = hour (GMT). The line segments of varying thickness connect the releases at 3 hours intervals ("chewing gum").

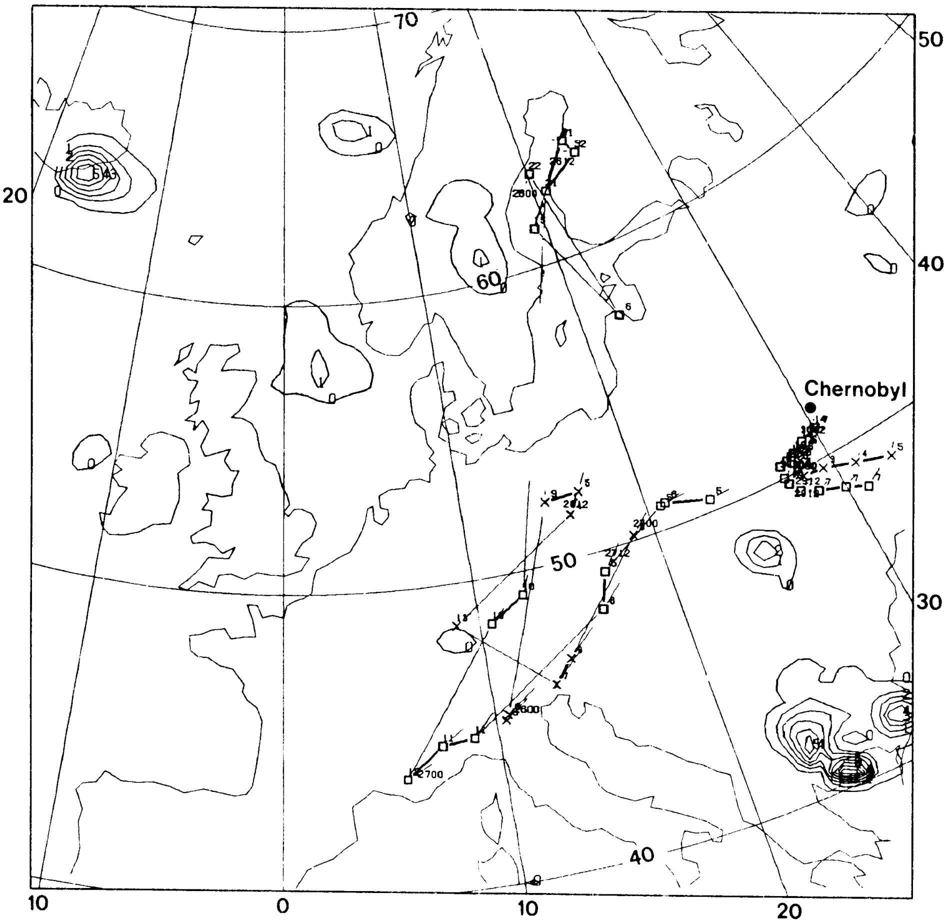

Fig. 5   As Fig. 4, for the forecast from 12 to 15 GMT on 30 April.

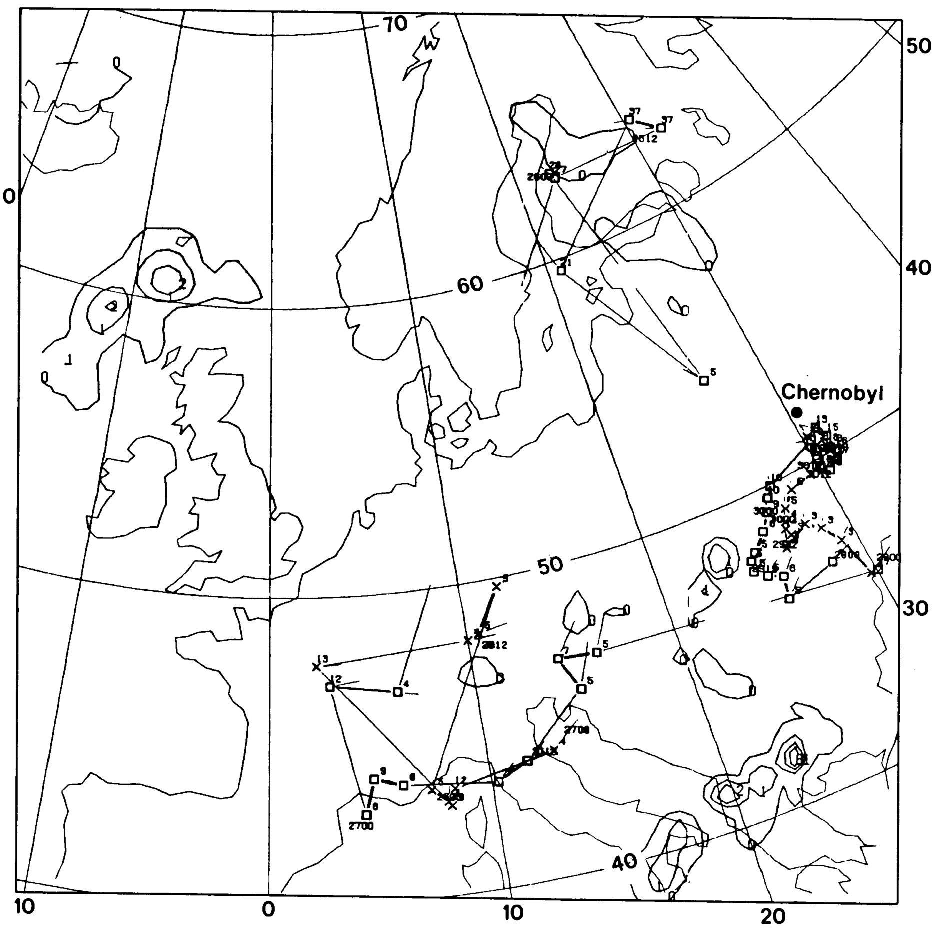

Fig. 6   As Fig. 4, for the forecast from 06 to 09 GMT on 1 May.

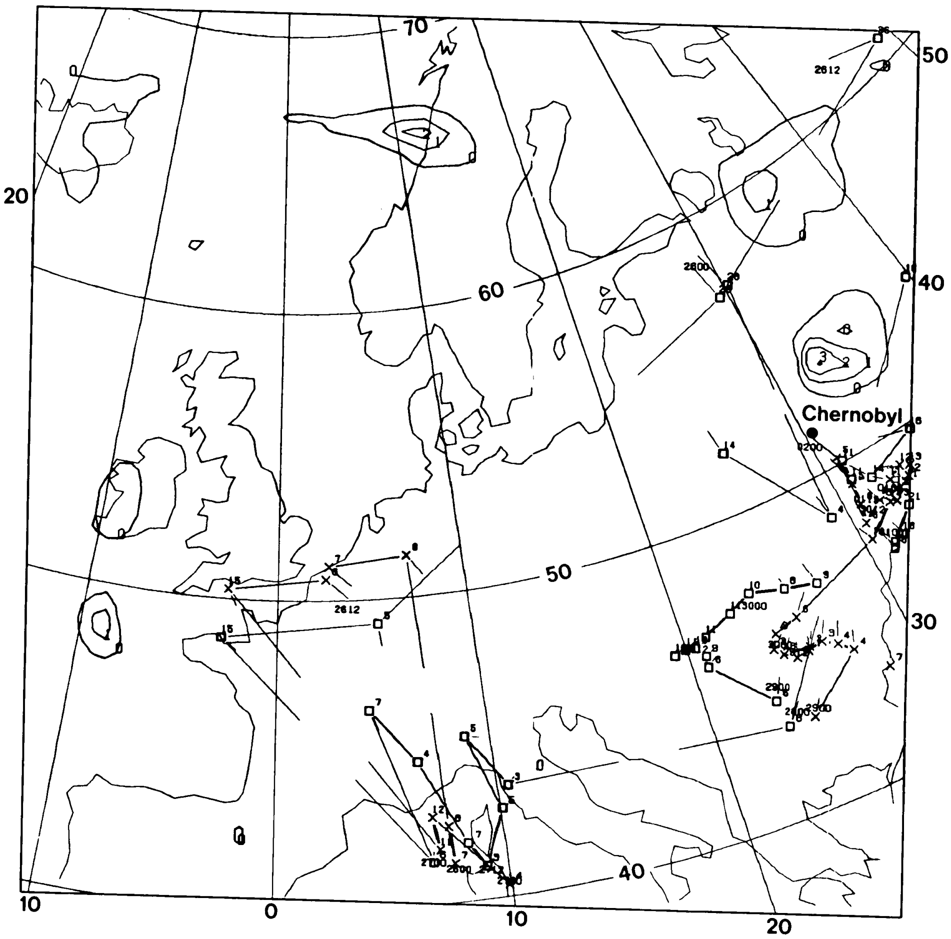

Fig. 7   As Fig. 4, for the forecast from 00 to 03 GMT on 2 May.

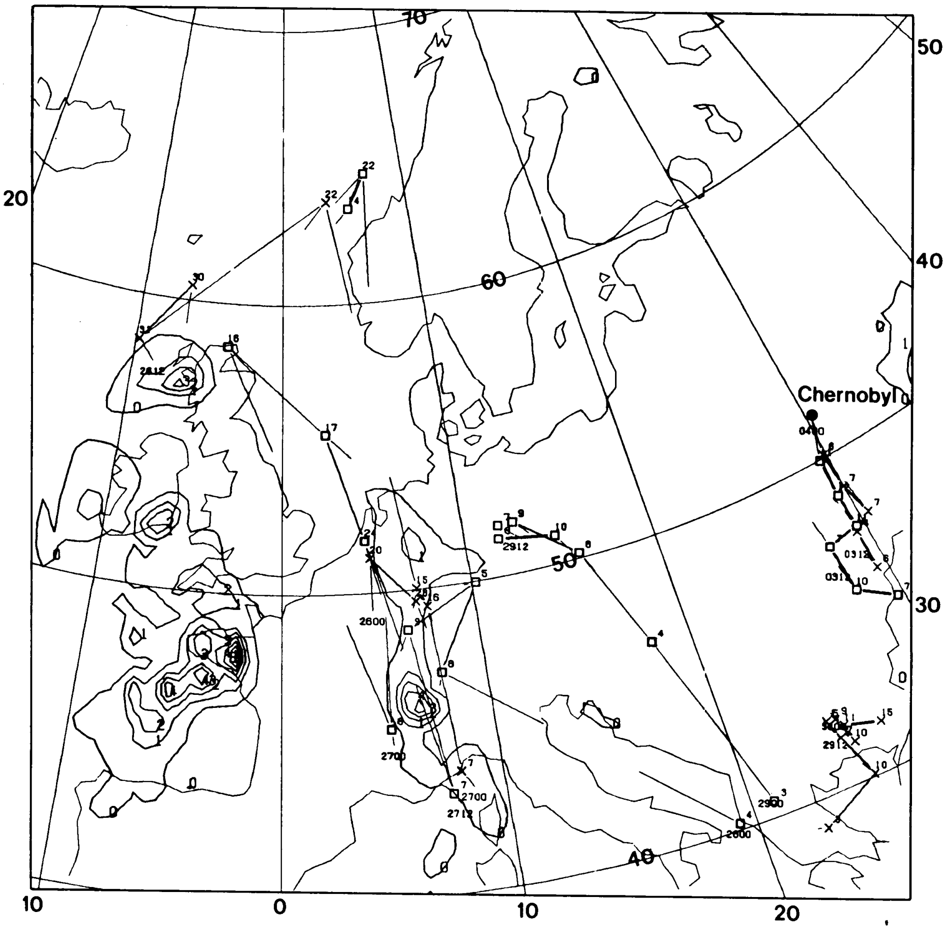

Fig. 8 As Fig. 4, for the forecast from 00 to 03 GMT on 4 May.

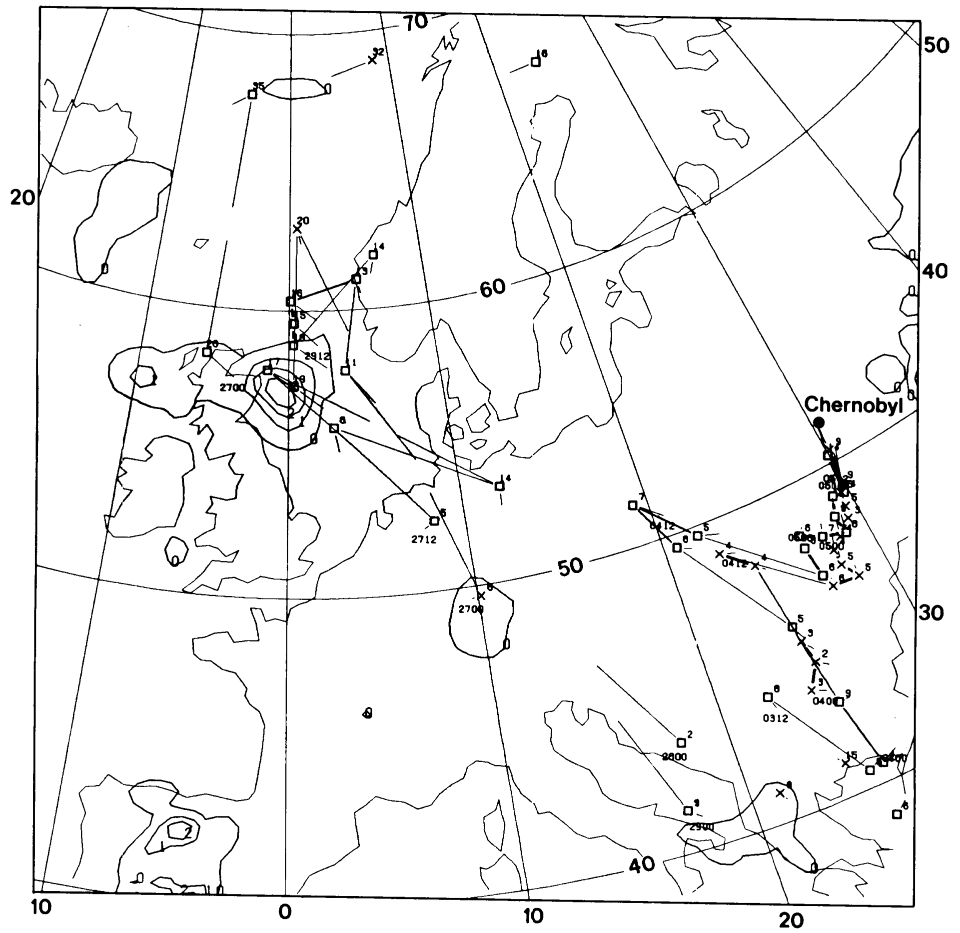

Fig. 9 As Fig. 4, for the forecast from 00 to 03 GMT on 5 May.

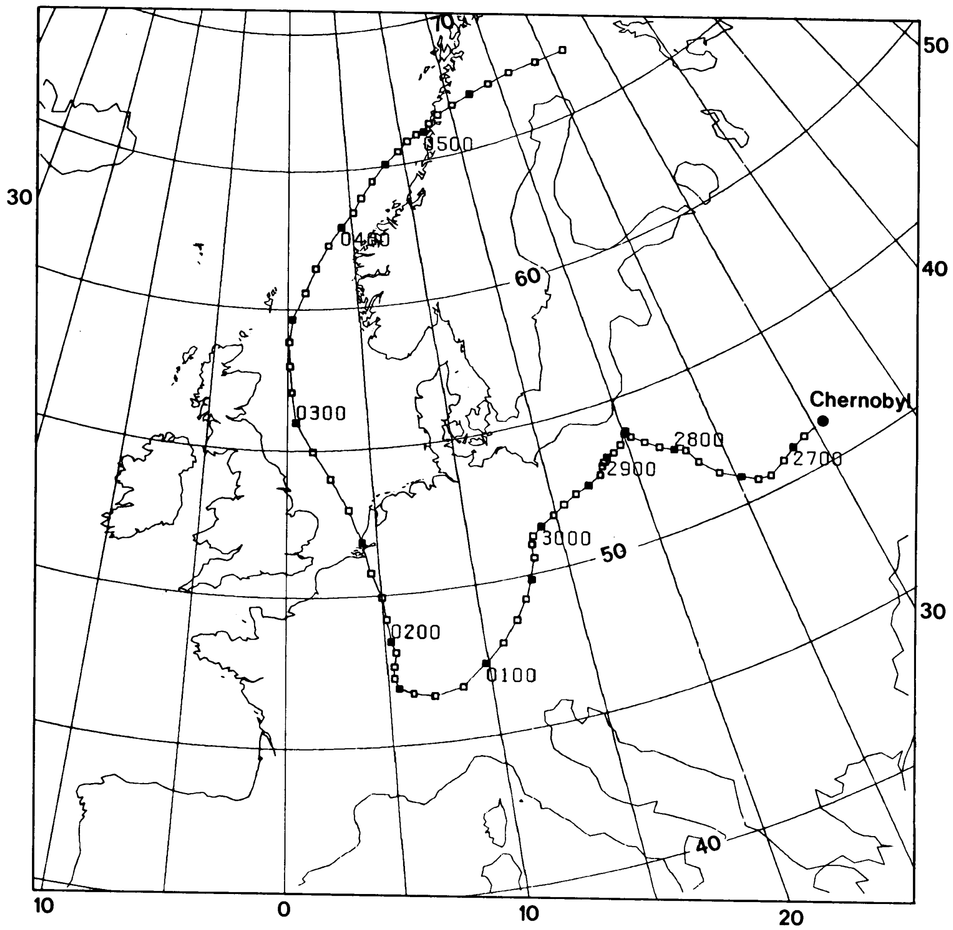

Fig. 10 Trajectory of air mass released at Chernobyl, at 18 GMT on 26 April 1986. Numbers indicate arrival times in the format DDHH, DD = day of month (April/May 1986), HH = hour (GMT).

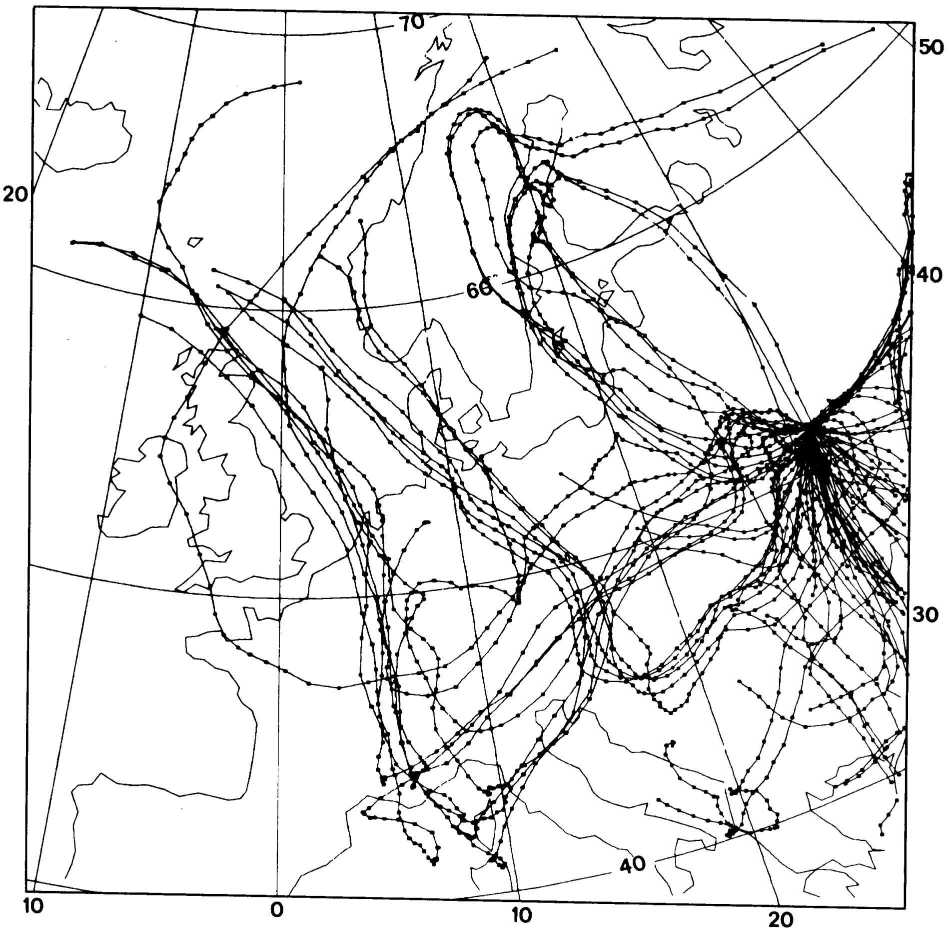

Fig. 11 Collection of all trajectories of air masses released at Chernobyl at 3 hours intervals, between CO GMT on 26 April and 03 GMT on 6 May 1986. Release level 1600 m. Symbols mark 3 hours intervals.

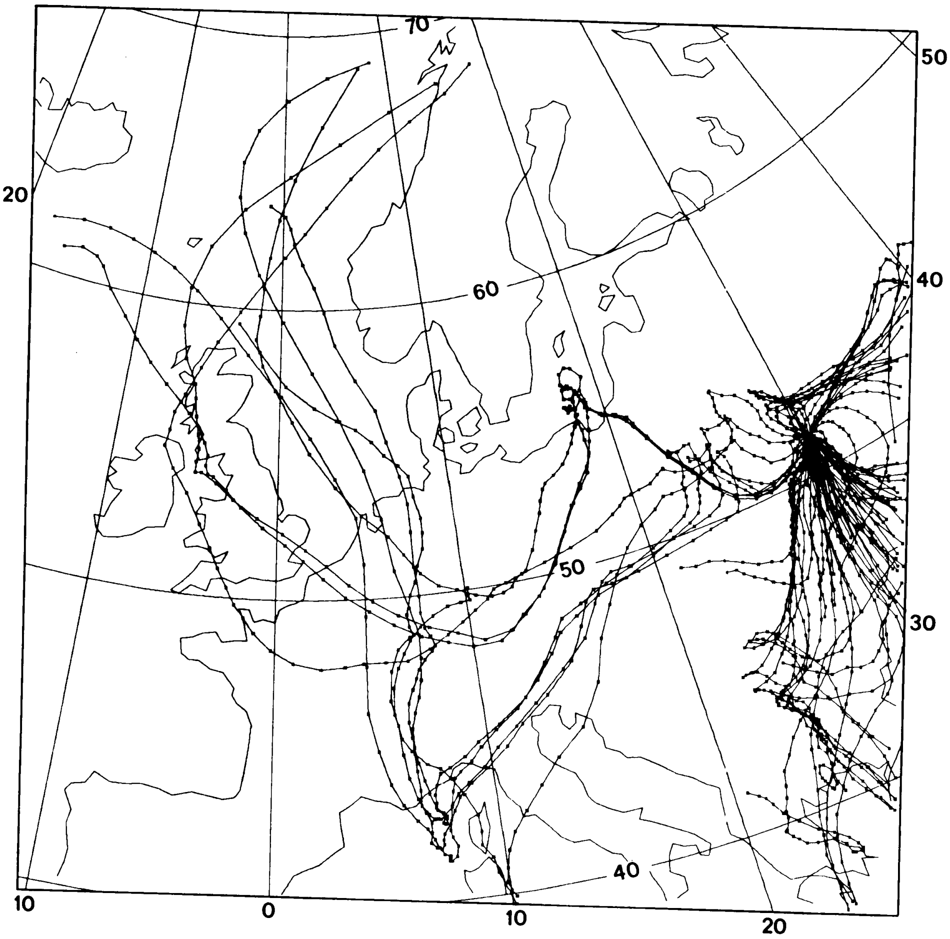

Fig. 12 As Fig. 11, release level is 600 m.

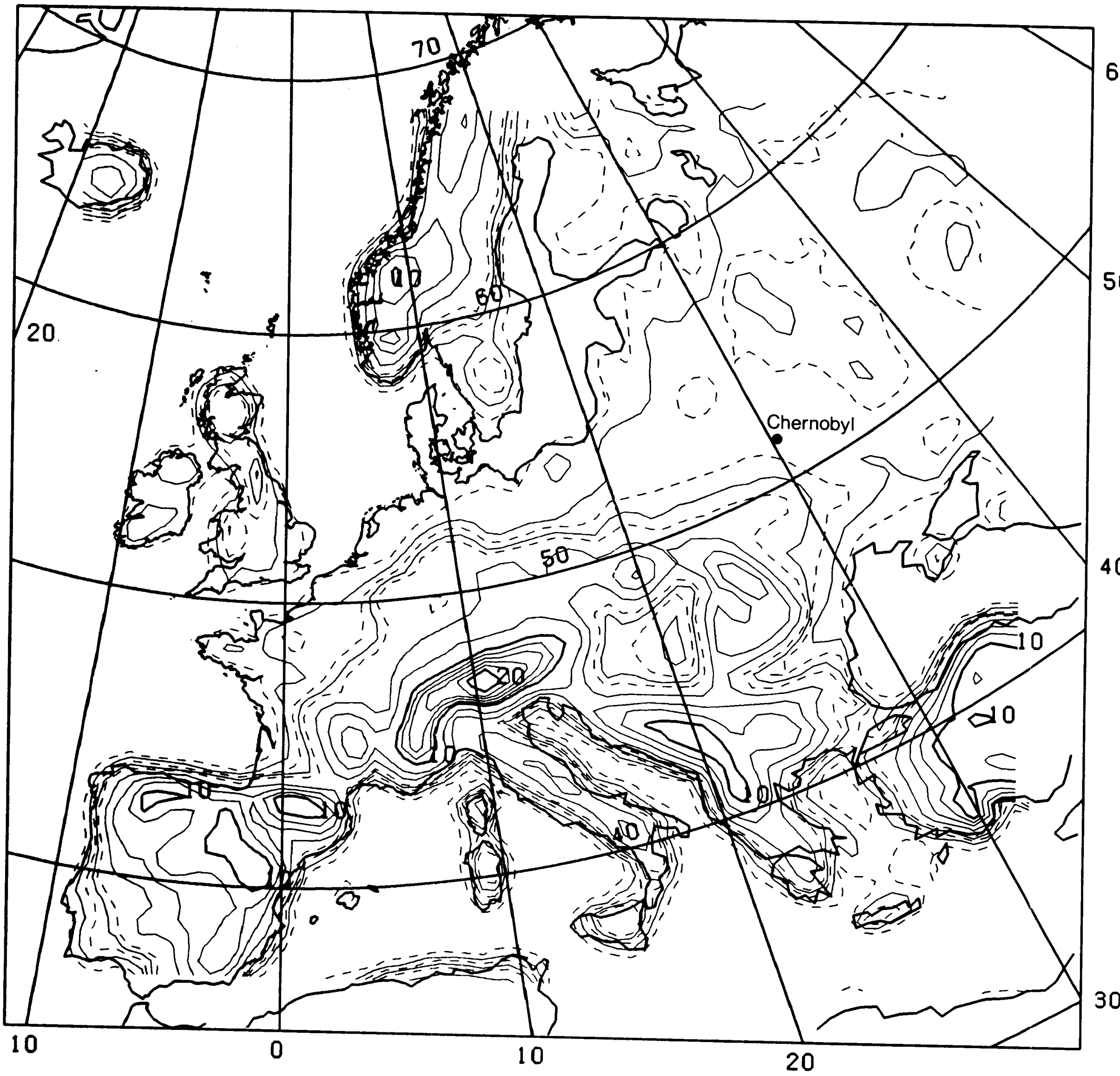

Fig. 13 Mean orography at full model resolution (61 km), contour interval is 200 m, with also a contour at 100 m, and (dotted) at 50, 150 and 250 m.