

**THE EFFECTS OF PRECIPITATION ON
ACCIDENTAL RELEASES OF RADIOACTIVITY**

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ABSTRACT

Two methods have been developed for modelling surface concentration distributions of activity arising from the washout of airborne radioactive material by precipitation. These are required for analysing possible accident consequences.

The first method is an analytic one dimensional model in which the airborne material and precipitation generating region are represented by simple mobile spatial distributions. This has been used for studies of the surface contamination resulting from the two distributions moving relative to each other at different velocities. Deficiencies in modelling wet deposition using a Gaussian plume representation for the material have been identified from these results.

The second model incorporates the two horizontal dimensions using a Gaussian-based puff form for the pollutant material. The puff, although Gaussian in its undepleted form, can be selectively depleted by rain which does not fall uniformly across its whole area. The depletion is calculated from a simple scavenging relation using rain intensity data measured by radar. This data is now available over most of England and Wales.

This model has been used in three different studies. Firstly, simple test cases where single releases of material encounter recorded precipitation data from a number of interesting situations. These include both fronts and isolated storms. The second study was of the deposition of radioactive material over England and Wales resulting from the Chernobyl accident. This has been a valuable validation study for the model, because the calculated deposition closely matches measured Cs-137 data.

The final study undertaken involves a series of hypothetical releases of radioactivity during 1985 from a site within an area of the UK for which we have assembled a complete year's rain data. This has provided statistical distributions of deposited material for an initial analysis of the suitability of such data in site selection studies and probabilistic risk assessment for nuclear installations.

To Katherine

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CONTENTS

TITLE	1
ABSTRACT	2
ACKNOWLEDGEMENTS	4
CONTENTS	5
TABLES	9
FIGURES	11
 Chapter 1 INTRODUCTION	
1.1 ATMOSPHERIC POLLUTION AND MODELLING	15
1.2 THE BEHAVIOUR OF AIRBORNE MATERIAL	16
1.2.1 Dispersion	16
1.2.2 Deposition	17
1.2.3 Precipitation and Wet Deposition	18
1.3 THE AREA OF STUDY	21
1.4 THE LIMITATIONS OF CURRENT MODELLING	22
1.5 A DESCRIPTION OF THE PRESENT WORK	24
1.5.1 The One-Dimensional Model	24
1.5.2 The RAIN-PATCH Model	25
1.5.3 The Studies Undertaken	26
References	27
 Chapter 2 ONE DIMENSIONAL ANALYTIC WASHOUT MODEL	
2.1 MODEL DESCRIPTION	29
2.2 GENERAL DERIVATION	32
2.3 SPECIAL CASE DERIVATIONS	32
2.3.1 Rain Overtaking Pollutant	32
2.3.2 Pollutant Moving in the Opposite Direction to the Rain	37
2.3.3 Uniform Advection	39
2.3.4 Stationary Rain-Band	40
2.4 THE SEGMENTED GAUSSIAN PLUME MODEL	41
2.5 CALCULATED DEPOSITION DISTRIBUTIONS	42
2.6 INTERPRETATION OF DEPOSITION LEVELS	48
2.7 CONCLUSIONS	51
References	51
 Chapter 3 TWO DIMENSIONAL NUMERICAL WASHOUT MODEL	
3.1 MODEL REQUIREMENTS AND DESCRIPTION	53
3.2 PRECIPITATION DATA	55

3.2.1	Studies of the Spatial Structure of Precipitation	55
3.2.2	Precipitation Intensities Measured by Radar	57
3.3	PUFF STRUCTURE	59
3.3.1	One Dimensional Puff Formulation	61
3.3.2	Two Dimensional Puff Formulation	64
3.4	SURFACE MAPPING OF DEPOSITION PATCHES	70
3.5	PUFF TRAJECTORIES	73
3.6	RADIOACTIVE DECAY AND DRY DEPOSITION	76
3.7	THE RAIN-PATCH PROGRAMS	78
	References	80
Chapter 4 MATERIAL REDISTRIBUTION WITHIN THE PUFF		
4.1	THE NEED FOR INTERNAL REDISTRIBUTION	82
4.2	REDISTRIBUTION IN ONE DIMENSION — DERIVATION	83
4.3	REDISTRIBUTION IN ONE DIMENSION — TESTING	86
4.4	REDISTRIBUTION IN TWO DIMENSIONS	93
4.5	REDISTRIBUTION IN THE RAIN-PATCH MODEL	97
	References	99
Appendix 4A	Derivation of the α - r - θ Equation	100
Appendix 4B	Derivation of the α - β - θ Equation	101
Appendix 4C	A Finite Difference Scheme for the α - r - θ Equation	102
Appendix 4D	Central Point FD Scheme for the α - r - θ Equation	103
Appendix 4E	Radially Weighted FD Scheme for the u - r - θ Equation	103
Appendix 4F	Conservation for the u - r - θ FD Scheme	105
Chapter 5 MODEL PARAMETERS		
5.1	INTRODUCTION	106
5.2	PUFF STANDARD DEVIATIONS	107
5.3	WIND VELOCITY HEIGHT CORRECTION	109
5.4	DRY DEPOSITION PARAMETERS	110
5.5	THE WET DEPOSITION COEFFICIENT	112
5.6	PARAMETER SELECTION USING RAIN-PATCH TEST RUNS	114
5.7	SAMPLE POINT POSITIONING AND DENSITY	121
5.8	REDISTRIBUTION FREQUENCY	129
5.9	DEPOSITION PATCH TERMINATION WITH DIRECTION CHANGE	130
5.10	RAIN INTENSITY LEVEL SETS	131

5.10.1 Rain Intensity Distribution Functions	131
5.10.2 Rainfall and Washout Distributions	134
5.10.3 Selection of Rain Intensity Level Sets	135
5.10.4 Comparison of Results using Different Level Sets	136
5.11 RADAR BEAM ELEVATION AND FRAME FREQUENCY	138
5.12 SUMMARY	139
References	140
 Chapter 6 PRELIMINARY RAIN-PATCH RESULTS	
6.1 INTRODUCTION	141
6.2 TEST SEQUENCES OF RAIN DATA	141
6.3 SAMPLE-POINT/SOURCE METEOROLOGY DEPOSITION COMPARISONS	143
6.4 RELATIVE RELEASE TIME COMPARISONS — SEQUENCE A	151
6.5 RELATIVE RELEASE TIME COMPARISONS — SEQUENCE B	156
6.6 RELATIVE RELEASE TIME COMPARISONS — SEQUENCE C	158
6.7 CONCLUSIONS	166
References	167
 Chapter 7 THE DEPOSITION OF CS-137 AND I-131 OVER ENG- LAND AND WALES AS A CONSEQUENCE OF THE CHERNOBYL ACCIDENT	
7.1 INTRODUCTION	169
7.2 THE PASSAGE OF THE INITIAL RIDGE OF MATERIAL ACROSS THE UK	171
7.3 THE DISTRIBUTION OF MATERIAL AT MIDNIGHT ON 1 MAY 1986	172
7.4 MODELLING THE INITIAL RIDGE USING RAIN-PATCH	176
7.5 CALCULATED TOTAL DEPOSITION OF CS-137 AND I-131	182
7.6 THE MEASURED DATA AVAILABLE FOR COMPARISON	184
7.7 THE COMPARISONS MADE	188
7.7.1 Correlation Coefficients	188
7.7.2 Scatter Plots	190
7.8 FURTHER ANALYSIS OF THE PASSAGE OF THE INITIAL RIDGE	195
7.9 SUMMARY AND CONCLUSIONS	199
References	199

Chapter 8	AN ANALYSIS OF THE USE OF RAIN-PATCH IN NU- CLEAR POWER STATION SITING STUDIES	
8.1	INTRODUCTION	201
8.2	THE WEATHER IN 1985	202
8.3	THE RAIN DATABASE	205
8.4	THE RELEASE SEQUENCES UNDERTAKEN	205
8.5	COMPARISON OF POINTS AND SOURCE MODE DISTRIBUTIONS	207
8.6	ANALYSIS OF THE DEPOSITION DISTRIBUTIONS	216
8.7	CONCLUSIONS AND FUTURE WORK	217
	References	221
Chapter 9	SUMMARY AND FUTURE WORK	
9.1	SUMMARY	222
9.2	FUTURE WORK	224

TABLES

2.1	Parameters common to all calculated deposition distributions	43
2.2	Parameters defining each deposition distribution	44
2.3	Contamination levels for 25 mSv ERL for releases normalized to 10^6 Bq	50
4.1	$\ u - \alpha\ _2$ for three values of the α - β scheme time step	92
4.2	Two-norm values for the conservation corrected α - β scheme	93
5.1	Pasquill stability categories	107
5.2	Parameter values required to give the puff standard deviations	108
5.3	Positions and times for uniform vertical mixing	110
5.4	Numbers of sample points required to give average spacing x at time t	125
5.5	The puffs used in selecting optimum puff sample point density	125
5.6	Deposition areas and run times for sample point density test runs	126
5.7	Total deposition area change comparisons for sample point density test runs	126
5.8	Deposition level change comparisons for sample point density test runs	127
5.9	Redistribution frequency testing results	129
5.10	Division of precipitation intensity, J , into the four ranges of intensity level values provided by the radars	130
5.11	Most efficient washout intensities for various values of time period, T	135
5.12	Comparison of four different intensity level sets using releases from test site S	137
5.13	Comparison of four different intensity level sets with a common minimum level of 0.22 mmhr^{-1}	137
6.1	Rain data sequences	142
6.2	Rain occurrence fractions for the frontal test sequence	156
6.3	Fractions of material deposited for sequence B runs	158
6.4	Rain occurrence fractions for the storm test sequence	161
6.5	Fractions of material deposited for sequence C runs	166
6.6	Rain occurrence fractions for sequence C runs	162

7.1	Locations and forms of measurement for time-sequence data	172
7.2	Time points used in obtaining local trajectories	173
7.3	Puff start locations and fractions deposited for wet deposition of Cs-137 using the 16-puff composite distribution	181
7.4	Correlation coefficients using grass data	188
7.5	Correlation coefficients using milk data	188
7.6	Correlation coefficients for NW England and Wales	189
7.7	Air concentration data	190
8.1	Total rainfall per month and percentage of 1951–70 average value for five locations around the release site	204
8.2	Average total and percentage rainfall for the five sites in table 8.1. Values given by month and by season	204
8.3	Analysis of deposition levels within rings about the release site	215

FIGURES

1.1	Cross section through a cold front (from Browning 1985)	19
1.2	Three dimensional structure of a convective storm (from Browning and Ludlam 1962)	20
2.1	Schematic diagram of the one dimensional model	29
2.2	Diagram of precipitation and pollutant function initial conditions for 'rain overtaking pollutant' special case derivation	33
2.3	Forms of surface deposition distribution, $G(x)$, for the 'rain overtaking pollutant' special case derivation with (a) $vS + uR > 0$ and (b) $vS + uR < 0$	36
2.4	'Rain overtaking pollutant' deposition distributions for high (25 mmhr^{-1}) rain intensity	46
2.5	'Rain overtaking pollutant' deposition distributions for low (2.5 mmhr^{-1}) rain intensity	47
2.6	'Stationary rain band' deposition distribution	48
2.7	'Pollutant direction opposing rain direction' and 'uniform advection' special case derivations	49
3.1	Structure of a wave depression	56
3.2	The locations of the five UK weather radar systems	60
3.3	Diagram of a simple linearised two dimensional Gaussian puff	61
3.4	One dimensional linearised Gaussian distribution with five sample points	62
3.5	Form of linearised distribution after washout of material at sample points three and four	65
3.6	Two dimensional puff structure	67
3.7	General triangular puff base element	69
3.8	Surface patch caused by washout at a sample point	71
3.9	Wind interpolation grid for the London radar area	74
3.10	Forms of $h(t)$	78
4.1	Test results from $u-x$ scheme	88
4.2	Perturbed Gaussian advanced with (a) no redistribution and (b) using the $u-x$ FD scheme	89
4.3	Perturbed Gaussian advanced (a) using the $\alpha-\beta$ FD scheme	90
4.4	Larger perturbation advanced with (a) the $\alpha-\beta$ scheme and (b) the $u-x$ scheme	91

4.5	Results using the $u-r-\theta$ scheme showing (a) a non-conservation problem and (b) the effects of the conservation correction	95
4.6	$u-r-\theta$ scheme solutions for a perturbed initial state	96
4.7	$u-r-\theta$ and $\alpha-r-\theta$ scheme comparisons for a central perturbation	98
4.8	Scheme comparisons for a perturbation uniform in r	99
4C.1	$\alpha-r-\theta$ scheme solution grid	102
4E.1	$u-r-\theta$ scheme solution grid	104
5.1	$h'(x)$ for various release heights	112
5.2	Relative deposition using three values of Λ	114
5.3	Test sequence — frontal system	116
5.4	Test sequence — storm system	118
5.5	Nine release site positions from which the three test sites were chosen	120
5.6	Test run results using release site S and the front test sequence	121
5.7	Test run results using release site SE and the front test sequence	122
5.8	Test run results using release site NE and the storm test sequence	123
5.9	Character level grid for test run results from site S	124
5.10	Intensity level frequency distribution	132
5.11	Plot of $\ln \ln \frac{r}{A} $ against $\ln J$	133
5.12	Forms of rain intensity distribution function and rainfall quantity distribution function	134
6.1	Midday synoptic charts for the front test sequence	142
6.2	Progress of storms across a 60 by 60 kilometre grid centred near Manchester Airport	144
6.3	Trajectories for front and storm test sequences	145
6.4	Trajectories for front test sequence delayed by 12 hours	146
6.5	Deposition distributions using the central release site with the storm sequence	148
6.6	Deposition distributions using the north release site with the storm sequence	149
6.7	Deposition distributions using the south release site with the front sequence	150
6.8	Fractions of material deposited for each sequence A run	152

6.9	Deposition distributions for the eleven run sequence using release site B with the front sequence	154
6.10	Trajectories followed by three hour separated releases from the north site using the storm sequence	157
6.11	Deposition distributions for the sequence of releases using the north release site with the storm data sequence	159
6.12	Midday synoptic charts for test sequence C	161
6.13	Trajectories followed by the hourly releases from the central release site using data sequence C	162
6.14	Deposition distributions for the sequence of releases from the central release site using data sequence C	163
7.1	Geostrophic trajectories followed by material released from Chernobyl during 26 April 1986	170
7.2	Backward trajectories positions at midnight 1 May 1986	174
7.3	Particulate concentration at Sellafield	176
7.4	Geostrophic trajectories from points along the initial ridge of material	177
7.5	Structure and initial position of 9-puff composite distribution	178
7.6	Distribution of deposited caesium-137 on grass	179
7.7	Structure and initial position of 16-puff composite distribution	180
7.8	Modelled distribution of wet deposited caesium-137	183
7.9	Modelled distribution of wet and dry deposited caesium-137	185
7.10	Modelled distribution of wet and dry deposited iodine-131	186
7.11	Scatter plots using grass data	191
7.12	Scatter plots using milk data	192
7.13	Caesium-137 in soil to 15 cm depth. Measured on grassland in 1977	194
7.14	Correlation coefficients for the time shifted model runs	196
7.15	Modelled distribution of wet deposited caesium-137 for 16-puff composite distribution delayed by 12 hours	198
8.1	Typical rainfall direction rose	206
8.2	Points mode whole year distribution	208
8.3	Source mode whole year distribution	209
8.4	Points mode summer season distribution	211
8.5	Source mode summer season distribution	212

8.6	Number of occurrences per month of releases experiencing greater than ten percent washout within the grid area	213
8.7	Total deposition per month as a percentage of the total deposition for the year	214
8.8	Smoothed points mode whole year distribution	216

CHAPTER 1.

INTRODUCTION

1.1 ATMOSPHERIC POLLUTION AND MODELLING

Human activities have for many centuries released waste materials into the atmosphere. Since the industrial revolution the quantities and varieties of such materials have increased enormously. These releases have often caused harm to man, either directly, for example by bronchial illnesses arising from smogs, or indirectly by damage to the environment. Two instances of current concern are the possible acidification effects caused by sulphur and nitrogen oxides released by industry and motor vehicles, and reductions in the levels of ozone in the upper atmosphere attributed to the action of chlorofluorocarbons released from refrigeration systems and aerosol spray cans (Rowland 1982).

Accidental releases of material are also frequently of great concern. Recent examples from the chemical industry are the accidents which occurred at Flixborough, Seveso and Bhopal. Another example, from the nuclear industry, is the accident which occurred at Chernobyl in the USSR in April 1986. The Chernobyl accident is very relevant to this work, which is concerned mainly with accidental releases to the atmosphere of radioactive materials. However, the work is applicable to other materials both for accidental releases and, to some extent, for continuous releases.

Concern about the harm being done to the environment by pollutant materials in the atmosphere has led to a great deal of research. One approach to this research is the use of various forms of model. These models have two roles. The first is as an aid to understanding the behaviour of pollutant materials in the atmosphere, for example, the route taken to a destination or the sequences of chemical changes undergone. Such information can then be used in finding ways to minimize environmental damage. The second form of modelling is predictive. This is of relevance to accidental releases and can either be done in advance, to assess the possible consequences

of hypothetical accidents or, following an accident, as an aid in deciding any appropriate action to be taken.

1.2 THE BEHAVIOUR OF AIRBORNE MATERIAL

Airbourne material is dispersed by the wind and removed from the atmosphere by coming into contact with the ground or other obstructions, or by incorporation into precipitation (rain, hail, snow etc.). These removal processes are collectively referred to as deposition.

1.2.1 Dispersion

Dispersion is achieved primarily by the natural motions of the atmosphere, although initially properties of the release, such as heat content and the velocity of the released material, may have an effect (Jones 1983).

In the horizontal plain atmospheric motions consist of a mean air-flow on which turbulent eddies are superimposed. At one extreme, the weather systems which come to the UK from the Atlantic can be considered as turbulence in the normal westerly airflow. More practically, the mean air flow will be a value for some fixed period, say an hour or a few hours, and turbulence will be any fluctuations over a shorter period. On this time-scale the larger turbulent eddies will be produced by the local terrain and will have dimensions comparable with that terrain. The energy from these eddies will then be transported down a cascade of successively smaller eddies until it is finally dissipated as heat by viscous action.

A similar situation occurs in the vertical, except that there is not normally any mean flow. The vertical turbulence originates at the surface where it is either produced mechanically by the action of the horizontal flow over the irregular surface, or by convection caused by the surface heating the lower levels of the atmosphere. In either case, its vertical extent is limited due to these surface effects becoming less apparent with height. The region through which they are apparent is referred to as the boundary layer.

Pollutant material discretely introduced into the atmosphere is clearly moved bodily by any mean flow, but it is also spread out by the turbulent

eddies. The eddies most effective in doing this at any time are those of a size comparable with the material distribution.

Dispersion is often further complicated by chemical and physical changes to the material concerned, for example, sulphur dioxide changing to sulphate. These reactions often have complicated dependencies on environmental properties such as sunlight, humidity, cloudiness and temperature.

1.2.2 Deposition

Dispersing material can be directly harmful if, for example, it is toxic or a gamma emitter, but another problem arises from its deposition onto surfaces such as crops and buildings. This comes about in a number of ways, which can be broadly split into the wet deposition processes which involve precipitation and dry deposition processes which do not.

The fundamental dry depositing mechanism is gravitational settling, which removes the larger particles, those greater than a few microns in diameter, from a release fairly quickly. Further from a release site, the processes depend more on the contact made between the cloud and surface material and their affinity for each other. Sulphur dioxide, for example, will be readily absorbed onto any damp surface, and for many materials this will be a two-way process, the surface giving up material after the passage of the airborne material when the air concentrations have dropped.

Wet deposition includes all the removal processes which involve precipitation. The various forms of precipitation will remove material but rain has been the most studied, and is possibly the simplest. Details of the wet deposition processes will be given in the next section, but some simple observations and comparisons with dry processes will be made here. Rain can remove material from some significant depth of the boundary layer. This gives it the potential to remove material far more quickly than dry processes, which only act at the surface, and are constrained by the speed with which removed material can be replaced by diffusion from above. Wet deposition is also dependant on the spatial and temporal distributions of rain. Thus rain could give rise to very high surface contaminations, over limited areas.

This local effect could be greatly enhanced by storm cells. These are relatively long-lived dynamic structures (Ludlam 1980) in which large quantities of boundary layer air are sucked up to higher levels of the atmosphere, consequently giving rise to large quantities of rainfall. Such storms usually move across country but it is possible for them to remain stationary over a hill, which was the case for the Hampstead storm of 14 August 1975 (Bailey *et al* 1981) which caused extensive flooding in London. This situation could lead to significant levels of local surface contamination from an extensive region of air contaminated at a relatively low level (Smith 1980). Such an area could easily escape detection in the aftermath of an accident.

The differing removal processes can also affect the consequences of deposition beyond the point at which material reaches the ground. Wet deposited material, for example, may frequently be washed off its point of first contact, into drains and rivers. Dry deposited material can build up on crops and buildings over a period of time. These differences could lead to very different consequences from the same quantity of deposited material.

1.2.3 Precipitation and Wet Deposition

Precipitation is a consequence of atmospheric motions on a very wide range of scales, from the movement of air-masses of dimensions of the order of thousands of kilometres, to the condensation of water vapour onto hygroscopic aerosol particles of a few micrometres in diameter. These and the intermediate scales all have associated complications when considering wet deposition and this can be illustrated using three ranges of scales. On the larger scales the problem is purely one of position. Material can only be wet deposited when rain is produced in, or falls through, polluted air. Thus any modelling of wet deposition requires some knowledge of two frequently independent entities, the spatial and temporal distributions of both the precipitation and the pollution.

The second category of problem is again one of relative position, but on the generally smaller scale of the rain production processes. Rain can result from a number of airflow conditions, which all have the consequence

of moving air above its condensation level. An interesting example of this is the warm conveyor-belt which takes moist, southerly, warm sector air northwards (in the Northern Hemisphere) ahead of the surface cold front, gradually raising it above the front, and consequently causing precipitation to form. The warm conveyor-belt has a number of variants as discussed by Browning (1985), one of which is shown in figure 1.1. Another example is the self-sustaining storm super-cell in which two airflows, one rising and one descending, wrap around each other so that the rainfall from one, evaporating in the other, maintains the cell. This, a major cause for concern, was mentioned in the previous section and is depicted in figure 1.2. Clearly, wet deposition will depend not only on polluted air being in the vicinity of rain, but also on the method by which it becomes incorporated into the dynamic structures associated with the rain. For example, there will be differences in deposition due to material being incorporated in rain during its formation, rather than by rain falling through polluted air. These are referred to, respectively, as rain-out and wash-out (Underwood 1983).

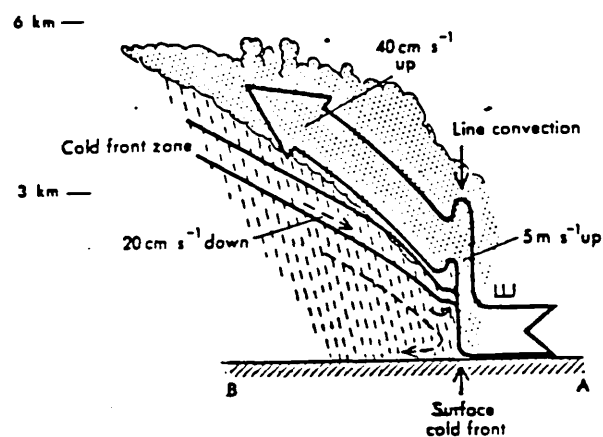


Figure 1.1 Cross-section through a cold front (from Browning 1985)

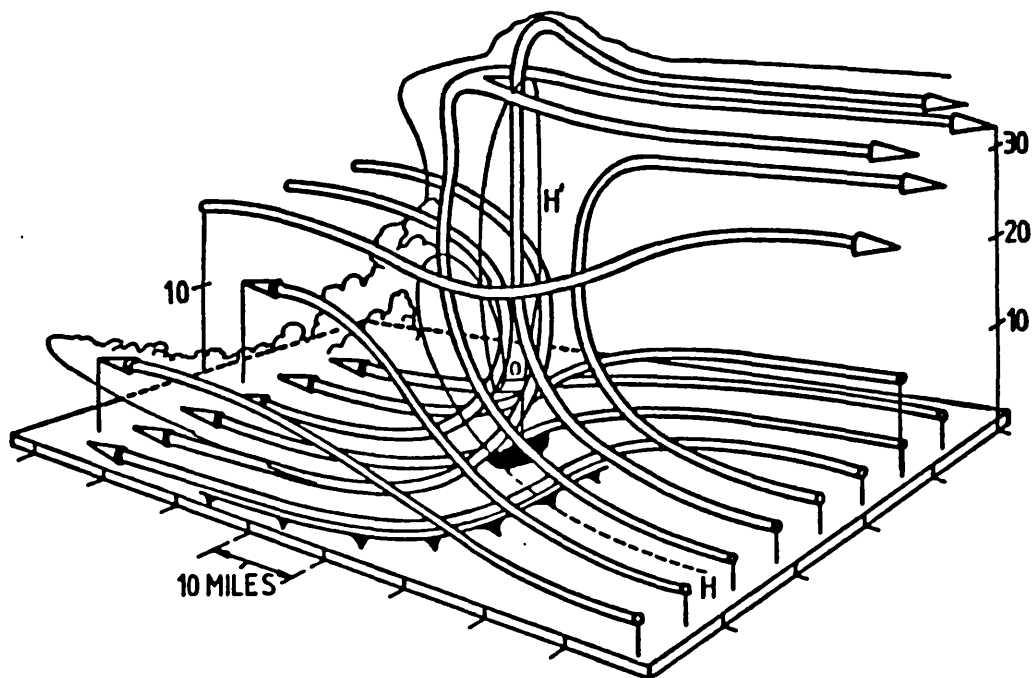


Figure 1.2 Three dimensional structure of a convective storm
(from Browning and Ludlam 1962)

Another consideration is the effect that these dynamic structures have on the positioning of material. Clearly material drawn into a frontal conveyor-belt will be moved significantly away from positions determined from surface or geostrophic wind trajectories. Similarly, large amounts of material incorporated into convective systems, such as a storm cell, may well be taken above the boundary layer by the updraughts. There it will be effectively safe from any form of deposition. These complexities are not considered here but will be discussed in the concluding chapter.

A third category of problem concerns the very small scale, the micro-physics of pollutants in the precipitation processes. This scale consists of the wash-out and rain-out processes mentioned above, both of which have many complications. These complications have been described by Slinn (1974) and more recently in a review carried out by Underwood (1983). Examples of these complications are that the behaviour of gaseous and particulate pollutant materials is very different; if particles are suitably hygroscopic they may enhance rain production, and gaseous material may diffuse out of a

raindrop once it has fallen into a region of a lower concentration of the gas. In this work a simple wash-out relationship has been used to represent both processes. Other current work will permit this to be improved in the future.

1.3 THE AREA OF STUDY

Wet deposition is a very significant factor in the ultimate fate of many airborne materials, but the range of processes involved in wet deposition present many complications to successful modelling. The complexities in the microphysical aspects have been well documented by Slinn (1974), and Fisher (1983) has described some of the complications introduced by topography.

Although the uncertainties in the modelling of wet deposition at all of the three scales described above would benefit from further study, it was decided in this work to concentrate on the larger scale problem, the spatial and temporal interaction of the pollutant and precipitation. The larger scale, from a practical point of view, is more important than the two smaller scales. The interactions on this scale will dictate to a great extent the areas where deposition occurs, while the other scales will control the levels of deposition within those areas. The areas of deposition can be influenced by rain system dynamics, the intermediate scale, and a clear division between the two larger scales is not always possible. However, despite the possible effects of intense stationary storm cells, the larger scale will in general, dominate the areas of deposition. Consequently improvements in the intermediate and microphysical scales are of limited use, if the modelling on the larger scales is predicting deposition in the wrong places.

Concern about wet deposition arose at the public inquiry into the building of the pressurized water reactor (PWR) at Sizewell. The likelihood and consequences of released material experiencing limited dispersion over relatively large travel distances, then encountering heavy rain, to give high deposited concentrations over a populated area, such as London, was one

issue raised. Such questions can be best answered by an examination at the larger scale of interactions.

Modelling on the larger scale is also of direct practical use following an accident. Here a quick evaluation of the areas of possible significant deposition is important for the positioning of monitoring teams and the planning of any relief operations. Such information would have been invaluable following the deposition over the UK from the Chernobyl accident.

1.4 THE LIMITATIONS OF CURRENT MODELLING

Existing models of dispersion and deposition have in general been fairly poor at representing the larger scale of pollutant and precipitation interaction. This is mainly due to the limited meteorological data available, in particular rain intensity data. In the UK rainfall is routinely recorded at a large number of locations as total values over a twenty-four hour period. This is both temporally and spatially inadequate to resolve the wet deposition processes of interest here. Temporally, it is inadequate because rain will not in general fall uniformly during a twenty-four hour period, and the possible variations to give the same totals — one brief intense shower or a longer period of drizzle, etc. — could give very different deposition distributions from a cloud of pollutant passing through during that time.

Spatially, in the UK, the recording stations are separated on average by some 30 to 40 kilometers, and are not uniformly distributed. They also tend to be positioned in locations accessible to the operators — valleys rather than hilltops. Since rain intensity can vary quite considerably over relatively short distances (Austin and Houze 1972) and is also very dependent on topography (Fisher 1983, Browning and Hill 1981) this relatively sparse network makes estimating rainfall at a general location, by some form of interpolation, extremely difficult.

Some of the recording stations do provide sub-daily totals, for example six hourly or hourly. This improvement in temporal resolution, however, is

more than offset by the reduction in spatial resolution to allow for much improvement in modelling.

At the simplest level of modelling this difficulty has been avoided by using meteorological data measured at only one location, typically the source of the release. Such models usually represent material with expanding Gaussian distribution profiles in the vertical and cross-wind directions, to simulate dispersion. They can either use fixed meteorology, where the conditions at the time of the release remain in force throughout the modelling period or some form of periodic adjustment is made. Typically the meteorological conditions are updated hourly.

One drawback with such a model is the assumption that the conditions occurring at the source, either at the release time or after the release are representative of the conditions experienced by the released material subsequent to its moving away from the source. This assumption is taken to apply over some limited range, typically 100 km. It is reasonably valid for certain meteorological parameters, for example wind direction, which controls the travel of the material, and cloud cover and insolation, used in determining the rates of dispersion. It is a much less valid assumption, however, for precipitation. Consequently calculations of wet deposition in such a model could be extremely inaccurate. An example of this type of model, which is termed a Gaussian plume model, is MARC (Clarke and Kelly 1981) which has been developed by the National Radiological Protection Board (NRPB).

The MESOS model (ApSimon and Goddard 1983), which has been developed at Imperial College, calculates deposition distributions over a longer range. This model makes use of grids of meteorological data covering an area comparable to that of Europe, and produced by interpolation using data from all the synoptic weather stations within the grid area. These stations provide three hourly readings of many relevant meteorological values, but exclude direct measurement of precipitation.

The routes followed by dispersing material are calculated from the atmospheric pressure data using the geostrophic balance equation. Other data

is then used to calculate dispersion and the boundary layer height. Wet deposition is calculated using a grid of rain intensity indices calculated from 'present weather codes'. These codes, recorded every three hours when the other synoptic readings are made, consist of 100 numbers categorising the weather at the measurement time or during the previous hour. Of these, numbers in the ranges 20–29 and 50–99 indicate various forms of precipitation.

An effective rainfall rate is determined for each weather code and used within MESOS to determine the wet deposition from within each grid cell. Using 'present weather codes' gives a better time resolution than rain gauges since it is one of the three hourly synoptic measurements and it is therefore also more quickly available. Rain gauge data often takes some weeks to collect and cross-check. Synoptic measurements are also made at sea, giving a more uniform coverage than gauges. It is, however, still a very coarse measure of precipitation since only that which occurs within sight of a station during a relatively brief period is recorded. Fairly significant areas of rain could be missed altogether or a brief, local event could be applied to a whole grid cell for a whole three hour period. Either of these errors could seriously distort the wet deposition calculation in the model.

1.5 A DESCRIPTION OF THE PRESENT WORK

1.5.1 The One Dimensional Model

A preliminary part of this work was the development of a model to perform a simple examination of the effect that a mobile rain distribution would have on wet deposition. In the model rain intensity and pollutant material are represented by simple block functions which move relative to each other. The derivation of the surface deposition function for the general case is presented together with that for a selection of specific case studies showing various configurations of the pollutant and precipitation distributions. These have been chosen to match situations which could occur in practice.

Although very simplistic, these studies do show the possible problems in ignoring the smaller scale mobile structures of rain. In particular a direct comparison is given between the results which a Gaussian plume model would give and those from an alternative interpretation of the same situation. This comparison shows very different deposition distributions with potentially very different radiological consequences.

The model and the comparisons performed with it are described in chapter two.

1.5.2 The RAIN-PATCH Model

There is clearly a limit as to how well the simple one dimensional model described above can simulate the complex three dimensional processes of the atmosphere. For this reason the RAIN-PATCH model was developed and this has formed a major part of this work. It is a two dimensional numerical model designed to use real meteorological data in determining the dispersion and deposition of released material.

The model calculates wet deposition using precipitation data recorded by weather radars. There are five of these radars now operating within the UK, giving coverage of most of England and Wales. They provide data on a 5 by 5 kilometre grid every five minutes and therefore overcome the resolution restrictions described above with the older forms of precipitation data measurement.

RAIN-PATCH models the dispersing material as a puff with Gaussian profiles in both horizontal directions. The structure and development of the model are described in chapter three, with the exception of one aspect, the redistribution of material within the puff. Since rain will not always fall uniformly across a whole puff, it can become distorted from the original Gaussian form. When this occurs material will diffuse between the areas of higher and lower concentrations within the puff. The scheme used to simulate this is described in chapter four.

1.5.3 The Studies Undertaken

Three different studies were undertaken using the RAIN-PATCH model. The first of these, contained in chapter six, is an extension of the simple case studies performed with the one dimensional model. This time, however, the rain data used are sequences recorded by the radar at Hambledon Hill, north of Manchester, and the released material is allowed to disperse and follow a trajectory obtained from surface wind data.

This study is in two parts. Firstly deposition distributions are calculated using the rain occurring over the puff of material during its travels. These are compared with the same calculation performed using only the meteorological situations occurring at the source of the release, but applied to the same puff. This is presented for three rain data sequences including a front which crossed the north of England in January 1984 and a series of storms which passed over Manchester in August 1981. The results, in agreement with chapter two, show the importance of using meteorological data close to a cloud of dispersing material.

The second part of the first study comprised a number of series of releases separated by some period of time for a selection of rain data sequences. These show the differences which can occur in deposition patterns due to relatively small changes in timing and confirm the need for the fine data resolution provided by the weather radar.

The second study is an analysis of the deposition of caesium-137 and iodine-131 isotopes over England and Wales as a consequence of the accident at Chernobyl. This is described in chapter seven. Because the model was designed to simulate releases from within, or near to, the areas covered by the radar data, such a remote release presented some difficulties. Eventually it was modelled using sixteen RAIN-PATCH puffs combined to form one composite distribution, which travelled across the UK from south-east to north-west. The distributions for each of the puffs were then combined to give total deposition distributions which were in good agreement with measured data. This was particularly true for the caesium-137 distribution when

compared with data from the Institute for Terrestrial Ecology for deposited caesium-137 on grass. This study was therefore very useful as a *test of* the model.

The final study, described in chapter eight, is a preliminary analysis of the use of RAIN-PATCH in power station siting studies. Two statistical deposition distributions have been built up around a site in south-west England by adding the deposition from modelled releases of material from that site occurring at frequent periodic intervals throughout 1985. This is a year for which we have an almost complete sequence of data from the Chenies radar in Buckinghamshire, which covers much of central and southern England and east Wales.

Such distributions are useful in assessing the risk to populations in the event of an accident from an existing or proposed nuclear installation. The two distributions differ in using the two meteorological sampling techniques described in the first study. Although in that study it was concluded that the best results were obtained by using rain and wind data local to the puff, the statistical distributions were considered to be significantly different from this earlier study for it to be important to repeat the comparison. They do in fact show that using meteorology from the source of the release is probably adequate for distributions within the vicinity of the release site, but not further away.

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CHAPTER 2.

ONE DIMENSIONAL ANALYTIC WASHOUT MODEL

2.1 MODEL DESCRIPTION

This model was developed as a very simple method of analysing the effects on surface deposition concentrations of the independent movement of both the pollutant material in the atmosphere and the region of rain generation. The pollutant cloud and rain intensity are represented as distributions which advect along the same path at different but fixed velocities, with the rain removing pollutant material to the surface whenever non-zero sections of the two distributions overlap. This is depicted in figure 2.1. The intention is to model situations where a discrete release of material moves across country at a fixed velocity and is overtaken by a rain system moving under the influence of a stronger wind at a higher level. For example, the rain ahead of a forward facing front could be considered in this way. This specific situation is not restricted by the pollutant and the rain having to follow the same path, since the two dimensional nature of a front means that the velocity components along the path of the pollutant distribution can be used for the rain.

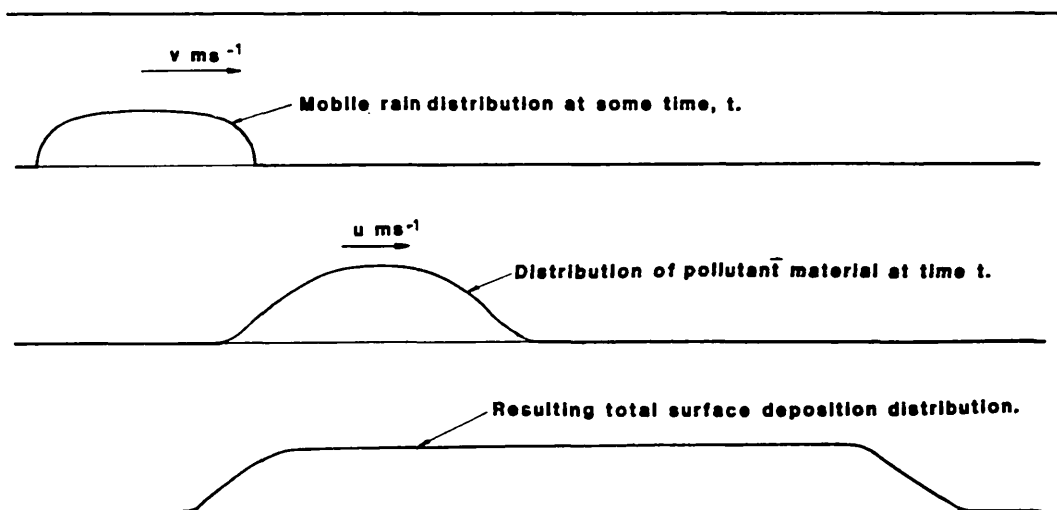


Figure 2.1. Schematic diagram of the one dimensional model.

Together with the fixed direction restrictions, the model also has a conceptual vertical separation into three layers, with the rain always falling from a layer above that of the pollutant, which is sandwiched between the rain level and the ground. The model therefore only includes washout, or rain scavenging, and no account is taken of mixing between the two layers. This is not unrealistic in the frontal case outlined above, where the layers are separated by the frontal surface, but should be borne in mind in the more general use of the model. Another simplification is that along-wind dispersion is not included because the model formulation precludes this. Some allowance however is made for this in the formulation of the specific situations analysed, and this is described in section 2.5. Lateral dispersion is allowed for by an appropriate reduction of the on-axis pollutant concentration with time.

Section 2.2 gives the derivation of the model in a general form, which is then followed, in section 2.3, by a selection of special-case derivations. In these, specific function forms and other conditions are imposed to simulate specific scenarios. For example, the first is a representation of the ‘rain catching the pollutant’ which was described above. These cases have been chosen to permit analytic solutions to the model and results from these are presented in section 2.5.

2.2 GENERAL DERIVATION

The precipitation function, $J(x, t)$, represents a distribution in precipitation rate with a fixed form which travels along the x -axis with velocity $v \text{ ms}^{-1}$. Although the form of the function is fixed, it can be modified uniformly in time to permit, for example, the starting and stopping of precipitation. The function is therefore in two parts. A ‘shape’ function, $J_0(x)$, which gives the form of the function at the initial time $t = 0$ and a modulating function, $F(t)$, which modifies the precipitation function uniformly in time, giving

$$J(x, t) = J_0(x - vt)F(t). \quad (2.2.1)$$

The pollutant distribution function, $P(x, t)$, is similarly split, but into three parts. These are the initial undepleted pollution cloud $P_0(x)$ which

advects with velocity $u \text{ ms}^{-1}$, a term $W(t)$ which adjusts the pollutant remaining in the cloud to simulate lateral dispersion and $D(x, t)$, an attenuation factor, giving the fraction of the cloud un-scavenged at distance x metres and at time t hours. The pollutant function is therefore

$$P(x, t) = P_0(x - ut)W(t)D(x, t). \quad (2.2.2)$$

Effectively $P(x, t)$ is a height integration on the x -axis of the air concentration $\chi(x, y, z, t)$ given by

$$P(x, t) = \int_{z=0}^H \chi(x, 0, z, t) dz, \quad (2.2.3)$$

where H is the atmospheric boundary layer height.

The term $W(t)$ represents the on-axis attenuation which would occur due to the lateral dispersion (sideways spreading) in a model containing both horizontal dimensions. This has been included to allow results from such models to be compared directly with those from this model.

The scavenging attenuation factor, $D(x, t)$, is a measure of the pollutant material remaining undepleted at the point in the distribution positioned at x at time t . It is expressed as the fraction remaining of the material at the corresponding point of the distribution at the time $t = 0$. $D(x, t)$ is therefore obtained by integrating over all the scavenging which has occurred at that point up to the time t .

Scavenging is modelled using the simple relation

$$\frac{d}{dt}q(t) = -\Lambda q(t), \quad (2.2.4)$$

for the depletion of an element of the pollution cloud, q , with time. The scavenging coefficient, Λ , is taken to be linearly related to rainfall intensity via the constant, Λ_0 . Thus we get

$$q(t_1) = q(t_0) \exp(-\Lambda_0 J'), \quad (2.2.5)$$

where J' is the total quantity of rain which has fallen through the pollutant cloud element q in the period $t = t_0$ to $t = t_1$. The complication in the model

arises in the calculation of J' , since this involves identifying all the rain falling through the required pollutant element during the period of interest. This results in

$$\begin{aligned} D(x, t) &= \exp \left\{ -\Lambda_0 \int_{t_0}^t J(x - u(t - t'), t') dt' \right\} \\ &= \exp \left\{ -\Lambda_0 \int_{t_0}^t J_0(x - u(t - t') - vt') F(t') dt' \right\}, \end{aligned} \quad (2.2.6)$$

where t_0 is any time prior to the occurrence of any scavenging.

The rate of deposition to the ground at position x and time t is then given by

$$\frac{\partial}{\partial t} g(x, t) = \Lambda_0 J(x, t) P(x, t), \quad (2.2.7)$$

which when integrated, and with $J(x, t)$ and $P(x, t)$ replaced by (2.2.1) and (2.2.2) respectively, gives a surface deposition function of

$$G(x) = \Lambda_0 \int_{t_0}^{\infty} W(t) J_0(x - vt) F(t) P_0(x - ut) D(x, t) dt. \quad (2.2.8)$$

2.3 SPECIAL CASE DERIVATIONS

2.3.1 Rain Overtaking Pollutant

This case, of rain catching up with pollutant moving more slowly but in the same direction, has already been described. It is modelled using ‘top-hat’ functions for $J_0(x)$ and $P_0(x)$, and with $F(t) = 1$ so that the rain is in a continuous, uniform, moving block. $W(t)$ is given a constant value, w , which is intended to be representative of the effect due to lateral dispersion at some specific time of interest. Figure 2.2 gives the initial positions of the rain and pollutant functions, which are defined by

$$J_0(x) = \begin{cases} J'' & \text{for } x_s + R \leq x \leq x_s \text{ with } R < 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.1)$$

and

$$P_0(x) = \begin{cases} P'' & \text{for } x_s \leq x \leq x_s + S \text{ with } S > 0, \\ 0 & \text{otherwise.} \end{cases} \quad (2.3.2)$$

J'' and R are constants giving, respectively, the intensity and length of the rain function’s top-hat. P'' and S similarly give the concentration and length

for the pollutant and x_s is the position at which the pollutant and rain first encounter each other. This occurs at time $t = 0$. The final condition is that the rain catches up with the pollutant and both are moving, which is expressed as

$$v > u > 0, \quad (2.3.3)$$

where u and v are the velocities of the pollutant and the rain distributions respectively.

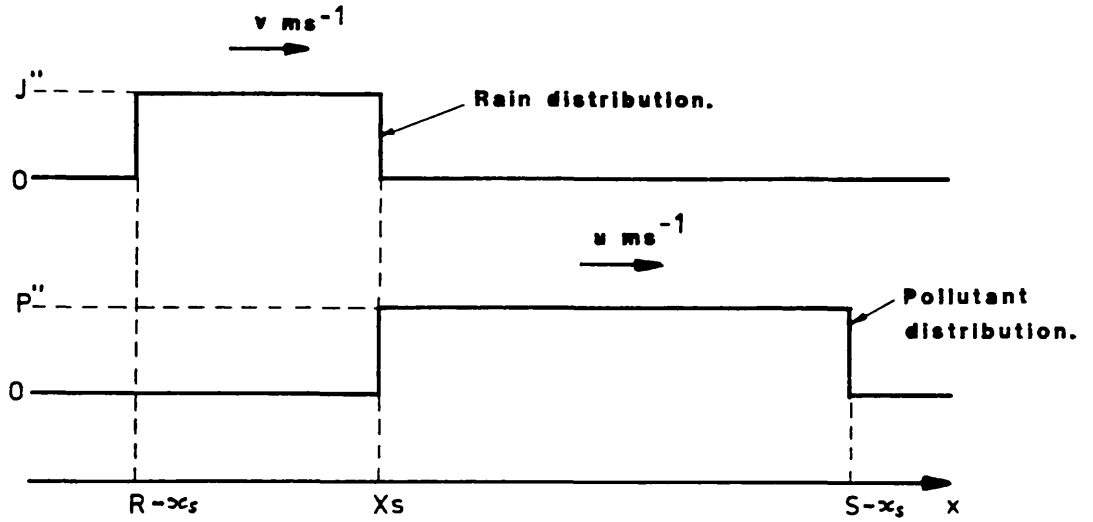


Figure 2.2. Diagram of precipitation and pollutant function initial conditions for 'rain overtaking pollutant' special case derivation.

In equation (2.2.6), $D(x, t)$ is expressed in terms of $J_0(x - u(t - t') - vt')$ and integrated over the time variable t' . Converting definition (2.3.1) to this variable and expressing the range limits in terms of t' gives

$$J_0(x - u(t - t') - vt') = \begin{cases} J'' & \text{for } \frac{x_s - x + ut}{u - v} \leq t' \leq \frac{x_s - x + R + ut}{u - v} \\ 0 & \text{otherwise.} \end{cases} \quad (2.3.4)$$

Therefore substitution into (2.2.6) gives

$$D(x, t) = \exp \left\{ -\Lambda_0 J'' \int_{t' = \frac{x_s - x + ut}{u - v}}^{t' = \min\left(t, \frac{x_s - x + R + ut}{u - v}\right)} dt' \right\} \quad (2.3.5)$$

The integration limits come from eliminating periods when J_0 is zero, as defined in (2.3.4), but of the choice of upper limits, only $t' = t$ is of interest.

This is because the alternative upper limit is appropriate only when it has stopped raining at the space-time point (x, t) , and that point can therefore make no contribution to the deposition function, $G(x)$. Using the limit $t' = t$ gives, from equation (2.3.5)

$$D(x, t) = \exp\left(\frac{-\Lambda_0 J''}{u - v}(x - x_s - vt)\right). \quad (2.3.6)$$

Similarly, equation (2.2.8) is in terms of $J(x - vt)$ and $P(x - ut)$, so converting definitions (2.3.1) and (2.3.2) accordingly gives

$$J_0(x - vt) = \begin{cases} J'' & \text{for } \frac{x - x_s}{v} \leq t \leq \frac{x - R - x_s}{v}, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.7)$$

and

$$P_0(x - ut) = \begin{cases} P'' & \text{for } \frac{x - S - x_s}{u} \leq t \leq \frac{x - x_s}{u}, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.8)$$

Substitution into (2.2.8) then gives,

$$G(x) = w \Lambda_0 J'' P'' \int_{t=\max\left(\frac{x - x_s}{v}, \frac{x - S - x_s}{u}\right)}^{t=\min\left(\frac{x - R - x_s}{v}, \frac{x - x_s}{u}\right)} D(x, t) dt, \quad (2.3.9)$$

and, substituting for $D(x, t)$ from (2.3.6) results in

$$G(x) = -w P'' \frac{(v - u)}{v} \exp\left(\frac{-\Lambda_0 J''}{u - v}(x_s - x)\right) \left[\exp\left(\frac{-\Lambda_0 J'' vt}{u - v}\right) \right]_{t=\max\left(\frac{x - x_s}{v}, \frac{x - S - x_s}{u}\right)}^{t=\min\left(\frac{x - R - x_s}{v}, \frac{x - x_s}{u}\right)} \quad (2.3.10)$$

The integration limits for equation (2.3.10) come from the definitions (2.3.7) and (2.3.8) and clearly for any position x , the most restrictive pair of limits, in terms of their integration ranges, apply. Therefore the x -axis can be divided into four ranges over each of which a different pair of limits applies and consequently also a different form of $G(x)$.

Integrating over the range

$$\frac{x - x_s}{v} \leq t \leq \frac{x - x_s}{u} \quad (2.3.11)$$

gives

$$G_I(x) = w P'' \frac{(v - u)}{v} \left[1 - \exp\left(\frac{-\Lambda_0 J''}{u}(x - x_s)\right) \right] \quad (2.3.12)$$

which is valid when the conditions

$$\begin{aligned}\frac{x - x_s}{v} &\leq \frac{x - x_s}{u}, \\ \frac{x - x_s}{u} &\leq \frac{x - x_s - R}{v}\end{aligned}\quad (2.3.13)$$

and

$$\frac{x - x_s - S}{u} \leq \frac{x - x_s}{v} \quad (2.3.14)$$

are satisfied. This occurs over the range

$$x_s \leq x \leq \min \left[\frac{(v - u)x_s - uR}{v - u}, \frac{(v - u)x_s + vS}{v - u} \right]. \quad (2.3.15)$$

Treating the other three pairs of limits the same way gives

$$G_{II}(x) = wP'' \frac{(v - u)}{v} \left[1 - \exp \left(\frac{\Lambda_0 J'' P''}{v - u} \right) \right] \quad (2.3.16)$$

over the range

$$\frac{(v - u)x_s - uR}{v - u} \leq x \leq \frac{(v - u)x_s + vS}{v - u}. \quad (2.3.17)$$

$$\begin{aligned}G_{III}(x) = wP'' \frac{(v - u)}{v} &\left[\exp \left(\frac{\Lambda_0 J'' S v}{(v - u)u} \right) - 1 \right] \\ &\times \exp \left(\frac{-\Lambda_0 J'' (x - x_s)}{u} \right)\end{aligned}\quad (2.3.18)$$

over the range

$$\frac{(v - u)x_s + vS}{v - u} \leq x \leq \frac{(v - u)x_s - uR}{v - u} \quad (2.3.19)$$

and

$$\begin{aligned}G_{IV} = wP'' \frac{(v - u)}{v} &\left[\exp \left(\frac{-\Lambda J''}{v - u} \left(\frac{(v - u)(x - x_s)}{u} - vS \right) \right) \right. \\ &\left. - \exp \left(\frac{\Lambda_0 J'' R}{v - u} \right) \right]\end{aligned}\quad (2.3.20)$$

over the range

$$\begin{aligned}\max \left[\frac{(v - u)x_s - uR}{v - u}, \frac{(v - u)x_s + vS}{v - u} \right] &\leq x \\ &\leq \frac{(v - u)x_s - uR + vS}{v - u}.\end{aligned}\quad (2.3.21)$$

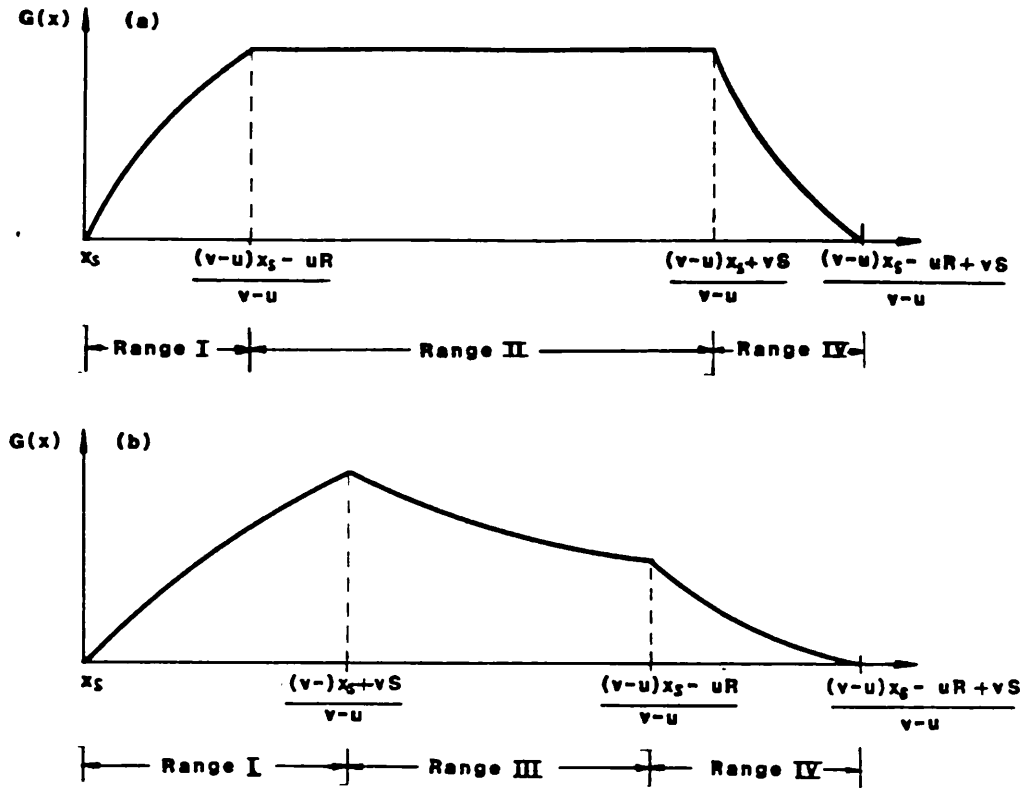


Figure 2.3. Forms of surface deposition distribution, $G(x)$, for the 'rain overtaking pollutant' special case derivation with (a) $vS + uR > 0$ and (b) $vS + uR < 0$

Certain observations can be made about the four ranges and the forms of the deposition functions which are shown in figure 2.3. Firstly, material is only deposited within the range

$$x_s \leq x \leq \frac{(v-u)x_s - uR + vS}{v-u}, \quad (2.3.22)$$

since x_s is the point at which the rain first encounters the pollutant, and the right hand limit is where the trailing edge of the rain first moves ahead of the slower moving pollutant distribution. Secondly, only three of the four ranges can exist at one time, since the limits of ranges II and III are the reverse of each other. The valid range for a given situation is defined by the value of $vS + uR$. If positive then range II is valid, if negative then range III, and if zero, neither exists.

Range I consists of positions where deposition initially occurs when the rain arrives with the pollutant already overhead but ceases to occur when the

trailing edge of the pollutant passes. The increase in total deposition through the range arises from the rain progressively overlapping the pollutant further and so increasing the separation between the 'start of rain' and 'end of pollutant'. The first region terminates when the rain ceases at a point with, or prior to, the trailing edge of the pollutant passing. The final range (IV) starts where the front of the rain passes the front of the pollutant, consequently deposition to points progressively further to the right of that point comes from increasingly more depleted cloud, and total deposition diminishes. The form of the central section depends on the order in which the terminating condition for the first region and the starting condition for the final region occur. If the first region's termination occurs first then there is a region of uniform deposition in the centre, as shown in figure 2.3a. The alternative case, shown in figure 2.3b, occurs for positions which do not receive material from initially undepleted cloud, since the rain reaches them first, but where deposition is terminated by the passing of the cloud rather than the rain. Consequently there is no region of uniform deposition.

2.3.2 Pollutant Moving in the Opposite Direction to the Rain

In this case the rain distribution advects in the direction opposite to that of the pollutant, corresponding to a reversal of the wind direction with height.

The rain and pollutant distribution are defined by

$$J_0(x) = \begin{cases} J'' & \text{for } x_s \leq x \leq x_s + R \text{ with } R > 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.23)$$

and

$$P_0(x) = \begin{cases} P'' & \text{for } x_s + S \leq x \leq x_s \text{ with } S < 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.24)$$

with $F(t) = 1$ and $W(t) = w$ as previously, and with the velocity constraints of $v < 0$ and $u > 0$. Converting $J_0(x)$ to the variable used in calculating the scavenging attenuation factor, (equation 2.2.6), gives

$$J_0(x - u(t - t') - vt') = J''$$

$$\text{for } x_s \leq x - u(t - t') - vt' \leq x_s + R \quad (2.3.25)$$

which, rearranged to give the range in terms of t' , becomes

$$\frac{x_s - x + ut}{u - v} \leq t' \leq \frac{x_s - x + R + ut}{u - v} \quad (2.3.26)$$

and by substituting into equation (2.2.6) and integrating we get

$$\begin{aligned} D(x, t) &= \exp \left\{ -\Lambda_0 J'' \left[t - \frac{x_s - x + ut}{u - v} \right] \right\} \\ &= \exp \left\{ \frac{-\Lambda_0 J''}{u - v} (x - x_s - vt) \right\} \end{aligned} \quad (2.3.27)$$

Similarly, converting $J_0(x)$ and $P_0(x)$ to the variables used in $G(x)$, the deposition function (equation 2.2.8), gives

$$\begin{aligned} J_0(x - vt) &= J'' \quad \text{for } x_s \leq x - vt \leq x_s + R \\ \Rightarrow \quad \frac{x - x_s}{v} &\leq t \leq \frac{x - x_s - R}{v} \end{aligned} \quad (2.3.28)$$

and

$$\begin{aligned} P_0(x - ut) &= P'' \quad \text{for } x_s + S \leq x - ut \leq x_s \\ \Rightarrow \quad \frac{x - x_s}{u} &\leq t \leq \frac{x - x_s - S}{u} \end{aligned} \quad (2.3.29)$$

And from substitution and integration we get

$$\begin{aligned} G(x) &= w \Lambda_0 J'' P'' \int_{\max(\frac{x-x_s}{u}, \frac{x-x_s}{v})}^{\min(\frac{x-x_s-R}{v}, \frac{x-x_s-S}{u})} D(x, t) dt \\ &= w P'' \frac{(u - v)}{v} \exp(-\Lambda_0 J''(x - x_s)) \\ &\quad \times \left[\exp \left\{ \frac{\Lambda_0 J'' vt}{u - v} \right\} \right]_{\max(\frac{x-x_s}{u}, \frac{x-x_s}{v})}^{\min(\frac{x-x_s-R}{v}, \frac{x-x_s-S}{u})} \end{aligned} \quad (2.3.30)$$

for the deposition function. This, in common with the previous case, has four distinct solutions, corresponding to four different regions of the x -axis.

These are given below:-

Range I

$$\frac{(u - v)x_s - vS}{u - v} \leq x \leq \min \left(x_s, \frac{(u - v)x_s + uR - vS}{u - v} \right) \quad (2.3.31)$$

$$G_I(x) = wP'' \frac{(u-v)}{v} \left[\exp \left(\frac{-\Lambda_0 J''}{(u-v)u} [(u-v)(x-x_s) + vS] \right) - 1 \right] \quad (2.3.32)$$

Range II

$$\frac{(u-v)x_s + uR - vS}{u-v} \leq x \leq x_s \quad (2.3.33)$$

$$G_{II}(x) = wP'' \frac{(u-v)}{v} \left[\exp \left(\frac{-\Lambda_0 R J''}{u-v} \right) - 1 \right] \quad (2.3.34)$$

Range III

$$x_s \leq x \leq \frac{(u-v)x_s + uR - vS}{u-v} \quad (2.3.35)$$

$$G_{III}(x) = wP'' \frac{(u-v)}{v} \exp \left(\frac{-\Lambda_0 J''}{u} (x-x_s) \right) \left[\exp \left(\frac{-\Lambda_0 J'' S}{u-v} \right) - 1 \right] \quad (2.3.36)$$

Range IV

$$\max \left(x_s, \frac{(u-v)x_s + uR - vS}{u-v} \right) \leq x \leq \frac{(u-v)x_s + uR}{u-v} \quad (2.3.37)$$

$$G_{IV}(x) = wP'' \frac{(u-v)}{v} \left[\exp \left(\frac{-\Lambda_0 J'' R}{u-v} \right) - \exp \left(\frac{-\Lambda_0 J''}{u} (x-x_s) \right) \right] \quad (2.3.38)$$

2.3.3 Uniform Advection

This situation models the pollutant moving with the rain, but with the rain falling for a limited period of time only. This is most likely to occur when the pollutant is incorporated into the rain generating region of the atmosphere. However, the model is still purely of scavenging therefore the conceptual layer separation is retained.

The functions defining this situation are given by

$$J_0 = \begin{cases} J'' & \text{for } x_s \leq x \leq x + R \text{ with } R > 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.39)$$

$$P_0 = \begin{cases} P'' & \text{for } x_s \leq x \leq x + S \text{ with } S > 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.40)$$

and

$$F(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T, \\ 0 & \text{otherwise.} \end{cases} \quad (2.3.41)$$

With $W(t) = w$, again, and the velocity constraint is $u = v > 0$. Since deposition can only occur where the pollutant and precipitation overlap,

then the definition $L = \min(R, S)$ can be used to simplify functions (2.3.39) and (2.3.40) to

$$J_0(x) = J'' \quad \text{for} \quad x_s \leq x \leq x + L \quad (2.3.42)$$

and

$$P_0(x) = P'' \quad \text{for} \quad x_s \leq x \leq x + L \quad (2.3.43)$$

This case also gives four surface concentration regions over four ranges of the x -axis. These are given by:-

Range I

$$x_s \leq x \leq \min(x_s + uT, x_s + L) \quad (2.3.44)$$

$$G_I(x) = wP'' \left[1 - \exp \left(\frac{-\Lambda_0 J''}{u} (x - x_s) \right) \right] \quad (2.3.45)$$

Range II

$$x_s + uT \leq x \leq x_s + L \quad (2.3.46)$$

$$G_{II}(x) = wP'' [1 - \exp(-\Lambda_0 J'' T)] \quad (2.3.47)$$

Range III

$$x_s + L \leq x \leq x_s + uT \quad (2.3.48)$$

$$G_{III}(x) = wP'' \exp \left(\frac{-\Lambda_0 J''}{u} (x - x_s) \right) \left[\exp \left(\frac{\Lambda_0 J'' L}{u} \right) - 1 \right] \quad (2.3.49)$$

Range IV

$$\max(x_s + uT, x_s + L) \leq x \leq x_s + L + uT \quad (2.3.50)$$

$$G_{IV}(x) = wP'' \left[\exp \left(\frac{-\Lambda_0 J''}{u} (x - x_s - L) \right) - \exp(-\Lambda_0 J'' T) \right] \quad (2.3.51)$$

2.3.4 Stationary Rain-Band

This derivation is included so that comparisons can be made between this model and results from a Gaussian plume model. The situation is of a pollutant distribution which moves under a band of rain which maintains a fixed position. This, as explained in section 2.4, is effectively how wet deposition is treated in a plume model.

The functions defining this situation are

$$J_0(x) = \begin{cases} J'' & \text{for } x_s \leq x \leq x_s + R \text{ with } R > 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.52)$$

and

$$P_0(x) = \begin{cases} P'' & \text{for } x_s + S \leq x \leq x_s \text{ with } S < 0, \\ 0 & \text{otherwise,} \end{cases} \quad (2.3.53)$$

with $F(t) = 1$, $W(t) = w$, $v = 0$ and $u > 0$. This gives one region of deposition of the form

$$G(x) = w\Lambda_0 J'' P'' \frac{(-S)}{u} \exp \left\{ \frac{-\Lambda_0 J''}{u} (x - x_s) \right\} \quad (2.3.54)$$

over the range $x_s \leq x \leq x_s + R$.

2.4 THE SEGMENTED GAUSSIAN PLUME MODEL

Wet deposition is frequently modelled by the inclusion of a scavenging term into a Gaussian plume model. This is the method used by the models MARC (Clarke and Kelly, 1981) and CRAC2 (Hemming *et al*, 1983), and is also the method recommended by the UK working group on atmospheric dispersion (Clarke 1979, Jones 1981). A simple means of achieving this, known as the segmented Gaussian plume, is to assess the conditions governing the material's dispersion and deposition at certain times, typically hourly. Between sampling times, the plume moves from its state at the most recent sampling time, expanding and depositing material according to the meteorological and surface conditions measured or imposed at that data sampling time. The common interpretation of this is to consider that at the time of sampling the conditions of interest change uniformly and universally to the new values which then persist until the next sampling time. An alternative interpretation is to consider the material to be moving through bands of meteorological and deposition conditions, with each band occupying the position that the material moved through during the period that those conditions were in force. The two interpretations are equivalent since a plume model does not include along-wind dispersion. The global change interpretation only affects material lying in regions corresponding to the bands of the banded interpretation.

The situation in which rain falls during a travel segment after one or more dry segments is meteorologically the same as the special case model for a stationary rain band, which was derived in section (2.3.4). The deposition which would result from a Gaussian plume model in these circumstances is given by

$$D_{GP}(x) = \frac{Q}{\sqrt{2\pi}\sigma_y(x)u} \exp\left(\frac{-\Lambda_0 J''}{u}(x - x_s)\right) \Lambda_0 J'' \quad (2.4.1)$$

obtained from Jones (1981). Using the approximation that the lateral dispersion is fixed at a value corresponding to the value it would have at downwind distance $x = x_s$, so that

$$w = \frac{1}{\sqrt{2\pi}\sigma_y(x_s)} \quad (2.4.2)$$

and noting that $Q = P''(S)$, since $S < 0$, then equations (2.4.1) and (2.3.54) are equivalent. Therefore the special case model of sub-section (2.3.4) is equivalent to the segmented Gaussian plume model for this specific wet deposition situation. This permits a direct comparison to be made between a wet deposition distribution resulting from a Gaussian plume, and that from the one dimensional model, with its more realistic representation of precipitation.

2.5 CALCULATED DEPOSITION DISTRIBUTIONS

Deposition distributions for a number of comparison cases have been calculated. These make use of the four special case model derivations of section 2.3, but the cases have a number of common factors.

The releases are all of 10^6 Bq, which is released instantaneously or over a half or one hour period. This material then moves at a steady 18 kmhr^{-1} (5 ms^{-1}) and first encounters rain after five hours of dry travel, at which time it is 90 km downwind. The released material is distributed uniformly over a length, S , which is the length that is imposed by the wind-speed and release duration, plus an along wind dispersion term. This term is taken as the lateral dispersion value from Clarke (1979) for dispersion category-D conditions after 100 km of travel. Since the material will be moving during the

interaction with the rain, the value at 100 km is more likely to be a mean value during the interaction than the value for 90 km. The pollutant distributions are positioned so that their leading edges reach the 90 km position after five hours of travel, rather than their centres. This is to facilitate comparisons between the different cases and does not affect the results, because it only serves to shift the start of the interactions to that position. The lateral dispersion parameter, w , is also calculated from the same 100 km, category-D value. Table 2.1 summarises these conditions common to all the distributions.

Table 2.1 Parameters common to all calculated deposition distributions.

Q	Quantity released	10^6 Bq
Λ_0	Scavenging constant	$5 \times 10^{-5} \text{ s}^{-1} \text{ mm}^{-1} \text{ hr}$
u	Pollutant advection velocity	5 ms^{-1}
x_s	Pollutant/rain initial interaction point	$9 \times 10^4 \text{ m}$
σ_y	Typical lateral standard deviation during the interaction	$7 \times 10^3 \text{ m}$

The rain intensity used for the majority of the cases is 25 mmhr^{-1} , which is a heavy rainfall rate and has been chosen because extreme cases are a major concern with wet deposition, for example when material which has travelled through dry conditions encounters heavy rain over a densely populated area. Two cases have, however, been plotted using the much lower rain-rate of 2.5 mmhr^{-1} . A fixed value of $5 \times 10^{-5} \text{ s}^{-1} \text{ mm}^{-1} \text{ hr}$ has been used for the scavenging constant, Λ_0 . A more detailed analysis of suitable values for this parameter is left to chapter five.

The length of the rain cloud for the fixed rainband case is the distance travelled in one hour by the pollutant. This is a typical time separation used for data sampling in segmented Gaussian plume models, and a consequence of this form of modelling is that if it is raining at a sampling time, then a band of that width occurs even if in practice the rain stops much sooner.

Again, for the sake of the comparisons being made, this length is normally also used for the rainbands in the other cases.

Table 2.2 gives the specific conditions for each of the ten calculated distributions. The first five of these distributions, plotted in figure 2.4, are examples of the 'rain overtaking pollutant' situation described in section 2.1 and derived in sub-section 2.3.1. The first three are for a one hour rain duration at a surface point which corresponds to an 18 km long rain function, but for the three different release durations of instantaneous, half an hour and one hour. These show that the range of the non-zero sections of the surface distributions increases with increased release duration, this range for the one hour release being nearly twice that of the instantaneous release, with the half hour release fitting between them. The longer pollutant distribution, arising from a longer release duration, gives rise to this longer surface distribution since it takes more time for the rain to move clear of the pollutant distribution, and consequently this happens further down-wind. There is, however, a corresponding reduction in the peak contamination with increasing release duration since the total quantity released is fixed and therefore spread more thinly in longer releases.

Table 2.2 Parameters defining each deposition distribution.

No.	R km	d hr	v ms ⁻¹	J mmhr ⁻¹
1	-18	0	10	25
2	-18	0.5	10	25
3	-18	1	10	25
4	-36	0	10	25
5	-36	0.5	10	25
6	-18	0.5	10	2.5
7	-36	0.5	10	2.5
8	18	0.5	0	25
9	18	0.5	-5	25
10	18	0.5	5	25*

- R - Length of rain distribution.
- d - Release duration.
- v - Rain distribution velocity.
- J - Rain intensity.
- * - Rain stops after one hour.

Distributions four and five are for a two hour rain duration at a surface point, and instantaneous and half hour release durations respectively. These are very similar to the distributions for the one hour rain duration and corresponding release duration. There are two reasons for this. Firstly, the start of the surface distribution, x_s , and the point at which it starts to drop sharply, which is the boundary between regions II and IV, are independent of the length, R , of the rain distribution. This can be seen in figure 2.3a. Consequently the general positions of the function pairs are the same. The second reason is the high rain intensity of 25 mmhr^{-1} . This removes most of the material from the pollutant distribution very quickly leaving little for the extra 18 km of rain distribution to remove and therefore little is added to the surface distributions. The high rain intensity also hides differences in the downwind tails of the distributions, which extend further for the longer rain distributions, but at too low a concentration to be visible on the curves of figure 2.4.

Distributions six and seven are for the lower, 2.5 mmhr^{-1} , rain intensity but otherwise match two and five respectively. The difference between them is much more marked than with higher rain intensity distributions, due to the slower removal of material. This is shown in figure 2.5. Also shown, for comparison, is distribution two, which has a peak value less than twice that of seven, and less than three times that of six. Again this shows that the level of distribution two is limited by material availability since it has not increased by as much as the increase in rain intensity.

Distribution eight is a 'stationary rain band' case and therefore closely corresponds to the distribution from a segmented Gaussian plume. It uses a half hour release and a one hour rain duration. Figure 2.6 shows this distribution together with distribution two, which is for the same release and rain durations, and can therefore be directly compared. The comparison, as expected, shows a very different distribution form with the peak of the stationary band distribution more than thirteen times that of distribution two. Consequently distribution two covers a greater range and extends 65 km

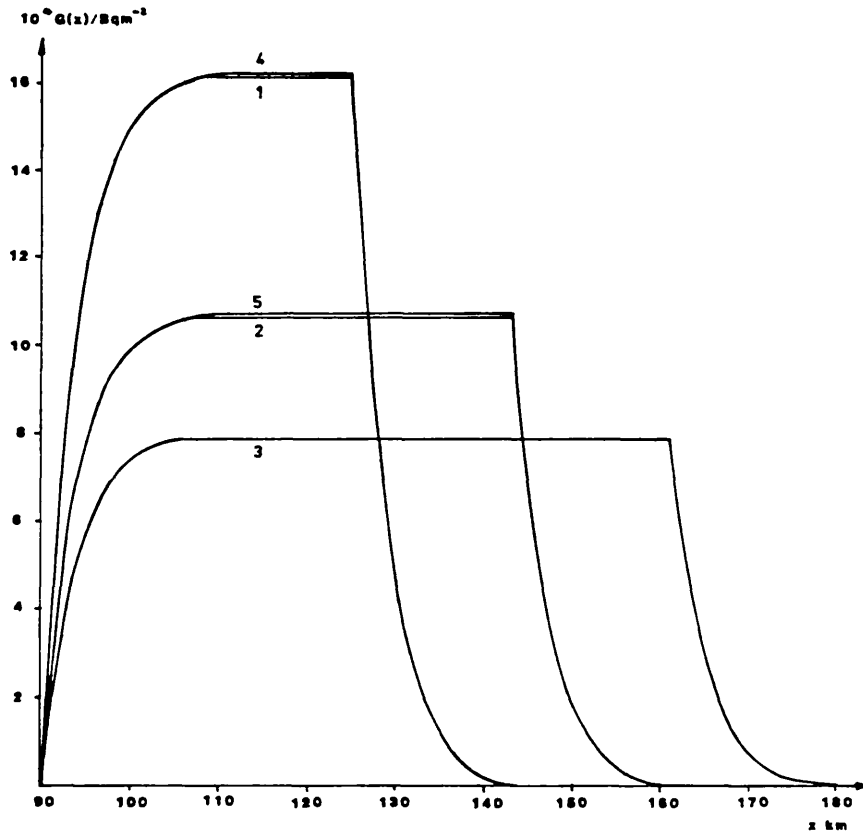


Figure 2.4. 'Rain overtaking pollutant' deposition distributions for high (25 mmhr^{-1}) rain intensity.

downwind from the point of first rain/pollutant interaction compared with just 16 km for distribution eight.

Both of these distributions could in theory arise from different models of the same situation. This could occur if the meteorological situation of a rain band catching up with a pollutant cloud, was also modelled using a segmented Gaussian plume, with a stationary rain band positioned by sampling the meteorological situation at or near the release site. Together with the different distribution shapes, the one from the plume model will also be positioned too close to the release site since the rain would reach the sampling position prior to reaching the moving pollutant cloud.

The consequence of using the physically more realistic model in this situation might be to have the maximum predicted level below some level of

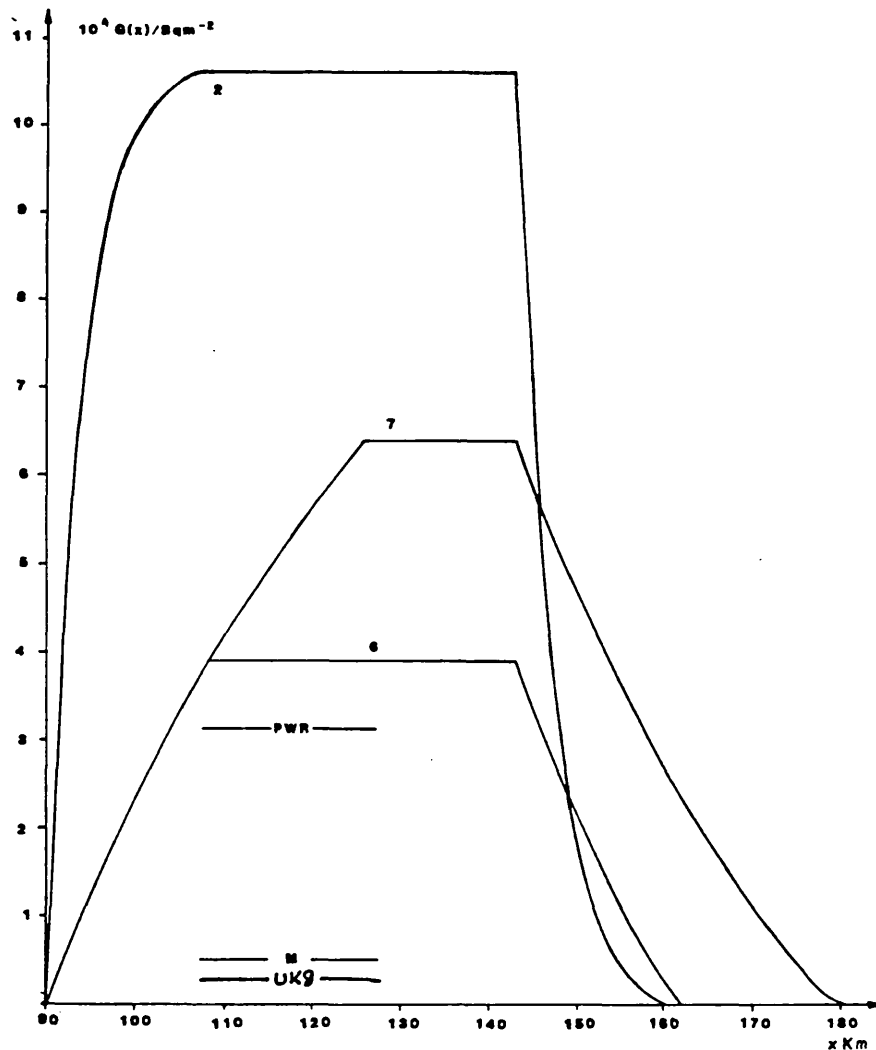


Figure 2.5. 'Rain overtaking pollutant' distributions for low (2.5 mmhr^{-1}) rain intensity. Distribution two included for comparison and 25 mSv ERL's also shown.

concern. Alternatively, if such a level is still exceeded it is likely to be exceeded over a much greater area than with a plume model. This is considered in more detail in the following section.

The final two distributions, nine and ten, are shown in figure 2.7. Distribution nine is for the rain and pollutant distributions moving in opposing directions and ten for two distributions moving together, but the rain only lasting for one hour. Both give narrower distributions with higher peak values than distribution two. In the first case this is because the opposing directions of movement constrain the surface range of the interaction and

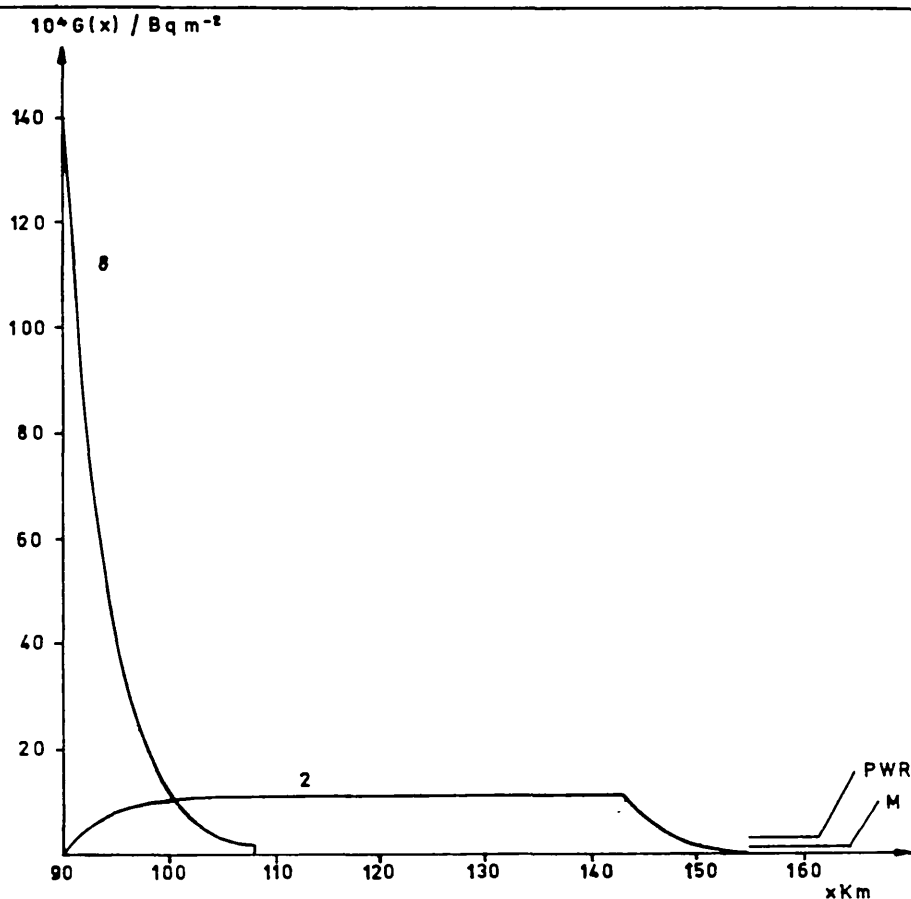


Figure 2.6. 'Stationary rain band' deposition distribution (8) with distribution two included for comparison and 25 mSv ERL's also shown.

in the second, because with the rain positioned over the puff there are no periods of partial overlap to extend the surface distribution.

2.6 INTERPRETATION OF DEPOSITION LEVELS

To show the significance to environmental consequences of the variations in distribution ranges and levels for the calculated distributions, the levels have been compared to an emergency reference level (ERL) of dose. The level chosen is that for sheltering due to exposure to gamma sources deposited on the ground, which is currently set at 25 mSv by the National Radiological Protection Board (NRPB, 1981) of the UK. This is used since it directly relates dose to surface position, unlike exposure from foods, such as milk, which can occur away from the original deposition site and consequently suffer from averaging processes.

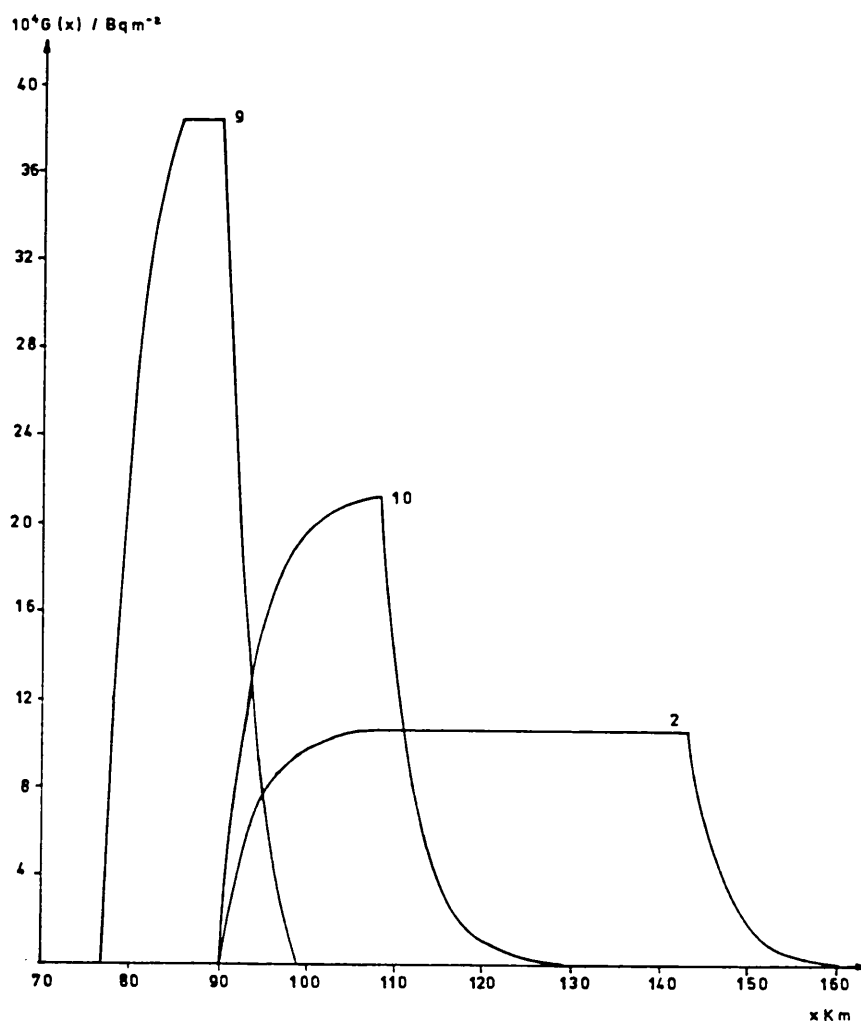


Figure 2.7. 'Pollutant direction opposing rain direction' (9) and 'uniform advection' (10) special case derivations, with distribution two for comparason.

The ranges over which this level would be exceeded by people resident permanently at a location for a year, are shown on the graphs of figures 2.5 and 2.6 for a selection of hypothetical reactor accidents. The accidents considered are a magnox single channel melt and depressurisation, a PWR design basis accident and six of the twelve categories of PWR degraded core accidents, which are referred to as UK1 to UK12. The six considered are for a half hour release. Estimates of the material released for the first two accidents were obtained from Taylor (1986) and from Kelly and Clarke (1982) for the others.

The significant gamma emitters released in these accidents have been identified by Stott (1986) and from these, by normalizing to the 10^6 Bq releases used in the ten sample distributions, the level of surface concentration at which the ERL is exceeded for each accident has been calculated. These levels are given in table 2.3 and, where possible, marked on figures 2.5 and 2.6.

Table 2.3 Contamination level for 25mSv ERL for releases normalised to 10^6 Bq.

Accident	Normalized ERL (Bqm^{-2})
UK2	3.93×10^{-6}
UK3	2.58×10^{-6}
UK5	5.15×10^{-6}
UK6	8.27×10^{-6}
UK7	7.48×10^{-4}
UK8	3.05×10^{-1}
PWR	3.09
M	0.46

UKn - PWR degraded core accidents with a half hour release.

PWR - PWR design basis accident.

M - Magnox single channel melt.

The first five accidents, UK2, 3, 5, 6 and 7, are so large that the ERL is exceeded wherever there is any wet deposition and would probably be exceeded by dry deposition alone, which is not included in the model.

The remaining three accidents do lie within the range of the calculated distributions and are shown in the figures.

Distribution two exceeds the ERL for all the accidents and from figure 2.6 it can be seen that this makes a considerable difference to the range over which excess contamination occurs, relative to distribution eight for the fixed rain band. This difference could clearly be significant in a real accident.

2.7 CONCLUSIONS

The most important result presented is the comparison between distributions two and eight in figure 2.6, especially when considering the difference in areas exceeding some threshold which are predicted by the two different models of the same situation. These areas may not even overlap. The results clearly indicate the shortcomings in wet deposition modelling using a simple Gaussian plume approach, and the need for better modelling techniques.

The other results presented cover a range of idealized meteorological circumstances, which a release of pollutant material could encounter. They differ mainly in the positioning and movement of their respective rain distributions. This serves to show the importance of including rain in deposition models in the meteorologically more realistic form of localized, mobile areas, rather than treating it as a uniform occurrence switched on and off.

The model presented here, however, is too restricted to be of practical use in modelling real accident situations. Even if the general surface distribution equation, equation (2.2.8), was solved numerically for general forms of the component functions, rather than for very simplified analytic forms, it would still be inadequate. In particular, the limitations restricting its general applicability are the uniform advection velocities, no along wind dispersion and, more fundamentally, only being one dimensional. For these reasons, having identified the need for modelling using more realistic precipitation information, a more sophisticated model was required and this is described in the following chapter.

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CHAPTER 3.

TWO DIMENSIONAL NUMERICAL WASHOUT MODEL

3.1 MODEL REQUIREMENTS AND DESCRIPTION

A study of the spatial distribution of wet deposited material needs to include both the two horizontal dimensions. In principle it would be possible to extend the case studies of chapter two using a two dimensional analytic model derived along similar lines to the one dimensional version. In practice this approach was not used due to inherent restrictions. These included problems with modelling dispersion and permitting non-constant pollutant advection, which would be difficult, or impossible, to overcome with this form of model.

A less restrictive form of model was therefore required and a number of options were considered. The most general would have been to use a three dimensional numerical solution of the equations governing the behaviour of the atmosphere, together with those describing pollutant dispersion and deposition. This could have been similar to a weather forecasting model such as the one described by Gadd (1985). However, such models were not considered suitable for this work for a variety of reasons. For example their modelling of cloud formations is often fairly crude, because clouds are often smaller than the model's grid size and this consequently affects the accuracy of their predictions of rain. Uncertainties in pollutant behaviour on the scale required by such models and their prohibitive computational expense also ruled out their use.

The required model needs to be able to provide two dimensional distributions of surface concentrations of deposited material arising from a release of pollutant material. To do this it needs to simulate the advection and dispersion of the material together with its interaction with precipitation and removal to the surface. Along-wind dispersion is clearly important in the relative positioning of material and rain, which ruled out a Gaussian plume

model, but which could be achieved using discrete puffs of material exhibiting Gaussian dispersion in both horizontal directions. The method used is therefore a Lagrangian model of a puff of material moving under the influence of the wind, and wherever it encounters rain it loses material to the ground beneath.

The next consideration is the form of the representation of the rain which it is to encounter, as the accuracy of this will greatly affect the accuracy of the surface concentrations. Rain measurements are made routinely at meteorological sites, but these form a sparse, irregular grid and readings are normally only of daily, or six hourly totals. This is both spatially and temporally inadequate to be used in improved wet deposition modelling. Two alternatives have, however, made improvements possible. The first is work on simulating rain systems with mobile 'areas' of rain of a uniform intensity. These are used in combinations of various sizes which persist for differing time periods such that the overall effect matches rain systems which have been studied. The second is the measurement of rain intensities by radar which is now routinely available for much of England and Wales.

Both forms of rain data are essentially two dimensional, although there is some limited vertical information available from the radar measured data. Consequently this model retains the layered form of the previous model, with the rain always considered to fall from a level above the region occupied by the puff of pollutant material.

A more detailed description of the two forms of precipitation data used is given in section 3.2 since the availability of this data has largely dictated the form of the model. This is followed by the mathematical description and necessary proofs of the model's structure and the method used to determine surface deposition distributions.

Together with precipitation, the model also needs meteorological data from which to determine the trajectory followed by a release of material. This is achieved using hourly averaged surface wind data, and the interpolation scheme used is presented in section 3.5. Penultimately, in section 3.6, the

methods used to incorporate radioactive decay and dry deposition into the model are explained before, finally, a description is given of the set of computer programs known collectively as RAIN-PATCH, which together form the model.

There remains one important aspect of the model, which is the simulation of the redistribution of material within the puff after it has become non-uniformly depleted. This is covered in chapter four.

3.2 PRECIPITATION DATA

3.2.1 Studies of the Spatial Structure of Precipitation

Prior to rain intensity data measured by radar becoming available, it was intended to use existing data on the spatial structure of rain systems to generate simulations of 'typical' rain systems for use as input to the model. A number of studies providing such data have been undertaken, two of particular note being those by Austin and Houze (1972) and Browning and Harrold (1969).

The first is a study of eight separate storms in New England. This was carried out using sequences of photographs of conventional, analogue, plan position indicator radar displays showing rain intensity data. From these the spatial structure of the storms was analysed and a set of hierarchical precipitation regions identified. The largest region, called the synoptic region, has an area of at least 10^4 km^2 . It is long lived but has only a low rain intensity. A typical storm consists of a synoptic region containing one or more of the next smaller regions, called the Large Meso Scale Area (LMSA), which have a shorter life but a greater rain intensity. The same principle applies to the remaining two region types, namely the Small Meso Scale Area (SMSA) and Cells, which are the smallest regions. Cells frequently occur within SMSAs, which in turn can occur in LMSAs but the ordering is not rigid and the intermediate regions may not always exist. Sufficient detail is given on the frequency of occurrence, typical dimensions and rain intensities of the various

regions for it to be possible to construct a 'typical' storm. This could then be used as precipitation data for a deposition model.

The work by Browning and Harrold is a study of a single wave depression which travelled across the British Isles on 16 October 1967. Together with a detailed analysis of the synoptic situation, a study of the surface rainfall distribution was carried out. This revealed a large area of uniform rain ahead of the surface warm front, followed by a series of bands of rain containing embedded cells of a higher rain intensity. These bands were of two types, one lying parallel to the warm front, and the other in the warm sector aligned parallel to the wind. Figure 3.1, taken from the paper, is a schematic representation of the situation constructed from a series of rainfall charts obtained during the passage of the depression. This work also has sufficient detail for the creation of a simulation of the depression.

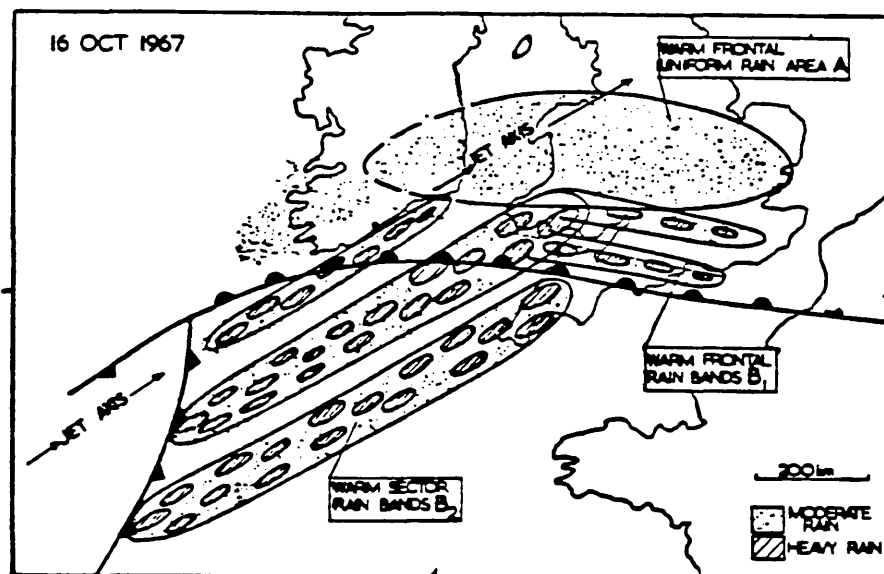


Figure 3.1. Structure of a wave depression. From Browning and Harrold (1969).

An initial version of the RAIN-PATCH computer model was developed to use these idealised representations of rain systems. This would have restricted its use to a limited number of case studies of fronts and storms, so

subsequent versions were developed to use radar-measured precipitation data directly. This has greatly extended the capabilities of the model.

3.2.2 Precipitation Intensities Measured by Radar

The original military users of radar were hampered by clutter, or unwanted echoes which could not be explained as echoes from fixed objects. Some of these were eventually identified as being caused by the scattering of the radar's microwave beam by precipitation particles. This phenomenon has since been put to use in meteorological research and, more recently, in operational weather forecasting.

The process is essentially that a transmitted pulse of microwave radiation, on encountering precipitation particles (the target), will have part of its energy scattered. Some of this scattered energy will be directed back to the receiver, co-located with the transmitter, and from this a number of properties of the target can be determined. The first property, the separation, r , of the transmitter/receiver and the target is a simple function of the time period, T , between the pulse's transmission and the reception of the returned signal. This is given by $r = cT/2$, where c is the transmission speed of microwaves in air. The second property is the component of the target's velocity along the direction of the line joining the transmitter/receiver and the target. This is determined from the frequency change (Doppler shift) of the returned signal relative to the transmitted signal.

The third property is the intensity of precipitation scattering the pulse. This is given as a function of the power, P_r , of the reflected pulse reaching the receiver, by

$$10 \log P_r = 10 \log Z - 20 \log r + C, \quad (3.2.1)$$

which is derived by Rogers (1979). C is a constant dependent on the characteristics of the radar and $10 \log Z$ is called the reflectivity factor, with Z defined by

$$Z = \int_{\text{Unit vol.}} N(D) D^6 dD. \quad (3.2.2)$$

Where D is the raindrop diameter, and $N(D)$ is the drop-size number density per unit volume.

If a typical drop-size spectrum is assumed, then Z can be related directly to a rainfall rate, J , which can be calculated from P_r , using equation (3.2.1). Using the Marshall-Palmer raindrop distribution (Rogers 1979) gives

$$N(D) = N_0 \exp(-41J^{-0.21}D), \quad (3.2.3)$$

where N_0 is a constant and therefore, from (3.2.2)

$$Z = N_0 \frac{6!}{41^7} J^{1.47} \quad (3.2.4)$$

The Meteorological Office currently has a network of five radars continually measuring precipitation data. Their locations are shown in figure 3.2 and work is underway to extend this network (Collier 1986). The individual radars are generally provided by consortia involving water authorities, local government and the Meteorological Office. Together with providing data for the water catchment areas local to the radar sites, the data is also collected centrally and used in the FRONTIERS (Forecasting, Rain Optimised using New Techniques of Interactive Enhanced Radar and Satellite data) forecasting scheme. This provides short range precipitation forecasts utilizing radar data together with data from Meteosat and it has been used operationally in Meteorological Office forecasts since 15 December 1986. A description of FRONTIERS, albeit at a pre-operational stage, is given by Browning and Carpenter (1984).

Each radar site in the network provides a regular grid of cell averaged, digital, rain intensity levels per scan of the radar. The radars normally scan at the four elevations of 0.5° , 1.5° , 2.5° and 4.0° with the data averaged over 5 km square grid cells and also scan at the surface elevation, 0.5° , with the data averaged onto a 2 km square grid. The 2 km cell scan provides a regular grid of data out to the 75 km 'quantitative' limit of the radar, whereas the lower 5 km cell scan gives a grid out to the 210 km maximum range of the radar, with the higher beam elevations reaching progressively less far. These

five scans are fitted into a five minute cycle so that each type of scan gives a sequence of precipitation distributions with a five minute time resolution and either a 2 km or a 5 km spatial resolution.

The data from a single site is transmitted and recorded in a packed format from which a square grid, centred near the radar site and containing a circle of intensities data, can be reformed. The cells in the grid beyond the boundary of the range circle are always set to zero intensity. In this form the data can be applied directly to a puff-like representation of a cloud of pollutant material moving across the area covered by the data grid and material washout can be calculated on scales comparable with those of the data. In practice some pre-processing of the levels of the recorded intensity data is performed and this, together with information on the accuracy of the data is discussed in chapter five.

The model has been used mainly with data from an 84 by 84 cell grid of 5 km square cells of surface beam data from a single radar site. The exception is the work on the Chernobyl accident which made use of composite grid data obtained from all five UK radars. This is a 128 by 128 cell grid of 5 km square cells covering the area marked by the dashed line in figure 3.2, although data is only available within the 210 km circles of the constituent radars and these grids are produced only every fifteen minutes.

3.3 PUFF STRUCTURE

The primary requirement of this model is to cope with the non-uniform depletion of the puff, caused by rain not falling uniformly across the whole area of the puff. This is achieved by only giving the puff a Gaussian form prior to any washout occurring. Subsequent to washout it becomes distorted according to the quantity of rain which has fallen through different parts of it. This is done by forming the puff from a piece-wise linear function, which matches a continuous Gaussian distribution at a finite set of points, called sample points. These points are joined by planar triangular sections, and this is shown in figure 3.3 for a very simple two dimensional puff.

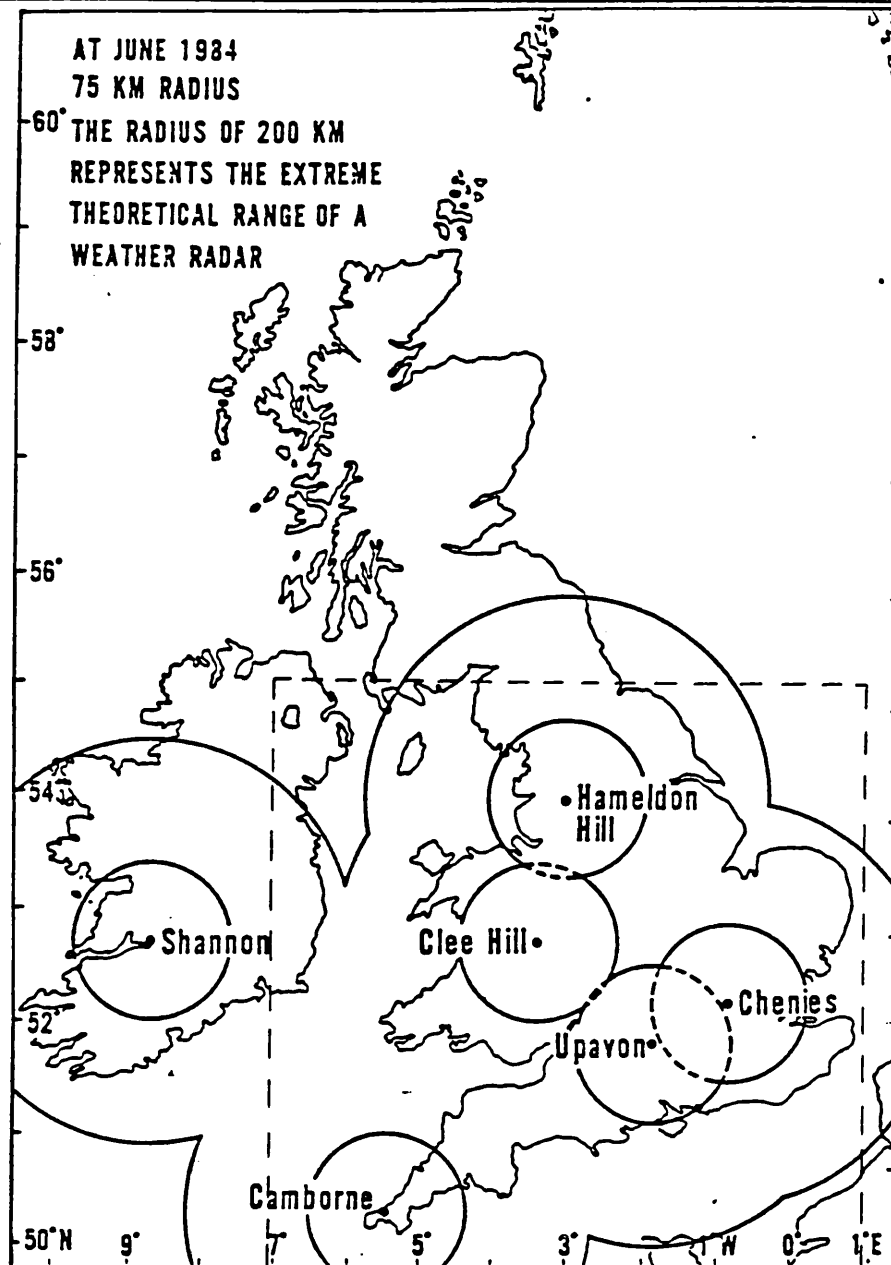


Figure 3.2. The location of the five UK weather radar systems which had been installed by June 1984, also shown is the location of an identical system at Shannon in the Republic of Ireland. The large circles, which have a radius of 200 kilometres, show the limit beyond which no data is obtained. The small circles of radius 75 kilometres, indicate the area within which it is possible to obtain measurements of sufficient accuracy to make flood forecasts. The dashed line gives the composite grid area. (From Collier 1986).

Sample points (SP's) move outwards as the puff expands so that they maintain their relative positions. These positions are defined in terms of the standard deviations of the two perpendicular Gaussian components of

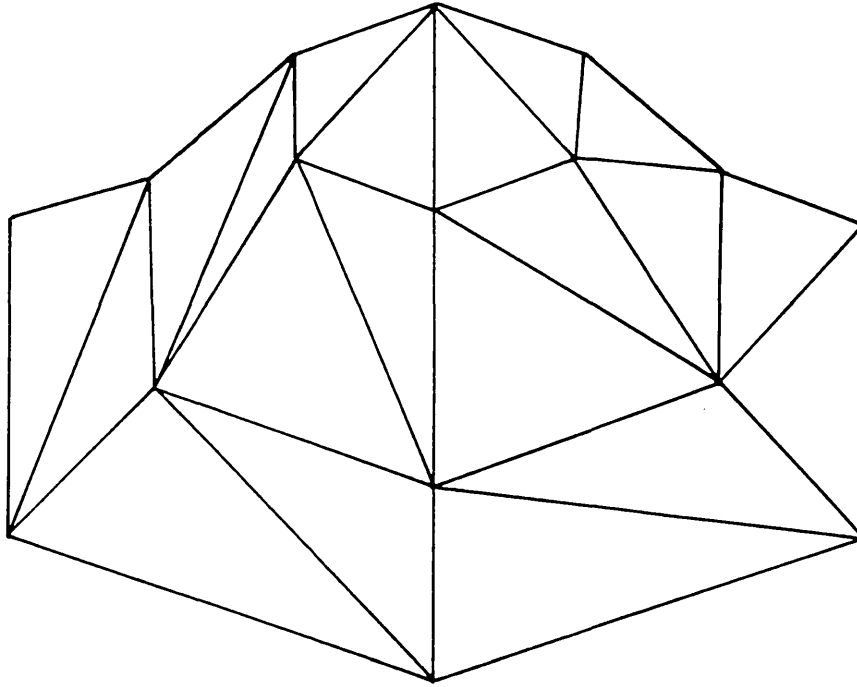


Figure 3.3. Diagram of a simple linearised two dimensional Gaussian puff.

the puff. They are also where the information defining the state of the puff locally to that SP is maintained. This includes how depleted it has become, the rain intensity currently in force, the start time for that rain intensity, and a list of the surrounding ring of adjacent SP's. This is required because washout effects occurring at an SP are considered to also occur as far out as a boundary of straight-line segments joining all the surrounding SP's, but with the magnitude of the effect reducing linearly to zero at that distance. Their positions are therefore required for calculating the region of ground over which any resulting deposition will occur.

A rigorous formulation of the puff structure of the model is now given. For clarity this is initially for a one dimensional puff and it is then extended to the two dimensional form where required.

3.3.1 One Dimensional Puff Formulation

The one dimensional linearized puff, $g(x, t)$, is defined via a set of sample points, $P = p_0(t), \dots, p_n(t)$ and the two boundary points, $b_1(t)$ and $b_2(t)$, using

$$g(p_i(t), t) = \tau G(p_i(t), t); \quad \forall i \in (0, n)$$

and

$$g(x, t) = 0 \quad \text{for} \quad x \leq b_1(t) \quad \text{and} \quad x \geq b_2(t), \quad (3.3.1)$$

where $G(x, t)$ is the continuous Gaussian distribution given by

$$G(x, t) = \frac{1}{\sqrt{2\pi}\sigma(t)} \exp\left(\frac{-x^2}{2\sigma^2(t)}\right), \quad (3.3.2)$$

and τ is the integral correction factor which is described below. Between adjacent sample and boundary points $g(x, t)$ consists of a series of straight line segments. This is shown in figure 3.4 for a simple case with only five sample points.

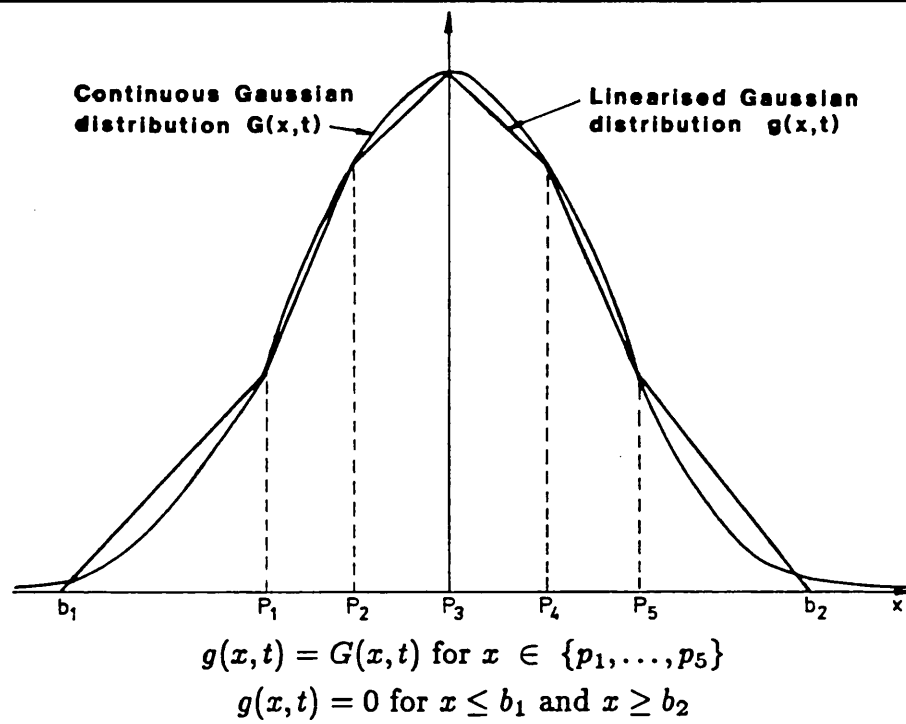


Figure 3.4. One dimensional linearised Gaussian distribution with five sample points.

Sample and boundary points move outwards from the puff centre as the puff expands to simulate dispersion. They maintain their relative positions according to the relation

$$G(p_i(t), t) = \beta_i G(0, t), \quad (3.3.3)$$

so that an SP is always at a point which, for the continuous Gaussian distribution, has a concentration which is a constant fraction of the concentration at that distribution's centre, at the same time. The constants β_i , where $0 < \beta_i \leq 1$, give this fraction and a similar definition is used for the boundary points. Knowing on which side of the puff origin an SP lies circumvents the ambiguity in the definition, which is equivalent to defining their positions in terms of the standard deviation, $\sigma(t)$. This can be shown by substituting equation (3.3.2) into the definition (3.3.3) and rearranging to give

$$p_i = (-2 \ln \beta_i)^{\frac{1}{2}} \sigma(t), \quad (3.3.4)$$

in which the first term is constant.

The integration correction factor, τ , in the definition (3.3.1), arises from the need for the total integral under $g(x, t)$ to be unity in the absence of any depletion. This is so that height integrated air concentrations can be obtained simply by multiplying $g(x, t)$ by Q , the total quantity of material represented by the puff. This factor is defined by

$$\tau \int_{b_1}^{b_2} g'(x, t) dx = 1, \quad (3.3.5)$$

where $g'(x, t)$ is identical to $g(x, t)$ except that no integral correction is made, and therefore the first clause of definition (3.3.1) reduces to

$$g'(p_i(t), t) = G(p_i(t), t). \quad (3.3.6)$$

The correction factor is constant, which can be demonstrated by considering the integral of $g(x, t)$ between the two adjacent SP's p_i and p_{i+1} , which, from the geometry of $g(x, t)$, gives

$$\begin{aligned} \int_{p_i}^{p_{i+1}} g(x, t) dx &= \frac{1}{2} [g(p_i, t) + g(p_{i+1}, t)] (p_{i+1} - p_i) \\ &= \frac{\tau}{2\sqrt{2\pi}} [\beta_i + \beta_{i+1}] \\ &\quad \times \left((-2 \ln \beta_i)^{\frac{1}{2}} - (-2 \ln \beta_{i+1})^{\frac{1}{2}} \right), \end{aligned} \quad (3.3.7)$$

by substitution from (3.3.1 – 3.3.4). Since the entire integral over $g(x, t)$ will be a summation of such terms, its form will also be a product of τ and a constant term, and since the integral is required to be constant, then τ must also be constant, as required.

Losses of material from a puff, due to depletion processes, are calculated and recorded at the sample points. This is done using the depletion factors, $\alpha_i(t)$, of which there is one associated with each SP. Initially, for an undepleted puff they all have unit value. These values are then reduced in response to the total rainfall occurring at an SP's location until zero is reached, representing total local depletion. The depleted puff has the value $\alpha_i(t)g(p_i(t), t)$ at the sample points, with consequently modified straight-line segments joining them, as shown in figure 3.5. This means that effectively any depletion at an SP is also applied to the regions out to adjacent SP's in inverse proportion to distance from the SP, and reducing to zero effect at the two adjacent SP's. Consequently, for a one dimensional puff, the material depleted from sample point i is represented by the area $A_i(t)$ bounded by the depleted and undepleted forms of the linearized puff. Thus

$$A_i(t) = \frac{1}{2} (1 - \alpha_i(t)) g(p_i, t) [p_{i+1}(t) - p_{i-1}(t)] \quad (3.3.8)$$

The second conservation requirement for the model is that if an SP becomes depleted by rain falling prior to a time t_1 and subsequently no more rain falls, then the depletion area, $A_i(t)$, should remain constant. This is the case, which can be shown by substitution of (3.3.1 – 3.3.4) into (3.3.8) to give

$$\begin{aligned} A_i(t) &= (1 - \alpha_i(t)) \tau \beta_i \left[(-2 \ln \beta_{i+1})^{\frac{1}{2}} - (-2 \ln \beta_{i-1})^{\frac{1}{2}} \right] \sigma(t) \left(\frac{1}{\sqrt{2\pi}\sigma(t)} \right) \\ &= \frac{\tau \beta_i}{\sqrt{2\pi}} (1 - \alpha_i(t)) \left[(-2 \ln \beta_{i+1})^{\frac{1}{2}} - (-2 \ln \beta_{i-1})^{\frac{1}{2}} \right] \end{aligned} \quad (3.3.9)$$

which is constant during any period when $\alpha_i(t)$ is unchanged.

3.3.2 Two Dimensional Puff Formulation

The two dimensional form follows directly from the one dimensional. The

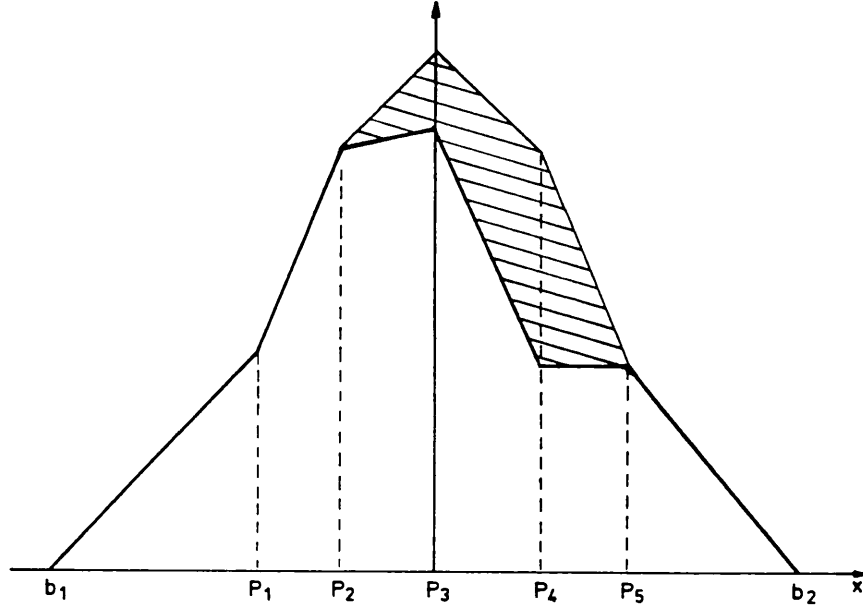


Figure 3.5. Form of linearised distribution after washout of material at sample points three and four. Hatched area gives total material removed.

sample points now lie in an area bounded by a set of boundary points, and points of both types move outwards as the puff expands, again retaining their relative positions. The linearized distribution, $g(x, y, t)$, in the regions between groups of three adjacent points is now formed from planar triangular sections.

Sample points can be positioned independently but for convenience in this work they are arranged on closed curves positioned at a constant fraction of the Gaussian peak value, and the boundary points lie on a closed curve which contains within it all the sample point curves. There is always a point at the centre of the distribution and the curves form ellipses defined by

$$G(x_i, y_i, t) = \beta_i G(0, 0, t), \quad (3.3.10)$$

where β_i performs the same function as in the one dimensional case and

$$G(x, y, t) = \frac{1}{2\pi\sigma_x(t)\sigma_y(t)} \exp\left(\frac{-x^2}{2\sigma_x^2(t)} + \frac{-y^2}{2\sigma_y^2(t)}\right), \quad (3.3.11)$$

is the continuous two dimensional Gaussian. Sample and boundary points are also constrained to lie at the intersection of these ellipses and lines which pass

through the puff centre, where the angular position of these lines is defined at a set time, t' , usually taken to be one hour after the puff release time, by the set of angles, $(\theta_1, \dots, \theta_N)$. If the sample point at the intersection of ellipse i and line n is at position $(x_{i,n}(t), y_{i,n}(t))$, then substitution of (3.3.11) into (3.3.10) gives

$$\exp \left(\frac{-x_{i,n}^2(t)}{2\sigma_x^2(t)} + \frac{-y_{i,n}^2(t)}{2\sigma_y^2(t)} \right) = \beta_i, \quad (3.3.12)$$

which permits the simple identities

$$x_{i,n}(t) = a_{i,n} \sigma_x(t)$$

and

$$y_{i,n}(t) = b_{i,n} \sigma_y(t), \quad (3.3.13)$$

for the SP's position where $a_{i,n}$ and $b_{i,n}$ are constants, such that $a_{i,n}^2 + b_{i,n}^2 = -2 \ln(\beta_i)$. At time $t = t'$, line n is positioned at angle θ_n , therefore

$$x_{i,n}(t') = r_{i,n} \cos(\theta_n)$$

and

$$y_{i,n}(t') = r_{i,n} \sin(\theta_n)$$

where

$$r_{i,n}^2 = x_{i,n}^2(t') + y_{i,n}^2(t'), \quad (3.3.14)$$

which by substitution into (3.3.12) gives

$$r_{i,n}^2 \left[\frac{\cos^2 \theta_n}{\sigma_x^2(t')} + \frac{\sin^2 \theta_n}{\sigma_y^2(t')} \right] = -2 \ln \beta$$

and therefore

$$r_{i,n} = \sqrt{\frac{-2\sigma_x^2(t')\sigma_y^2(t') \ln \beta}{\sigma_y^2(t') \cos^2 \theta_n + \sigma_x^2(t') \sin^2 \theta_n}} \quad (3.3.15)$$

so from

$$x_{i,n}(t') = a_{i,n} \sigma_x(t') = r_{i,n} \cos \theta_n \quad (3.3.16)$$

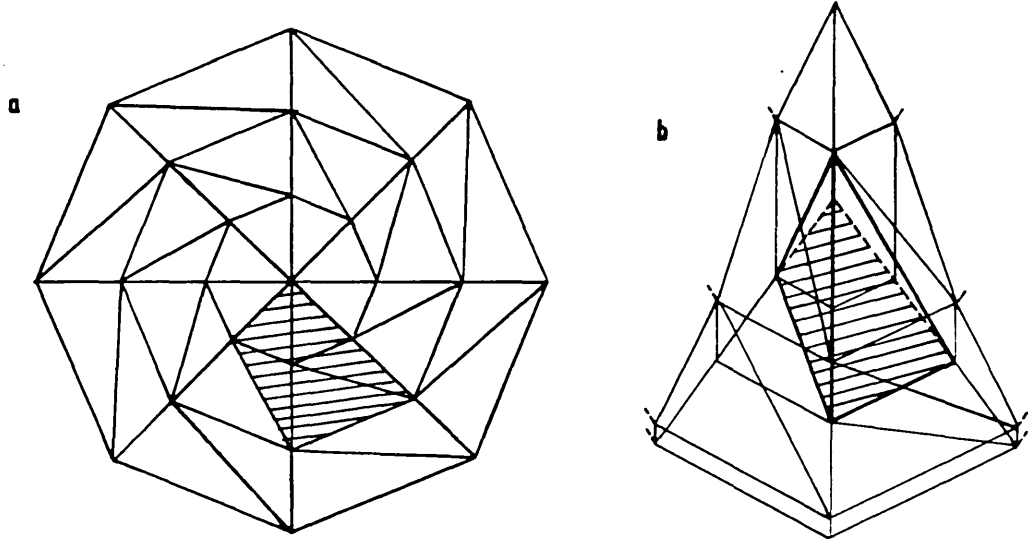


Figure 3.6. Two dimensional puff structure showing (a) plan view and (b) a section of the puff giving the volume pyramid for an SP. This has the hatched area as its base.

we get

$$a_{i,n} = \frac{r_{i,n} \cos \theta_n}{\sigma_x(t')}$$

and similarly

$$b_{i,n} = \frac{r_{i,n} \sin \theta_n}{\sigma_y(t')} \quad (3.3.17)$$

for the constants in the SP position expressions.

If the puff expands both laterally and transversely at the same rate, so $\sigma_x(t) = \sigma_y(t)$ for all values of t , then the points will always lie on the same lines, but if this is not the case then they still lie along straight lines, but the lines will move around the centre point of the puff as it expands. This can be shown by considering the angle $\theta'_{i,n}(t)$ at which the SP defined by β_i and θ_n , lies at time t . From definitions (3.3.13) and (3.3.17),

$$\theta'_{i,n}(t) = \arctan \left(\tan \theta_n \frac{\sigma_x(t')}{\sigma_y(t')} \frac{\sigma_y(t)}{\sigma_x(t)} \right) \quad (3.3.18)$$

which contains no terms in β_i , therefore the angle at which points lie is independent of their distance from the puff centre, so all the points which lie on the line at angle θ_n originally remain in a straight line.

Figure 3.6a shows a plan view of a simple puff consisting of eight lines of SP's on two circles, with a third circle of boundary points. The lines are considered to start from the origin and the more general ellipses have reduced to circles in this case since $\sigma_x(t) = \sigma_y(t)$ for all values of t . This simple puff has 17 SP's including the central one, and an outwardly anticlockwise spiral convention has been used to divide up the quadrilaterals, formed by the intersection of the lines and circles, into the required triangular segments. Again analagous to the one dimensional case, each SP has an associated depletion factor, $\alpha_{i,n}$, which records the depletion of the SP at and local to each SP. The material local to an SP which is affected by washout at that SP can be considered, in terms of the distribution, to be a pyramid. This pyramid has its apex at the position $\alpha_{i,n}(t)g(x_{i,n}(t), y_{i,n}(t), t)$ and its base corners positioned at the SP's which form the triangles having the apex SP as a common vertex. This is shown in figure 3.6b for a part of the puff shown in figure 3.6a.

A consequence of this is that strictly only one conservation condition is required, rather than the two given in the one dimensional case. This is that each pyramid should have a constant volume for a general value of the depletion factor, $\alpha_i(t)$, during any period when $\alpha_i(t)$ is unchanged. This is the case, which can be shown by considering the volume, $V_{i,n}(t)$, of the pyramid associated with the SP on circle i and line n :

$$V_{i,n}(t) = \frac{1}{3} \alpha_{i,n}(t) \beta_{i,n} g(0,0,t) A_{i,n}(t) \quad (3.3.19)$$

where $A_{i,n}(t)$ is the base area of the pyramid. From

$$g(0,0,t) = \frac{1}{2\pi\sigma_x(t)\sigma_y(t)} \quad (3.3.20)$$

for $V_{i,n}(t)$ to be independent of time during periods when $\alpha_{i,n}(t)$ is constant requires that

$$A_{i,n}(t) = A'_{i,n} \sigma_x(t) \sigma_y(t) \quad (3.3.21)$$

where $A'_{i,n}(t)$ is a constant of proportionality. Since the only time dependence in (3.3.19) comes from the standard deviation terms they will cancel if

$A_{i,n}(t)$ has this form. Figure 3.6a shows that $A_{i,n}(t)$ consists of a number of triangular elements arranged around the surface position of $SP(i,n)$, therefore it is sufficient to show that a triangle formed from any three SP surface positions has an area given by a function of the form $A''\sigma_x(t)\sigma_y(t)$, with A'' constant, so that $A_{i,n}(t)$ can be obtained by addition of the appropriate triangle areas, and consequently have the form given in (3.3.21).

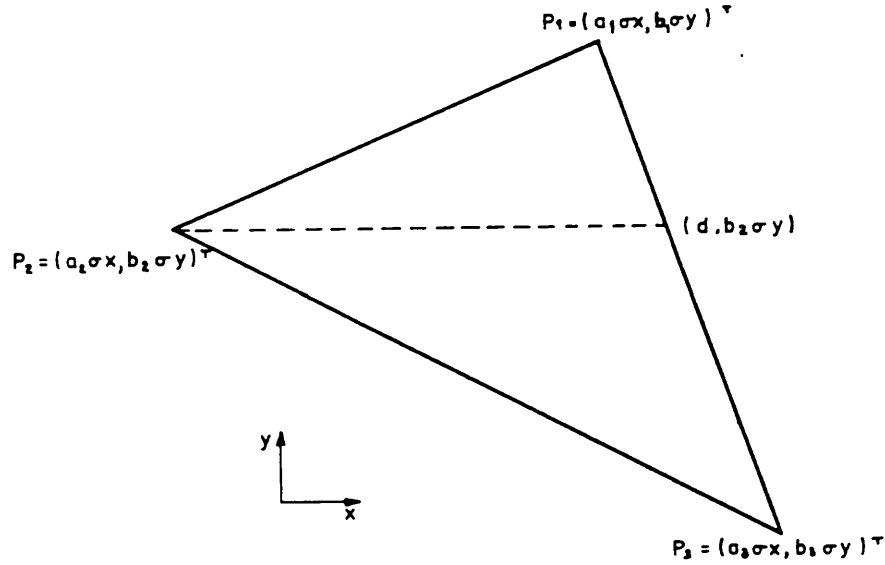


Figure 3.7. General triangular puff base element.

Consider the general triangle defined by $p_i(x, y) = (a_i\sigma_x, b_i\sigma_y)^T$ with a_i and b_i constants, for $i = 1, 2, 3$, and choosing the numbering order so that $b_1 \geq b_2 \geq b_3$, as shown in figure 3.7. Now consider the point $p_4 = (d\sigma_x, b_2\sigma_y)^T$ lying on the line from p_1 to p_3 . The area, A , of this triangle is now given by

$$\begin{aligned} A &= \frac{1}{2}(d - a_2)\sigma_x((b_1 - b_2)\sigma_y + (b_2 - b_3)\sigma_y) \\ &= \frac{1}{2}(d - a_2)(b_1 - b_3)\sigma_x\sigma_y \end{aligned} \quad (3.3.22)$$

which has the required form since d is also a constant. This can be shown by considering that point d lies on the straight line between points p_1 and p_3 so

$$\frac{b_1\sigma_y - b_2\sigma_y}{b_1\sigma_y - b_3\sigma_y} = \frac{a_1\sigma_x - d\sigma_x}{a_2\sigma_x - a_3\sigma_x}$$

and therefore

$$\frac{b_1 - b_2}{b_1 - b_3} = \frac{a_1 - d}{a_2 - a_3} \quad (3.3.23)$$

which can have no time dependence. Consequently the pyramid volume is of the required form

$$V_{i,n}(t) = V'_{i,n} \alpha_{i,n}(t) \quad (3.3.24)$$

where $V'_{i,n}$ is a constant.

A summation over $V'_{i,n}$ for all the SP's then gives the total undepleted volume of the distribution, from which an intergral correction factor, τ , can be determined, corresponding to this value for the one dimensional case.

Material is removed from these pyramids using the simple scavenging relation

$$\frac{d}{dt} V_{i,n}(t) = -\Lambda(J(t)) V_{i,n}(t) \quad (3.3.25)$$

and consequently, from (3.3.24),

$$\frac{d}{dt} \alpha_{i,n}(t) = -\Lambda(J(t)) \alpha_{i,n}(t) \quad (3.3.26)$$

which has the solution

$$\alpha_{i,n}(t) = \alpha_{i,n}(t_0) \exp \left(- \int_{t_0}^{t_1} \Lambda(J(t)) dt \right) \quad (3.3.27)$$

where $\Lambda(J'(t))$ is the scavenging coefficient, a function of the rain intensity $J(t)$. The form of this function is described in chapter five.

3.4 SURFACE MAPPING OF DEPOSITION PATCHES

If precipitation of a uniform intensity falls at the location of SP(i, n) during the period t_1 to t_2 hours then, from (3.3.24), a quantity of material,

$$D_{i,n}(t_1, t_2) = V'_{i,n} (\alpha_{i,n}(t_1) - \alpha_{i,n}(t_2)) \quad (3.4.1)$$

is removed from the puff. This material comes from the pyramid associated with that SP and is consequently deposited onto the ground over the area traversed by the that pyramid during the period t_1 to t_2 .

If the puff advects with a uniform velocity during the period t_1 to t_2 then the area over which material has been deposited can be obtained simply from the two sets of points at the positions of the SP's defining the pyramid's base at the two times. This area is then the smallest convex irregular polygon containing all the points. Strictly this is only an approximation to the area, since for general forms of $\sigma_x(t)$ and $\sigma_y(t)$, SP's will not follow straight lines even when the puff advection velocity is uniform, but this is considered not to significantly affect the surface deposition areas. A simple surface deposition polygon is shown in figure 3.8.

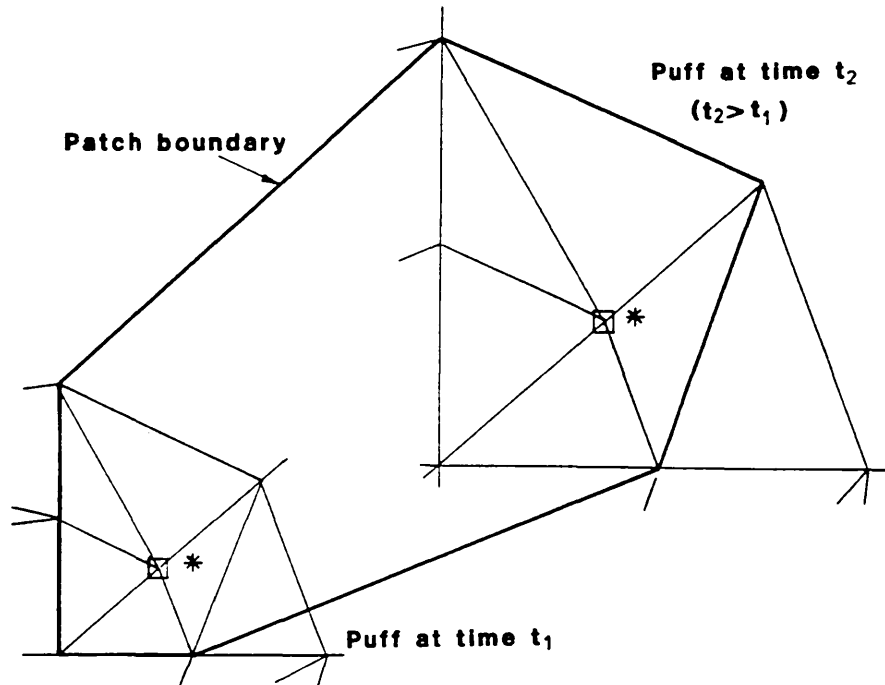


Figure 3.8. Surface patch caused by washout at the sample point marked '*' over the period t_1 to t_2 .

Three methods of mapping the deposited material, $D_{i,n}(t_1, t_2)$, onto the surface-patch area have been considered. The first and simplest is to spread the material uniformly over the area, but this takes no account of the pyramid shaped volume from which the material originated. The alternative is to create a weighting function, $W_{i,n}(x, y, t_1, t_2)$, of unit volume, which is zero at and beyond the surface-patch boundary, has a non-zero value along the line

followed by the SP(i, n) between the times t_1 and t_2 and is a linear combination of the nearest boundary and the nearest centre-line points elsewhere. Consequently giving a surface deposition of

$$s_{i,n}(x, y, t_1, t_2) = W_{i,n}(x, y, t_1, t_2) D_{i,n}(t_1, t_2) \quad (3.4.2)$$

Two forms for the value along the centre-line have been used, The first form uses a uniform value between the SP's positions at t_1 and t_2 . This gives a surface distribution which is a better match of the pyramid from which the material originated and should be a good approximation in cases where there is relatively little washout. In situations where the rain intensity causing the deposition is heavy, or the period t_1 to t_2 is long, the pyramid would be significantly more depleted at t_2 than it was at t_1 , and consequently less material would be washed out towards the end of the period relative to the beginning. In these cases using a uniform centre-line value would underestimate deposition at the earlier end of the patch and overestimate at the later end. The second form for the centre-line values avoids this by being proportional to $\alpha_{i,n}(t)$ along the centre-line, so deposition along the patch will match the washout at the appropriate position. The constant of proportionality is chosen to preserve the unit integral under $W_{i,n}(x, y, t_1, t_2)$.

Total deposition, $S(x, y)$, is clearly the sum of all the individual patches, $s_{i,n}(x, y, t_1, t_2)$.

In cases where the pollutant advection velocity is not uniform in the period t_1 to t_2 a number of alternatives exist. The patch area could be constructed out of suitable curves, with a curved centre-line, to cope with the directional changes. Speed changes would automatically be taken care of if the weighting function were proportional to $\alpha_{i,n}(t)$. Alternatively $s_{i,n}(x, y, t_1, t_2)$ could be derived for a uniform velocity and a suitable mapping imposed when adding this into $S(x, y)$, the total deposition. A third, simpler, alternative is to divide the time period t_1 to t_2 into a number of sub-periods, t_1 to t_a , t_a to t_b , etc., such that the velocity is uniform, or approximately uniform

during each period. In this case $s_{i,n}(x,y,t_1,t_2)$ will be replaced by a number of patches, one per sub-period, each of which will be added into $S(x,y)$ independently.

3.5 PUFF TRAJECTORIES

The bulk movement of the puff is, in general, calculated from wind fields produced by spatial linear interpolation of measured mean hourly wind data. No interpolation in time is used so trajectories are formed from straight line segments of at least one hour's duration.

Geostrophic trajectories such as those used in the MESOS model (ApSimon and Goddard 1983) were not used because the synoptic pressure data from which these are obtained are only recorded every three hours. For the relatively short travel distances in this model this is too long a time scale, and the use of hourly wind data was therefore considered preferable. The averaging over an hour in the data proved adequate in smoothing the sharp direction changes caused by local wind fluctuations which are normally associated with trajectories calculated from surface winds. Local systematic topographical effects should hopefully be at a minimum owing to the choice of the locations for the stations providing the data.

A simple linear interpolation scheme has been used to obtain surface wind values between measuring stations. This is because little would be gained from using a higher order scheme without consideration of the vertical dimension by including higher level wind data and topographical information. Methods such as the program WAFT (ApSimon *et al* 1983) do exist to do this but a very simple interpolation scheme has been chosen here to be in keeping with the simplicity of the rest of the model.

The wind velocity components for a given point are determined from the most recent values at the closest one, two or three measuring sites. The number of sites used for a particular point is predetermined and dependent on the relative positioning of the nearest measuring sites. Figure 3.9 gives the

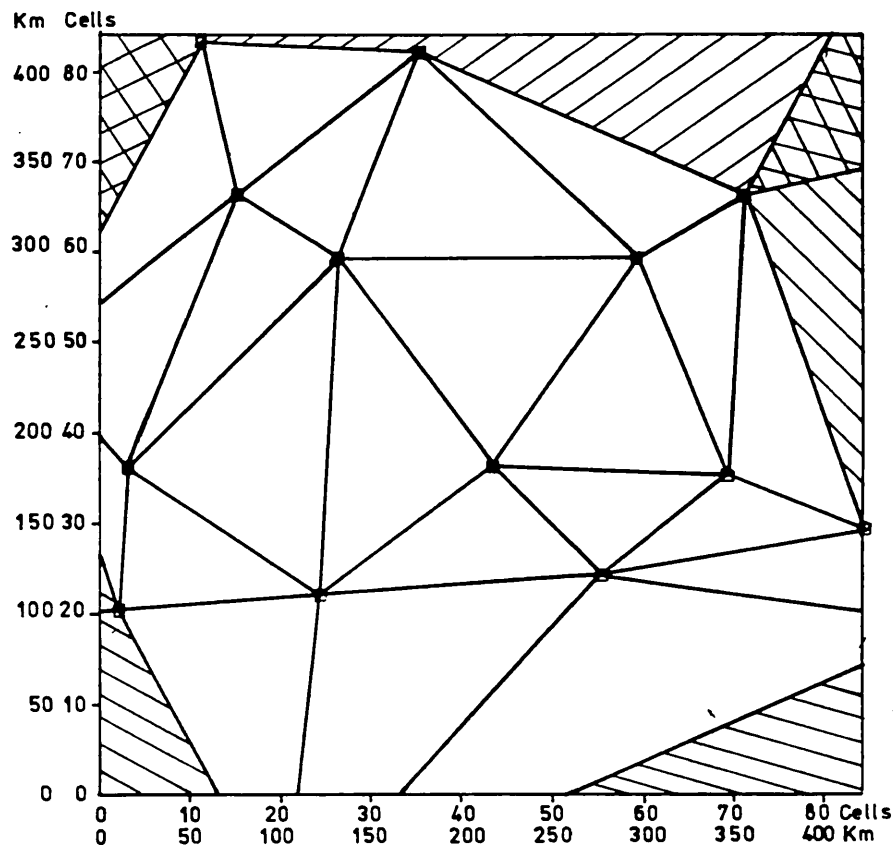


Figure 3.9. Wind interpolation grid for the London radar area. Three wind data sites are outside the area and not shown. Interpolation uses three sites in the clear areas, two in the hatched areas but only a single site in the cross-hatched areas.

regions for which different combinations of sites are used in the interpolations for trajectories in the area covered by the London radar.

Interpolated values for points lying within a triangle of three sites are obtained from the most recent values for those three sites. The choice of the triangles is normally straightforward but where there is ambiguity, for example in dividing a quadrilateral formed from four sites, then divisions are made using the shortest diagonals to avoid long thin triangles as much as possible.

Regions not lying within these triangles make use of two data sites wherever possible, but the velocity from just the closest site is used in regions which do not lie between their two nearest sites, and where the possible second sites would not be representative of that region. Linear interpolation

would, in any case, only give such sites a very limited influence. This is the case for the cross-hatched regions in figure 3.9.

The use of the model is normally limited to the period during which released material is within the range of a particular radar. This makes it possible to simplify trajectory calculations by pre-calculating interpolation coefficients at locations which form a grid containing the area of radar coverage. Wind velocities for a general point are then taken to be the current interpolated value at the nearest grid location. For convenience these locations have been chosen as the centres of the 5km square cells of the 84 by 84 cell grids.

This method also permits the removal of a site from the interpolation for a location if the effect of that site on that location is minimal. This gives a saving in both coefficient storage and calculation times. The criterion taken for this is that if a site contributes less than ten percent to the interpolational value of a grid location then the coefficients are recalculated to exclude that site. It is therefore possible for locations near a vertex of a triangular three-site interpolation region to reduce to just taking that vertex's wind velocity value. Thus dispensing with the calculations for the minor effects of the two remote vertices.

Trajectories are calculated using wind velocity values at half the atmospheric boundary layer height. These are obtained by applying constant corrections to both the speed and direction of the corresponding interpolated surface wind. These corrections, obtained using results from Smith (1975), are described in chapter five.

Releases external to the interpolation grid are given an initial velocity at which they move until they reach the grid. They then, in common with internal releases, follow trajectories calculated from 'mid-boundary layer' height winds until they leave the grid area.

A puff continues at the velocity with which its centre left the grid area until it is entirely clear of the grid, at which time the model run terminates. No allowance is made for puffs looping back into the area.

3.6 RADIOACTIVE DECAY AND DRY DEPOSITION

Together with wet deposition, two further processes will deplete a cloud of released material and therefore need to be included in the model.

The first of these is radioactive decay. This clearly only applies to releases of radioactive materials and can be modelled by a simple time-dependent attenuation factor. This could be included in the model in a number of ways, but for simplicity has been included in equation (3.4.1), the calculation of $D_{i,n}(t_1, t_2)$. This is the quantity of material to be deposited due to washout at $SP(i, n)$ over the period t_1 to t_2 , which is reduced by a factor obtained by applying the appropriate decay rate from the time of release to the mean time, $(t_1 + t_2)/2$, for that deposition patch.

The second process is dry deposition, which is loss of material from the cloud where it is in contact with the ground or vegetation. This process only involves the lower boundary of the puff, and the simplest model is to assume that a constant fraction of the material in the surface level of the puff is lost to the surface but that vertical turbulent diffusion is rapid enough to maintain the vertical concentration profile with the same form that it would have in the absence of dry deposition. The horizontal redistribution speeds apparent from the work discussed in chapter four tend to support this assumption. Using this representation for dry deposition enables it to be included in the model using an 'equivalent rain rate', which is the precipitation intensity which would be required to remove material at the same rate as the dry deposition rate.

This intensity can be derived by considering the associated pyramid for $SP(i, n)$ which is shown in figure 3.6b. If the pyramid surface is defined by the function $w(\mathbf{r}, t)$, which is only non-zero for values of the position vector, $\mathbf{r}$, lying within the pyramid's base area, $A_{i,n}(t)$, then the surface air concentration, $c(\mathbf{r}, t)$, arising from the material represented by $SP(i, n)$ is

$$c(\mathbf{r}, t) = \frac{h(t)\alpha_{i,n}(t)w(\mathbf{r}, t)}{H(t)} \quad (3.6.1)$$

where $H(t)$ is the height of the surface boundary layer and $h(t)$ is a dimensionless function to correct for cases when the material is not uniformly mixed throughout the boundary layer.

The dry deposition rate for the pyramid is then given by

$$\frac{d}{dt}D(t) = \int_{A(t)} v_d c(\mathbf{r}, t) da \quad (3.6.2)$$

where v_d is the dry deposition velocity and da is an area element of $A(t)$. From (3.6.1) and

$$V'_{i,n}(t) = \int_{A(t)} w(\mathbf{r}, t) da$$

where $V'_{i,n}(t)$ is the undepleted pyramid volume, (3.6.2) becomes

$$\frac{d}{dt}D(t) = v_d \frac{h(t)}{H(t)} \alpha_{i,n}(t) V'_{i,n} \quad (3.6.3)$$

This can be compared with the equation for the quantity remaining in the pyramid during and after wet deposition, which is given by

$$\frac{d}{dt} (V'_{i,n} \alpha_{i,n}(t)) = -\Lambda(J(t)) V'_{i,n} \alpha_{i,n}(t) \quad (3.6.4)$$

obtained by substituting (3.3.24) into (3.3.25). Therefore a rain intensity rate, J_d giving a deposition rate equivalent to the dry deposition rate can be achieved by equating the right hand sides of (3.6.3) and (3.6.4) and solving for J . Noting that (3.6.3) records the gain in surface material and (3.6.4) the loss of airborne material this gives

$$\Lambda(J_d(t)) = v_d \frac{h(t)}{H(t)} \quad (3.6.5)$$

which is in fact more useful than the actual value J_d since it can be incorporated directly into the scavenging equation (3.3.25).

Including dry deposition in this way is relatively straightforward in this model since it requires no special treatment of the puff or surface patches. The only complicating factor is $h(t)$, the correcting factor required prior to material becoming initially mixed throughout the depth of the boundary

layer. The two basic forms for this function are given in figure 3.10. It has unit value after time t_u when the boundary-layer becomes uniformly mixed and prior to time t_u it changes linearly to the unit value from $h(0)$, the initial value. $h(0)$ is greater than one for low level releases where the surface concentration is initially high and conversely $h(0)$ is less than one for higher releases. The linear form prior to time t_u is only a rough approximation used for simplicity which should not significantly affect the model. Work on obtaining appropriate values for $h(0)$ and t_u is discussed in chapter five as is obtaining suitable values for the other parameters, v_d and $H(t)$.

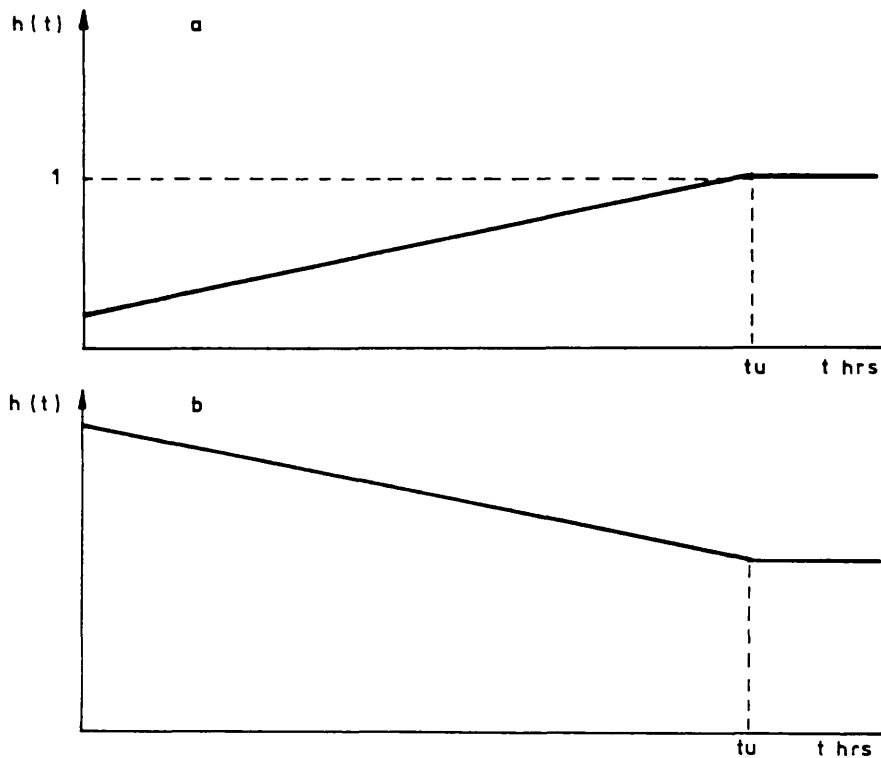


Figure 3.10. Forms of $h(t)$ for (a) a high level release with initially low surface concentrations and (b) a low level release with initially high surface concentrations.

3.7 THE RAIN-PATCH PROGRAMS

It has already been mentioned that the two dimensional model described in this chapter is used in a computational form known as the RAIN-PATCH model. In this section a brief description of RAIN-PATCH is given since it

is this model which provides the results presented in later chapters. This is given here rather than at the end of the following chapter because, although the internal redistribution of material within the puff, covered in that chapter, is an important correction to the model, it will operate adequately without it.

RAIN-PATCH consists of four programs which are run in sequence to obtain a surface deposition pattern from a release. There are also two ancillary programs, one to create puff descriptions to define a release and another to analyse the resulting surface deposition patterns. The pre-processing programs required by the rain and wind data are not described here.

The puff creation program creates a file containing the specification for a release. This is used by three of the four main RAIN-PATCH programs. The data specified is primarily the quantity and location of a release, together with an initial velocity. Also specified is the complexity of the puff used to model the release and its rate of expansion. The complexity is in terms of the number and location of sample points, where location criteria are initially specified by ellipse β values and angular θ positions, the latter being specified at the defining time of one hour after the release. This information, together with the form of the standard deviations controlling the expansion, permit the calculation of the integration correction factor, τ , and consequently the model always uses a pre-corrected release quantity. The basic data forming the puff specification are provided by the user and then converted into the required form for the model, which as well as using a converted release quantity also uses SP locations in the standard deviation form of definition (3.3.17) rather than θ and β values.

The first RAIN-PATCH program determines the trajectory followed by a puff. It does this using a grid of pre-calculated interpolation coefficients and surface wind speed and direction data for the area and period of interest. Release location and initial velocity data is obtained from the puff specification file, although the velocity data is only used for releases outside the area of the interpolation grid.

The second program uses the radar data to assign rain intensities to Sample Points. It determines the positions of the SP's at the time of each frame of rain data using the puff centre position from the release trajectory and SP location data from the puff specification. The correct rain intensities for these positions are then obtained from the file of rain data and wherever the intensity at an SP changes this is recorded and used in the third program for calculating deposition.

The bulk of the work is done by the third program which uses the rain intensity change data, together with dry deposition equivalent rain rates, to calculate the washout at each SP. The surface areas over which this material is deposited are also determined using information on adjacent SP's from the puff specification and this is then recorded along with the quantity deposited, corrected for decay. This program also calculates any redistribution of the material within the puff if this is required.

The final RAIN-PATCH program combines all of the deposition patches of the third program onto a specified regular grid using one of the mapping forms described in section 3.4. These grids can then be analysed using the second ancilliary program which provides data on the distribution of concentration levels, both for the whole grid and within specified annuli centred on the release site.

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CHAPTER 4.

MATERIAL REDISTRIBUTION WITHIN THE PUFF

4.1 THE NEED FOR INTERNAL REDISTRIBUTION

A puff will cease to have a Gaussian distribution if a part of its material is removed by precipitation which does not fall uniformly across its whole area. When this occurs, the very simple and convenient dispersion properties of the Gaussian distribution no longer apply and this needs to be taken into account in the Gaussian-based puff model of chapter three.

The consequence of, for example, one area of a puff becoming significantly more depleted than the remainder, is that as well as the whole puff continuing to expand, material will also diffuse into the more depleted area of the puff from the surrounding less depleted portions. The effect is such that perturbations are smoothed out. Situations can be envisaged where ignoring this process could significantly distort calculated surface deposition distributions. An extreme example is to consider a puff distorted by local heavy rain early in its travels and later encountering more widespread rain. The resulting later deposition will be biased away from the surface regions traversed by the earlier depleted region of the puff. This biasing is likely to be unrealistic for all but the shortest time separations between the periods of washout, due to this redistribution of material within the puff.

Described in this chapter is the development of a scheme to include internal redistribution in the basic two dimensional model of section 3.3. This is achieved by periodically making adjustments to the puff depletion factors to simulate the movement of material from one part of the puff to another.

In common with the model, the correction scheme was first formulated in one dimension. However, unlike the model, the one dimensional version was then directly tested, and results from this are presented here. It was then extended to two dimensions and tested prior to forming the version

incorporated into the RAIN-PATCH model. The correction scheme's use and effectiveness in RAIN-PATCH is discussed in chapter five.

4.2 REDISTRIBUTION IN ONE DIMENSION — DERIVATION

The redistribution correction scheme is a finite difference (FD) formulation of a diffusion equation, which uses the puff's sample points as its solution grid points. The complication in this is that the grid of sample points expands.

This scheme is based on the one dimensional, turbulent diffusion equation

$$u_t(x, t) = k(t)u_{xx}(x, t) \quad (4.2.1)$$

which has, as a solution, the Gaussian distribution,

$$g(x, t) = \frac{Q}{\sqrt{2\pi}\sigma(t)} \exp\left(\frac{-x^2}{2\sigma^2(t)}\right) \quad (4.2.2)$$

when the turbulent diffusivity coefficient, $k(t)$, is of the form

$$k(t) = \sigma(t)\sigma_t(t) = \left(\frac{1}{2}\sigma^2(t)\right)_t \quad (4.2.3)$$

The equation (4.2.1), referred to as the u - x equation, is converted to a form which closely matches the structure of the puff discribed in section 3.3. The process requires a change of both variable and co-ordinate system. The variable is changed to $\alpha(x, t)$, which is a continuous function corresponding to the discrete depletion factor values, α_i , of the puff formulation. It is defined by

$$u(x, t) = \alpha(x, t)g(x, t) \quad (4.2.4)$$

so $\alpha(x, t)$ describes a function in terms of its distortion from a Gaussian distribution in the same way as an α_i value relates the depletion at a puff's sample point to the corresponding undepleted value. Substituting (4.2.4) into (4.2.1) gives the α - x equation

$$\alpha_t(x, t) = k(t) \left(\alpha_{xx}(x, t) - \frac{2x}{\sigma^2(t)} \alpha_x(x, t) \right). \quad (4.2.5)$$

The co-ordinate conversion is to the variable β , which defines positions in terms of their Gaussian distribution value as a fraction of the Gaussian distribution value at the origin. This corresponds to the β_i values of equation (3.3.4) which define the sample point positions. β is defined in terms of the Gaussian distribution by

$$g(x, t) = \beta g(0, t) \quad (4.2.6)$$

which from equation (4.2.2) gives

$$\beta = \exp\left(\frac{-x^2}{2\sigma^2(t)}\right) \quad (4.2.7)$$

Converting to this variable, equation (4.2.5) becomes the α - β equation

$$\alpha_t = \frac{-k}{\sigma^2} (2\beta^2 \ln \beta \alpha_{\beta\beta} + (1 + 2 \ln \beta) \beta \alpha_{\beta}) \quad (4.2.8)$$

where function variables have been omitted for brevity.

The α - β equation models the movement within the puff of material represented by a function giving its departure from a Gaussian concentration distribution, and on a co-ordinate system defined in terms of the expanding Gaussian distribution. This form is analagous to the representation of the puff given in section 3.3 and consequently a finite difference solution scheme for the α - β equation should be obtainable which will directly relate to a puff specification. A scheme should be formulated specifically which uses the puff's set of sample points as its solution grid and consequently the scheme's α values at the grid points are the sample points' depletion factors. If such a scheme is advanced in time then its effect would be to simulate the material redistribution which would occur over that time within the puff.

There are a number of practical considerations in obtaining such a scheme. The first is accuracy, since the spread of sample points on the x -axis could become rather large, leading to large errors in the solutions. Scheme stability also needs to be considered in this context. The second main consideration is material conservation, which is of particular concern given the remoteness of the α - β equation from the physically based u - x equation.

These points were studied by comparing results from α - β equation schemes with those from an implicit finite difference scheme for the u - x equation on a conventional fixed grid. These results from the optimum version of the α - β scheme are discussed in section 4.3.

The optimum scheme is an implicit finite difference scheme given by

$$\alpha_j^{n+1} - \alpha_j^n = \frac{k}{\sigma^2} \left(\frac{A_j}{b_j} - B_j \right) \alpha_{j-1}^{n+1} - \frac{k}{\sigma^2} A_j \left(\frac{1}{a_j} + \frac{1}{b_j} \right) \alpha_j^{n+1} + \frac{k}{\sigma^2} \left(\frac{A_j}{b_j} + B_j \right) \alpha_{j+1}^{n+1} \quad (4.2.9)$$

for $j \neq 0$, where $j = 0$ is the grid location at the puff's centre. α_j^n is a discrete solution value at time $t = n\Delta t$ and position β_j and the values A_j and B_j are defined by

$$A_j = -4 \frac{\beta_j^2 \ln \beta}{a_j + b_j} \Delta t$$

and

$$B_j = \frac{(1 - 2 \ln \beta_j) \beta_j}{a_j + b_j} \Delta t \quad (4.2.10)$$

The grid index, j , matches the increasing direction of the x -axis so $\beta_j > \beta_{j+1}$, and therefore $a_j = \beta_{j-1} - \beta_j$ and $b_j = \beta_j - \beta_{j+1}$. Because the consequence of $\beta \rightarrow 1$ at the puff centre is that $\ln \beta \rightarrow 0$, it was found that the scheme of equation (4.2.9) did not move material fast enough in the region of the puff's centre. In that region, this was overcome by using an implicit finite difference scheme for the equation

$$\alpha_t = \frac{-k}{\sigma^2} \alpha_\beta \quad (4.2.11)$$

which is the α - β equation for β having a unit value and consequently terms in $\ln \beta$ are neglected. This local scheme is therefore

$$\alpha_0^{n+1} - \alpha_0^n = \frac{-k}{\sigma^2} \frac{\Delta t}{\Delta \beta} (\alpha_1^{n+1} - \alpha_0^{n+1}) \quad (4.2.12)$$

where $\Delta \beta = \beta_0 - \beta_1 = 1 - \beta_1$.

The α - β equation, being second order, requires two boundary conditions. Zero derivative conditions are used for both of these. This was found

to be necessary because the alternative would be to impose a fixed value at one end of the solution domain. The point then becomes a source or a sink of material with undesirable results. If the point is given a non-unit value, material will move and distort an initially undistorted puff. If it is given a unit value then material will flow into a depleted puff from the outside.

The lack of at least one fixed boundary condition will not normally give a unique solution. This is avoided here by explicitly maintaining material conservation at intervals during the implementation of the scheme.

This scheme produces a tri-diagonal matrix which in consequence can be directly inverted to solve for each time step.

Both the main scheme and the modified puff centre scheme can be shown to be unconditionally stable for cases when the grid point separation in β is uniform. This is achieved by using the Fourier mode method described in Richtmyer and Morton (1967). For more general sample point positionings comparison tests with results from the u - x equation scheme were relied upon to indicate any instability.

4.3 REDISTRIBUTION IN ONE DIMENSION — TESTING

The α - β scheme was tested by direct comparison with an implicit finite difference scheme for the u - x equation. This is given by

$$u_j^{n+1} - u_j^n = k(t) \frac{\Delta t}{\Delta x^2} \left(u_{j-1}^{n+1} - 2u_j^{n+1} + u_{j+1}^{n+1} \right) \quad (4.3.1)$$

which is also unconditionally stable for a uniform spatial grid point separation, therefore the comparisons always use this form of grid. The solution makes use of the symmetry of the Gaussian about $x = 0$ to solve only on the positive half axis. The symmetric boundary condition $u_x(0) = 0$ is used with the second condition that $u(x_{\max}) = 0$, where $x_{\max}$ is taken to be remote enough to have no effect on the solution.

The comparisons presented below all use a standard deviation of the form $\sigma = 0.5t$ and consequently, from (4.2.3), a turbulent diffusivity coefficient of $k = 0.25t$. The initial solution is always based on a Gaussian

distribution with $Q = 100$ units of material and at the time $t = 10$ hours, since the Gaussian distribution is singular for $t = 0$.

The first result uses only the u - x scheme to show the tendency for any distortion to be smoothed out and the material distribution to return to a Gaussian form. The initial state is shown by curve P in figure 4.1a. It is based on the Gaussian form but reduces by 50% at $x = 3$ km, and with this reduction decreasing to give the Gaussian values at $x = 0$ km and $x = 10$ km. The curve A is also Gaussian but representing the same quantity (having the same total integral) as the perturbed function. A discrete two-norm or root-mean-square value evaluated at the grid points is used to compare curves. For the curves P and A this is denoted by $\|P - A\|_2$ and has the value 0.17 initially.

The perturbed function is then advanced using the u - x scheme on a 1 km grid and with a 0.2 hour time step. Figures 4.1b–4.1d show the form of the function at one hour intervals. Clearly the perturbed function returns very rapidly to a Gaussian form with the distortion measured by the two-norm roughly halving every hour.

The second test starts from a linearized Gaussian puff which has been perturbed at one sample point. This puff is defined by eleven sample points, with the first positioned at the puff origin ($\beta = 1.0$) and subsequent point positions defined by β values reducing by 0.1 down to $\beta = 0.1$ (ie. $\beta = 0.9, 0.8, \dots, 0.1$). The final outermost point is given by $\beta = 0.05$. These points have unit α values, except for the point at $\beta = 0.7$ which has an α value of 0.7. This gives the distribution shown by the $t = 10$ hours (initial time) curve of figure 4.2a. The $t = 11$ hours and $t = 12$ hours curves of figure 4.2a show the effect of neglecting redistribution for such a perturbed puff. No correction is made for these curves and the pronounced dip in the distribution is maintained as the puff expands. This can be compared with figure 4.2b in which the same initial state is advanced using the u - x FD scheme. Here the perturbation quickly disappears and the $t = 12$ hours curve is virtually indistinguishable from the corresponding corrected volume

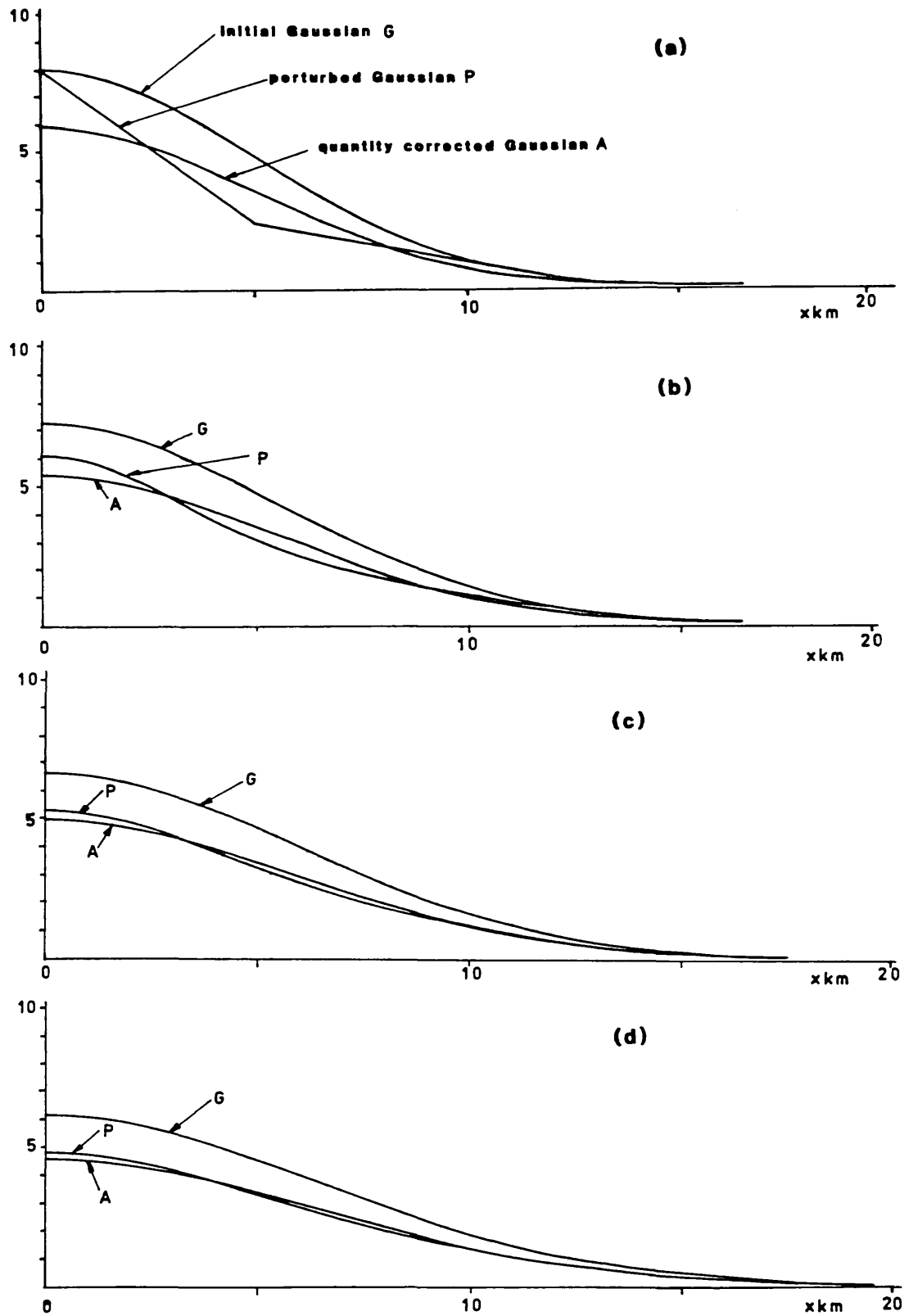


Figure 4.1. Test results from u - x scheme. (a) Initial conditions at $t = 10$ hours. Curve P is reduced below the Gaussian value in the range $x = 0$ to $x = 10$ km and has the value 2.42 at $x = 5$ km (50% of Gaussian value), $\|P - A\|_2 = 0.17$. (b) Curves advanced by one hour to $t = 11$ hrs., $\|P - A\|_2 = 0.07$. (c) $t = 12$ hrs., $\|P - A\|_2 = 0.04$. (d) $t = 13$ hrs., $\|P - A\|_2 = 0.02$.

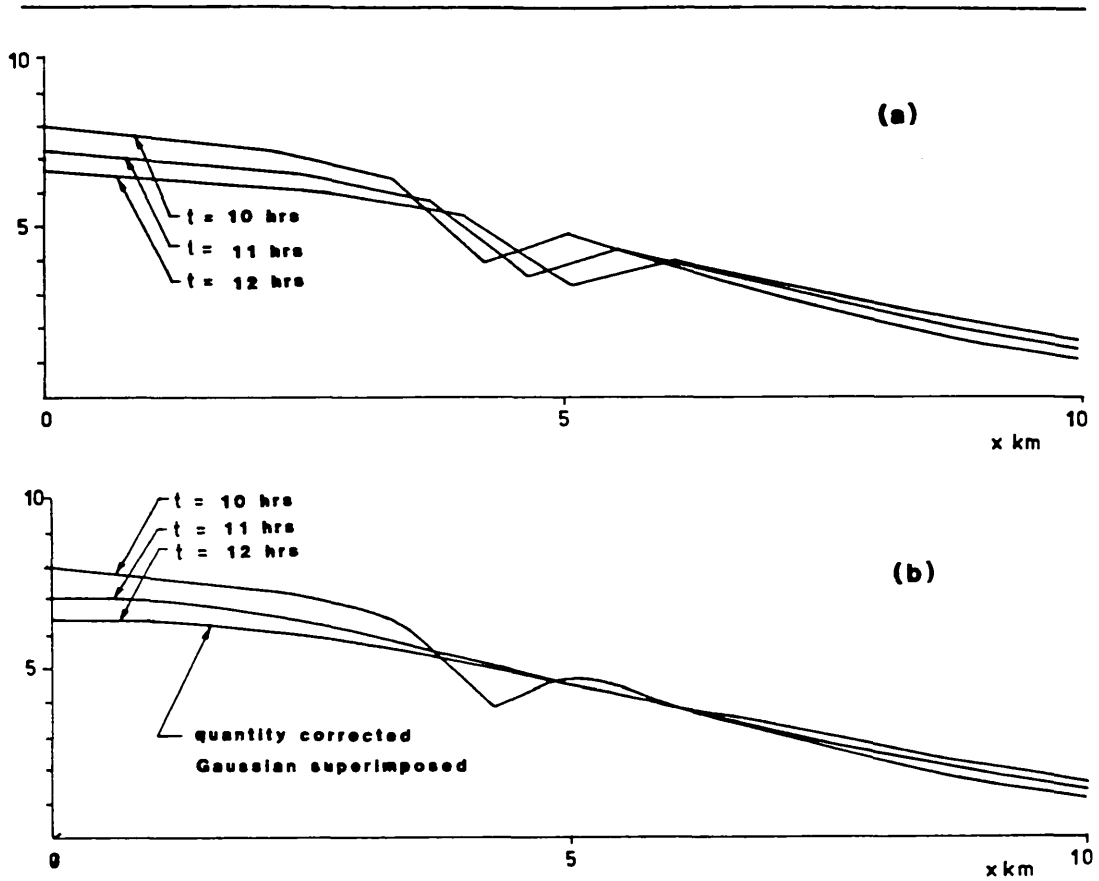


Figure 4.2. Perturbed Gaussian advanced with (a) no redistribution and (b) using the u - x FD scheme with $\Delta x = 0.25$ km and $\Delta t = 0.2$ hrs.

Gaussian. The u - x scheme initial state is obtained by interpolation from the α - β curve which results in some smoothing of the corners despite the small, 0.25 km, grid size of the u - x scheme. A time step of 0.2 hours was used.

In figure 4.3a the α - β scheme has been applied to the same initial condition in two time steps of 0.2 hours, both of which are plotted. This can be compared with the u - x scheme solutions given in figure 4.3b and the $t = 10.4$ hours curves from each scheme can be compared directly in figure 4.3c. The reduced time separation between the curves is necessary due to the speed of the redistribution.

The final test results presented below are for a distribution with a much larger perturbation, spread over two sample points. The same β values as for the previous test are used but the non-unit α values are at $\beta = 0.8$ and $\beta = 0.7$, both of which have α values of 0.2. This was intended as

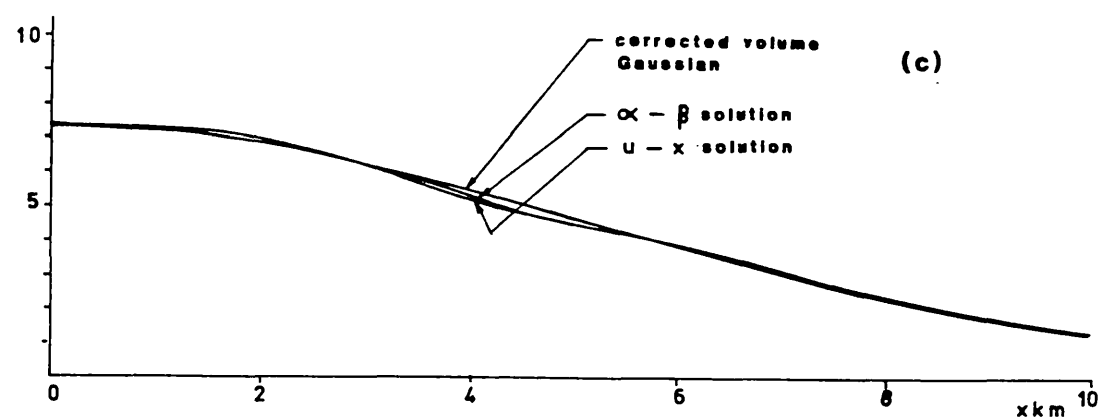
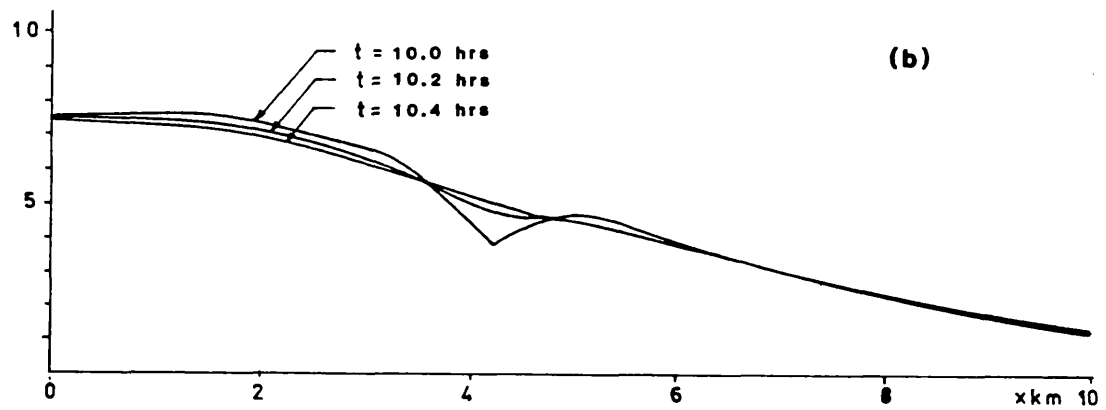
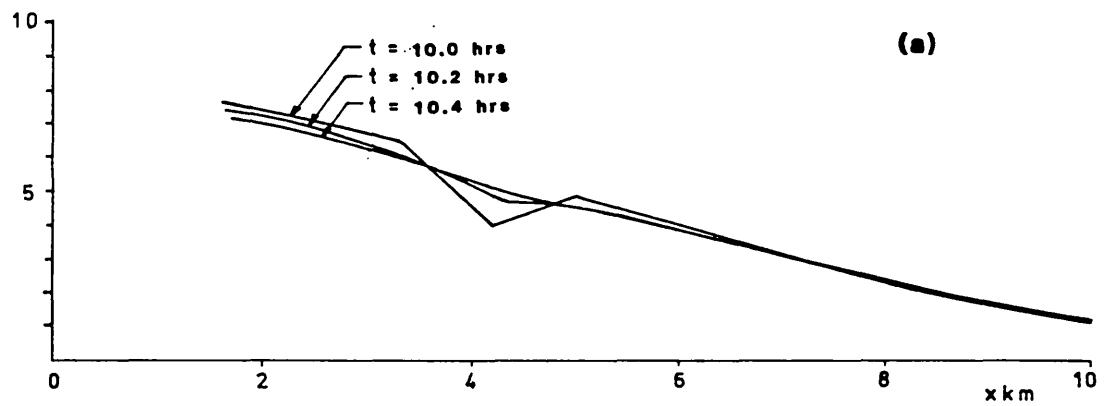


Figure 4.3. Perturbed Gaussian advanced (a) using the α - β FD scheme, with $\Delta t = 0.2$ hrs. (b) using the u - x scheme, with $\Delta x = 0.25$ km and $\Delta t = 0.2$ hrs. (c) shows the $t = 10.4$ hrs curves for both schemes, together with the volume corrected Gaussian.

a major test of the α - β scheme since the distribution is virtually split by the perturbation, which is sufficiently close to the origin to demonstrate the effects of the modified scheme used there.

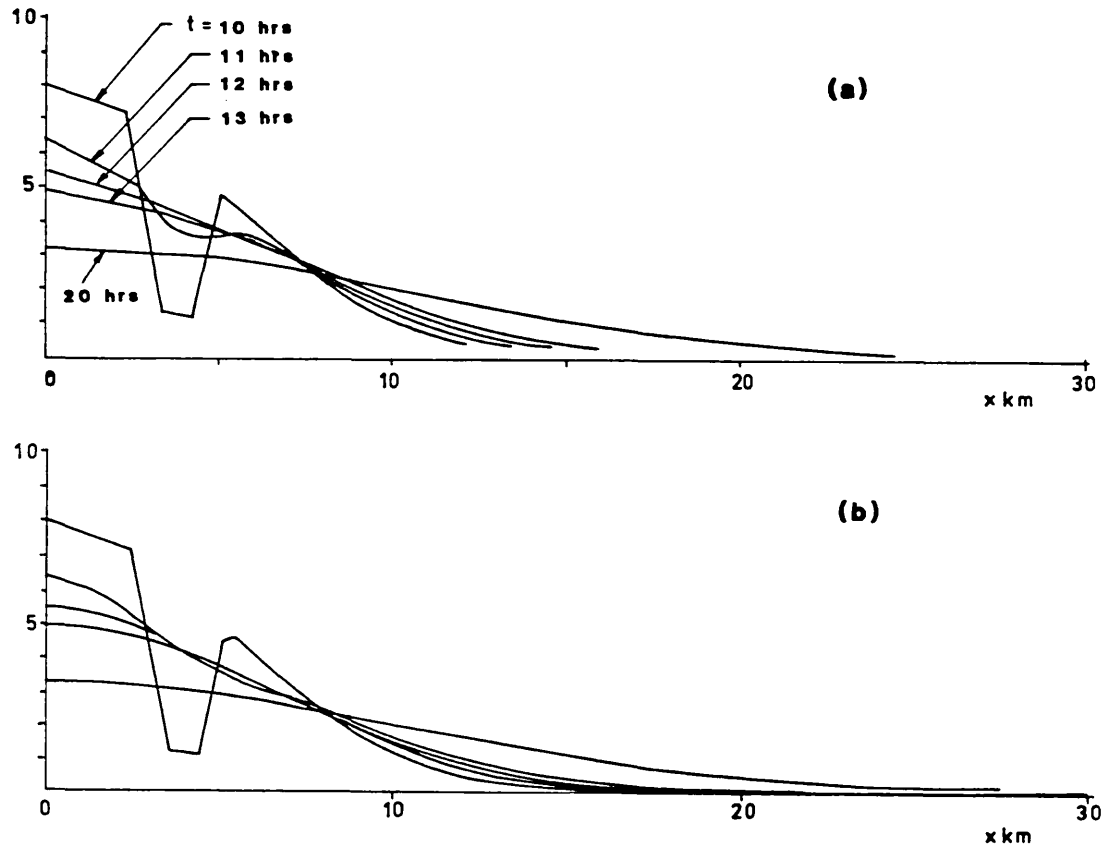


Figure 4.4. Larger perturbation advanced with (a) the α - β scheme and (b) the u - x scheme.

Figure 4.4a gives the initial distribution with α - β scheme solutions at four subsequent time points. Figure 4.4b gives the equivalent u - x scheme solutions.

Clearly the match at $t = 20$ hours is very close but a number of points should be noted. The α - β scheme's second curve, at $t = 11$ hours, shows a dip at the position corresponding to that of the original perturbation, which is not apparent in the u - x scheme curve for the same time. This is a consequence of using a single time step to advance the α - β scheme. Table 4.1 gives the two-norm values for the u - x and α - β scheme differences for three different α - β scheme time steps, with in each case a 0.05 hour time step for the u - x

scheme. In general, these show little difference between the curves despite the dip in the $t = 11$ hours curve of figure 4.4a. This occurs because the large perturbation cannot be effectively eliminated in only one time step. This was not considered to be a significant problem because of the size of the perturbation in this case, and a single maximum time step is routinely used for the α - β scheme.

Table 4.1. $\|u-\alpha\|_2$ for three values of the α - β scheme time step, Δt .

t hrs	Δt hrs.		
	0.05	1.0	10.0
10	0	0	0
11	0.097	0.093	—
12	0.104	0.091	—
13	0.119	0.110	—
20	0.116	0.163	0.142

The values of table 4.1 would be expected to diminish with reduced α - β scheme time step. The table shows that they increase. This is because the α - β scheme is non-conservative, which has the effect of slightly increasing the α - β distributions integral in x -space with every time step of the scheme. This increase is effectively greater for smaller time steps since the scheme must be applied more often to progress through a given period. The results of figure 4.4a were obtained using a conservation correction after each time step of the α - β scheme to avoid this problem. It works by integrating the α - β function in x -space and then applying a uniform correction to each α -value such that this integral returns to its original value. Its effect can be judged from table 4.2 giving the corresponding two-norm values which are much smaller than those of table 4.1. The increase in $\|u - \alpha\|$ relative to $\|u - g\|$ at $t = 20$ hours, where g is the volume corrected Gaussian distribution, is to

Table 4.2. Two-norm values for the conservation corrected α - β scheme.

t hrs	$\ u-\alpha\ $	$\ u-g\ $
10	0	0.574
11	0.089	0.116
12	0.064	0.052
13	0.055	0.036
20	0.027	0.012

be expected as the α - β function consists of fairly long straight line segments at that stage which cannot readily match the finer grid u - x solution.

4.4 REDISTRIBUTION IN TWO DIMENSIONS

The method used to calculate redistribution in two dimensions is in principle the same as the one dimensional version previously described. There are, however, a number of complications caused by the additional dimension and the need to represent it in polar coordinate form. This form is required in order that the scheme's grid can match the structure of the two dimensional puff.

A major complication arises because sample points cannot only move radially relative to the puff centre, but can also, in their rows, rotate about the puff's centre, one row relative to another. This was shown in section 3.3 and greatly complicates the derivation of a two dimensional polar coordinate form of the α - β equation. A special case version of this equation, the α - β - θ equation, is given in appendix 4B, but this is only valid when $\sigma_x(t) = \sigma_y(t)$ for all time. The extension to the more general version was not undertaken and the two dimensional redistribution scheme was based directly on the α - r - θ equation.

The α - r - θ equation is analagous to the α - x equation. It is described in appendix 4A, and its finite difference implementation is given in appendix 4C. Its variable, α , is a two dimensional continuous function corresponding to the puff's depletion factors, and these values are calculated directly at the sample points, as in the one dimensional α - β scheme. The difference caused by using

the (r, θ) -coordinate system rather than a two dimensional expanding system is that positions in (r, θ) -space for the sample points require to be calculated prior to each time step of the scheme. This was chosen in preference to calculating the complex finite difference scheme coefficients which would have arisen in using an expanding coordinate system. In effect, it treats the sample points as a fixed grid during a time step, and consequently there is some choice of the time at which the grid is fixed though this is normally taken as the mid-point of the time step.

The α - r - θ equation, in common with the α - β equation, is not valid at the origin. As with the α - β equation, this has been dealt with by deriving a modified equation and scheme for the central and innermost ring of sample points. Details of these for the optimum forms are given in appendix 4D.

The comparison tests for the α - r - θ scheme were made against a fixed grid scheme for the two dimensional diffusion equation in polar coordinates. This scheme, known as the u - r - θ scheme, is described in appendix 4E. Polar coordinates were used to facilitate the comparisons between the schemes but resulted in the fixed grid scheme being non-conservative. This is analysed in appendix 4F, and demonstrated in figure 4.5a. The figure shows an extreme case, because $\sigma_x \neq \sigma_y$. A much better match is achieved in figure 4.5b, which has the same initial conditions but with a correction applied as the u - r - θ scheme curves are plotted. This is achieved by integrating the functions and applying a uniform multiplication correction to them during plotting so that the plotted versions have the required original integral. There are, however, still some discrepancies in the curves at the origin where non-conservation is most apparent and gives relatively more curve distortion for less material error.

A second problem with the u - r - θ equation is a limit, imposed by the computer, on the number of grid points. This not only reduces overall accuracy, but may also prevent the grid boundary becoming sufficiently remote to have no effect on the solution. Therefore, in summary, unlike the u - x scheme which, for the comparisons being made could be considered perfectly

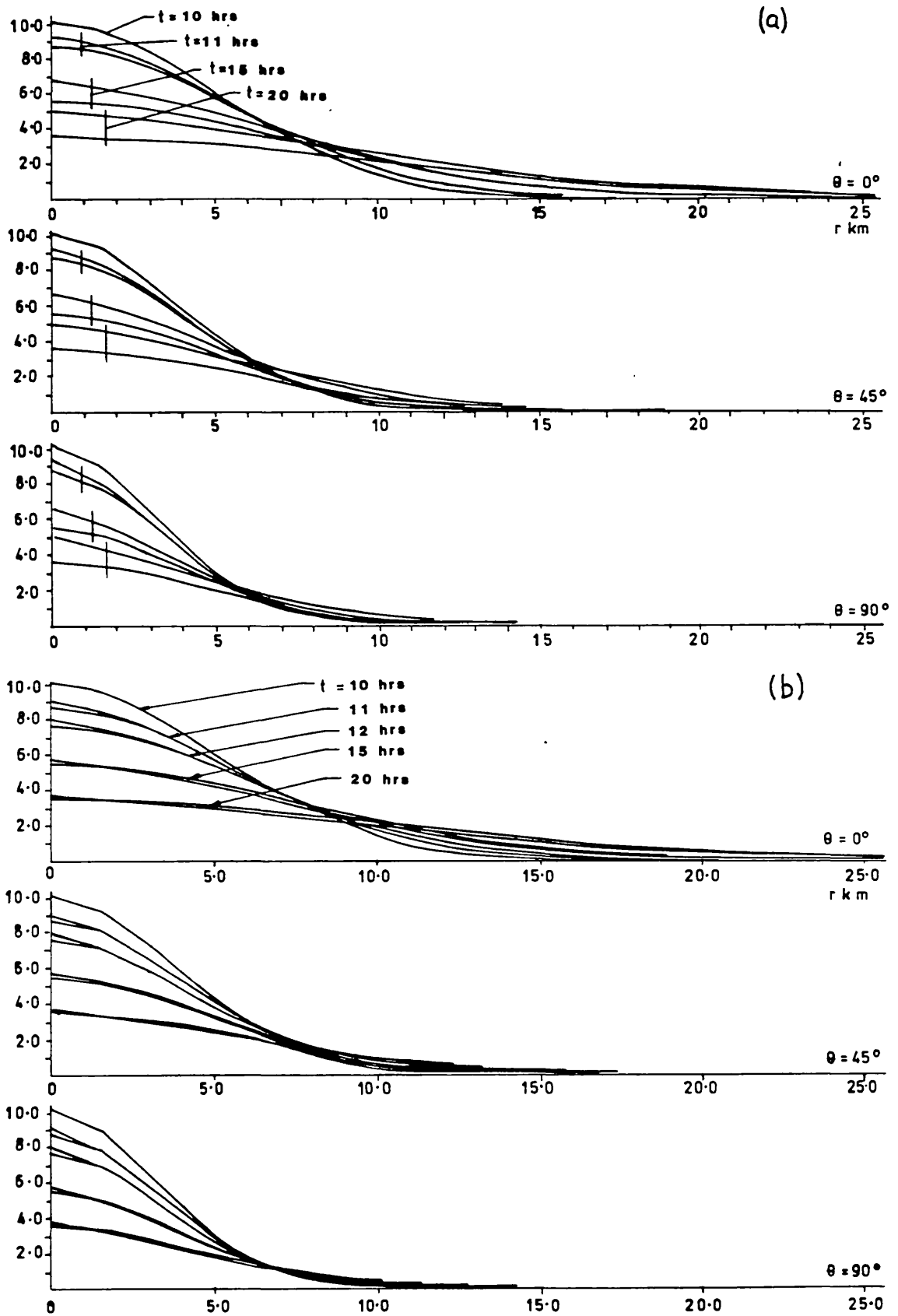


Figure 4.5. Results using the $u-r-\theta$ scheme for $\sigma_x = 0.5t$ and $\sigma_y = t^{1/2}$ showing (a) a non-conservation problem and (b) the effects of the conservation correction. Upper curve of each pair is from the scheme, lower curve is the exact Gaussian solution. (8 rows of 18 points with $\Delta r = 1.5$ km and $\Delta t = 0.5$ hrs)

accurate, the $u-r-\theta$ scheme results can only be taken as a general guide to the form of a solution. Despite this, the scheme does work satisfactorily for distorted Gaussian initial states, which diffuse to a Gaussian form in times comparable with those of the one dimensional case. An example of this is given in figure 4.6.

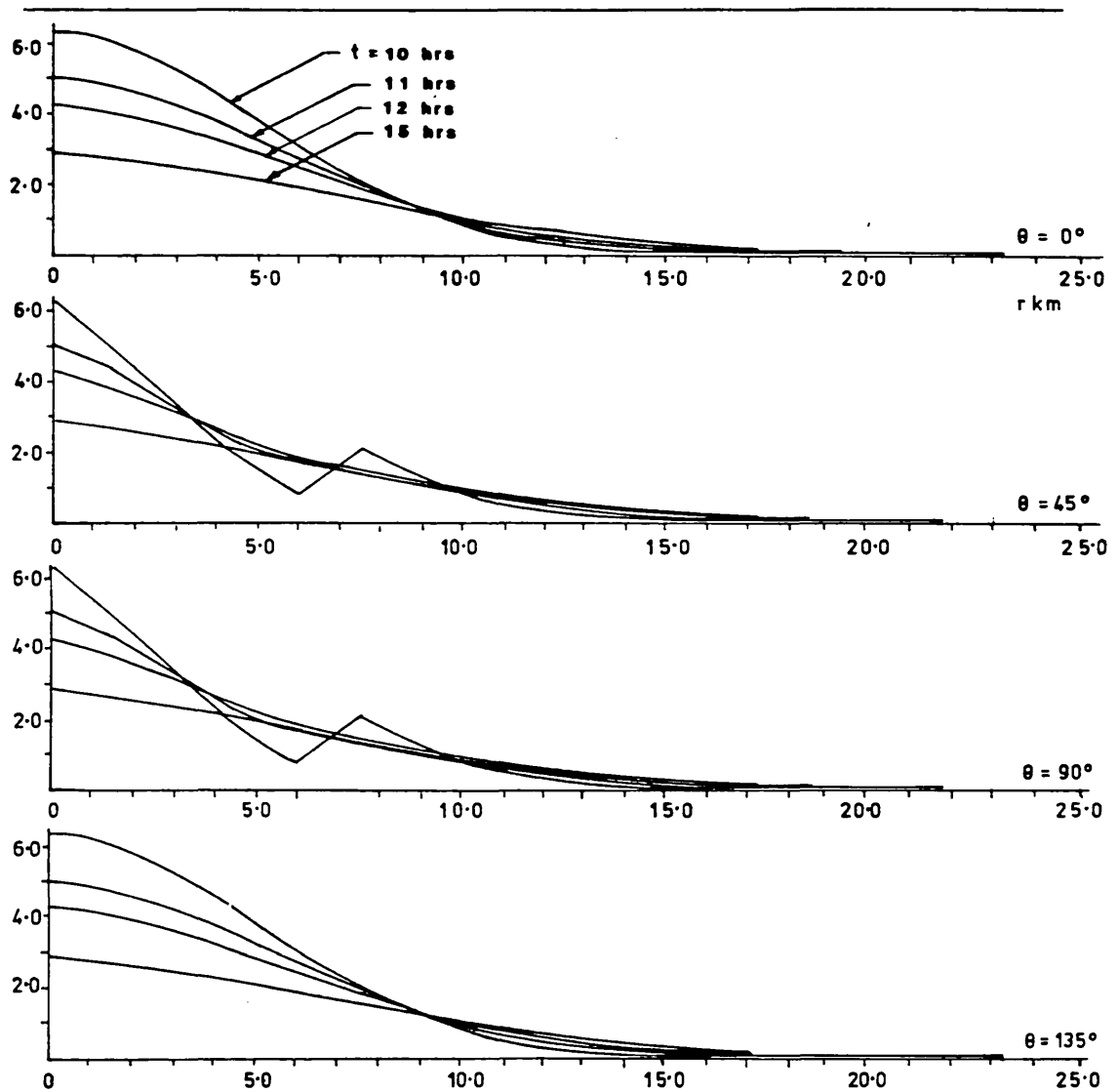


Figure 4.6. $u-r-\theta$ scheme solutions for a perturbed initial state. Same scheme and grid as for figure 4.5b but initial condition reduced over the range 2 km to 9 km for grid points on $\theta = 45^\circ$ and 90° . The reduction is 50% at 6 km.

Both the α - r - θ and u - r - θ schemes, being implicit, require a matrix inversion at each time step. The Gauss-Seidel iterative scheme was used for these with a convergence measure of $\|u_n - u_{n-1}\|_2 / \|u_{n-1}\|_2$ for the u - r - θ scheme, where u_n and u_{n-1} are the current and previous solution vectors, and the corresponding measure using α_n and α_{n-1} is used for the α - r - θ scheme. For both schemes, iteration terminated when the appropriate measure went below 0.001, which for the u - r - θ scheme gave solutions acceptably close to solutions using Gaussian elimination.

A range of comparison tests were carried out between the two schemes, using a variety of perturbed Gaussian initial states. These included test cases with uniform perturbations around the puff at a constant β position, or along a line of constant θ . Both $\sigma_x = \sigma_y$ and $\sigma_x \neq \sigma_y$ cases were used. Also examined were the more realistic cases where an area of the puff had been reduced as if by a localized storm.

Two typical test cases are presented. The first, in figure 4.7, starts from a distribution reduced at the central sample point to 0.8 of the unperturbed Gaussian value. The second has a ring of sample points reduced to a zero concentration and is shown in figure 4.8. Both cases show a discrepancy between the two curves at the origin, but this can be attributed to the non-conservation problem of the u - r - θ scheme despite appropriate volume correction being applied to both schemes. These two cases, together with the other test cases undertaken, show a match between the two solution schemes which is adequate to show that the α - r - θ scheme is correctly redistributing material on a grid which matches the two dimensional puff formulation of sub-section 3.3.2. Therefore the scheme is suitable to be used to provide a redistribution correction to the puff in the RAIN-PATCH model.

4.5 REDISTRIBUTION IN THE RAIN-PATCH MODEL

The redistribution scheme is included in the third program of RAIN-PATCH. It can be used whenever the model time is advanced by encountering a rain-data/sample-point interaction which is for a later time than the previous

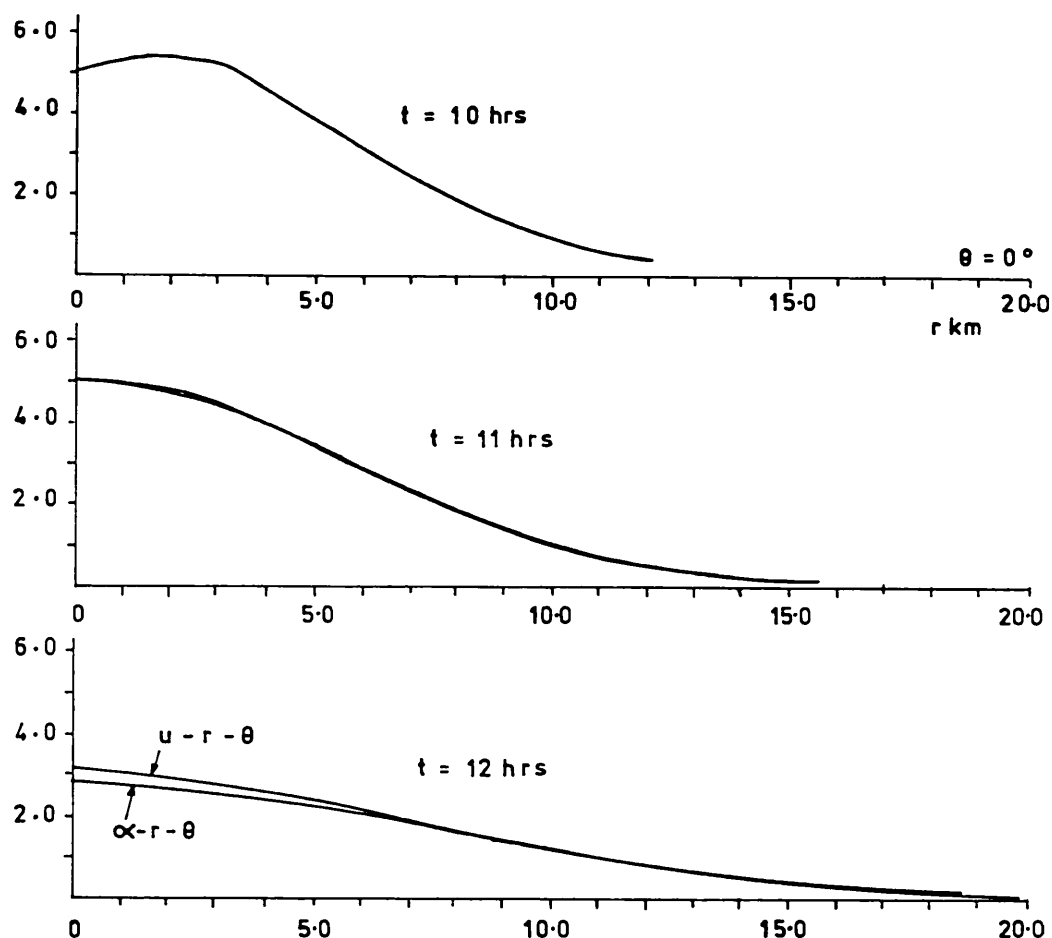


Figure 4.7. $u-r-\theta$ and $\alpha-r-\theta$ scheme comparisons for a central perturbation. $u-r-\theta$ scheme as for figure 4.5, $\alpha-r-\theta$ scheme uses 8 rows of SPs positioned at $\beta = 100\%$, 90% , 70% , 40% , 15% and 4.4% .

interactions. There is also the option to invoke the scheme only when the model time has advanced by at least some preset duration.

This method of incorporating redistribution into RAIN-PATCH in effect splits the two processes of material washout and redistribution. This is because when the scheme is used it advances the state of the model to the new time but makes no allowance for any washout during the period of that redistribution time step. The washout appropriate to each sample point for that period is then calculated using the sample point depletion factor values provided by the redistribution scheme. The order of the processes could be reversed but the separation would remain. In reality, both processes occur simultaneously and could be better modelled by imposing a relatively short

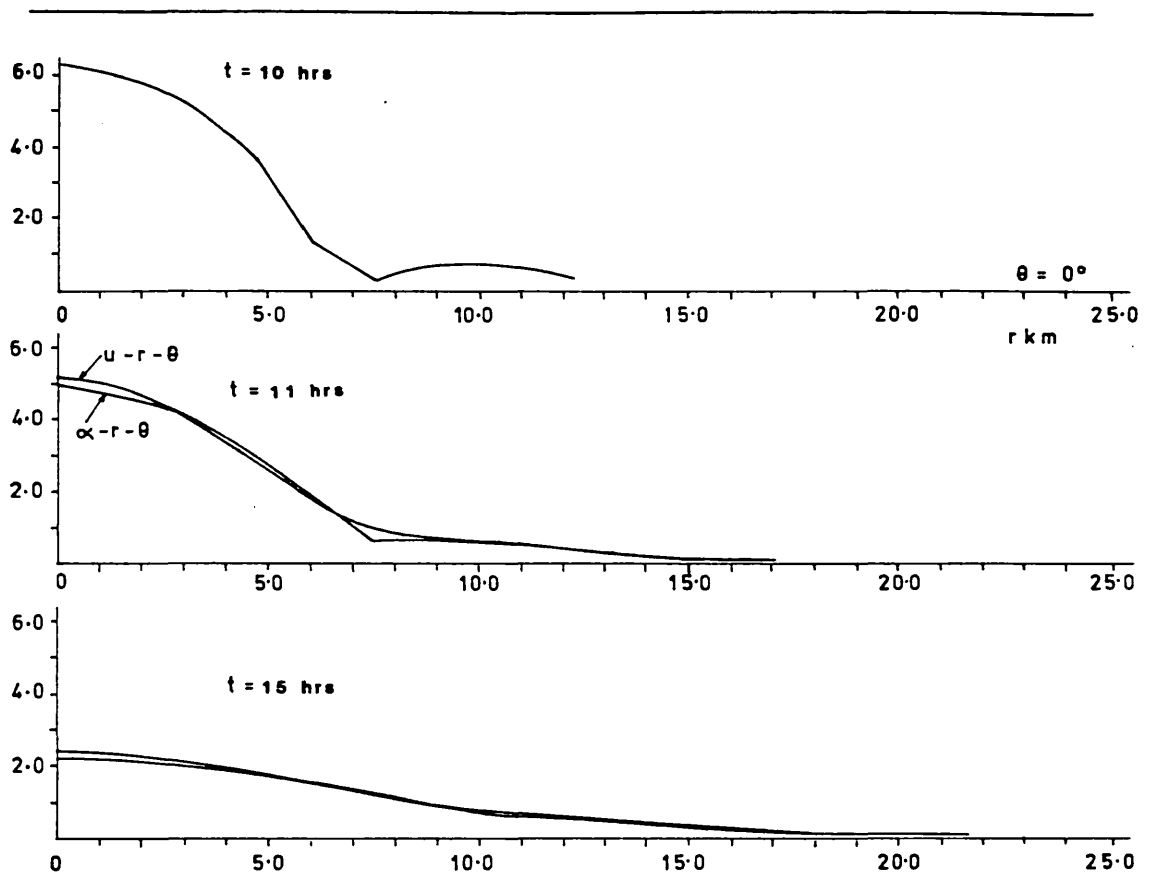


Figure 4.8. Scheme comparison for a perturbation uniform in r . Schemes and grids as for figure 4.7.

maximum time step on the model for both redistribution and washout which would minimise the splitting of the processes. In practice this was not done since the problem was not considered to affect the model's accuracy sufficiently, and the time step imposed by the time separation of interactions during periods of rain is, in any case, never excessive. Model development test runs showing the effects of including redistribution and justifying the statements above are presented in chapter five.

REFERENCES.

Richtmyer, R.D. and Morton, K.W. (1967) *Difference methods for initial-value problems*. Interscience Publishers.

Appendix 4A. Derivation of the α - r - θ equation.

In common with the one dimensional situation, a diffusion equation which has the Gaussian distribution as a solution is initially required. For simplicity this is obtained in Cartesian coordinates, so the Gaussian distribution is given by

$$g(x, y, t) = \frac{Q}{2\pi\sigma_x(t)\sigma_y(t)} \exp\left(\frac{-x^2}{2\sigma_x^2(t)}\right) \exp\left(\frac{-y^2}{2\sigma_y^2(t)}\right) \quad (4A.1)$$

and the diffusion equation by

$$\frac{\partial u}{\partial t} = k_x(t) \frac{\partial^2 u}{\partial x^2} + k_y(t) \frac{\partial^2 u}{\partial y^2} \quad (4A.2)$$

The former is a solution of the latter if the standard deviations and turbulent diffusivities are related by

$$\frac{1}{2} \frac{d}{dt} \sigma_x^2(t) = k_x(t)$$

and

$$\frac{1}{2} \frac{d}{dt} \sigma_y^2(t) = k_y(t) \quad (4A.3)$$

The diffusion equation is subsequently used in the polar coordinate form of

$$\begin{aligned} \frac{\partial u}{\partial t} = & (k_x c^2 + k_y s^2) \frac{\partial^2 u}{\partial r^2} + (k_x s^2 + k_y c^2) \left(\frac{1}{r^2} \frac{\partial^2 u}{\partial \theta^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \\ & + \frac{2cs}{r} (k_y - k_x) \frac{\partial^2 u}{\partial r \partial \theta} \end{aligned} \quad (4A.4)$$

Where $c = \cos \theta$, $s = \sin \theta$ and function variables have again been dropped for brevity.

Defining $\alpha(r, \theta, t)$ to be a two dimensional version of $\alpha(x, t)$ and substituting

$$u(r, \theta, t) = \alpha(r, \theta, t) g(r, \theta, t) \quad (4A.5)$$

into equation (4A.4) gives the α - r - θ equation:

$$\begin{aligned}
\frac{\partial \alpha}{\partial t} = & (k_x c^2 + k_y s^2) \frac{\partial^2 \alpha}{\partial r^2} + \frac{1}{r} (k_x s^2 + k_y c^2) \frac{\partial^2 \alpha}{\partial \theta^2} \\
& + \frac{2cs}{r} (k_y - k_x) \frac{\partial^2 \alpha}{\partial r \partial \theta} \\
& + \left[\frac{1}{r} (k_x s^2 + k_y c^2) - 2r \left(\frac{c^2}{\sigma_x^2} + \frac{s^2}{\sigma_y^2} \right) (k_x c^2 + k_y s^2) \right. \\
& \quad \left. - 2rc^2 s^2 \left(\frac{1}{\sigma_y^2} - \frac{1}{\sigma_x^2} \right) (k_y - k_x) \right] \frac{\partial \alpha}{\partial r} \\
& - 2cs \left[\left(\frac{1}{\sigma_y^2} - \frac{1}{\sigma_x^2} \right) (k_x s^2 + k_y c^2) + \left(\frac{c^2}{\sigma_x^2} + \frac{s^2}{\sigma_y^2} \right) (k_y - k_x) \right] \frac{\partial \alpha}{\partial \theta}
\end{aligned} \tag{4A.6}$$

Appendix 4B. Derivation of the α - β - θ equation.

The equation corresponds to the α - β equation of the one dimensional formulation. It was derived for the special case that $\sigma_x(t) = \sigma_y(t) \forall t$, which is the condition under which the θ -coordinates of two dimensional puff sample point positions are time independent.

Analogous to the one dimensional β variable defined by equation (4.2.6), β in two dimensions is defined by

$$g(r(\beta), \theta, t) = \beta g(0, \theta, t) \tag{4B.1}$$

where $g(r(\beta), \theta, t)$ is the two dimensional Gaussian distribution in polar coordinates and consequently

$$\beta = \exp \left(\frac{-r^2}{2} \left(\frac{c^2}{\sigma_x^2} + \frac{s^2}{\sigma_y^2} \right) \right) \tag{4B.2}$$

The α - β - θ equation was then obtained by converting the α - r - θ equation (4A.6) to this variable which gives

$$\begin{aligned}
\frac{\partial \alpha}{\partial t} = & \frac{k_x}{\sigma_x^2} \left[-2\beta^2 \ln \beta \frac{\partial^2 \alpha}{\partial \beta^2} - \frac{1}{2 \ln \beta} \frac{\partial^2 \alpha}{\partial \theta^2} \right. \\
& \left. - \left(2\beta \ln \beta \left(1 + \frac{1}{2 \ln \beta} \right) + \beta + 4\beta \ln \beta \right) \frac{\partial \alpha}{\partial \beta} - 2cs \frac{\partial \alpha}{\partial \theta} \right]
\end{aligned} \tag{4B.3}$$

Appendix 4C. A finite difference scheme for the α - r - θ equation.

An implicit space-centred scheme was used. If the α - r - θ equation is expressed as

$$\frac{\partial \alpha}{\partial t} = A \frac{\partial^2 \alpha}{\partial r^2} + B \frac{\partial^2 \alpha}{\partial \theta^2} + C \frac{\partial^2 \alpha}{\partial r \partial \theta} + D \frac{\partial \alpha}{\partial r} + E \frac{\partial \alpha}{\partial \theta} \quad (4C.1)$$

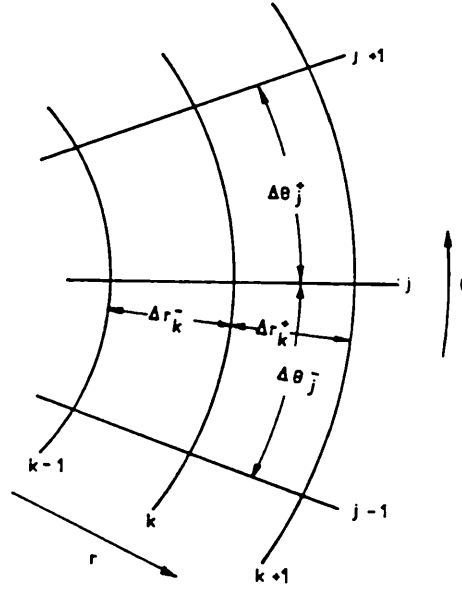


Figure 4C.1. α - r - θ scheme solution grid.

where the coefficients $A, \dots, E$ can be obtained by comparison with equation (4A.6) the scheme is then given by

$$\begin{aligned} \frac{\alpha^{n+1} - \alpha^n}{\Delta t} = & \frac{2A}{\Delta r_{j,k}} \left(\frac{\alpha_{k+1} - \alpha_k}{\Delta r_k^+} - \frac{\alpha_k - \alpha_{k-1}}{\Delta r_k^-} \right) \\ & + \frac{2B}{\Delta \theta_{j,k}} \left(\frac{\alpha_{j+1} - \alpha_j}{\Delta \theta_j^+} - \frac{\alpha_j - \alpha_{j-1}}{\Delta \theta_j^-} \right) \\ & + D \left(\frac{\alpha_{k+1} - \alpha_{k-1}}{\Delta r_{j,k}} \right) + E \left(\frac{\alpha_{j+1} - \alpha_{j-1}}{\Delta \theta_j} \right) \\ & + \frac{C}{\Delta \theta_{j,k}} \left(\frac{\alpha_{k+1,j+1} - \alpha_{k-1,j+1}}{\Delta r_{j+1,k}} - \frac{\alpha_{k+1,j-1} - \alpha_{k-1,j-1}}{\Delta r_{j-1,k}} \right) \end{aligned} \quad (4C.2)$$

Omitted subscripts are either j or k as appropriate, and omitted superscripts are $n+1$. The grid point difference values are defined in figure 4C.1, together with the relations $\Delta r_{j,k} = \Delta r_{j,k}^+ + \Delta r_{j,k}^-$ and $\Delta \theta_{j,k} = \Delta \theta_{j,k}^+ + \Delta \theta_{j,k}^-$.

Appendix 4D. Central point FD scheme for the α - r - θ equation.

A number of the terms of the α - r - θ equation (equation 4A.6) cease to be defined, or go to zero at the origin. The optimum solution to this for the α - β equation was to use a reduced equation at the origin with such terms neglected. The same procedure for the α - r - θ equation gives

$$\frac{\partial \alpha}{\partial t} = (k_x c^2 + k_y s^2) \frac{\partial^2 \alpha}{\partial r^2} \quad (4D.1)$$

where the neglected terms are those in θ derivatives, those containing r and the term containing $1/r$. This last term would clearly dominate at or near the origin, but its absence leaves a simple diffusion equation.

A finite difference formulation of equation (4D.1) is used to determine redistribution effects at the central sample point and its effect on the surrounding innermost ring of sample points. This is given by

$$\begin{aligned} \frac{\alpha_0^{n+1} - \alpha_0^n}{\Delta t} &= \sum \frac{(k_x c^2 + k_y s^2)}{(\Delta_{j,0}^+)^2} (\alpha_{1,j}^{n+1} - 2\alpha_0^{n+1} + \alpha_{1,j}^{n+1}) \\ &= \sum \frac{(k_x c^2 + k_y s^2)}{(\Delta_{j,0}^+)^2} 2(\alpha_{1,j}^{n+1} - \alpha_0^{n+1}) \end{aligned} \quad (4D.2)$$

In effect a one dimensional diffusion equation is applied between the central sample point and each point on the innermost ring, with a reflective boundary condition used for the central sample point in each case. This reintroduces the spatial consideration neglected from equation (4D.1) but does not introduce the need for sample points to be in straight rows across the puff's centre.

Appendix 4E. Radially weighted FD scheme for the u - r - θ equation.

The u - r - θ equation is solved using an implicit, space-centred finite difference scheme in a radially weighted variable, $v_{j,k}^n$. This form of variable is

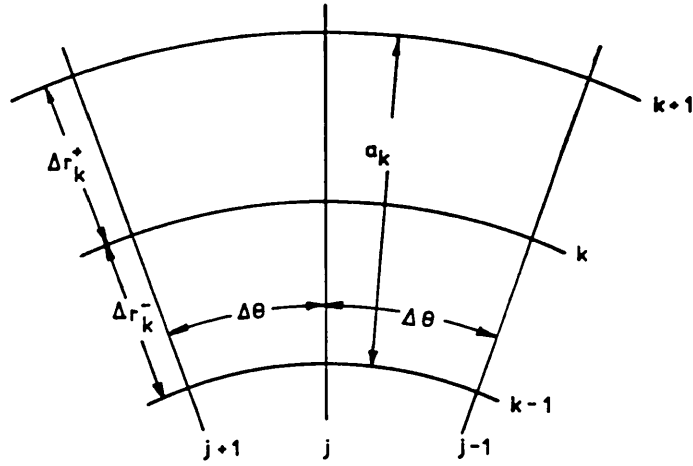


Figure 4E.1 $u-r-\theta$ scheme solution grid.

used to give a scheme with acceptable conservation properties. It is defined by $v_{j,k}^{n+1} = a_k u_{j,k}^n$ where $a_k = \Delta r_k^+ - \Delta r_k^- = r_{k+1} - r_{k-1}$ and the Δ -terms are defined in figure 4E.1.

With the $u-r-\theta$ equation expressed as

$$\frac{\partial u}{\partial t} = A \frac{\partial^2 u}{\partial r^2} + \frac{B}{r^2} \frac{\partial^2 u}{\partial \theta^2} + \frac{B}{r} \frac{\partial u}{\partial r} + \frac{C}{r} \frac{\partial^2 u}{\partial r \partial \theta} \quad (4E.1)$$

where the coefficients can be obtained by comparison with equation (4A.4), and using the grid defined in figure 4E.1, the scheme is given by

$$\begin{aligned} \frac{v_{j,k}^{n+1} - v_{j,k}^n}{a_k \Delta t} = & \frac{2A}{(\Delta r_k^+ + \Delta r_k^-)} \left[\frac{\frac{v_{k+1} - v_k}{a_{k+1}} - \frac{v_k - v_{k-1}}{a_k}}{\Delta_k^+} - \frac{\frac{v_k - v_{k-1}}{a_k} - \frac{v_{k-1} - v_{k-2}}{a_{k-1}}}{\Delta_k^-} \right] \\ & + \frac{B}{r_k^2 a_k \Delta \theta^2} (v_{j+1} - 2v + v_{j-1}) \\ & + \frac{B}{(\Delta r_k^+ + \Delta r_k^-) r_k} \left(\frac{v_{k+1} - v_{k-1}}{a_{k+1}} - \frac{v_{k-1} - v_{k-2}}{a_{k-1}} \right) \\ & + \frac{C}{2\Delta \theta} \left[\frac{\frac{v_{j+1,k+1} - v_{j+1,k-1}}{a_{k+1}} - \frac{v_{j-1,k+1} - v_{j-1,k-1}}{a_{k-1}}}{(\Delta r_k^+ + \Delta r_k^-) r_k} - \frac{\frac{v_{j-1,k+1} - v_{j-1,k-1}}{a_{k+1}} - \frac{v_{j-1,k-1} - v_{j-1,k-2}}{a_{k-1}}}{(\Delta r_k^+ + \Delta r_k^-) r_k} \right] \end{aligned} \quad (4E.2)$$

where omitted sub and superscripts are j , k or $n+1$ as appropriate.

Appendix 4F. Conservation for the $u-r-\theta$ FD scheme.

For a grid uniform in θ , the scheme of equation (4E.2) is conservative if

$$\sum v_{j,k}^n = \sum v_{j,k}^{n+1} \quad (4F.1)$$

where the summations are taken over all of the grid points. Ignoring any effects due to grid boundaries and substituting from equation (4E.2) for $v_{j,k}^n$ gives

$$\sum (1 - a_k \Delta t \delta_{j,k}) v_{j,k}^{n+1} = \sum v_{j,k}^{n+1} \quad (4F.2)$$

where $\delta_{j,k}$ is a summation over all the coefficients of $v_{j,k}^n$ arising from the summation over the right-hand side of equation (4E.2) for all the grid points. Clearly conservation requires that all the $\delta_{j,k}$ terms are zero. This is not the case for equation (4E.2), where

$$\delta_{j,k} = \frac{1}{r_{k+1}r_{k-1}} \left(\frac{2 \cos \Delta\theta \sin \Delta\theta}{\Delta\theta} (c^2 - s^2)(k_y - k_x) - (k_x s^2 + k_y c^2) \right) \quad (4F.3)$$

and which is therefore not strictly conservative under any conditions.

Two points due to the $1/(r_{k+1}r_{k-1})$ term in (4F.3) should be noted. Firstly, non-conservation will rapidly decrease with distance from the origin and, secondly, a grid point at the origin cannot be used. The second point is also apparent from consideration of the form of the $u-r-\theta$ equation at the origin.

CHAPTER 5.

MODEL PARAMETERS

5.1 INTRODUCTION

The two dimensional model described in chapters four and five is intentionally very general in its specification. A model implementation, however, needs to be specific in all aspects. In this chapter the choices available within each of the model's areas of variability are examined and an optimum case, or range of cases, identified.

Some variability is limited by external influences, for example, rain data grid and grid cell sizes are restricted to those in which the data is supplied. The remaining variability falls into two categories: that for which optimum values, or sets of values, can be obtained from sources external to the model, and that requiring the examination of a range of options from which appropriate selections can be made.

The first category consists of results obtained from the literature, or adapted from standard values, and these were identified first. They were then used during the examination of parameters in the second category, which was done by performing a set of test runs with the RAIN-PATCH implementation of the model. These runs used a range of values for each of the parameters being considered, so that suitable values for each could be identified from analysis of the results.

Making these parameter selections will in many cases reduce the generality of the original model specification, and so must be done with due consideration for the intended uses of the model. One such consideration is the model's intended scale of operation. This scale has been dictated by two limitations which together form bounds to the operational range of the model. The first is the rain data grid size, which for a single site has a diameter of 420 km, and for the composite grid a maximum dimension of 640 km. Since the model can only properly operate in these areas it is therefore limited to travel distances of a few hundred kilometres, which correspond to

travel times of a few tens of hours. The work done on the contamination following the Chernobyl accident is included in this restriction since in effect a number of pseudo-local sources were used. The second scale limitation is a lower bound. This is also imposed by the radar data which uses a 5 by 5 kilometre grid cell size and therefore restricts the model to this minimum resolution.

The following four sections cover parameters whose optimum values were obtained, at least initially, from external sources. In two of the cases, however, later testing and verification model runs were also carried out. Section 5.6 then gives a general description of the use of RAIN-PATCH in determining the remaining parameters which are then discussed in the subsequent sections. The final section is a summary of the form of the model used to obtain the results discussed in the following three chapters.

5.2 PUFF STANDARD DEVIATIONS

The standard deviation values used for the majority of the model's runs are adapted from Clarke (1979). They apply to the turbulent diffusion of a release of material occurring over a short period of much less than thirty minutes. This is appropriate to a puff model, since longer releases can be represented by a sequence of puffs.

Table 5.1. Pasquill Stability Categories.

Stability category	Description	Typical wind speed at 10m (ms^{-1})	Typical mixing layer depth (m)
A	Unstable	1	1300
B		2	900
C		5	850
D	Neutral stability	5	800
E	Stable	3	400
F		2	100
G		1	100

Table 5.2. Parameter values required to give the puff standard deviation from the relation $\sigma = Ct^m$ for each stability category.

Stability category	m	C
A	0.909	1.071
B	0.908	1.549
C	0.910	2.762
D	0.913	1.730
E	0.910	0.744
F	0.910	0.360
G	0.904	0.124

Clarke gives standard deviation values for each of the seven Pasquill stability categories (Pasquill and Smith, 1983). These categories, based on atmospheric stability, directly relate to the dispersive properties of the atmosphere, and their major characteristics are given in table 5.1. The standard deviation values are given as functions of distance which have been converted to a function of time of the form $\sigma(t) = Ct^m$ using a height corrected typical wind velocity for each category. These velocities, also listed in table 5.1, are for a height of 10 m which is corrected to the half boundary layer height using the method described in section 5.3. The resulting parameters, C and m , for each of the categories are listed in table 5.2.

There are two points to note when using these standard deviation values. First, they are intended as lateral dispersion values for a Gaussian puff. In the model they have been used for both required horizontal standard deviations. This takes no account of any along-wind spreading of material due to a finite release period. However this should not be significant if individual releases are kept to, at most, a few minutes duration with longer releases modelled using sequences of puffs. The alternative of extending the along-wind standard deviation was not used because this could only be done for releases along an axis direction.

The second point to note is that the values from the report are only considered to be reliable to a range of no more than 100 km. Model runs using data from a single radar site will, on average, go twice this distance. This can

in part be justified because the puff follows a trajectory obtained from mean hourly wind data so longer time period effects are included. However, these play no part in determining the puff dimensions at later times, when longer time period fluctuations would have an effect due to the puff's increased size. This factor needs to be considered in situations where significant deposition occurs at distances greater than 100 km for a single run. Deposition in these cases could be at lower levels over a wider area, but for cases when many runs are added together the effect is probably not significant.

A minimum standard deviation value of 0.05 km is also imposed whenever a smaller value would otherwise be used. This is required to prevent RAIN-PATCH from trying to process surface deposition patches of zero or near zero area. Any errors caused by sample points being prematurely moved across deposition grid boundaries are not considered significant due to the small size of this limiting value relative to typical grid cell sizes.

5.3 WIND VELOCITY HEIGHT CORRECTION

The hourly mean wind data from which puff trajectories are calculated are measured at the standard height of 10 metres above ground level. The puff however represents material uniformly spread throughout the depth of the boundary layer so the wind velocity at half the height of the boundary layer is typically used to advect the puff.

Corrections to the speed and direction of the 10 metre wind values to give approximate half boundary layer values were derived from the results of Smith (1975). These values have only a minor dependence on stability category so that the constant values of a speed increase by a factor of two and a direction change of 9° are used under all conditions, which correspond to surface conditions appropriate to 'large open fields' or 'root crops' which are probably typical of the areas covered by the radar data. Specific meteorological situations may differ significantly from these values, which are average values, and this needs to be considered in interpreting RAIN-PATCH results.

The results of Smith (1975) are used here at levels higher than those for which they were derived in the absence of better quantitative results, since they agree well with accepted values.

5.4 DRY DEPOSITION PARAMETERS

There are two aspects of the dry deposition scheme in the model which need to be defined. These are the dry deposition velocity, v_d , and the function, $h(t)$, which corrects for the initial non-uniform vertical distribution of material.

Dry deposition velocity is primarily a function of the material under consideration and the two nuclides I-131 and Cs-137 are considered to be the materials released in this work because they are the major depositable nuclides of environmental concern in most hypothetical accidents. The dry deposition values used for them in RAIN-PATCH are 0.003ms^{-1} for iodine and 0.001ms^{-1} for caesium, which correspond to the values used in the MESOS model (ApSimon et al 1985).

Table 5.3. Positions and times of uniform vertical mixing.

Stability category	Uniform vertical mixing position, x_u (km)	Uniform vertical mixing time, t_u (hours)
A	15.7	2.18
B	27.7	1.92
C	67.6	1.88
D	283.1	7.86
E	280.3	12.98
F	45.7	3.17

The vertical dispersion correction function, $h(t)$, has a unit value at and beyond the position at which the dispersing material becomes uniformly mixed throughout the height of the boundary or mixing layer. Clarke (1979) suggests that this has occurred when the vertical standard deviation of the dispersing material is equal to the boundary layer height. These positions have been calculated for each stability category using the form of the vertical standard deviations from Clarke and the typical boundary layer depths from

table 5.1. They are given in table 5.3 together with the times after the release at which they occur, where these times have been calculated using the typical, corrected wind velocities for each stability category described in section 5.2.

Prior to uniform vertical mixing, dry deposition and therefore $h(t)$ are strongly dependent on the height of a release of material. This can be shown using the function $h'(x)$, which is $h(t)$ converted to the x variable. From the discussion above, $h'(x_u) = 1$ where x_u is the position where the vertical standard deviation matches the boundary layer height. Therefore $h'(x)$ can be defined by

$$h'(x) = c(x) / c(x_u) \quad (5.4.1)$$

over the range $0 < x < x_u$, where $c(x)$ gives the surface concentration value from the vertical dispersion of a release at height r in the boundary layer. $c(x)$ uses a vertical Gaussian distribution with reflections at the ground and boundary layer, modelled using five virtual sources. This is given by

$$c(x) = \frac{1}{\sigma_z(x)} \left[\exp\left(\frac{-r^2}{2\sigma_z^2(x)}\right) + \exp\left(\frac{-(2H+r)^2}{2\sigma_z^2(x)}\right) + \exp\left(\frac{-(2H-r)^2}{2\sigma_z^2(x)}\right) \right] \quad (5.4.2)$$

where H is the boundary layer height and $\sigma_z(x)$, the vertical standard deviation, again uses the values of Clarke. Constant terms, which would cancel in $h'(x)$, have been neglected.

Figure 5.1 shows $h'(x)$ for a selection of release height values in category-D stability conditions. The first and obvious conclusion from the graphs is that $h'(x)$ has a unit or near unit value, from well before the position x_u , for all the release height values; it is within about fifteen percent of the value one for all the curves at 100 km and within a factor of two of that value at 30 km. At shorter distances the release height value has a very marked effect, especially for the lower level releases. For these, dry deposition is initially very much enhanced relative to the higher releases, which is to be expected.

Possible accidents would not, in general, be of low level, non-buoyant releases. Therefore the curves showing very high levels of initial dry deposition can be neglected. The remainder can be adequately modelled using a

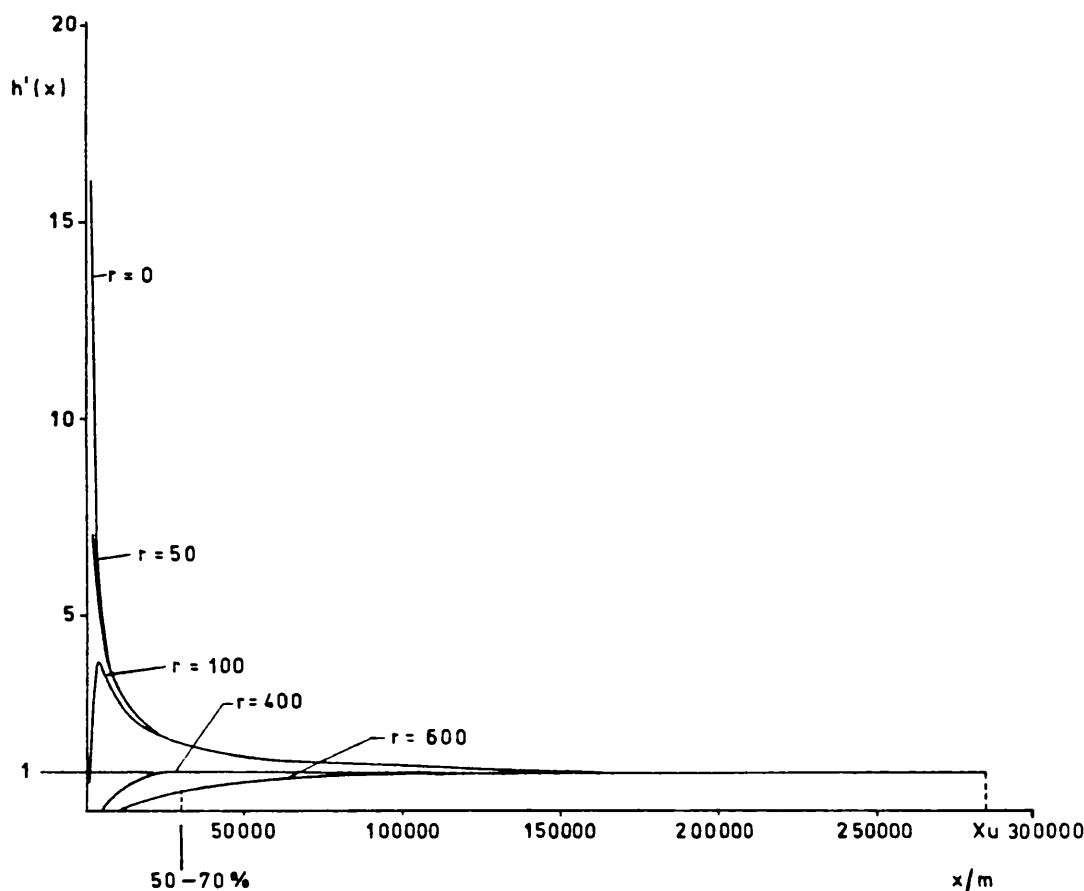


Figure 5.1 $h'(x)$ for various release heights.

constant unit value for $h'(x)$ over its full range. Clearly this will give errors within the first few kilometres of a release site but, for reasons given above, the model cannot be considered completely satisfactory in this range, and dry deposition errors should not significantly worsen this situation for two reasons. First, if wet deposition does not occur close to the release site, then the surface patches arising from dry deposition alone will be fairly large and will average any errors over a correspondingly large area. Second, when wet deposition does occur there, the levels will generally mask the dry deposition levels, making any errors in them insignificant.

5.5 THE WET DEPOSITION COEFFICIENT

The two models presented in this work calculate the interaction between precipitation and pollutant using a simple scavenging relation. This is given

by equations (2.2.4) and (3.3.23) for the one dimensional and two dimensional models respectively. This relation has only one parameter, the wet deposition coefficient, Λ , for which suitable values need to be found.

From consideration of the general wet deposition problem described in chapter one, a simple scavenging relation is clearly a gross oversimplification. This presents some difficulty in defining suitable values for Λ . Even considering a specific type of pollutant leads to both theory and experiment providing ranges of values which may cover a number of orders of magnitude. A review of the whole subject, which includes a discussion of the values of Λ used in a variety of wet deposition studies was carried out by Underwood (1983). From this the form $\Lambda = 10^{-4} J s^{-1}$, where J is rainfall intensity in mmhr^{-1} , was identified as typical and was used initially in the RAIN-PATCH model.

The $10^{-4} J s^{-1}$ value was later considered to be too large and indeed a smaller value of $5 \times 10^{-5} J s^{-1}$ had previously been used in the one dimensional model. This was supported by the report of Jones (1985) which recommended a deposition coefficient of the form $\Lambda = a J^b s^{-1}$ for particulate material where the two parameters, a and b , are considered to lie, respectively, in the ranges 3×10^{-5} to 3×10^{-4} and 0.7 to 0.9. This range is considered by Underwood to be too restrictive but since ultimately only a single value can be used in a model run it seemed appropriate to make use of a value from this range.

Using a value as accurate as possible for the deposition coefficient is important for two reasons. Firstly, for a given situation of precipitation and pollutant the resulting deposition will correlate directly with the deposition coefficient so, for example, if its value is too large then deposition will be overestimated. This then leads to the second consideration: since there is only a finite reservoir of pollutant in the atmosphere any error in its removal at a location will affect the situation downwind of that location. This is apparent from figure 5.2 which shows relative deposition from three RAIN-PATCH runs which differ only in the deposition coefficient value used. The values are the end points and an approximate mid-point value from the range

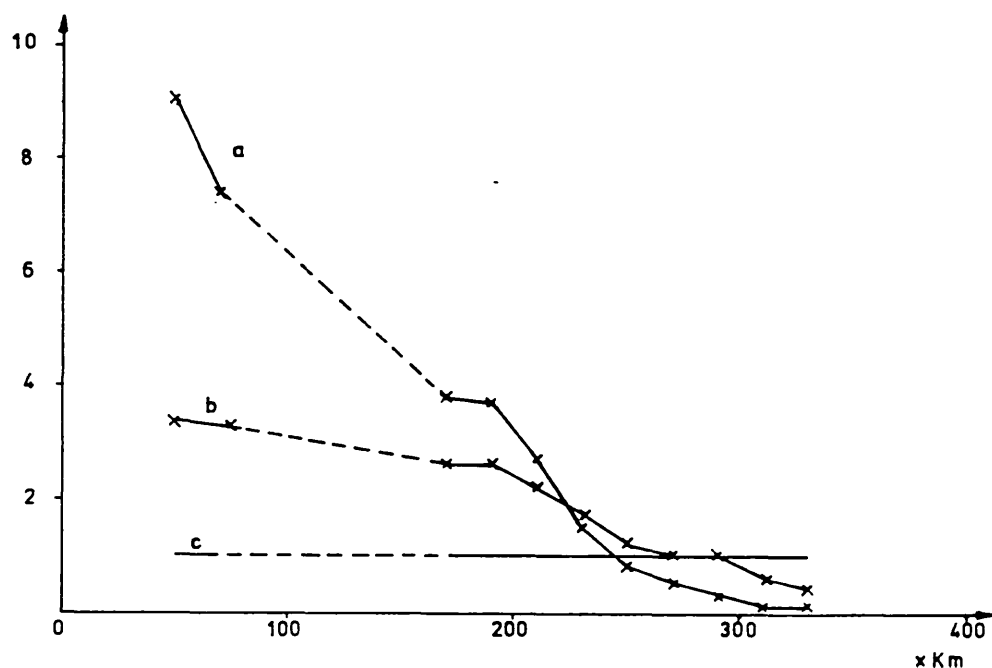


Figure 5.2. Relative deposition using three values of Λ . (a) $3 \times 10^{-4} J^{0.9}$, (b) $10^{-4} J^{0.8}$ and (c) $3 \times 10^{-5} J^{0.7}$ with deposition values scaled by the value for $\Lambda = 3 \times 10^{-5} J^{0.7}$. (Dashed lines indicate a region of no deposition)

due to Jones and the results at each downwind distance are scaled using the deposition quantity predicted using the smallest of the coefficient values. The deposition initially is much higher for the higher coefficients but decays with distance until eventually they are both lower than the values predicted with the smaller coefficient value.

Distortion of deposition with distance owing to inaccurate deposition coefficient values needs to be considered in analysing model results. Unfortunately this is difficult to avoid given the uncertainty in 'correct' coefficient values. In this work the compromise value of $\Lambda = 10^{-4} J^{0.8}$ has been used predominantly since it is approximately in the middle of the range given by Jones, but improved estimates of the parameter would be desirable.

5.6 PARAMETER SELECTION USING RAIN-PATCH TEST RUNS

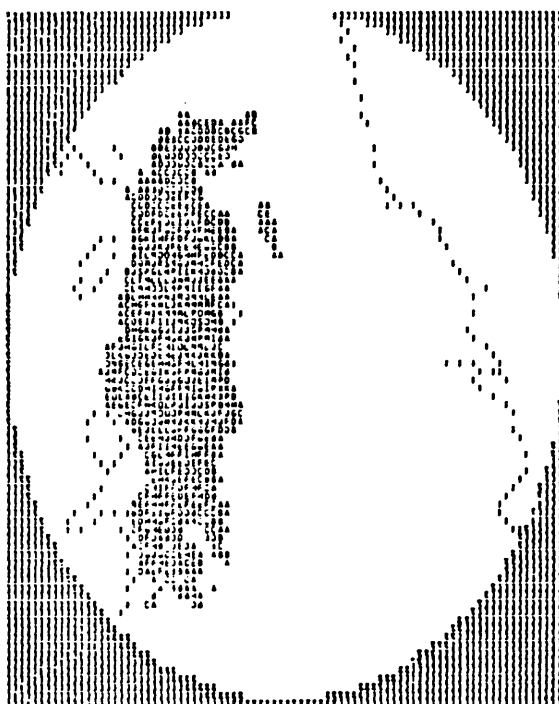
The remaining parameters were examined using the RAIN-PATCH implementation of the model and two five hour sequences of rain data. These two

sequences, both of them from the Manchester radar site, were chosen to give enough wet deposition for the effects of adjusting the various parameters to be readily assessable.

The first sequence is from 2200 hours on 21 January 1984 to 0300 hours on the 22 January. During this period a front moves through the data area bringing rain and snow together with gale force winds. A series of diagrams showing where precipitation was recorded by the radar are given in figure 5.3. These show a pronounced band of rain, initially near to the western boundary of the data area, which moves east to a more central position during the first two hours. During the next two hours sub-bands of rain form behind the main band which subsequently moves further east and decays, leaving the sub-bands positioned over the Pennines.

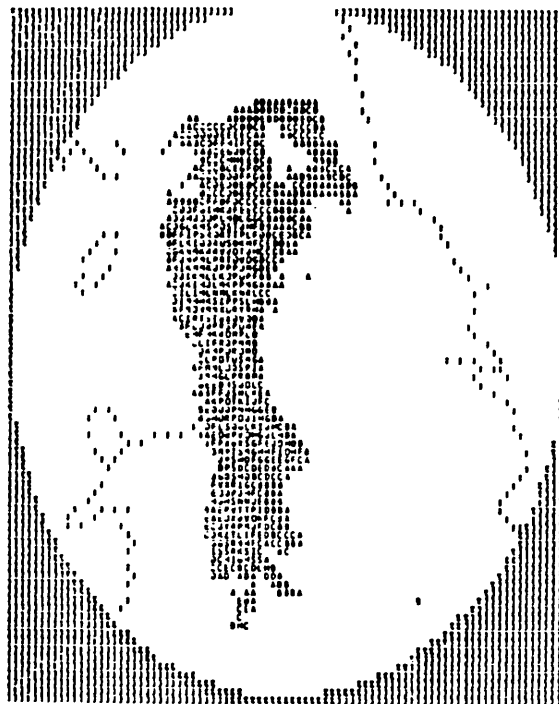
The second test sequence of data is from an intense storm which occurred over Manchester during 5 and 6 August 1981. This event has been described and analysed in detail in the paper by Bader, Collier and Hill (1983) and will be considered in more detail in chapter six. The sequence used here runs from 1600 hours to 2100 hours on 6 August 1981 and is shown in figure 5.4. It consists of a large area of intense rain centred on Manchester which moves very little during the period under consideration, although North Wales does clear and rain starts to fall along the north east coast towards the end of the five hours.

Trajectories from nine possible release sites were examined for each of the two sequences. These sites, positioned uniformly across the data area, are shown in figure 5.5. They were situated independently of surface considerations and a number are positioned over the sea. For each site the release was considered to occur at the beginning of the sequence of rain data, and from these, three releases were selected, two for the front and one for the storm. These releases remained in the data area for sufficient time and encountered enough rain to be useful in the parameter selection. The three selected sites are the positions in figure 5.5 marked S and SE for the front and NE for the storm.



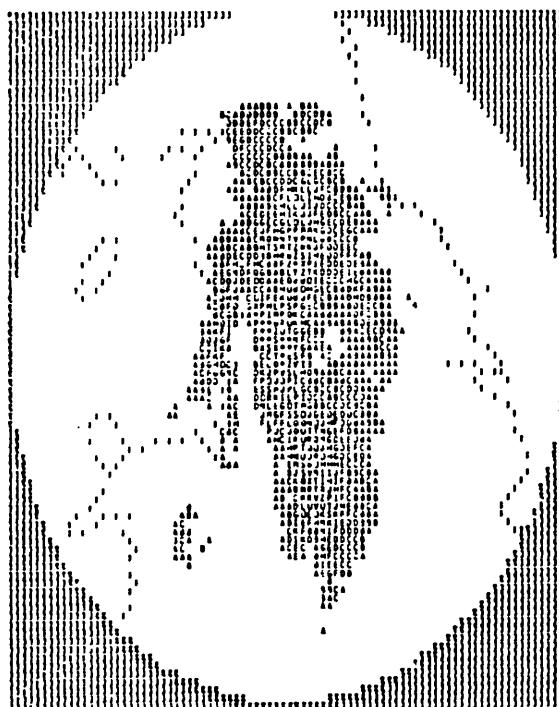
2200

21 Jan '84



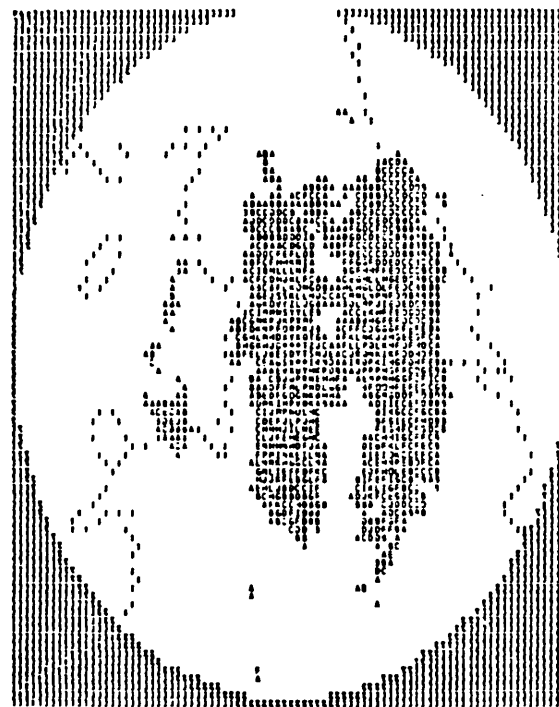
2300

21 Jan '84



0000

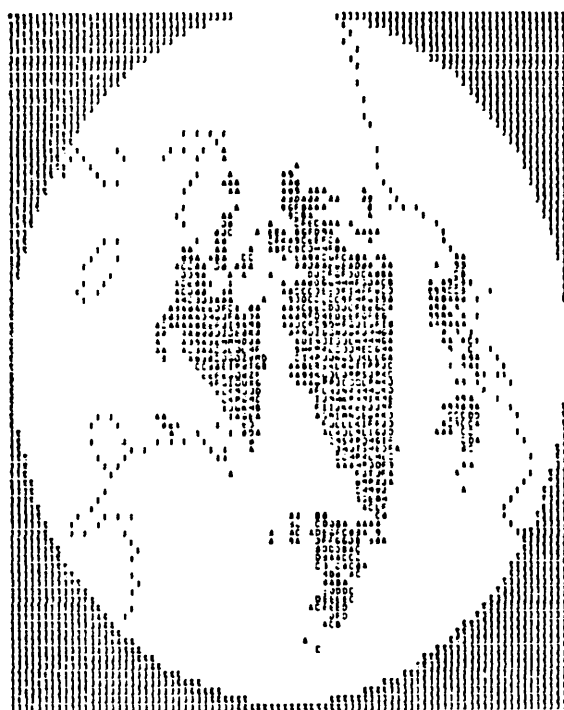
22 Jan '84



0100

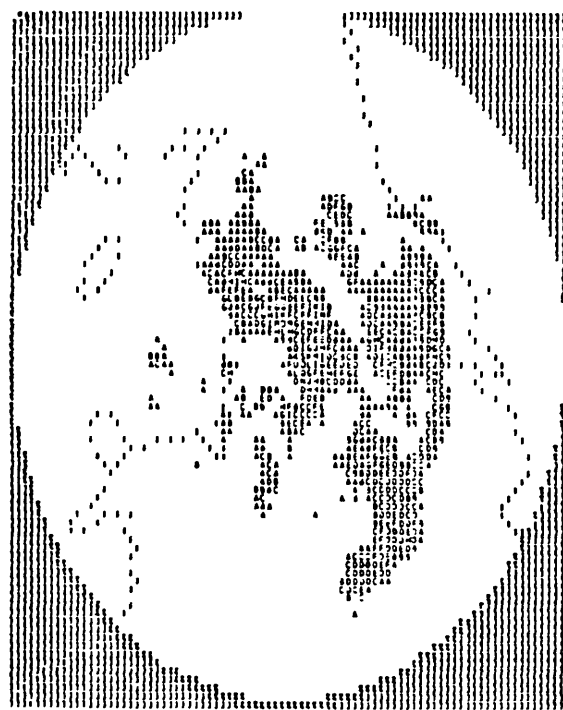
22 Jan '84

Figure 5.3. Test sequence — Frontal system.



0200

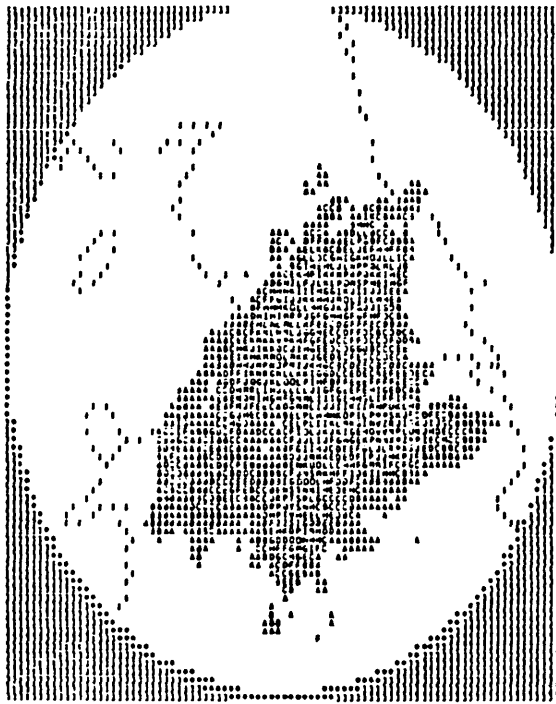
23 Jan '84



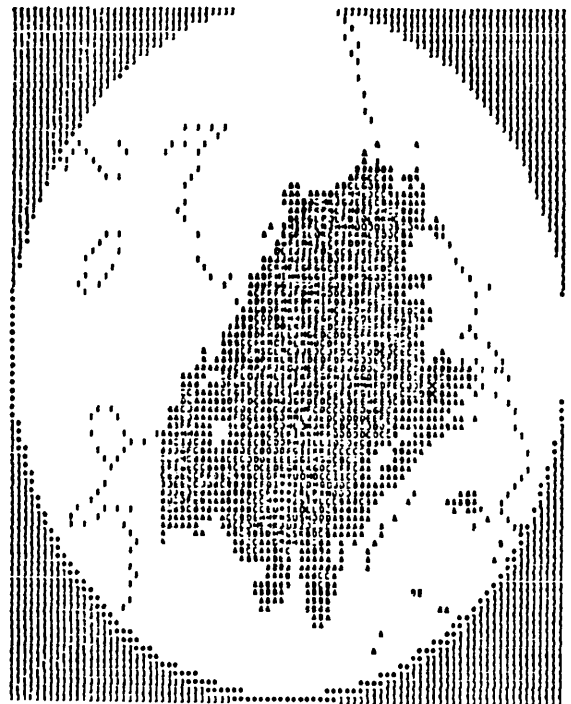
0300

24 Jan '84

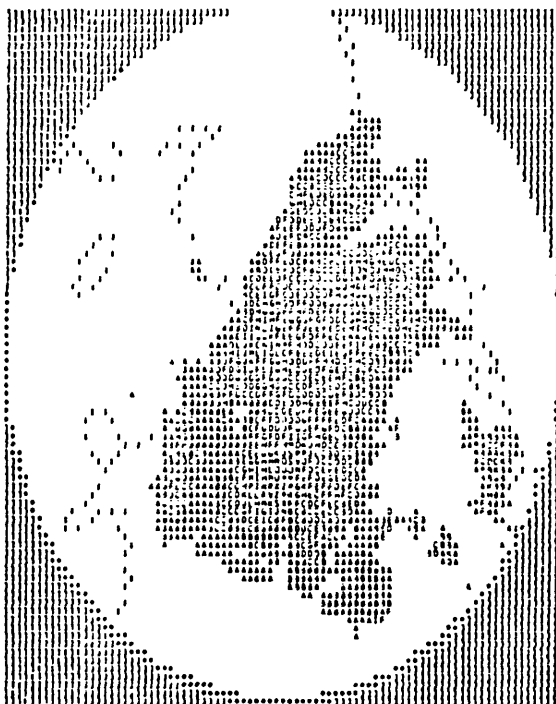
Figure 5.3 continued.



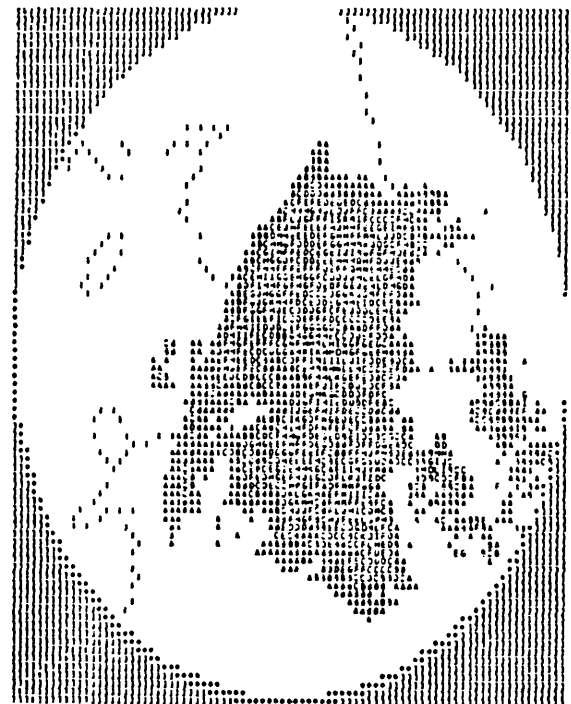
1600 6 Aug '81



1700 6 Aug '81

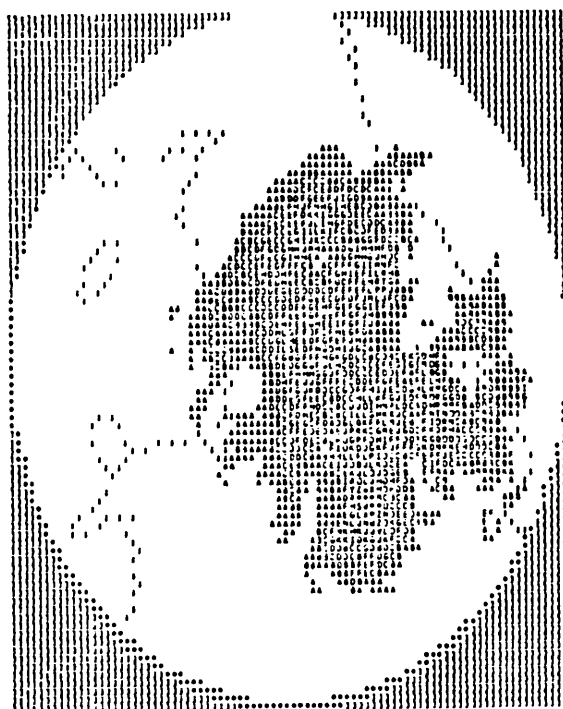


1800 6 Aug '81

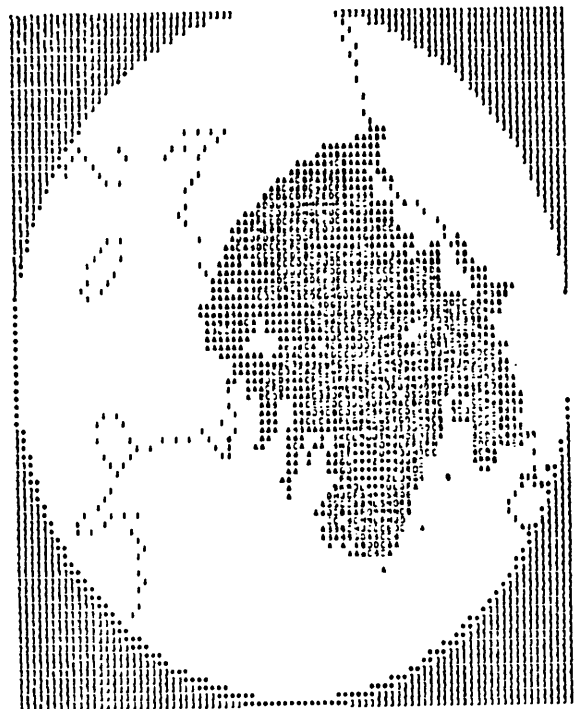


1900 6 Aug '81

Figure 5.4. Test sequence — Convective storms.



2000 6 Aug '81



2100 6 Aug '81

Figure 5.4 continued.

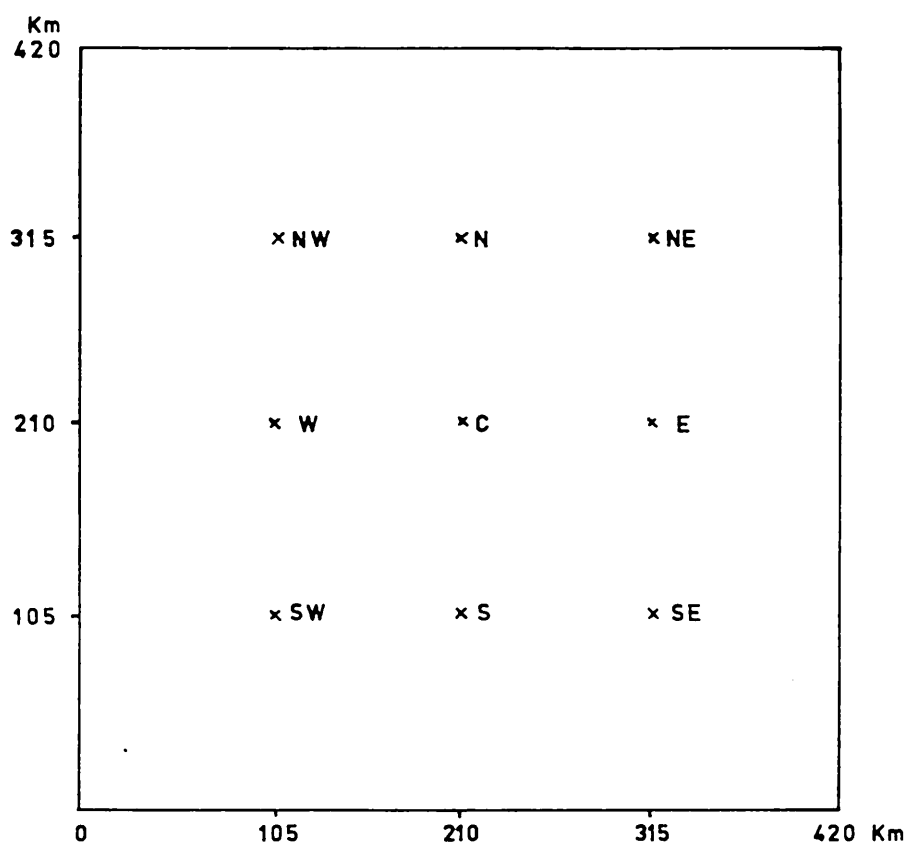


Figure 5.5. Nine release site positions from which the three test sites were chosen.

Contoured diagrams of the surface deposition for the three test releases are given in figures 5.6 to 5.8. The coastline has been included in the figures to give an indication of scale. They were produced using the optimum model parameters whose selection is discussed in this chapter for a release of 1000 Bq. Also shown, in figure 5.9, is a 'character levels grid' for the front test sequence using release site S. This has the level of deposited material in each grid cell represented by a character and is the form of data used in the selection of the optimum parameters. The characters used are the letters 'A' to 'Z' to represent some level being exceeded by one to twenty-six times, with '+' representing exceeding the level by twenty-seven to thirty times and '*' for more than thirty times. In the figure the level used is $10^{-3} \text{ Bqkm}^{-2}$.

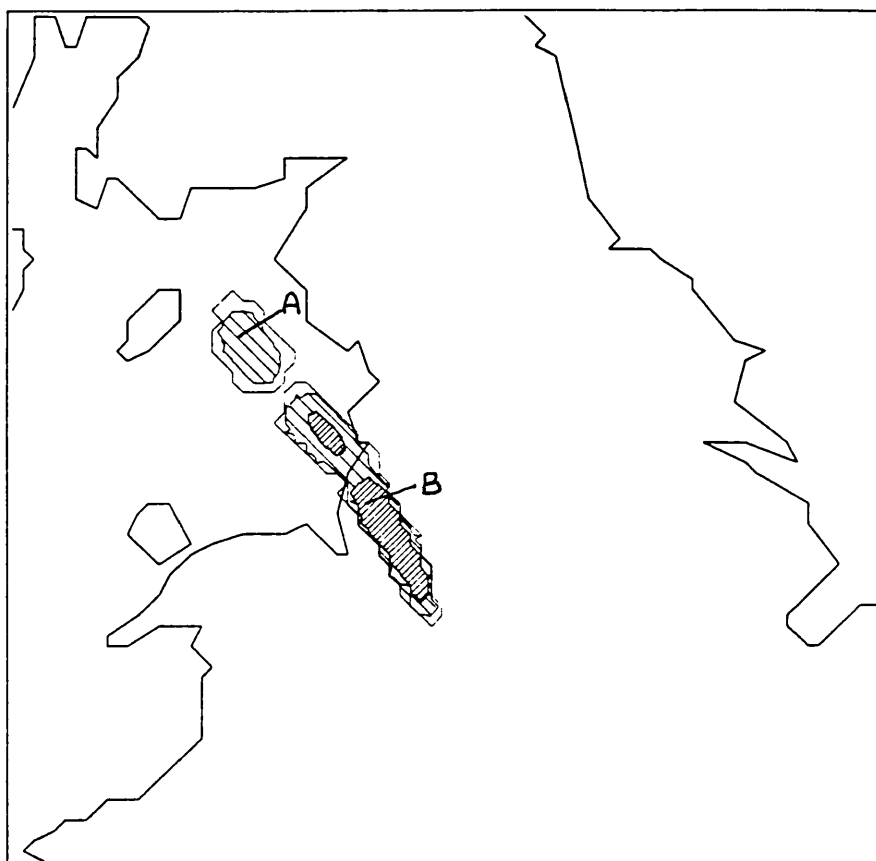


Figure 5.6. Test run results using release site S and the frontal test sequence. Contour levels: 10^{-8} , 10^{-3} and $5 \times 10^{-2} \text{ Bqkm}^{-2}$ from a 1000 Bq release.

This form of data permitted direct comparisons to be made of areas exceeding some level either over the whole grid or in selected areas, and significant changes in levels between runs could also be easily identified.

5.7 SAMPLE POINT POSITIONING AND DENSITY

Even with the restriction that sample points lie on the intersection of concentric ellipses and straight lines through the puff's centre there is still significant choice in the precise form of a puff. The first consideration is the extent to which a puff should extend from the central position. Typical values for this are 2.5 or 3 standard deviations which correspond, respectively, to Gaussian concentration values which are 4.4% or 1.1% of the puff's central concentration. At these distances the Gaussian distribution, which gives concentrations at any distance, ceases to be such a good model of the dispersing

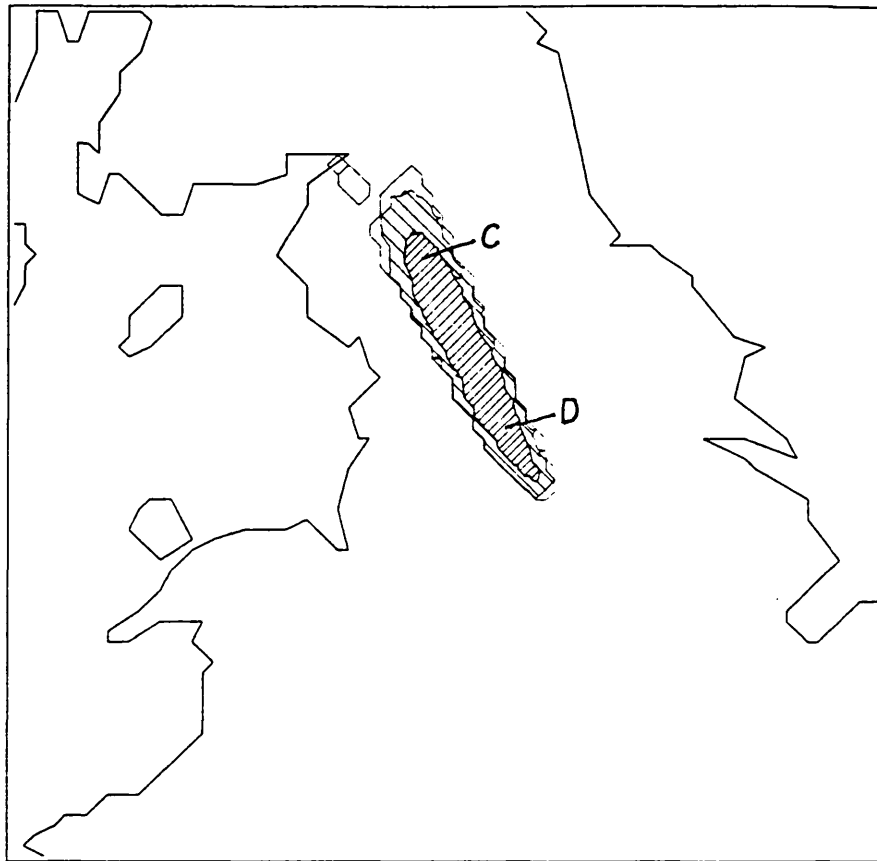


Figure 5.7. Test run results using release site SE and the frontal test sequence. Contour levels as for figure 5.6.

material, which has a finite extent, and so an acceptable approximation is to assume zero concentrations at some distance. In the RAIN-PATCH model implementation the cut-off distance is taken at 2.5 standard deviations.

The distribution of sample points within the puff, independent of their number, also offers some choice. The form chosen has the rings (ellipses) of sample points spaced with equal separation and the rows positioned so that the spacing between rows at the point half way from the puff's centre to the boundary matches approximately the ring spacing. This gives a sample point spacing which increases linearly from the puff's centre, which is desirable since concentration decreases away from the centre; so the region of highest concentration has the greatest points density.

The number of sample points in a puff is subject to two main considerations. There need to be sufficient points so that the spatial structure of

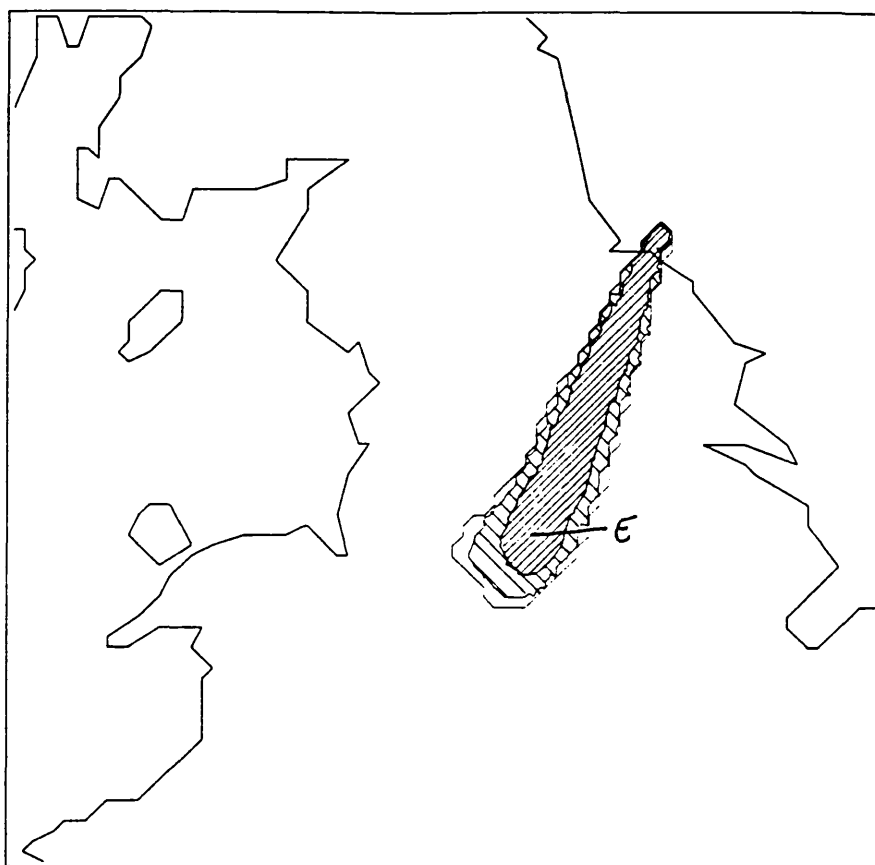


Figure 5.8. Test run results using release site NE and the storm test sequence. Contour levels as for figure 5.6.

the precipitation is adequately encountered, so that events are not missed or those that are intercepted do not have their effects spread unreasonably wide by the inter-sample point distances. Conversely there cannot be so many points that the data storage requirement or model run times become excessive for the computer being used. A further consideration arose out of the early model version which used a block structured representation of rain. This gave smoother surface deposition distributions for more sample points and the criterion of, on average, at least one sample point per surface grid cell was easily arrived at for optimum results. Since the model is generally used with the surface grid matching the precipitation data grid, this criterion would also satisfy the first consideration given above.

Table 5.4 gives the number of sample points required to meet a selection of average spacing distances for category-D dispersion conditions over a range

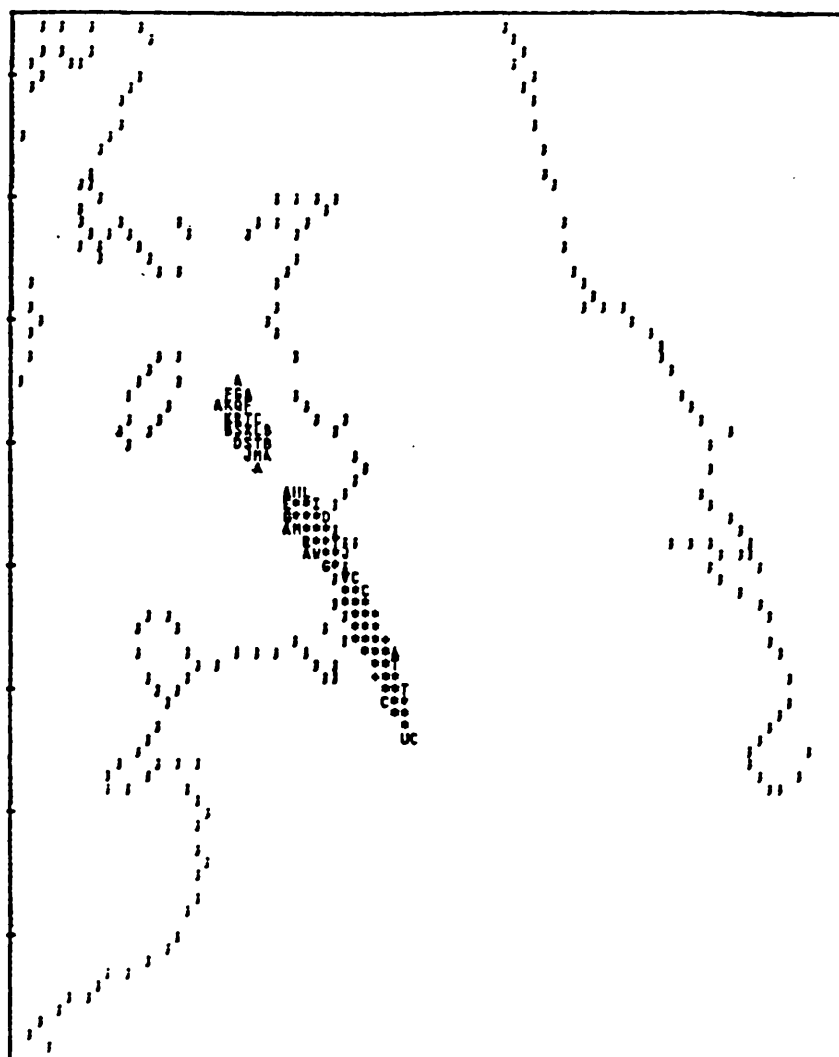


Figure 5.9. Character level grid for test run results from site S.

of times. The criterion given above corresponds to the 5 km average spacing distance which, from the table, can be quickly seen to require a very large number of sample points, so that the second consideration of data size and computing times comes into effect. Therefore the final choice of puff was carried out by performing test runs with puffs of a variety of sample point densities.

Four puffs were used in the test. Their sample point positionings, given in table 5.5, were chosen to meet the spacing requirement given above and to have the number of sample points approximately doubling from one puff to the next. Model runs were then carried out using all four puffs from all three

Table 5.4. Numbers of sample points required to give average spacing x at time t .

time, t hours	spacing, x km			
	5	10	15	20
1	2	0.6	0.3	0.1
2	8	2	0.9	0.5
3	17	4	2	1
4	29	7	3	2
5	44	11	5	3
6	61	15	7	4
7	81	20	9	5
8	103	26	11	6
9	128	32	14	8
10	155	39	17	10
11	185	46	21	12
12	216	54	24	14
13	250	63	28	16
14	287	72	32	18
15	325	81	36	20
20	548	137	61	34
25	823	206	91	51
30	1147	287	127	72
40	1936	484	215	121
50	2906	727	323	182
100	10261	2565	1140	641

Table 5.5. The puffs used in selecting optimum puff sample point density.

Number of sample points	Number of rows	Number of rings
17	8	2
37	12	3
65	16	4
121	24	5

test release sites. The four results for each site were then compared to see the effects of sample point density on the total area over which contamination was predicted and the effects on the predicted levels within these areas.

Taking the area contaminated first, the relevant results are summarized in tables 5.6 and 5.7. The results for each run given in table 5.6 show a

Table 5.6 Deposition areas and run times for sample point density test runs. The times in each sequence have been normalized by the time for the 17 point puff.

Site	Puff size in SPs	Depn. area in 5 ² km ² grid cells	Normalized model run time	Fraction of material deposited
S	17	214	1	0.538
	37	225	1.74	0.546
	65	234	2.85	0.549
	121	231	5.13	0.552
SE	17	171	1	0.506
	37	190	1.62	0.496
	65	191	2.38	0.485
	121	197	4.39	0.491
NE	17	194	1	0.773
	37	199	1.83	0.768
	65	199	3.06	0.769
	121	203	5.70	0.767

Table 5.7. Total deposition area change comparisons for sample point density test runs.

Site	Puffs used in comparison		Total area change (5 ² km ²)	Total area change as % of area for 121 point puff
S	17	37	15	6.5
	37	65	13	5.6
	65	121	8	3.5
SE	17	37	28	14.2
	37	65	14	7.1
	65	121	9	4.6
NE	17	37	11	5.4
	37	65	8	3.9
	65	121	7	3.4

consistent increase of area with sample point density. This indicates that in a puff with more points the extra sampling points encountering more rain have a greater effect than the rain encountered being spread more widely in a simpler puff. However, the fraction of material deposited does not show any consistent trend, which indicates that the effect is largely a redistribution of

deposited material rather than more deposition. This is supported by the deposition in the extra areas being at very low levels.

Table 5.7 gives the differences in areas deposited upon for each of the adjacent pairs of runs, and shows that the rate of increase in area reduces with sample point density. Since the four test puffs have their numbers of sample points roughly doubling with each increase in point density, this reduction in area increase can be interpreted as a convergence. This indicates that the use of puffs with more sample points should show less of an increase in area, and since the area changes between the two highest point density puffs used are, in each sequence, reasonably small any further possible increase should not be excessive.

Table 5.8. Deposition level change comparisons for sample point density test runs. Negative level changes indicate a decrease in average level with increasing puff number.

Location in figs. 5.6-5.8	Site	Letter increment (Bqkm ⁻²)	Sample area (5 ² km ²)	Mean percentage level change over sample area		
				17-37	37-65	65-121
A	S	10 ⁻³	15	15.9	20.5	11.4
B	S	5.10 ⁻²	10	4.8	2.4	0
C	SE	10 ⁻³	14	11.6	10.9	-3.1
D	SE	5.10 ⁻²	13	0	-10.3	2.6
E	NE	2.10 ⁻²	19	-1.1	3.2	0

The changes in the predicted levels of deposition were analysed over selected areas of the deposition patterns. The central positions for these areas are marked on figures 5.6 to 5.8 and the results are given in table 5.8. These show that the mean fractional level changes cover a wide range of values, but a tendency for them to reduce with increasing sample point density is discernible although not as obvious as in the area analysis. The magnitudes of these level changes were in one case greater than twenty percent, and exceeded ten percent in a number of cases, which again compares unfavourably with the area results. Some of the level changes were negative, however, which does indicate that the levels are probably fluctuations and there is

no tendency for them to increase progressively with an increasing density of sample points.

The large level change values may be partly attributed to the simple analysis used. This, as outlined above, is in terms of changes in predicted levels indicated by the characters displayed in grids such as that of figure 5.9. The deposition levels from a run may typically cover three orders of magnitude and the level change results show a correlation with the level increment used in the analysis. Normally, since this increment is selected to give a good spread of coverage over the region of deposition, analysis areas can often contain a significant number of lower value letters for which any changes give a relatively larger mean letter change. This is apparent from the analysis for the areas centred at locations A and C in the figures, which being further from the release sites have on average lower levels than for the areas centred on B and D and show significantly higher mean level changes. This is also borne out by the total deposition values as a fraction of the quantity released which are given in table 5.6. Since these do not change significantly the mean level changes must be predominantly local effects away from the areas of highest deposition.

Despite allowance for the method of analysis the change in predicted levels with sample point density is still large, especially in relation to the change in area. This is a consequence of the simplicity of the model and results may be improved by using a coarser grid, which has a smoothing effect on the surface distributions.

In summary, the increase in contaminated area with puff complexity does favour a more complex puff, but the effect is minor since area changes are small. This is fortunate since the main use of the model is to study spatial effects for which accurate modelling of the spread of material is important. The effects of puff complexity on the predicted levels of deposition also favour more complex puffs, so in general a puff with the maximum sample points that computing limitations permit should be used. Greater puff complexity increases the computing time required for the model, but not

in direct proportion as can be seen from the normalised times in table 5.6. However data storage requirements do increase in proportion and there is also some increase in the size of the files used between the different stages of RAIN-PATCH. Because of these considerations the 65 point puff has mainly been used throughout this work.

5.8 REDISTRIBUTION FREQUENCY

If the redistribution scheme is used, then there is a choice in how frequently it is applied. The maximum frequency would be to invoke it every time the sample point/precipitation interaction time advanced, but less often might give a significant saving in computer time.

Table 5.9. Redistribution frequency testing results.

Locn. in figs. 5.6 & 5.8	Site	Mean deposition level change from no redistribution to:-		
		max. rate	hourly	two hourly
A	S	-4.1%	- 5.1%	- 4.1%
E	NE	17.0%	17.0%	14.2%

Two of the test release sites were used in determining the optimum rate for redistribution, and mean deposition level result comparisons between various runs are given in table 5.9. These results show that the redistribution frequency has little effect but that there is an effect when redistribution is included, which is comparable with that observed in the puff complexity analysis. Also, the direction of the effect changes between the two sets of runs, with mean levels reducing for the storm but increasing for the front. This could only have been as a result of conditions local to the levels analysis area since it was not reflected in the total quantities of material deposited.

The effect of redistribution is significant compared to other factors, such as puff complexity, so it is considered a worthwhile correction to have in the model. This is especially true since the test runs have not been selected as situations where redistribution will be particularly significant, such as those described in chapter four. It is used at its maximum frequency since

the savings with the lower frequencies were not significant relative to total model run times.

5.9 DEPOSITION PATCH TERMINATION WITH DIRECTION CHANGE

Section 3.4 gives three options for including puff advection direction changes in the mapping of deposition onto the surface grid. Of these the third, in which a patch is split into a sequence of sub-patches, has been used in RAIN-PATCH. Each sub-patch is for a section of the trajectory which is either straight or sufficiently straight that corners are not cut off during the mapping.

Since both computing time and data file sizes increase with the number of sub-patches, two sets of test runs, using sites S and NE were carried out to examine by how much a trajectory direction needed to change before it became necessary to split a deposition patch. The RAIN-PATCH model can be set to produce deposition patches from any sample points being depleted when the trajectory being followed by the puff changes direction by at least some specified amount. Further depletion from those sample points will give rise to new patches. Test runs using 1° , 5° and 10° for these cut off angles were performed and the results compared. The two sets of results showed no significant changes in either area or mean level but there were changes in both computation time and file size for the frontal system test sequence, although not for the storm. In going from the 1° to 10° case the reduction in run time was 23% with a file size reduction of 29% for the frontal case. The lack of run time and file size changes for the storm test case are probably due to the larger trajectory direction changes occurring outside the main areas of precipitation, and consequently not affecting any of the deposition patches.

The 10° patch termination angle has subsequently been used in the model. The lack of change in the deposition distributions for the angles tested would be likely to continue for larger angles but these were not applied

because they would certainly cause errors during longer periods of purely dry deposition.

5.10 RAIN INTENSITY LEVEL SETS

The precipitation data provided by the radars is in terms of 208 levels of intensity. These are separated by one thirty-second of a mmhr^{-1} for levels below 2mmhr^{-1} and with increasing level separations for ranges at higher intensities. The four ranges and level separations are given in table 5.10.

Table 5.10. Division of precipitation intensity, J , into the four ranges of intensity level values provided by the radars.

Range of uniform level separation (mmhr^{-1})	Level separation (mmhr^{-1})	Number of levels
$0 \leq J < 2$	$1/32$	64
$2 \leq J < 8$	$1/8$	48
$8 \leq J < 32$	$1/2$	48
$32 \leq J < 128$	2	48

Since the RAIN-PATCH model produces a surface deposition patch every time the precipitation intensity changes at a sample point, there is scope for reducing computation times by merging the 208 original levels into fewer levels with wider separations. This would give less apparent spatial and temporal variability in the precipitation data and consequently fewer surface deposition patches. The feasibility of this was examined by initially analysing the distributions of intensity in the original data and their effect on deposition. This is presented in the following two sub-sections, with the derivation of the reduced rain intensity level sets used in the model and test results in sub-sections 5.10.3 and 5.10.4.

5.10.1 Rain Intensity Distribution Functions

The distribution of precipitation intensities was examined by adding up the occurrence of each intensity level for five sequences of radar data and

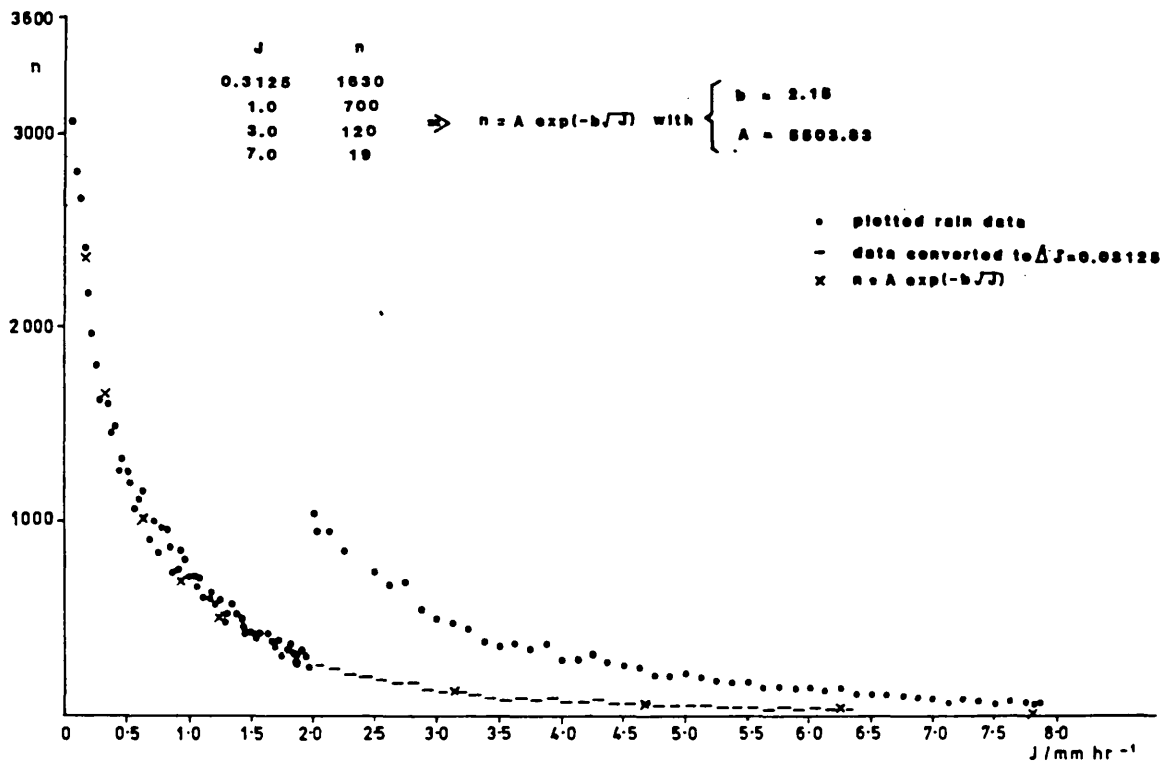


Figure 5.10. Intensity level frequency distribution.

obtaining function forms for the results. The five sequences considered are the front and the storm from which the two test sequences were extracted, a sequence covering the passage of an occluded front which was also from the Manchester radar and two sequences from the London radar. These are the first six days of 1985 and six days of data starting from 6 May 1985. Figure 5.10 gives the number of occurrences of an intensity level, n , plotted against intensity, J , for the first storm sequence. This has a form typical of all five sequences, which are exponential functions of the form

$$n = A \exp(-bJ^c) \quad (5.10.1)$$

A number of points from the function

$$n = 5503.83 \exp(-2.15\sqrt{J}) \quad (5.10.2)$$

are also shown in figure 5.10 by way of confirmation. This, however, assumes $c = 0.5$, so a more detailed analysis was performed using the equation

$$\ln \left| -\ln \frac{n}{A} \right| = \ln b + c \ln J \quad (5.10.3)$$

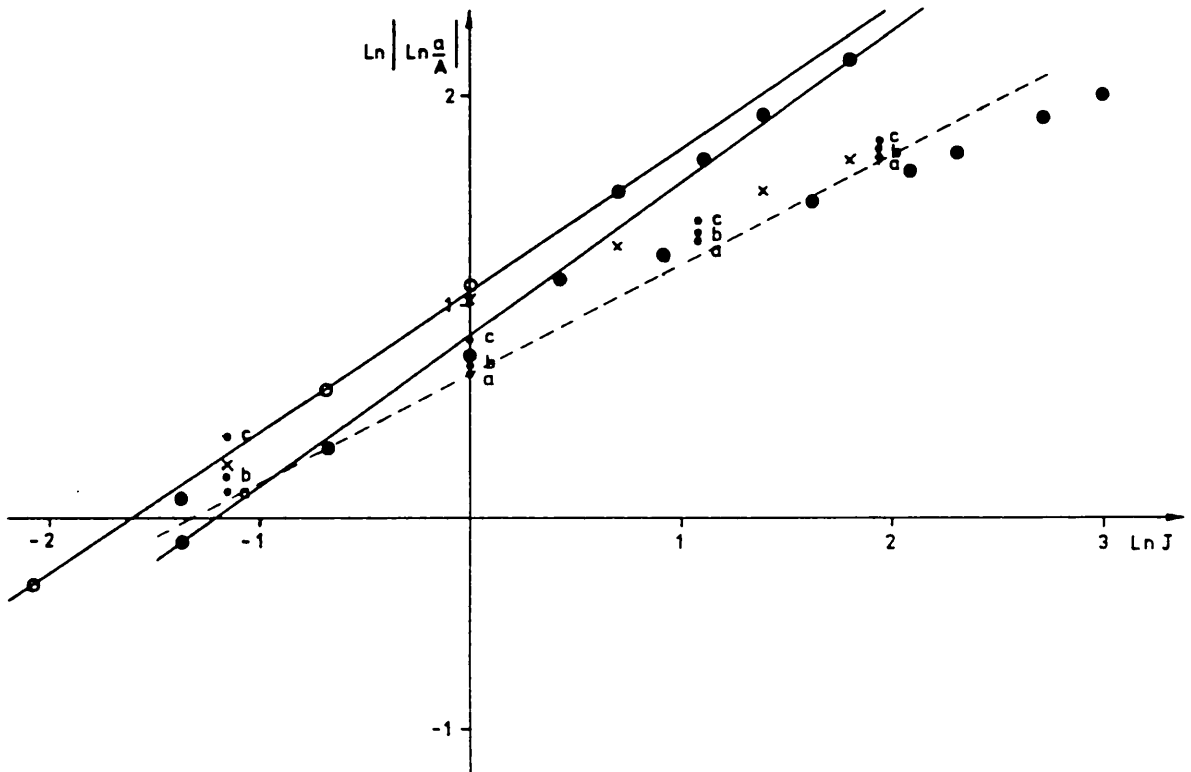


Figure 5.11. plot of $\ln |\ln \frac{n}{A}|$ against $\ln J$, for the front test sequence with $A = 5000$ (a), $A = 5500$ (b) and $A = 7000$ (c), the storm test sequence (x), an occluded front (o) and two London radar, six day sequences (o and ●).

which was derived from (5.10.1), and results from all the data are given in figure 5.11. The coefficient A is obtained from graphs such as figure 5.10 and so three values have been used for the first front's data to show the dependence of the curves in figure 5.11 on this value. Clearly the dependence of both intercept and slope is fairly minor and does not influence the results obtained from the curves.

The curves in figure 5.11 fall into two distinct bands with different slopes, the steeper corresponding to London radar data and the other to Manchester. Taking average intercept and slope values for each group gives the equation

$$\frac{n}{A} = \exp(-2.15\sqrt{J}) \quad (5.10.4)$$

as the best fit for the Manchester radar site data and

$$\frac{n}{A} = \exp(-2.46J^{0.7}) \quad (5.10.5)$$

as the best fit for the London site data.

This discrepancy in the coefficients between the two sites is due to the different types of data analysed rather than being directly related to site factors. The data used from the London site are sequences with no particular meteorological consideration in their choice but the Manchester data are specifically chosen because of their interesting rain situations. They have a greater predominance of relatively higher intensities which may be affecting the distributions.

5.10.2 Rainfall and Washout Distributions

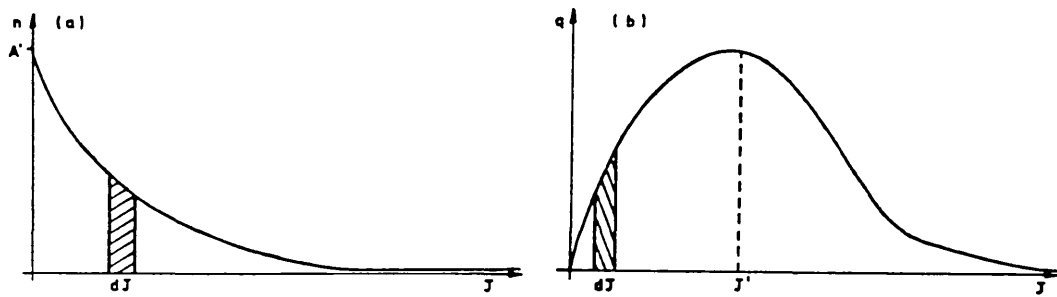


Figure 5.12. Forms of (a) rain intensity distribution function and (b) rainfall quantity distribution function.

The rain intensity distribution function

$$n(J) = A' \exp(-bJ^c) \quad (5.10.6)$$

shown in figure 5.12a can be interpreted as given that it is raining, then $n(J)dJ$, is the probability that the rain intensity is in the range J to $J+dJ$. A' is chosen to give the function a unit integral in the range $0 \leq J < \infty$.

From this the normalised rainfall quantity distribution

$$q(J) = BJ \exp(-bJ^c) \quad (5.10.7)$$

can be obtained. This, shown in figure 5.12b, can be interpreted as given that it has rained, then $q(J)dJ$ is the fraction of the total quantity of rain

which fell at intensities in the range J to $J + dJ$. The value J' in the figure is the intensity at which the greatest quantity of rain fell and has the values 0.87 mmhr^{-1} for the Manchester distribution given by equation (5.10.4) and 0.46 mmhr^{-1} for equation (5.10.5), the London distribution.

Table 5.11 Most efficient washout intensities for various values of T and using $\Lambda = 10^{-4} \text{ s}^{-1}$.

T		Most efficient intensity (mmhr^{-1})
seconds	minutes	
300	5	0.844
600	10	0.823
900	15	0.804
1200	20	0.787
1800	30	0.754
3600	60	0.675

The fraction of airborne material removed by rain of intensity $J \text{ mmhr}^{-1}$ over a period of T seconds is $(1 - \exp(-\Lambda_0 J T))$, using the simple linear scavenging relationship. This then gives the removal efficiency distribution

$$d(J; T) = C (1 - \exp(-\Lambda_0 J T)) \exp(-bJ^c) \quad (5.10.8)$$

where $d(J; T)dJ$ can be interpreted as the relative efficiency at removing material of rain in the range J to $J + dJ$ over the period T' . This function has the same form as $q(J)$ and a number of numerically calculated most efficient intensities for various values of T (for the Manchester site) are given in table 5.11. These results show a decrease in this value with increasing T .

The time period T has been introduced owing to the discrete nature of the radar measured data. In the limit $T \rightarrow 0$ the rainfall and removal efficiency distributions are identical since a washout coefficient which is linear in J has been used. If this were not the case, any nonlinearity would be retained in $d(J; T)$.

5.10.3 Selection of Rain Intensity Level Sets

Consideration was initially made of using the removal efficiency distribution

to generate sets of rain intensity levels. These levels would have been spaced such that on average each would have been responsible for an equal quantity of material washout or, equivalently, the integral of the distribution between each adjacent pair of levels would have been constant. This was found to be impractical owing to the very small contributions to total washout made by intensities above a few mmhr^{-1} . For example, typically sixty percent of material will be removed by intensities up to 3.6 mmhr^{-1} .

The removal efficiency distribution does not include any spatial or temporal considerations but the model may be used deliberately in areas of higher intensity. Therefore, despite the limited effects from these intensities, the very large spacings of the higher levels given by the removal efficiency distribution could be detrimental to the model.

The alternative method used to generate rain intensity level sets is in terms of a washout fraction, $w(J; T)$, defined by

$$w(J; T) = \exp(-J \Lambda_0 T) \quad (5.10.9)$$

This gives the fraction of material remaining after T seconds of washout of $J \text{ mmhr}^{-1}$. By taking T as the time separation of the frames of radar data used in the model a set of rain intensities, $\{J_i\}$, can be obtained from (5.10.9) for some sequence of washout function values. The intensity J_i is then assigned to all the cells which in the original data had intensities ranging from $0.5(J_{i-1} + J_i)$ to $0.5(J_i + J_{i+1})$.

This form of intensity levels set covers the full range of intensities and could be refined to have more levels in the region of higher washout efficiency.

5.10.4 Comparison of Results using Different Level Sets

Four different level sets have been used in comparison test runs. These had 10, 20, 33 and 50 intensity levels, the levels within each set having a uniform

Table 5.12 Comparison of four different intensity level sets using releases from test site S.

Level sets being compared		Area change from set a to set b	Total depn. quantity change from set a to set b
a	b	%	%
10	20	230	36
20	33	21	7
33	50	19	5

separation of washout fractions. Test runs from all three sites were carried out for each level set and results from site S are presented in table 5.12.

The results show very large changes in both the area of any deposition and in the total deposition quantity between the sets with ten and twenty levels. These changes reduce with increasing numbers of levels but the 19% change in area between the 33 level and 50 level set is still excessive. In part, these changes are due to the reducing minimum intensity level which occurs with increasing numbers of levels. Since rain below half of the minimum intensity level is interpreted as zero, reducing this lowest intensity includes more low intensity rain previously neglected.

Table 5.13 Comparison of four different intensity level sets with a common minimum level of 0.22 mmhr^{-1} .

Level sets		Area change	Total depn. change
a	b	%	%
10	20	7	31
20	33	9	7
33	50	8	3

This effect was eliminated by including the minimum intensity from the 50 level set (0.22 mmhr^{-1}) in the other three sets and results using these modified sets, for site S, are given in table 5.13. The area changes are now significantly smaller although the changes in total deposition are largely unaltered. This indicates that the previous large area changes were for areas at a low level of deposition resulting from the lower rain intensities.

The remaining changes are largely a consequence of the form of the removal efficiency distribution. Using an intensity level's value for all intensities within a range centred at that value can distort the washout effect of those intensities, if the distribution is non-linear over that range. This effect would be expected to be greater for wider ranges, which is the case since area and deposition changes are larger for the level sets with fewer levels, each representing a wider range of intensities.

The results presented indicate that as many intensity levels as possible should be included. The 50 level set has therefore been used exclusively in this work since computing limitations preclude a greater number. Using more than fifty levels would probably only have a small effect on total deposition but table 5.13 indicates that the change in area might still be relatively large. This change would mainly affect areas with low levels of deposition, so using the 50 level set should give acceptable results.

5.11 RADAR BEAM ELEVATION AND FRAME FREQUENCY

As discussed in sub-section 3.2.2, the radars provide data at four different beam elevations. Data from any of these could be used in the model but the two higher beams have not been used because they only provide data over restricted areas relative to that of the lower two beams, and would consequently reduce the model's effective range. Runs using the two lower levels were carried out. These showed some differences in total areas deposited upon and some variations in the distance of areas of deposition from the radar site, but the areas of most deposition were largely similar. The differences could be accounted for by the beams encountering rain systems at different ranges, and this was particularly apparent for fronts. For consistency, the surface level, 0.5° , beam has been used mainly in this work since it is the only level available for the composite grid data obtained from all of the radar sites.

The composite grid data also dictates the rate at which rain data is used. Frames of this data are available only every fifteen minutes rather than at

five minute intervals which is the case for a single site. A fifteen minute frame frequency has therefore been used for both forms of data. Using data at five or ten minute intervals for single site runs significantly increased computing time, and test runs showed there to be little gain in doing this.

5.12 SUMMARY

The analysis described in this chapter was to identify the optimum values for the various parameters defining aspects of the model. This was done to give as general a model as possible, so that little further adjustment of the parameters was required during the use of the model. Subsequent work therefore used the optimum parameter values identified in this chapter in all but a very few cases. These cases and the specific changes are identified where they occur.

To this end, the analysis was limited to only identifying optimum parameter values and in a number of cases could have been extended to obtain further, although less immediately relevant, results. This applies to the rain and washout distributions in particular.

The results do, however, indicate the sensitivity of the model to the parameter values. This has been particularly useful where optimum values have been dictated by computing limitations, and it has been possible to obtain indications of the effects of parameter values free from these constraints. The overall trend identifiable from this is that apart from at the very lowest levels of deposition, the area deposited upon is reasonably constant. Confidence that the model is depositing material in the correct positions is therefore possible, although this is highly dependent on the accuracy of the trajectories used.

The levels of deposition showed much greater variability and should therefore be considered less reliable. This is best illustrated by figure 5.2 which shows significant along wind shifts in quantity deposited with deposition coefficient and needs to be considered when using the model.

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CHAPTER 6.

PRELIMINARY RAIN-PATCH RESULTS

6.1 INTRODUCTION

In this chapter a number of preliminary studies using the RAIN-PATCH model are described. These are of two types, the first being a study of the differences in deposition resulting from the use of sample point meteorology compared with source meteorology. The former calculates washout at a sample point using the rain occurring at that sample point, whereas the latter involves using only the meteorological conditions occurring at the source of a release and applying them to the entire puff. This study is described in section 6.3.

The second study involves sequences of releases which encounter selected rain events. These are to show, within the limits of the model, some of the possible range of outcomes from dispersing material encountering frontal and convective rain systems. Three studies out of the six undertaken are presented in sections 6.4 to 6.6. The remaining three serve to confirm these results.

Essentially these studies are a two dimensional equivalent of the simple idealized material/rain interactions used in chapter two. They demonstrate a basic use of the model which is then extended in the following two chapters, containing more detailed case studies.

6.2 TEST SEQUENCES OF RAIN DATA

The sequences of rain data used in the studies in this chapter come from the Manchester radar. This is located on Hambledon Hill in Lancashire and has been in operation since 1980. The six sequences used are listed in table 6.1. They cover a number of frontal and isolated convective systems which have been chosen to be reasonably typical of the great variety of rain systems which the UK experiences.

Two sequences, A and B in the table, are described below in more detail since they are used in both the studies in this chapter. They are also the data from which the shorter test sequences used in chapter five were taken. These shorter test sequences were chosen to be periods of significant rain. This was appropriate for selecting optimum parameter values but, for the studies in this chapter, longer sequences have been used to permit a more realistic distribution of periods and regions of rain and no rain. The only other sequence for which results are presented is C which is described in section 6.6.

Table 6.1. Rain data sequences.

	Data period	Description
A	1645 21 Jan 84 – 1147 22 Jan 84	Frontal rain.
B	1807 5 Aug 81 – 1500 7 Aug 81	The 'Manchester Storm'.
C	1200 8 Dec 83 – 1801 9 Dec 83	Rain around a depression.
D	0300 14 Dec 83 – 1201 15 Dec 83	Extensive frontal system.
E	1800 1 Aug 84 – 2358 2 Aug 84	North moving occlusion followed by showers.
F	0600 1 Feb 84 – 1200 2 Feb 84	Frontal rain followed by showers from WNW.

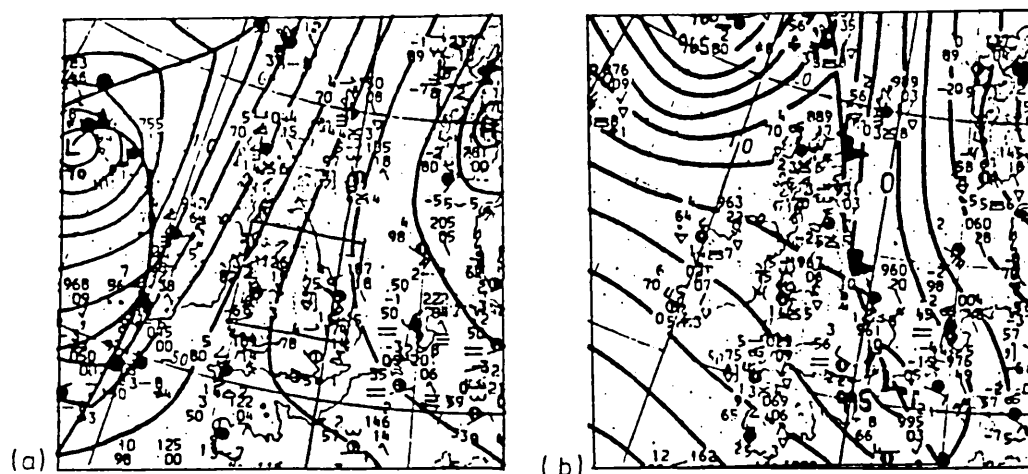


Figure 6.1. Midday synoptic charts for the front test sequence. (a) 21 January 1984, (b) 22 January 1984.

The first sequence, A, is almost thirty hours of data covering the 21 and 22 January 1984. This is the period in which a cold front moved across the UK from the west, giving rise to periods of heavy rain, with some snow, and gale force winds in the north of England. The midday synoptic charts for 21 and 22 January 1984 are given in figure 6.1. Frontal systems such as this frequently cross the UK, typically every three or four days during the winter months, and often bring extensive rain. This sequence, although presenting more extreme weather than usual, gives a good example of the rain bands which can occur with such systems. These are described in section 5.6 and shown in figure 5.3 for the more intense period of the system.

The sequence B is 45 hours of data for the 5 to the 7 August 1981. During this period intense rain fell over much of the UK, especially the Greater Manchester area. A detailed study of the synoptic situation and the resulting rainfall distributions, in which extensive use is made of radar data, is given in Bader *et al.* (1983). In outline, thundery rain moved into England from the south-west during the afternoon of the 5 August and at the same time storms developed over east Wales and the Midlands. This was followed by further storms moving into southern England from France during the night of the 5 August. Figure 6.2 gives the areas of rain depicted by the radar during the passage of the storms. This figure makes use of all five radars but only data from the Hambledon Hill site is used here, since this covers the Manchester area which experienced particularly intense and enduring rainfall.

6.3 SAMPLE-POINT/SOURCE METEOROLOGY DEPOSITION COMPARISONS

These comparisons were performed by initially obtaining deposition results from a number of pairs of runs using both the sequences A and B of rain data and a simple 13-point puff. Each results pair consisted of one run using wind and rain data local to the puff's position (points mode) and a second run which only used data appropriate to the location from which the puff was

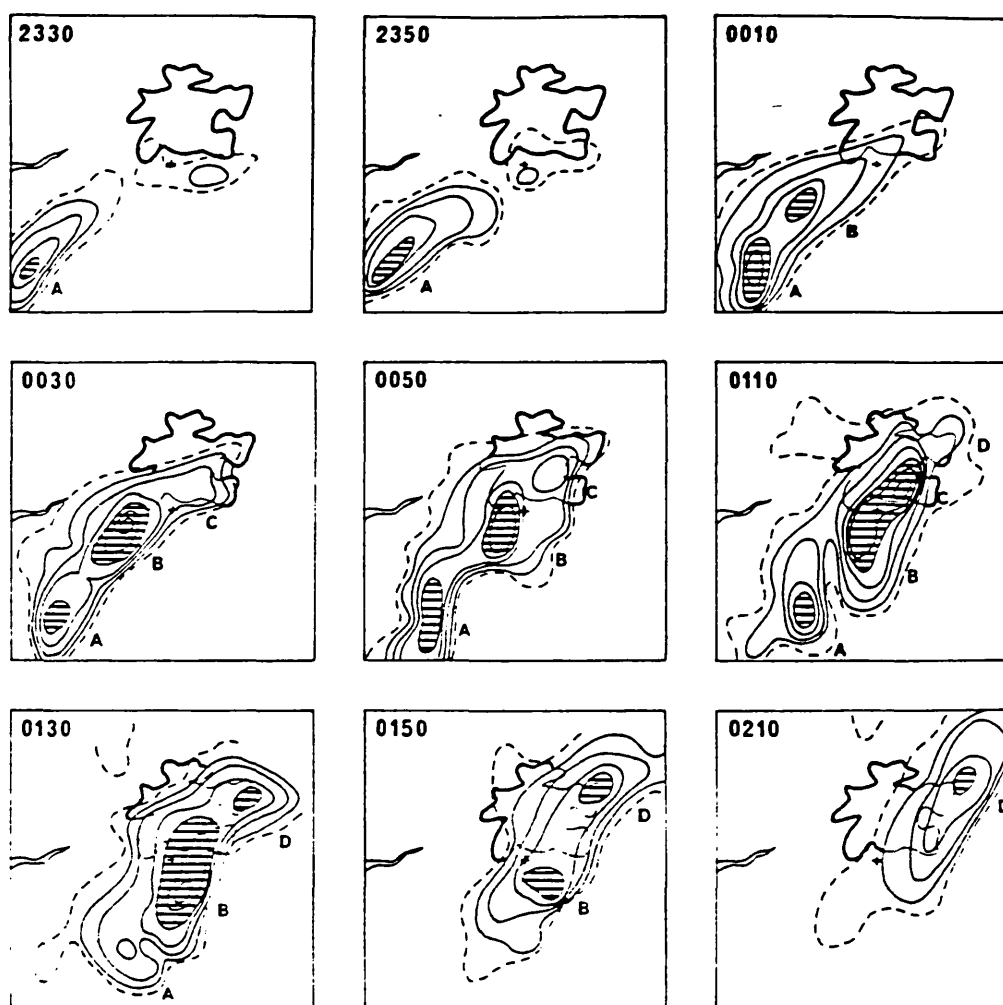


Figure 6.2. Progress of storms across a 60×60 km square centred near Manchester Airport (indicated by +). Contours are drawn at 5 mmhr^{-1} (dashes), then multiples of 10 mmhr^{-1} , with intensities over 40 mmhr^{-1} shown by hatching. (From Bader *et al.* 1983)

released (source mode). The full fifteen minutes time resolution was used for all the runs.

Five release sites were used with each data sequence and the resulting trajectories are shown in figure 6.3. These show a much greater separation, within the grid area, for the storm (B) than for the front (A). This is due in part to the greater local variations within a storm compared to a frontal system where the wind direction changes within an air mass will be relatively small. These effects however, are exaggerated due to the slower wind velocities associated with the storm making any direction differences more

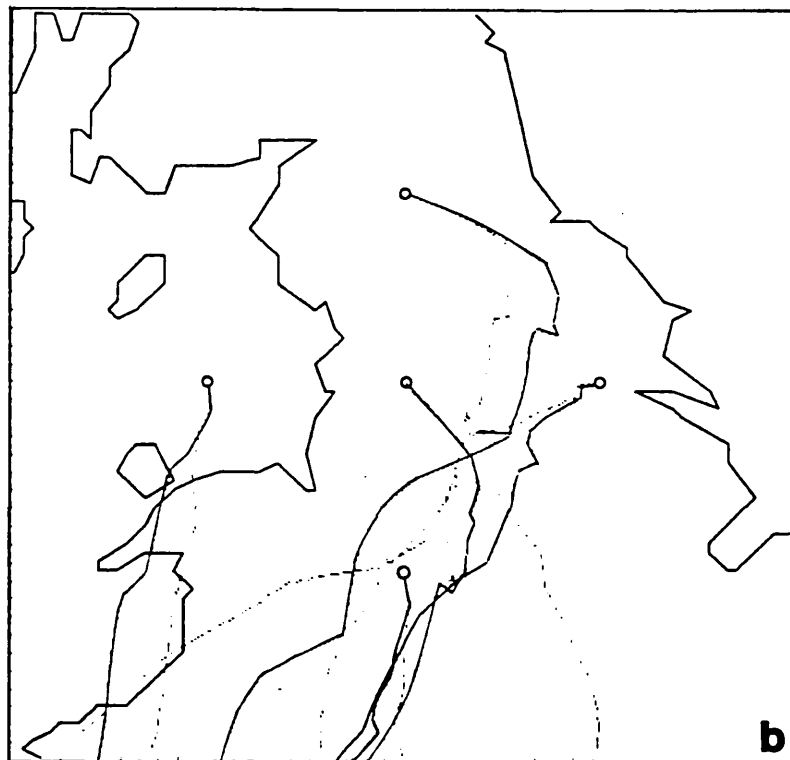
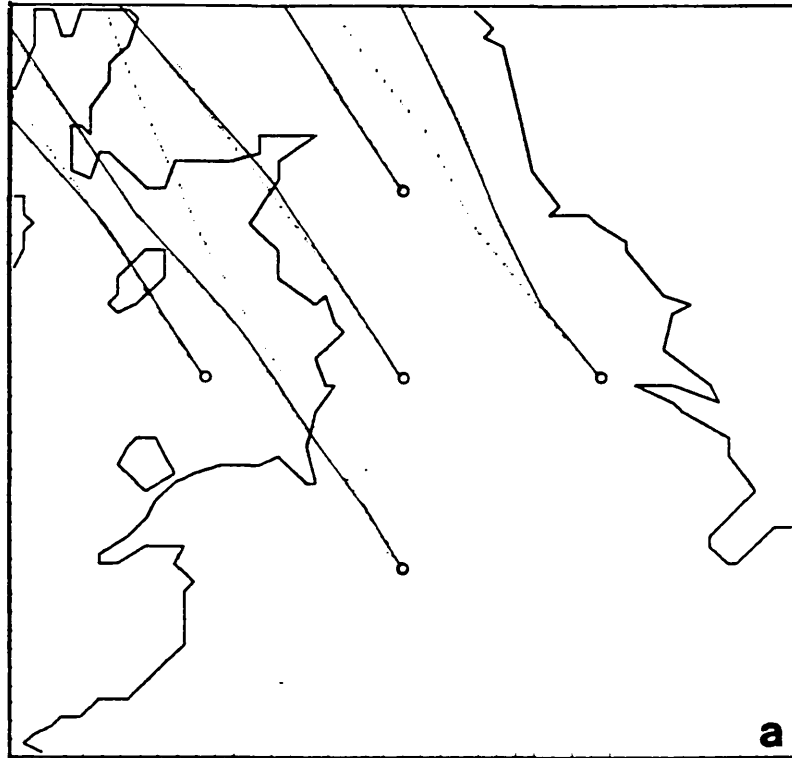


Figure 6.3. Trajectories for (a) front test sequence and (b) storm test sequence. Solid line for points mode, lighter line for source mode.

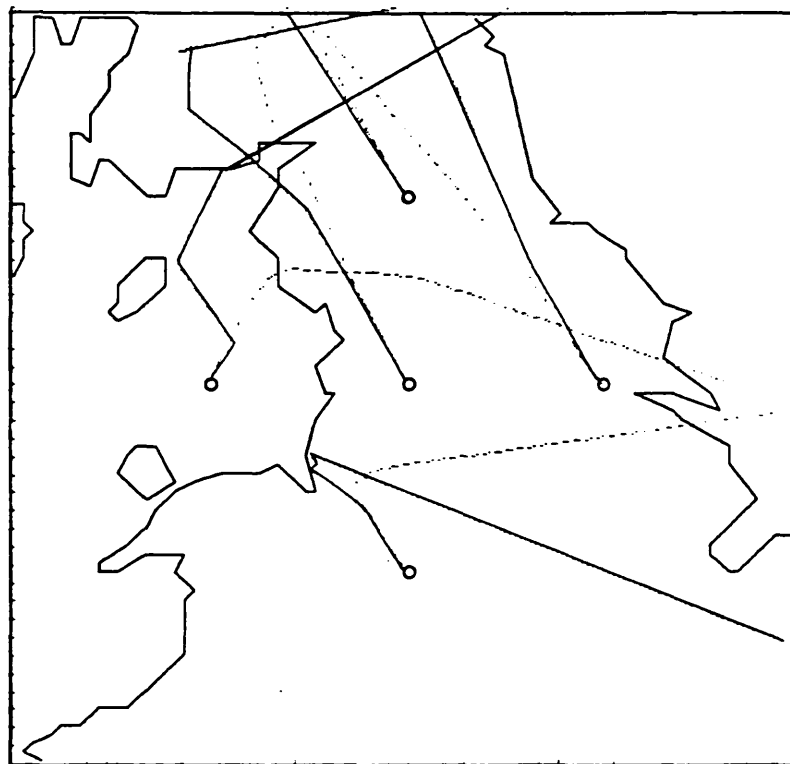


Figure 6.4. Trajectories for the front test sequence delayed by 12 hours. Solid line for points mode, lighter line for source mode.

apparent. The situation can be dramatically changed if a frontal surface moves between a puff and its point of release. Figure 6.4 shows trajectories for releases occurring twelve hours after the start of the frontal data sequence. Although linearly interpolated surface wind trajectories cannot be very accurate in the vicinity of a front, the dramatic direction change in both the southern and western releases is probably typical of what would happen in that situation.

A simple 13-point puff was used initially to allow a large number of runs to be performed relatively quickly. From these results, pairs of runs were selected to be repeated with the more accurate 65-point puff. The selection was based on areas of deposition which, from chapter five, are relatively insensitive to sample point density. The pairs chosen were those which remained in the grid area long enough to give useful results and which showed significant

differences between the two runs in each pair. Therefore the three pairs of runs selected — one using the frontal sequences and two using the storm — can be considered worst cases.

Figure 6.5 shows the pair of results using the central release site with the storm data sequence. In this case, although the total ground areas with the higher levels of contamination are comparable, the position of this area for the source mode run is shifted to the south-east of that for the points mode run. The extent of this shift is such that these areas do not overlap although they are adjacent.

The results from the northern release site show a different discrepancy (figure 6.6). Here, although the ground areas affected by deposition are similar, the concentrations are very different. In the points mode case there is a high concentration area in the vicinity of the release site which does not occur for points mode. Instead, there is a high concentration area much further south, near to the grid boundary. The discrepancy occurs because although the system of storms was moving northwards, the surface winds advecting the release were in general moving it south, so that the points mode run encountered heavy rain much closer to the release site than the source mode run.

The frontal data sequence case (figure 6.7) uses the south release site. This gives an area of deposition north-west of the release site for the points mode. For the source mode, however, there are two regions of deposition. These are a region of smaller area and lower concentration than those from the points mode, positioned closer to the release site, and a larger region of relatively high concentration in the north-west corner of the grid area. Despite following similar trajectories the deposition patterns for the two runs do not overlap anywhere.

These results all correspond to the case, discussed in chapter two, of the advection direction of the rain system opposing that of the pollutant cloud. Whereas in chapter two the differences in the form of the deposition distribution under various idealized situations was examined, these results

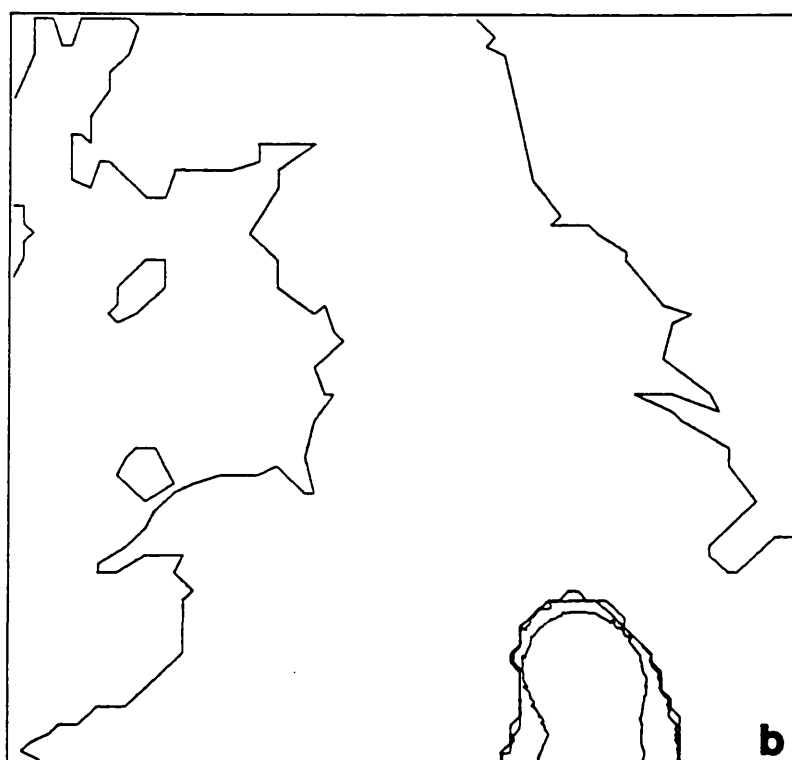
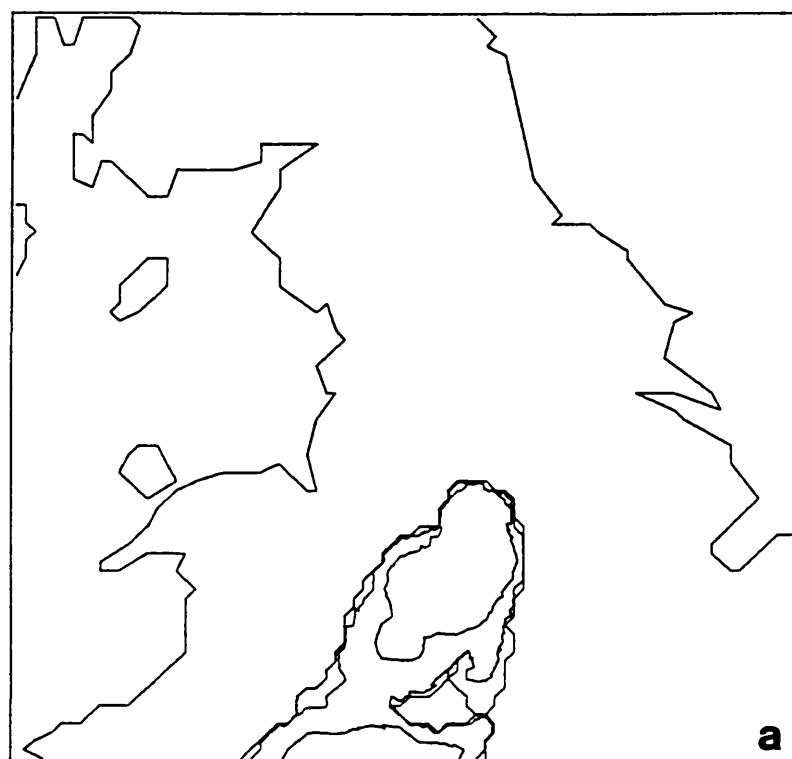


Figure 6.5. Deposition distributions using the central release site with the storm sequence. (a) points mode and (b) source mode.

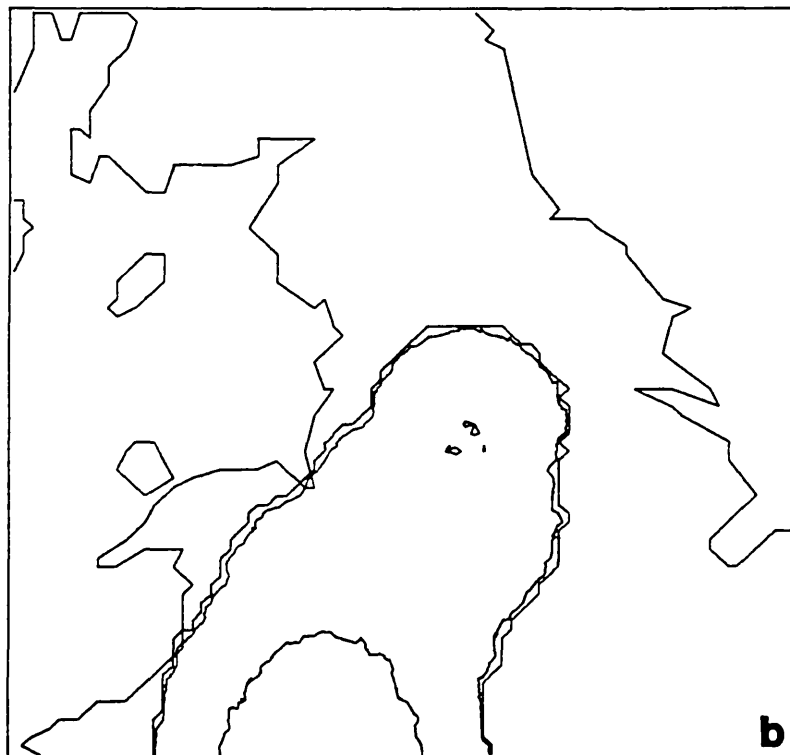
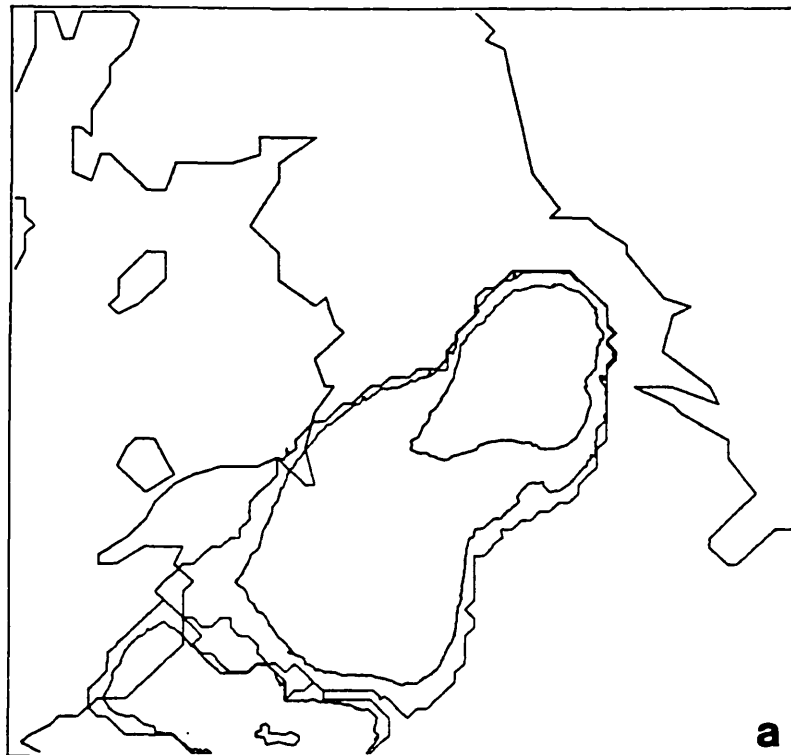


Figure 6.6. Deposition distributions using the north release site with the storm sequence. (a) points mode and (b) source mode.

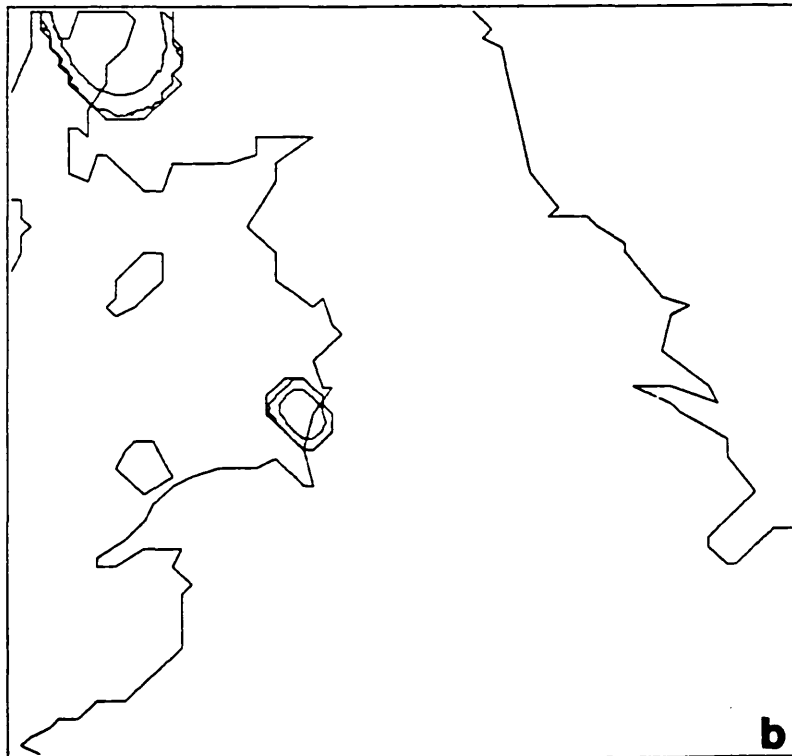
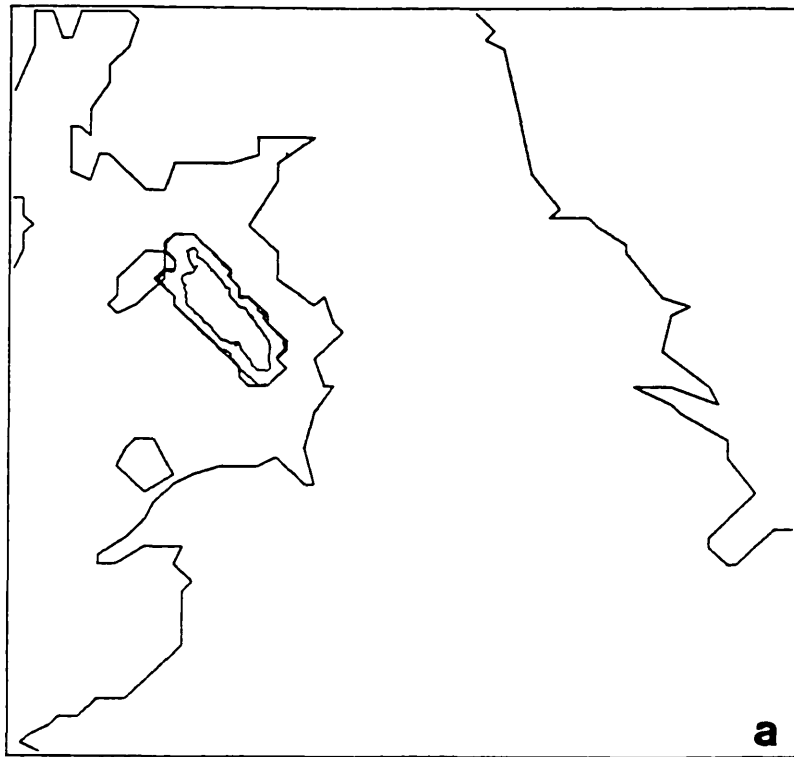


Figure 6.7. Deposition distributions using the south release site with the front sequence. (a) points mode and (b) source mode.

highlight another difference between the two modes, namely very significant differences in the areas deposited upon. These areas only overlap to any extent in one out of the three cases and are therefore a major consideration. Clearly, if a model using release site meteorology is predicting wet deposition in the wrong location it is of very limited use under any circumstances.

The deposition concentrations do not show the sharp peaks of chapter two due to the nature of the model. In source mode the model has a uniform switching on and off of rain over the whole puff rather than a fixed rainband under which the puff moves. Nevertheless, excessive concentrations over large areas can still occur due to intense localized rain at a release site being applied over the whole area of a puff. This is the case in the area of high deposition levels in figure 6.7b.

6.4 RELATIVE RELEASE TIME COMPARISONS —

SEQUENCE A

This study comprises four series of model runs using sequence A of rain data. The runs in each series are separated by an hour and use the same release site, but a different site is used for each series. The sites lie along an east-west line 105 km from the rain data grid's southern boundary with a separation of 60 km between each, the approximate distance travelled by the major leading rain bands in an hour as they traversed the data area. The sites are positioned towards the south since the trajectories from these travel initially towards the north.

These runs were carried out using a 13-point puff for computational economy and the resulting total deposition is plotted in figure 6.8. The results show a peak in deposition for releases separated by one to two hours from three of the four sites. This corresponds to the hour's delay in the rain reaching each successively more easterly site and is to be expected.

However, the most easterly site, D, gives a curve clearly matching that of C, the site 60 km to the west, and does not exhibit the expected delay. This has been attributed to the disruption of the smooth progress of the

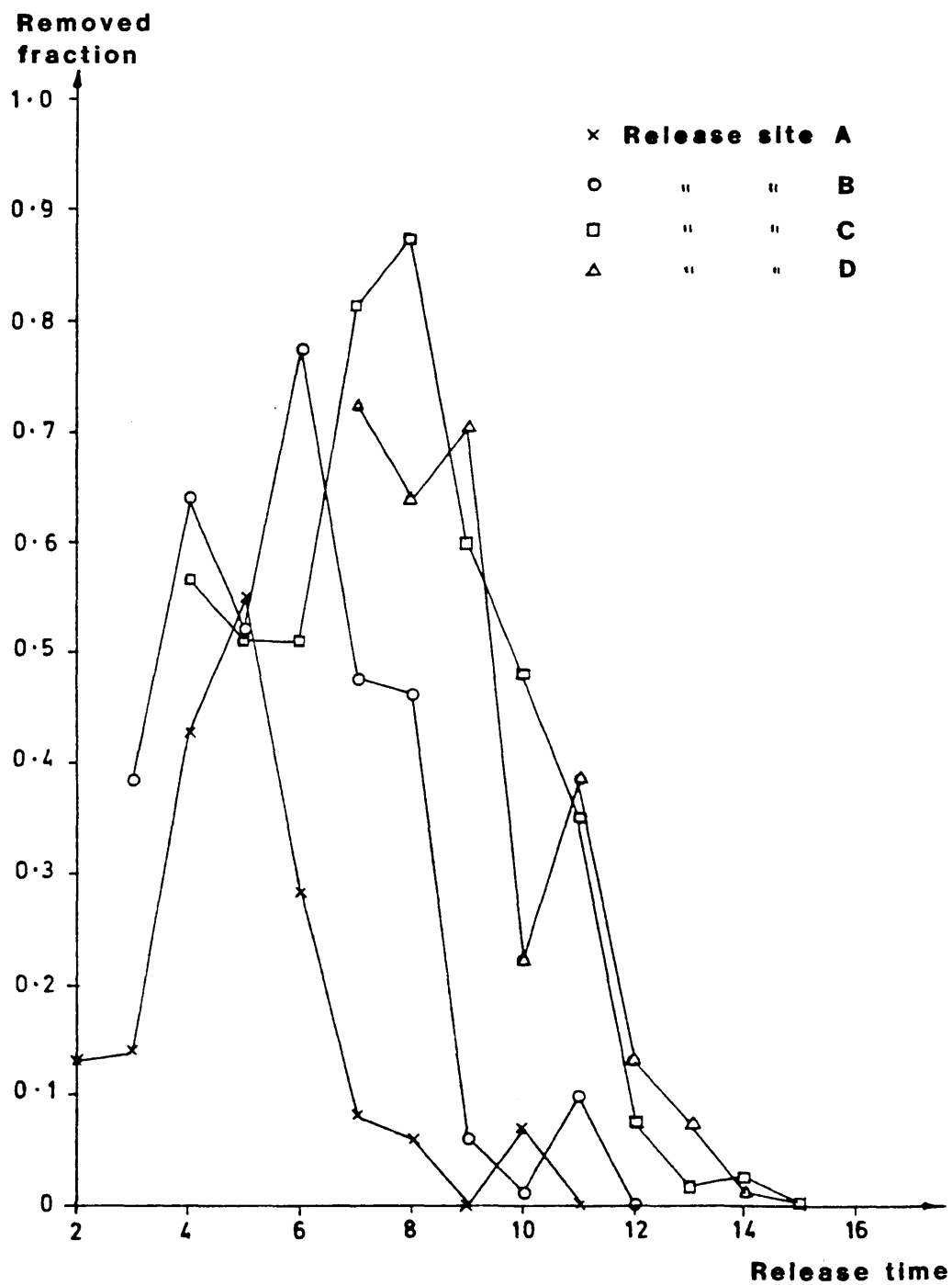


Figure 6.8. Fraction of material deposited for each sequence A run.

frontal system by the Pennines with orographically forced (enhanced) rain breaking out ahead of the main banded structure. The peak deposition for both the release sites C and D occurs with trajectories extensively in the Pennine region of Northern England which corresponds with this change in the rain's distribution.

The trajectories for releases occurring in the warm sector ahead of the cold front all show similar behaviour. Initially they travel NNW at about 45 km hr^{-1} under the influence of the warm conveyor belt ahead of the surface cold front (Browning 1985). On encountering the front, they turn north or north-east and travel significantly more slowly. This is largely a consequence of the interpolation used in the calculation of the trajectories which takes no account of the frontal surface, and is therefore effectively taking the average of the winds on both sides of the front. This effect generally occurs behind the regions of significant rain and therefore adds little to the calculated deposition distributions.

A sequence of eleven runs for releases separated by an hour were repeated for release site B using the full 65-point puff, the first release being at the beginning of the data sequence: 1643 hrs., 21 January 1984. Figure 6.9 gives the results of the runs. The first point to note is the significant changes which can occur in both the regions of any deposition (outer contour) and the regions of high level deposition (inner contour) between runs adjacent in release time. This is particularly to be noted between runs 0 and 1 and between runs 8 and 9, which exhibit especially large changes of area. Also significant is the deposition near to the release site which occurs more frequently in the later runs as the rain approaches the site. Whether or not this occurs can have significant local effects due to the more concentrated form of the released material in these regions.

A study of rain occurrence frequency was also carried out using this data sequence. For these, the fraction of the total time that rain was occurring at the source of the release, the puff's centre or any of a puff's sample points was recorded. The results for each sequence of runs are presented in

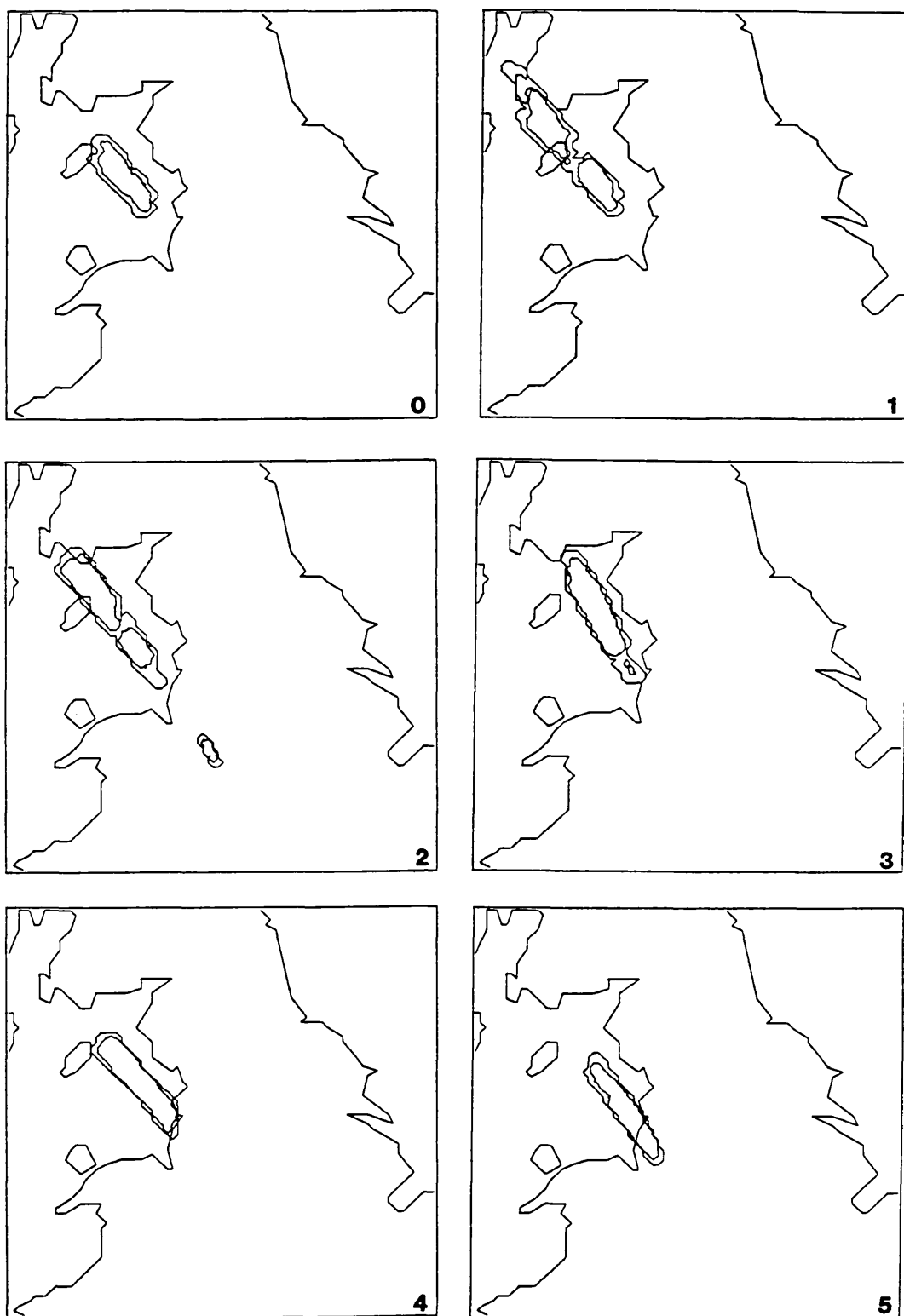


Figure 6.9. Deposition distributions for the eleven run sequence using release site B with the front sequence. Numbers are release time in hours after the start of the data sequence.

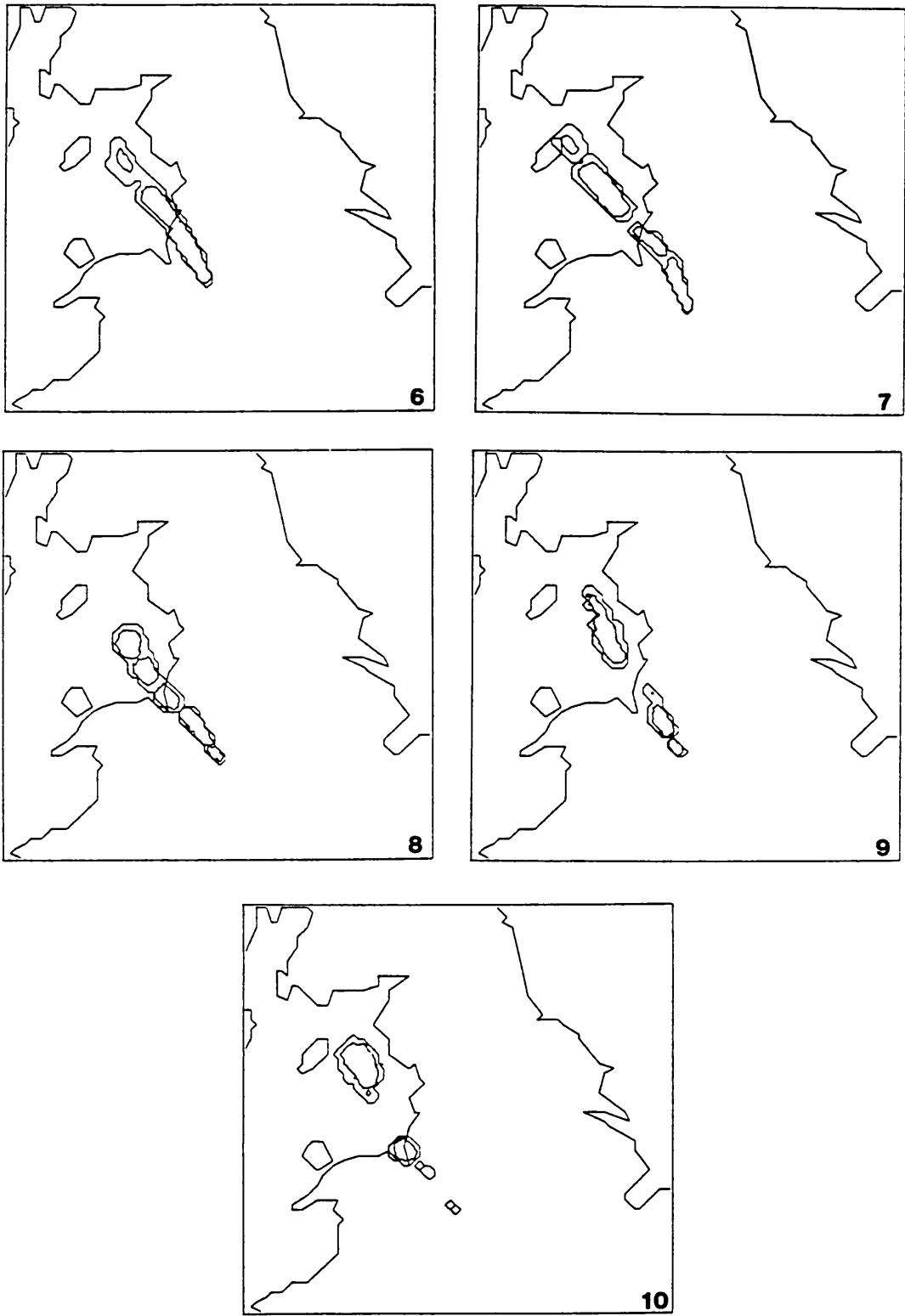


Figure 6.9. Continued.

Table 6.2. Rain occurrence fractions for the frontal test sequence A. Values are mean and (in brackets) standard deviation for the occurrence of rain as a fraction of the total run time for all three meteorological sampling modes.

Release site	A		B		C		D	
Points mode	0.50	(0.27)	0.45	(0.18)	0.53	(0.22)	0.58	(0.13)
Center mode	0.37	(0.33)	0.21	(0.33)	0.31	(0.18)	0.32	(0.19)
Source mode	0.15		0.24		0.36		0	

table 6.2. These results confirm the difference between source and sample points meteorology since they show that rain occurs somewhere over the puff with greater frequency than it occurs at the source. The results also show a third intermediate mode in which data at one mobile point permanently within or close to a puff is used. This third mode also shows significant differences in rain occurrence frequency from those of points mode. In general these differences have been either comparable or less than those between points and source mode.

6.5 RELATIVE RELEASE TIME COMPARISONS — SEQUENCE B

For this test sequence two release sites were used, one at the grid centre and the other half-way from the centre to the north edge. A series of releases separated by three hours were modelled from each site.

The trajectories show much greater variation than was the case for the frontal test sequence. This is to be expected due to the very pronounced local dynamics associated with convective systems relative to the much larger movements of relatively uniform air masses associated with fronts. The trajectories from the northern release site, shown in figure 6.10, generally travel SSW but there is a good deal of variation between them. The first heads initially ESE before swinging to the south, then south-west. Neither is the direction change uniform. The swing is initially to the west moving to a more southerly direction before returning to a WSW direction. Similar variation is shown by the releases from the central site.

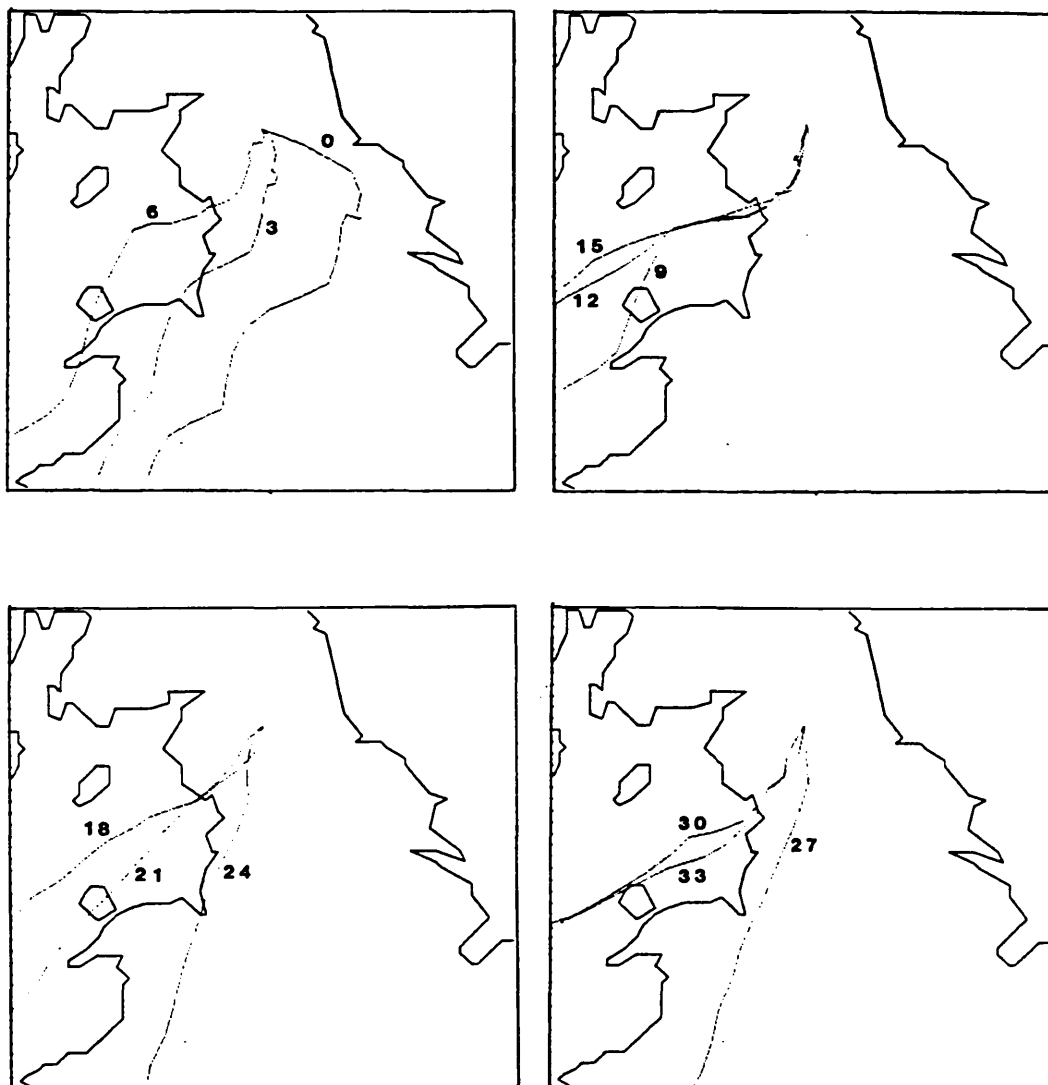


Figure 6.10. Trajectories followed by releases separated by three hours from the north site and using the storm sequence. Numbers are release time in hours after the start of the sequence.

Table 6.3 gives the quantities of material deposited by the releases from the northerly site with the resulting deposition patterns given in figure 6.11. The quantities show significant variation which corresponds to the varying amounts of intense rain encountered, but the patterns are more consistent with most of their variability being due to the individual trajectories followed. The later distributions are shorter, due to the southerly limit of the approaching rain area moving north.

Table 6.3. Fraction of material deposited for sequence B runs.

Release time	Fraction deposited
0	0.99
3	0.93
6	0.71
9	0.72
12	0.78
15	0.79
18	0.73
21	0.65
24	0.87
27	0.77
30	0.20
33	0.22

The rain occurrence frequency results for these releases are given in table 6.4. The figures for the two release sites differ greatly from each other and also from the figures for the frontal sequence runs, but in all cases, rain always occurs somewhere over the puff with a greater frequency than at either of the single point sites.

6.6 RELATIVE RELEASE TIME COMPARISONS —

SEQUENCE C

Results from this third sequence are presented because of a number of interesting points which they demonstrate. The meteorological situation consists of a depression which moved down the country during the first 24 hours of the 30 hour data sequence bringing mild but windy and wet weather. The situation at 12 GMT on the 9 December 1983 showing the low is given in figure 6.12.

A series of initially hourly, but later two hourly, releases from the grid centre was modelled through the system and the trajectories followed are shown in figure 6.13. These show the effect of the fairly compact low on the movement of the material since the earlier releases circle the low in a tight curve finally moving in a direction opposed to that taken at the time of release. Some later releases, 10 to 16 hours into the data sequence, also

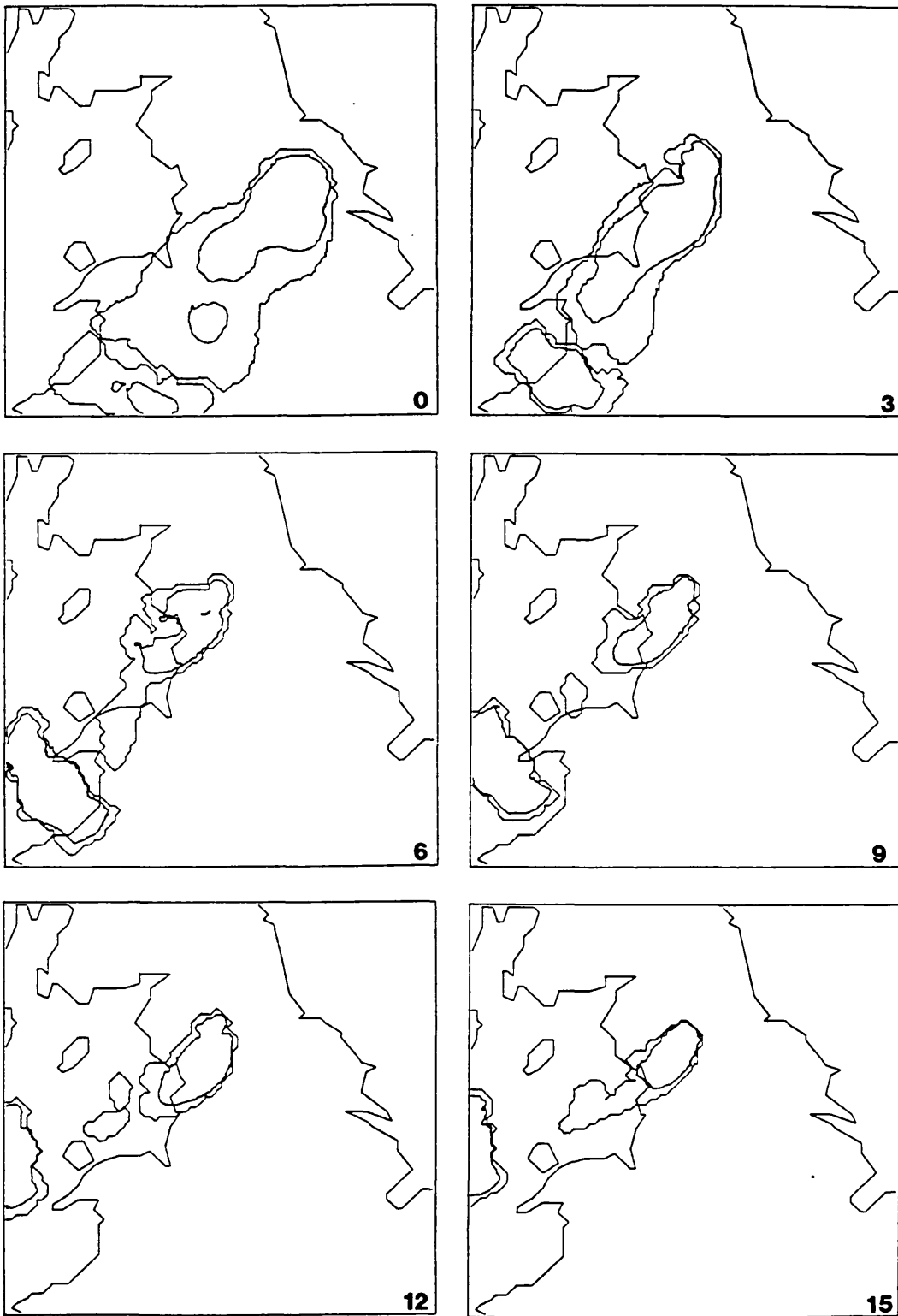


Figure 6.11. Deposition distributions for the sequence of releases using the north release site with the storm data sequence. Numbers are release time in hours after the start of the data sequence.

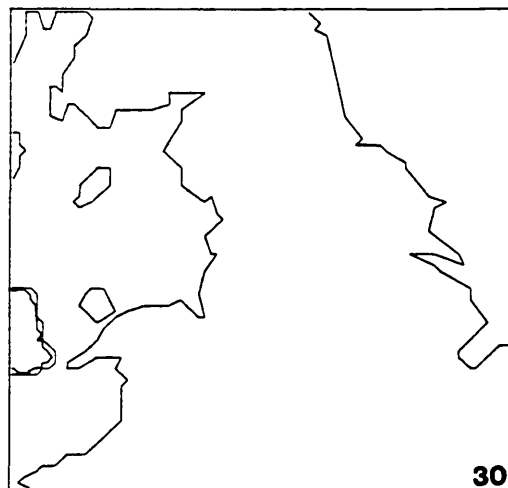
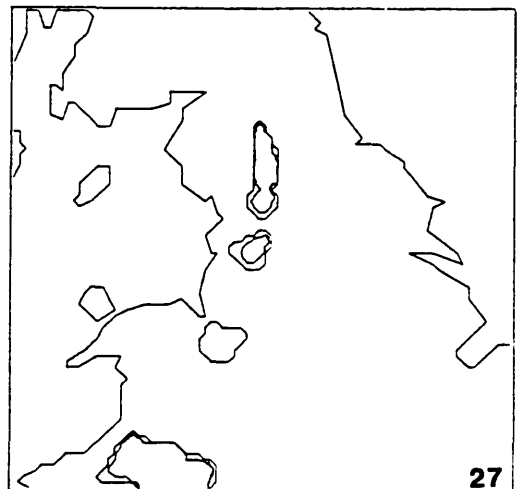
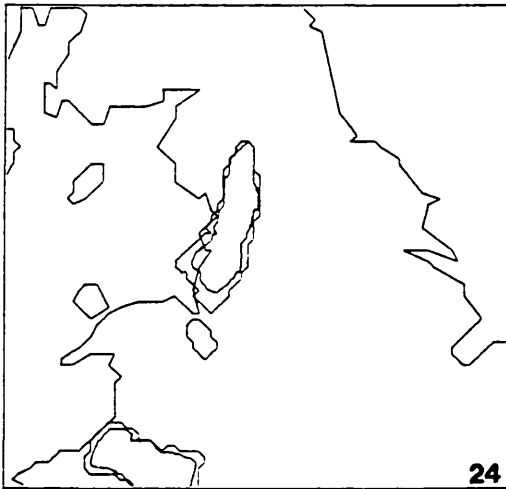
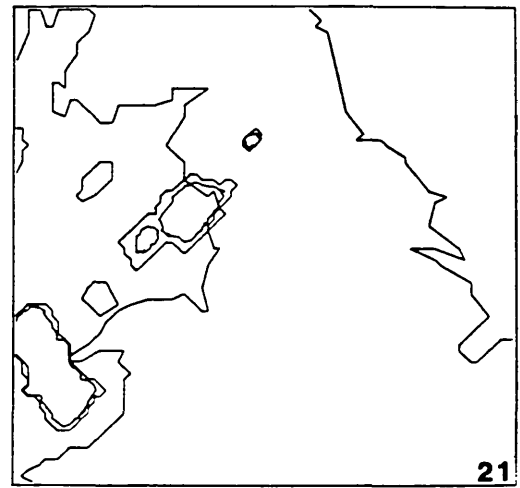
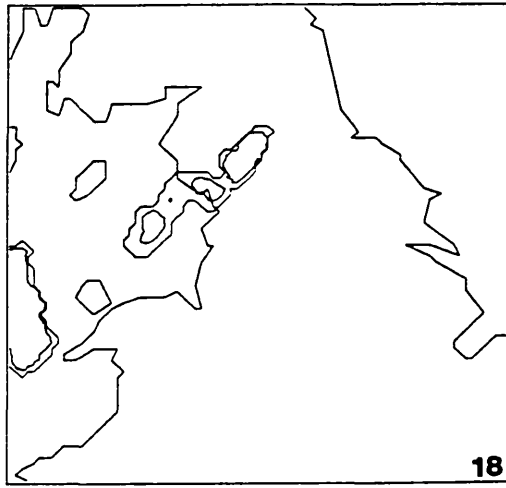


Figure 6.11. Continued.

Table 6.4. Rain occurrence fractions for the storm test sequence B.
Values as for table 6.2.

Release site	Central		North	
Points mode	0.86	(0.11)	0.54	(0.14)
Center mode	0.50	(0.39)	0.16	(0.11)
Source mode	0.29		0.04	

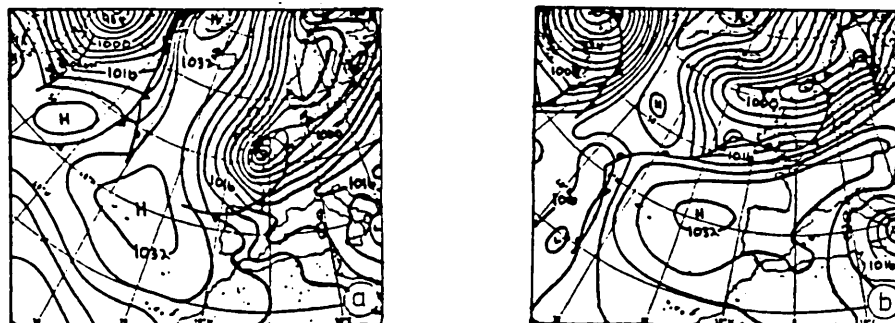


Figure 6.12. Midday synoptic charts for data sequence C. (a) 8 December 1983. (b) 9 December 1983.

change direction but this is a much more abrupt change occurring in the vicinity of the release site and will not have been modelled very accurately by the linearly interpolated trajectories.

The surface deposition patterns for these releases are given in figure 6.14 and the quantities of material deposited are listed in table 6.5. The surface patterns clearly reflect the curved trajectories with some earlier releases covering very large areas. This is an indication of both the slowness of the movement of the material, which allows the puff to expand greatly within the grid area, and of the widespread nature of the rain during this period. This does not, however, include the first release which leaves the eastern edge of the grid and although, by comparison with the later releases, it should probably turn anticlockwise and recross the grid area, this does not happen due to the limits of the area covered by the surface wind data.

Also worth noting is that despite the very widespread deposition from some of the earlier releases, it is some of the later releases that leave the grid area more rapidly which give rise to the greatest quantities of deposition. In

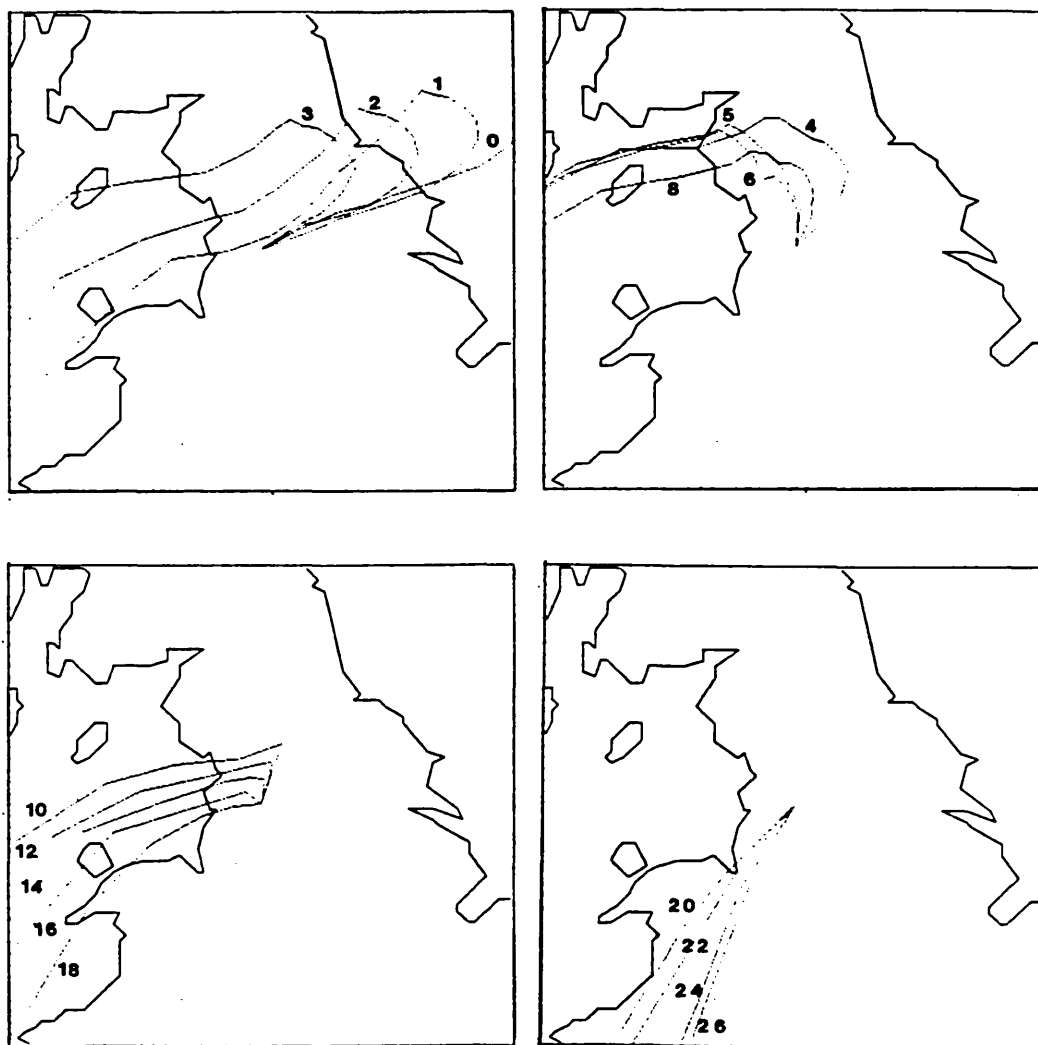


Figure 6.13. Trajectories followed by the hourly releases from the central release site using data sequence C. Numbers are release time in hours after the start of the data sequence.

a number of these cases the puff is almost entirely depleted of material by the time it reaches the grid boundary.

Table 6.6. Rain occurrence fractions for sequence C. Values as for table 6.2.

Points mode	0.76	(0.25)
Centre mode	0.58	(0.33)
Source mode	0.67	

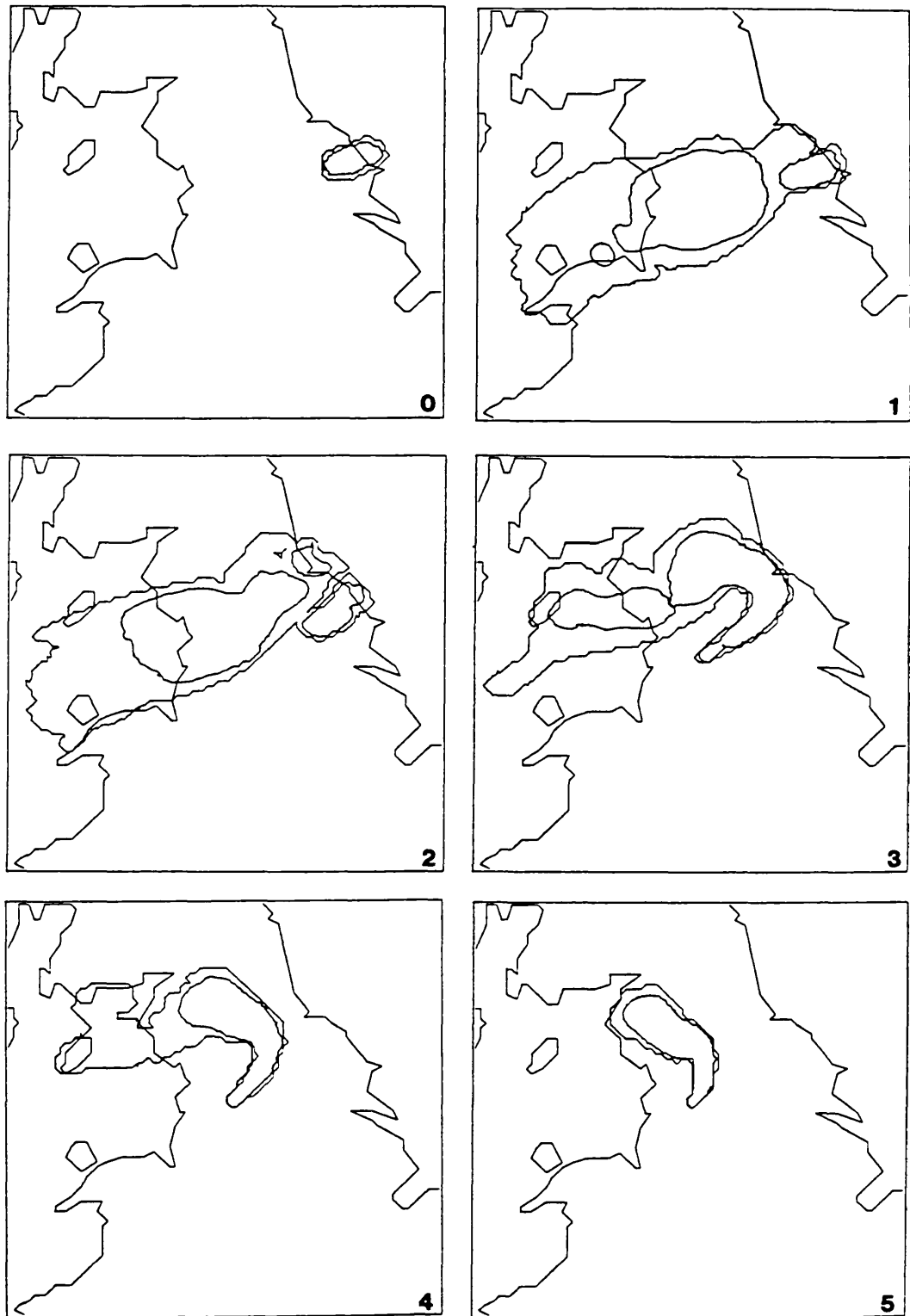


Figure 6.14. Deposition distributions for the sequence of releases using the central release site with data sequence C. Numbers are release time in hours after the start of the data sequence.

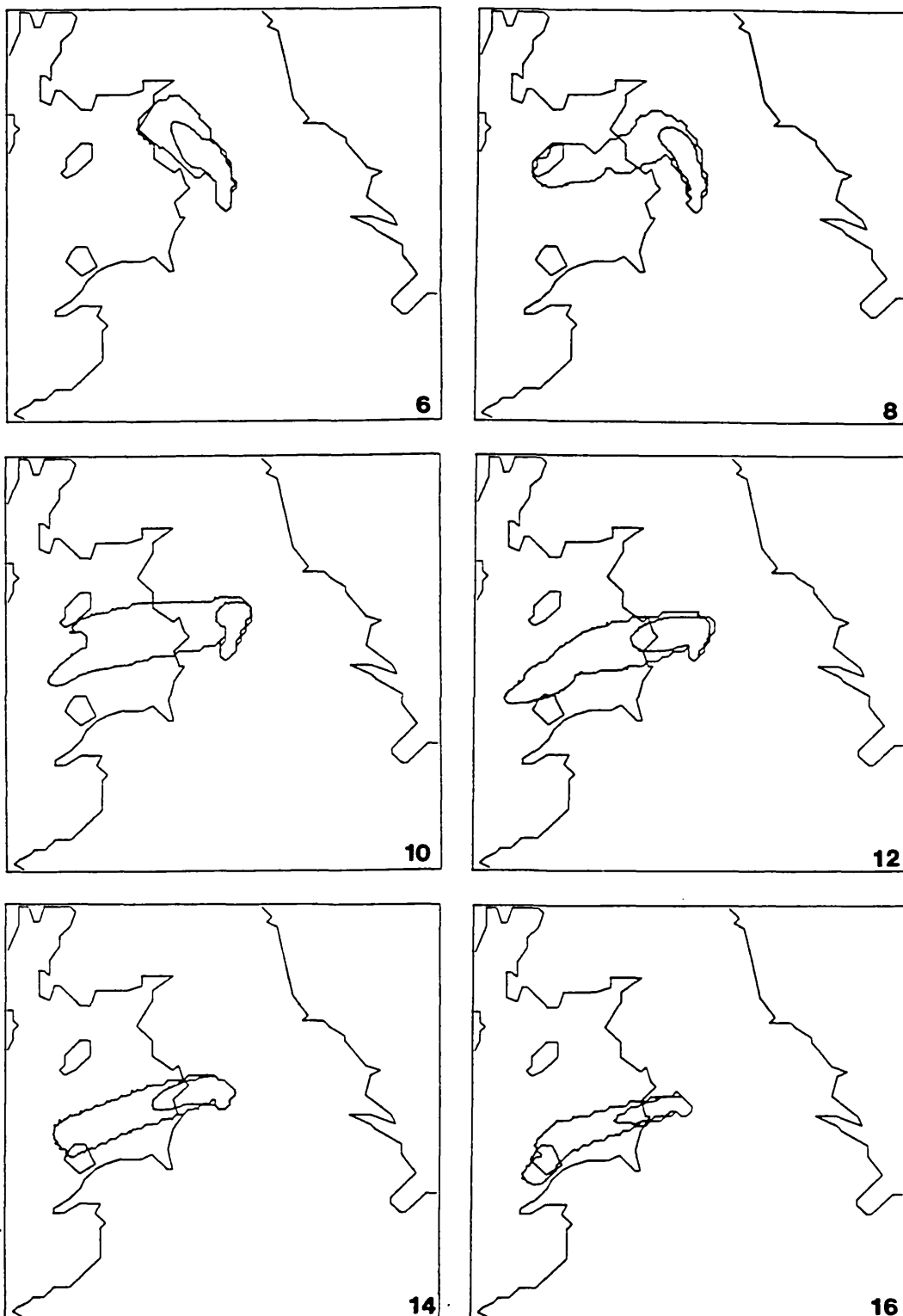


Figure 6.14. Continued.

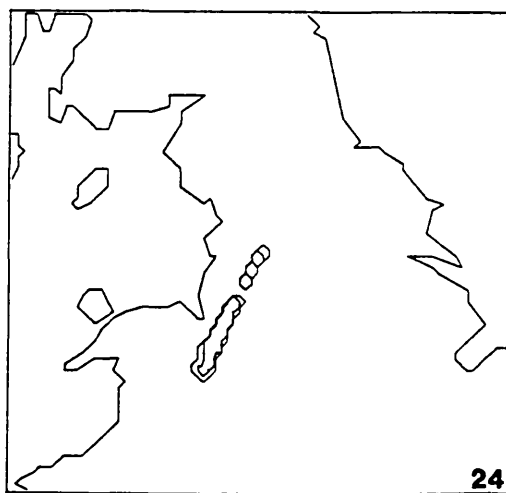
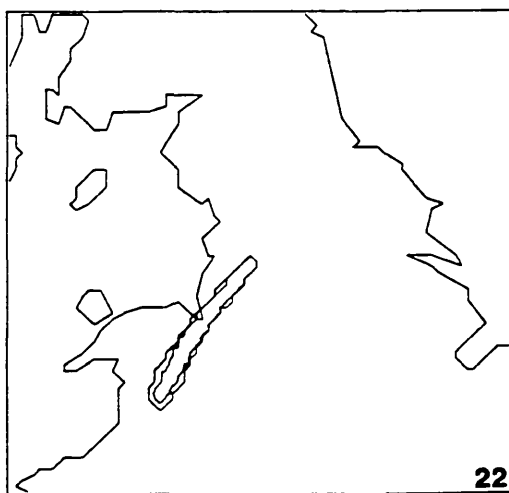
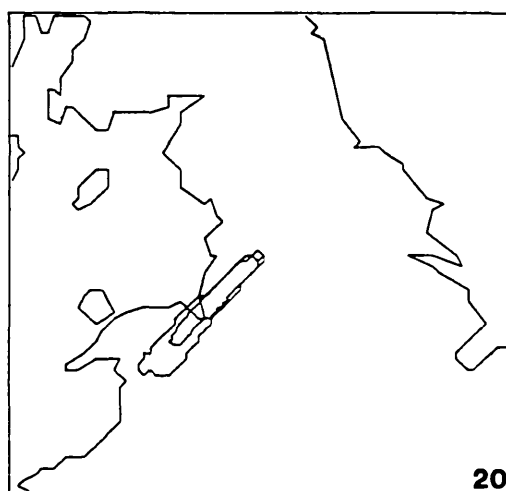
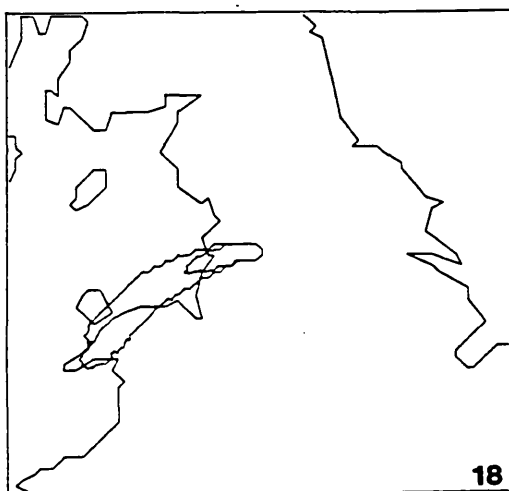


Figure 6.14. Continued.

Table 6.5. Fraction of material deposited for sequence C runs.

Release time	Fraction deposited
0	0.63
1	0.97
2	0.98
3	0.77
4	0.78
5	0.88
6	0.99
8	1.00
10	1.00
12	1.00
14	1.00
16	1.00
18	1.00
20	0.97
22	0.79
24	0.49
26	0.32

A final point to note with these model runs is the ordering of the rain occurrence frequency for source meteorology and central sample point meteorology (Table 6.6). In the previous case presented, rain occurs for a greater fraction of the time at the puff's centre than it does at the source of the release. In this case however, the almost continual rain across the centre of the grid area during the period of the data has reversed the situation, although not by much. However, there is still rain occurring somewhere over the puff for a greater fraction of the time than at either single point location.

6.7 CONCLUSIONS

The main conclusion of this chapter is a further confirmation of the need to use meteorological data local to a cloud of dispersing material. The one dimensional model of chapter two did show this, but the RAIN-PATCH model, being two dimensional, using real meteorological data and applying the same sampling techniques to the trajectory calculations as to the rain data, adds further emphasis.

An alternative meteorological sampling scheme is to apply the rain intensity occurring at a point in the vicinity of the puff to the whole puff. This has been examined for the run sequences, by recording the fraction of the total run time that it was raining at such a point, this being the puff's central sample point. When compared with similar figures for points mode meteorological sampling, which give the fraction of time when rain is occurring over at least one sample point within the puff, the points mode value is predominantly higher. This indicates the frequent non-uniformity of rain over the puff's area, detail which would be lost if single site sampling were used. Since little computational saving is gained by using this sampling scheme it has not been considered further.

The release sequences studied also show the importance of correct spatial and temporal positioning of dispersing material relative to rain systems. The three cases presented give an indication of the factors involved over the variety of rain producing meteorological situations which can occur across the British Isles. The sequences of releases separated by relatively short periods of time show significant variation in quantity of material wet deposited and in the resulting surface deposition patterns. This further indicates the importance of correct timings in modelling accidental releases. Partly, this variety will be due to trajectory variations, and therefore applies equally to dry deposited material, but the much greater variability of rain intensity significantly adds to the total deposition's variability.

The importance of correctly timing the advection of material is considered further in the following chapter. Topographical effects, which were apparent in some of the runs using the frontal test sequence, are discussed again in chapters eight and nine.

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CHAPTER 7.

THE DEPOSITION OF CS-137 AND I-131 OVER ENGLAND AND WALES AS A CONSEQUENCE OF THE CHERNOBYL ACCIDENT

7.1 INTRODUCTION

On 26 April 1986 an accident at the nuclear power plant at Chernobyl in the Ukraine resulted in the release of large quantities of radioactive material to the atmosphere. The bulk of the release occurred unevenly over the following ten days before it was reduced to a much lower rate. The released material was spread across much of Europe and beyond (Smith 1987) but, outside the USSR, the main concern was contamination of foodstuffs by I-131, Cs-137 and Cs-134. The first of these is only of concern in the short term but the caesium isotopes are potentially a hazard over a longer period, due to their longer half-lives. The released caesium attaches itself to aerosol particles which are very effectively wet deposited but the iodine travels predominantly in a *gaseous* form which increases the importance of dry deposition for this isotope.

Deposition patterns for Cs-137 and I-131 over England and Wales resulting from the accident were produced by the RAIN-PATCH model. To do this it was first modified to use the composite radar picture which is in the form of a 128 by 128 cell grid of 5 by 5 km cells. This is formed from the data obtained from all five weather radars and therefore covers all of England and Wales. It was provided by the Meteorological Office for the period of 1540 hrs 29 April 1986 to 0525 hrs 11 May 1986 for use in this study.

Material initially reached the UK on 2 May. This had escaped from the reactor during 26 April and followed an indirect route across Europe, dictated by a fairly complex weather system (Smith, 1987). Its ultimate entry into the UK occurred from the south east when the collapse of a high pressure ridge running from Biscay to Northern Europe permitted material

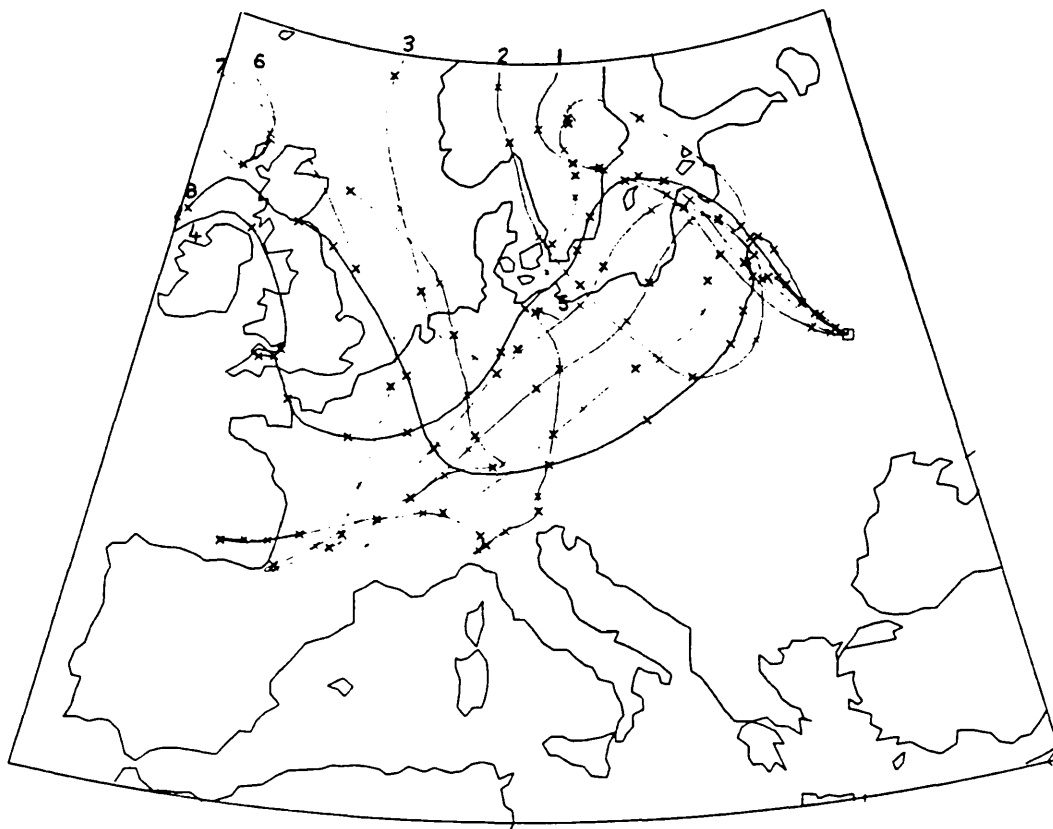


Figure 7.1 Geostrophic trajectories followed by material released from Chernobyl during 26 April 1986. Release No. 1 at 0300 hrs., No. 2 at 0600 hrs. etc.

to move northwards from the continent. A number of the routes taken by sections of the release leading to, or near to, the UK, are shown in figure 7.1.

This preliminary front of material gave rise to a significant part of the deposition across England and Wales. Other material following it, which became involved in thunderstorm activity on 3 May and a part of the initial ridge which recrossed the country four days later, will have added to the levels of deposition. No other part of the release directly affected the UK.

In the following sections the timing data used to position this ridge of material correctly are first analysed. These are then used in describing the form of the ridge at midnight on 1 May, and the trajectories followed by the individual puffs forming the ridge are obtained. The puffs and trajectories are then used in the model to provide deposition patterns for both Cs-137

and I-131. These results are compared with various sets of measured data by direct comparison of contoured results, scatter plots and the calculation of correlation coefficients. Finally, a simple analysis of the effect of the accuracy of the timing of the passage of the material on the calculated deposition patterns is presented.

7.2 THE PASSAGE OF THE INITIAL RIDGE OF MATERIAL ACROSS THE UK

Geostrophic trajectories originating from Chernobyl, such as those of figure 7.1 which were calculated using the MESOS model (ApSimon and Goddard 1983), worked very well during calculations of the dispersion across Europe. The RAIN-PATCH model, however, requires trajectories of an accuracy comparable with the rain data resolution of 15 minutes and 5 km for optimum results. After more than 4000 km of travel over six days, geostrophic trajectories would be considerably less accurate than this. Local trajectories were therefore obtained using air concentration time-sequence data from a number of sites in England and Wales. These did not achieve the optimum accuracy mentioned above but were sufficiently accurate for use in the model.

Suitable air concentration data was provided from six locations: Berkeley Nuclear Laboratories (BNL) (Hancock and Woollam, 1986 and Macdonald, 1986); UKAEA at Harwell (Cambray *et al.* 1987); BNFL at Sellafield (Garland, 1986) and the nuclear power stations at Trawsfynydd, Wylfa and Dungeness (Macdonald, 1986). This data was composed of two types: some were obtained from air filters exposed for periods short enough to give an indication of the passage of the material on, at most, a time scale of a few hours. Other data was from Geiger detectors including the sensitive GEMS (Guardian Environmental Monitoring System) equipment produced by GEC. The latter gave a much better time resolution of a few minutes. The forms of data provided by each site are listed in table 7.1.

Each data sequence was analysed for three time points: the time when material was first detected at a location; the time of arrival of the peak of

Table 7.1. Locations and form of measurement for time-sequence data.

Location	Measurement type
Berkeley Nuclear Laboratories Gloucestershire	A, GEMS
UKAEA Harwell Oxfordshire	G
BNFL Sellafield Cumbria	A
CEGB Trawsfynydd, Wales	GEMS
CEGB Wylfa, Wales	GEMS
CEGB Dungeness, Kent	G
A	Air filter
GEMS	Guardian Environmental Monitoring System
G	Other forms of Geiger tube detector

activity; and the time at which the activity level had returned to approximately its original level. For data from air filters both the beginning and end time of the filtering period containing a required time point have been used in determining the required trajectories. The third sort of time points are the least precise since the departure of the original ridge of material is much less pronounced than its arrival. Only four such times could be identified with sufficient precision to be of use. Table 7.2 lists all the time points used.

Geostrophic trajectories were then calculated backwards in time for each time point at each measurement location. A ten degree backing angle and a speed reduction of ten percent were used in their calculation to give trajectories approximating those at half the height of the atmospheric boundary layer. This was the level at which trajectories were considered to be reasonably typical of those followed by the bulk of the material. The positions these trajectories reached at midnight on 1 May 1986 are given in figure 7.2.

7.3 THE DISTRIBUTION OF MATERIAL AT MIDNIGHT ON 1 MAY 1986

At this time, the majority of backward trajectories originated at the time

Table 7.2. Time points used in obtaining local trajectories. All dates are May 1986 and times are GMT. (A1a, A1b etc. denote start and finish times for air filter data)

Number	Location	Time
Start times		
A1a	BNL	0845 1st
A1b	BNL	1550 2nd
A2	BNL	0300 2nd
A3	Harwell	0800 2nd
A4a	Sellafield	0800 2nd
A4b	Sellafield	1830 2nd
A5	Trawsfynydd	1500 2nd
A6	Wylfa	1600 2nd
Peak times		
B1a	BNL	2010 2nd
B1b	BNL	2130 2nd
B2	BNL	0700 2nd
B3	Harwell	1600 2nd
B4a	Sellafield	2330 2nd
B4b	Sellafield	0130 3rd
B5	Trawsfynydd	1600 2nd
B6	Wylfa	1700 2nd
B7a	Dungeness	0300 2nd
B7b	Dungeness	0500 2nd
Finish times		
C1	BNL	1120 3rd
C2	BNL	2200 2nd
C4	Sellafield	1930 3rd
C6	Wylfa	0100 3rd

points described in the previous section lie in the region from 48° to 51° North and from 2° West to 6° East. This is an area positioned largely south of Britain, 51° N lying just north of the south coast, and it is centred some way to the east of the British Isles. 51° N, over the range 2° West to 4° East, is shown in figure 7.2 to be the position of the front edge of the material at that time. The Harwell and Sellafield particulate sampling results give filter period start and finish positions which lie either side of this line and, with

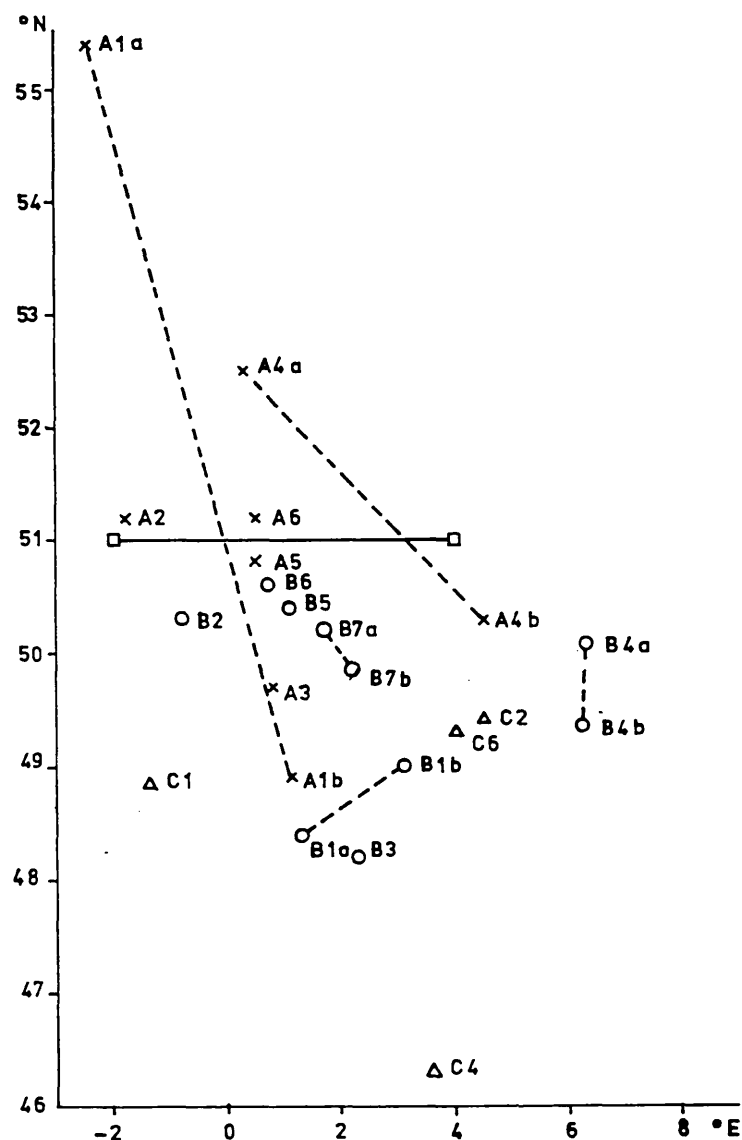


Figure 7.2. Backward trajectories positions at midnight on 1 May 1986. The measurement location codes are given in table 7.1 and the line at 51° N marks the assumed front of the material at that time.

the exception of the Harwell Geiger result, the other results all lie close to this line.

The peak value results are more spread. The main group lies in a region centred about 45' south of the centre of the front edge line at 50° North. The Sellafield results give a position over 2° further east and slightly further south, and the BNFL particulate measurement and Harwell results lie

about 1°30' south of the main group. The position of the Sellafield results is explained by this site being much further north than the other locations providing data. Since the airflow across the country during the relevant period is predominantly south-easterly, trajectories reaching Sellafield at the appropriate times would be expected to start from a position to the east of those for the other measurement locations.

The other displaced results are not so easily explained. Both the start time and peak time results for the Harwell trajectories give positions approximately one degree of latitude south of the positions expected from the other results. This corresponds to a time error of about four hours. The measurements used come from an unshielded Geiger counter, positioned only one metre above grassland, which could have been affected by deposited material. The start and peak times may have only become apparent above the normal scatter of data points some time after the actual events, owing to the cumulative effects of deposited material increasing the measured values.

No satisfactory explanation for the BNL particulate data results has been found. The BNL Geiger counter results fit in very well with those from other locations but the delay in excess of twelve hours in the peak detected by the air filters corresponds to a peak located south of that indicated by the other results. A peak in that position does not give good results when using the RAIN-PATCH model compared to results from the more northerly position. This gives credence to the timings from the Geiger counter over those of the air filter, and will be discussed further in the next section. A ridge linking the locations of the bulk of the peak measurement values to the Sellafield values therefore seems most likely for the peak concentrations of material at midnight on 1 May.

Three of the four trajectories from final time points are at expected positions at midnight on 1 May. These are for the Wylfa and BNL Geiger counter data, which both occur just south of the positions for the ridge given above, and for the Sellafield data which gives a point much further south. The first two points indicate a limited southerly extent to the initial ridge.

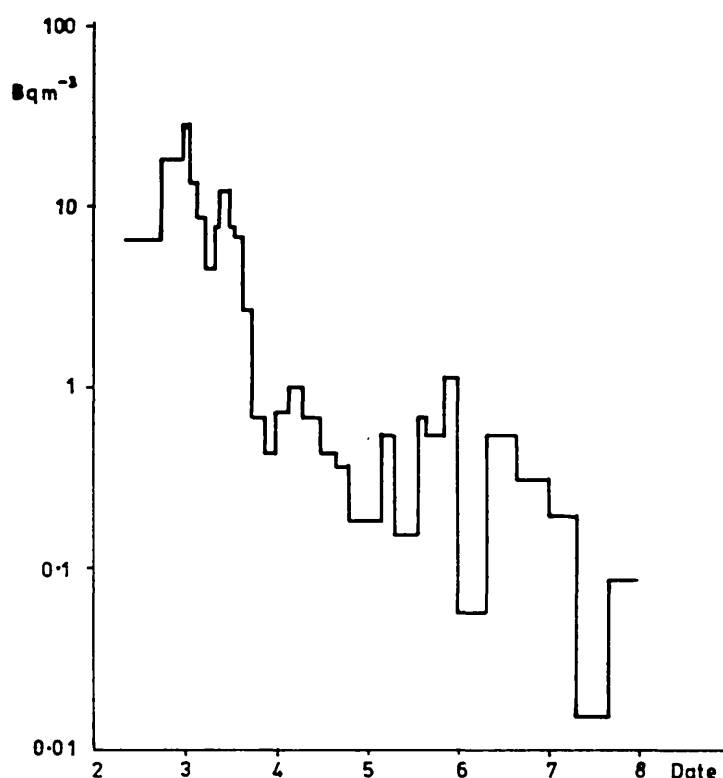


Figure 7.3. Particulate concentration in air at Sellafield, May 1986.

The third, Sellafield, is more interesting. The particulate concentration in air at Sellafield is shown in figure 7.3. This shows that the initial high levels occurred in two peaks. The second, less pronounced peak possibly corresponds to a second wave of material originating from Chernobyl slightly later on 26 May. This does not occur at the other measurement locations which implies that this second wave was restricted to the east of the country but possibly extended further into Scotland than the initial ridge. A back trajectory from the midpoint between the two peaks lies close to the other final time points.

The more westerly position of the BNL final time point is because it occurs after the passage of the front and is consequently back tracked in an airmass with a greater westerly component in its direction of travel.

7.4 MODELLING THE INITIAL RIDGE USING RAIN-PATCH

The ridge of material described in the previous section has been modelled

using composite distributions consisting of a number of overlapping RAIN-PATCH puffs. Each puff follows its own geostrophic trajectory defined by its position at midnight on 1 May. The deposition distributions resulting from each puff are combined to give a total deposition pattern corresponding to the composite material distribution.

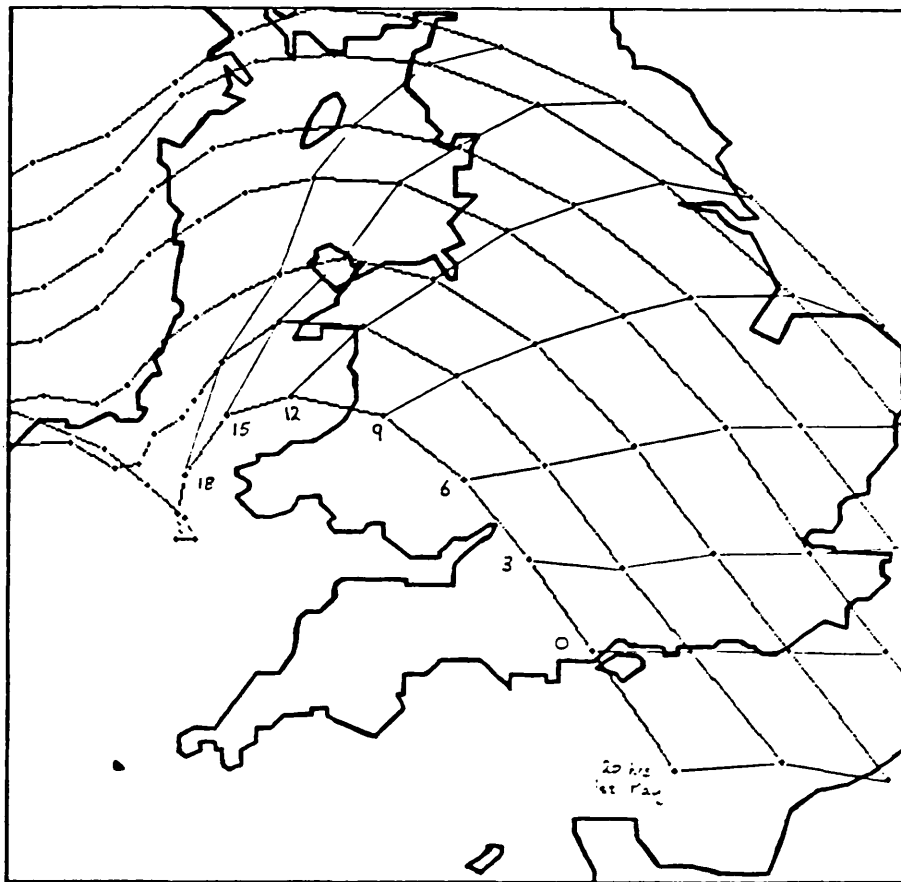


Figure 7.4. Geostrophic trajectories from points along the initial ridge of material.

The composite distributions used are constructed at their position at midnight on 1 May because this is just prior to the bulk of the ridge crossing the south coast of England. This time also comes after the end of the northwards swing of the material due to the dissipation of the band of high pressure previously blocking it to the north. The swing distorts the form

of the ridge of material and would cause difficulties in forming a composite distribution at an earlier time which would retain a uniform structure after the direction change. Figure 7.4 shows a number of geostrophic trajectories all originating at midnight on 1 May from various locations within the region of the material ridge at that time. All the trajectories remain nearly parallel to each other as they cross England and Wales, which indicates that a composite distribution formed from non-expanding puffs would retain a coherent structure during this travel.

In practice a false time, earlier by four hours, is used for the start of the RAIN-PATCH runs. The puff positions of these times were obtained by backtracking using the first geostrophic trajectory component starting at midnight. This has the advantage of moving the front of the composite distribution clear of the south coast but causes very little distortion of the puff positions, and therefore deposition distributions, over southern England.

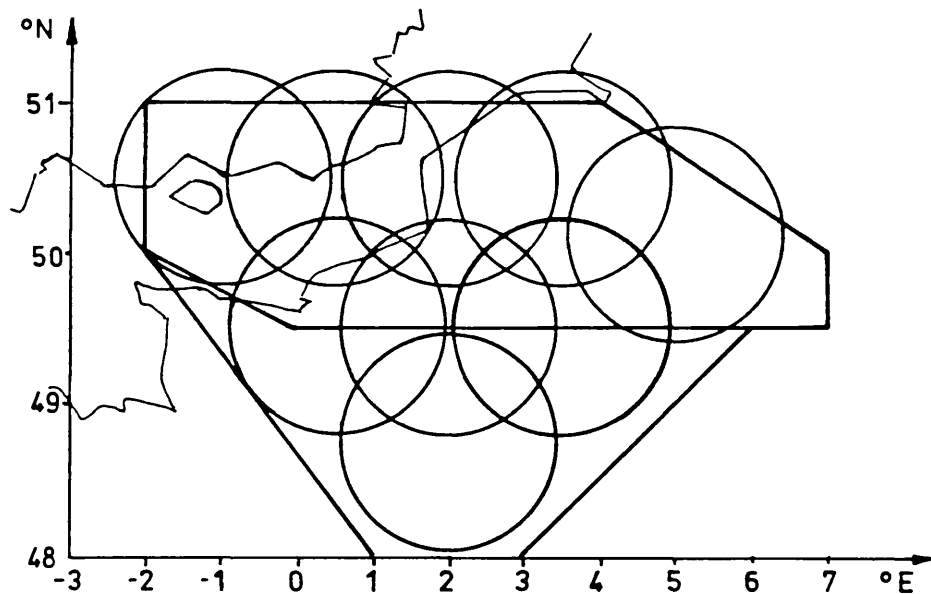


Figure 7.5. Structure and initial position of the 9-puff composite distribution.



Figure 7.6. Distribution of deposited caesium-137 on grass (Bqm^{-2}) from analysis by the Institute for Terrestrial Ecology.

Two composite distributions were used in this modelling. The first used nine relatively large 65-sample point puffs with a 36 km standard deviation. Their midnight on 1 May positioning is given in figure 7.5. This distribution covers not only the specified region of the material ridge but also extends south to include the, probably erroneous, BNL particulate measurement peak value position.

When used for modelling the wet deposition of Cs-137, this distribution gave results in broad agreement with measured results for deposited Cs-137 on grass, provided by the Institute for Terrestrial Ecology (ITE) and shown in figure 7.6. On closer analysis, however, these results did not have the same fine detail as earlier preliminary results. In particular, some areas of deposition which had appeared in earlier results were now missing. Also, the four puffs positioned behind the initial line seemed to give rise to deposition in areas at odds with the ITE results. This final point confirms earlier doubts about the validity of the BNL air filter data. For these reasons a composite distribution using more puffs with a smaller diameter was subsequently used.

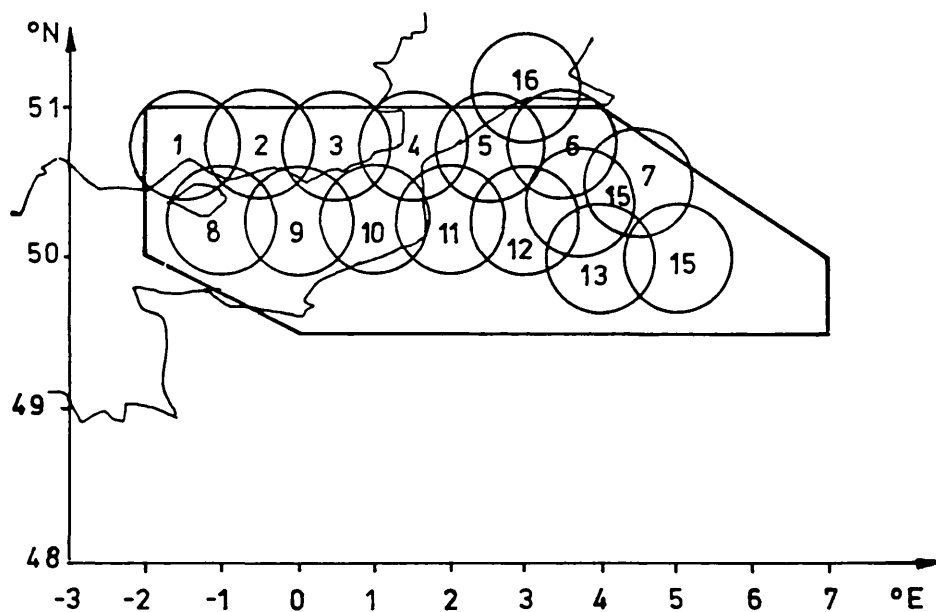


Figure 7.7. Structure and initial position of the 16-puff composite distribution.

This second composite distribution, shown in figure 7.7, consisted initially of 14, but later 16, 121-sample point puffs positioned in two rows to match the supposed position of the material ridge. These puffs have a standard deviation of 20 km giving an average sample point spacing of 8.1 km, compared to the 19.7 km for the larger puffs. This is comparable with resolution of the rain data, so very little rain should be missed with this composite distribution.

Table 7.3. Puff start locations and fractions deposited for Cs-137 wet deposition using the 16-puff composite distribution.

No.	Latitude	Longitude	Depn. fraction (%)
1	50°45' N	1°30' W	13
2	50°45' N	0°30' W	9
3	50°45' N	0°30' E	25
4	50°45' N	1°30' E	25
5	50°45' N	2°30' E	13
6	50°45' N	3°30' E	5
7	50°30' N	4°30' E	1
8	50°15' N	1°00' W	18
9	50°15' N	0°	31
10	50°15' N	1°00' E	16
11	50°15' N	2°00' E	2
12	50°15' N	3°00' E	6
13	50°00' N	4°00' E	20
14	50°00' N	5°00' E	1
15	50°22.5' N	3°45' E	7
16	51°7.5' N	3°00' E	17

The puff locations and the fraction of material removed from each puff during its passage across the UK are given in table 7.3. The two original rows of puffs (numbers 1 to 7 and 8 to 14) both deposit comparable quantities of material over comparable areas and when combined give a distribution matching the ITE data results shown in figure 7.6 reasonably well. The predicted levels over Cumbria do not, however, have levels increased relative to other areas, such as North Wales, to the extent that would be expected from the ITE results. Three possible reasons for this were identified. First, the

Manchester radar system, which provided the data over that area, was known to be faulty during that period and occasionally, about once per hour, scans were omitted from the composite rain data picture. Consequently rain which would have been adding to the material removed is absent from the modelling. Second, the ridge of material which crossed the country may not have been of a uniform concentration. If there had been relatively more material towards the eastern end this would have led to relatively more deposition over Cumbria.

Two extra puffs, 15 and 16 in figure 7.7, were added to improve the deposition in Cumbria. They follow trajectories which encounter the rain considered to have caused the bulk of the deposition over the area. Also, since they start from the eastern end of the ridge, they had the effect of increasing the amount of material there relative to the western end. This takes no account of the missing data but nonetheless greatly improves the resulting deposition distribution, which is shown in figure 7.8.

Thirdly, the second ridge of material, apparent from the air concentration data in figure 7.3 and mentioned above, will have added to the levels occurring in Cumbria, but not those elsewhere.

7.5 CALCULATED TOTAL DEPOSITION OF CS-137 AND I-131

These distributions are dependent primarily on the quantity of material which is taken to be incorporated within the 16-puff distribution. This in turn depends on the quantities of material released on 26 April. Values for the quantities of material released on a daily basis were provided by the Soviet authorities (USSR, 1986) for the ten day period from 26 April to 5 May. These show estimates of 1.7×10^{17} Bq of I-131 and 1.1×10^{16} Bq of Cs-137 for the 26 April, but since they are based on limited contamination data from within the USSR there is a large uncertainty in these values. This is quoted as $\pm 50\%$ for the total quantities released and will be larger for estimates for shorter release periods.



Figure 7.8. Modelled distribution of wet deposited caesium-137. Contour levels are close hatched for $> 5000 \text{ Bq m}^{-2}$, hatched for $> 1000 \text{ Bq m}^{-2}$ and 50 Bq m^{-2} .

A two hour section of the material released on the 26 April is assumed to have reached the 16-puff distribution. The quantities involved have been calculated as one twelfth of the total day's release, with allowance for decay and dry deposition losses during the journey from Chernobyl to the UK. This latter has been calculated using (from Smith, 1987)

$$Q_{\text{UK}} = Q_{\text{REL}} \exp\left(\frac{-v_d x}{uL}\right) = Q_{\text{REL}} \exp\left(\frac{-v_d T}{L}\right) \quad (7.5.1)$$

where v_d is the appropriate dry deposition velocity, x is the distance travelled (4100 km) over time T (135 hours) at velocity u (8.4 ms^{-1}) and L is the

boundary layer height. Q_{REL} and Q_{UK} are, respectively, the quantity of material released and the quantity reaching the UK.

This gives the values for Q_{UK} of 8.4×10^{14} Bq and 4.8×10^{15} Bq for Cs-137 and I-131 respectively. These have been suitably rounded and are appropriate to a boundary layer height of between 2000 m and 3000 m, which is typical of the boundary layer heights calculated for this period by the MESOS model.

The washout coefficients and dry-deposition velocities used in the modelling will also affect the results obtained. A number of studies (Cambray *et al.* (1987), Hancock and Woolam (1986) and Smith (1987)) calculated that the dry deposition velocity for caesium was significantly lower than the normally accepted value of 0.1 cms^{-1} . The value due to Smith of 0.045 cms^{-1} is typical and has been used in the calculations here.

Smith also calculates a value of 0.256 cms^{-1} for the dry deposition velocity of iodine. This is a weighted value which takes account of about 80% of the iodine being in a gaseous form, which dry deposits more readily than the particulate form. The value is close to the generally accepted value of 0.3 cms^{-1} .

The results given in the previous section use the washout coefficient of $10^{-4} J^{0.8}$, where J is rain intensity in mmhr^{-1} , for calculating wet deposition. This was identified as a suitable approximation in chapter five and has therefore been used in the calculations here.

The calculated deposition distributions for Cs-137 and I-131 are given in figures 7.9 and 7.10. Clearly there are large uncertainties in these results so a comparison with measured data was carried out and is presented below.

7.6 THE MEASURED DATA AVAILABLE FOR COMPARISON

Together with the time sequence air concentration data, used for the timing of the initial ridge, and the caesium levels on grass provided by the ITE, data was also provided by the National Radiological Protection Board (NRPB) (HMSO, 1986). This is a compilation of data from various sources consisting of air concentrations and concentrations in rainwater, on grass and in cows'

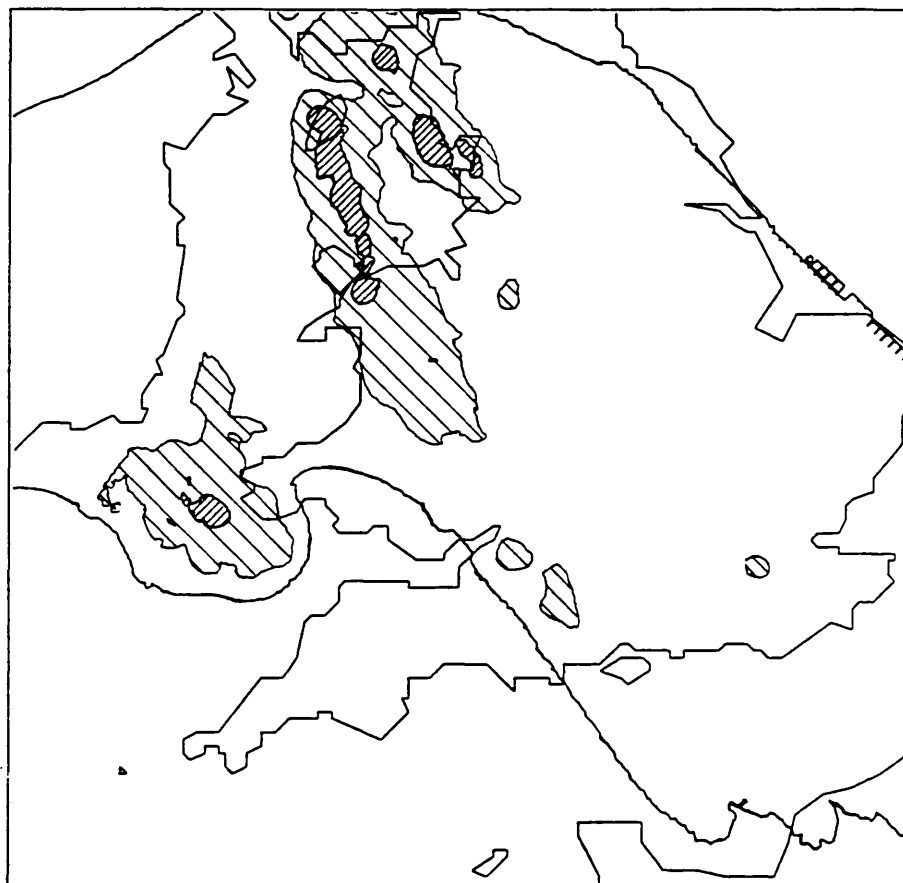


Figure 7.9. Modelled distribution of wet and dry deposited caesium-137. Contour levels: close hatched for $> 5000 \text{ Bq m}^{-2}$, hatched for $> 1000 \text{ Bq m}^{-2}$ and 50 Bq m^{-2} .

milk. The first two forms were not used directly in the comparisons with the model since RAIN-PATCH only provides time-integrated deposition data. Modifications could have been made to provide figures for comparison with these data but since the data were only available for a very limited number of locations this was not considered worthwhile. However a simple comparison between measured peak air concentrations and a mean value for the 16-puff distribution was made.

The ITE data consisted of contoured levels, which were used in the analysis already discussed, and the raw data, comprising 248 measured levels, with measurement location grid references. The measurements were made

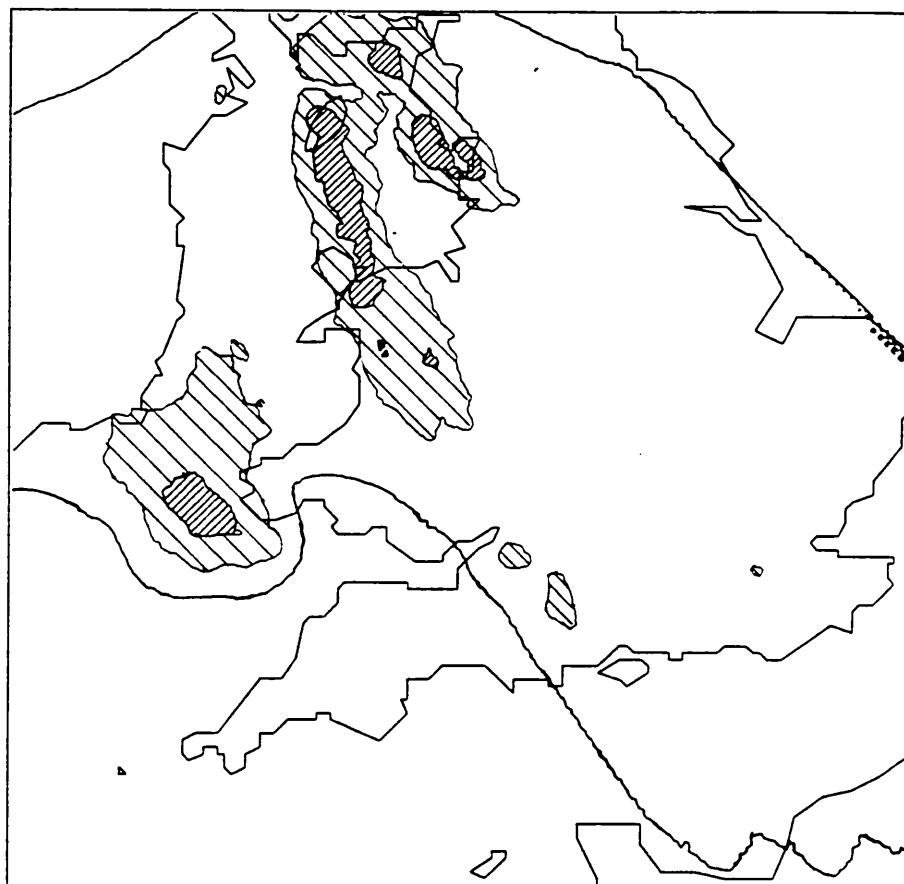


Figure 7.10. Modelled distribution of wet and dry deposited iodine-131. Contour levels are close hatched for $> 5000 \text{ Bqm}^{-2}$, hatched for $> 1000 \text{ Bqm}^{-2}$ and 50 Bqm^{-2} .

during September and October 1986 but precise times for each measurement were not available.

This data set proved very useful both because of its size and because it is from one organisation. This makes the measurements more consistent by reducing uncertainties about the amount of attached soil and root included in the samples. Other uncertainties affecting how much deposited material is retained by the grass (interception factor), for example foliage density, will still affect the data. The interception factor can vary typically between 0.1 and 0.5. Very low values of 0.06 for iodine and 0.12 for caesium were measured by Fulker (1987) shortly after the deposition at a lowland farm

in West Cumbria. The larger value of 0.25 recommended by the NRPB was considered more representative of the whole of the UK, although some indication towards a smaller value is given below.

With the cows' milk data, data from dairies or the Milk Marketing Board was not used due to the indeterminate area averaging it would contain and the lack of guarantee that the locations given for the measurements were representative of the milk's origin. This left data from farms or locations which could reasonably be assumed to be farms. For both milk and NRPB grass data very few measurement locations were provided with grid references. Values from other locations were only used where they could be positively identified from the AA Road Atlas. This left 66 locations for the grass concentration data and 185 for the milk. With the grass data where close locations could not be distinguished, for example various locations on a hill, a mean value has been taken.

For the NRPB grass data, only measurements made during the period 3 to 13 May inclusive are used. Where sequences of measurements were made at one location, only the earliest value has been included. No correction has been made for environmental losses in this data due to the very significant location dependence which has become apparent for these processes. This is illustrated by the persistence of high caesium levels in the highland areas of Wales and Cumbria, contrary to expectation from accepted loss rates derived from lowland areas.

With the milk data, because of the greater interest in I-131, which has only a short, 8.1 day, half-life, only measurements taken during the period 4 to 7 May have been used. This was possible owing to there being many more milk measurements than grass measurements. Again no correction for environmental losses has been made; to do so would require detailed knowledge of the farming practices affecting each measurement. This need has been well illustrated by Wilkins *et al.* (1987) who have studied the effects of two different farming methods.

7.7 THE COMPARISONS MADE

A number of different comparisons were made between the RAIN-PATCH model results and the measured data. The first of these was a straightforward visual comparison between the contoured ITE data of figure 7.6 and contoured caesium deposition results. This, as previously described, was used in finalising the form of the composite distribution used in producing the deposition patterns of figures 7.8 to 7.10.

Some distortion and smoothing has been introduced to both sets of data by the contouring but the model is clearly identifying the areas of higher levels of deposition over Cumbria and North Wales.

7.7.1 Correlation Coefficients

The second comparison was to calculate Spearman's Rank Correlation Coefficient (Freund and Walpole, 1980) for the various comparable pairs of measured and modelled results. These results are listed in tables 7.4 to 7.6. They are obtained from the ranking order, in levels of contamination, between the modelled and measured data. This is therefore a more objective comparison than the purely visual one.

Table 7.4. Rank correlation coefficients using grass data.

	NRPB (61 points)	ITE (248 points)
Cs wet, 7 puffs	0.55	0.58
Cs wet, 14 puffs	0.60	0.69
Cs wet, 16 puffs	0.61	0.71
Cs wet and dry, 16 puffs	0.67	0.75
I wet and dry, 16 puffs	0.56	0.75

Table 7.5. Rank correlation coefficients using milk data. Numbers of data points given in brackets.

	5th only	4th-7th
Cs-137	0.67 (43)	0.68 (101)
I-131	0.57 (54)	0.44 (124)

Table 7.6. Rank correlation coefficients for sub-areas. Numbers of data points given in brackets.

	NW England.	Wales
Cs wet only, ITE grass	0.48 (32)	0.67 (120)
Cs wet and dry, ITE grass	0.47 (32)	0.68 (120)
I wet and dry, milk 5th only	0.46 (13)	0.13 (15)
Cs wet and dry, milk 4th-7th	0.31 (38)	0.37 (18)

Table 7.4 gives results using both sets of grass data and shows improvements in correlation in changing from the seven puff to the fourteen puff composite distribution and from the fourteen puff to the sixteen puff version. The correlations for the ITE data show greater improvements than for the NRPB data. This indicates an expected bias towards the ITE data, since this was used, in its contoured form, in finalising the form of the sixteen puff distribution.

The improved correlations when dry deposition is included in the modelling are also expected since measured data is always of total deposition comprising both wet and dry. The low correlation for the iodine on grass result relative to the caesium results is caused by not taking radioactive decay into account in the measured data. This would have no effect on the caesium results due to its very long half-life. The effect of neglecting the decay of iodine is also apparent in the milk data results, since using data measured during the period 4 to 7 May slightly improves the correlation for caesium relative to that for data just from 5 May, but significantly reduces the correlation for iodine.

Table 7.6 shows better correlations for caesium with the ITE data over Wales than over NW England. This is largely a consequence of the greater number of points in Wales but material which arrived later in NW England, as mentioned earlier, will also account for this.

In general the correlation values show a good degree of agreement between the measured and the modelled results. Values significantly better than these could not reasonably be expected owing to the limitations in the modelling and in the measured data, as outlined above.

7.7.2 Scatter Plots

Scatter plots comparing the measured data against the modelled results for total deposition of both Cs-137 and I-131 are given in figure 7.11 for grass data and figure 7.12 for milk data. They all show a considerable degree of scatter. This is to be expected in view of the large variability observed on a local scale in the measured data and it is in agreement with the correlation values.

A line corresponding to agreement between measured and modelled values has been drawn on the figures for grass data (7.11a to 7.11c). These lines are positioned using the NRPB's recommended interception factor of 0.25. For the ITE data (figure 7.11a) the line lies above the bulk of the points, indicating that the model is in general overpredicting the levels of deposition. However, for the other two sets of results the lines lie below the bulk of the points indicating an underestimation. This is particularly true for the caesium data given in figure 7.11b.

The more consistent nature of the grass data measurements from the ITE, the better correlation values with this data and the comparison of measured and modelled air concentrations given below, all support the conclusion that the model results are an overestimation of the actual levels of deposition

Table 7.7. Measured air concentration data used in calculating source term adjustment factors. (Bqm^{-3})

Location	Measurement period time and date (May 1986)	Measured I-131	Total I-131	Cs-137	Cs-134
Dorset	1100 2 – 1500 3	0.29	1.16	0.15	0.09
Gloucestershire	2110 2 – 2130 2	2.1	8.4	0.66	0.36
Kent	0800 2 – 1200 2	3	12	1.8	–
Kent	1100 2 – 1200 2	8	32	5	1
Oxfordshire	1800 2 – 2110 2	3.03	12.12	1.4	0.64
Oxfordshire	1510 2 – 1620 2	5.32	21.28	1.9	0.9
Suffolk	1800 2 – 1900 2	6.7	26.8	2.7	–
Lancashire	2020 2 – 2120 2	24.4	24.4	0.84	–

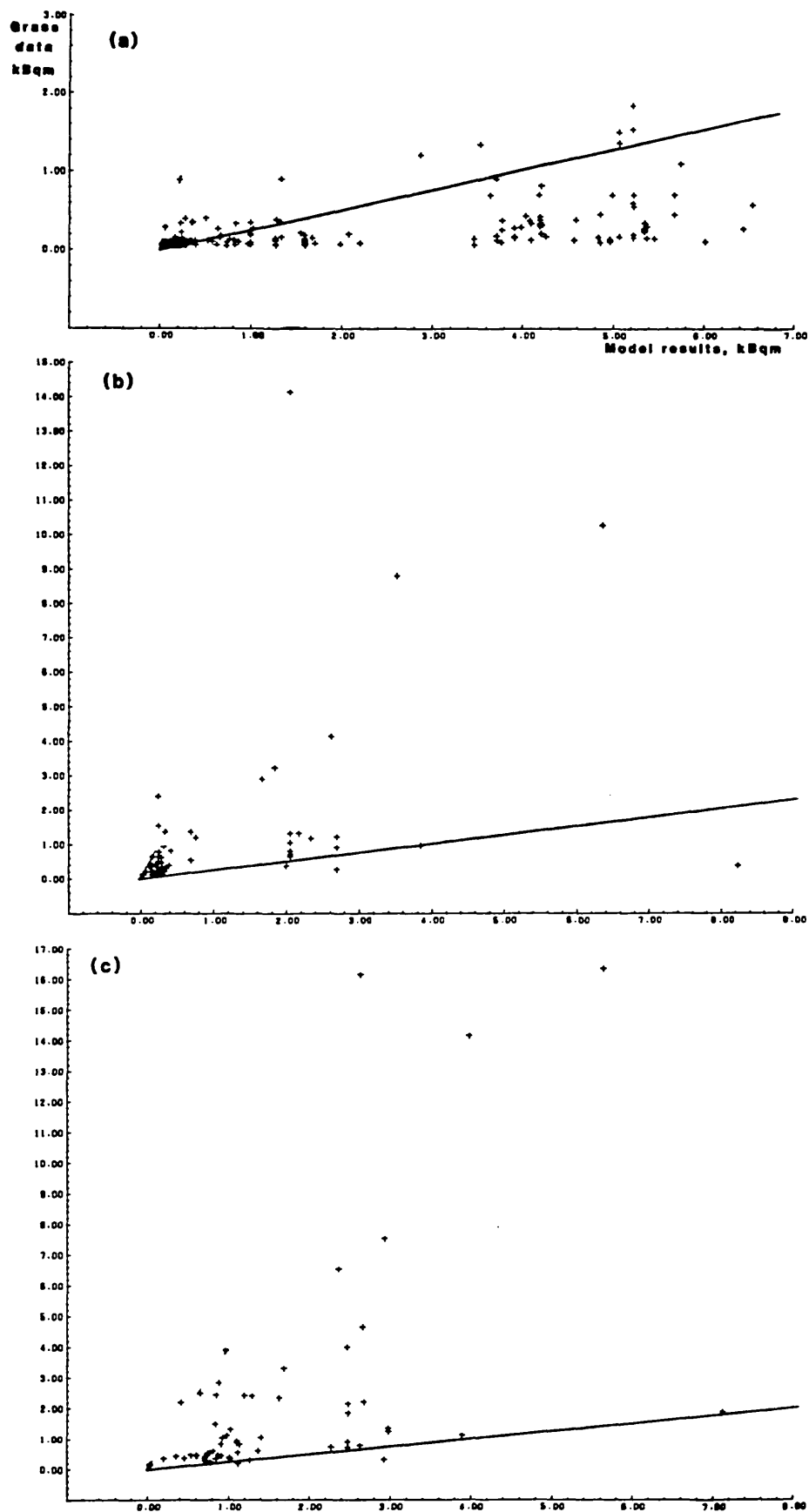


Figure 7.11. Scatter plots of measured deposition on grass against modelled total deposition for (a) ITE caesium data, (b) NRPB caesium data and (c) NRPB iodine data.

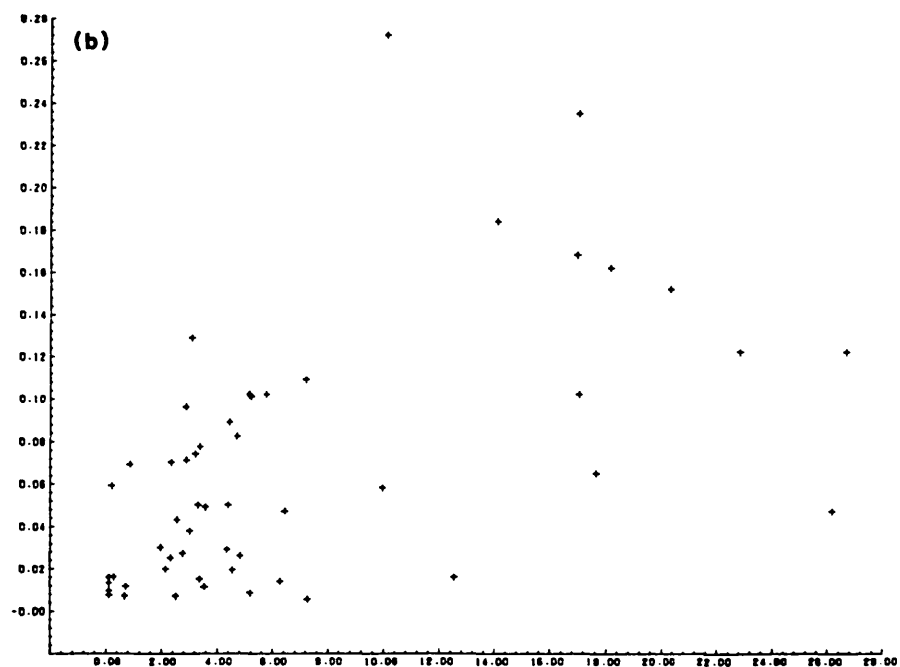
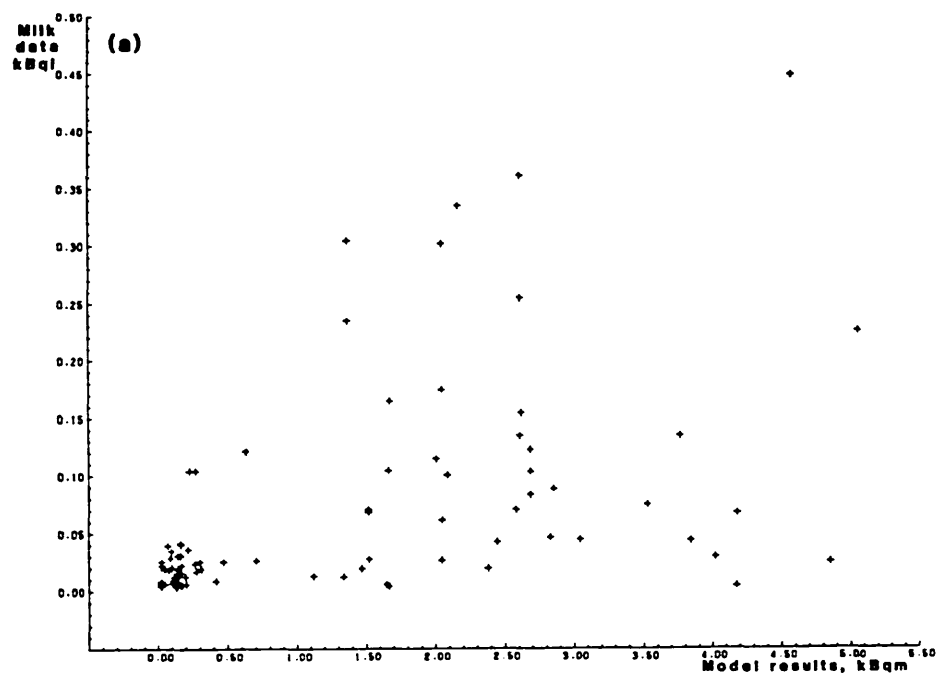


Figure 7.12. Scatter plots of measured activity levels in milk against modelled total deposition for (a) NRPB caesium data and (b) NRPB iodine data.

Two methods have been used to try to assess the size of this overestimation. First comparisons were made between measured peak air concentrations and values calculated for the composite distribution. Seven suitable measured data values from across the UK were available from the data compiled by the NRPB (HMSO, 1986) and are listed in table 7.7. These comprised one Maypack measurement, giving total air concentrations, and six filter measurements which only record particulate values, and for which the iodine values were multiplied by a factor of four to allow for the gaseous component. Air concentrations of 5 Bqm^{-3} for caesium and 27 Bqm^{-3} for iodine were calculated for the composite distributions. These assume that all the material calculated to have reached the distribution is spread evenly throughout it to a depth of 3000 m. This then gives average measured to modelled value ratios of 0.75 for iodine and 0.44 for caesium.

It proved possible also to obtain a value for the overestimation of the caesium from the ITE grass data, since this data set gives the best correlation values. A least squares best-fit straight line (Freund and Walpole, 1980) was calculated using the ITE grass data and the modelled total caesium deposition. This had a slope of 0.03 and an intercept of 78.4 Bqm^{-2} . The slope divided by the interception factor then gives the adjustment to the source term required to give a best-fit line with a unit slope. Using an intercept factor of 0.25 gives an adjustment factor of 0.12, but larger values are obtained if a smaller interception factor is assumed. For example an interception factor of 0.1, which is comparable with the values measured by Falker (1987), gives an adjustment factor of 0.30, which is in better agreement with the value of 0.44 obtained from the air concentrations.

The positive intercept value corresponds to pre-Chernobyl caesium not included in the modelling. A diagram showing the levels of this in 1977, also produced by the ITE (Cawse and Horrill, 1986) is given in figure 7.13. They are generally fairly low and so have been neglected in the previous analysis.

From this work the best estimates of total caesium and iodine deposition are those given in figures 7.9 and 7.10 but with the levels reduced to 0.75

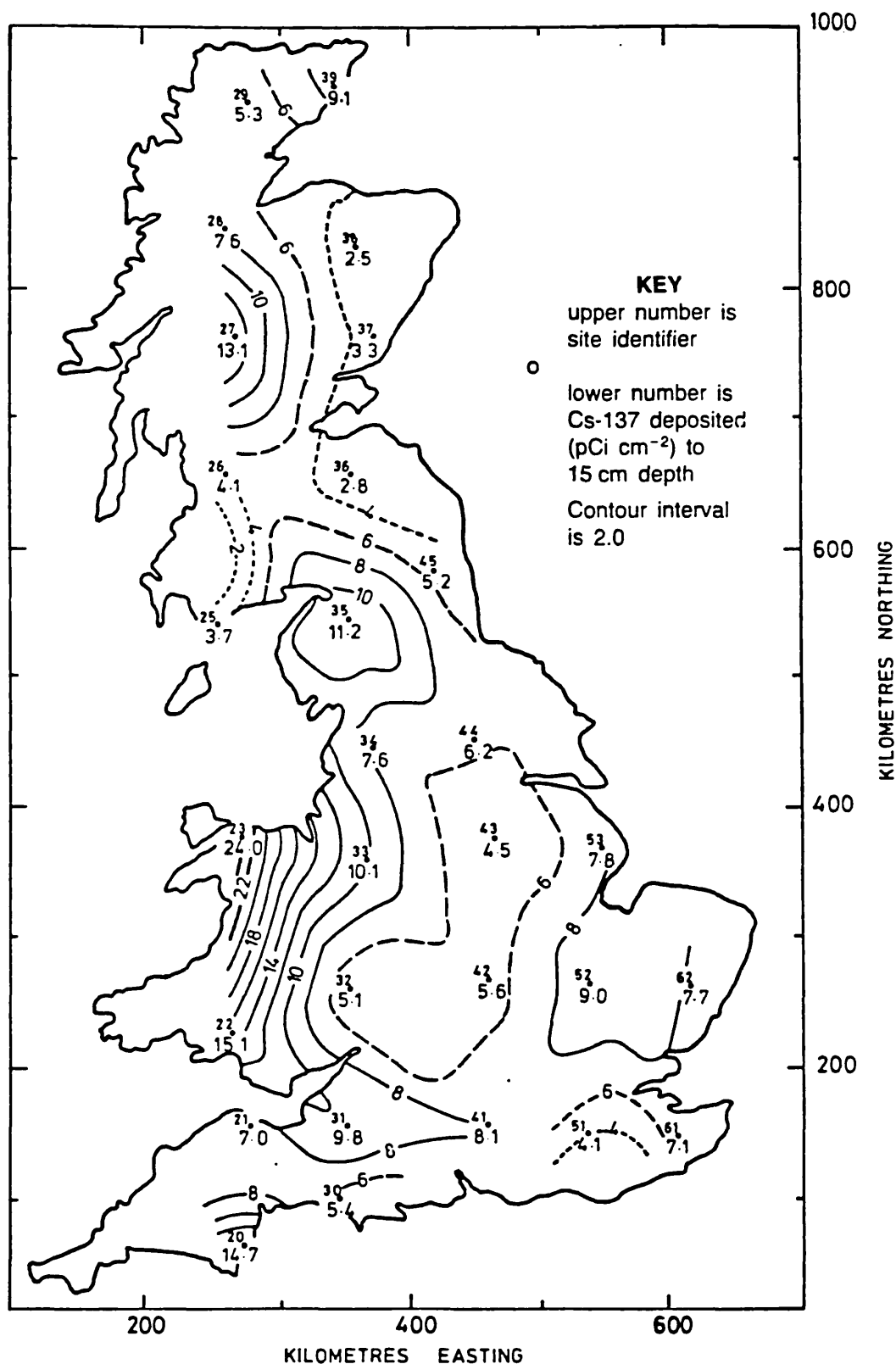


Figure 7.13. Caesium-137 in soil to a 15 cm depth. Measured on grassland in 1977. From Cawse and Horrill (1986)

of those given for the iodine and to between 0.2 and 0.4 of those for the caesium. This assumes an interception factor lower than the value of 0.25.

7.8 FURTHER ANALYSIS OF THE PASSAGE OF THE INITIAL RIDGE

A simple study of the importance of the correct timing of the ridge in obtaining the best caesium and iodine deposition patterns was carried out for two reasons. Firstly, it acted as a further check that the ridge was being reasonably correctly modelled and that the timing data was not being misinterpreted. Secondly, it gave an indication of the precision required in the timing data to resolve correctly the material arriving from a release external to the UK. This would be of importance in planning a response to possible future accidents.

The study was carried out using the 16-puff composite distribution by delaying or advancing its start time relative to midnight, 1 May. The initial positions of the 16-puffs were unchanged but new trajectories and distribution patterns were calculated for each new start time. Since the computational saving in not calculating dry deposition was significant these results were only obtained for modelling the wet deposition of Cs-137. This was possible since the wet-only optimum case gives nearly as good a rank correlation as that for modelled wet and dry deposition.

The significance of the results obtained needs careful consideration. Clearly the form and position of the 16-puff composite distribution is subject to some uncertainty and movement north or south will be approximately equivalent to a time change at the positions given in figure 7.7. For the longer time changes, however, this relationship breaks down because trajectories from Chernobyl which reach the UK at these modified times do not in general pass through the 16-puff distribution's starting position. For these cases the distribution is best interpreted as a very extensive and somewhat unrealistic release occurring in northern France. This is still useful for the

second application of this study, namely future timing resolution requirements.

The time shifts used range between plus and minus six hours in steps of one hour, together with plus and minus twelve hours and twenty-four hours. First the new trajectories were calculated. These were all very similar for the six hours and below time shifts. Up to plus six hours there is a slight southerly swing to include South Wales and some narrowing of the band of trajectories, but neither effect is very marked. Going backwards to minus six hours has the band of trajectories broadening to the north to extend further into South West Scotland. The larger time shifts, surprisingly, give similar effects with the trajectories moving further up the UK and covering more of Scotland.

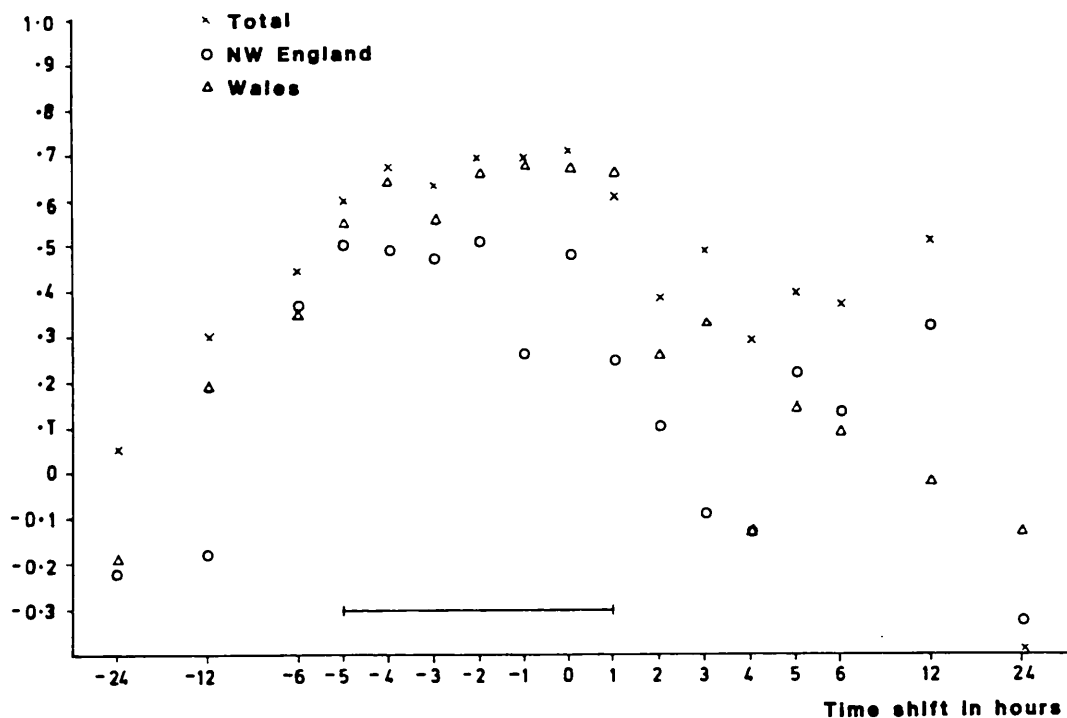


Figure 7.14. Correlation coefficients for the time shifted model runs.(Line indicates range of almost constant total correlation value)

The main comparison made between the time shifted and original deposition pattern was by means of correlation coefficients for the whole area, together with sub-area ones for Wales and North West England. These are shown in figure 7.14. The main feature in these results is the plateau covering a time-shift range from one hour after midnight, 1 May to five hours before. The total correlation for the midnight release time has the greatest value but there is little change over the range. The correlation values for Wales match closely the total area one over this range, which is to be expected since that sub-area contains nearly half the total data points. As is also expected, over this period the deposition patterns look very similar, with a ridge running across Wales and the Irish Sea to the Isle of Man and high levels over or near NW England. This pattern breaks down for the later releases, accounting for the reduced correlations.

The two significantly reduced NW England correlation values at plus and minus one hour correspond to the high levels in that region moving south from Cumbria into Lancashire.

The improved total correlation at plus twelve hours, relative to the other later times after plus one hour is a consequence of the greater total deposition. For this start time, over three times as much material is deposited than for the original time and it is spread across a larger area. This partly makes up for the missing dry deposition to give the relatively larger correlation value despite a very different distribution pattern which can be seen from figure 7.15. One consideration, however, is that if the released material had reached northern France twelve hours later the deposition across the UK might have been significantly greater.

The plateau of figure 7.14 occurs because there is rain over the high deposition areas of north west England, the Irish Sea and Wales for most of the early afternoon of 2 May, which is when the appropriate time-shifted distributions pass across these areas. Since the 16-puff distributions are very extensive, some part of either always encounters rain over each of these areas during the period, and since the measured deposition is very high over two

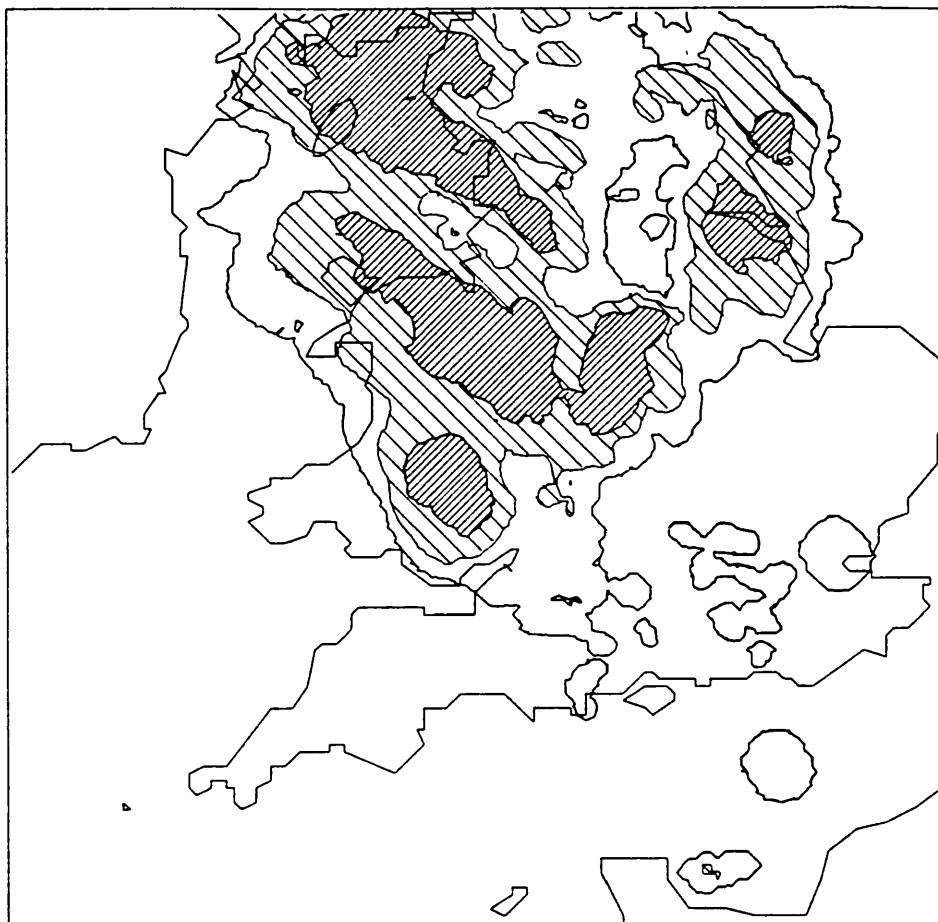


Figure 7.15. Modelled distribution of wet deposited caesium-137 for the 16-puff composite distribution delayed by 12 hours.

of these areas the correlations are also high. The plateau does not, however, imply that the ridge could have passed across earlier since the front of the ridge is well-defined by the time sequence data.

The six hour plateau gives an upper limit to the time resolution required to give the accuracy of deposition obtained here. This long period is a consequence of the persistent rain on the afternoon of 2 May and the great expanse of the composite distributions, as mentioned above. The large drop in correlation in changing from a one hour to a two hour delay is more significant. This shows the sort of change which can occur over an hour, and it could possibly be even larger for a more local release.

7.9 SUMMARY AND CONCLUSIONS

A number of fortuitous occurrences made it possible for the RAIN-PATCH model to be used in obtaining caesium and iodine deposition patterns resulting from the Chernobyl accident. The model was developed to study wet deposition from hypothetical releases of pollutant material within the areas covered by the weather radars, which provide the rain data for the wet deposition calculations. It proved possible to use it to model the deposition from this much more remote release because of the prevailing meteorological conditions. These dictated that the material initially crossed the UK in a well defined ridge. Also, it was fortunate that sufficient locations had suitable equipment available and made appropriate measurements for it to be possible to reconstruct the position of the ridge with sufficient accuracy for the modelling.

The good correlations obtained with the grass and milk data serve to further confirm the importance of the initial ridge in producing the measured deposition. Later material, though, particularly that which became incorporated in the thunder storms on 3 May, will also have added to the levels.

The final part of the study, showing the sensitivity of the results to changes in the time at which the ridge crossed the UK, shows the data timescale required in this form of modelling. Despite the six hour plateau in correlation levels, other changes serve to show the importance of the correct timing of events in the modelling.

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CHAPTER 8.

AN ANALYSIS OF THE USE OF RAIN-PATCH IN NUCLEAR POWER STATION SITING STUDIES

8.1 INTRODUCTION

The siting of nuclear power stations is a compromise between economic considerations, dictating that they should be close to the sources of power consumption, and safety considerations which try to move them away from populated areas. These safety considerations require that any contamination of the local population be kept to a minimum should an accident occur. The previous two chapters have demonstrated the part played by rain in dictating the distribution of deposited material following an accident, and this clearly needs to be considered when selecting power station sites.

The requirement in siting studies is for a probability distribution of deposition around a proposed site, based on the occurrence of the different types of weather in the area. If used in conjunction with the population distribution for the area, and the probabilities of various accidental releases of material, estimates can be made of the risks to the population. A suitable deposition distribution can be produced using RAIN-PATCH by modelling a sequence of releases, spread throughout a period containing sufficient occurrences of different types of weather to be representative of all the weather occurring at that location. The deposition patterns resulting from each release are then added together to give what can be interpreted as a probability distribution of deposition.

This direct approach to calculating the distribution implicitly contains all the correlations between the different factors affecting the deposition; for example, rain intensity and wind direction, and rain intensity and topography.

The most straightforward means of obtaining a sequence of weather representative of that normally experienced at a location is to use data from a whole year. This covers all the seasonal effects, and in a normal year

will contain a selection of the more extreme occurrences. A sequence for the whole of 1985 from the London radar site at Chenies in Buckinghamshire was therefore obtained. This site provides data covering virtually the whole of the south and midlands of England and East Wales, the only major exceptions being Devon and Cornwall. The deposition from sites on both the south and east coasts could therefore be studied, together with sites on the Severn Estuary, which should have characteristics similar to a west coast location.

This preliminary study uses only one site, situated near the Severn Estuary. However, two distributions are calculated for the site, one using points mode meteorological sampling and the other source mode as described in chapter six. The differences between the two modes were examined in that chapter but it was considered important to ascertain how those differences applied to results compiled from long sequences of runs. This study was therefore carried out first.

In the following section a description of the weather which occurred in 1985 is given. Since no two years are the same, the significant differences from the expected values of, for example, total rainfall, need to be considered when interpreting the model results. This is followed by a description of the database comprising the year's radar measured rainfall and associated wind data. Since its construction was a major undertaking its form and possible alternative uses are outlined.

The details of the two run sequences undertaken are then given in section 8.4, prior to analysing the two sets of results. This analysis is carried out in two stages. First a comparison of the source and points mode results followed by an analysis of the points mode distribution.

8.2 THE WEATHER IN 1985

This section concentrates mainly on the amount of rain which fell during the year, because this is a quantity of direct importance to this work. The other comparably important quantity, the distribution of wind direction, is not considered since suitable data was not readily available. It is also of less

direct use than rain data since a wind direction distribution does not directly relate to routes followed, or destinations achieved, by trajectories.

In temperature terms the first half of the year was unimpressive, with all the months below average in temperature except for April. Rainfall was more variable with some months below average but others above. For example, along parts of the east coast there was less than 10% of expected rainfall in February, but May was wetter than usual in central and eastern parts of England, and June was very wet everywhere. The two notable rain events in the year occurred in May and June. 58.1 mm of rain fell in one storm at Brize Norton in Oxfordshire on 20 May, 51.3 mm of it within two hours, and 54 mm of rain fell at Bristol Weather Centre on 21 June.

The second half of the year shows equal variety, with two consecutive months, September and October, having less than 30% of their normal rainfall; together with a drier than usual November they form the seventh driest Autumn since records began in 1727. The second half of September was also the warmest since that date. The autumn was partly countered by December which had much greater than normal rainfall, and August which was above average except over parts of central England.

Table 8.1 gives the total monthly rainfall and its percentage value of the 1951 to 1970 average for five sites positioned in a rough circle about Berkeley in Gloucestershire, the release site used in this study. Average rainfall values for these sites are given in table 8.2, together with seasonal averages, where December, January and February have been taken to be winter.

The monthly averages show a variation from 177% of expected rain in June, to only 44% occurring in September. A smaller but probably more significant spread extends to the seasons. Winter and spring are both reasonably normal but the summer was wetter than usual and the autumn, as mentioned above, exceptionally dry. These discrepancies from the normal need to be borne in mind if this year's data were used in siting studies to ensure that a more normal year could not significantly modify any conclusions.

Table 8.1. Total rainfall per month and percentage of 1951–70 average value for five locations around the release site.

	Heathrow		Boscombe Down		Rhoose		Elmdon		Bedford	
	mm	%	mm	%	mm	%	mm	%	mm	%
JAN	41	80	67	92	57	66	40	69	44	94
FEB	30	79	33	63	62	98	42	86	26	70
MAR	34	79	53	95	73	112	32	63	29	67
APR	33	81	39	93	55	104	64	145	27	69
MAY	67	135	56	103	54	87	60	107	46	105
JUN	89	174	77	148	125	205	103	194	83	160
JUL	35	69	31	71	99	137	53	102	47	91
AUG	59	102	99	150	172	198	56	78	46	84
SEP	11	20	31	50	66	73	17	30	12	26
OCT	18	32	29	45	33	39	31	60	26	57
NOV	30	48	47	60	48	47	77	124	45	88
DEC	18	147	139	174	130	138	83	128	89	168

Table 8.2. Average total and percentage rainfall for the five sites in Table 8.1. Values given by month and by season.

	Monthly average		Seasonal average		Percentage of year's total rain
	mm	%	mm	%	
JAN	50	79	Winter		8
FEB	39	81	181	105	6
MAR	44	86	Spring		7
APR	44	100	145	97	7
MAY	57	106			9
JUN	95	177	Summer		14
JUL	53	98	234	134	8
AUG	86	128			13
SEP	27	44	Autumn		4
OCT	27	45	103	54	4
NOV	49	69			7
DEC	92	151			14

The two extreme seasons almost cancel out to give 663 mm of rain or 96% of the expected value for the whole year, as an average across the five sites considered.

8.3 THE RAIN DATABASE

Prior to performing the studies described in subsequent sections the year's data had to be processed and converted into a suitable form for storage and use in the model. This was itself a major undertaking.

A single tape of binary data was provided for every day of 1985, each containing data from all but the highest level scan of the Chenies radar. This was converted to a more convenient hexadecimal character representation with all the data for the year finally stored on twenty 2400 foot tapes. The format conversion gave a fifty percent increase in data size, but this was considered acceptable in the light of the greater convenience during its use.

The storage format contains all the levels of rain intensity recorded by the radar. A second stage of processing is required to produce RAIN-PATCH input files, which have a smaller set of levels. The set containing 50 levels, described in chapter five, was used for this. The year was finally spanned by two RAIN-PATCH input files per month with a five day overlap between files. This overlap was to ensure that the final release for each file left the grid area prior to reaching the end of the available rain data.

The other set of input data, wind, is archived in the format used by the model. This entailed some pre-processing to convert it to chronological order with data from all seventeen recording sites stored together for each, hourly, recording time.

As well as the following deposition studies, this data has a number of other applications based mainly on the study of rain distributions. For example it could be analysed in terms of areas of similar rain intensity in different types of meteorological situations. This could be similar to the work carried out by Austen and Houze (1972) which was described in chapter three.

8.4 THE RELEASE SEQUENCES UNDERTAKEN

The site of Berkeley in Gloucestershire was chosen for this initial study because of a preference for using a location on the west of the grid area. Most rain in Britain comes from the west or south west as indicated by the direction

rose in figure 8.1, which is for a typical lowland UK location (Smith 1981). Consequently a westerly site will receive more rain than elsewhere. Whilst quantity of rain is not the only factor affecting deposition distributions it is clearly significant.

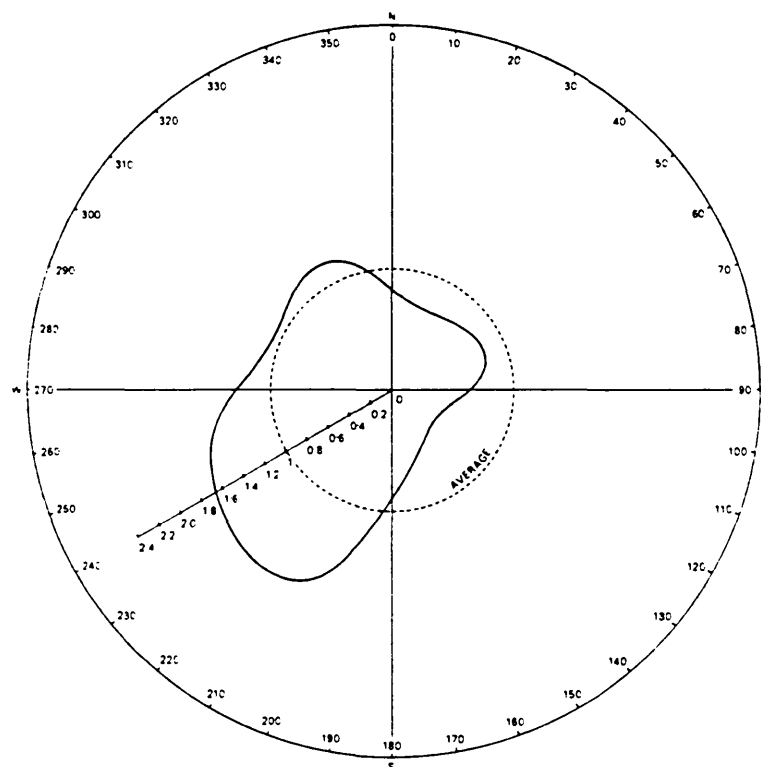


Figure 8.1. Typical rainfall direction rose.

The statistical deposition distributions for a site are constructed by summing together the RAIN-PATCH calculated deposition distributions for a series of a finite number of hypothetical releases from the site. How this series of releases is chosen could easily have some bearing on the results obtained. The more releases undertaken the more representative the final result, but time and computational costs also need to be considered. A series with the first release occurring at 10.00 hrs on 1 January 1985 and thereafter spaced every 29 hours throughout the year was finally selected. This gives approximately one release per day but avoids the release being at the same time each day and suffering bias from diurnal effects. For example, a strong sea breeze might occur at the same time of day over a period of days. Releases

occurring at the same, or nearly the same, time each day could easily be biased in their travel directions. This will be avoided, however, by the five hour change between release times on consecutive days.

The material considered in these hypothetical releases is Cs-137. This is because its half-life is long enough to neglect in these calculations, it is radiologically very significant and it wet deposits very easily. The final point makes wet deposition relatively more important than with other nuclides, and consequently allows dry deposition to be neglected in the analysis. Comparison of the Cs-137 distributions of the previous chapter, where only wet deposition and wet and dry deposition have been calculated, shows that the significant levels are dominated by the wet deposition.

The deposition distribution resulting from the two sequences of runs undertaken are shown in figures 8.2 and 8.3 for, respectively, points mode sampling and source mode sampling.

8.5 COMPARISON OF POINTS AND SOURCE MODE DISTRIBUTIONS

The first comparison is a straightforward visual one between the contoured plots of the two total-year distributions, followed by those for the individual seasons. In using the contoured plots, it should be remembered that because of the range limit of the radar, rain data only covers the area of the largest circle which can be contained within the square plot area. Points mode data is therefore restricted to this region except for a small amount of overrun by the puffs. However, source mode results have no such restrictions since the data sampling point never moves. Consequently this additional area should not be included when comparing the plots.

The $0.1 \text{ units km}^{-2}$ contour in figure 8.2 is the lowest level which is not merely indicating the position of the radar data range limit. At this level there are clearly differences between the two modes, with the points mode showing a smooth, more uniform distribution; the source mode has two significant areas of lower level approaching fairly close to the release

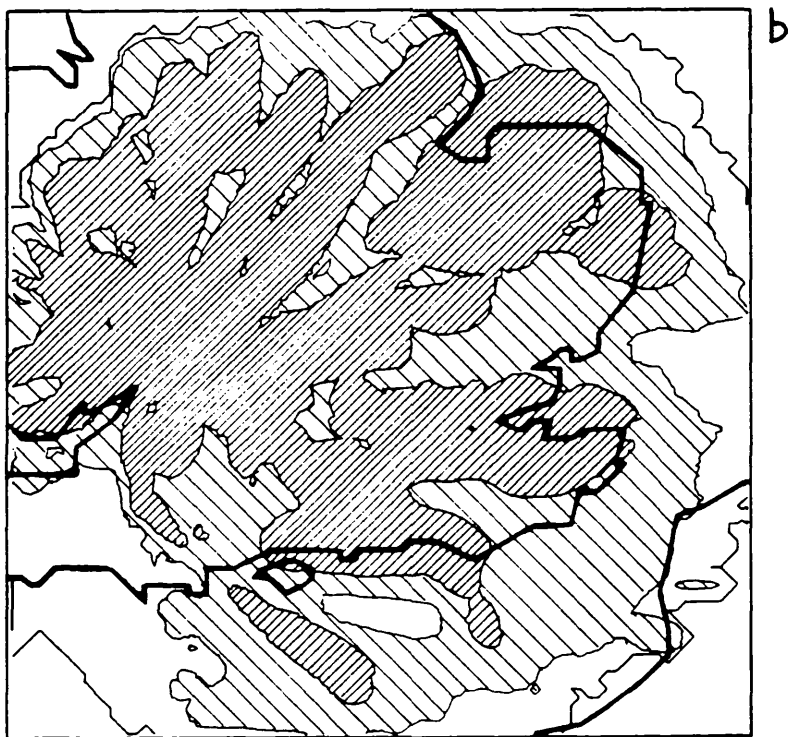
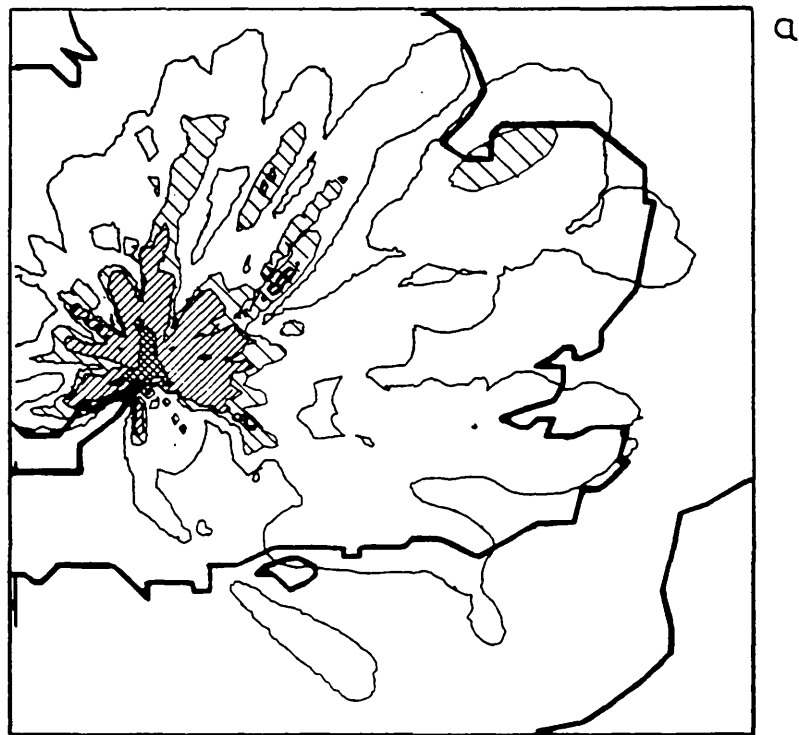


Figure 8.2. Points mode whole year distribution. Contour levels:
 (a) cross hatched $> 5 \text{ units km}^{-2}$, close hatched $> 1 \text{ unit km}^{-2}$,
 hatched $> 0.5 \text{ units km}^{-2}$ and $0.1 \text{ units km}^{-2}$,
 (b) close hatched $> 0.1 \text{ units km}^{-2}$,
 hatched $> 0.01 \text{ units km}^{-2}$ and $10^{-7} \text{ units km}^{-2}$.

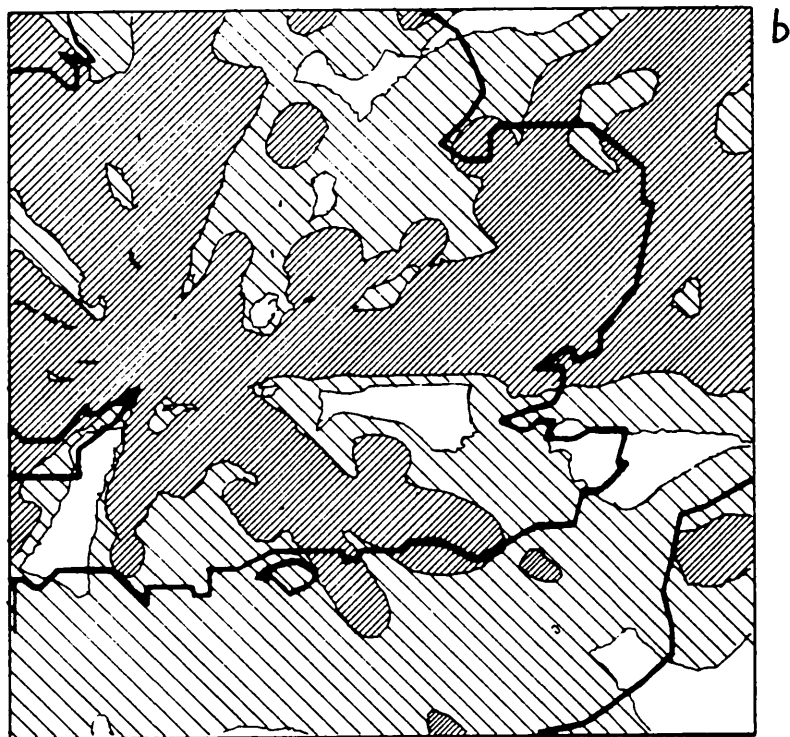
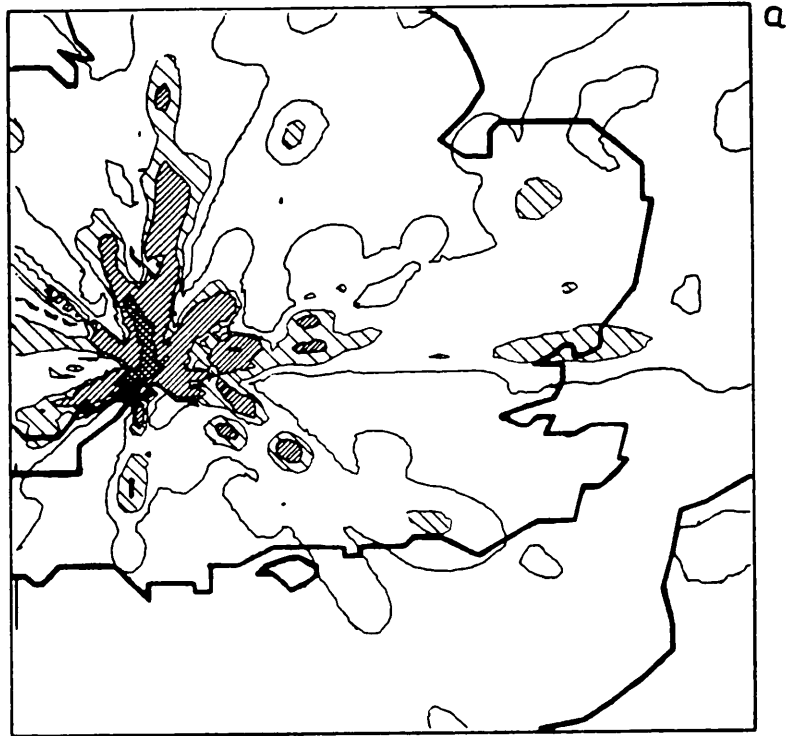


Figure 8.3. Source mode whole year distribution. Contour levels as for figure 8.2.

site: one covering much of central England and the east Midlands and the other a wedge covering Berkshire, Greater London and Kent.

There are two aspects to the consideration of the higher levels. First, the patterns immediately around the release site and second, the higher levels occurring more remotely. Those local to the release site match very well, between the two modes, with the highest levels predominantly contained within approximately a semi-circle to the north of the site. At the 1 unit km^{-2} the source mode contour is less smooth than is the case for points mode and if a smoothed curve was drawn for that level, it would extend further north but not as far east or west as would be the case for points mode. A similar, but less pronounced, situation holds for the other contour levels.

The distribution of the more remote higher levels is very different between the modes. These correspond to specific rain events interacting with specific releases. They differ because the meteorological sampling mode greatly affects the deposition distribution obtained from a specific release as discussed in chapter six. However, deposition from individual releases is not critical to the overall statistical pattern required, so the differing remote higher levels are not a major concern.

The individual seasons show greater variation between the two modes. This is exemplified by figures 8.4 and 8.5 which show, respectively, points mode and source mode for the summer (June to August) total deposition distribution. The variation is in fact comparable with that of the corresponding contour levels in the total year distribution, where the similarities occur at the higher levels. The higher levels occur over smaller areas in the seasonal distributions and still show similarity between the modes. The greater variation is then just a consequence of having fewer releases contributing to the seasonal distributions, and individual releases showing a marked difference between source and points mode.

The second comparison is in terms of the deposition occurring during the different months. Figure 8.6 shows the number of occurrences per month of greater than ten percent washout from a release within the grid area, and

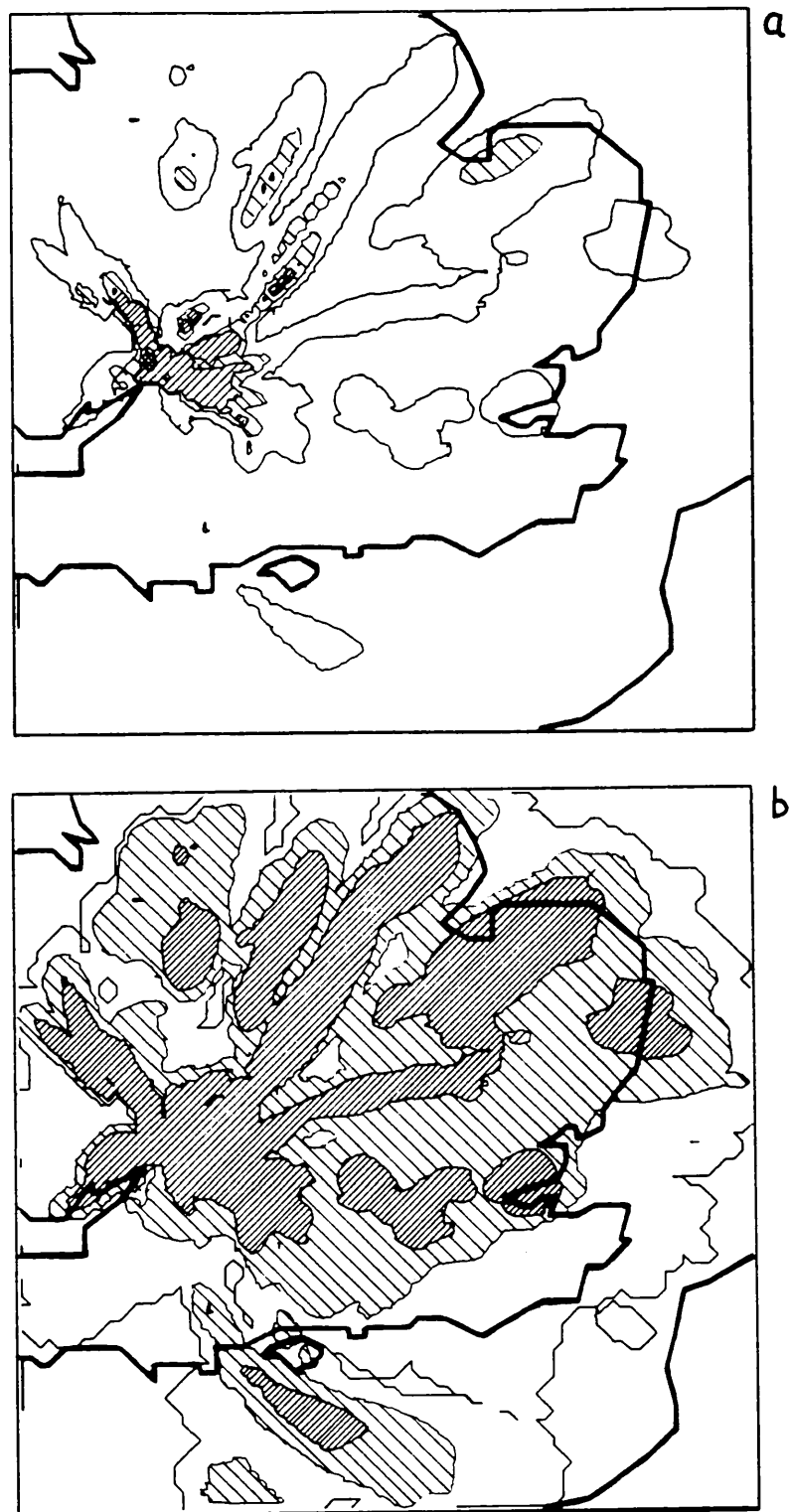


Figure 8.4. Points mode summer season distribution. Contour levels as for figure 8.2.

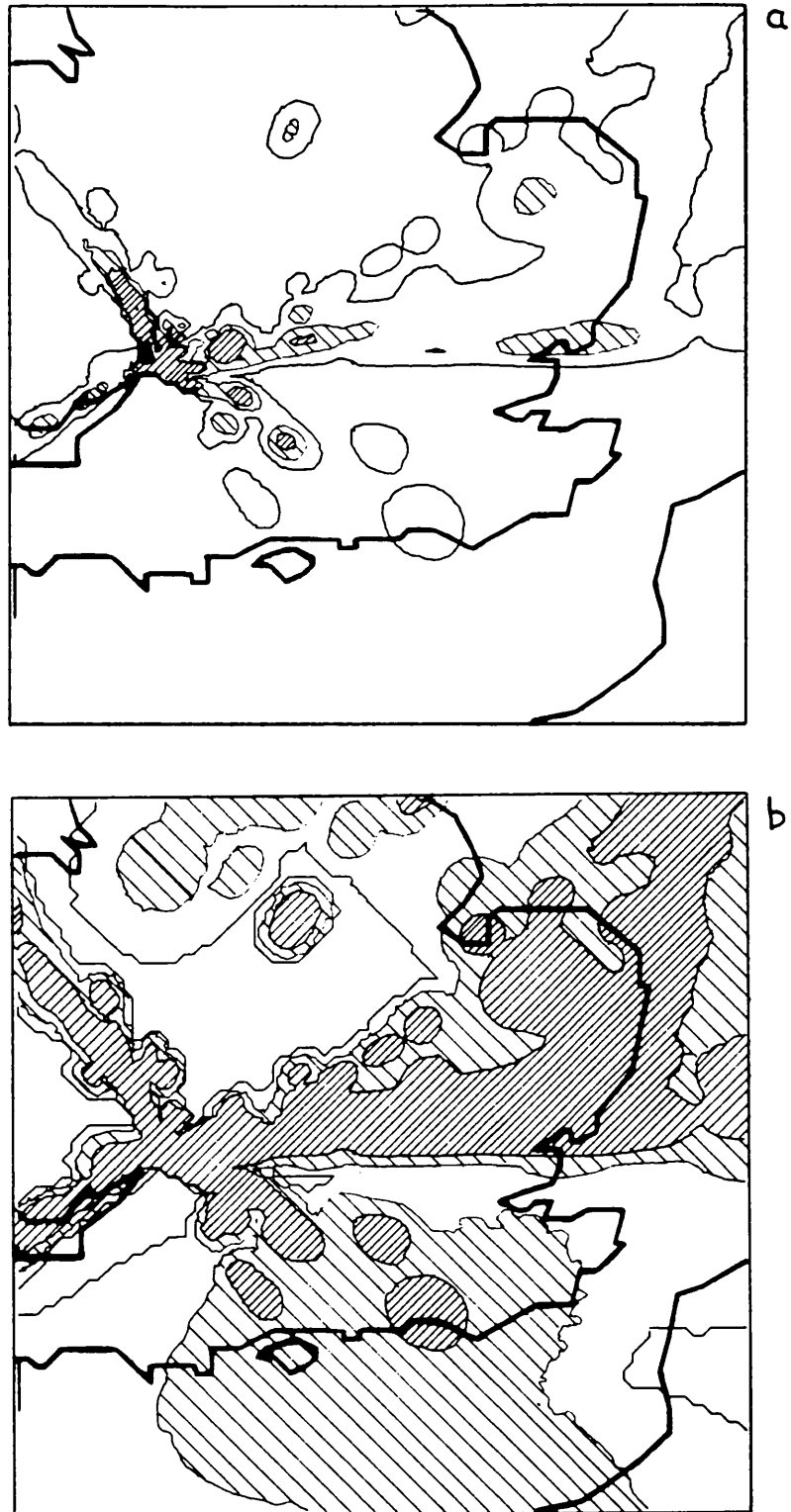


Figure 8.5. Source mode summer season distribution. Contour levels as for figure 8.2.

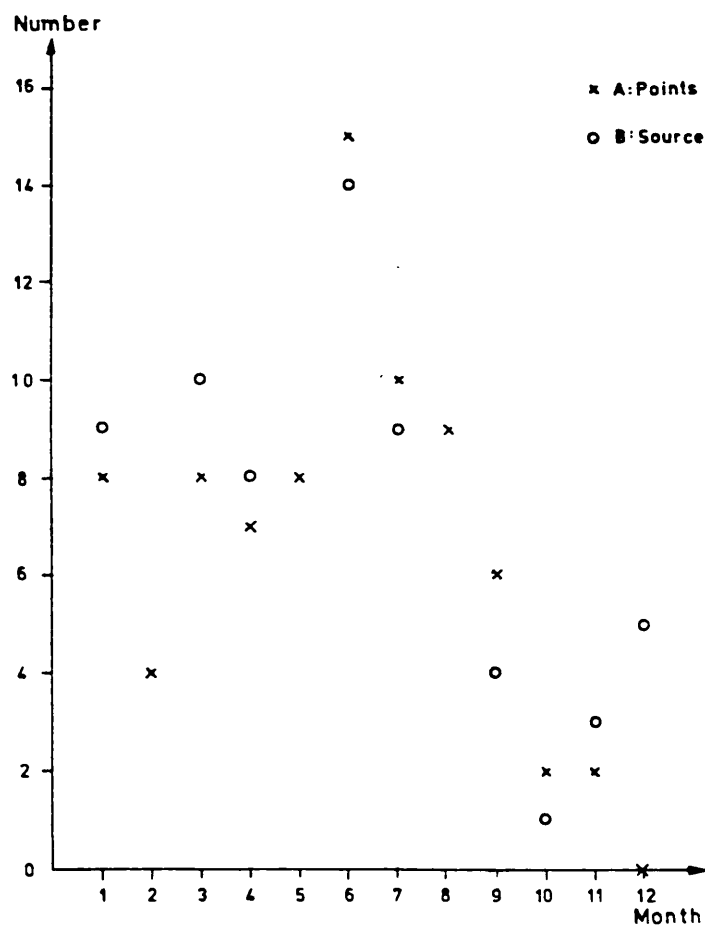


Figure 8.6. Number of occurrences per month of releases experiencing greater than ten percent washout within the grid area.

figure 8.7 shows the deposition per month as a percentage of that for the year. The latter is shown as a percentage of the total year's deposition to eliminate effects introduced by the radar data circle being smaller than the grid area.

The two figures show very good correlation between the two modes used, with only December showing a significant difference on both figures and July showing differences only on the total deposition figure. The former corresponds to rain frequently occurring in the south west of the area during December 1985 and enhancing the deposition in source mode relative to points mode. The latter is due to deposition over the south east, arising

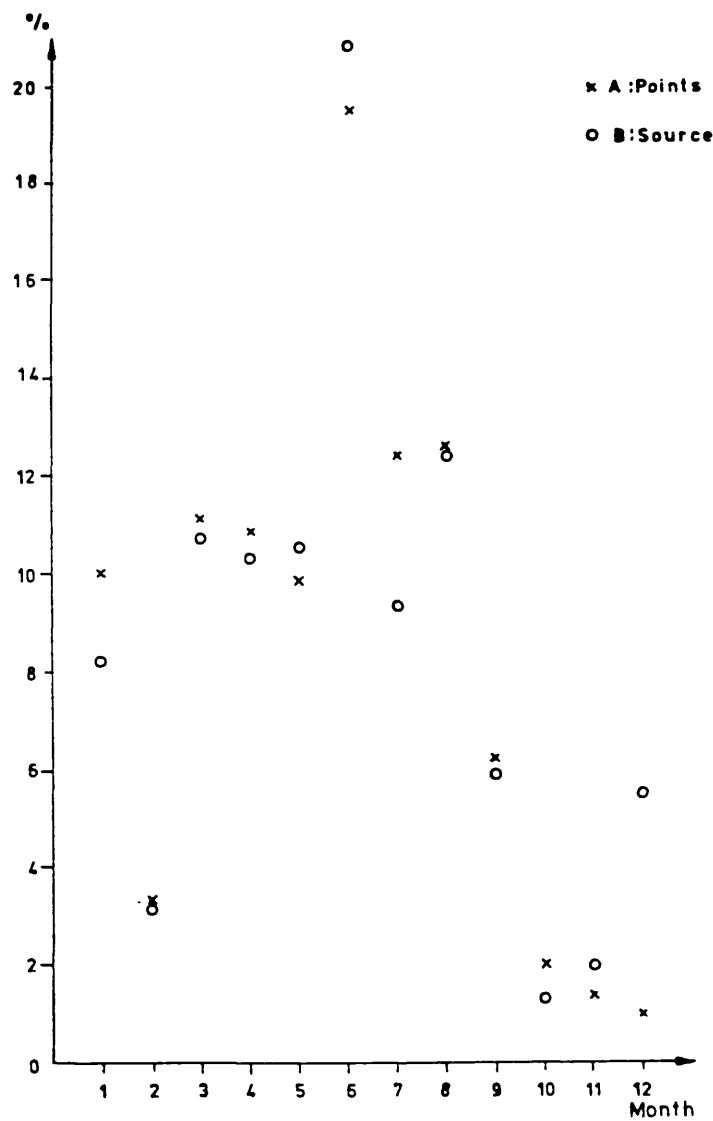


Figure 8.7. Total deposition per month as a percentage of the total deposition for the year.

from rain which did not extend to the release site and consequently did not contribute to source mode deposition.

The third comparison was a direct analysis of the two total deposition patterns for the year. These were divided into a number of rings centred on the release site. The bearing to the cell containing the maximum deposition within each ring, that deposition level and the mean level of deposition within each ring were determined and are shown in table 8.3.

Table 8.3. Analysis of deposition levels within rings about the release site.

Ring position	Maximum deposition level	Maximum deposition direction	Mean deposition
km	units km ⁻²		units km ⁻²
Points mode			
0 – 20	20.0	350°	4.52
20 – 50	7.5	347°	1.26
50 – 80	4.4	359°	0.38
80 – 120	1.7	055°	0.18
120 – 160	1.2	030°	0.16
160 – 200	0.6	031°	0.10
200 – 250	1.0	058°	0.12
250 – 300	0.8	058°	0.09
300 – 350	0.2	077°	0.02
Source mode			
0 – 20	17.3	257°	3.94
20 – 50	9.1	356°	1.12
50 – 80	5.6	074°	0.48
80 – 120	2.1	008°	0.26
120 – 160	1.2	003°	0.15
160 – 200	1.2	003°	0.12
200 – 250	0.9	087°	0.12
250 – 300	0.9	087°	0.11
300 – 350	0.3	087°	0.09

In practice they were of little use, owing to the maximum deposition in the more remote rings often occurring in one of the remote areas of higher deposition and so not being representative of the general statistical pattern. The mean deposition values were also frequently biased due to the incomplete analysis rings at the greater ranges, resulting from the release site being positioned towards the edge of the grid.

In conclusion, the significant differences between source and points mode meteorological sampling, identified in chapter six for individual runs, are not so apparent at the high levels of deposition when long series of runs are summed together. The significance of this will be discussed in section 8.7.

8.6 ANALYSIS OF THE DEPOSITION DISTRIBUTIONS

The most obvious feature of the distribution is that the areas of higher levels are predominantly to the north of the release site. This is surprising. Rain occurs most frequently in Britain associated with frontal systems which normally arrive from the Atlantic. Therefore a significant westerly component would be expected in the rain-bearing airflows (see figure 8.1), giving a deposition distribution with some easterly bias.

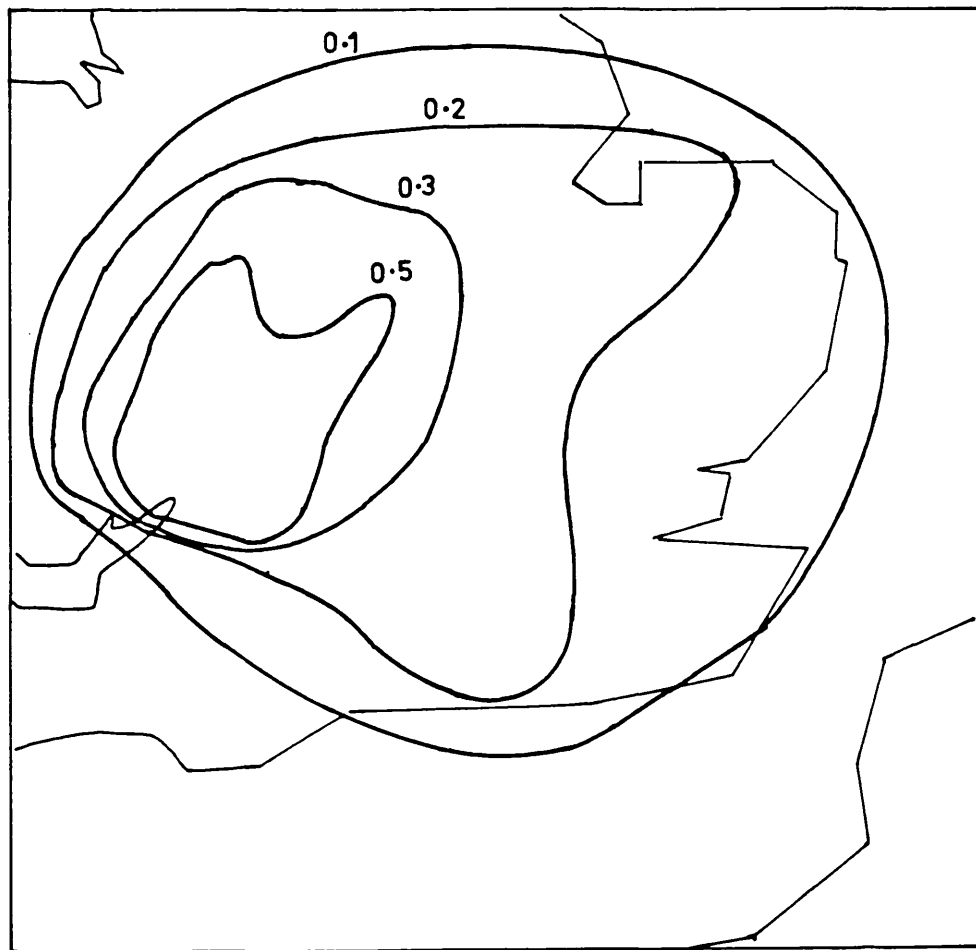


Figure 8.8. Smoothed points mode whole year distribution.

An easterly bias is more apparent at the lower contour levels in points mode. This can be seen most clearly in figure 8.8, which shows smoothed contours for a number of levels. These contours have been produced by hand with the intention of removing the more obvious individual release effects in the distribution and giving an approximate range for each level in each direction. The method employed in doing this can be seen by comparing the 0.1 and 0.5 unit km^{-2} contours of figures 8.2a and 8.8.

The lack of an easterly bias with the high contour levels is thought to be a consequence of topography. Much of South Wales, which lies immediately west of the release site, is very hilly. Therefore rain-bearing winds from the south west will flow up the Severn Estuary but swing northwards as they pass these hills. Consequently, since these airflows will bring the majority of the rain, deposition will frequently occur to the north of the site.

This local effect will be apparent in both modes, but will also account for the difference between the two modes, further from the site. This is due in source mode to the local northward swing affecting the trajectories over the whole grid area.

8.7 CONCLUSIONS AND FUTURE WORK

The similarities, near to the release site, between the source and points meteorological sampling mode deposition distributions are easily explained. Since the data locations being sampled are close to each other initially, the rain intensities and wind velocities obtained would not be expected to differ much, on average, between the modes. This is especially true of the wind data, which is provided from a very sparse grid of measurement locations. The rain data will show, on any occasion, variation over a shorter range but effects due to this can be expected to disappear when averaged over a year. Therefore, close to a power station, the consequences of an accidental release can be assessed using meteorological data from the station only. This is the current technique.

At greater distances, differences between the two distributions become apparent. This has already been partially attributed to the backing of south-westerly airflows due to Welsh topography. Clearly other similar local wind conditions will be missed by source mode, together with spatial changes in the pattern of precipitation, thereby giving adequate cause for the differences in the distributions.

The differences between the points mode distribution and that which could be produced using a plume model, as described in chapter two, for the same set of releases would probably be larger than the differences between the two RAIN-PATCH model modes. This would arise because of the problem of the very high levels of predicted deposition when rain initially occurs in a plume model due to the lack of along wind dispersion. This was described in chapter two. Consequently individual releases would be even more apparent in a distribution produced using a plume model.

An obvious consideration is the distance out to which source mode gives an acceptable match to points mode. This will correspond to the distance over which the average characteristics of both wind and rain do not change from those of the source. A major factor in this will be topography, which affects both wind and rain, and consequently will make the acceptable maximum distance for source mode site-dependent. From the distribution presented a distance of a few tens to perhaps one hundred kilometres could be deduced but further analysis would be required to confirm this.

The points mode distribution for the year, figure 8.2, is surprisingly ragged in appearance. It is formed from the summed deposition from 299 releases spanning the year. This was expected to give a somewhat smoother distribution, at least in the vicinity of the release site. The raggedness arises for two reasons. First, some individual releases give regions with very high levels of deposition which are still apparent even in the total year's distribution. This accounts for the raggedness at the greater ranges from the source. The second reason is that there is possibly a directional preference for deposition near to the source. This could again be a consequence of topography,

and an examination of the correlation between occurrence of rain and wind direction at the release site would be useful in ascertaining if this is indeed the case.

Despite the raggedness in the contours of figure 8.2, a smoother version has been produced in figure 8.8, since this would be most useful in assessing risk. This ignores any possible wind/rain correlations as mentioned above and is very approximate. A smoother initial distribution would give more confidence in the smoothed version and this could possibly be obtained using more releases, which would consequently increase computing costs.

Once obtained there are still a number of questions concerning the accuracy of the distribution. Inaccuracies in the trajectories would be expected to be minimised by the averaging over the year. Although, as mentioned in chapter six, improvements in the calculation of trajectories would be very beneficial, of greater concern is the accuracy of the rain data. This is constantly calibrated using a number of telemetry rain gauges which should make any inaccuracies at least comparable with other uncertainties in the modelling, for individual runs. However, for the statistical distributions, consistent under or over estimates of intensities in an area should significantly bias the results. This could be corrected by using a correction distribution for the whole grid, based on the ratio of the total rain falling in each cell in the year as measured by the radar, and a distribution obtained from all the rain recording stations within or near to the grid area. This distribution could be a linear interpolation between the measuring sites but with corrections for topography. Since measuring locations tend to be in valleys for ease of access they do not always well represent rainfall on higher areas. For example, the feeder-seeder mechanism (Browning and Hill 1981) which enhances rain intensities at ground level over hills would not show up at many measurement locations. It would, however, be possible to determine correction factors for this.

Errors in other factors, such as washout coefficients, will also lead to accumulative errors in the distributions. Ideally other methods of calibration should be used to correct for these, but this would not be so straightforward.

The departure of 1985 from the average year in terms of total rainfall, as discussed in section 8.2, could also be corrected for in a similar way. This could be done monthly, seasonally, or for the whole year by adjusting the levels of deposition according to the discrepancy between total rainfall occurring during the period and the expected value for this. Either correction values averaged over the grid or a distribution calculated from local values could be used. This would need to be done with some care since it makes no allowance for departure from the average in other factors, such as wind direction, which could be equally significant.

This preliminary analysis has outlined the potential of the direct use of radar measured rain data in siting studies. Clearly, however, work still needs to be done to ensure that calculated deposition distributions do not suffer any avoidable bias which could be introduced by the data. This will entail a number of predominantly meteorological studies as outlined above. Once this is complete, RAIN-PATCH could be used to generate distributions around a number of sites. In particular, one on the east coast, for example Sizewell, and a south coast site such as Dungeness, would form a useful comparison with a corrected distribution for Berkeley. These should show interesting differences due to the varying rainfall characteristics which occur around Britain. It would also be useful to obtain a year's data for a true west coast location to compare with Berkeley.

Producing distributions by summation of separate release distributions is, however, expensive. 299 RAIN-PATCH runs were used to produce each distribution presented here and possibly more would be required to produce acceptably smooth results. An alternative approach would be to use a selection of RAIN-PATCH produced distributions to devise a parameterisation scheme which could be used to provide distributions for other sites. This would need to incorporate at least the effects of wind/rain correlations and

the effects of topography on the final distribution. If such a scheme proved possible, deposition distribution could be calculated directly from existing meteorological data or obtained by direct calculation from radar derived total rainfall data.

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CHAPTER 9.

SUMMARY AND FUTURE WORK

9.1 SUMMARY

The first part of this work consisted of case studies which used the one dimensional analytic washout model. These studies used various configurations of rain intensity and pollutant distributions to show the importance of considering the small scale structure and mobile nature of rain in calculating wet deposition. Of particular importance was the comparison between the deposition distribution obtained from the model for the simple situation, where a band of rain overtakes a pollutant cloud, and the distribution from a Gaussian plume model for the same situation. A marked difference was shown in both areas and levels of deposition, which, when related to the 25 mSv 'emergency reference level' for dose using hypothetical pressurised water reactor accidents, gave significantly different population dose consequences.

The greater part of the work involved the development and use of a two dimensional numerical washout model known as RAIN-PATCH. It was undertaken to extend the simple one dimensional analysis to two dimensions and to make it more realistic, by using real meteorological data. Rain intensity data measured by weather radar was available which was used directly in the calculation of wet deposition within the model.

After the construction of the model, optimum values for the parameters required in its use were identified. Where possible, these were obtained from the literature, but otherwise they were identified by analysing the effects of varying the values of the parameters, one at a time, over series of model runs. From this it was calculated that the model is reliable in its prediction of the areas over which deposition occurs, but the actual levels of deposition within those areas have a greater uncertainty. This has been taken into account during the subsequent use of the model.

The initial two dimensional case studies confirmed the conclusion from the one dimensional studies; that for acceptable deposition results, rain intensity data local to the dispersing material should be used in calculating washout. Additionally it was apparent that the variation in rain intensity over the dispersing material could also be significant. Subsequent case studies examined the timing of the passage of the dispersing material by modelling releases separated by relatively short time periods of up to a few hours. A selection of sequences of precipitation data was used, each containing a rain system of interest. The small shifts in release time could result in very different deposition distribution patterns. This was a consequence of the structure within the rain system and was also apparent from the modelling of the passage of the Chernobyl cloud across England and Wales.

Deposition distributions for Cs-137 and I-131 were obtained from the modelling of the Chernobyl cloud. To achieve this the RAIN-PATCH model was extended to use a composite grid of data made up from all five operational weather radars. The timing of the passage of the cloud of material was calculated from air concentration time sequence data from a number of sites within the UK. The distributions obtained were in good agreement with measured data, in particular they identified the high levels of deposition over NW England and North Wales. This study therefore served as *encouraging support* not only of the model, but also of the technique in calculating wet deposition directly from radar measured rain intensity data.

The final study was an analysis of the possible use of the model in power station siting studies. To achieve this two probability distributions of wet deposition were produced. Each consisted of the combined deposition from a series of 299 modelled releases, spread throughout 1985, from a site within the area covered by the London radar. As part of this work an almost complete record from the London radar for the whole of 1985 had been compiled. One of the distributions consisted of deposition calculated from rain data at the source of the release and the other used data at the position of the dispersing material. It was concluded that using a distribution based on

the meteorological conditions at the proposed site, an adequate distribution was given on which to base the risks to populations within no more than 100 kilometres of the site. However, at greater distances, the limited spatial scale of rain and topographical effects made it important to use data local to the dispersing material in calculating such risks.

In conclusion, this work has identified the need to consider the spatial structure on the smaller scales and the mobile nature of rain systems in the modelling of wet deposition. Due to the fortuitous availability of rain intensity data, measured by weather radar, it has proved possible to develop a model which incorporates these properties of rain. A result of this has been to carry out a number of studies using the model which would not previously have been possible.

9.2 FUTURE WORK

Possible extensions to the so far limited use of the model in power station siting studies have already been described in section 8.7. Other possible areas of further work include improvements and extensions to the model and the development of a 'real-time' version of the model. A real-time version would use radar and other meteorological and radiological data as it was recorded, or soon after, and would be intended for immediate post-accident analysis.

The first area in which the existing model could be improved is the calculation of puff trajectories. A simple linear interpolation between a number of mean hourly surface wind velocity readings has been used in the calculation of puff trajectories in all except the Chernobyl work, where geostrophic trajectories were calculated. The linear interpolation scheme is not considered to be very accurate and an improved scheme would greatly enhance the model's accuracy. One option would be to calculate trajectories from wind fields produced by a forecasting model.

The model may be extended to allow for the different rates of washout which occur with different rain systems. This could take the form of a parameterisation scheme based on analysis of the dynamics and microphysics of

rain systems. If this were the case, a scheme to classify the types of rain system within the radar measured data would also then be required. Other refinements, such as permitting diurnal variation of the boundary layer height, with consequent losses of material from the boundary layer, and the inclusion of the chemical processes involved in the dispersion phase of acid deposition, could also be undertaken, but these would greatly add to the complexity of the model.