KfK 3566e
April 1985

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Kernforschungszentrum Karlsruhe GmbH
ISSN 0303-4003

Vergleich der Ausbreitungsmodelle UFOMOD und MESOS

Zusammenfassung

In der Deutschen Risikostudie für Kernkraftwerke wird zur Berechnung der Ausbreitung von Radionukliden in der Atmosphäre ein relativ einfaches Modell angewendet, das im Nahbereich um den Emittenten ($\approx$ 20 km) verifiziert wurde. Da die Berechnungen im Unfallfolgenmodell UFOMOD bis über 500 km Entfernung durchgeführt werden, erscheint es angebracht einen Vergleich mit einem Modell durchzuführen, das zur Berechnung des weiträumigen Transportes von Radionukliden bis zu 1000 km und mehr entwickelt wurde. Ein derartiges Modell ist das Trajektorien-Puffmodell MESOS. Die Verifikation des Modells erfolgte über den Vergleich von Messungen und Modellrechnungen in Europa zur Zeit des Windscale Unfalls.

UFOMOD und MESOS werden anhand berechneter Luftkonzentrationen von Edelgasen, abgelagerter bzw. noch in der Atmosphäre vorhandener Nuklidmengen sowie berechneter Bodenkontaminationen durch Caesium 137 und Jod-131 an wohldefinierten Orten in unterschiedlichem Abstand und Ausbreitungsrichtung vom Ort der Freisetzung (MESOS) und an wohldefinierten Orten in unterschiedlichem Abstand gemittelt über alle Ausbreitungsrichtungen (UFOMOD) miteinander verglichen (Freisetzungshöhe 10 m).

Im Mittelwert unterscheiden sich mittlere Luftkonzentrationen und Bodenkontaminationen um Faktoren kleiner als fünf. Vergleicht man die am Boden abgelagerten Nuklidmengen getrennt nur für die trockene bzw. nasse Deposition integral über alle Ausbreitungsrichtungen (MESOS und UFOMOD), so zeigen sich größere Modellunterschiede vor allem in der Berechnung der nassen Deposition. Die Abweichungen erreichen in diesem Falle den Faktor zwei. Wird dagegen die Wahrscheinlichkeit dafür, daß ein Ort beaufschlagt wird, zusätzlich berücksichtigt, so unterscheiden sich beide Modelle an ausgewählten Orten um Faktoren bis 10.

Es wird gezeigt, wie mit Hilfe von zusätzlichen Informationen durch MESOS-Rechnungen die UFOMOD-Berechnungen verbessert und an die Realität angeglichen werden können.

Comparison of the UFOMOD and MESOS Atmospheric Dispersion Models

Abstract

The German Risk Study on Nuclear Power Plants uses a relatively simple model to calculate the atmospheric dispersion of radionuclides. The model was verified in the local range (approx. 20 km). As the calculations in the UFOMOD accident consequence model are carried out for distances up to 500 km, it is advisable to compare the UFOMOD model with a long-range transport model, e.g. the MESOS model. The MESOS model calculates the long-range transport of radionuclides up to several 1000 km. It was verified on the basis of data collected after the Windscale accident over several hundreds of kilometers.

Both models are compared in terms of calculated time-integrated air concentrations of radionuclides, dry and wet deposition as well as in percentages of radionuclides still in the atmosphere, or deposited on the ground. MESOS and UFOMOD carry out calculations for well-defined locations in different distances and in different directions from the point of release. However, each direction of transport is as probable as the other in the UFOMOD model (emission height 10 m).

On the average, the mean air concentration and ground-level contamination differ by a factor less than five. Comparing the amounts of nuclides deposited by dry deposition only without considering wet deposition and vice versa, with no concern of the transport directions (MESOS and UFOMOD), differences appear between the models, especially in the calculation of wet deposition. Differences in wet deposition amount up to a factor of two. However, if the probability of being exposed is taken into account for a special location, the models differ by factors up to 10 at selected locations.

It is shown how UFOMOD calculations can be improved and adapted to reality by additional information from MESOS calculations.

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1. Motivation for Model Comparison

In the German Risk Study on Nuclear Power Plants (DRS) the overall risk is evaluated which originates in accidents occurring in nuclear power plants. Descriptions of the model applied and results of calculations performed with the UFOMOD model have been published in /FA81/ and /HA80/. The risk is described by frequency distributions for somatic early health effects (fatalities due to acute radiation syndrome), somatic late health effects(fatalities due to leukemia or cancer), and for the genetic impact (genetically significant dose).

To be able to calculate the damage to health the dispersion and deposition of radioactive pollutants after an accidental release into the atmosphere has to be considered up to a distance of 540 km. The applied atmospheric dispersion model was verified within a distance of approximately 20 km (a detailed description of the model will be given in Section 2.1). This simple model has been used until now also for calculations covering greater distances because beyond about 20 km only late health effects occur. On account of the linear dose-risk relation this number is approximately independent of whether a given amount of activity is distributed over a narrow or broad sector if the other boundary conditions remain unchanged. Strictly speaking, this applies at and beyond 80 km distance because for distances greater than 80 km it was assumed in the DRS calculations of damage that the population is uniformly distributed in the azimuthal direction.

This assumption of a linear dose-risk relation, in the absence of a threshold value up to the dose zero, might be revised in Phase B of the DRS. According to recent findings /KE82 and OB82/ non-linear functions and partly also the introduction of threshold values are proposed. Therefore, it will be necessary to calculate more accurately the activity concentration in the air and the ground contamination at larger distances from the emitter too.

A suitable model is the MESOS trajectory model with its meteorological data from synoptic stations and ships over Western Europe (a detailed description of this model will be given in Section 2.2). The model was verified on the basis of data collected after the Windscale accident over several hundreds of kilometers /AP80/. It is investigated in this report how well the calculations based on the dispersion model as used in the DRS agree with the MESOS model.

2. Description of the Dispersion Models

2.1 UFOMOD

The model used in Phase A of the German Risk Study on Nuclear Power Plants (DRS) to describe atmospheric dispersion and deposition is a submodel of the UFOMOD accident consequence model with its four submodels (see also Fig. 1):

- atmospheric dispersion and deposition model,
- dosimetry model
- protective action model,
- health effects model.

A detailed description of UFOMOD is given in /FA81/. A detailed description, above all of the submodel of atmospheric dispersion and deposition of radioactive pollutants, is contained in /VO82/.

The basic features of this submodel will be outlined below:
The radioactive material is released into the atmosphere from the external containment or the exhaust air stack. The plume travels away from the source of emission at wind velocity. The air concentration decreases continuously in the course of this movement, mainly due to turbulence in the atmosphere, to dry deposition, and to washout by precipitation, if any.

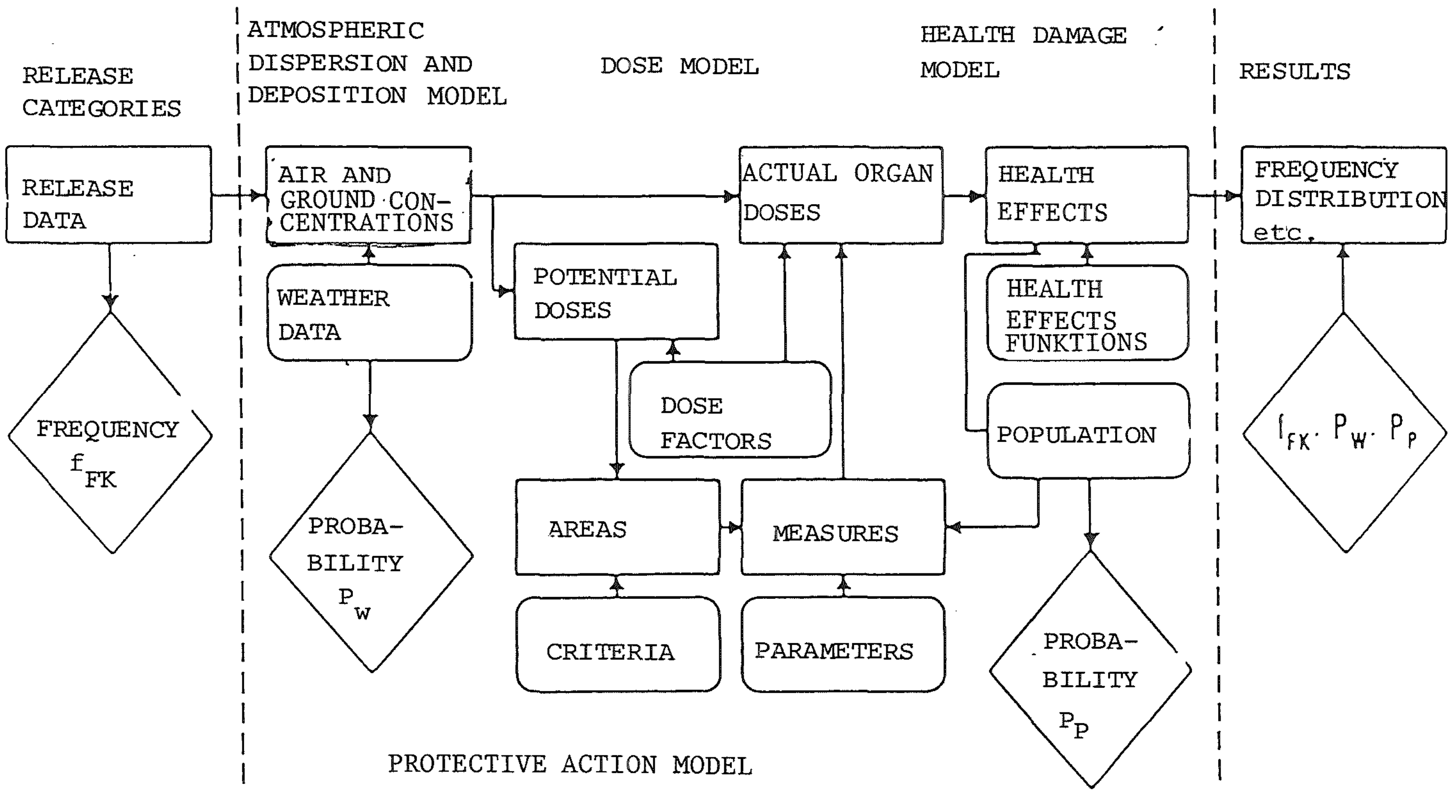

Fig. 1: Schematic representation of the accident consequence model.

Among the great variety of models describing atmospheric diffusion, a special solution of the diffusion equation has been found to be useful in practical work, which is the Gaussian distribution. It is used to describe the concentration distribution in a section normal to the transport direction. This so-called "Gaussian diffusion model" is used in UFOMOD. It has been confirmed by experiments up to distances of $\approx$20 km. This is typical of the range in which early fatalities are possible, provided enough activity is released, and also in which reliable knowledge of the dose distribution is required because of the nonlinear dose-effect relation.

The same model is also used at distances $>$ 20 km. This is justified as, on the one hand, there are some experimental results that do not contradict its applicability even over larger distances, and, on the other hand, precise knowledge of the dose distribution is not the decisive factor with respect to the result important in this area, which is the number of late fatalities.

The standard deviation of the Gaussian bellshaped curve is given by the horizontal and vertical diffusion parameters, $\sigma_y(x)$ and $\sigma_z(x)$, respectively. The diffusion parameters used were determined by diffusion experiments conducted at the Karlsruhe Nuclear Research Center. These parameters are representative of terrain with rough surfaces (forest, settlements) /TH76a and TH76b/. For smooth terrain (North German lowlands), these parameters are modified correspondingly /NE77/.

As in the protective action submodel the number of the population is known for given areas (circular segments), the average doses of such areas must be calculated. Therefore, the Gaussian distribution of the activity concentration in the azimuthal direction is replaced by a step function. The number of steps is seven (see Fig. 2). In Fig. 2 the population fields (numbered 1 through 7) in a given range of distances have been entered schematically below the steps.

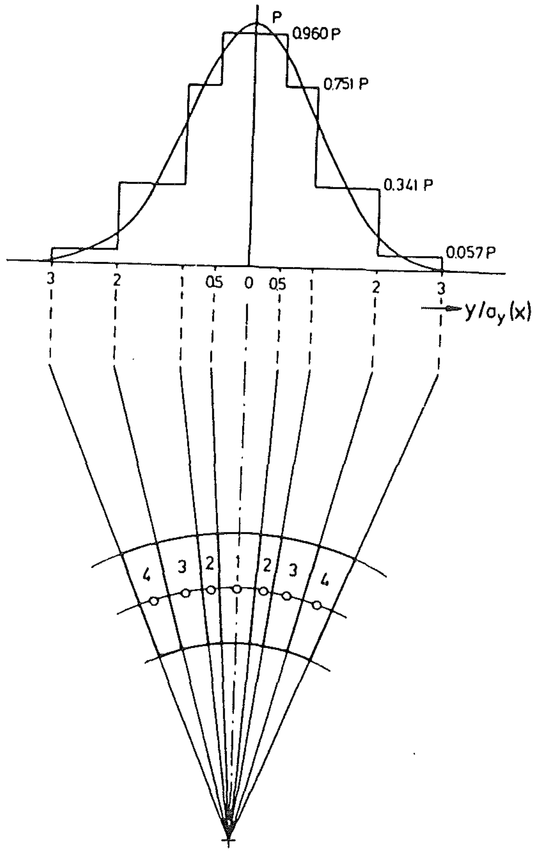

Fig. 2: Approximation of the Gaussian distribution by a step curve.

The turbulent vertical atmospheric exchange is mostly limited by a mixing layer height. For this reason, the $\sigma_z(x)$ parameter is kept constant as soon as a maximum value has been reached. Reductions in concentration will then only be achieved by horizontal diffusion.

The rise of the radioactive plume as a consequence of the thermal energy released is calculated in accordance with the formulas of Briggs /BR69, BR70/ as expanded by Nester /NE78/, to take into account the building wake effect.

Both in the calculation of concentration and of the plume height a mean wind velocity $\bar{u}$ must be introduced. To calculate $\bar{u}$ the wind profile is averaged over the effective height of emission. The wind profile exponent varies from 0.07 to 0.44 as a function of the stability class. During travelling the shape of the activity plume its width and height as well as its plume centerline and transport velocity undergo variations. The shape adopted by the activity plume during the first hours of a weather sequence has been represented in a side view (Fig. 3) and in a top view (Fig. 4).

The original radioactivity content of the plume is reduced as a consequence of radioactive decay and of dry and wet deposition. To determine the fraction of dry deposition the so-called "source depletion" model is used. The amounts of pollutants in the plumes are diminished by the respective amounts deposited. The constant of proportionality between the rate of deposition and the instantaneous ground level atmospheric concentration constitutes the deposition velocity.

In addition to dry deposition pollutant particles or radionuclides are increasingly deposited on the ground in case of precipitation. The amount of radioactivity washed out by precipitation and deposited on the surface element dF is proportional to the activity plume. An exponential decrease of activity concentration is supposed for precipitation.

The time constant is generally termed the washout coefficient. This washout coefficient depends on the intensity of precipitation determined from the weather data measured every hour at the point of the source. This model feature constitutes a very coarse simplification of real conditions.

The meteorological data used to calculate the radioactivity concentrations of the air and the contamination of the soil, namely wind speed, diffusion category, and information about precipitation, are adapted at hourly intervals to the measured real weather patterns. The meteorological parameters measured on the site are assumed to have the

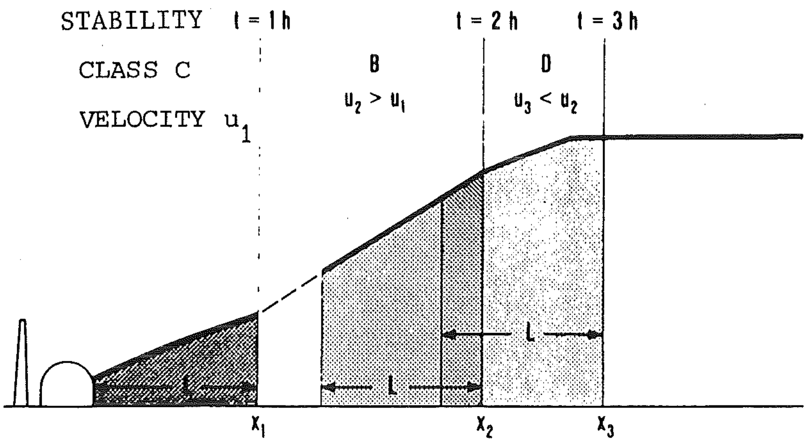

Fig. 3: Side view of the activity plume.

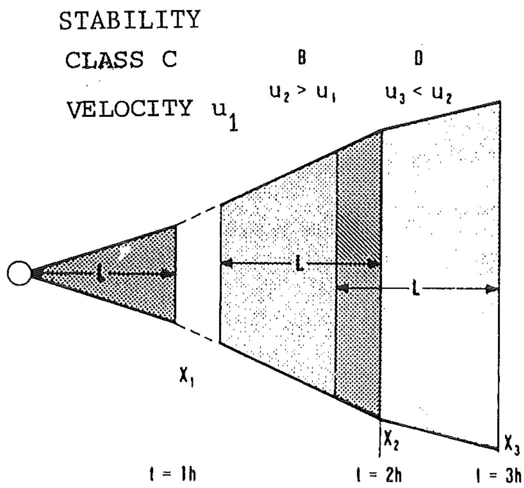

Fig. 4: Top view of the activity plume.

same values over all distances at the same time. This is done for 115 weather sequences whose starting times are equidistantly shifted (Δt= 3-days plus 5-h difference) over the time span of one year.

For the present model comparison Δt was given the value of seven hours; see also Section 3.1.

Each weather sequence results in a radioactivity concentration and ground contamination field. The direction of plume travel is assumed to be of equal probability in any direction, i.e., all wind directions have equal probabilities. It is implemented in the model in such a way that the direction of transport points into the centers of each of thirty-six 10-deg sectors with the same probability.

UFOMOD includes an option allowing to approximate the trajectories of the activity plume. This option does not constitute a trajectory model in the proper sense but it prevents only the activity concentration fields to be overestimated in case of a release of several hours duration.

As a matter of fact, application of this option implies that in case of release of several hours duration the activity concentration fields of the individual plumes are not completely superimposed but the differences in wind directions of consecutive plumes are rather taken into account in the process of superposition. This option is not effective in a one hour release because in that case no superposition takes place.

Another improvement of the model not used in Phase A of the Risk Study concerns fixing in advance of a real wind direction distribution at the point of source. The equal probability distribution of wind directions can be replaced by the actual distribution at the respective site. The distribution of directions of geostrophic wind could be chosen if the frequencies of occurrence of the calculated concentrations were to be determined realistically at several 100 km distance from the source. It will be shown in Section 4.4 how this requirement can be fulfilled.

2.2 MESOS

One of the difficulties in calculating the long-range pollutant transport and dispersion lies in the fact that with increasing distance from the source the meteorological conditions at the site of the source lose in importance. Therefore, the MESOS trajectory model was developed at the Imperial College, London; it calculates trajectories of discrete puffs released every 3 hours from a selected source and allows for depletion by natural decay, dry and wet deposition according to the local conditions up to 1000 km and beyond. Continuous emissions are simulated as series of puffs while short-term emissions may be represented by single puffs only. The model uses empirical and simple analytical equations and a meteorological data base giving synoptic data*) and the surface pressure measured at 3 hourly intervals at the synoptic stations and ships throughout most of a year from April 1973 to February 1974 between 44^{0} and 62^{0} N and 10^{0}W and 20^{0}E /WR79/. The radioactive decay and the formation, decay and deposition of daughter nuclides and their respective daughters are taken into account in the model version upgraded at the Karlsruhe Nuclear Research Center. The MESOS model consists of two parts, a purely Lagrangian part in which trajectories and the vertical dispersion of successive puffs are calculated in discrete time steps according to local conditions and an Eulerian part in which the generated so-called puff histories are used to calculate the exposures in a specified grid of points.

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*) Temperature, relative humidity, "present weather situation" (coded), amount of clouds, level of cloud base.

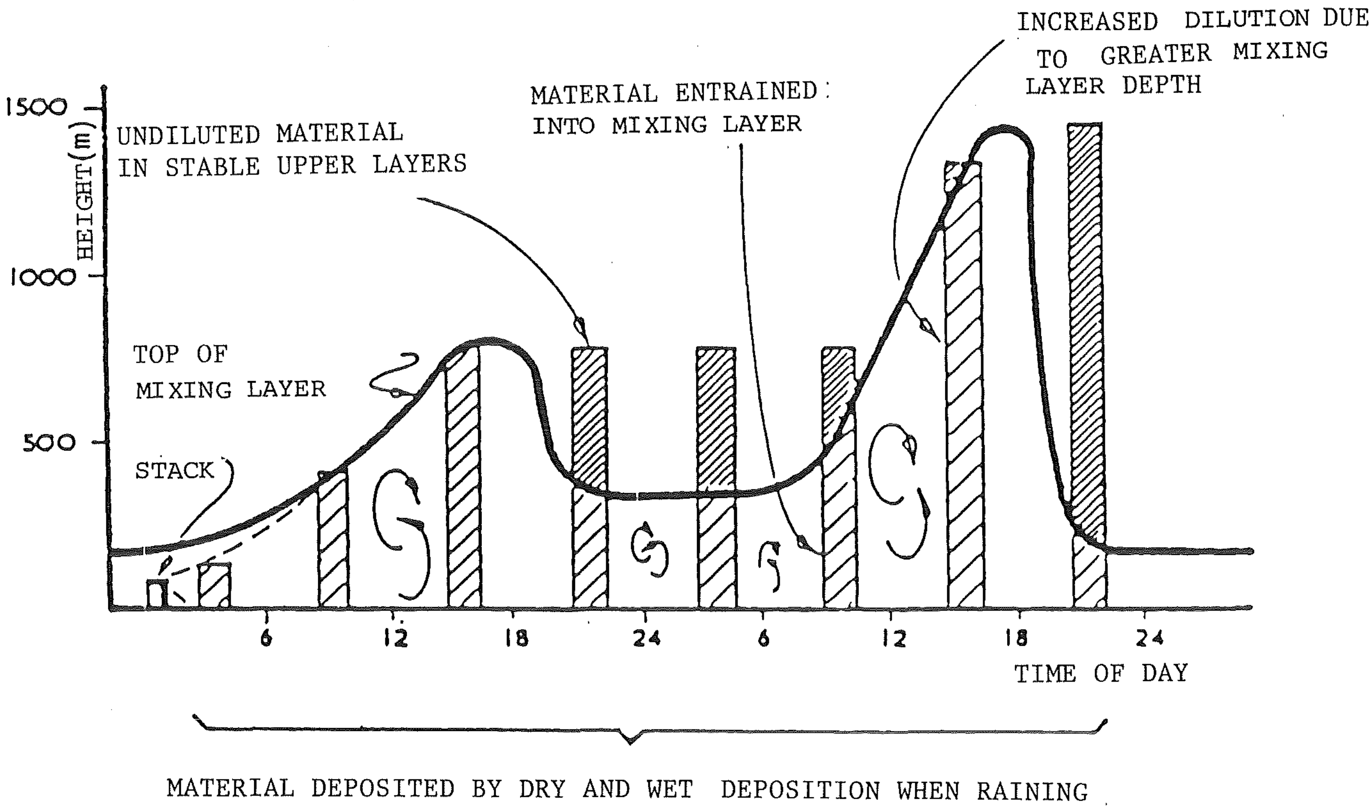

Fig. 5 : Vertical dispersion of the plume.

a) Puff Development Module (PDM)

Each expanding puff is advected with a mean wind based on the geostrophic wind but backed and reduced in strength according to the likely wind profile over the vertical extent of the puff. The vertical dispersion of a puff is calculated using $_z$parameters for the appropriated stability class at the time until the puff attains the bottom or the top of the mixing layer. Then total mixing is assumed and the puffs form vertical columns. The subsequent vertical evolution of the puff is determined by the variation in height of the top of the mixing layer. Pollutants may be transported into series of stably stratified layers with negligible turbulence after the mixing layer has shrunk. These pollutants cannot be depleted by dry deposition on the ground until the top of the mixing layer rises again. Then the pollutant previously isolated will be entrained into the mixing layer. At great distances this fact may cause high concentrations near ground(see Fig.5). The vertical and lateral puff expansions as well as dry and wet deposition of pollutants and radioactive decay give rise to a dilution and depletion of pollutants present in a puff. A constant concentration profile is used within the mixing layer. By introduction of an effective deposition velocity, that means a deposition velocity with a stability dependent resistance term added, the pollutant flow towards the ground is simulated in the model ("source depletion"). Depending on the pollutant, wet deposition constitutes a significant depletion mechanism. The precipitation rate varies according to the intensity and duration of precipitation.

b) Puff Exposure Module (PEM)

In the MESOS model it is assumed that a continuous release behaves like an assembly of intermediate puffs fanning out between the tracked puffs started every 3 hours and with intermediate dispersion and depletion found by interpolation. The trajectories and widths of succeeding puffs P_1 and P_2 started at the times t_0 and $t_0 + \Delta t$ (Δt = 3 hours) span the release and define plume boundaries. The area under this plume is exposed completely by the passing pollutant plume. The synoptic lateral expansion of the plume is thus described explicitly by the divergence of the successive trajectories. Turbulent dispersion of the individual puffs in the lateral direction leads to a broadening of the pollutant plume beyond the delineating trajectories (see Fig. 6).

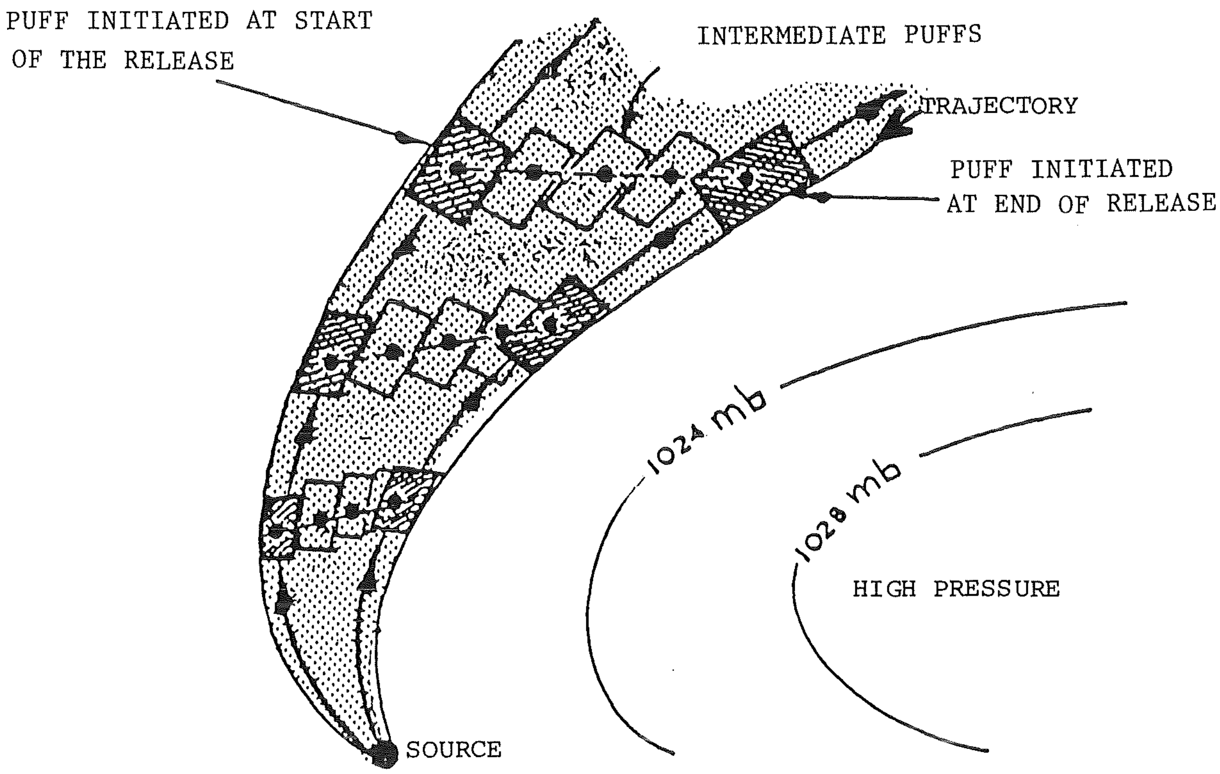

Fig. 6 : Lateral Dispersion

This representation of a plume allows exposures to be derived at a given point R from the calculated historic development of the boundary puffs P_1 and P_2. Suppose the puff P has a quantity $Q(t_0,t)$ remaining airborne in the mixing layer as its centre passes over R. The exposure time at R will depend on the longitudinal dispersion L and the transport velocity u at the time of overhead passage of the puff. Since the puff will take a time (L/u) to pass completely over the point, the time-integrated atmospheric pollutant concentration from one single puff will be

$$\frac{Q(t_o,t)}{B \cdot h \cdot L} \cdot \frac{L}{u} = \frac{Q(t_o,t)}{B \cdot h \cdot u}$$

where B designates the puff width and h its vertical extension. All intermediate puffs passing by the point R at a distance smaller than half the puff width contribute to the environmental impact at that point. Consequently, the sum of time-integrated concentrations and depositions from a release over the period (Δt) is calculated as follows:

Time-integrated air concentration: $\Psi_R \cdot \left[\frac{Q(t_o,t)}{B \cdot h \cdot u}\right]_R$

$[Ci\ m^{-3}\ s]$

Dry deposition: $\Psi_R \cdot \left[\frac{Q(t_o,t)\ Ve}{B \cdot h \cdot u}\right]_R$

$[Ci\ m^{-2}]$

v_e = effective rate of deposition

Wet deposition: $\Psi_R \cdot \left[\frac{Q(t_o,\ t)}{B \cdot u}\right]_R$

$[Ci\ m^{-2}]$

λ = washout coefficient

where Ψ_R designates the fraction of release contributing to the environmental impact at point R.

The environmental impact due to continuous emissions is simulated as environmental impacts from consecutive releases. A source strength varying with time can likewise be taken into account by suitable weighting of the environmental impact resulting from three hours release.

For the comparison of models performed here 2024 puffs were released at three hourly intervals and tracked over Europe.

3. Comparison of Models

3.1 Concept of Model Comparison

With the UFOMOD and MESOS dispersion models calculations were made of environmental impacts up to 900 km distance from a 10 m high source at the Jülich site giving rise to an accidental release of 1 Ci each of iodine-131 (I-131), cesium-137 (Cs-137) and noble gas. Jülich was selected as the source site because the meteorological conditions prevailing in the more distant neighbourhood of the source do not undergo major modifications by local orographic particularities. In a first step the amount of nuclides remaining airborne and of nuclides deposited by dry and wet deposition, resp. were balanced at various distances from the source without regard of the direction of the trajectories. Statistical characteristics of distributions of air concentrations and ground contaminations by dry and wet deposition, resp. were compared at selected places.

In a further step the spatial distribution of the expectation value of ground contamination in the more distant neighbourhood of the source (1200 km at the maximum) was examined. This product of ground contamination and probability of occurrence is an important intermediate result in risk analyses. The risk of an impairment of the health actually results largely from the nuclides deposited on the ground. However, it is not only the degree of ground contamination which is decisive for the size of the risk, but also the probability that a contamination takes place at all.

The spatial distribution of this expectation value differs basically for the two models because the MESOS model calculates trajectories from the pressure field over Europe, varying in direction according to the local conditions. It does not start from an equal distribution of frequencies of 36 dispersion directions and from straight trajectories at the point of emission. This means that the MESOS model calculates different probabilities of occurrence for different places with respect to ground level contamination whilst the UFOMOD model assumes the same probability of occurrence at each place around the source.

The nuclides mentioned before were selected because of their different deposition characteristics (cf. Table 1). Regarding elemental iodine-131 it is assumed at present that the rates of deposition are of comparable orders of magnitude for dry and wet depositions whilst in case of cesium-137 nuclides are deposited mainly by wet deposition. Noble gas remains airborne.

Table 1: Input data for MESOS-UFOMOD comparison calculations

Site: Jülich 50.92^{o} N / 6.42^{o} E
Stack height: 10 m

Nuclide	I-131 (elemental)	Cs-137	Noble Gas
Rate of deposition in ms^{-1}	0.01	0.001	-
Washout coefficient $\lambda = a\ I^{b}$ in s^{-1}	$0.8 \times 10^{-4} I^{0.6}$	$0\ 8 \times 10^{-4} I^{0.8}$	-
Half-life in d	8.1	1.1×10^{4}	

In both dispersion models the same approach is made for calculating dry deposition (cf. Section 2). The comparison of wet deposition regarding cesium activities reveals above all the differences in calculation of wet deposition. Whereas in the UFOMOD model only three grades of rainfall intensity have been taken into account so far ($<$ 1mm/hour, 1-3mm/hour, $>$ 3mm/hour) the MESOS model offers grades 0-9 to calculate the precipitation parameter I at the location of the plume from the values reported by the local synoptic stations about the current weather situation. These grades vary according to the intensity and duration of precipitation (see Table 2).

Table 2: Precipitation parameters for the most frequent types of precipitation

Type of Precipitation		Rate of Precipitation in mm/h	Parameter of Precipitation I
Rain	light	0.0 - 0.5	1
	moderate	0.5 - 4.0	5
	heavy	> 4.0	9
Shower	light	0.0 - 2.0	1
	moderate	2.0 - 10.0	2
	heavy	10.0 - 50.0	6
Drizzle	light	0.2	1
	moderate	0.5	2
	heavy	0,75	2

In the MESOS model the precipitation parameter is generally reduced through multiplication by the factor 0.5 and, in case this factor takes the value 1, multiplication by the factor 0.25. A remarkable improvement of wet deposition modeling for the UFOMOD model is proposed in /V083/.

In Section 4 the different model calculations are compared with each other. In addition, the attempt is made to improve the dispersion model in UFOMOD with additional information resulting from calculations with the more complex MESOS model. On the one hand, it was attempted to adapt by specific parameter variations the UFOMOD results to those of MESOS regarding the mean values of air concentration and contamination, respectively. Besides, the frequency distribution of the directions of transport at different distances from the emitter, calculated with MESOS, was used to calculate the distribution of the expectation value of ground contamination and probability of exposure in more distant surroundings of the emitter.

3.2 Specific Difficulties in Intercomparison of UFOMOD and MESOS Models

3.2.1 Meteorological Data Valid for Different Periods of Time

For statistical investigations of the dispersion and deposition of radionuclides with the MESOS model the synoptic data and surface pressure data are available for the period 1973/74 collected between 44^{o} and 62^{o} northern latitude, 10^{o} western and 20^{o} eastern longitude at three hourly intervals. The grids are resolved into one degree of latitude and two degrees of longitude for synoptic data and into 0.5 degree of latitude and 1 degree of longitude for pressure data. The MESOS model starts each puff with an activity of 1 Ci, at three hourly intervals and follows its fate at 10 minutes intervals within the first three hours and subsequently once per hour with 107 time steps at the maximum. By contrast, the UFOMOD dispersion model requires meteorological data from the site of the source at one hour intervals. They were not available before 1977 for the Jülich site. The data problem could neither be solved satisfactorily for other sites similarly suited for comparison.

3.2.2 Different Durations of Releases and their Importance for the Mean Plume Width

It is assumed in UFOMOD that the 1 Ci activity is uniformly released within one hour and broadening of the plume is calculated via the process of turbulent diffusion during this hour. By contrast, in the MESOS model the process of release takes place continuously over three hours. The variations of the mean synoptic conditions during this time interval generally give rise to a mean horizontal broadening of the plume. Moreover, turbulent diffusion, being a second order process, contributes to plume broadening using a constant rate. UFOMOD contains this mean horizontal plume broadening in an indirect way only via the dispersion parameters determined in the experiment. Therefore, it can be expected that, on an average, the MESOS plume has a larger horizontal extension over great distances.

3.2.3 Calculation of Statistical Characteristics at Selected Places on the Basis of Different Data Ensembles

The statistical characteristics at selected distances from the emitter were calculated with UFOMOD from 1251 single releases in a year, each of the 36 dispersion directions being assigned equal probability in this model. By contrast, 2024 puffs were started with the MESOS model; but the trajectories may change their directions after each time increment, if applicable. Therefore, statistical characteristics were calculated with the MESOS model at selected points in the north, east, south and west of the source at distances of 200, 400, 900, 1200 km in the north and east, 200, 400, 600, 700 km in the south, and 200, 400, 900 and 1100 km in the west. The statistical characteristics were calculated from an ensemble of 328 values at the maximum and 64 values at the minimum at the individual points which means that a released plume passed over one point 328 times at the maximum.

The number of single observations for statistical analysis could be increased at a later time by expansion of the meteorological data base. Nevertheless, certain weather situations are precluded for meteorological reasons from occurring at given points in the area of environmental impact which, while neglecting the direction of dispersion, are incorporated in the calculation of the statistical characteristics; in other words, the statistical characteristics are determined in principle from different data ensembles in MESOS and UFOMOD, even if the data bases were the same.

Minimum and maximum values of environmental impact at a given place, calculated with the MESOS model, may differ much more than in the calculations using UFOMOD where the minimum value is always geared at a given ratio to the maximum value below the plume axis and the latter essentially depends on the age of the plume. By contrast, all those MESOS puffs make contributions to the environmental impact at a given place which pass by the respective place at a distance less than half the puff width. The puff width is calculated from the transport time. Depending on the atmospheric conditions during the transport the mean plume width may undergo very strong variations and adopt very high values. The ratio of puff to plume width determines decisively the contribution to the environmental impact. Therefore, extremely small contributions can be expected. Compared to UFOMOD, the variation with time of the top of the mixing layer plays an important role in the MESOS calculations of air concentration and ground contamination, respectively. Pollutant can be isolated from the mixing layer and entrained to the layer at any time step, later on.

4. Results

4.1 Concentration of Noble Gases in the Air

In a first step the calculated air concentrations of noble gases are compared in order to be capable of attributing differences in the results solely to modelling of long-range transport and dispersion.

The mean values of air concentration in the layer nearest to the ground are calculated with UFOMOD from the known 1251 weather sequences corresponding to 1251 releases, multiplied by seven (number of steps of the approximation function). In this way it is taken into account that a field point considered is not bound to lie below the plume axis but might be touched by the plume boundary. This yields 10,757 values of air concentrations. In the process of averaging each individual value is taken into account independent of the direction in which dispersion takes place. By contrast, MESOS selects from the sum of 2024 releases considered only those for averaging which at clearly specified locations give an activity concentration not equal to zero. These differences in data ensembles have been mentioned already in Section 3.2.

At 900 km distance from the emitter at the Jülich site the number of trajectories followed by MESOS has reduced to 1427 trajectories because in the dispersion sectors of 150-200 degrees, i.e. in the southern direction, the 900 km limit lies beyond the area covered by the model. This implies in turn that some selected weather conditions are not included in the calculation.

In Table 3 and Fig.7 the MESOS results obtained at locations in three distances, north, east, south and west of the source. The mean values of air concentrations for the four directions differ by the factor 1.3 to 1.7. The mean values calculated by UFOMOD are on the average higher by the factor 2.0. Reasons are the narrower plume width in the UFOMOD model, a transport velocity lower on the average, and the transport of the whole mass in the atmospheric mixing layer as well as straight line dispersion.

The near ground level air concentration can be reduced with UFOMOD if the calculations are based on higher wind velocity or transport velocity. Whilst in the reference run a velocity is used which should be understood as the mean value applicable to the lowest 100 m of the atmosphere, a higher wind velocity is obtained as the mean value applicable to the lowest 500 m of the atmosphere. This assumption is based on the consideration that in calculating dispersion over a horizontal distance of several hundred km not only a near ground atmospheric layer of 100 m but a much thicker layer must be considered. A new run with UFOMOD using higher transport velocities, gives UFOMOD mean values of air concentrations lower by the factor 0.62.

The maximum values of noble gas air concentration in the layer nearest to the ground are nearly the same in both models up to 400 km distance. With increasing distance from the source the UFOMOD values are clearly higher which means that the differences in the models already indicated get more significant.

However, the minimum values calculated with UFOMOD are distinclty above the MESOS values. This is above all due to the differences in calculating activity for a certain location; see also Section 3.2.3.

4.2 Deposited Activity and Activity still Present in the Atmosphere

To understand in quantitative terms the importance of different model approaches for deposition calculations of ground level contamination were made with both models taking into account either dry or wet deposition.

It is obvious from Table 4 and Fig.8 that the ground level contamination by dry deposition calculated with the MESOS model is lower by an average of up to 20% than the contamination calculated with UFOMOD. As the MESOS model for all distances calculates lower noble gas air concentrations (about 50% for single points) and dry contamination, the calculated result is in line with the considerations above. Moreover, the resistance term introduced in addition in the MESOS model reduces the rate of deposition for extremely stable stratification.

In the MESOS model, depending on the weather situation, pollutants are transported also in stable layers above the mixing layer. These pollutants cannot participate in the process of dry deposition.

To validate this latter hypothesis much higher mixing layer levels were used as a trial in the calculations with UFOMOD which led to lower near ground air concentrations. The values chosen correspond to those in Phase A of the German Risk Study. This procedure is intended to simulate the model character of MESOS outlined in the preceeding paragraph. Up to 200 km distance hardly any reduction is observed; beyond that distance roughly 10 to 20% less activity is deposited on the ground compared with the reference run using lower heights of the mixing layers. If as in Section 4.1, a new run is performed for UFOMOD with higher wind and transport velocities, respectively, dry deposition is further reduced.

Calculations of ground level contamination exclusively via wet deposition of nuclides, using the MESOS and UFOMOD models, show marked differences. These differences result from different calculations of the precipitation parameter I from the meteorological data available (cf. Section 3.1). The MESOS model offers ten stages for this parameter, UFOMOD only three, however with the value of the third stage exceeding the maximum value in the MESOS model. Whereas the UFOMOD model calculates deposition for all distances on the basis of the precipitation situation at the site, MESOS refers to the weather currently prevailing at the location of the plume. This means that starting from the Jülich site it can be expected that a multitude of trajectories move into the low mountain regions where precipitation is more abundant and reach areas with less precipitation at great distances, east of the source (cf. Fig. 15). The calculations show (cf. Table 5 and Fig. 8) that up to 200 km distance from the source twice the amount of pollutants are deposited according to the MESOS model whilst at 900 km distance both models, MESOS and UFOMOD, calculate roughly the same amounts deposited of about 50%.

Realistic calculations on dry deposition and wet deposition take into account both dry and wet deposition. Table 6 and Figure 10 show results for aerosols and iodine. If one compares the results of the MESOS and UFOMOD models, nearly the same differences appear for the aerosol contamination as in the calculations neglecting dry deposition. The differences in iodine contamination are similar to those obtained in the calculations neglecting wet deposition according to the deposition rates dominating for each specific nuclide (cf. Section 3.1).

4.3 Ground Level Contamination by Aerosols and Iodine

Study of the Special Volume 8 of the German Risk Study /FA81/ to find out the classification of late health effects by exposure pathways yields an average portion of more than 90% of both exposure pathways, namely external radiation from the ground and ingestion, for all release categories. As ingestion and radiation from the ground are directly proportional to the amounts of activity deposited, these two variables take a high valency in the model comparison performed here.

In Figs.11 and 12 and in Tables 7 and 8, similar to the foregoing Section 4.1, MESOS results are indicated for locations situated in four directions at different distances from the source and an UFOMOD average value is given for all directions. Regarding iodine-131 UFOMOD shows the tendency of a higher level of contamination in the near source area and a quicker reduction of ground level contamination with increasing distance. For aerosol, however, the average values in the near source area and the reduction of mean values with increasing distance as calculated with UFOMOD, roughly agree with the MESOS values as far as the western direction is concerned.

A further interpretation of the tendency of mean values of contamination to decrease with increasing distance from the source should be avoided because a mean value obtained for all directions of dispersion is compared with single values obtained for various directions. For instance, the aerosol contamination in the northern direction shows even a slight increase in mean contamination between 400 km and 900 km. This type of effect is encountered above all in areas characterized by abundant precipitation provided that aerosols contaminate the soil mainly through wet deposition. Another possibility offered by the MESOS model of calculating relatively high contaminations even at great distances from the source applies to the long-range transport above the mixing layer. This isolated material enters the mixing layer after breakup of inversion and hence gets deposited on the ground by dry deposition.

If one compares the maxima and the minima calculated with the MESOS and UFOMOD models, one finds above all at great distances from the emitter higher maxima resulting from MESOS, which is according to expectations (see Section 3.2.3) and, independent of the distance, lower minima resulting from MESOS (see Section 3.2.3). The MESOS based calculations demonstrate that due to variations in meteorological conditons it is not generally valid to state that: "For each location in the wake of a point source contamination decreases with increasing distance from the source."

4.4 Expectation Values of Ground Level Contamination

If one considers the spatial distribution of the expectation value of ground level contamination for aerosols and iodine in the model area between 44^{o} and 62^{o} N and 10^{o} W and 20^{o} E (cf. Figs.13 and 14), the course of the isolines exhibits a highly complex structure. This expectation value is defined as the product of ground contamination and probability of occurence*). Its spatial distribution is calculated with the MESOS model. An expectation value of aerosol contamination greater than 3 x 10^{-13} Ci m^{-2} is found within about 200-500 km around the source. Whereas the expectation value decreases very rapidly in the south-western direction from the source the reduction of the expectation value in eastern and south-eastern directions extend over a range more than three times larger. This is explained by the distribution of precipitation in the area described by the model. Precipitation is a meteorological parameter undergoing extremely high variation in terms of space (cf. Fig. 15). A strong reduction in the annual amounts of precipitation in the south-western direction quickly results in a reduction of aerosol contamination from $3x10^{-12}$ to $3x10^{-13}$ Ci m^{-2} in the south-western direction whereas high amounts of precipitation cause only slow reduction in ground level contamination in the southern regions of the Federal Republic of Germany. An accumulation of the isolines of aerosol and iodine contamination is observed south of the main crest of the Alps where the annual amount of precipitation decreases by nearly 50%. Isolines for values smaller than $1x10^{-13}$ Ci m^{-2} are calculated by the MESOS model for each place south of the Alpine mountain chain, central France and the United Kingdom up to southern Sweden, and beyond the eastern boundary of the map.

Generally, the isolines of the expectation value of iodine contamination adopt a more leveled course with less pronounced differences in the various directions. The reason lies in the higher importance of dry deposition for ground contamination. If one compares the spatial distributions of the expectation value of aerosol and iodine contamination one finds that at greater distances from the source higher values can be found of aerosol contamination compared with iodine contamination although this relation is reversed in nearly all directions of dispersion of isolines greater than or equal to $3x10^{-13}$ Ci m^{-2}.

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*)This is the conditional probability of occurrence, i.e. the activity release takes the probability of occurrence of unity.

Assuming an equal distribution of the directions of dispersion all locations have the same expectation values in all directions at the same distance from the source according to the UFOMOD model.

Calculations based on UFOMOD were performed only for distances of 200 up to 900 km. In the representation chosen here, cf. Fig.16, the isolines form ellipsoids around the source. This figure shows the decisive differences in calculations between the MESOS and UFOMOD models. For different areas the calculated expectation values differ by about a factor of 10. Spatial structures, as described before, cannot be represented in this version with UFOMOD.

As in the preceding sections the attempt was made also in this case to adapt the UFOMOD calculation to reality referring to additional information from MESOS calculations. By including the frequency distribution of the direction of trajectory travel at various distances from the source a spatial distribution of the expectation value was constructed. Figure 18 shows the number of trajectories crossing each 10 degree sector centered on the source at distances of 200, 400, 750, 900 km from the source. In all distances the majority of trajectories move eastward because of the prevailing weather situations. A second maximum is found in the west-south-west direction; it is due to the continental high pressure situations of long durations which determine our weather, especially during winter and summer. An interesting phenomenon is the maximum appearing in the south-south-western direction at 750 km distance from the source. Obviously, quite a number of trajectories in the Alps originally moving south-eastwards are directed southwards.

The modified UFOMOD calculations yield results which fit well the MESOS calculations (cf. Fig.17). Now spatial structures are recorded satisfactorily also with UFOMOD. This means that taking into account the direction of dispersion as an additional parameter at each point in space and time is decisive for calculating the expectation value of contamination.

5. Conclusions

The comparison of the UFOMOD and MESOS dispersion models shows differences up to a factor of 5 in the mean air concentration and ground level contamination, respectively, as well as much greater differences regarding the minimun and maximum values. Despite specific difficulties in comparison of the meteorological data for a common period and different durations of release these differences can be attributed unequivocally to the non-steady-state and inhomogeneity of the MESOS model, to taking into account the direction of dispersion as an additional degree of freedom, and to calculation of the plume width.

Differences in modelling result in differences by factors up to ten in the calculation of the expectation value of ground level contamination. As shown in Section 3.1, such differences even affect the result regarding the risk. Therefore, it is necessary from the meteorologist's point of view to perform risk calculations covering the European area with long-range atmospheric transport models such as the MESOS trajectory model used here.

However, it is possible to greatly improve the calculation of simple models such as the dispersion model contained in the UFOMOD accident sequence model using additional information from calculations based on MESOS, and to adapt them to reality. However, to decide the extent to which a more complex dispersion model is necessary for more realistic calculations of a collective damage or risk in the European area, followup calculations would have to be made to supplement the study under consideration. Such a decision will have to be taken on the basis of assumptions to be made concerning the dose-effect relation without or with threshold to be used, and modelling of population distribution for long-range distances as well as the protective measures and countermeasures to be taken in the future.

6. Literature

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Table 3: Statistical characteristics of noble gas time-integrated air concentracions, in Ci s m^{-3}

Mean Value

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	2.0 E-9 *	1.9 E-9	1.6 E-9	2.1 E-9	3.3 E-9
400	9.9 E-10	9.1 E-10	7.5 E-10	1.1 E-9	1.8 E-9
900	3.7 E-10	4.8 E-10	--	6.3 E-10	9.6 E-10

Maximum

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	2.6 E-8	1.5 E-8	2.3 E-8	2.8 E-8	2.4 E-8
400	9.0 E-9	5.9 E-9	7.2 E-9	8.1 E-9	9.4 E-9
900	2.2 E-9	4.1 E-9	--	4.4 E-9	7.6 E-9

Minimum

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	1.4 E-12	4.8 E-12	1.3 E-11	6.0 E-12	3.3 E-11
400	9.0 E-12	2.5 E-14	3.6 E-12	2.1 E-12	6.4 E-11
900	5.5 E-12	2.0 E-13	--	1.4 E-11	2.5 E-11

* means 2.0×10^{-9}

Table 4: Percentages of deposition of activity and remaining activity, respectively, not taking into account wet deposition.

Iodine

Distance in km	Deposited Activity in %		Remaining Activity of Plume in %	
	MESOS	UFOMOD	MESOS	UFOMOD
200	46	52	54	48
400	56	68	44	32
900	67	87	33	13

Table 5: Percentages of wet deposition of activity and remaining activity, respectively, not taking into account dry deposition.

Iodine

Distance in km	Deposited Activity in %		Remaining Activity of Plume in %	
	MESOS	UFOMOD	MESOS	UFOMOD
200	25	12	75	88
400	38	24	62	76
900	50	48	50	52

Table 6: Percentages of deposited activity and activity still airborne, respectively, taking into account dry and wet depositions.

Aerosol

Distance in km	Deposited Activity in %		Remaining Activity of the Plume in %	
	MESOS	UFOMOD	MESOS	UFOMOD
200	24	19	76	81
400	36	29	64	71
900	48	50	52	50

Iodine

Distance in km	Deposited Activity in %		Remaining Activity of the Plume in %	
	MESOS	UFOMOD	MESOS	UFOMOD
200	56	57	44	43
400	69	74	31	26
900	81	92	19	8

Table 7: Statistical characteristics of ground contamination
Aerosol in Ci m^{-2}

Mean Value

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	2.9 E-12*	6.0 E-12	2.5 E-12	7.6 E-12	8.0 E-12
400	2.3 E-12	4.1 E-12	1.3 E-12	2.6 E-12	4.3 E-12
900	2.5 E-12	1.7 E-12	--	1.2 E-12	1.4 E-12

Maximum

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	5.1 E-11	2.1 E-10	2.0 E-10	7.7 E-10	3.3 E-10
400	3.7 E-11	8.3 E-11	4.2 E-11	5.5 E-11	7.2 E-11
900	5.5 E-11	4.3 E-11	--	2.8 E-11	2.3 E-11

Minimum

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	1.3 E-17	2.0 E-18	6.0 E-18	2.1 E-18	4.6 E-14
400	1.0 E-17	2.6 E-19	3.2 E-18	5.0 E-18	2.4 E-14
900	1.1 E-15	5.5 E-17	--	8.3 E-18	9.1 E-15

* means 2.9×10^{-12}

Table 8: Statistical characteristics of ground contamination.
Iodine in Ci m^{-2}

Mean Value

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	5.9 E-12*	9.2 E-12	3.2 E-12	8.0 E-12	1.4 E-11
400	2.2 E-12	4.3 E-12	1.0 E-12	2.0 E-12	4.8 E-12
900	1.0 E-12	1.1 E-12	--	6.2 E-13	6.1 E-13

Maximum

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	6.5 E-11	2.0 E-10	1.2 E-10	6.1 E-10	1.7 E-10
400	2.5 E-11	7.5 E-11	1.6 E-11	3.8 E-11	5.2 E-11
900	1.0 E-11	1.9 E-11	--	8.9 E-12	7.8 E-12

Minimum

Distance in km	MESOS				UFOMOD
	North	East	South	West	
200	7.5 E-18	1.0 E-18	2.7 E-18	1.0 E-18	1.3 E-14
400	2.0 E-16	1.6 E-19	2.1 E-18	3.2 E-18	5.8 E-15
900	1.3 E-15	6.3 E-17	--	1.2 E-17	2.8 E-16

* means 5.9×10^{-12}

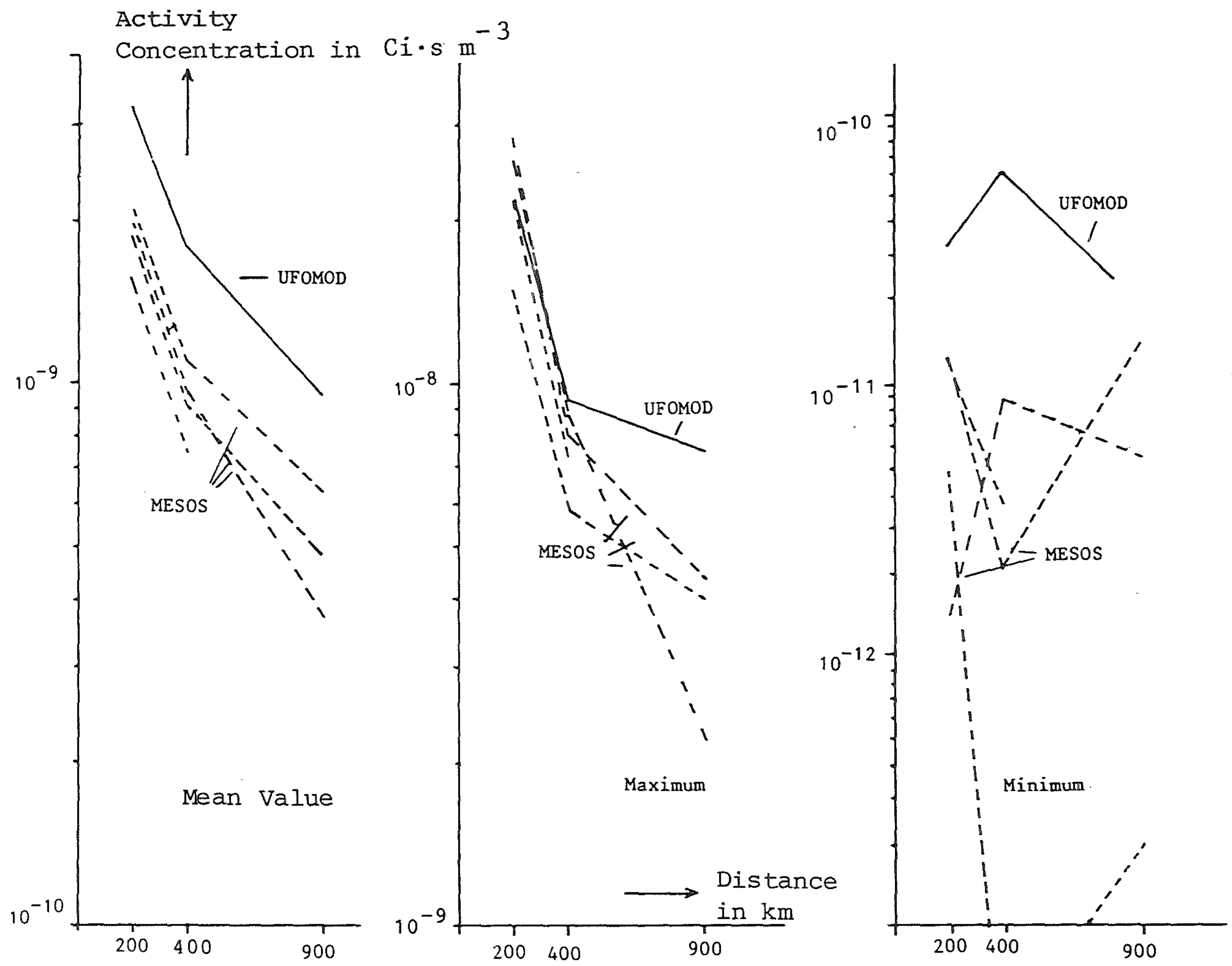


Fig. 7: Statistical characteristics of noble gas concentration in air, in Ci·s m^{-3}.

(The dashed plots apply to MESOS in directions N, E, S, and W.)

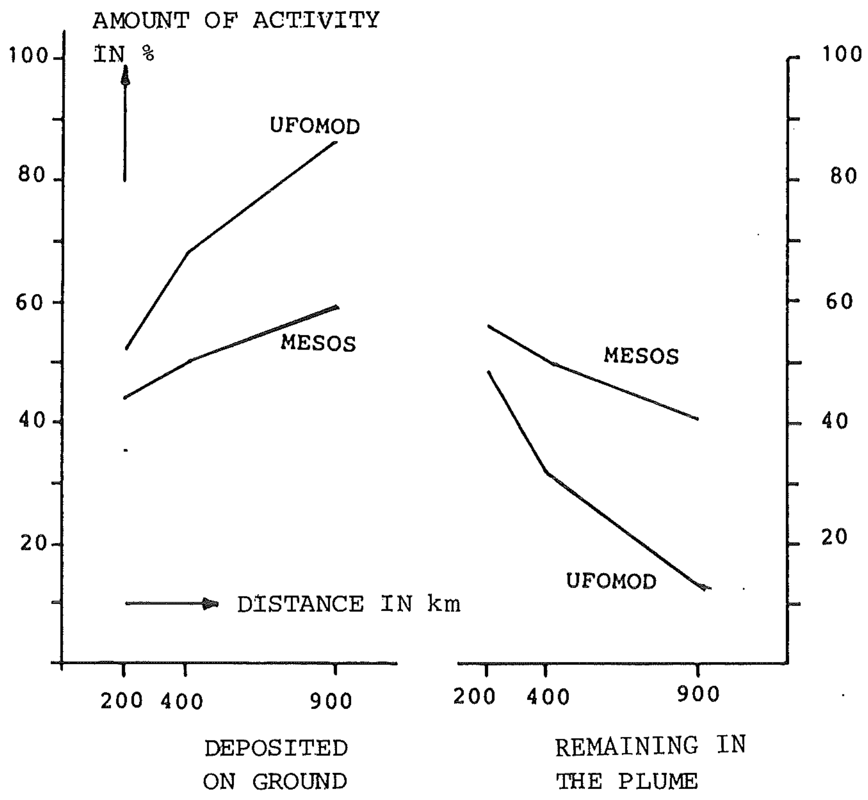


Fig. 8: Percentages of dry deposition of iodine activity and iodine activity remaining, respectively, not taking into wet deposition

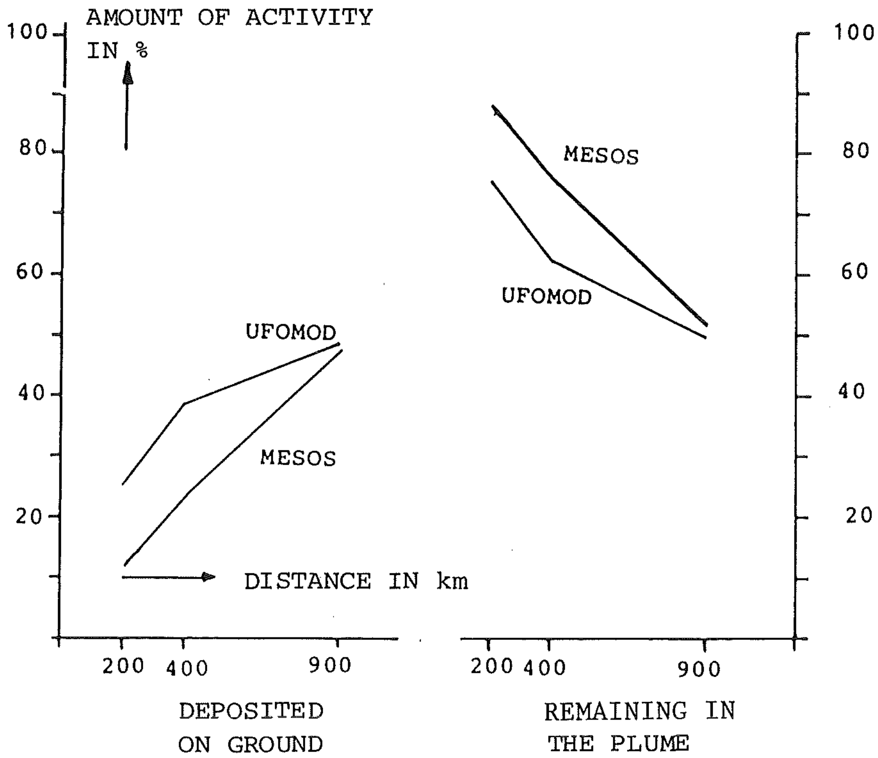


Fig. 9: Percentages of wet deposition of iodine activitv and iodine activity remaining, respectively, not taking into account dry deposition.

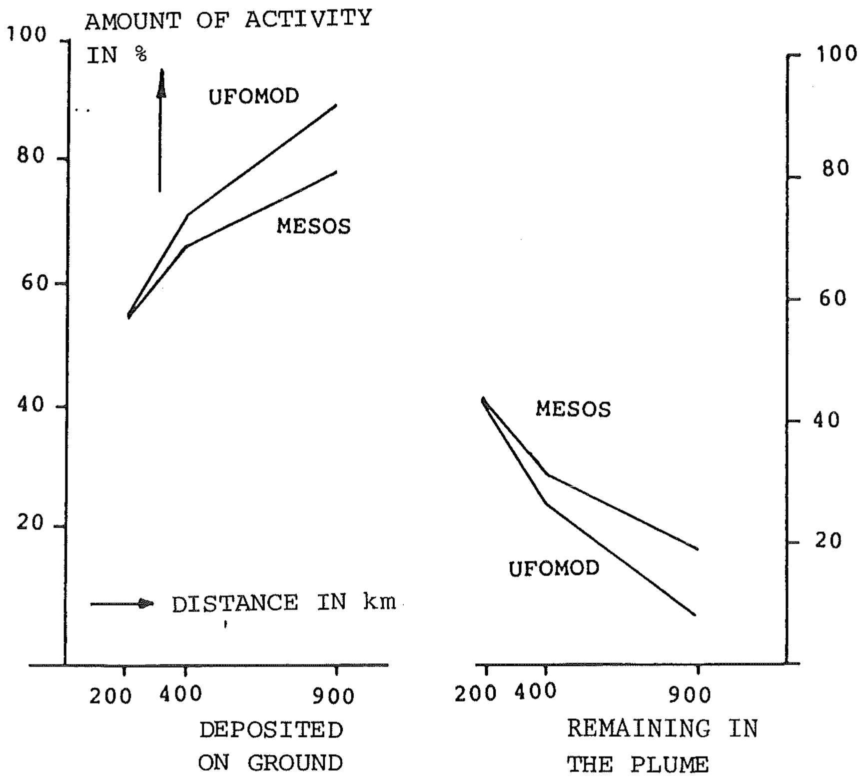


Fig. 10: Percentages of deposited iodine activity and iodine activity remaining, respectively, taking into account dry and wet deposition.

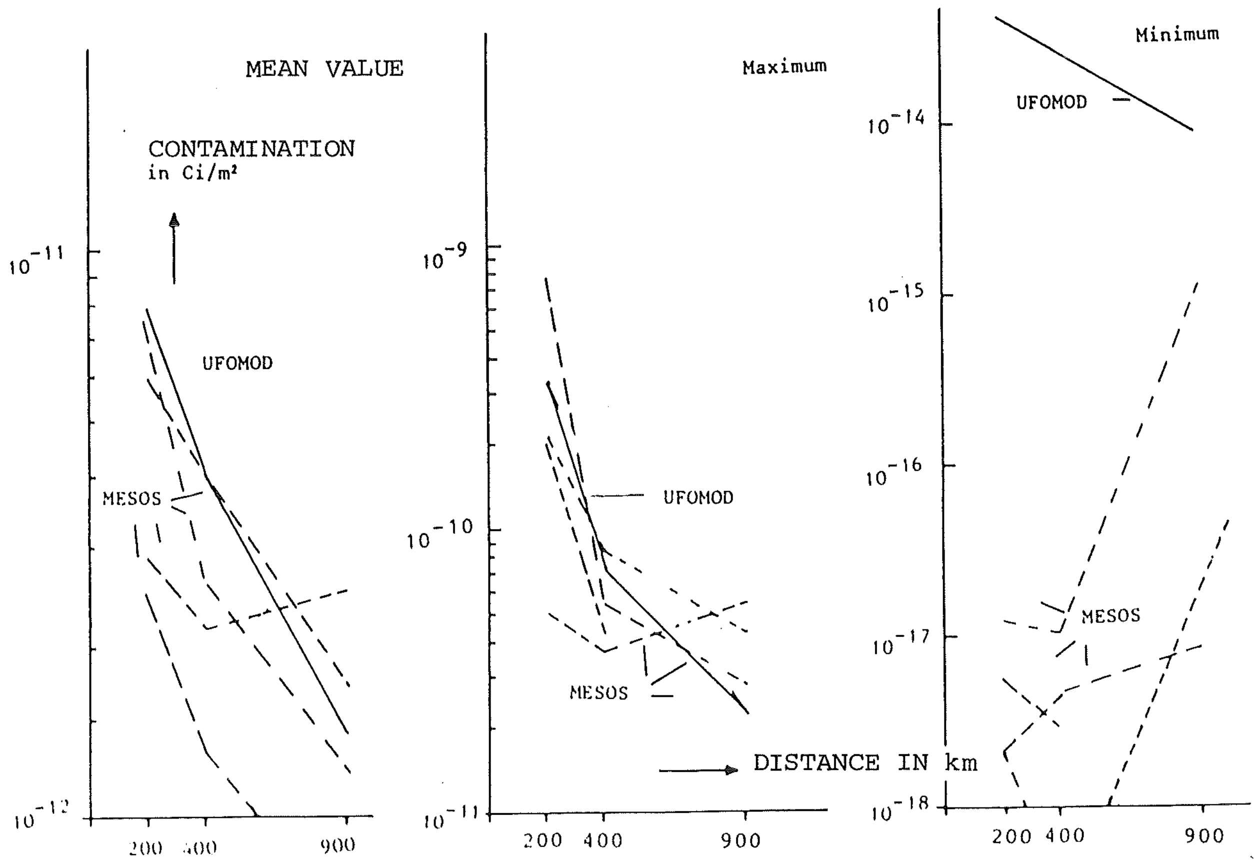


Fig. 11: Statistic characteristics of aerosol contamination in Ci m^{-2}. (The dashed curves apply to MESOS in directions N,E,S, and W.)

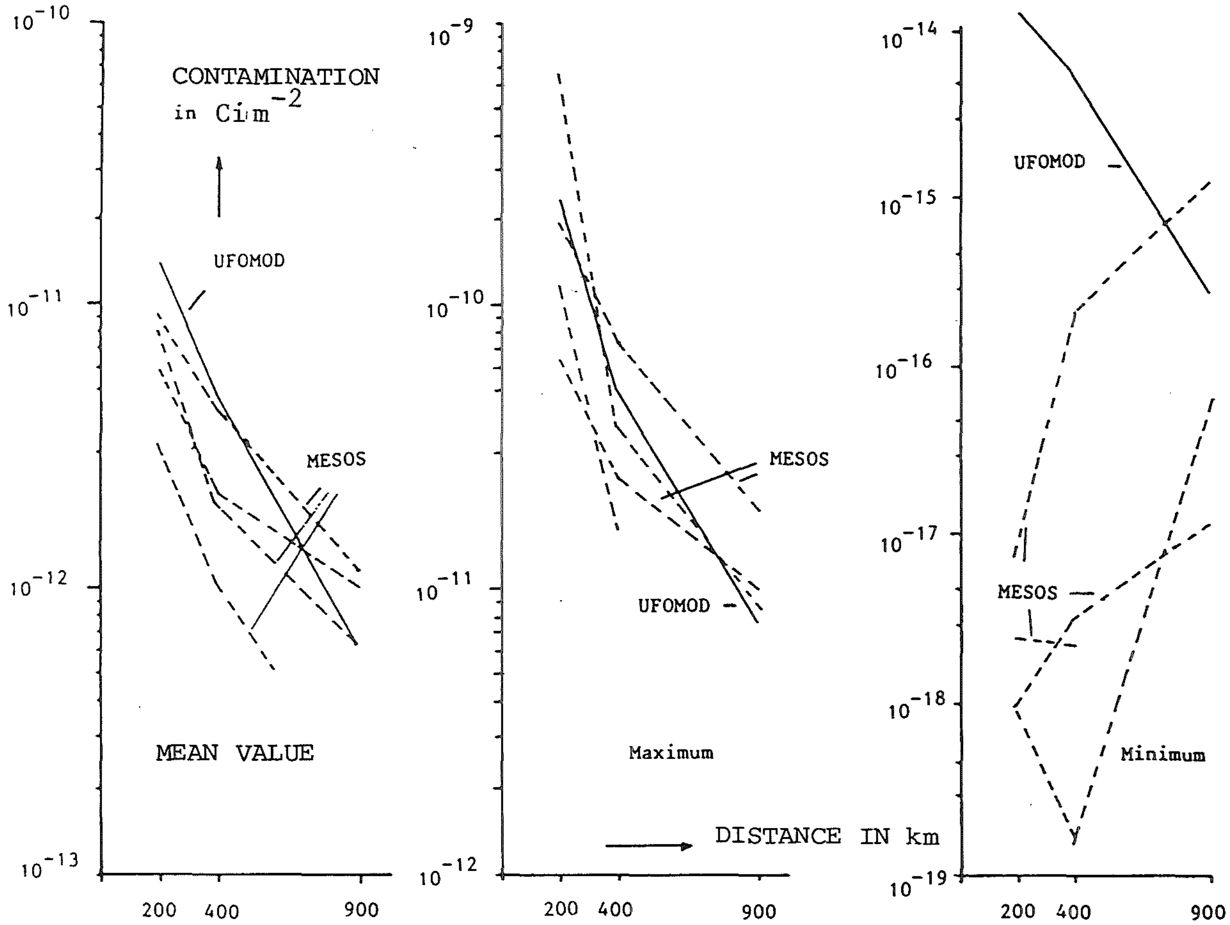


Fig. 12: Statistical characteristics of iodine contamination in Ci m^{-2}.
(The dashed curves apply to MESOS in directions N,E,S, and W.)

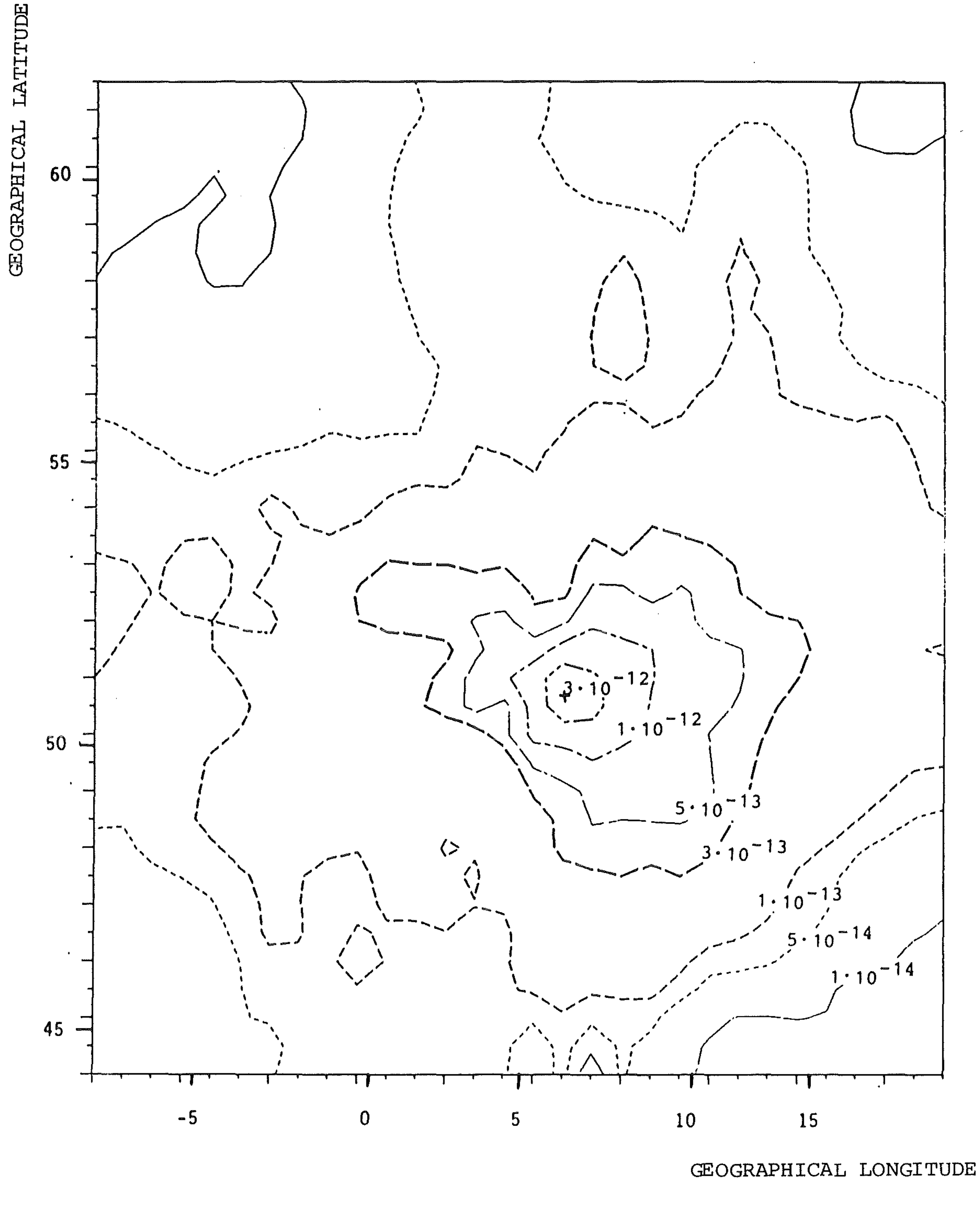


Fig. 13: Distribution of the expectation value of aerosol contamination in Ci m^{-2} (source strength 1 Ci). (+ location of the source)

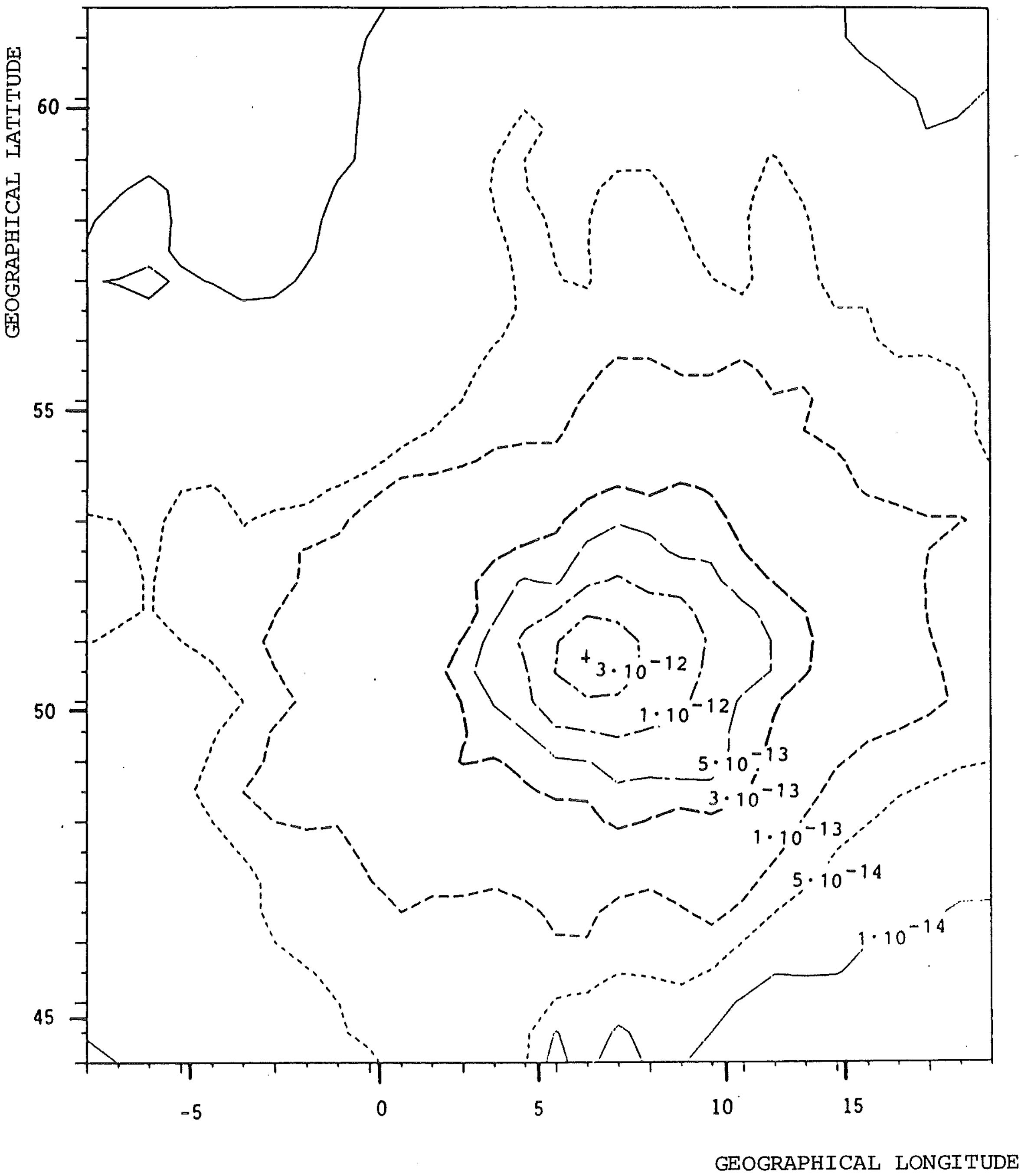
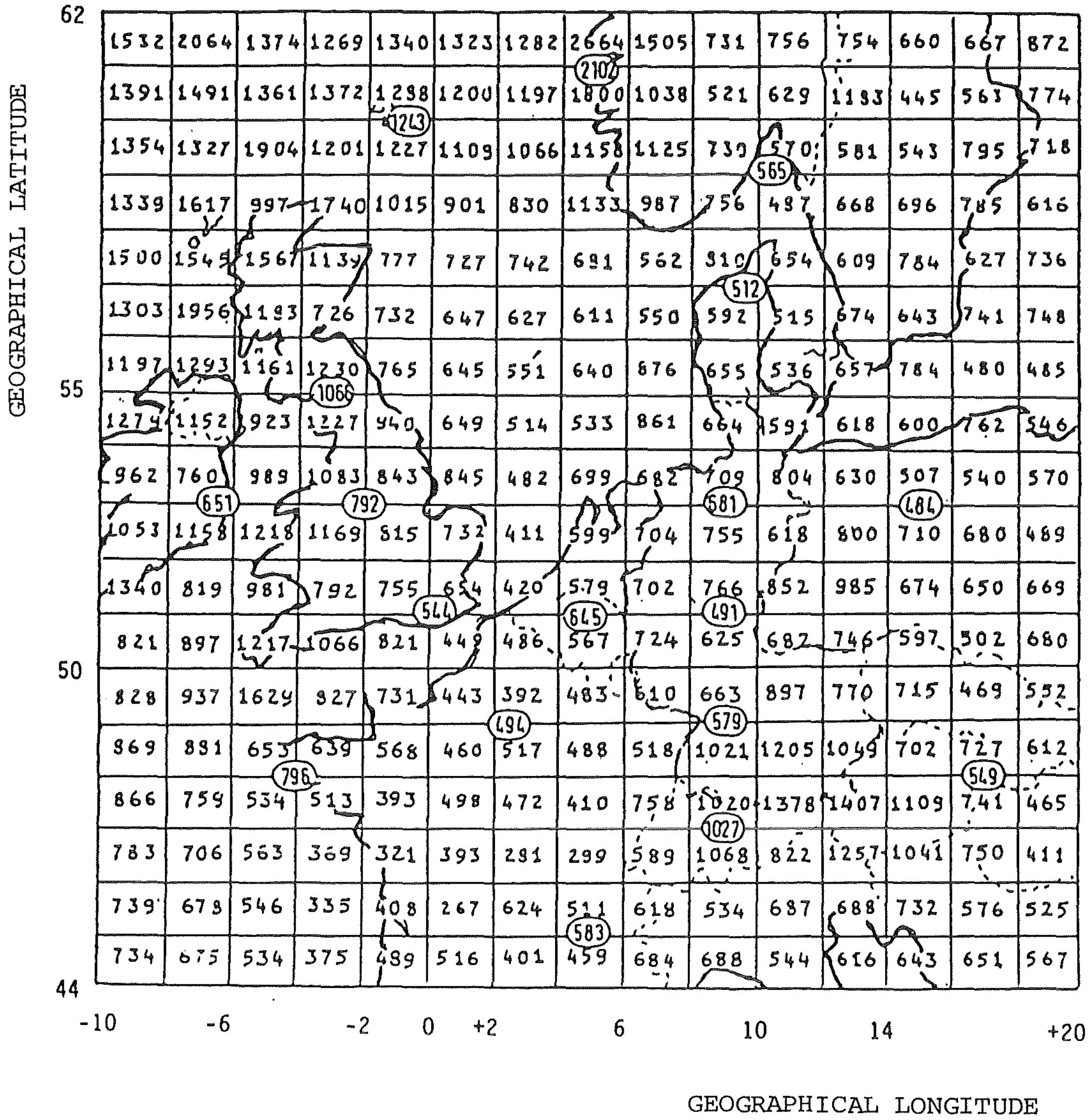


Fig. 14: Distribution of the expectation value of iodine contamination in $Ci \cdot m^{-2}$ (source strength 1 Ci). (+ location of the source)



Annual amount of precipitation at weather stations (WMO (1973-74))

Fig. 15: Comparison of annual amounts of precipitation: MESOS data basis - measurements at weather stations. (This figure is adapted from /WR82/.)

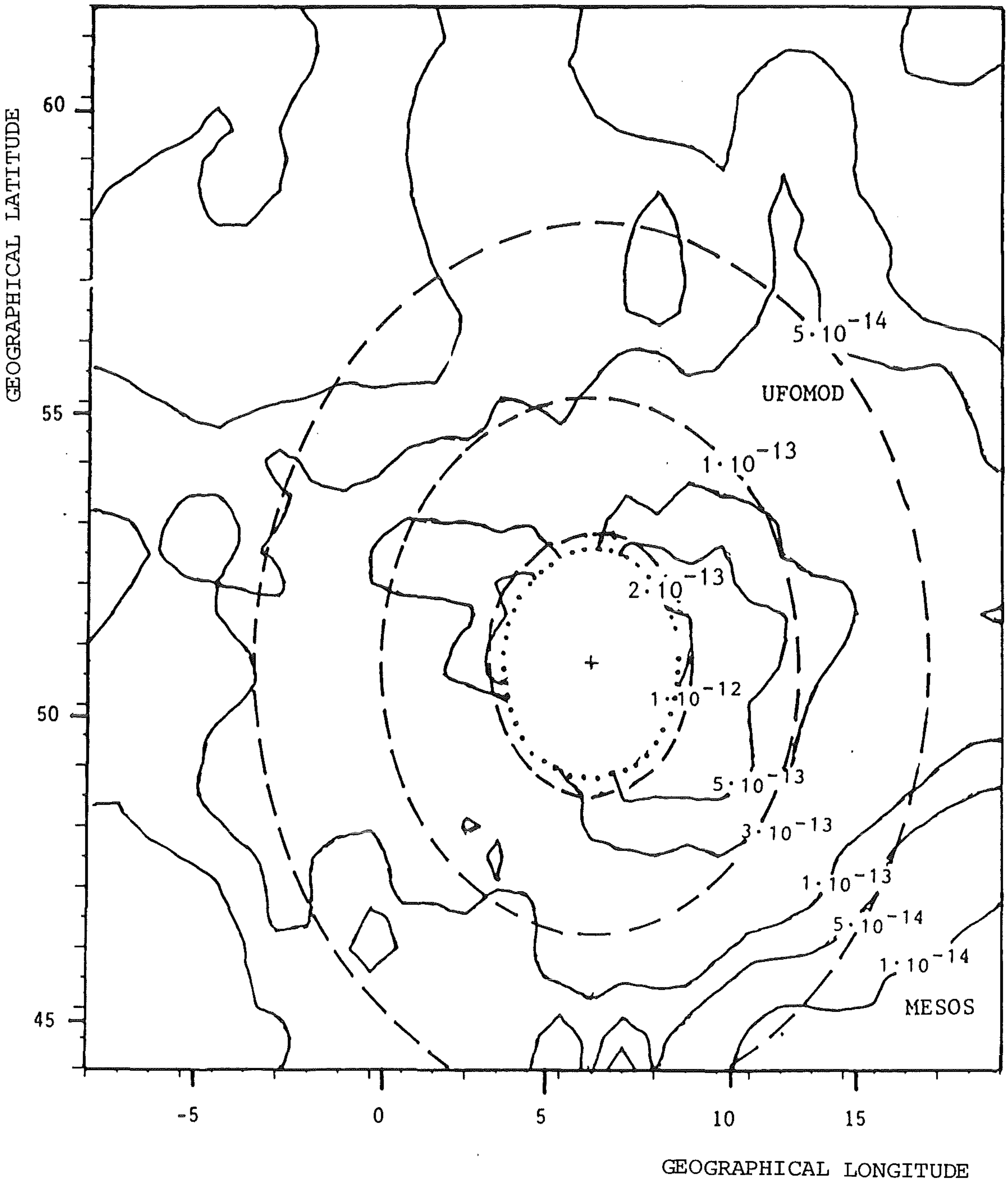


Fig. 16: Comparison of the expectation values of aerosol contamination in Ci m^{-2}, calculated with the MESOS and UFOMOD models. (Within the zone encircled by dots, < 200 km, no comparison was made. Source strength: 1 Ci , location of the source: +)

——————— MESOS

------- UFOMOD

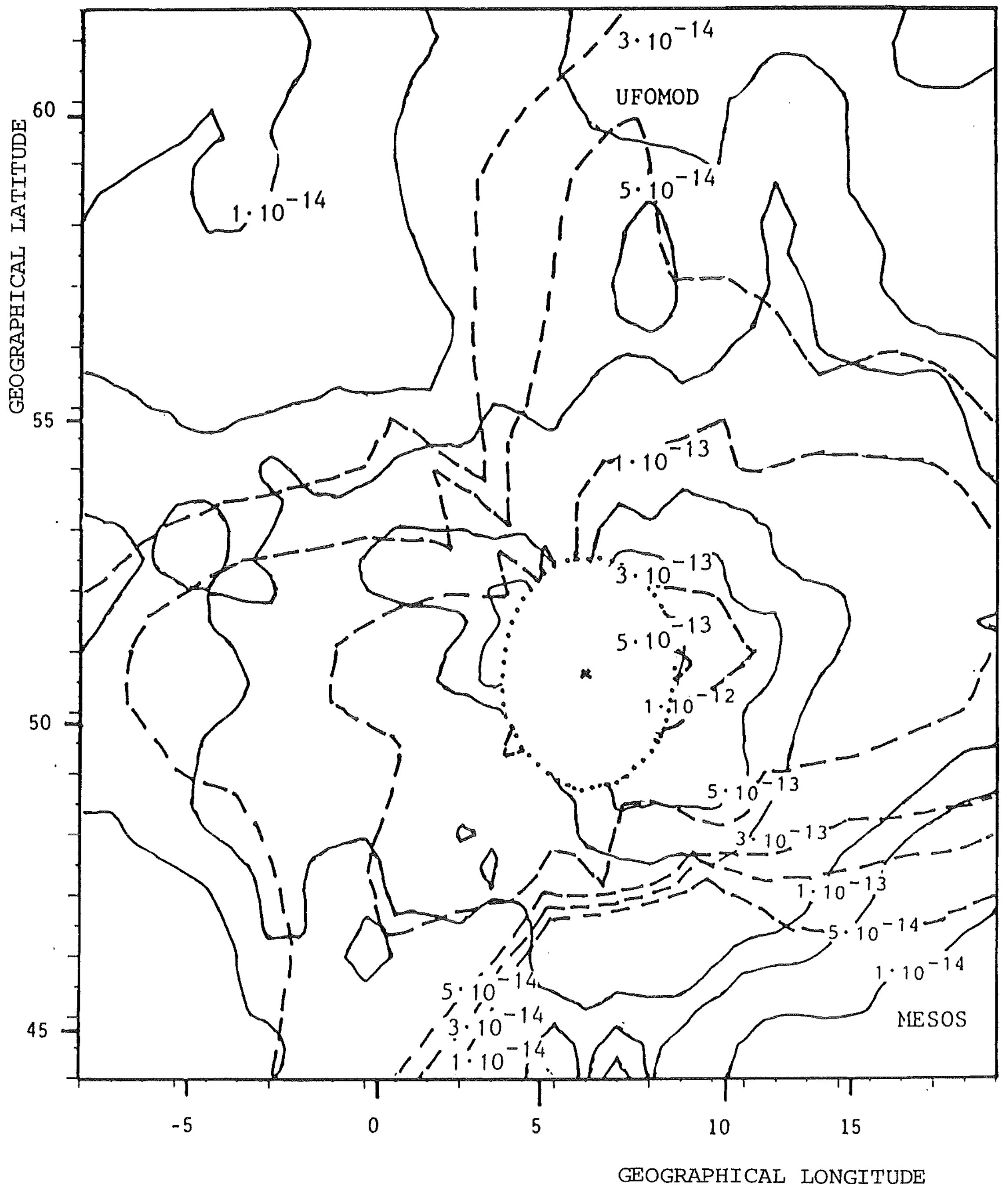


Fig. 17: Comparison of the expectation values of aerosol contamination in Ci m^{-2}, calculated with the models MESOS and a version of UFOMOD modified on the basis of MESOS results.
(Within the zone encircled by dots, < 200 km, no comparison was made. Source strength 1 Ci, location of the source : +)

———— MESOS

-------- UFOMOD

NUMBER OF CROSSINGS

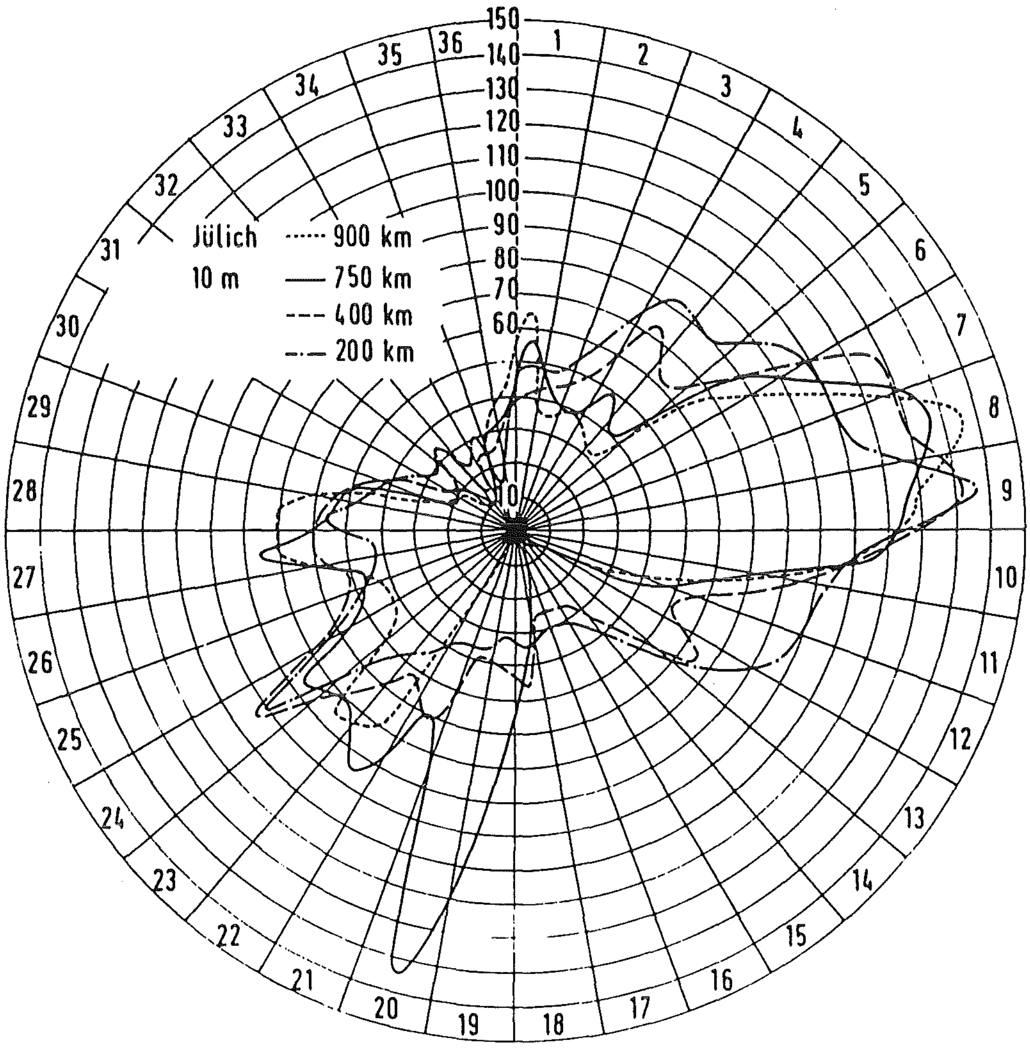


Fig. 18: Trajectory rose showing number of trajectories crossing each ten degree sector centered on the source at distances of 200, 400, 750 and 9oo km from the source.
(Height of the source is 10 m)