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Simulation of The Radioactive Plume over Europe Following the Chernobyl Incident

by

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1 Introduction

1.1 General

The UK Meteorological Office's operational Nuclear Accident Model 'NAME' is used to simulate the transport and dispersion of airborne pollutants over long ranges (typically >100km). It provides estimates of both instantaneous and time-integrated air concentrations of pollutant together with estimates of the accumulated deposition of pollutants to the ground by both wet and dry deposition processes.

As with any model, validation against observed data is vital for testing model accuracy. Due to the scale and nature of the problem, very few good test cases are available. The unfortunate Chernobyl incident, where large quantities of radioactive material were injected into the atmosphere over a period of 10 days following the failure of a nuclear power plant at Chernobyl in the Ukraine, is one of the few test cases available for validating long-range dispersion models. Since the incident a great deal of information has been collected and published describing the spread of the radioactive plume, which eventually covered much of Europe, and the associated deposition of radioactive material to the ground. Unfortunately there remains some uncertainty in the source term, i.e. how much radioactivity was released, and at what times.

Based on the available data a comparative study between a number of long range dispersion models was undertaken in 1989 as part of the 'Atmospheric Transport Model Evaluation Study' or ATMES. An early version of the NAME model was included in the study. Unfortunately the results from the NAME model were disappointing. The model generally underestimated air concentrations and associated depositions to the ground. One of the key problems was identified as being the way in which boundary layer depths were calculated. Full details of the ATMES comparison and NAME results can be found in [1], and a discussion of the boundary layer problem in [3].

Since 1989 the NAME model has undergone a number of significant modifications and improvements, and the Met Office has become a Regional Specialist Met Centre (RSMC) with international responsibilities for predicting the spread of radioactive material in the event of a release into the atmosphere. It was therefore decided that a second validation study against the Chernobyl data would be desirable and of benefit.

1.2 The Chernobyl Incident.

At the time of the accident, at 0123 local time on 26th April 1986 (or late on 25th UTC), a depression lay across W and central Europe with a high over NW Russia. Thus the radionuclides were released into a SE'ly drift, and were carried steadily NW across Belorus and NE Poland to the Baltic Sea. By 28th/29th April a frontal system associated with the depression lay over S Scandinavia, with a consequent washout of radionuclides over Central and S Norway and Sweden. The plume itself split three ways at this time, some material passing NW over Norway to Iceland and the N Atlantic, some NE across Finland and Arctic

Russia, and a third tongue pushing SW between a ridge of high pressure building NE across W Europe and low pressure now over the Balkans.

This finger accounted for considerable wet deposition over Austria and surrounding regions, and pushed a tongue S of the Alps across N Italy. A movie of the NAME simulation suggests that this material 'burst' through or over the Alps about 1st May, to be engaged and swung N by low pressure approaching Europe from the W. Material reached Britain early on 2nd May, crossing the S coast and pushing N, with wet deposition taking place where the plume was intercepted by rather showery rain on and ahead of a cold front associated with the depression. The plume was largely washed out, with 'hot spots' over N Wales, the Isle of Man, the Lake District, and parts of S, W and central Scotland. According to the simulation some diffuse material later moved back across the UK from the W after looping around the low pressure areas in the Western Approaches, but there is little observational confirmation of this.

Most of the activity reaching W Europe was released in the first day or so of the incident. The later emissions drifted E over the Ukraine and Russia, and more persistently S over the Black and Aegean Seas, Turkey, Greece, and across the E Mediterranean to Egypt.

2 The Current Operational NAME Model

Details of the NAME model can be found elsewhere [2], so only a brief summary is given here. The release of pollutants is modelled by releasing large numbers of 'particles' into the 'model atmosphere', and allowing each of the particles to be carried along passively by the ambient three-dimensional wind flow (i.e. the model is of the Lagrangian type). On-line forecast or analysed wind fields and other meteorological data are obtained from the Global and Regional versions of the UK Meteorological Office's numerical weather prediction model (the Unified Model). Forecast data is available to 144 hours for the global model and 36 hours for the regional model. In addition, ten day rolling archives of analysed data are available for both versions. Vertical data is obtained at 10 η levels, up to $\eta \approx 0.3$ (where η is the vertical coordinate used in the Unified model).

Boundary layer depths are calculated from unified model vertical wind and temperature profiles using one of two techniques. The usual method [3] is to take the maximum of a Richardson number (the model level at which the Richardson exceeds a critical value, set at 1.3) and a parcel method (the level at which the dry adiabatic lapse rate curve followed from a near-surface temperature intersects the environmental lapse rate curve). An alternative 'sigma' based technique is sometimes used [4], this estimates the boundary depth by using the potential temperature gradient and windspeed at successive heights to determine a stability parameter which is correlated with the Gaussian dispersion parameters (σ_x,σ_y). The boundary level top is defined at the point where the square root of the product of the Gaussian dispersion parameters drops below a critical value determined empirically from observations.

The boundary layer is assumed well mixed. Turbulent diffusion in the horizontal is allowed for in the NAME model by randomly displacing the particles at the end of each 15 minute 'timestep', using a suitable diffusivity, while vertical diffusion is handled simply by randomly reassigning the height of each particle within the boundary layer at each timestep. Thus each particle tends to experience a mean boundary layer wind over a period of time. Above the boundary layer, in the free troposphere, both horizontal and vertical diffusion are much reduced, and are handled using the random displacement method. A more detailed description and account of the performance of the diffusion scheme is given in [11].

A mass of pollutant is associated with each particle at release. This mass is then depleted as time passes to represent various depletion processes including wet and dry deposition and, for radioactive plumes, radioactive decay. Wet deposition is dealt with in the conventional way, being taken as proportional to the current concentration times an empirical power law of rainfall rate. NAME has comprehensive facilities for handling rain, snow, convective, dynamic or orographic precipitation, together with a high-resolution archive of radar rainfall imagery, but for the most part they could not be applied to the data available for the Chernobyl simulation.

Dry deposition is computed from a standard deposition velocity formulation, at present using a constant value for each species. Turbulent deposition of pollutant taken up in low cloud (or hill fog) droplets is parametrised in a similar fashion to dry deposition, but using a suitably adjusted deposition velocity (a value related to the 'turbulent 'deposition of momentum).

The model output consists of instantaneous and time-integrated air concentrations based on the Unified Model global and/or regional grids in six vertical 'slabs', the lowest representing the boundary layer. Accumulated wet and dry deposition fields are also generated on the same horizontal grids. When available, high resolution wet deposition fields are also output.

3. Data Used in the Chernobyl Simulation

3.1 Meteorological Data

Wind, temperature and pressure data were obtained from ECMWF, as UK Meteorological Office Unified Model data are incomplete for that period. The ECMWF global model analyses covered the period 25 April 1986 to 10 May 1986, with a six hour time interval, a spatial resolution of 1.125 degrees in both longitude and latitude, and covering the area from 81W to 40.5E and 29.25N to 90N. The available data included the three wind components and temperature at the lowest 9 full η levels (the lower half of the atmosphere, up to $\eta \approx 0.5$), together with surface winds, temperature and pressure.

Precipitation covering the same time period was supplied by KNMI in the Netherlands. The data consisted of six hour accumulations of precipitation (rain and snow combined), on a grid of resolution of 1 degree in longitude and 0.5 degree in latitude, covering a smaller area of 40W to 40E and 35N to 70N.

3.2 Interpolation to the NAME Grid

The ECMWF data was interpolated onto the Unified Model regional grid for input to the NAME model as follows:

(i) All horizontal data fields, both surface and model level, were bi-linearly interpolated horizontally to the unified model regional grid, with temperature, pressure and vertical velocity being interpolated to the regional 'temperature' grid, and horizontal wind components to the regional 'wind' grid.

(ii) At each 'wind' grid point the horizontal wind components (u and v) were linearly interpolated in the vertical to the NAME full model levels. Similarly, the vertical velocity component was interpolated to model half levels. For NAME levels above the available ECMWF data values were set to those of the highest available level.

(iii) Units were converted, including:

- horizontal wind components based on North/South and East/West components (in m/s) to regional grid based components (in knots);

- vertical velocity from dp/dt, where p is pressure and t is time, to $\dot{\eta}$ (per second) using

$$\dot{\eta} = \frac{dp}{dt}\left[\frac{1}{p_*} + \left(1 - \frac{p_0}{p_*}\right)\frac{\Delta A}{\Delta p}\right] \quad (1)$$

where p_* is surface pressure, p_0 is defined as 10^5 Pa, p is pressure and A is defined for each η level ($\eta = Ap_0 + B$). ΔA and Δp were calculated for a given half level from values of A and p at adjacent full levels.

Precipitation data were similarly interpolated bi-linearly onto the regional 'temperature' grid. Note that the precipitation data area only covers a portion of the ECMWF data area.

3.3 Source data

Estimates of the quantity of radioactive material emitted into the atmosphere over time were taken from the original ATMES technical specification document and are shown in Table 1. It was assumed that material was released from ground level up to the quoted centre of plume height. Particles were distributed pro-rata in the NAME levels within this depth. From 24 hours after the start of the release the quoted centre of mass height is 600 m or less, which implies that all the material was injected into the lowest NAME level (i.e. η=1 to 0.9303, i.e. up to 600 m). However, it was felt that some of the hot radioactive material probably penetrated into higher levels, and so 20% of the particles were released in level 2 (η=0.9304 to 0.8698).

4 NAME MODEL SIMULATIONS

4.1 Base Case

The current operational regional version of the NAME model was used to predict the spread and deposition of the two main radionuclides released, Caesium 137 and Iodine 131, for a period of 228 hours (9.5 days) from the initial time of release (taken as 0000GMT on 26 April 1986). Instantaneous air concentrations and accumulated wet and dry depositions were output every 12 hours (at 0000 and 1200 GMT). Output data were dumped to a local workstation to facilitate data analysis and plotting.

The main modifications required to the model were to the data accessing routines, in order that the meteorological data could be read from the interpolated files, which were in a non-standard form. Minor changes were also required for the model to operate with a time interval between data of 6 hours rather than the usual 3 hours.

A 'base case' simulation was defined with inputs of:

(i) a diffusion coefficient of 10,000 m^2s^{-1}: the spread is proportional to the square root of the diffusivity;

(ii) 600 particles/hour release rate throughout the simulation;

(iii) a release profile as defined in section 3.3;

(iv) default boundary level calculation, i.e. the maximum of a parcel and critical Richardson number method with a minimum boundary level of η=0.98 (approx. 160m); and

(v) standard wet deposition with no orographic corrections (no high resolution rainfall data were available).

4.2 Base Case Results

Figure 1 shows the predicted spread of the plume for Cs-137 at 48 hour intervals starting 60 hours after the initial release, and Figure 2 shows the calculated total deposition (i.e. sum of dry and wet deposition) to the ground for the same times. The crosses indicate locations where detailed comparisons of concentration as a function of time were made with observations.

Initially the simulated plume heads north-west towards S Sweden before being split three ways as discussed in Section 1.2. The largest component moves slowly towards central Europe, crossing Poland, S Germany, Czechoslovakia and Austria. High depositions occur along the direction of the initial plume and over Southern Sweden and Norway. The movement SW to N Italy and the spread to the UK is well simulated. By this stage high depositions have occurred in rainfall over southern Germany, Austria and Czechoslovakia. By T+204 hours the plume has spread over most of the UK , with the wet deposition over Scotland, NW England and East Anglia well shown. Further material from Chernobyl has also spread S over Greece and the E Mediterranean. By T+204 hours activity has accumulated over most of Europe, with only Denmark and Spain escaping with minimal amounts. The overall patterns for the spread and deposition for Iodine-131 were very similar.

This qualitative picture is in good agreement both with observations and previous model simulations [e.g. 5, 6 & 7]. Figure 3 shows the modelled cumulative deposition of Cs-137 at T+228, the end of the simulation, together with the ATMES contour plot of measured cumulative deposition and a map of the measurement locations used in generating the deposition plot. Given the coarse resolution and omissions of the 'measured' data the match is fair. Where observational data is available, the model has correctly identified the main areas of high deposition, i.e. central Norway and Sweden, around Austria, and northern Greece. The predicted values of deposition show reasonable agreement over Scandinavia and central Europe, but are low over Greece. This may be due to there being further deposition over Greece after 5 May 1986, the end of the simulation.

For a more quantitative comparison, Figures 4&5 show a series of concentration versus time plots for a number of locations spread through Europe comparing model predicted values with observed data, with Figure 4 showing the plots for Cs-137 concentrations and Figure 5 showing those for I-131. Care should be taken when making direct comparisons between the model and observed data as the observed data corresponds to a wide range of sampling times (from a few minutes to 24 hours) at differing time intervals, whilst the model concentrations are instantaneous calculations with a time interval of 12 hours. Also shown for comparison are the model data obtained by applying a smoothing filter (5x5 grid cell block average) to the air concentration data. This reduces large local variations in concentration due to low particle densities, as well as showing where 'near misses' have occurred.

Inspection of the Cs-137 concentration versus time data shows a number of features:

(i) for most of the locations the model has been reasonably successful at predicting the first and subsequent arrivals of the plume;

(ii) following the onset of high concentration values at a given location and time, the observed concentrations often remain higher for a longer period of time than predicted by the model. This could be partly explained by resuspension of radioactive material following the passage of the main plume [8];

(iii) bearing in mind (ii) the general patterns of model concentrations versus time are in reasonable agreement with the observed data;

(iv) smoothing the data leads to an overall improvement in the match, implying excessive local variations in the predicted concentrations due to too low a particle density, and perhaps too low a plume 'spread';

(v) the match between absolute concentration values is variable, with the model both over- and under-predicting concentrations depending on location, but overall the model seems to have underestimated air concentrations.

The results for I-131 are very similar, though predicted concentrations seem a little lower relative to observed data. This suggests that Iodine was depleted too quickly, possibly due to too high a dry deposition velocity. Insufficient deposition data is available for Iodine-131 to determine whether calculated depositions are too high.

4.3 The Plume Over the United Kingdom

Smith and Clark [9] have made a detailed study of the passage of the Chernobyl plume over the UK and the subsequent patterns of deposition. Figure 6 shows their best estimate of the position of the radioactive plume between T+144 (0000Z on 2 May 1986) and T+220 (1800Z on 4 May 86), and Figure 7 shows the corresponding model simulation. Considering that the plume reached the UK some seven days after the start of the release (and analysis of the model particle trajectories shows that the part of the plume that crossed the UK originated from the first day of release), the match between the model and observed plume is surprisingly good. The model correctly shows the plume initially crossing the south-east coast early on the 2 May 1986 before sweeping north-westward over England and North Wales. The model boundary layer plume then decays rapidly as it crosses into Scotland, largely due to wet deposition. Peak concentrations in excess of $5Bq/m^3$ are predicted over the South which matches reasonably well with 'observed' peak values in the region of $10Bq/m^3$.

Figure 8 shows a contour map of the estimated total deposition of Cs-137 over the UK following the main passage of the plume, based on analysis by the Institute of Terrestrial Ecology, also shown is the model predicted total deposition (wet and dry) of Cs-137. Whilst lacking in detail the model has correctly identified the main areas of high deposition; the north-west and to lesser extent East Anglia. The lack of detail is not surprising given the coarse resolution of the meteorological data (e.g. winds and rain) used in the model.

4.4 Potential Sources of Error

Whilst the model has successfully predicted the overall development of the Chernobyl plume, and identified many of the areas of high deposition, there remain significant differences between the model predictions and observations. A number of potentially significant sources of error can be identified, which can be split into those specific to the situation being modelled and those generic to the NAME model itself.

4.4.1 Errors specific to the situation

(i) A key limiting factor to the Chernobyl simulation is the available meteorological data. The ECMWF analysis data originated from a global model with a horizontal resolution of 1.125 degrees, and a time interval of 6 hours rather than the usual 3 hours. Many smaller synoptic features will have therefore been poorly resolved, and the low resolution may also have resulted in poorly defined boundary layer depths [12,3]. Similarly, the precipitation data was of a low spatial resolution (1 by 0.5 degrees), again only available at 6 hour intervals, and containing no information about precipitation type (e.g. rain/snow or convective/dynamic). Another problem is that data were only available for the lower half of the atmosphere, up to an η value of ≈ 0.5. Analysis of particle positions indicated that some particles were advected to this level even by T+132 hours, thus in the later stages of the simulation a significant number of particles could not be advected correctly.

(ii) Interpolating the meteorological data onto the limited area grid will have degraded the data further, with smoothing in both the horizontal and vertical. In particular this may have been a problem in calculating boundary layer heights from vertical temperature and wind profiles, as temperature and wind gradients at the boundary layer top will have been smoothed out to some extent. Adapting the NAME model grids directly to the available data would have overcome this problem, but it was felt that this would have required too many changes to the model.

(iii) Inspection of the air concentration plots shows 'patchy' areas of large local variations in concentrations, mainly due to low particle densities. This is a particular problem in the later stages of the simulation, where sections of the plume have been highly dispersed. An example is the plume over the UK on days 7 and 8, which originated from just part of the material released on the first day. A number of individual particles can also be seen over the Atlantic.

(iv) There is considerable uncertainty in the source terms, both in the quantity of radioactive material released and the vertical profile of the release with time. Air concentrations and depositions will be directly related to errors in the quantity of material released, but the effect of uncertainties in the release profiles will be more variable. Material released too high will be transported in high level winds with less dispersion and little or no interaction with the ground near the source; and material released too low will be depleted too rapidly by dry and possibly wet deposition processes, especially if boundary layer depths are underestimated. The uncertainty in the total amount of material released has been quoted as up to a factor of two [1].

(v) Inconsistencies in the observed data are possible, as the air concentration measurements come from a wide variety of sources using a range of measuring techniques and sampling times.

4.4.2 Model Errors

The main areas of the model which are likely to have the largest impact on the accuracy of the model predictions for Chernobyl include:

(i) Boundary layer depth - the correct estimation of boundary layer depth is critical for the correct simulation of plume dispersion and for dry deposition to the ground. Whilst much improved since the first ATMES test, the correct calculation of boundary layer depths remains a potential problem for models of this type. One particular problem in

the Chernobyl simulation is that night time boundary levels are being defaulted to the minimum level (η=0.98 or 160m for the base case). As the deposition velocity is inversely proportional to the boundary layer depth this can result in high depletions by dry deposition for particles in the night-time boundary layer. In addition the spread of the plume may be reduced as dispersion is lower above the boundary layer [see the discussion in 11].

(ii) Dry deposition - dry deposition is parametrised here using a fixed deposition velocity for each species. In reality the deposition velocity will depend on the boundary layer conditions, surface characteristics, time of day, and the nature of the species (e.g. particle size distribution). This may have caused either over or underestimates, depending on location and time in addition to the difficulties discussed under (i).

(iii) Wet deposition - due to their complexity a full and complete description of wet deposition processes is not yet available. At the time of these integrations, no distinction could be made between convective and dynamic rain; furthermore, depletion of mass was applied over a fixed depth from the surface to η=0.8, and no account could be made for enhanced deposition over hilly areas (orographic enhancement). Exactly where and when this parametrisation will lead to under or over-estimates in deposition is difficult to say, but errors will certainly be compounded in the later stages of the simulation and where rain areas have intercepted the plume.

(iv) Diffusion - limitations in the diffusion scheme, which is based on a fixed diffusivity, may lead to errors in the shape of the plume, especially near the source. The results indicate that the overall spread of the plume may have been underestimated, although [11] found that the fixed diffusivity could lead to overestimates near the source.

These potential problems do not represent a full or complete list, but are felt to represent the parts of the model that are likely to have caused the largest errors in the simulation. Many of these problems are receiving attention in the development off the next version of the model.

5 SENSITIVITY TESTS

In order to address some of the issues discussed above a further series of simulations were performed to test the model sensitivity against: (i) the number of particles used; (ii) the method of calculating boundary levels and (iii) the value of diffusion coefficient.

5.1 Number of Particles

Figure 9 shows the predicted air concentration fields from a simulation based on a release of 4000 particles/hour rather than 600 particles/hour (used in the base case and the usual maximum for the NAME model). These can be directly compared with the base case air concentration plots in Figure 1. Using such a large number of particles is computationally expensive, the simulation took some 9 hours of CPU time on the Met Office's Hitachi mainframe.

The overall air concentration patterns are unchanged, but using a greater number of particles has clearly 'smoothed' and 'filled in' the fields in areas of low particle density, such as over the UK at T+156, resulting in reduced local variations. Figure 10 compares the resultant air concentration data versus time with observed data for Cs-137 (these can be directly compared with the base case data shown in Figure 4). The overall patterns of concentration versus time are very similar to those obtained in the base case, though there are some differences in the

detail, which probably reflect greater scatter in the 600 particles/hour data. Figure 11, which shows the *magnitude* of the differences in the concentration and deposition fields at T+156, further illustrates the differences between the two simulations. Whilst the difference plots indicate that the overall plume shape and deposition patterns are consistent between the two simulations (there are no large differences at the edges of the plume to indicate different shapes), the 'patchy' nature of the plot shows the effect of too few particles. The effect is less clear in the deposition fields as these represent accumulations over time, and will therefore be smoothed to some extent.

For the Chernobyl simulation these results suggest that 600 particles/hour is a sufficient compromise between accuracy and computational speed for most areas, though more particles are required for maximum accuracy, especially for long range simulations and for detailed local concentrations and depositions. This is broadly in agreement with Maryon [10].

5.2 Boundary Layer Depth Calculations

Three simulations were performed to test the sensitivity of the model to boundary layer calculations. These included: (i) using the 'sigma' method option; (ii) reducing the minimum allowable boundary layer depth to η=0.99 (approximately 80m) rather than η=0.98; and (iii) using a fixed 500 m boundary layer depth. Figures 12 and 13 show the resultant air concentration data using the sigma technique, and Figures 14 and 15 the results for the fixed 500 m boundary layer. These data can be directly compared with the base case results in Figures 1 and 4.

The boundary layer plume appears significantly reduced in area and lower in air concentrations when using the sigma technique; this is borne out by the concentration versus time plots. Inspection of calculated boundary layer depths has shown that this is due to the sigma method returning, on average, significantly lower boundary layer thickness than the default technique (the maximum of a parcel based and Richardson number method).

Reducing the minimum boundary level to 0.99 does not appear to have made any significant differences to the shape of the plume. Similarly, the detailed air concentration versus time data are very similar to those from the base case.

As might be expected, using a fixed 500 m boundary level leads to significantly different plume concentrations from the base case, in some areas concentrations are higher and in others lower; but overall concentrations seem to be lower. However, the total extent of the surface plume is relatively unchanged. These observations are borne out by the concentration versus time plots---the fixed boundary layer plots (Figure 15) are for the most part inferior to the base run of Figure 4.

These tests illustrate the importance of estimating correct boundary layer depths in the NAME model (and Lagrangian dispersion models in general).

5.3 Diffusion Coefficient

To test the sensitivity of the model to changes in the diffusion constant, simulations were performed with diffusion constants of 0 and 5300 m^2s^{-1}(compared to the base case value of 10000 m^2s^{-1}). Figures 16 and 18 show the resultant air concentration plots, and Figures 17 and 19 the resultant air concentration versus time plots.

The main differences are in the near source region, where reducing the diffusion coefficient significantly reduces the width of the plume, resulting in higher air concentrations and

different patterns of wet and dry deposition. However, the subsequent development of the plume is relatively unaffected by the diffusion coefficients. Only careful inspection shows slightly reduced plume spread in some areas. This clearly illustrates that for long range dispersion, the processes of chaotic advection dominate whilst in the near source region it is the turbulent diffusion and vertical shears, especially in the boundary layer [13].

6 SUMMARY AND CONCLUSIONS

(i) The limited area NAME model was used to simulate the spread of the radioactive plume over Europe resulting from the failure of a nuclear power plant at Chernobyl in the Ukraine on 26 April 1986.

(ii) The simulations were based on meteorological data from ECMWF model analyses, and precipitation data from KNMI model analyses. The meteorological data was interpolated horizontally and vertically onto the Unified Model limited area grid. Source term data was based on the ATMES (Atmospheric Transport Model Evaluation Study) specification.

(iii) A good qualitative agreement was found between the model simulations and observed data. In general the model correctly predicted the overall spread of the plume over Europe and identified the main areas of high deposition (mainly in areas of high rainfall). On average the model seemed to slightly underestimate air concentrations, more so for Iodine 131.

(iv) The main sources of error can be split into those specific to the Chernobyl simulation, and those inherent to the model. Those specific to the situation include: the low spatial and temporal resolution of the meteorological data; the loss of detail due to the interpolation of the met data; and uncertainties in the source term and observed data. Sources of error generic to the model include: errors in the calculation of the boundary layer depths and limitations in the wet and dry deposition parametrisations.

(v) Sensitivity tests illustrated the sensitivity of the model to boundary level calculations. The alternative sigma technique returned lower boundary levels, which had a significant effect on the plume characteristics.

(vi) The simulations were relatively insensitive to changes in the diffusion constant used, clearly demonstrating the dominance of chaotic advection as the dominant mechanism of dispersion at long ranges.

(vii) This work has confirmed the need for further development and validation of the diffusion scheme for shorter range problems, the wet and dry deposition parametrisation and the calculation of boundary layer depths.

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From	To	Cs-137 TBq	I-131 TBq	Effective plume centre of mass height(m)	NAME release profile used
0000Z 26/04	0060Z 26/04	4400	38000	1500	level 1:0.45 level 2:0.35 level 3:0.2
0600Z 26/04	0000Z 27/04	17600	152000	600	level 1:0.8 level 2:0.2
0000Z 27/04	0000Z 28/04	7000	55000	600	level 1:0.8 level 2:0.2
0000Z 28/04	0000Z 29/04	5500	41000	300	level 1:0.8 level 2:0.2
0000Z 29/04	0000Z 30/04	4100	28000	300	level 1:0.8 level 2:0.2
0000Z 30/04	0000Z 01/05	3000	19000	300	level 1:0.8 level 2:0.2
0000Z 01/05	0000Z 02/05	3000	17000	300	level 1:0.8 level 2:0.2
0000Z 02/05	0000Z 03/05	5500	28000	300	level 1:0.8 level 2:0.2
0000Z 03/05	0000Z 04/05	6300	30000	300	level 1:0.8 level 2:0.2
0000Z 04/05	0000Z 05/05	8100	35000	300	level 1:0.8 level 2:0.2
0000Z 05/05	0000Z 06/05	8900	36000	300	level 1:0.8 level 2:0.2
0000Z 06/05	0000Z 07/05	110	74000	300	level 1:0.8 level 2:0.2

Table 1 *Estimated source data and vertical profiles used in simulations . (level 1 is from η=1 to 0.930, level 2 from η=0.930 to 0.87 and level 3 from η=0.83 to 0.70) (from [1])*

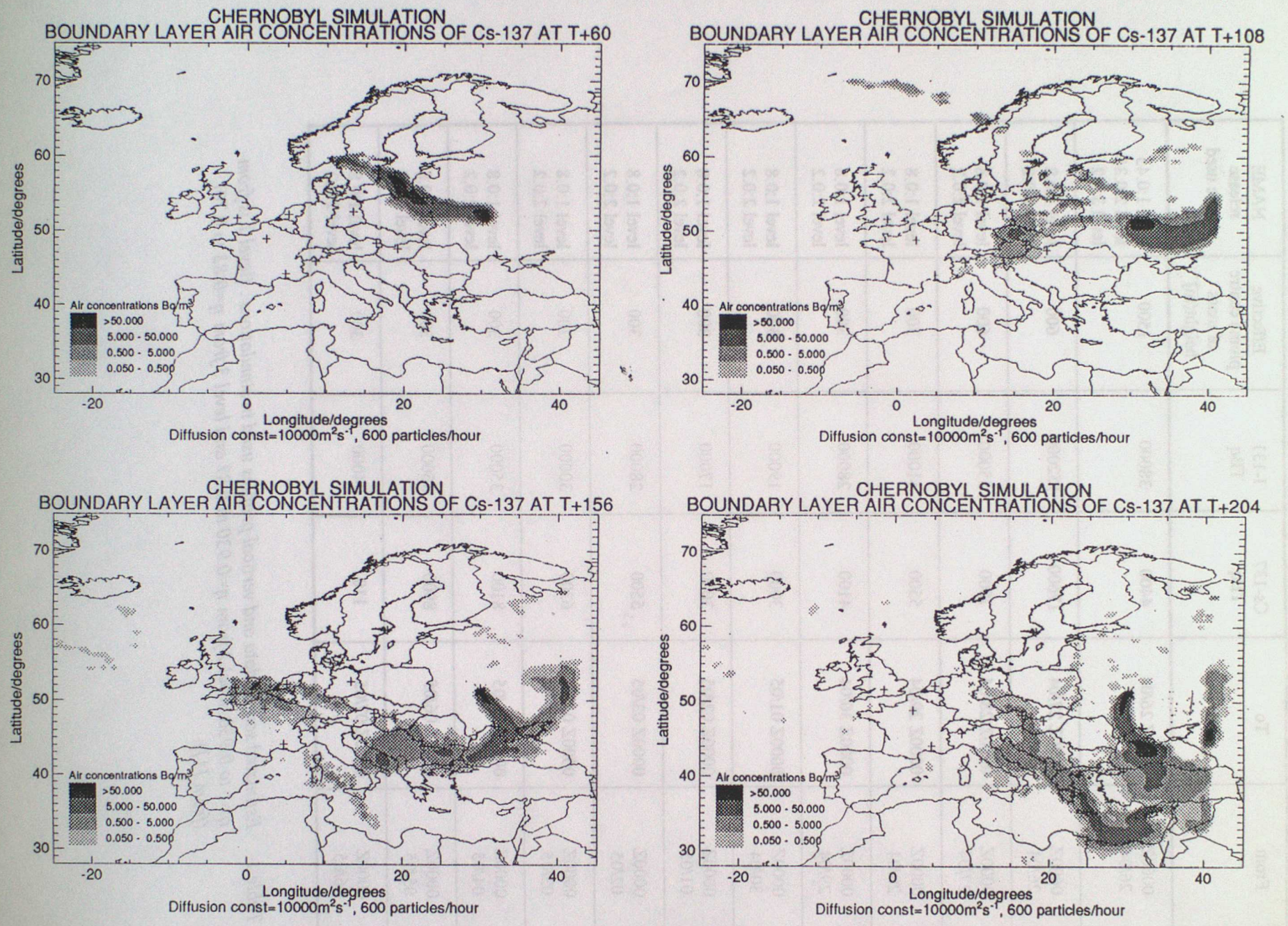


Figure 1 Base case Cs-137 air concentrations

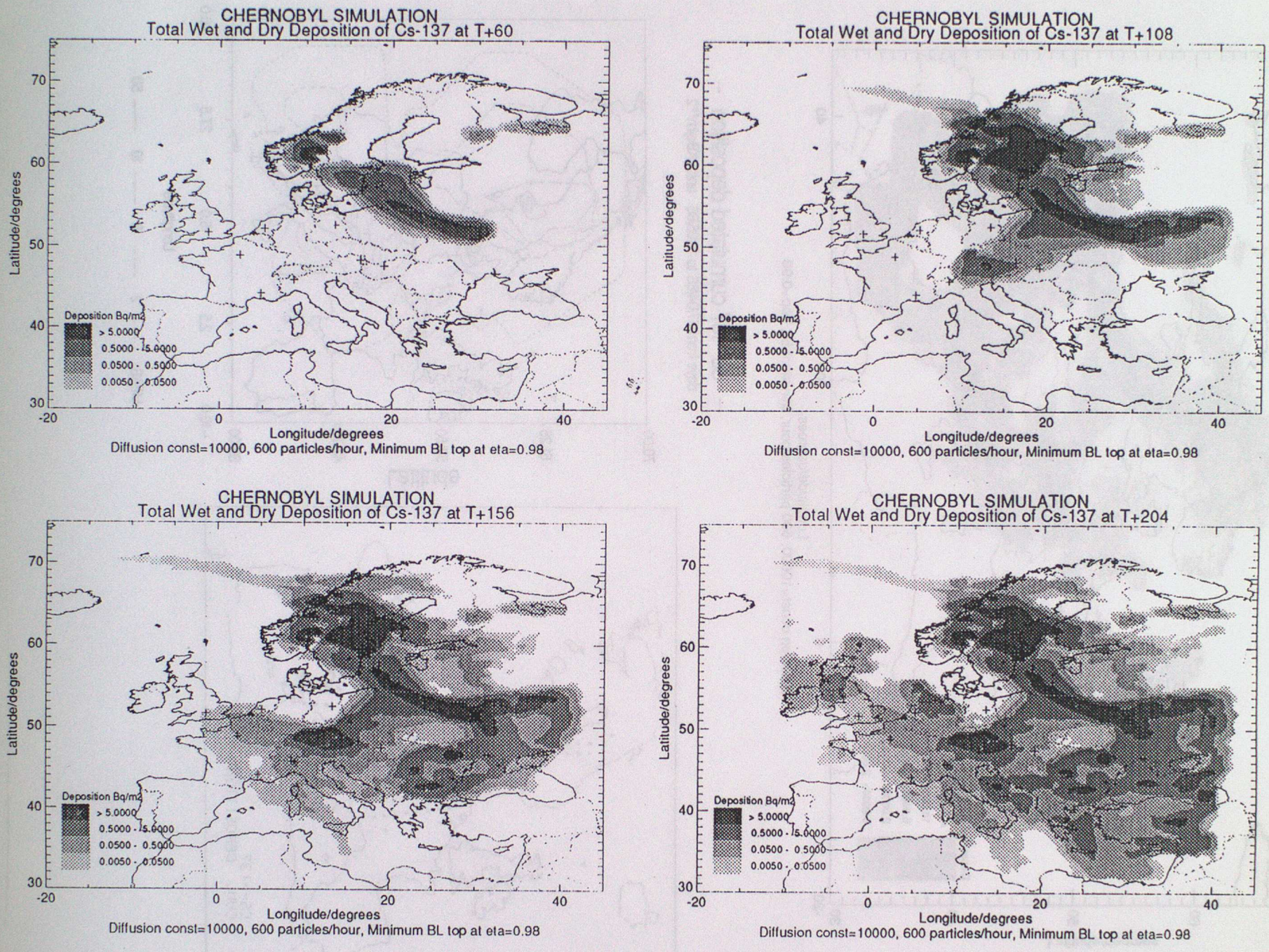
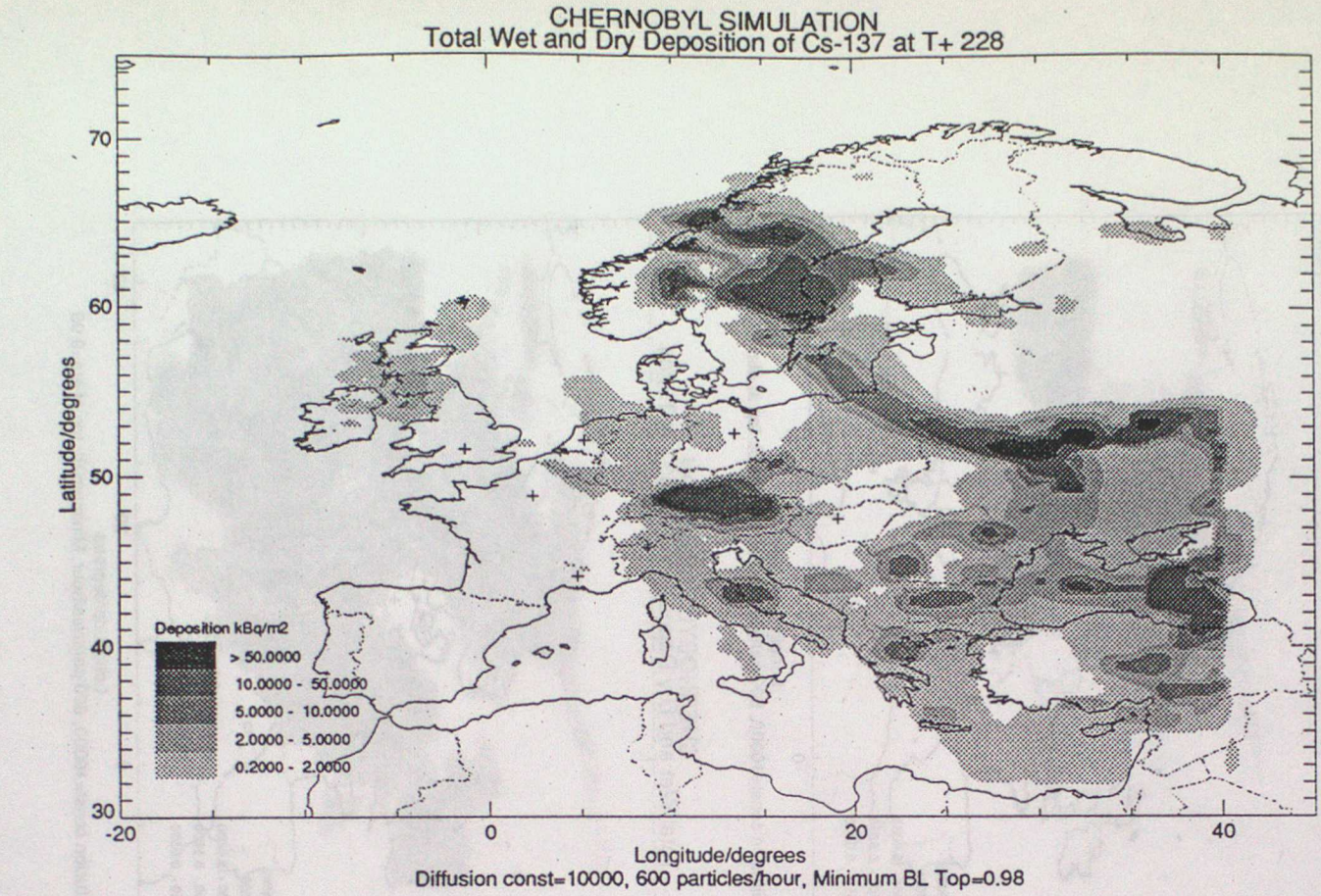
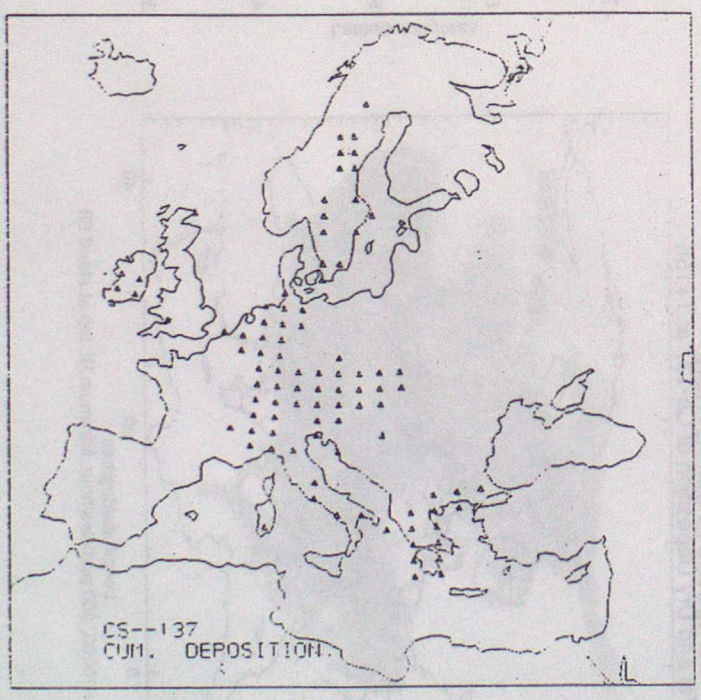


Figure 2 Base case Cs-137 total depositions





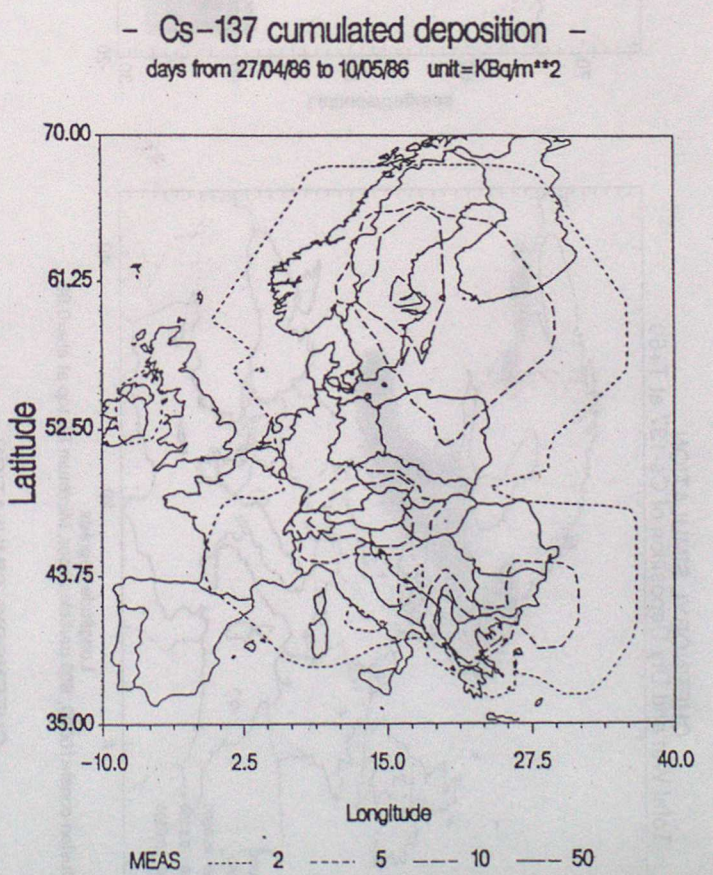


Figure 3 Model predicted total deposition (top), locations of measured deposition (bottom left) and measured deposition contour plot (bottom right) (observed data from [1])

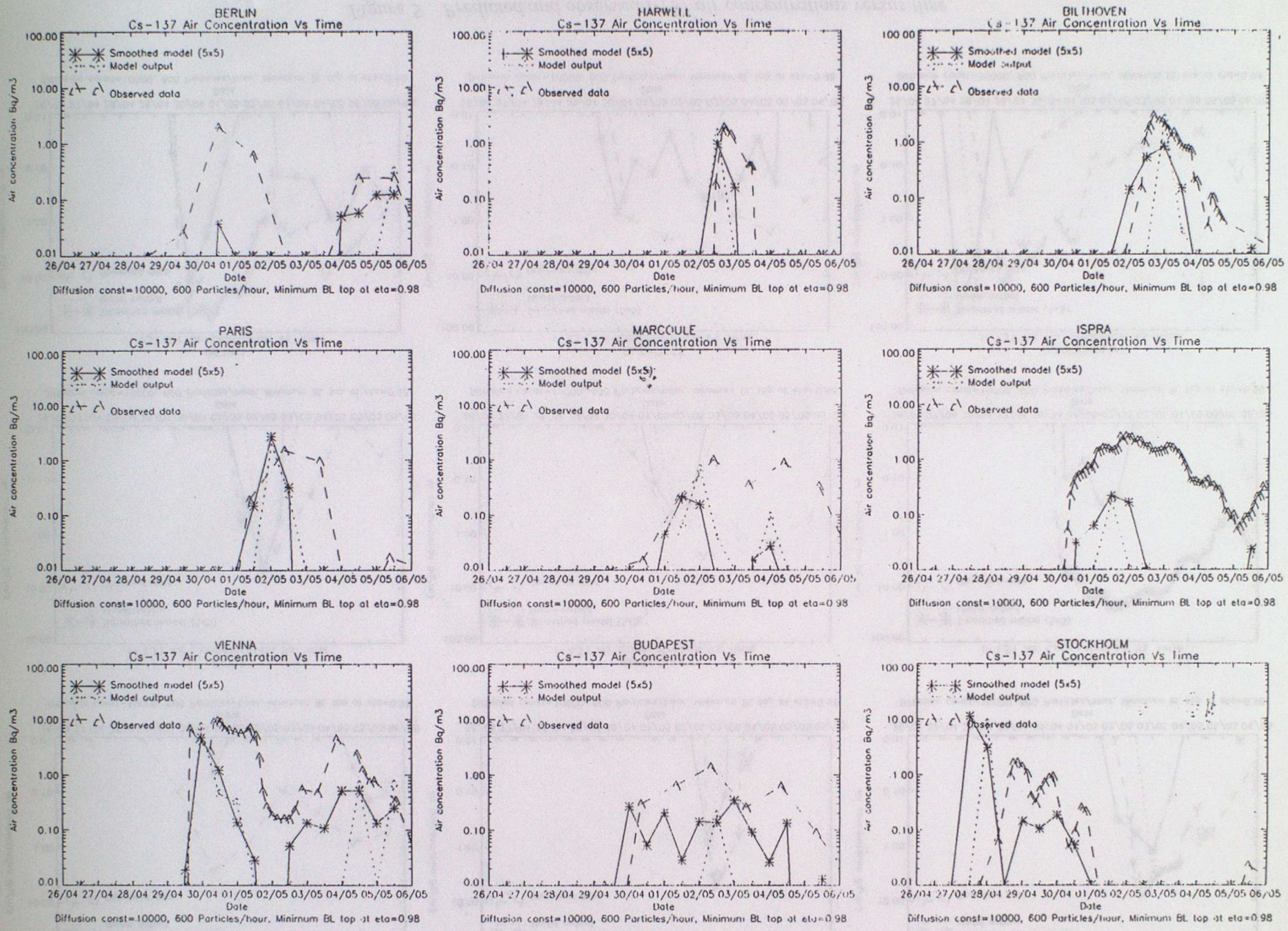


Figure 4 Predicted and observed Cs-137 air concentrations versus time

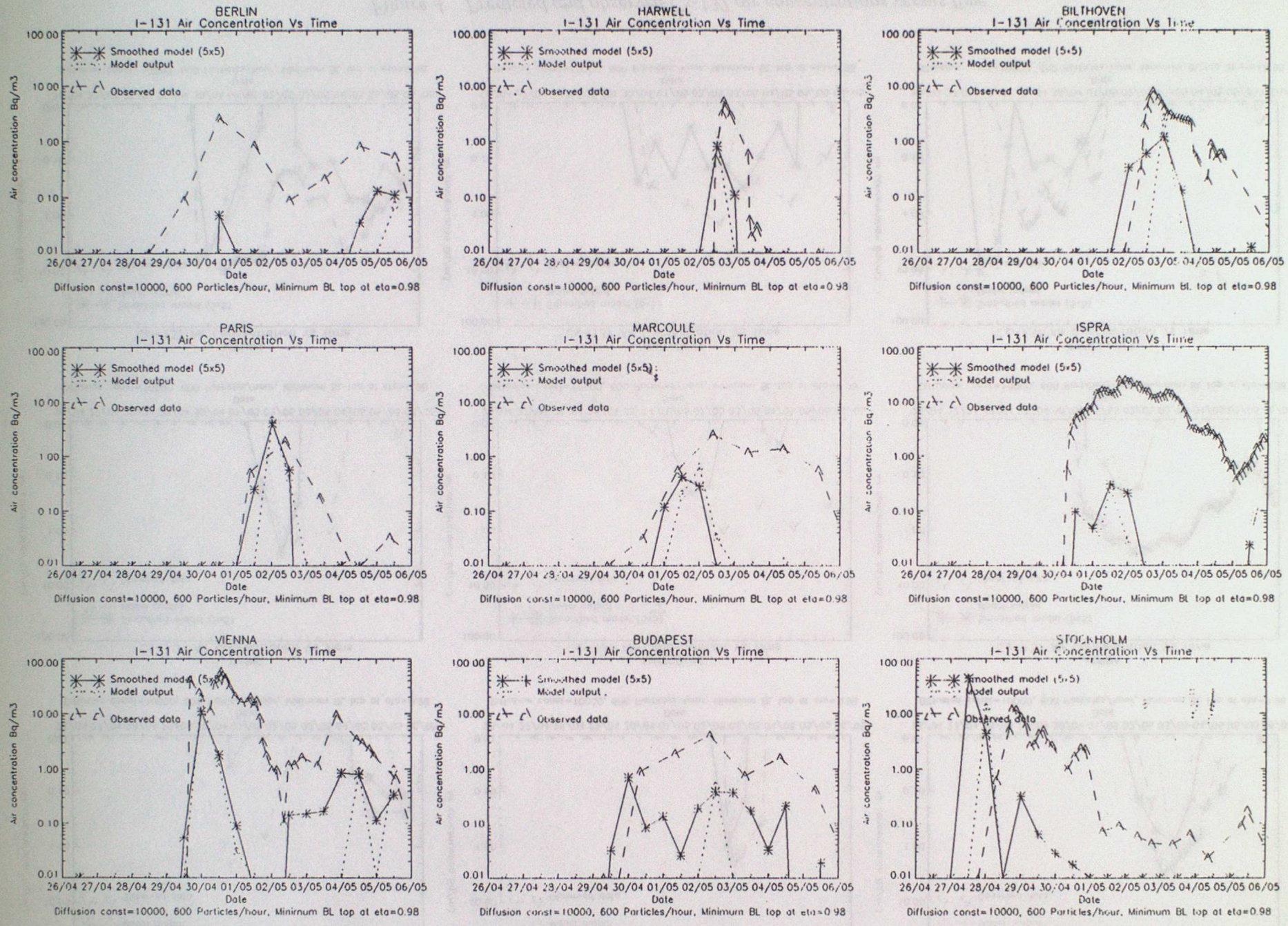


Figure 5 Predicted and observed I-137 air concentrations versus time

Figure 6 Position of the radioactive cloud over the UK. Hatched areas indicate where rainfall was reported. Contours are in Bq/m³ (from [6])

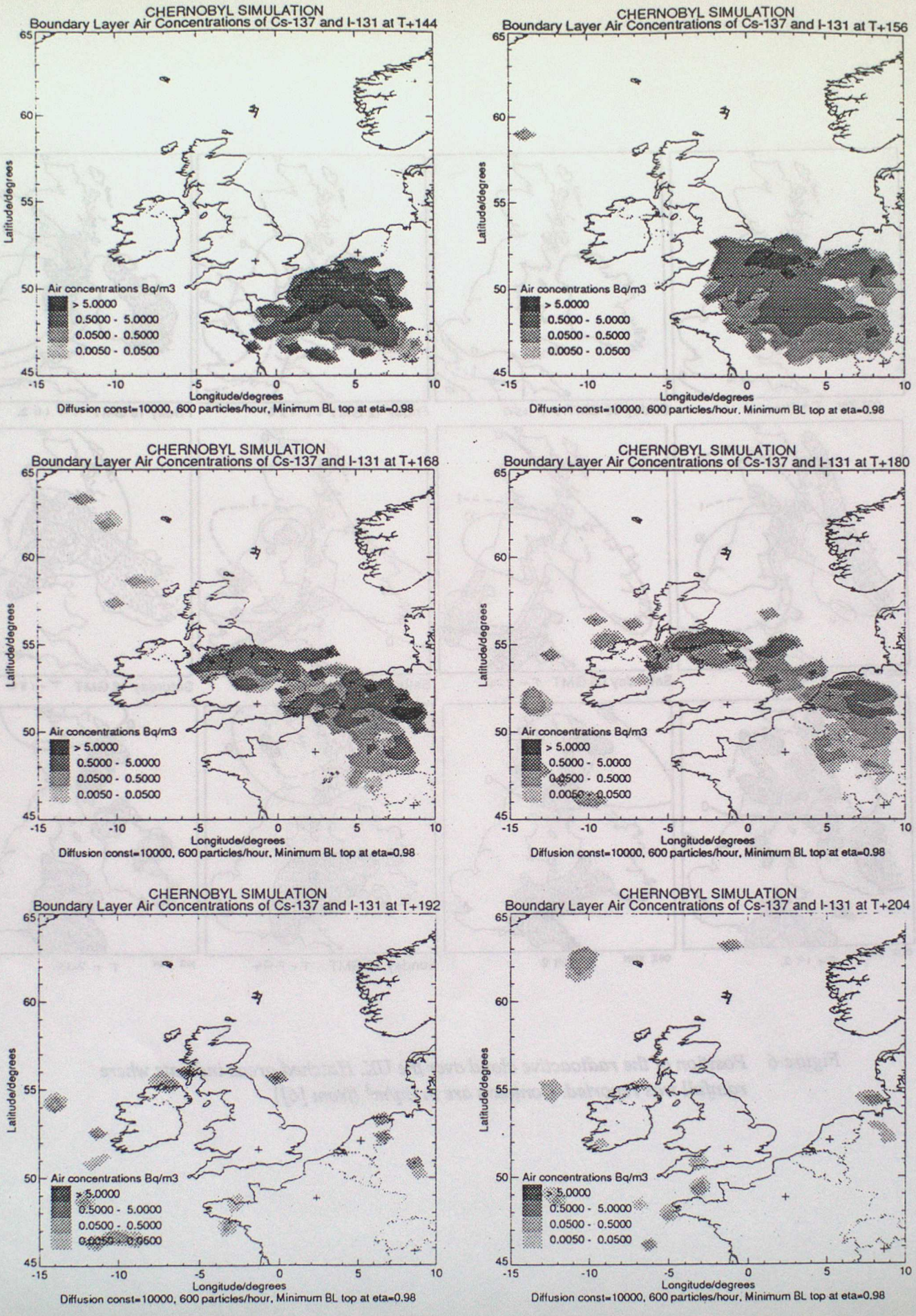
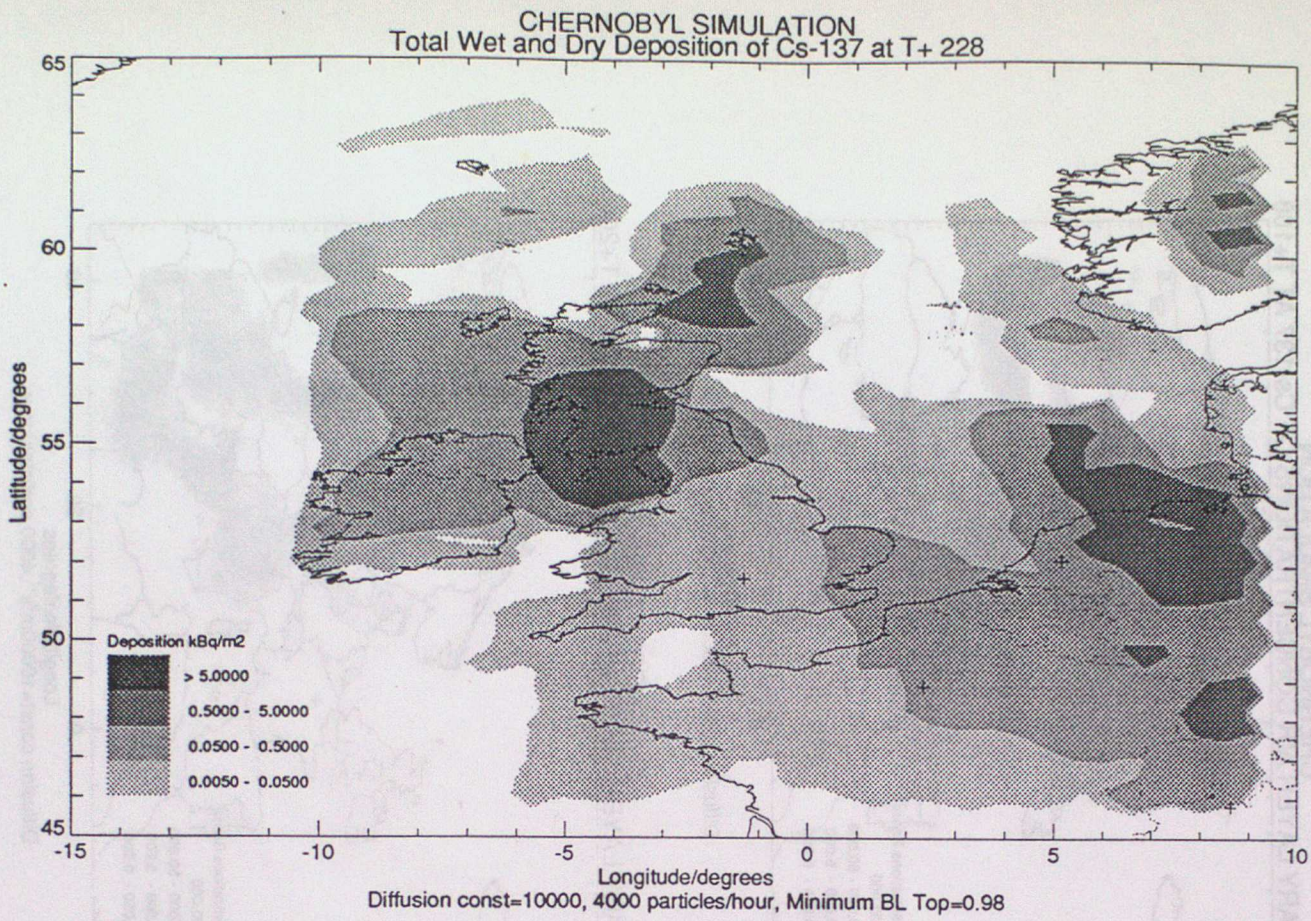


Figure 7 Model predicted positions of the radioactive cloud at various times as shown. Hatched areas indicate where rainfall was reported. Contours are in Bq/m^3.



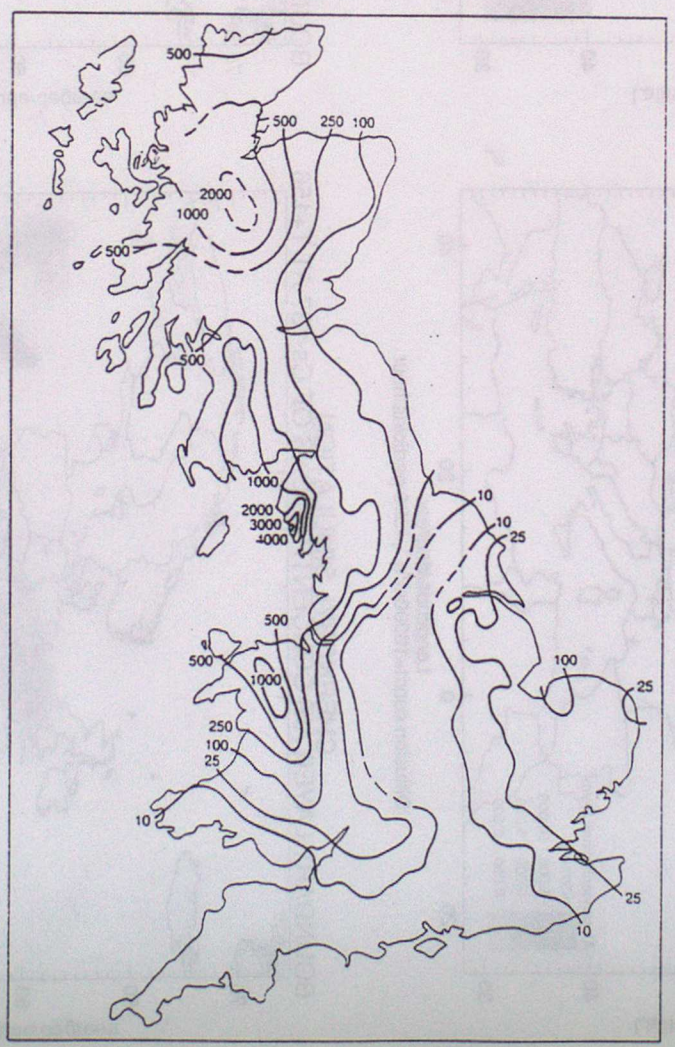


Figure 8 Model (top) and observed (bottom) deposition over the UK. Observed deposition (Bq/m²) based on analysis by the Institute of Terrestrial Ecology (from [6])

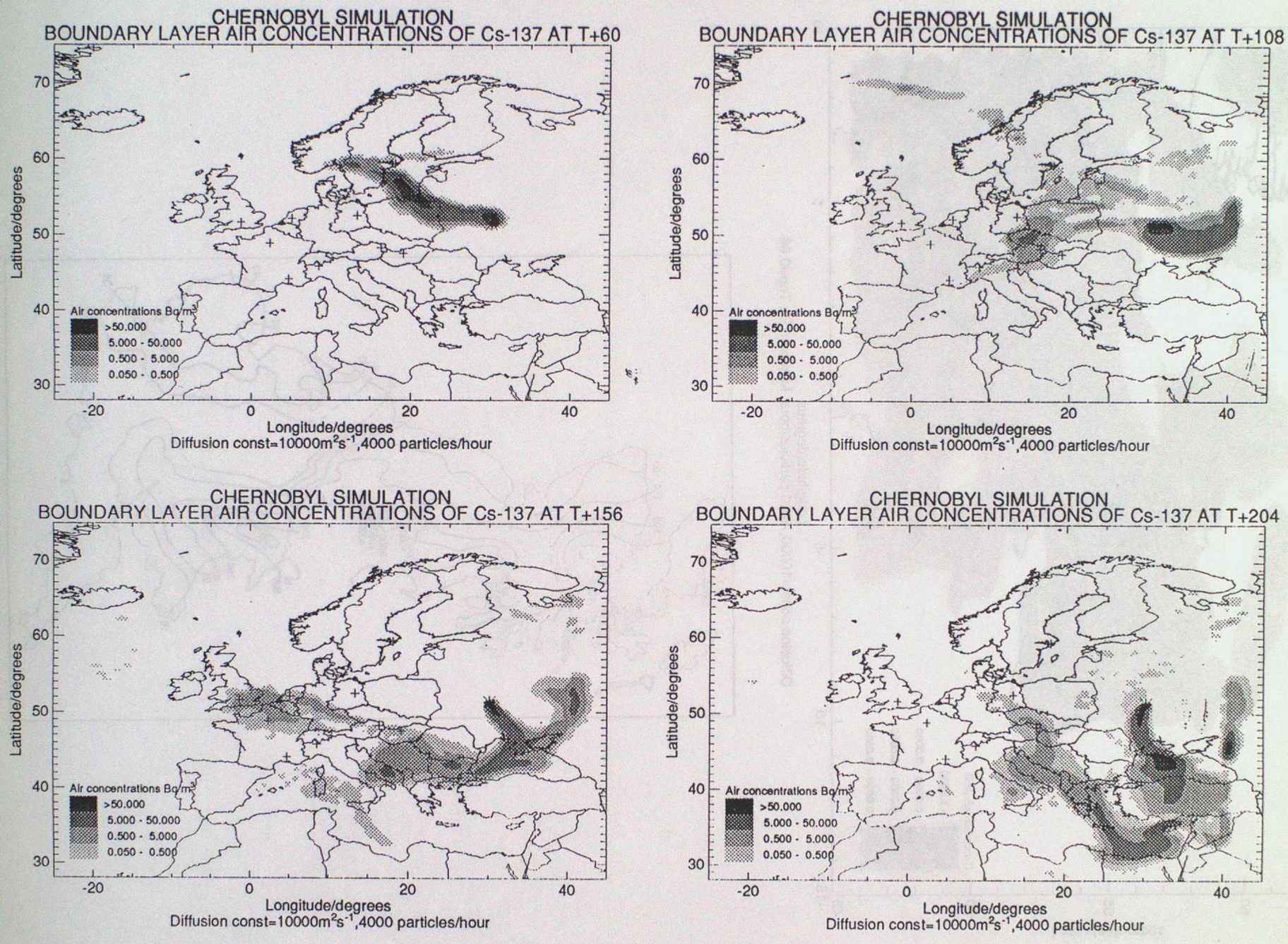


Figure 9 Air concentrations for 4000 particle/hour simulation

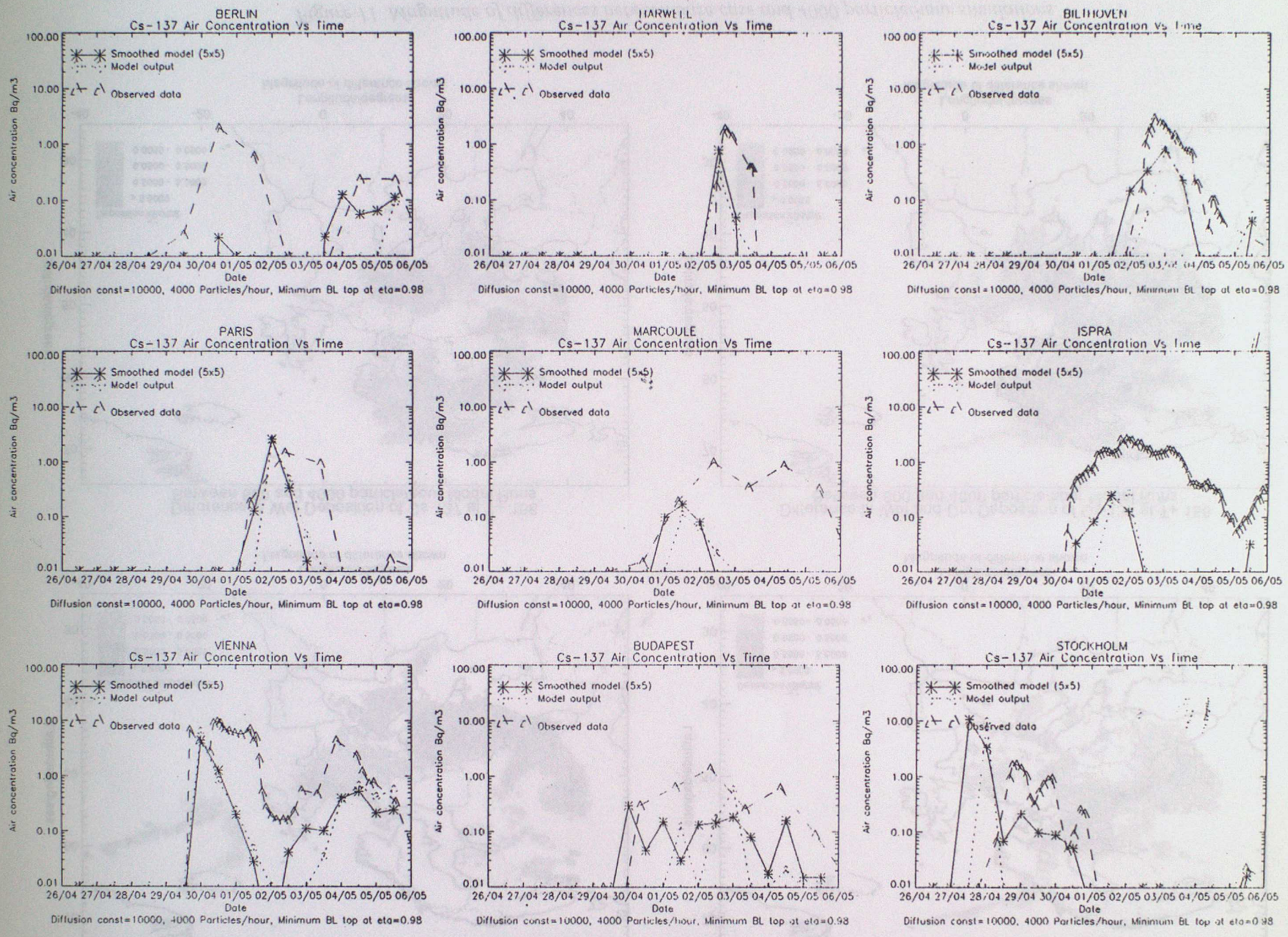


Figure 10 Predicted and observed Cs-137 air concentrations versus time for 4000 particle/hour simulation

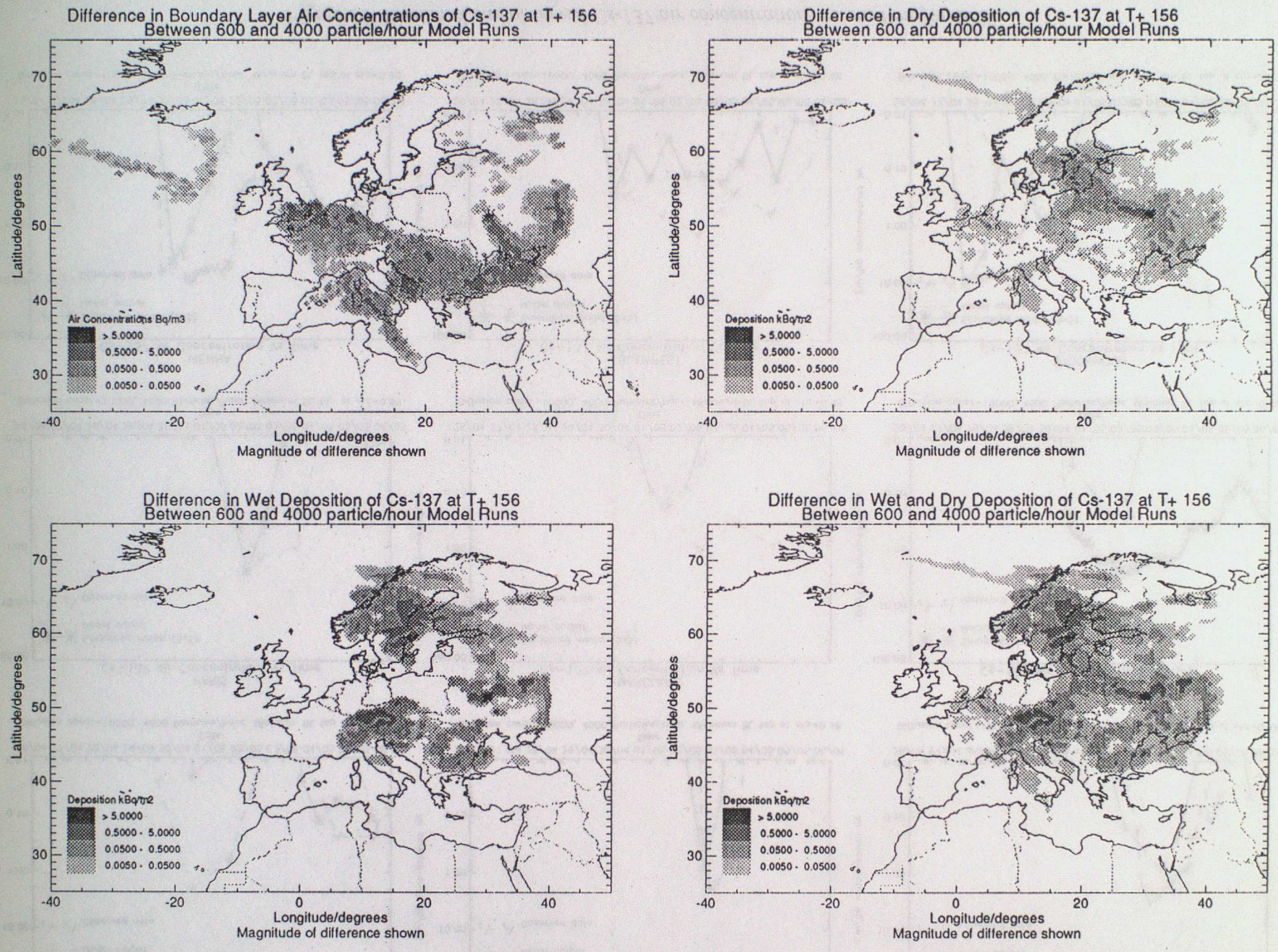


Figure 11 Magnitude of differences between base case and 4000 particle/hour simulations.

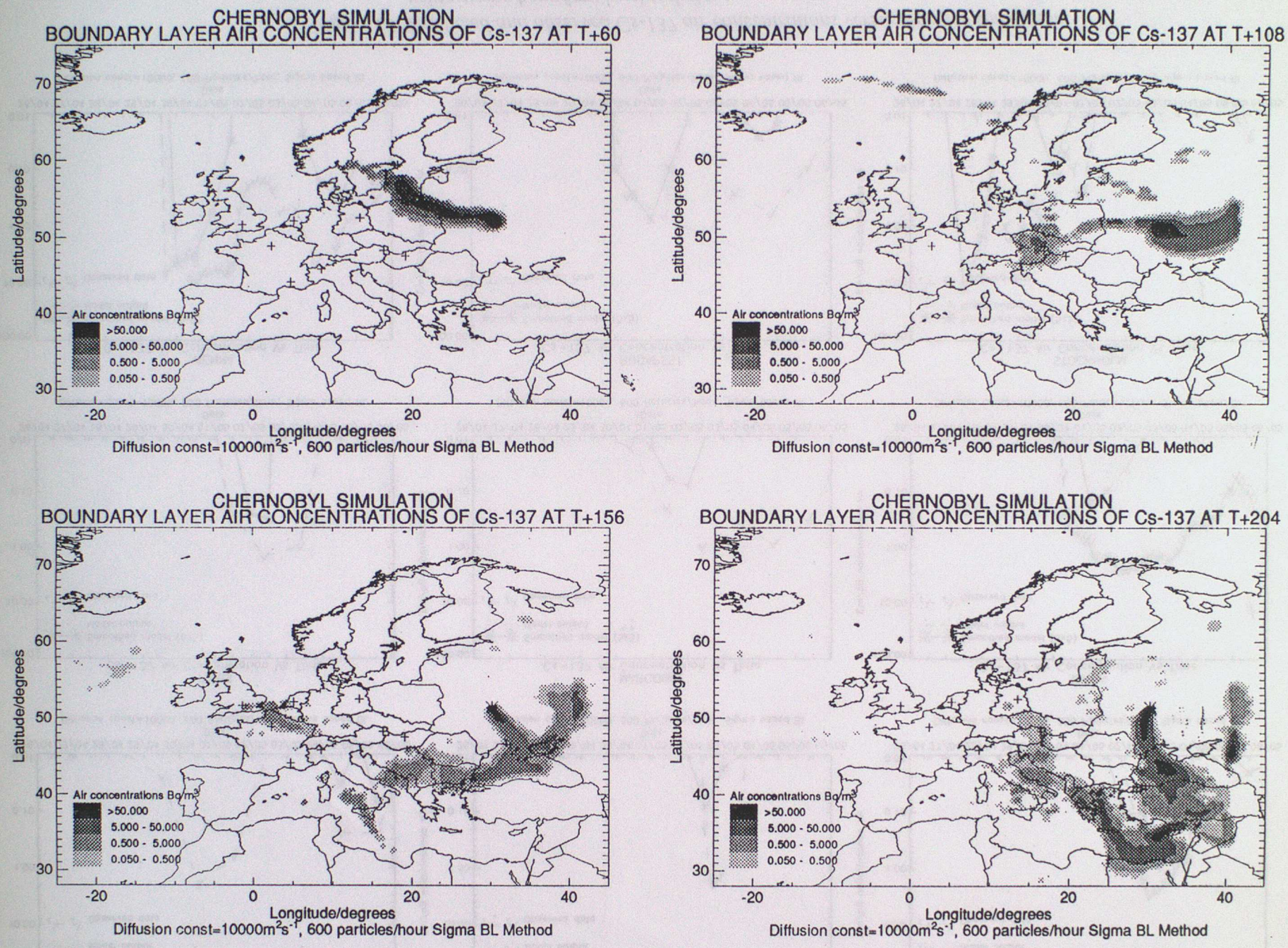


Figure 12 Air concentrations for simulation using sigma boundary level technique

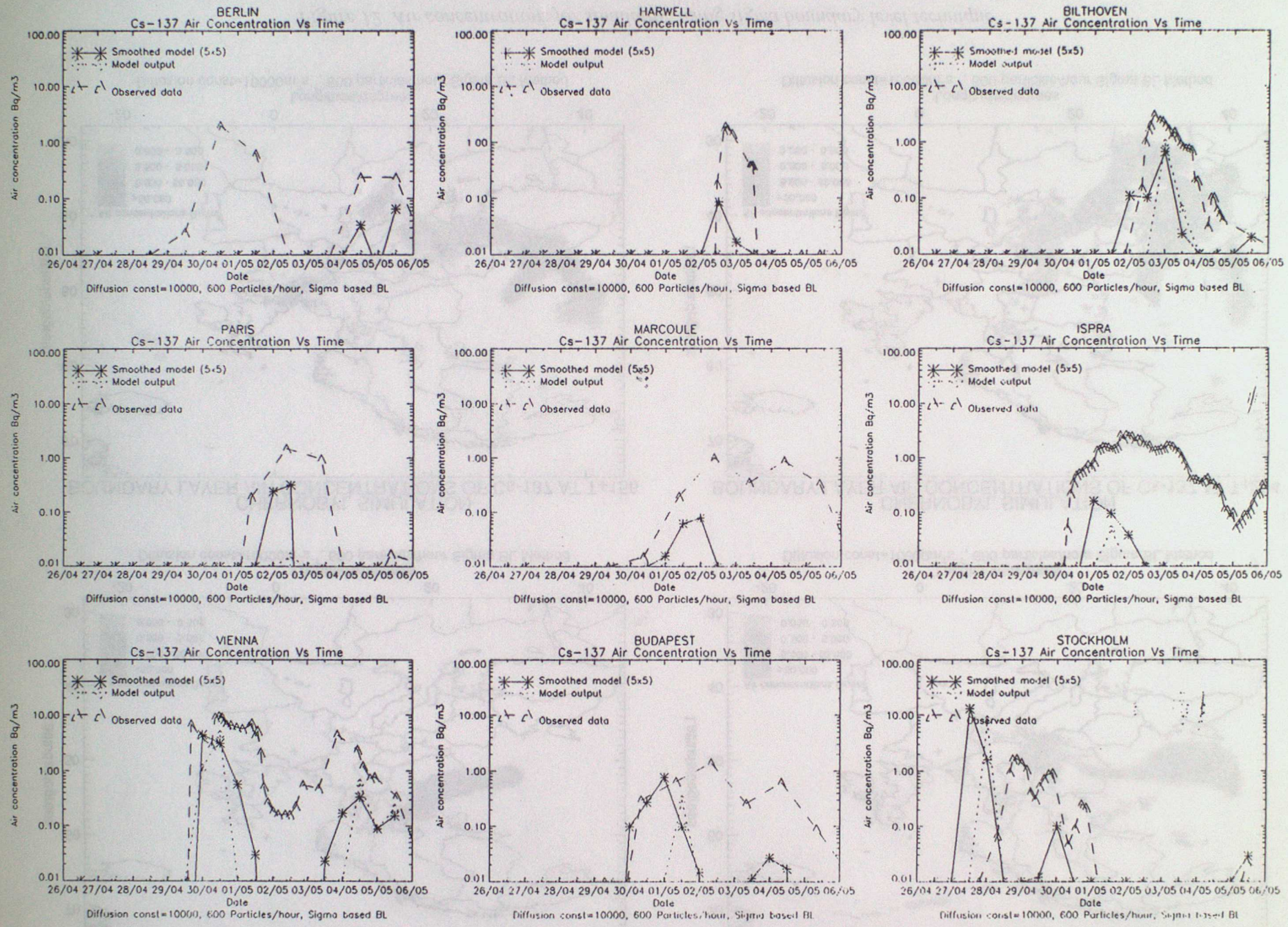


Figure 13 Predicted and observed Cs-137 air concentrations versus time for simulation using sigma boundary level technique

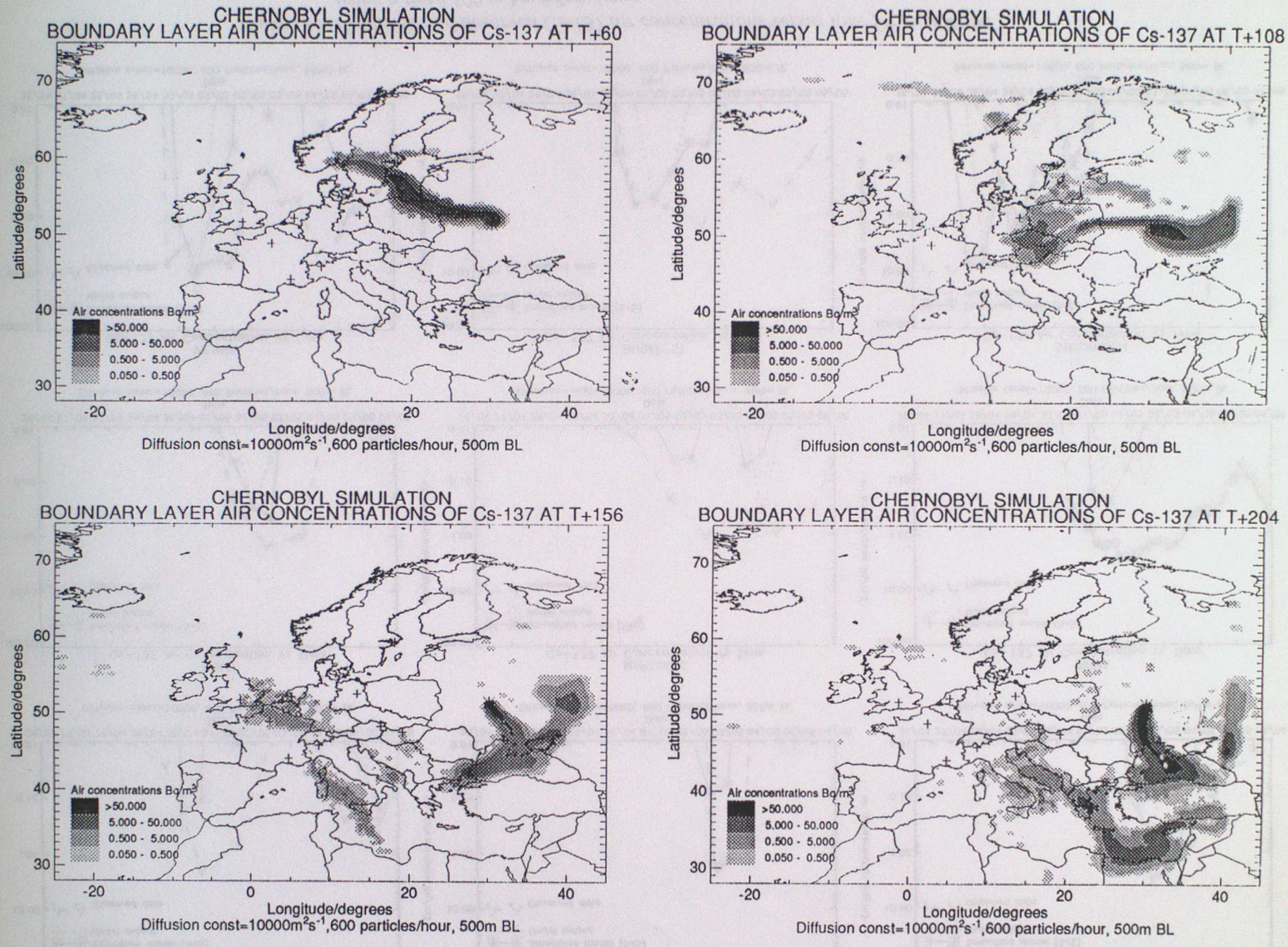


Figure 14 Air concentrations for simulation using a fixed 500 m boundary layer

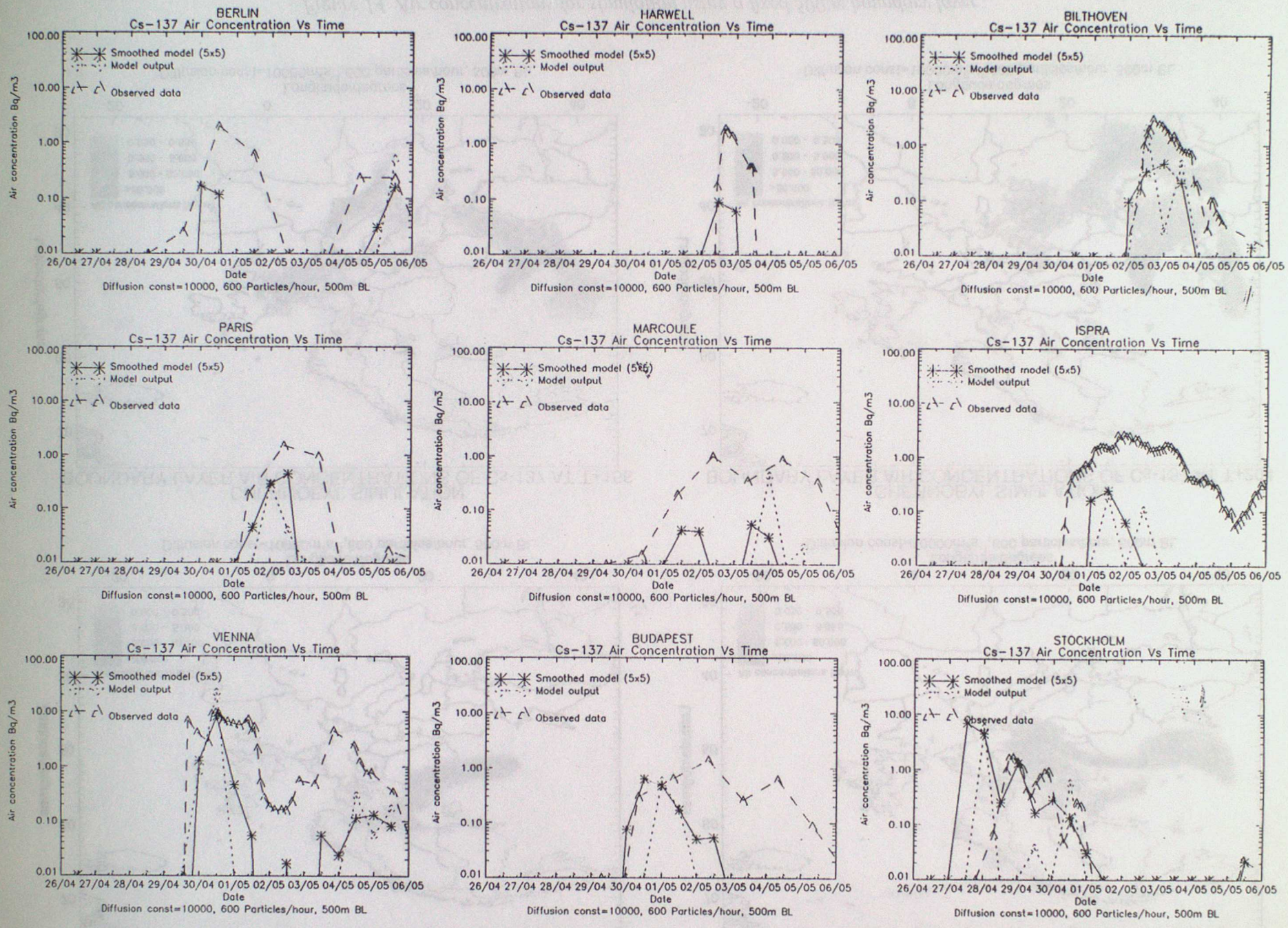


Figure 15 Predicted and observed Cs-137 air concentrations versus time for simulation using a fixed 500 m boundary layer

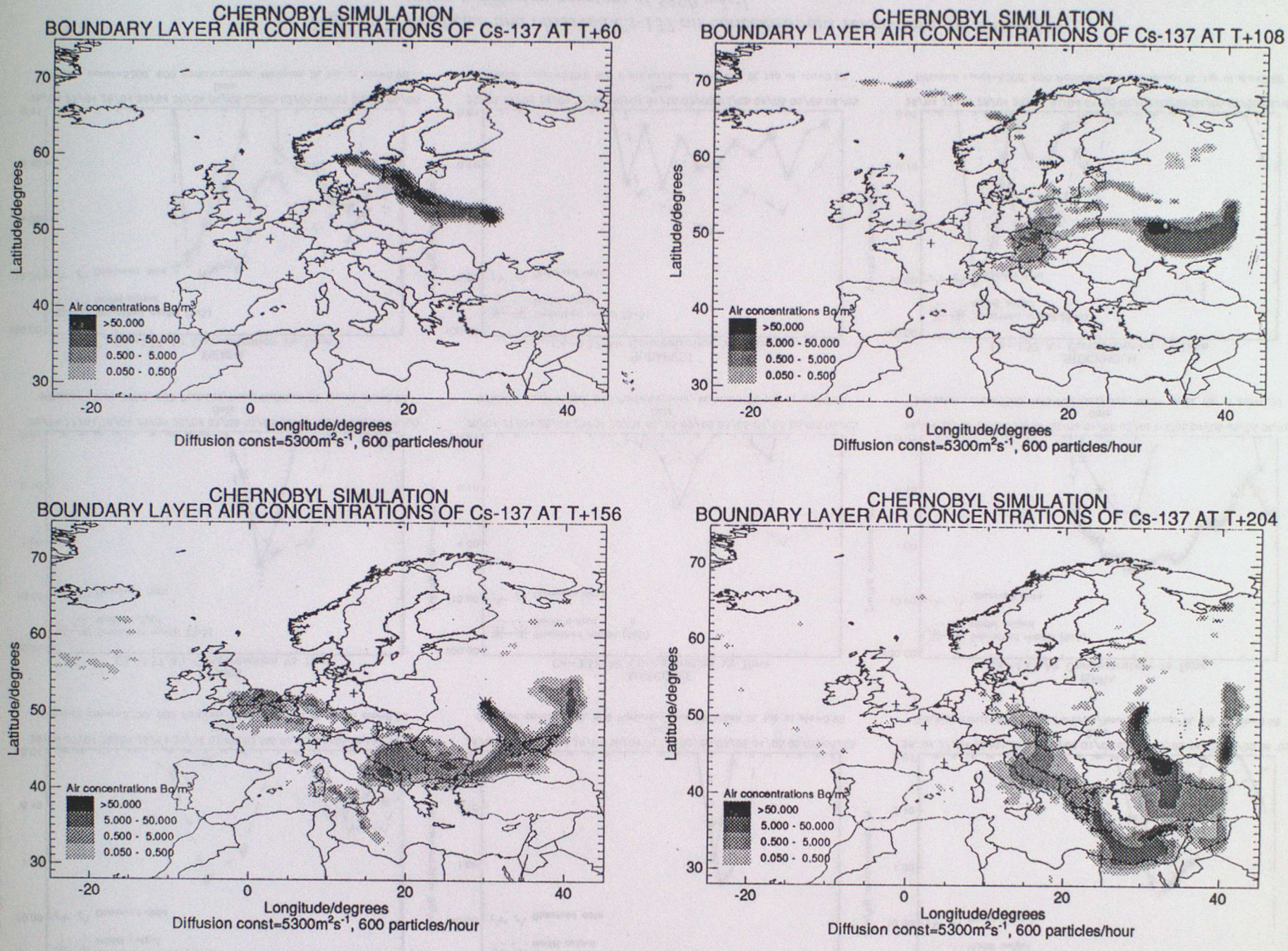


Figure 16 Air concentrations for simulation using a diffusion constant of 5300 m^2s^{-1}

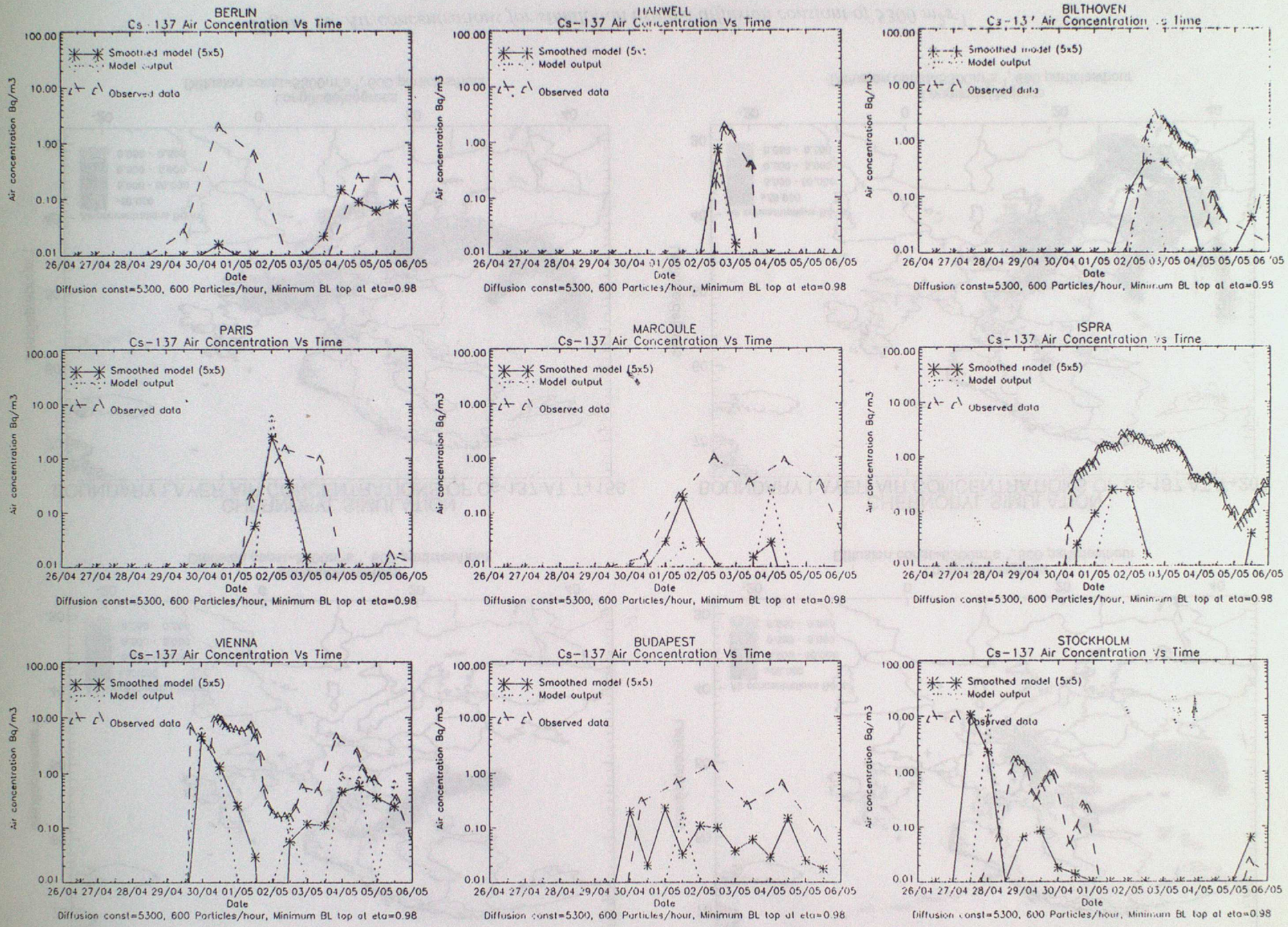


Figure 17 Predicted and observed Cs-137 air concentrations versus time for simulation using a diffusion constant of 5300 m^2s^{-1}

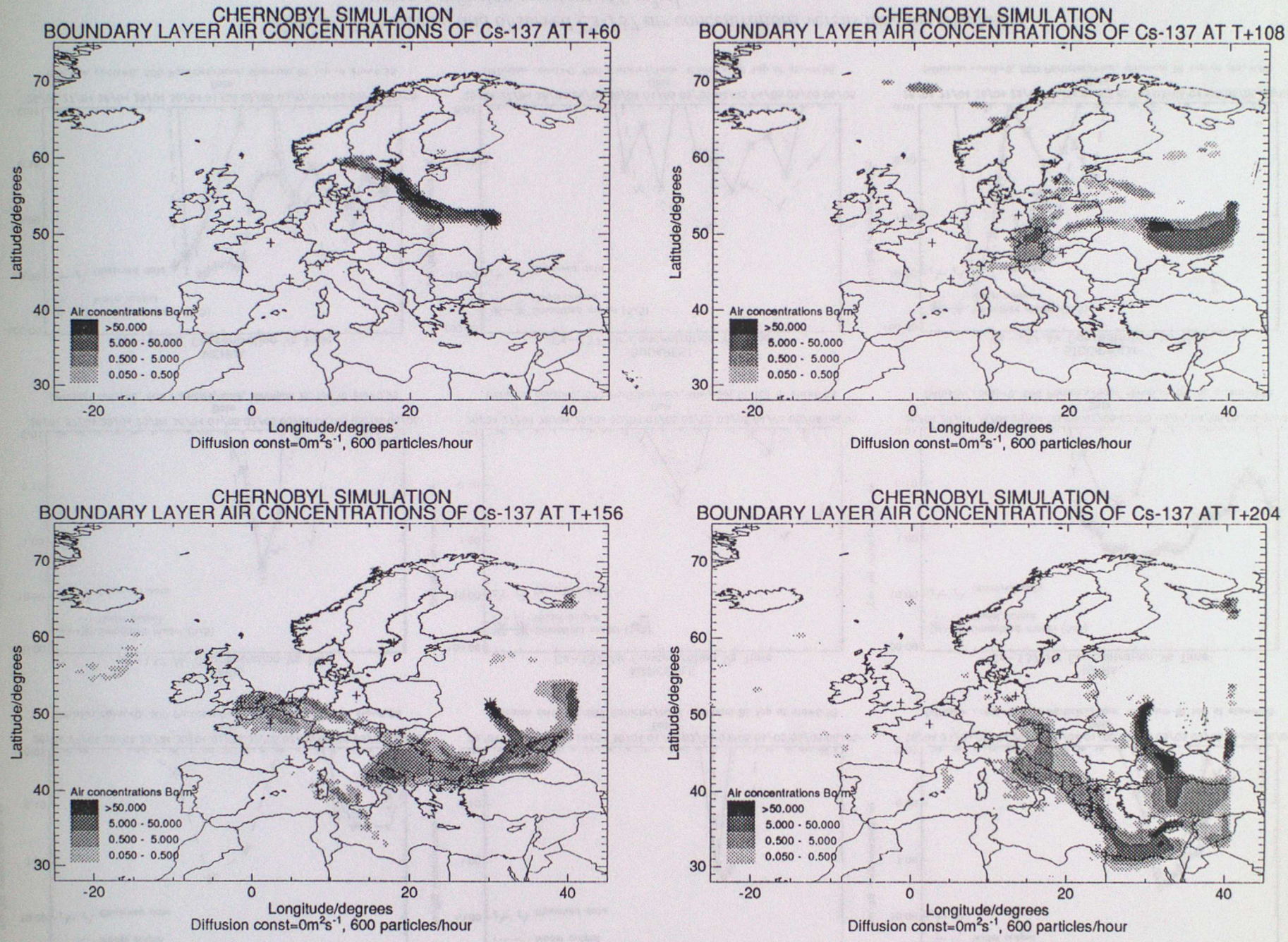


Figure 18 Air concentrations for simulation using a diffusion constant of 0 m^2s^{-1}

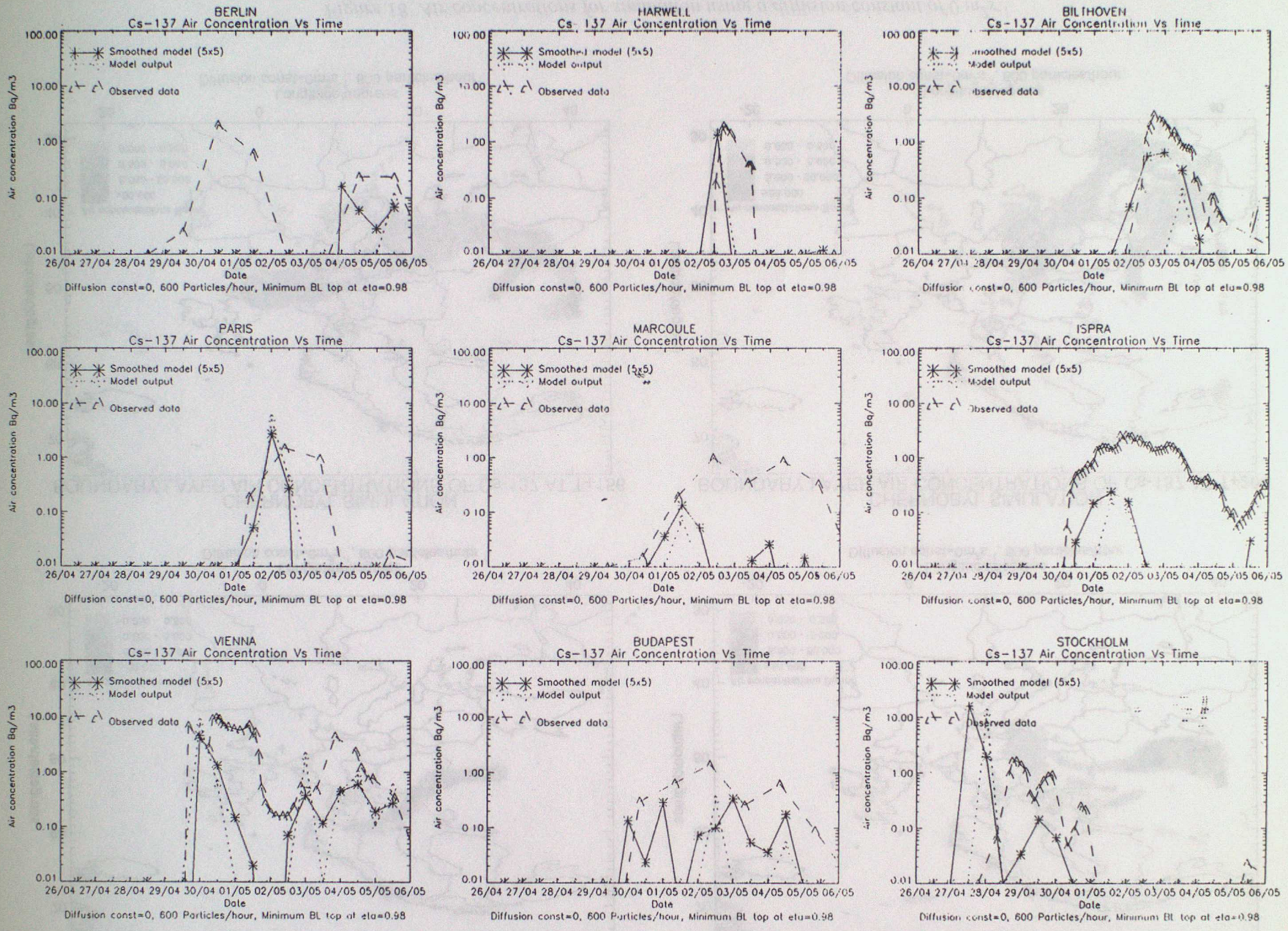


Figure 19 Predicted and observed Cs-137 air concentrations versus time for simulation using a diffusion constant of 0 m^2s^{-1}