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MODELING OF ATMOSPHERIC TRANSPORT AND DEPOSITION OF HEAVY METALS IN THE KATOWICE PROVINCE

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Abstract

A large part of Poland's heavy industry, notably hard coal mining, ferrous and non-ferrous metallurgy and power generation, is located in the Katowice province. Therefore, this heavy industrialized region, which is populated by four million people, experiences considerable problems with air pollution. In the METKAT study launched by the International Institute for Applied Systems Analysis we attempt to model atmospheric depositions of arsenic (As), cadmium (Cd), lead (Pb) and zinc (Zn) which are among the highest in Europe.

The applied modeling approach consists of performing detailed simulations of atmospheric transport and deposition of heavy metals with horizontal grid spacing of 5 km within one 150x150 km cell of the EMEP grid covering the Katowice province. For this purpose we implemented the Lagrangian Particle Dispersion and Deposition (LPDD) model driven by two mesoscale/regional meteorological models. Preliminary deposition calculations for the entire 1992 year and a series of sensitivity experiments for cadmium were run using relatively simple but computationally efficient hydrostatic meteorological model (MESO). The deposition results from the MESO/LPDD modeling applied to the mesoscale domain were supplemented by contributions from other emission sources in Europe calculated with the aid of the Heavy Metals Eulerian Transport (HMET) model.

The performed sensitivity tests indicate that the calculated depositions depend primarily on the quality of emission data (magnitude, spatial distribution and aggregation). Also land use data seem to be relatively important when estimating the location and magnitude of peak depositions. The proposed modeling approach shows some potential to reproduce local maxima in the deposition fluxes of heavy metals which cannot be resolved by long range transport models. However, very high Cd deposition values observed in the region cannot be reproduced by the model with available emission inventory even when emission from selected sources was increased by two orders of magnitude. The model calculations do not take into account reemision of particulates from post-mining areas and waste dumps, which may contribute considerably to ambient concentrations. A receptor-oriented modeling approach based on an influence function concepts is proposed as a tool to further investigate contributions of different potential emission sources to the observed depositions.

A series of additional 24-hour simulations for idealized synoptic conditions were run with the LPDD model linked to the Colorado State University RAMS (Regional Atmospheric Modeling System). The purpose of these simulations was to investigate the potential effect of regional scale topography on mesoscale atmospheric transport within the Katowice province. Although the terrain of this province is not very complicated, the Sudeten and Carpathian

Mountains surrounding this region from the south may significantly affect transport and deposition there.

1 Introduction

A large part of Poland's heavy industry, notably hard coal mining, ferrous and non-ferrous metallurgy and power generation, is located in the Katowice province. Therefore, this heavy industrialized region populated by four million people experiences serious problems with air pollution. Air concentrations and deposition of heavy metals including arsenic (As), cadmium (Cd), lead (Pb) and zinc (Zn) are among the highest in Europe. Heavy metals deposit onto surfaces at relatively low rates. However, due to their toxicity and accumulation in soils, long-term deposition needs to be evaluated (Bartnicki et al., 1996; Olendrzynski et al., 1996).

The METKAT (heavy METals in the KATowice province) study was launched by the International Institute for Applied Systems Analysis in cooperation with two Polish research institutions, Institute for Ecology of Industrial Areas (IEIA), Katowice, and Institute of Meteorology and Water Management (IMWM) in Warsaw. The goal of this project was to investigate high local values of heavy metals deposition in the Katowice province with the aid of available mathematical models. Long-range transport models applied to the area of the entire Europe cannot simulate high values of local deposition fluxes due to their low spatial resolution. A typical grid cell of the long-range models can cover the whole Katowice province. Therefore, in the METKAT project, we proposed to apply a high resolution transport and dispersion model linked to a three-dimensional mesoscale/regional meteorological model in addition to existing long-range transport models. An important part of the project was preparation of emission, terrain and meteorological input data with resolution suitable for mesoscale modeling.

The modeling approach proposed for the Katowice province is presented in the next section followed by short descriptions of all mathematical models utilized in the study and necessary input data. Sections 5 and 6 present the performed meteorological and deposition simulations including sensitivity experiments. Additional meteorological simulations are described in section 7. Finally, conclusions from the performed simulations and some directions for future research are discussed.

2 Modeling approach

The modeling approach proposed in the METKAT project for heavy metals deposition in the Katowice province consists of

- performing a detailed simulation of atmospheric transport and deposition of heavy metals within a mesoscale modeling domain covering the Katowice province, and

- calculating a deposition background from all emission sources not included in the selected mesoscale domain with the aid of available long range transport models.

The deposition modeling within the Katowice region should satisfy the following postulates:

- a required output should include concentrations, dry, wet and total deposition of heavy metals on 5 km grid.
- a detailed structure of emission field should be taken into account with a separate treatment of major point sources.
- dry deposition should depend on a spatial land use distribution.
- atmospheric transport and diffusion should take into account the effects of land use distribution and local terrain topography.
- computer models should be efficient enough to allow one to perform long-term deposition calculations (month-year).

We attempt to achieve the above goals by applying a three-dimensional meteorological mesoscale model and use its output to drive a high-resolution transport and deposition model. This modeling approach requires three sets of input data as illustrated in Figure 1: (1) meteorological data, (2) land use and terrain elevation data, and (3) emission data. A grid spacing, $\Delta x = 5$ km, for deposition calculations was chosen in relation to a spatial resolution of available emission and terrain data.

Mathematical models selected for the project are described in the next section. A new mesoscale transport and deposition model based on a Lagrangian particle model was developed and implemented for the present study. Long-term three-dimensional meteorological simulations can be very computer time consuming. Therefore, a serious compromise must be found between accuracy of modeling and factors affecting time of computations which include not only model sophistication but also size of a modeling domain and grid resolution. A relatively simple 3-dimensional model MESO seems to be a good candidate for long-term mesoscale simulations on a limited domain. We recommend to evaluate this model against a more advanced and more computationally expensive CSU RAMS. The latter model can also cover a larger modeling domain with the aid of nested grids approach.

Within time limits of the present project a series of long-term deposition simulations was performed with the aid of output from the 1-dimensional version of the MESO model. This simplification allowed us to run several sensitivity experiments to investigate a role of emission data accuracy and aggregation, land use representation and interannual variability of meteorological conditions. Some idealized short-term 3-dimensional simulations were also performed with the CSU RAMS in order to investigate importance of terrain topography in the area surrounding the Katowice province and to select a proper size and grid resolution of the modeling domain.

The deposition background of heavy metals from all European emission sources located outside the Katowice region was calculated with the aid of the HMET model.

These long range simulations were performed on a grid used by EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe). The EMEP grid (Fig. 2) consists of 39×37 cells in polar stereographic projection and has spatial resolution of 150×150 km at 60° N latitude. It covers all of Europe, a large part of Northern Atlantic and northern coast of Africa. The mesoscale deposition modeling domain was selected as one 150×150 km cell (25,19) of the EMEP grid covering the Katowice province (Fig. 3). The modeling domain used in the meteorological simulations with the CSU RAMS is larger and covers mountains south of the Katowice province (Fig. 3 and 4).

3 Mathematical models

3.1 Transport and deposition models

3.1.1 Lagrangian Particle Dispersion and Deposition Model

A new dispersion model called Lagrangian Particle Dispersion and Deposition (LPDD) model was developed specifically for the purpose of the METKAT project. This model is derived from a family of Lagrangian Particle Dispersion (LPD) models being a part of a Mesoscale Dispersion Modeling System (MDMS).

The MDMS, designed for use on personal computers and workstations, was originally developed at the Department of Meteorology of the Warsaw University of Technology, Poland in the late 1980's (Uliasz, 1990a; Uliasz, 1990b; Uliasz, 1993). During last years, the LPD models were intensively used in several applications on UNIX workstations at Colorado State University (CSU) linked to different meteorological models including a MESO model from the MDMS, CSU RAMS and MIUU (Meteorological Institute, Uppsala University) mesoscale model. The applications cover simulations of the atmospheric transport in different geographical areas including the coastal zone of Baltic Sea in northern Poland (Uliasz, 1990b), the Black Triangle of Central Europe (Uliasz et al., 1993), Shenandoah National Park in the eastern United States (Uliasz, 1993), the southwestern United Stated with Grand Canyon National Park (Uliasz et al., 1996) and the Mediterranean Sea Basin. Validation studies include a simulation of the Øresund 1984 meteorological and tracer field experiment performed over a land-water-land area (Uliasz, 1990b) and simulations of regional transport in the southwestern United States with the aid of tracer of opportunity (methylchloroform) (Uliasz et al., 1994; Uliasz et al., 1996).

Atmospheric transport is simulated in the LPD models by tracking a large set of particles representing elements of pollutant mass. Particles are driven by wind and turbulence fields derived from a meteorological model. A simplified advection algorithm for particles based on a fully random walk scheme instead of a Markov chain scheme was adopted in the LPDD model. This is an acceptable approximation for mesoscale and regional dispersion studies (Uliasz, 1994) and allows one to perform efficiently long-term particle simulations even for multiple emission sources. To further improve model efficiency an aggregation procedure was proposed for emission data used in the present study. Parameterizations of dry and wet deposition were adapted, with some modifications, from the HMET model (Bartnicki et al., 1993).

The unique feature of the LPDD model is a capability to use two different options for dispersion modeling: a traditional source-oriented mode to calculate concentrations forward in time and a receptor-oriented mode to calculate influence functions backward in time. The influence function which characterizes dispersion conditions in the atmosphere for a given receptor is determined from backward in time particle trajectories.

3.1.2 HMET model

The Heavy Metals Eulerian Transport (HMET) model has been developed to study the long-range, long-term transport, deposition and overall budget of As, Cd, Cu, Pb, and Zn in Europe (Bartnicki et al., 1993; Bartnicki, 1994; Bartnicki, 1996). This model simulates transport and deposition of heavy metals on the EMEP grid system with horizontal grid step of approximately 150 km. Meteorological input consists of the velocity field at 925 hPa, precipitation and mixing height. Velocity and precipitation fields are updated every 6 hours and new values of mixing height are available every 12 hours. The dry deposition velocities for each metal depend on the particle size distribution and surface roughness at a given grid cell. Wet deposition is proportional to the precipitation intensity for the previous 6 hours and a constant scavenging ratio. Model equations are solved by the positive definite pseudospectral method which provides accurate numerical solutions for the advection problem. Another version of the HMET model is working on a finer grid with a horizontal step of 50 km.

3.2 Meteorological Models

3.2.1 MESO model

The MESO model is a main part of the MDMS (Uliasz, 1990a; Uliasz, 1993). It is a 3-dimensional mesoscale meteorological model which can be run in 1- and 2-dimensional versions as well. The model is based on primitive equations in a hydrostatic formulation in terrain following coordinates. Condensation processes in the atmosphere are not included, however, precipitation estimated from observation is treated as input to a soil-vegetation submodel. Turbulence parameterization based on a prognostic equation for turbulent kinetic energy (the Mellor-Yamada level 2.5 scheme) provides all necessary turbulent characteristics required by the LPDD model. The MESO model has been applied in complex terrain of coastal areas of the Baltic Sea (Uliasz, 1990b) and of the eastern United States (Uliasz, 1993) as well as for idealized terrain studies (Pielke and Uliasz, 1993). Long term (several months) simulations were performed for the Sudeten Mountains in the Black Triangle of Central Europe using both 1- and 3-dimensional versions of the MESO model (Uliasz et al., 1993). The model was validated with the aid of observations collected during Øresund 1984 meteorological and tracer field experiment (Uliasz, 1990b). The MESO model can be applied for mesoscale domains with horizontal sizes of a few hundred kilometers using a regular or telescoping grid.

For the purpose of the present project the MESO model was adapted without major changes. Some modifications were required in order to continuously run this model for the entire year. Data from a single aerological station were assimilated during the simulation by the nudging technique. Precipitation and clouds fields estimated from observations at surface synoptic stations were averaged over the deposition domain and used as input for the soil-vegetation submodel.

3.2.2 Regional Atmospheric Modeling System - RAMS

The CSU RAMS is a primitive equation, prognostic modeling system which has evolved from the mesoscale model developed by Pielke (1974) and the cloud-scale model of Tripoli and Cotton (1982) and Cotton et al. (1982). It is among the more widely used prognostic mesoscale codes. The RAMS is a highly modular modeling system with a variety of potential applications from large eddy simulations to real-time forecasts of large scale weather patterns. A user can select different options from a namelist framework in order to create a model configuration which is the best suited for a particular application. The CSU RAMS can be configured with any number of nested grids where the finest grid is usually located in the area of interest and the coarse grid is covering much larger regional domain. This approach allows for interaction between mesoscale phenomena and synoptic scale circulation.

An overview of RAMS features and its recent meteorological applications can be found in Pielke et al. (1992) and Nicholls et al. (1995). Applications to air quality problems are reviewed in Pielke et al. (1991) and Lyons et al. (1993). Recent applications of RAMS in this area include modeling impacts of mesoscale vertical motions on dispersion in coastal areas (Lyons et al., 1995) and providing meteorological input to photochemical grid models for the Lake Michigan Ozone Study (Eastman et al., 1995; Lyons et al., 1995). The CSU RAMS can be used for long term simulations, however, it is much more computer expensive than the MESO model. An example of this type of applications includes the meteorological simulations performed for the southwestern United States on two nested grids for the entire year of 1992 (Uliasz et al., 1996).

4 Input data

4.1 Meteorological data

Routine meteorological data from six Polish synoptic stations: Opole, Częstochowa, Katowice, Racibórz, Kraków and Bielsko Biała (Fig. 3) and radiosounding data from the aerological station at Legionowo located about 200 km northeast of the area were used in the METKAT project (Mazur and Hrehoruk, 1996). These data were prepared for two years: 1992 and 1993. The radiosounding data (speed and wind direction, potential temperature and specific humidity) available every 12 hours, were utilized to initialize each meteorological simulation and then were continuously assimilated into the MESO model with the aid of nudging technique. Precipitation and cloud cover data available every 6 hours from the synoptic stations were interpolated on 5 km grid covering the deposition modeling domain using optimal interpolation methods (Fig. 5). The precipitation and cloud cover fields were used as input for the both MESO (soil-vegetation parameterization) and LPDD (wet deposition parameterization) models. In the case of 1-dimensional meteorological simulations these fields were averaged over the entire deposition modeling domain.

4.2 Land use and elevation data

The mesoscale meteorological simulations require detailed information on land use distribution and terrain elevation within the modeling domain. Additionally, the land use information is required by the LPDD model to estimate surface roughness for the dry deposition parameterization.

Three land use data sets have been prepared for the project:

1. The detailed land use information for the Katowice province was prepared by the Institute of Ecology of Industrial Areas (IEIA) in Katowice (Hławiczka et al., 1996). The following land use types are distinguished: (1) arable land, uncultivated grass, transportation tracks, (2) permanent grass land (excluding peat bogs), (3) low, medium and high peat bogs, (4) coniferous forest, (5) mixed forest, (6) deciduous forest, (7) major park complexes (8) low urban area (up to 3-story buildings), (9) mixed urban areas - city centers, (10) high urban areas - housing districts, (11) industrial areas, (12) industrial areas with no buildings (old excavation sites, warehouses, storehouses), (13) lakes and water reservoirs, (14) waste damps. The data were provided in two formats: (1) 5×5 km grid cells with the area fractions of individual land use types, and (2) 0.5×0.5 km grid cells with the dominant land use type. Unfortunately, these data cover the administrative boundaries of the Katowice province only. Figure 6 shows land use in the Katowice province as a distribution of aggregated land types: agriculture (1-3), forest (4-7), urban/industrial (8-12 and 14) and water (13). A dominant land type in each 1×1 km square was plotted.

2. Additional land use information was extracted from the Baltic Sea Drainage Basin GIS Database available in the form of ARC/INFO files on the World Wide Web (WWW). Geographically the database covers all countries in the Baltic Sea drainage basin including Poland. This data set was derived from two principle sources: the Digital Chart of the World (DCW) and the European Space Agency (ESA) Remote Sensing Forest Map of Europe. DCW is a 1:1 000 000 scale global vector database created by Environmental Systems Institute (ESRI). The ESA forest map was generated using the NOAA-11 AVHRR 5 channel sensor with a 1 km pixel. The raster data were later vectorized. A total of six land cover classes were generated: (1) forest, (2) open land, (3) urban, (4) open water, (5) glacier, and (6) unknown land (forest or open land). The

unknown land class is located where there were inconsistencies in land/ocean and land/water delineations between the two data sets mentioned above.

3. The above data were enhanced with the additional information for the modeling domain outside the Katowice province with the aid of the 1:200000 and 1:50000 maps for southern Poland (Mazur and Hrehoruk, 1996). The following land use types were distinguished: (1) open land, (2) villages and small towns (less than 10 000 inhabitants), (3) open waters, (4) coniferous forest, (5) mixed forest, (6) deciduous forest, (7) medium towns (10-50 thousand inhabitants), (8) large towns (50-100 thousands inhabitants), (9) cities with population above 100 000, (10) wet lands, and (11) unknown land: mixed forest or open land (in the Czech and Slovak Republics).

In the preliminary meteorological and deposition simulations reported here, only the original land use data from the Baltic Sea Drainage Basin GIS Database (2) were used. A terrain data processor built in the MESO model was applied to prepare these data for the specified model grid. A number of patches with different land use types was determined for each grid cell and a fractional area of each patch was estimated. Next, characteristic parameters of vegetation canopy typical for a given land use type were assigned to the patch. For simplicity a single soil texture type - sandy loam - was assumed in the whole modeling. However, it is possible to assign different soil types (and some other ground surface characteristics, e.g. snow cover) to each individual land patch. In order to use more fully the available land use information in the future simulations, it will be necessary to integrate the above land use data into the single database. It may require aggregation of some land use types reported in the more detailed data sets.

The terrain height data were extracted from the GLOBE Project (Global Land One-Kilometer Base Elevation). A spatial resolution of these data is 30 arc-second latitude-longitude grid for latitudes lower than 50 degrees. For higher latitudes the resolution drops to 1 arc-minute (longitude). The terrain elevation data were interpolated and averaged for the grids required by the MESO and RAMS simulations using a terrain data processor from the MESO model.

4.3 Emission data

The deposition simulations required emission data for As, Cd, Pb, and Zn for the entire area of the 150 x 150 km EMEP grid cell covering the Katowice province. These data were obtained from the three sources:

1. Emission inventory for the Katowice province prepared by the IEIA (Hławiczka et al., 1996).
2. Information on emission from major point sources outside the Katowice province (Pacyna, 1996).
3. Emission from volume sources outside the Katowice province estimated as proportional to population density.

Table 1: Aggregation of emission data used in the reference transport and deposition simulations (N_E is a number of emission sources and E is emission rate in *tons/year* from each source category)

SOURCE CATEGORY	As		Cd		Pb		Zn	
	N_E	E	N_E	E	N_E	E	N_E	E
point sources	21	5.80	29	8.48	17	159.59	12	366.97
5×5 km volume sources	10	2.21	20	4.01	7	21.10	4	56.85
10×10 km volume sources	97	3.82	97	4.56	97	84.51	97	244.08
large volume sources	7	1.35	7	1.78	7	41.05	7	56.60
total	135	13.19	153	18.82	128	306.25	120	724.50

The Katowice province covers 30% of the deposition modeling domain but it provides 75, 81, 79, and 82% of the As, Cd, Pb and Zn emission respectively. The population density in the neighboring provinces is close to the average one in Poland (121 $persons/km^2$) and in the Katowice province it is nearly five times higher (592 $persons/km^2$).

The LPDD model can handle releases from multiple emission sources with arbitrary geometry and time characteristics. There is no numerical or oversmoothing problems which appear in numerical grid transport models, like the HMET model, in the case of narrow plumes released from point or line sources. For buoyant sources, i.e. sources with hot gas release, plume rise is calculated and particles are released from the effective stack height which may be even several times higher than its physical height. The plume rise calculations require additional information on stack parameters (height, diameter, exit velocity and temperature).

Computer time required by the LPDD model is dependent on the number of particles involved in the calculation, and in turn, on the number of emission sources. Therefore, some aggregation of emission sources is necessary for practical reasons, especially, for the long term simulations. The following emission sources aggregation procedure was applied in the performed simulations:

1. Emission rate estimated from the population density is assigned to a grid of 5×5 km volume sources within the modeling domain outside the Katowice province.

2. Major point emission sources are selected with the emission rate exceeding prescribed threshold value, $E_{p,min}$. All remaining smaller point sources contribute to the grid of 5×5 km volume sources. Each of the selected major point sources is treated separately in the LPDD model. Particles are released from effective stack heights calculated in accordance with current meteorological conditions.

3. Major 5×5 km volume emission sources are selected with the emission rate exceeding the prescribed threshold value, $E_{v,min}$. Emission from the remaining 5×5 km volume sources is added to the grid of 10×10 km volume sources.

4. The 10×10 km volume sources outside the Katowice province are aggregated into seven large volume sources covering the most of this area.

The same height of 50 m was assumed for all volume sources. A set of emission sources for a given simulation consists of point sources, 5×5×0.05 km volume sources, 10×10×0.05 km volume sources, and a few larger volume sources with a low emission outside of the Katowice province.

Additionally, some other source emission aggregations were used in the sensitivity experiments. Statistics of emission sources for As, Cd, Pb, and Zn after the aggregation procedure as it was used in the reference deposition simulations is given in Table 1 and their spatial distributions are presented in Figures 7-10. The following threshold emission values, $E_{p,min} = 0.1, 0.1, 10, 10$ $tons/year$ and $E_{v,min} = 0.1, 0.1, 10, 10$ $tons/year$ for As, Cd, Pb, and Zn respectively were used.

5 Meteorological simulations

Meteorological simulations using a 1-dimensional configuration of the MESO model were performed for the entire year of 1992 and nine months (April-December) of 1993 using different representation of land use within the deposition modeling domain:

1. Exchange processes between the atmosphere, soil and vegetation calculated separately for different land-use categories and then averaged according to the area fraction of different categories within the deposition modeling domain

2. Uniform land cover within the modeling domain for transport and deposition simulations - bare soil

3. Uniform land cover within the modeling domain for transport and deposition simulations - typical agriculture land

4. Uniform land cover within the modeling domain for transport and deposition simulations - mixed woodland

Each simulation was performed continuously for the entire year (or nine months in 1993) with the assimilation of radiosounding data by nudging and continuous update of precipitation and cloud cover from observations averaged over the deposition modeling domain. Profiles of wind velocity components, potential temperature and turbulent kinetic energy were stored every hour to be used next as input for the LPDD model. The output from the meteorological simulation (1) was used in all reference deposition simulations while others were applied to sensitivity experiments.

Meteorological input data for 3-dimensional simulations will be the same as for the 1-dimensional simulation except precipitation and cloud cover which will be spatially distributed (as it is taken into account in the deposition simulations). In the case of the 3-dimensional meteorological simulations, the LPDD model will obtain all meteorological information including precipitation fields through the MESO model, while in the case of the 1-dimensional meteorological simulations the spatially distributed precipitation and cloud information is prepared specially for the LPDD

Table 2: Summary of Cd total depositions calculated in sensitivity experiments (D_{min}, D_{mean}, D_{max} - minimum, mean, and maximum total deposition in mg/m^2)

EFFECT	EXPERIMENT	D_{min}	D_{mean}	D_{max}	D_{max}/D_{mean}
	reference simulation	0.009	0.126	0.758	6.0
emission aggregation	150×150 km source	0.020	0.105	0.162	1.5
	50×50 km grid	0.011	0.103	0.350	3.4
	10×10 km grid	0.007	0.103	0.503	4.9
plume rise for major point sources	plume rise	0.002	0.055	0.352	6.4
	no plume rise	0.001	0.059	0.407	6.9
land use	bare soil	0.007	0.113	0.582	5.2
	agriculture land	0.007	0.124	0.695	5.6
interannual variability (Apr-Dec)	1992	0.007	0.099	0.634	6.4
	1993	0.010	0.111	0.651	5.9

model (Fig. 1). Computer requirements (computer time and disk space) for the 3-dimensional meteorological simulation are about 2 orders of magnitude higher than for the one-dimensional runs. The one-dimensional simulation for the entire year can be completed in approximately 1 hour using Sun workstations in the IIASA computer network.

6 Transport and deposition simulations

6.1 Reference simulations

The primary goal of transport and deposition simulations was to perform the reference calculations of deposition of all four metals for the entire year of 1992 using a detailed emission information. The reference simulations were performed using emission data aggregated into major point sources with plume rise and volume sources of different size. This configuration of emission sources was assumed as a compromise between accuracy of emission representation and computer time required by the simulations. The results of these simulations are presented in Figure 11.

The additional goal was to investigate the role of different factors in uncertainty of the modeling results by running a series of sensitivity experiments for deposition of cadmium. These experiments are summarized in Table 2.

6.2 Sensitivity experiments

6.2.1 Emission data aggregation

The first series of sensitivity experiments was designed to study the effect of emission source aggregation on deposition patterns of Cd and maximum values of deposition fluxes. The following four numerical experiments were performed and compared (Fig. 12-13):

- The total emission of Cd was distributed uniformly within the 150x150 km modeling domain and in the layer from 0 to 500 m. This setup corresponds to the emission treatment in the HMET-150 model. However, in contrast to the HMET model, the precipitation and surface roughness are variable within the modeling domain. This experiment resulted in the nearly uniform deposition field.

- The total emission of Cd was aggregated into a grid of 50x50 km volume sources. This emission treatment is similar like in the new HMET-50 model. The pattern of deposition in this simulation starts to correspond with location of real emission sources in the region and maximum values are much higher than in the previous experiment.

- The total emission of Cd was aggregated into a grid of 10x10 km volume sources. The increased resolution of the emission field results in a further increase of the local maximum value of deposition fluxes.

- The reference simulation performed with the most realistic representation of emission sources with a separate treatment of the major point sources.

The mean deposition flux over the 150×150 km modeling domain is nearly the same in the above experiments while its maximum values increases with the increased resolution of the emission field as illustrated by the ratio of the maximum to mean deposition flux (1.5, 3.4, 4.9, and 6.0).

Additional numerical experiments were performed in order to demonstrate importance of the proper treatment of major point sources. Figure 14 presents the Cd total deposition fields calculated separately for the major point sources included in the reference simulation with and without plume rise calculations. Taking into account the plume rise results in significantly lower values of the total deposition. It should be pointed out that realistic plume rise calculations require additional information on emission sources namely stack parameters (height, diameter, exit velocity and temperature) as well as detailed information on a vertical structure of the atmospheric boundary layer (profiles of wind speed, temperature, and turbulence characteristics).

6.2.2 Interannual variability of meteorological conditions

Two additional experiments, with a configuration identical to the reference simulations, were performed for nine months (April-December) of 1992 and 1993, in order to investigate the effect of interannual variability of meteorological conditions. In both experiments, the same aggregated emission field of Cd from 1992 was used.

The calculated deposition fields show small differences between these two years (Fig. 15). It is interesting to note that the mean and maximum deposition fluxes are somewhat higher for 1993 (0.111 and 0.651 mg/m^2) than for 1992 (0.099 and 0.634 mg/m^2), although the mean amount of precipitation during the analyzed period over the modeling domain was higher in 1992 (429 mm) than in 1993 (332 mm). The calculated deposition patterns are very similar for these two years. However, it would be worthwhile to analyze more years to explore the problem of interannual variability in more detail.

6.2.3 Land use representation

Land use can affect deposition of heavy metals in two ways. First, the dry deposition strongly depends on roughness related to land surface cover. Second, land use and terrain topography influence flow and mixing in the atmosphere which govern the atmospheric transport. In the one-dimensional meteorological simulations used in the study, the land use variability is not fully represented. However, the deposition simulations were repeated using output from the different meteorological simulations with various land use representation. Simulations performed for the uniform land use (bare soil, agriculture) within the modeling domain and the reference simulation performed for the averaged land use (Fig. 11) show quite significant differences in deposition patterns and maximum values. It indicates necessity of further exploring the role of the land use representation with the aid of the 3-dimensional meteorological simulations.

6.3 Comparison between HMET and LPDD models

The long range transport and deposition model, HMET, was run for the entire 1992 in order to provide a background from European emission sources for the mesoscale deposition calculations performed with the LPDD model. The HMET was validated against heavy metals deposition observation in Europe (Bartnicki, 1994). Therefore, a comparison between results from the LPDD and HMET model can be useful as a test and preliminary validation for our mesoscale deposition calculations.

Two versions of the HMET were used: HMET-150 running on the EMEP grid with 39×37 gridpoints and $\Delta x = 150$ km, and HMET-50 running on the 117×111 grid with $\Delta x = 50 km$. The 150×150 km mesoscale deposition domain used in the LPDD simulations corresponds to the (25,19) grid cell in the HMEP-150 and to the nine grid cells (73,55)...(75,57) in the HMET-50. Three sets of simulations with different emission configurations were performed with both HMET-150 and HMET-50:

1. *All sources.* The first set of simulations was a standard run of the HMET model for the case of all European emissions.

2. *Background.* This simulation was used to provide the total deposition of heavy metals in the mesoscale deposition domain originating from European sources located outside this domain. Therefore, all European emission sources were used excluding the sources located in the mesoscale deposition domain.

3. *Deposition domain.* Transport and deposition were simulated taking into account emissions from the mesoscale deposition modeling domain only.

Table 3: Total deposition in mg/m^2 computed by two versions of the HMET model with Δx = 150 km and Δx = 50 km with emissions from (1) the entire Europe (all sources), (2) from the entire Europe except the 150×150 km deposition modeling domain (background), and (3) from the deposition modeling domain only.

EMISSION	all sources		background		deposition domain	
METAL	HMET150	HMET50	HMET150	HMET50	HMET150	HMET50
As	0.81	1.37	0.49	1.10	0.31	0.40
Cd	0.36	0.54	0.13	0.30	0.22	0.30
Pb	10.23	15.24	4.46	10.10	5.51	6.82
Zn	16.84	24.30	4.51	11.15	11.64	16.03

The total deposition results obtained in the above simulations are summarized in Table 3. It can be seen that the total deposition fluxes with the mesoscale deposition domain computed by the HMET50 model for all four metals are about 50% higher than those from the HMET150 model. This indicates that the removal processes are more efficient in the HMET50 model. The total emission for the grid cell (25,19) were the same for both sets of simulations (HMET150 and HMET50). In all HMET simulations the emission data provided for Europe by Pacyna (1996) (1992 for the Czech Republic, 1993 for Poland) were used.

Table 4 presents a comparison between total deposition simulated by the LPDD model and the HMET-150 and HMET-50 for the case of emissions from the mesoscale deposition domain only. The deposition estimates given by the LPDD are of the same order but lower than those from HMET runs. This can be partly explained by comparing the emission used by both models. The LPDD model uses the emission data provided by the IEIA (Hławiczka et al., 1996) which are lower (except Cd) than those from the European database (Pacyna, 1996). There are also some small differences in the area for which the deposition is calculated in both models. It was assumed for simplicity in the LPDD model that the mesoscale deposition domain, namely EMEP grid cell (25,19), can be approximated by a square of 150×150 km. In fact, due to the design of the EMEP grid, it is an irregular tetragon with the area of $m_f(150 \times 150)$ km, where for this particular grid cell, the map factor $m_f \approx 0.902$. Therefore, the deposition values obtained with LPDD model should be divided by the map factor, m_f, for the direct comparison with both HMET models in which this correction is already taken into account.

6.4 Comparison with observations

The maximum value of the Cd deposition flux obtained in the reference simulation is 0.76 mg/m^2. This value should be increased by the background values calculated by the HMET model, 0.13 mg/m^2. The deposition measurements in the Katowice province from the SANEPID (Provincial Sanitary Board) network show in 1992 values

Table 4: Comparison of total deposition mg/m^2 computed by the LPDD model and two versions of the HMET model with $\Delta x = 150$ km and $\Delta x = 50$ km with emissions $tons/year$ from the 150×150 km deposition modeling domain

MODEL	LPDD		HMET150		HMET50	
METAL	emission	deposition	emission	deposition	emission	deposition
As	13.2	0.09	22.9	0.31	22.9	0.40
Cd	18.8	0.13	16.5	0.22	16.5	0.30
Pb	306.3	2.15	370.5	5.51	370.5	6.82
Zn	724.5	4.81	832.3	11.64	832.3	16.03

which are higher - up to two orders of magnitude (SANEPID, 1994). According to these measurements there are two separate zones with very high Cd deposition: a small zone around the Szopienice zinc smelters with the maximum above 70 mg/m^2, and much larger zone near the zinc smelters in Bukowno and an adjusted zinc mining area with maximum values above 20 mg/m^2. The Cd emission reported for each of these smelters are about 100 $kg/year$.

In an attempt to explain this discrepancy between the model and observations an additional deposition simulation was performed for only these two point sources. We took emission levels reported for these two zinc smelters in the early 1980's namely 25 $tons/year$ for each of them (Fig. 17). The calculated maximum values of the Cd deposition fluxes are about 5 mg/m^2, which still cannot fully explain the observed values. However, we should note that the observed maxima refer to point observations while the model results refer to a 5×5 km grid. Therefore, the observed and computed values are not directly comparable.

We can conclude that emission data for these specific sources are not reliable. On the other hand, the deposition measurements in the areas with the high deposition of heavy metals may be contaminated by local conditions, i.e., mineral dust. This problem needs further exploration. The implemented modeling system, especially, the influence function approach discussed in the next section, is providing practical tools to investigate a nature of heavy metal emission in this region.

6.5 Influence functions

The LPDD model allows one to perform backward in time simulations in order to calculate influence functions as an alternative approach to atmospheric transport modeling (Uliasz, 1994). The influence function provides information on potential impact of any emission source to pollution at a selected receptor. Pollution at the receptor may be defined in various ways depending on the application, e.g., as the average concentration or long-term deposition flux. The influence function characterizes atmospheric transport and deposition processes from the point of view of the receptor. A value of the influence function at the location of the emission source multiplied by its emission rate, gives a contribution of this source to the pollution at the receptor. Two examples of the influence functions (Fig. 18) were calculated in the project. They were determined for the Cd air concentration in 1992 at the following receptors:

- the 5×5×0.25 km receptor located in the Olkusz/Bukowno mining region with high values of measured Cd deposition
- the 5×10×0.25 km receptor covering the Goczalkowice Reservoir (the major reservoir of drinking water in the region)

The influence functions are presented for the specific layer of the atmosphere, i.e., the influence function for the 0-25 m layer shows the potential impact from low emission sources, and the influence function for the 25-500 m layer determines the potential impact from the elevated sources located within this layer.

The influence functions seem to be a very useful tool for application in the current or similar projects. Especially, they may be used for

- identification (verification) of emission sources from measurements assuming that there are enough observations and that the locations of the sources to be identified are known,
- elimination of sources which due to atmospheric transport and deposition cannot have a significant impact on pollution observed at the considered receptor
- performing emission scenario exercises without a need to repeat the numerical simulations.

This approach would allow us to learn more about transport and deposition in the Katowice region, where emission data seem to be uncertain, and it is not clear how deposition measurements are affected by local mineral dust in the areas of current and old zinc mining. It would be especially useful to use some geographical information system (GIS) software, or any other visualization tool, as a vehicle for interactive emission scenario exercises.

7 Meteorological simulations with the CSU RAMS

Terrain topography within the Katowice province and the 150×150 km deposition domain is not very complex. However, this region is surrounded from south by the Sudeten and Carpathian Mountains, with a wide Moravian Pass just southwest from the Katowice province. The potential effect of terrain topography on atmospheric transport and deposition in this region can be only investigated with the aid of three dimensional meteorological modeling. There are several questions which need to be addressed before a 3-dimensional meteorological model can be implemented for long term deposition calculations:

- What location and extent of a meteorological modeling domain is necessary for reproducing the effect of terrain topography surrounding the Katowice province?
- What is the necessary resolution of meteorological modeling (horizontal grid spacing)?

- Can a simple hydrostatic mesoscale model (e.g., the MESO model) provide satisfactory results?

It should be pointed out that the three-dimensional mesoscale modeling is computationally expensive, especially, when it is applied for longer time period. Usually, a certain compromise between accuracy of modeling and available computer resources and time limits must be chosen for practical applications. Time of computation is related not only to model sophistication but also to the number of grid points used in the simulations. In order to investigate the above problems a series of simulations was performed with the aid of the CSU RAMS. This model is more advanced and more computationally expensive than the MESO model. Therefore, the RAMS is used only for a series of short simulations while the MESO model is a candidate for long term simulations.

The modeling domain selected for the RAMS simulations covers the deposition domain and extends towards southwest to include the Sudeten and Carpathian Mountains (Fig. 3-4). Terrain elevation data for the 320×320×8 km were prepared from the GLOBE Project data base. In order to isolate the topography effect, a uniform ground surface - agriculture land - was assumed. The CSU RAMS was configured to reproduce conditions typical for the middle of July. A nonhydrostatic version was used and condensation processes in the atmosphere were neglected. Simulations were run for 24 hours starting at 00.00 GMT for different geostrophic wind speeds (5 and 20 m/s) and directions (N,E,S,W). A single grid with a constant grid step in the horizontal and a stretching grid in the vertical was used in all simulations.

The following four sets of numerical simulations with the CSU RAMS were designed:

- 3-dimensional high resolution simulations ($\Delta x = 5$ km, 65×65×30 grid points). These simulations should reproduce the terrain effects relatively well.
- 3-dimensional coarse resolution simulations ($\Delta x = 10$ km, 33×33×30 grid points). The goal of these simulations was to investigate whether the essential topographical effects can be reproduced on a coarser grid using less computer resources. The CSU RAMS in this configuration ran several times faster than with the 5 km grid with more grid points, which also required a shorter time step of integration.
- 3-dimensional coarse resolution ($\Delta x = 10$ km) simulations with terrain elevation reduced to 500 m above see level. By removing the mountains from the modeling domains, the effect of local topography in the Katowice province was isolated.
- 1-dimensional simulations (no topography effect) were used as a reference for the 3-dimensional simulations.

The LPDD model was used as a flow visualization tool to illustrate a complexity of transport conditions in the performed simulations. Plumes of a passive tracer were emitted from four point sources located at the corners of the deposition modeling domain. Particles were released at the height of 50 m, and at a rate of 80 particles per hour from each source. This emission rate was doubled for the simulations with

Table 5: Summary of the 3-dimensional (3-D) and 1-dimensional (1-D) meteorological simulations performed with the CSU RAMS

simulation	grid points	Δx [km]	U [m/s]	direction	topography
3-D	65×65×30	5	5 and 20	N, E, S, W	included
3-D	33×33×30	10	5 and 20	W	included
3-D	33×33×30	10	5 and 20	W	reduced: $z_g < 500$ m
1-D	5×5×30	60	5 and 20	N, E, S, W	$z_g = 0$ m

a higher geostrophic wind speed to obtain similar number of particles within the modeling domain for visualization purposes. Figures 19-30 show all particles looking from the top. It should be noted that due to vertical motions there are significant differences in particle elevations above the ground and some parts of the plume may not touch the ground surface at a given time.

Streamlines derived from the simulated u and v wind components were used as another visualization tool. The streamlines are presented at 200 m model level. All 3-dimensional RAMS simulations were performed in a terrain following coordinate system. The model vertical coordinate, z^*, is defined as $z^* = H(z - z_g)/(H - z_g)$, where z - Cartesian vertical coordinate, H - height of modeling domain, and z_g - terrain elevation above sea level.

The performed simulations indicate that the Carpathian and Sudeten Mountain with the Moravian Pass between them may strongly affect flow and dispersion conditions in the Katowice region, especially, in the case of low winds. This is true for all wind directions, however, this effect of mountains is less significant for stronger winds. The local topography within the deposition modeling domain (its southern part) has also visible effect of pollution transport in the region (Fig. 29-30).

The obtained results have important implications for a selection of modeling domain for 3-dimensional meteorological simulations in the region. In order to correctly include the effect of topography the meteorological modeling domain must cover area much larger than the Katowice province or the 150×150 km deposition modeling domain. This domain should include at least a part of the Sudeten and Carpathian Mountains. Most of the terrain effects on plume dispersion, was reproduced by meteorological simulations on a coarser grid (Δx = 10 km). Therefore, for long-term simulations it seems possible to use a coarser and more computationally efficient grid. A practical compromise can be achieved by using nested grids (in RAMS) or a telescoping grid (in MESO).

The performed RAMS simulations do not address a problem of land use influence on atmospheric transport. Mesoscale circulations similar to sea- and land-breezes can develop as a results of land surface variability (e.g., differences in vegetation or urban canopy, soil type or soil moisture, snow cover). Even if the differences in surface turbulent heat fluxes between different land patches are not strong enough to create a distinct mesoscale circulation, they can affect significantly vertical structure of the atmospheric boundary layer and in turn atmospheric dispersion. These effects were demonstrated by simulating atmospheric dispersion over a series of land patches with different soil water content (Pielke and Uliasz, 1993).

Although, the terrain may have a significant effect on transport of passive tracer in the Katowice region, the performed test simulations do no allow us to evaluate how important the topography effect is for the long term averaged deposition calculations. It would be recommended to conduct a comparison between long term (weeks, months) deposition calculated with 1- and 3-dimensional meteorology. Another computationally cheaper alternative would be to design a test in 1- and 3-dimensional version where hypothetical winds varies in all (or most probable) speeds and directions and various precipitation scenarios are covered.

8 Conclusions

The modeling approach proposed for the Katowice province, allows one to simulate atmospheric transport and deposition of heavy metals in mesoscale taking into account landscape variability, local atmospheric circulation, precipitation fields and detailed information about emission sources. Transport and deposition of heavy metals in the Katowice region is simulated with the aid of three dimensional mesoscale/regional meteorological models (MESO or CSU RAMS) and the LPDD model. Deposition of heavy metals from the sources located outside the assumed mesoscale domain are calculated with the aid of the long range transport models (HMET150 and HMET50).

The mesoscale modeling system provides a unique feature to calculate the influence functions backward in time for selected receptors in order to perform emission scenario exercises and identification of emission sources based on measurements. This feature may be especially useful in the Katowice province to study uncertainty of emission inventory.

The modeling system consisting of mesoscale meteorological and transport/deposition models and the long range transport models can be easily applied to other geographical regions for which necessary input data can be provided. It is also possible to link any soil model working in a vertical column of soil into one or more grid points of the LPDD model which could provide the amount of precipitation and deposition of metals.

The performed meteorological and deposition simulations demonstrate that:

- The proposed modeling approach demonstrates the potential to reproduce local maxima in the deposition fluxes of heavy metals.
- Maximum deposition fluxes are very sensitive to aggregation of emission sources. Especially important are major point sources which require calculation of plume rise.
- Deposition patterns show visible sensitivity to land use even in the simplified representation of land use implemented in the study.

- Interannual variability of meteorological conditions causes less significant changes in the deposition patterns.

- Terrain topography within the Katowice province as well as mountains surrounding it from the south may have significant influence on the deposition of heavy metals.

- Very high Cd deposition values observed in the region cannot be fully explained by the model with available emission inventory, even when emission from selected sources was increased by two orders of magnitude.

Further research on modeling of heavy metals deposition in the Katowice province should include implementation of a three-dimensional mesoscale meteorological model for long term simulations. It would involve a selection of a meteorological modeling domain, grid resolution and model sophistication level, to provide a satisfactory compromise for deposition calculations with available or anticipated computer resources. In the present study the LPDD model was used with the 1-dimensional version of the MESO model which provided a detailed description of the atmospheric boundary layer structure in vertical but ignored terrain induced mesoscale circulations. Deposition simulations in this configuration could be effectively run even for a multi-year period. It rises a question whether this simplified approach is satisfactory for long term calculations at least as a first approximation. Therefore, it is necessary to evaluate these deposition simulations against similar simulations but performed with the three-dimensional meteorological fields.

Another direction of future research is related to application of the influence function method. We recommend to apply this tool together with the improved transport and deposition models to investigate the uncertainty of the emission inventory and reliability of deposition observations in the Katowice province. This approach should allow us to explore reasons of discrepancy between the simulated and observed deposition fluxes of heavy metals in this region.

In a forthcoming follow-up study we will use the information on the re-emission of particulate matter (including heavy metals) from a number of dumping sites and post-industrial areas in the Katowice province. These data are now being gathered by the IEIA (Katowice) within the framework of a collaboration agreement with IIASA's IND Project. Also, the impact range of particular dumping sites will be estimated together with the particle size distribution (wherever possible). Additionally, a more detailed statistical analysis of deposition measurements and comparison with model results will be performed. It is hoped that the new activities will result in more realistic computer simulations of the heavy metal deposition in the Katowice province, thus providing the basis for subsequent impact assessment and policy oriented studies.

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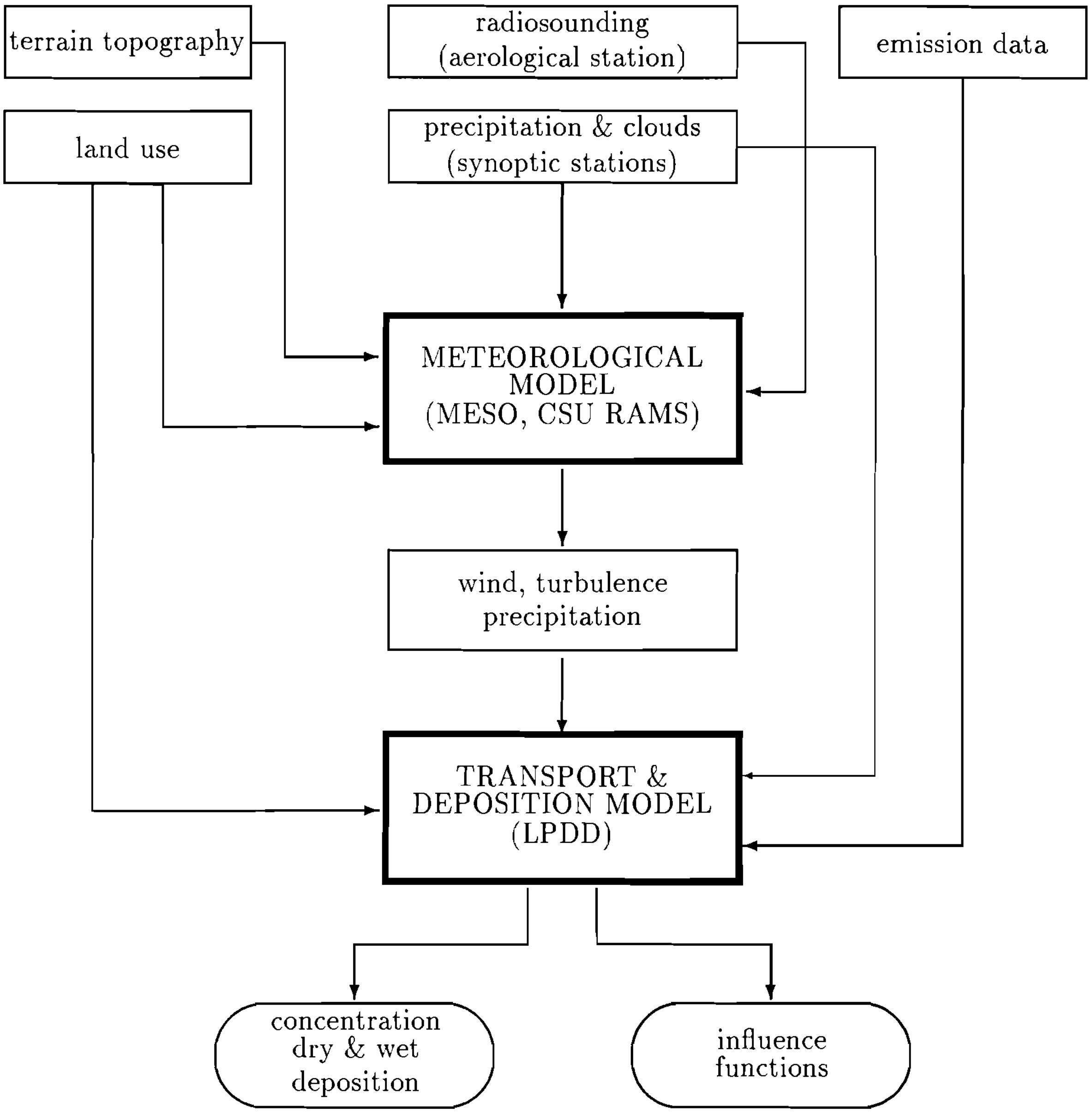

Figure 1: Data flow between mesoscale meteorological and transport/deposition models

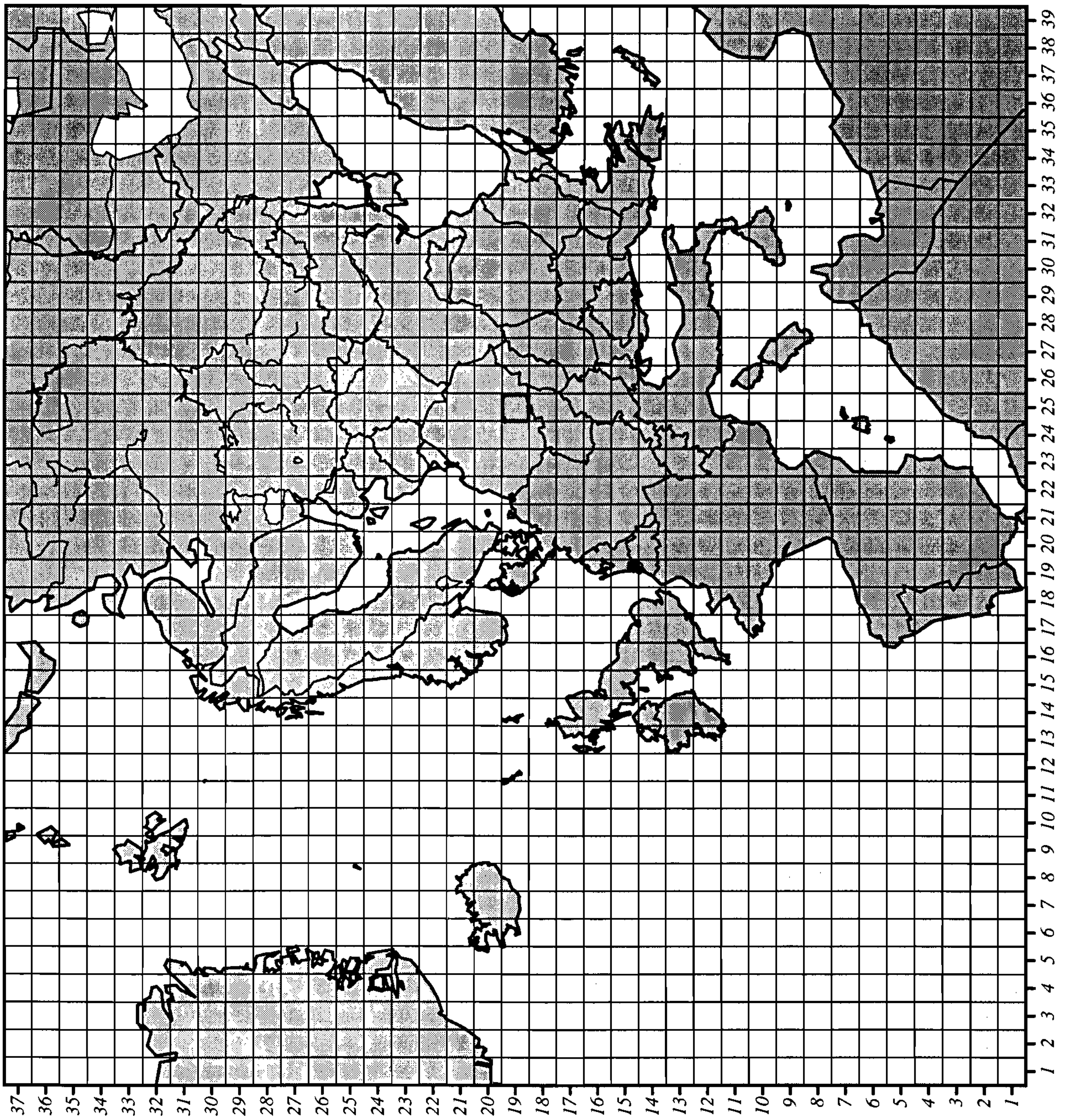

Figure 2: Modeling domain for long range transport and deposition of heavy metals in Europe used in the HMET model

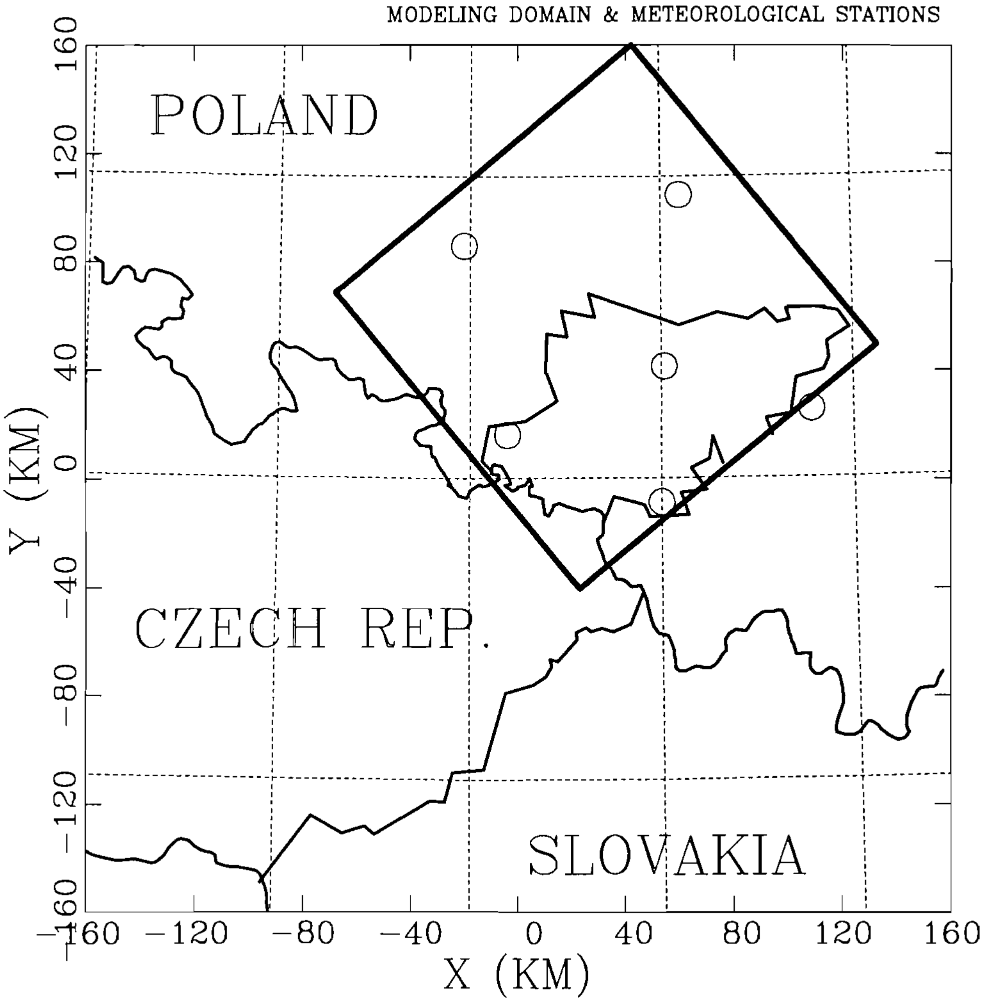

Figure 3: Modeling domain used in 3-dimensional meteorological simulations. The 150×150 km square, (25,19) cell of the EMEP grid, covering the Katowice province in the southern Poland is the deposition modeling domain. Meteorological stations used to derive precipitation and cloud cover fields are marked by circles.

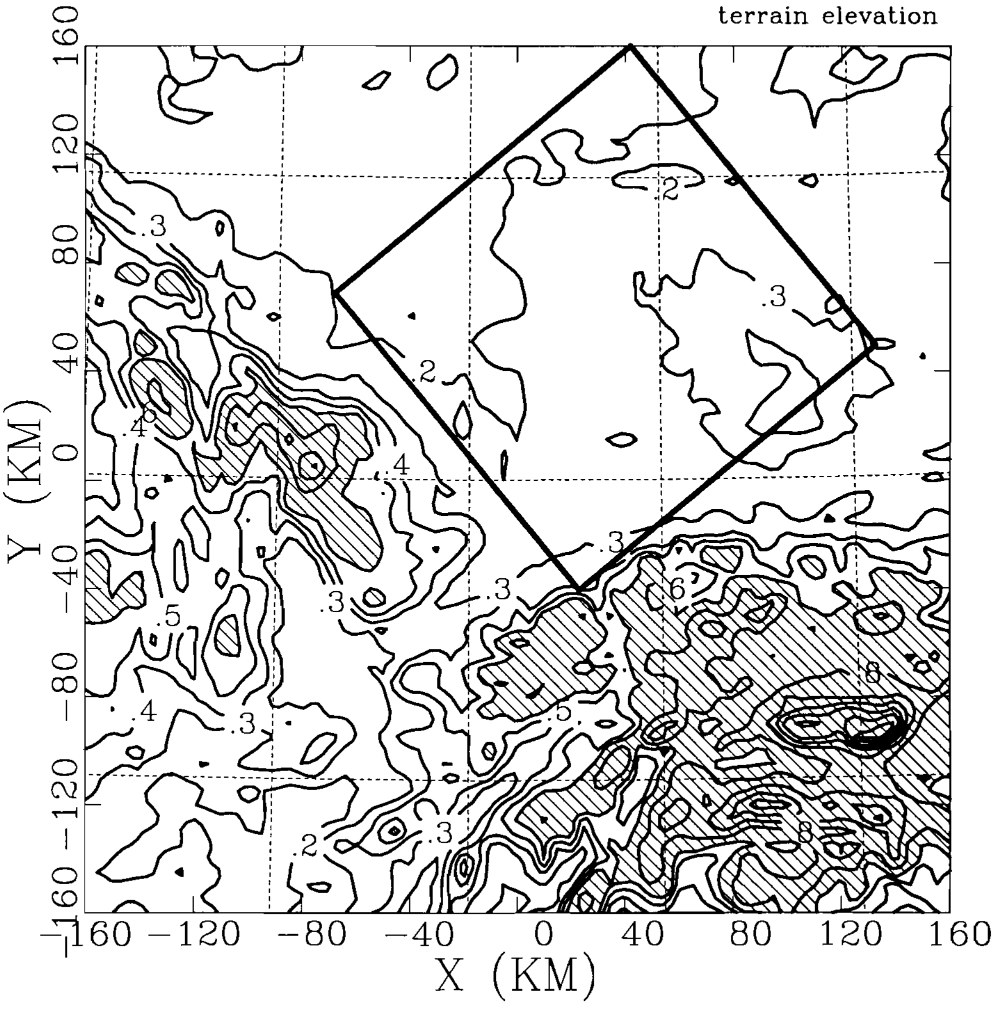

Figure 4: Terrain topography in the meteorological modeling domain

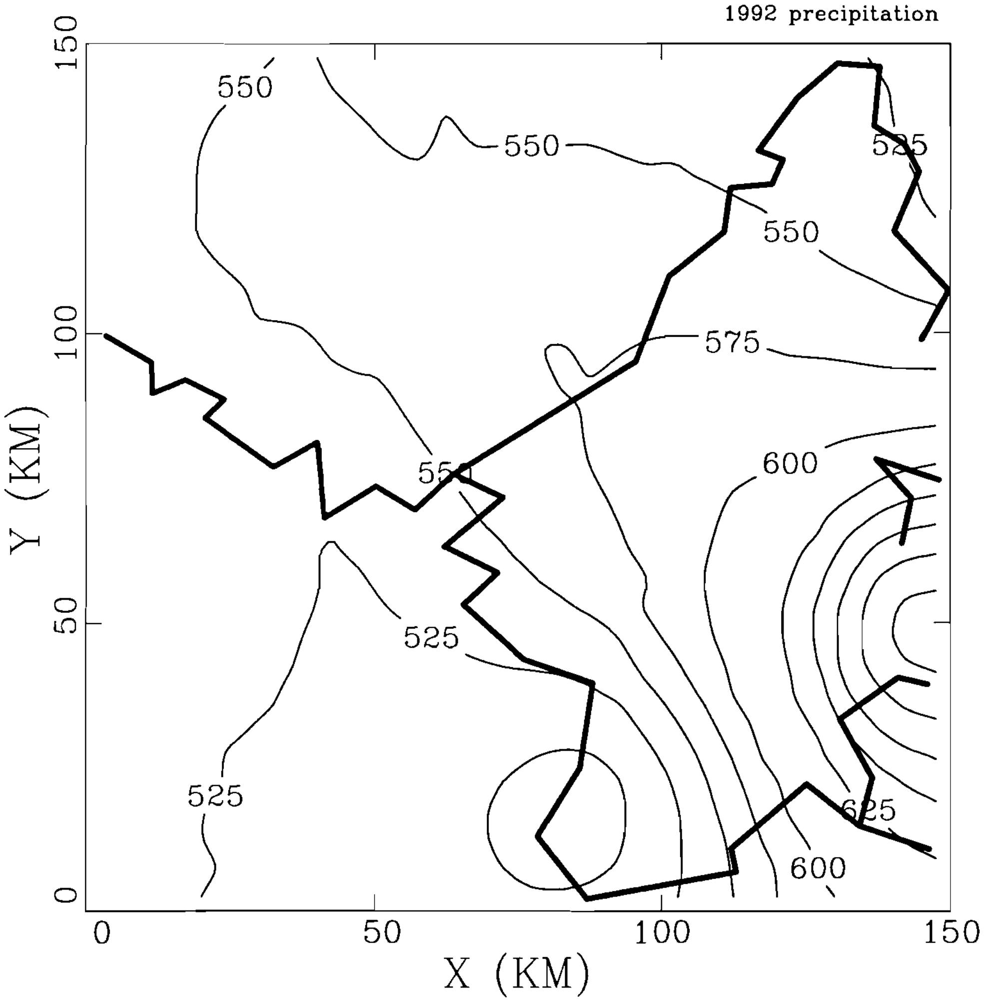

Figure 5: Precipitation [*mm*] in 1992 within the deposition modeling domain

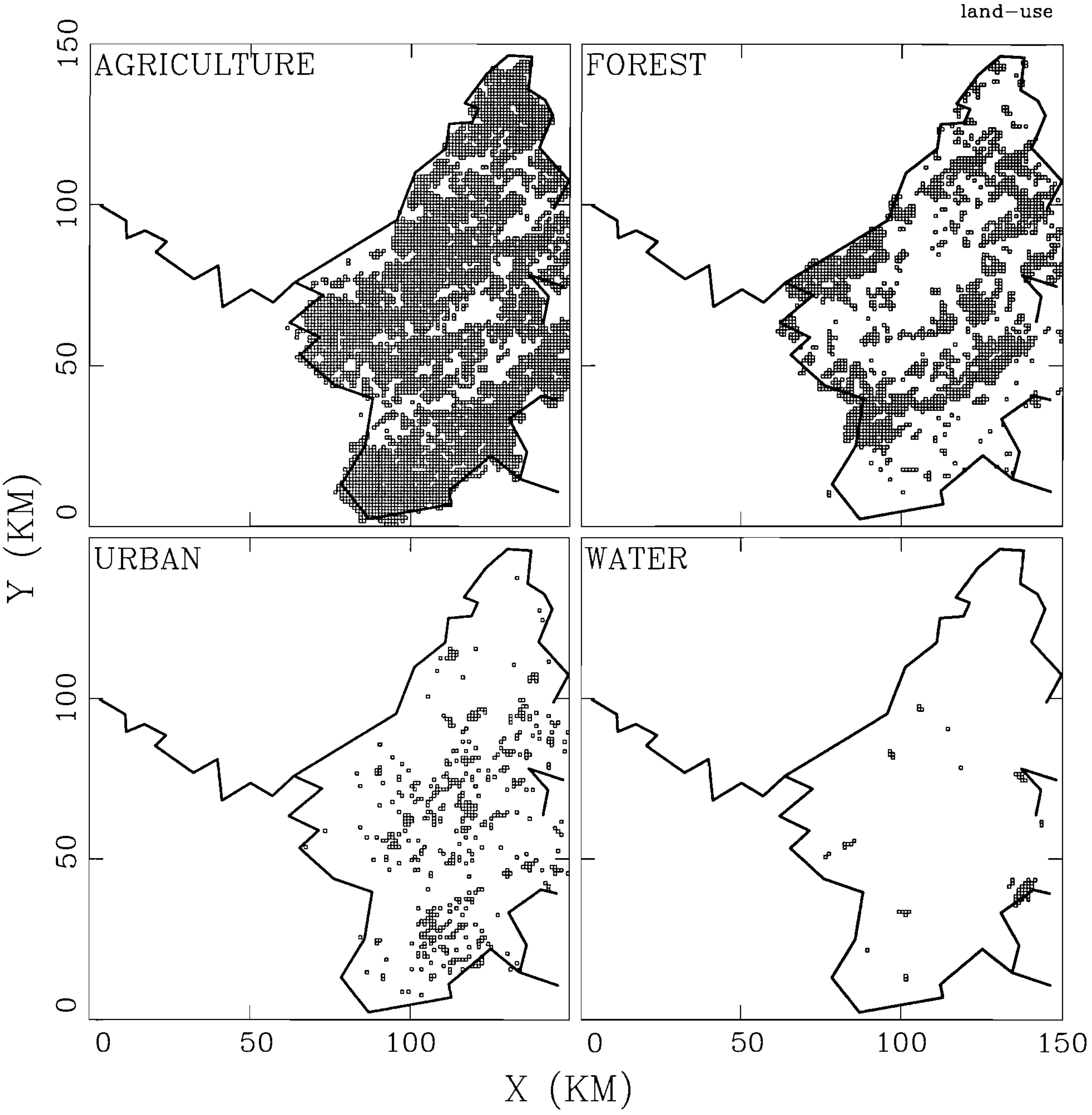

Figure 6: Land use in the Katowice province derived from the IEIA data

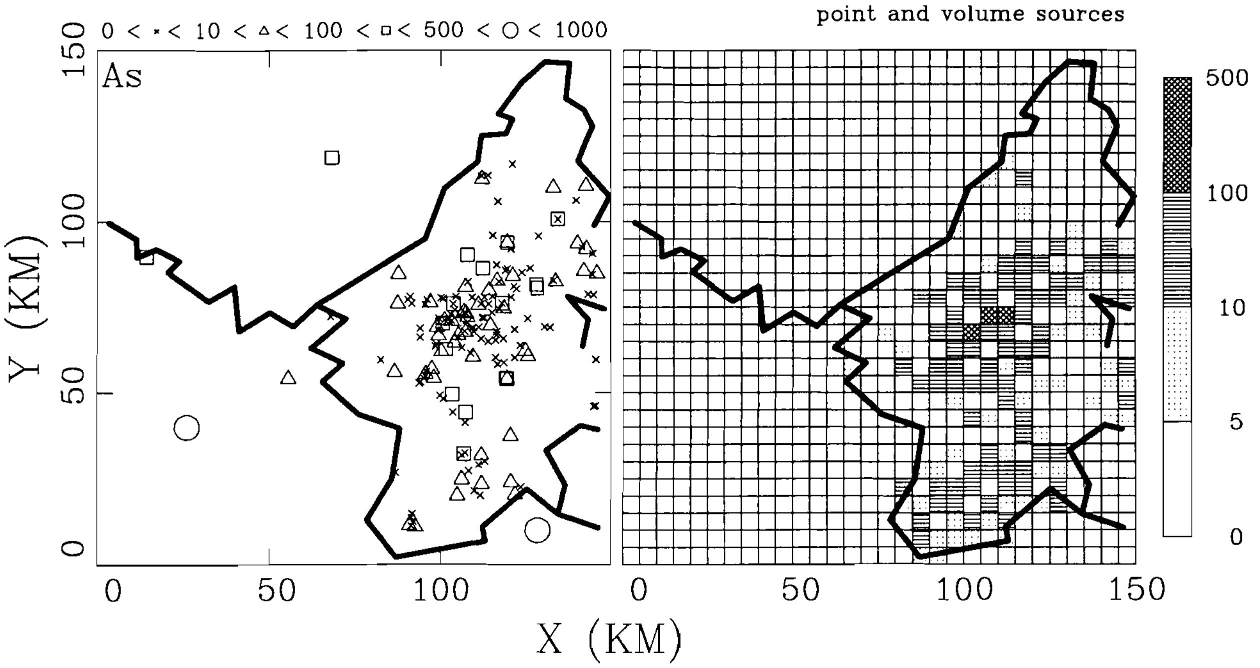

Figure 7: Emission of As in 1992 [kg/year]: point sources (left) and volume sources (right)

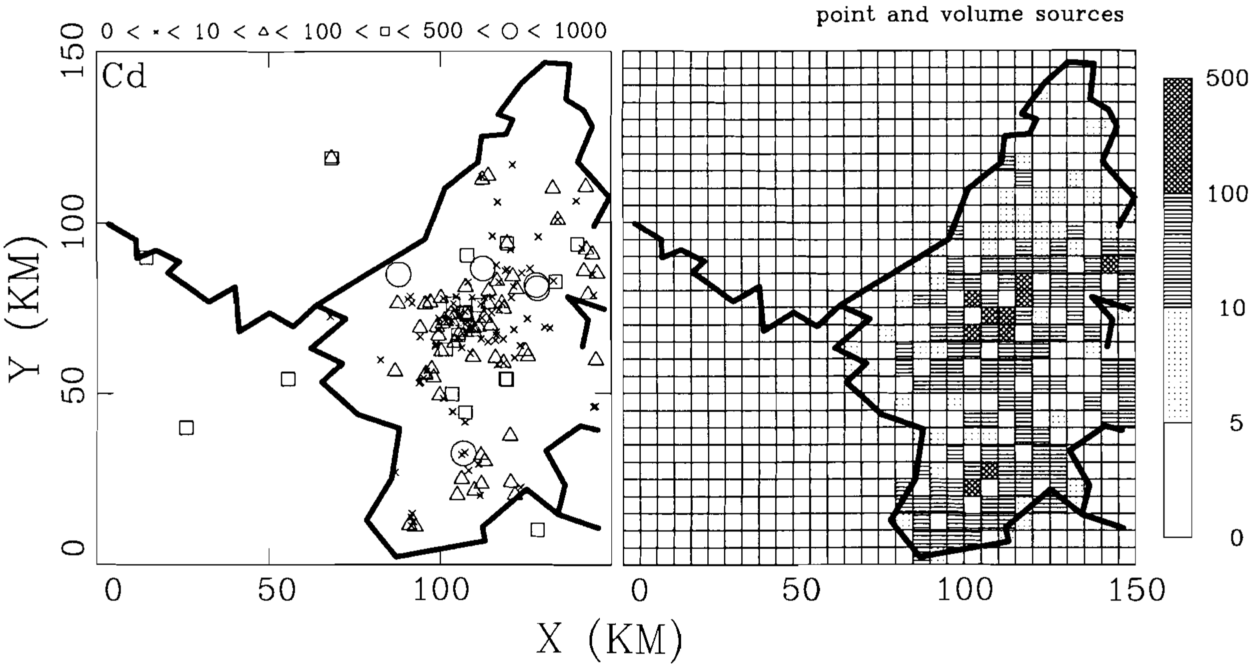

Figure 8: Same as Fig. 7 but for Cd

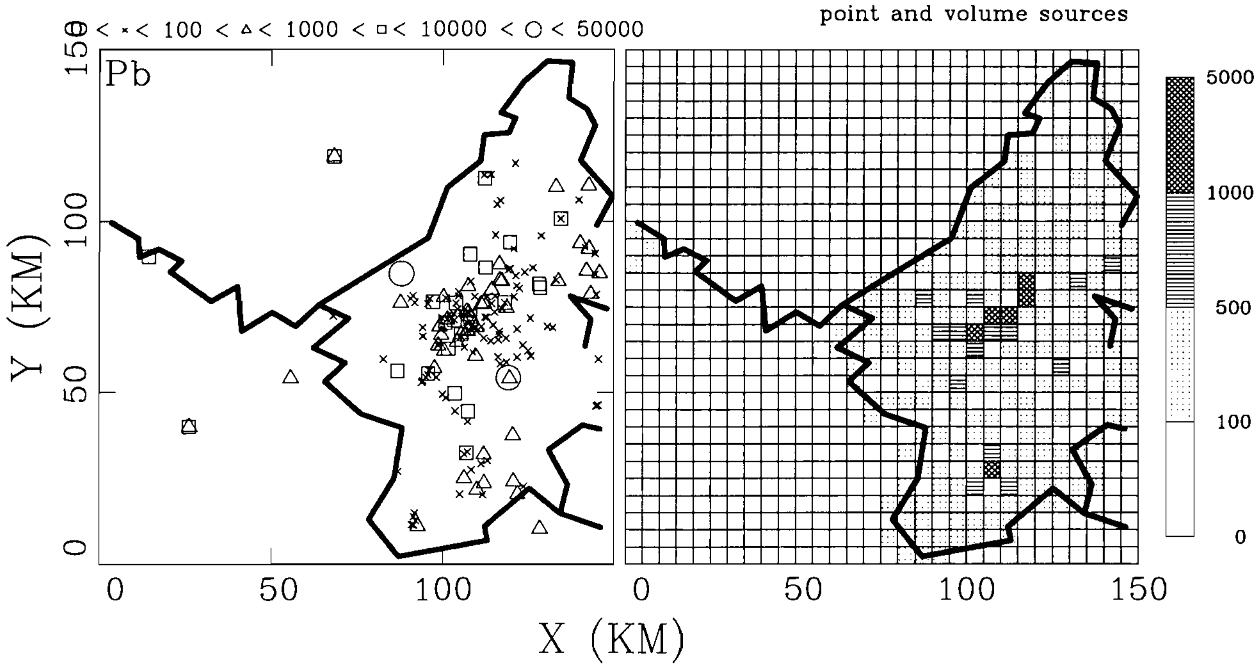

Figure 9: Same as Fig. 7 but for Pb

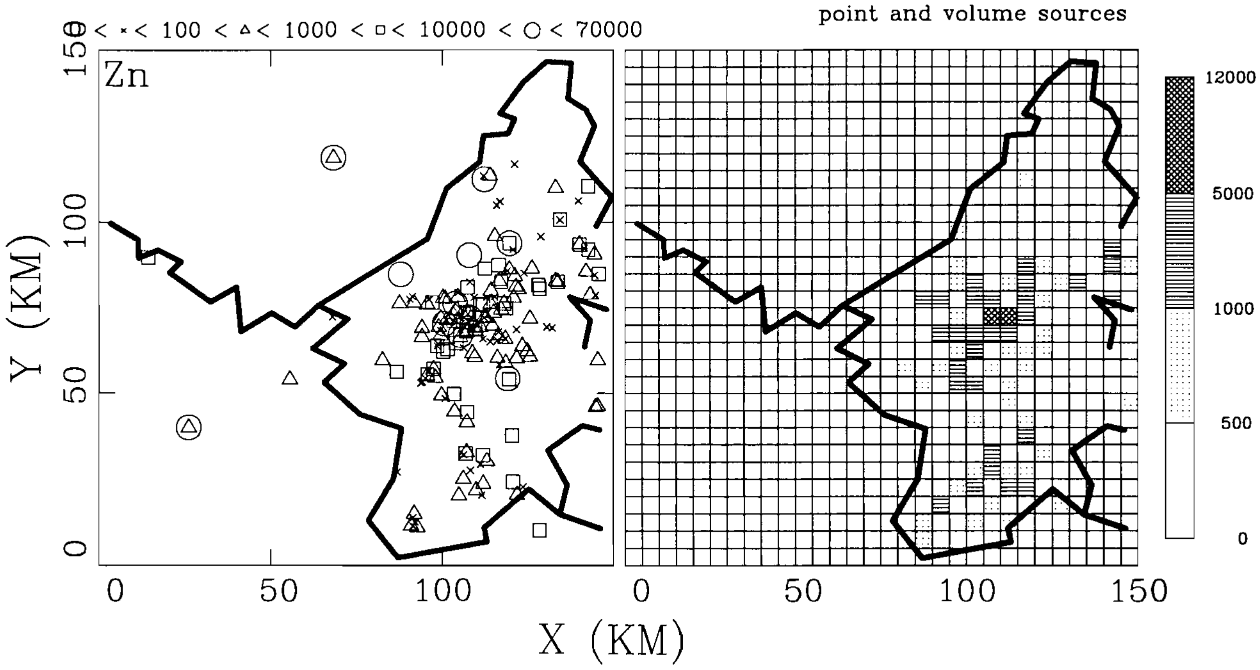

Figure 10: Same as Fig. 7 but for Zn

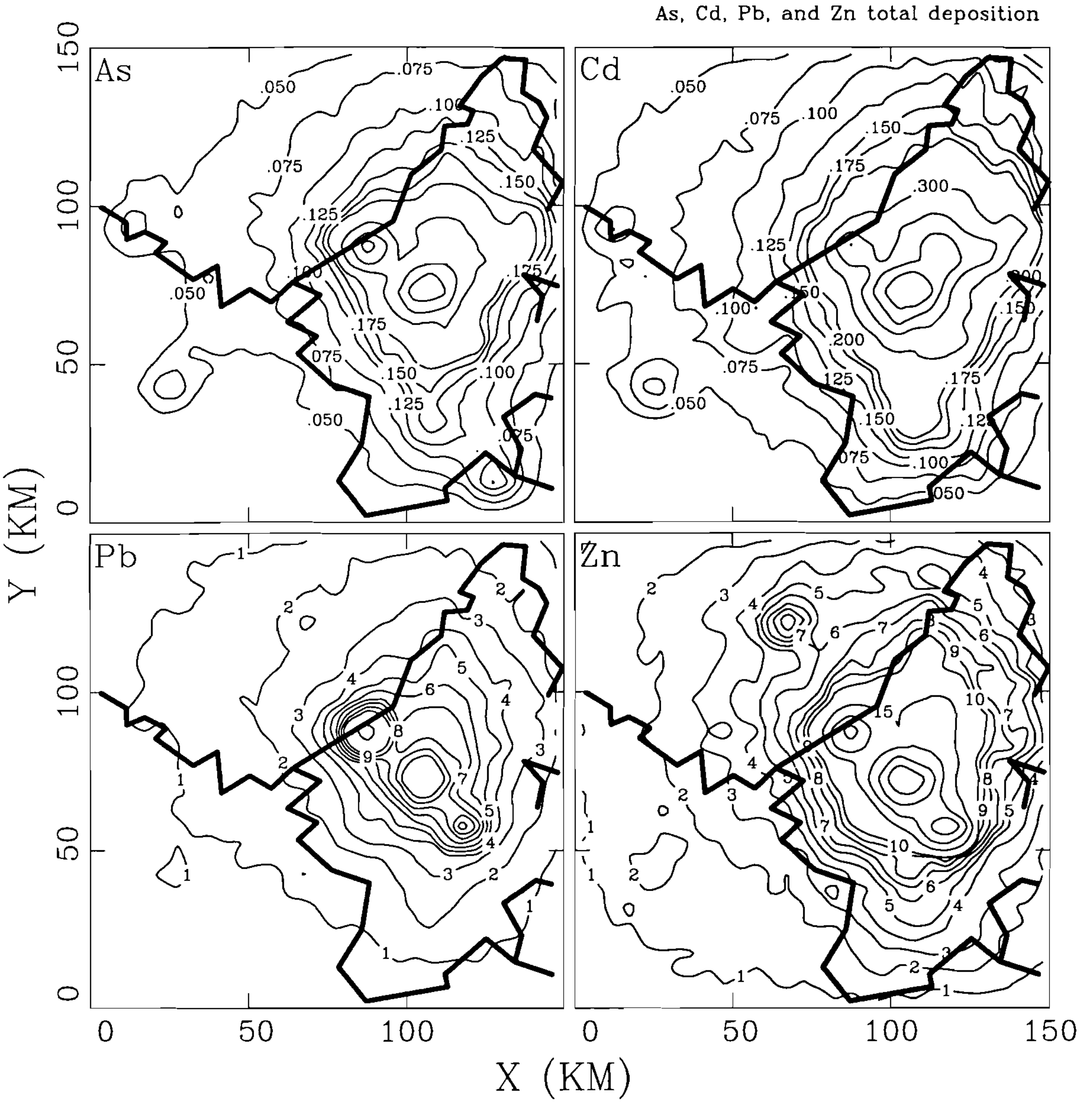

Figure 11: Total deposition [mg/m^2] of As, Cd, Pb, and Zn in 1992 calculated in the reference simulations for the aggregated emission sources

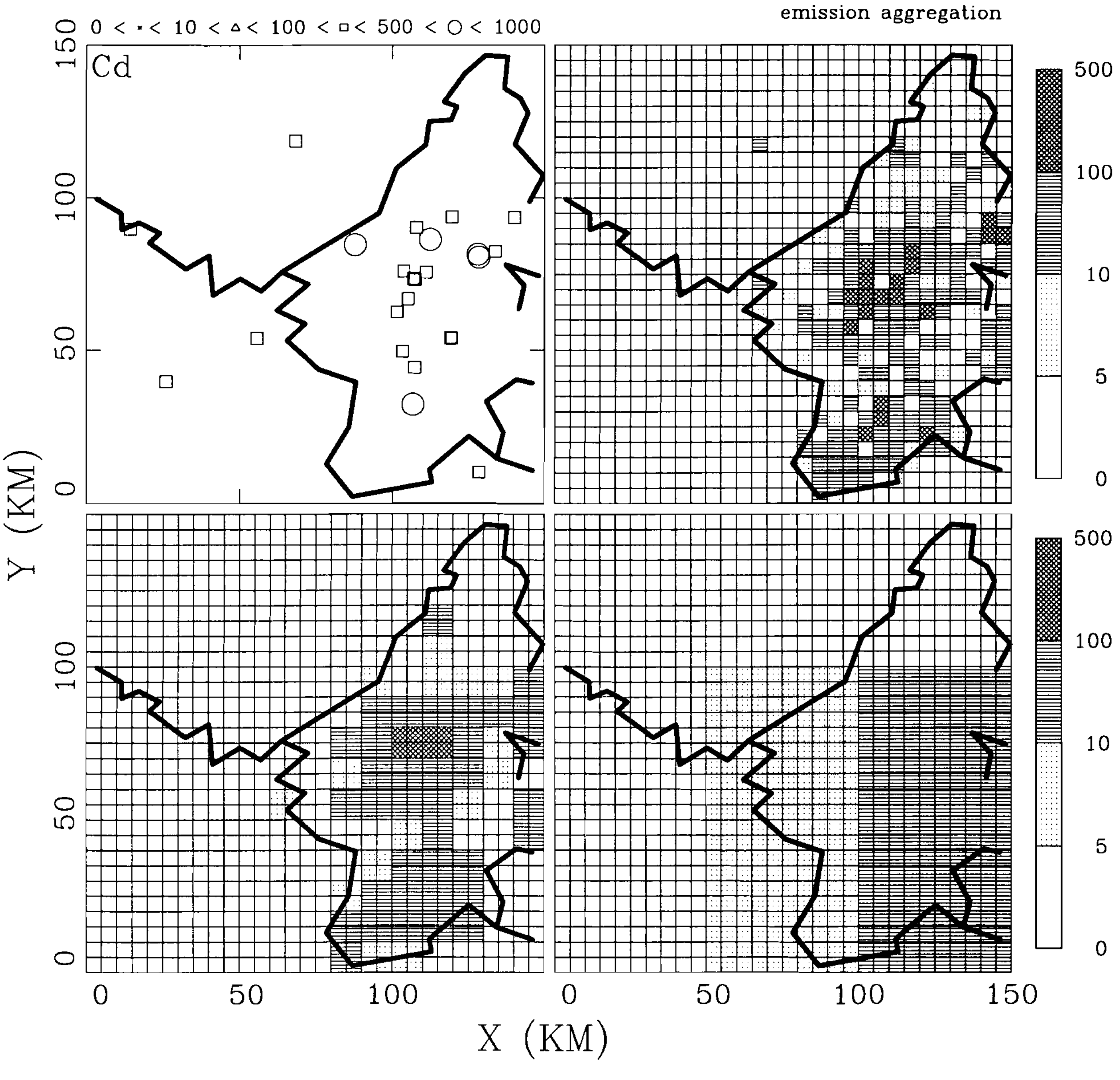

Figure 12: Aggregation of emission sources [kg/year] for Cd: a) major point sources and b) 5×5×0.05 km volume sources used in the reference simulation, c) 10×10×0.5 km volume sources, d) 50×50×0.5 km volume sources

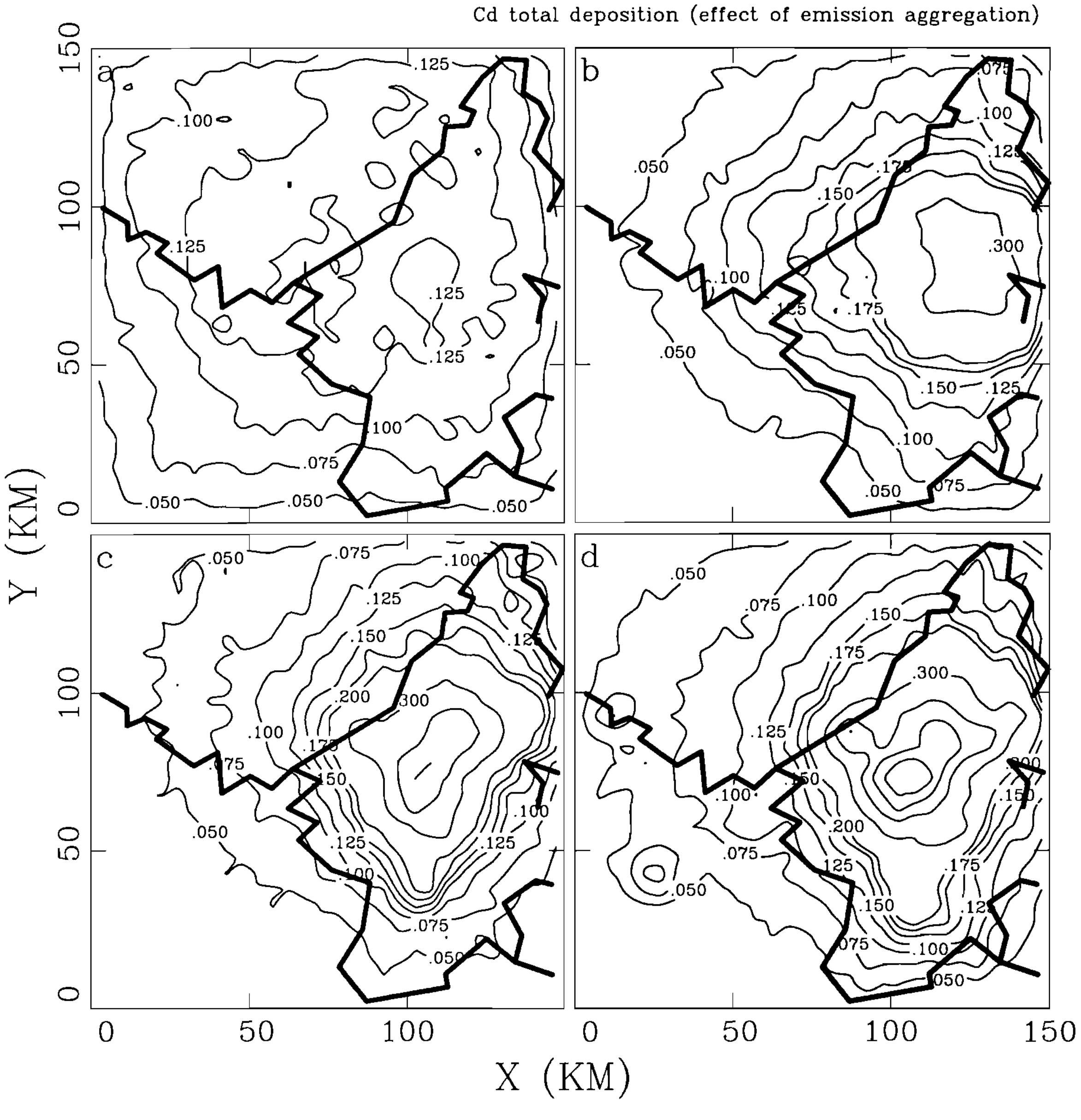

Figure 13: Total deposition of Cd [mg/m^2] in 1992 calculated with different aggregation level of emission sources: a) a single 150×150×0.5 km volume source, b) a grid of 50×150×0.5 km volume sources, c) a grid of 0×10×0.5 km volume sources, d) a grid of 5×5×0.05 km volume sources and major point sources (reference simulation)

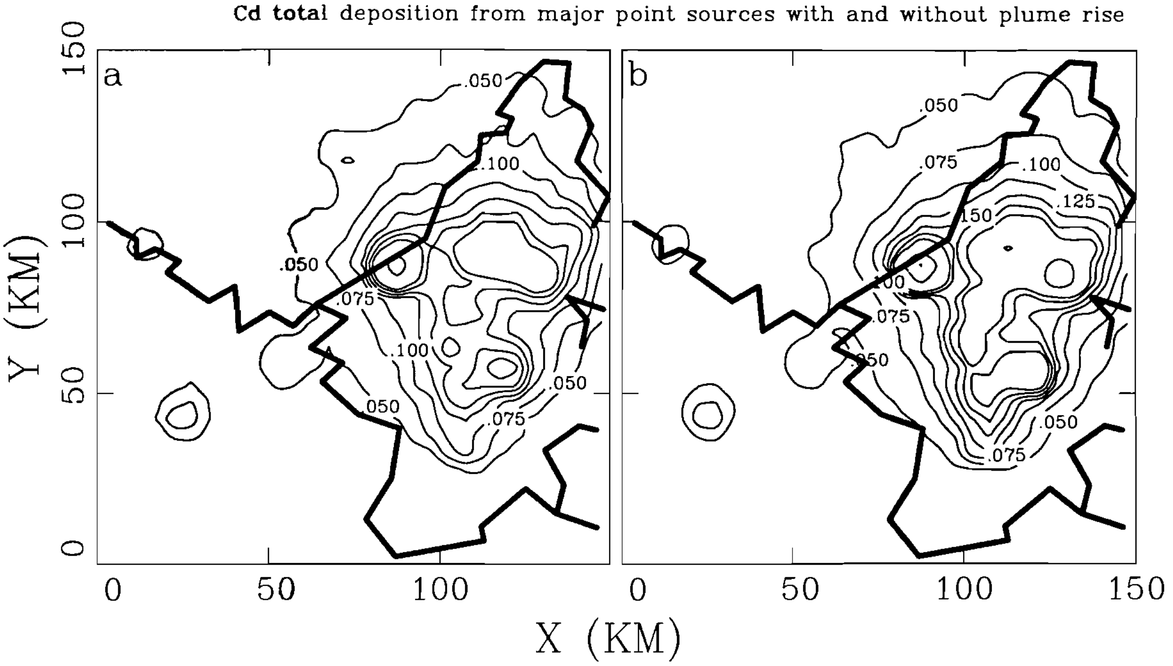
Cd total deposition from major point sources with and without plume rise

Figure 14: Total deposition of Cd $[mg/m^2]$ in 1992 calculated for the major point sources taken into account in the reference simulation with (left) and without (right) plume rise calculations

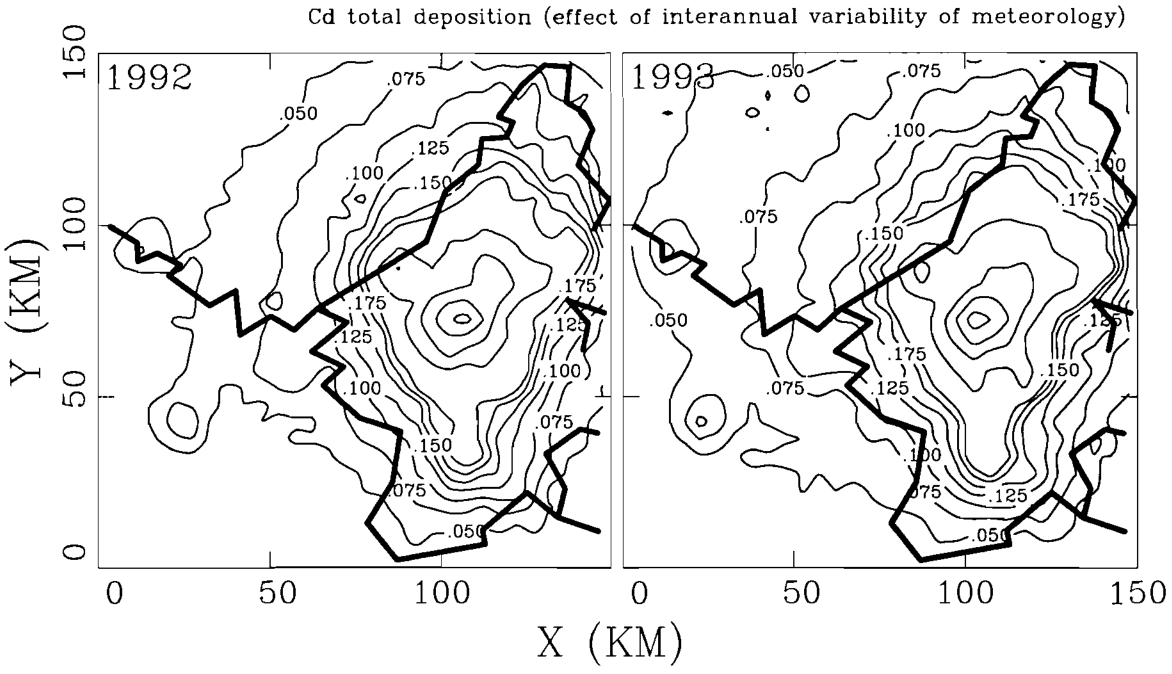
Cd total deposition (effect of interannual variability of meteorology)

Figure 15: Total deposition of Cd $[mg/m^2]$ during nine months (April-December) of 1992 (left) and the same period of 1993 (right) calculated for the emission sources aggregated as in the reference simulation

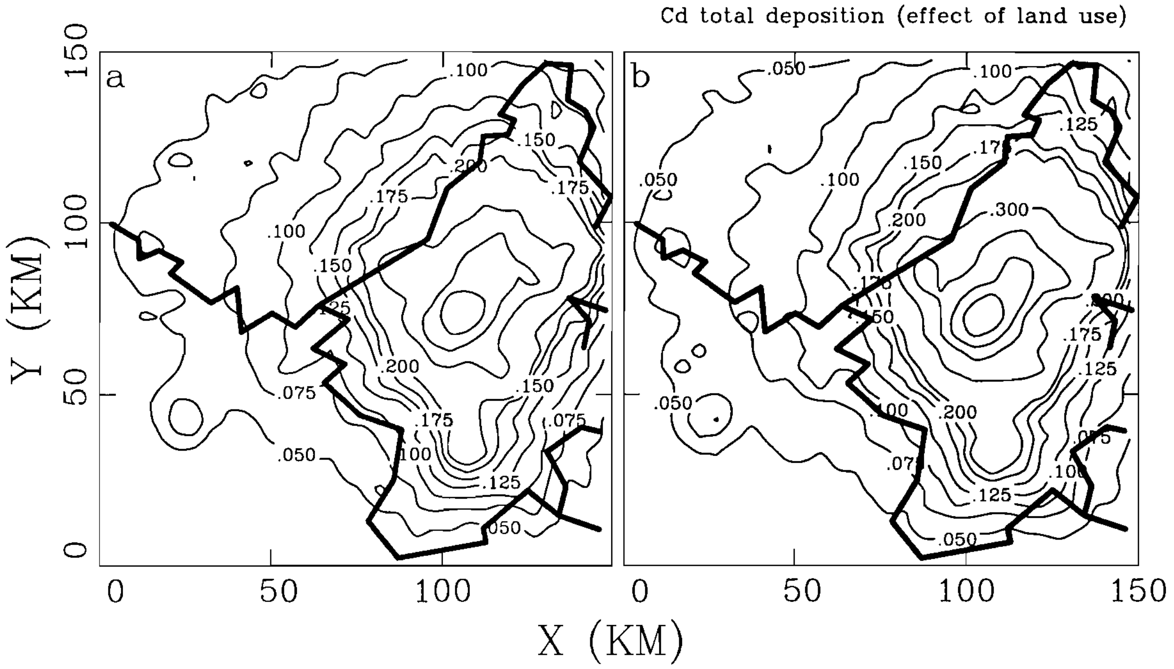

Figure 16: Total deposition of Cd [mg/m^2] in 1992 calculated the same emission sources as in the reference simulation but for the uniform land surface: a) bare soil, b) agriculture land

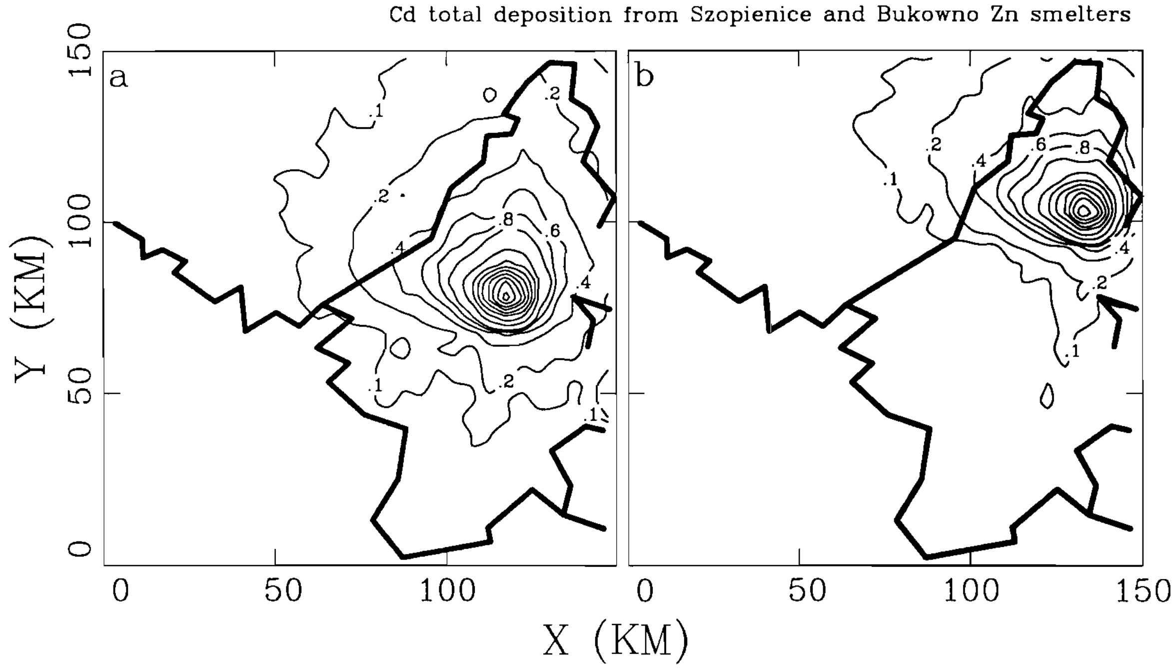

Figure 17: Total deposition of Cd [mg/m^2] in 1992 calculated for two point sources located in (a) Szopienice and (b) Bukowno zinc smelters with the emission rate increased to 25 *ton/year* of Cd each

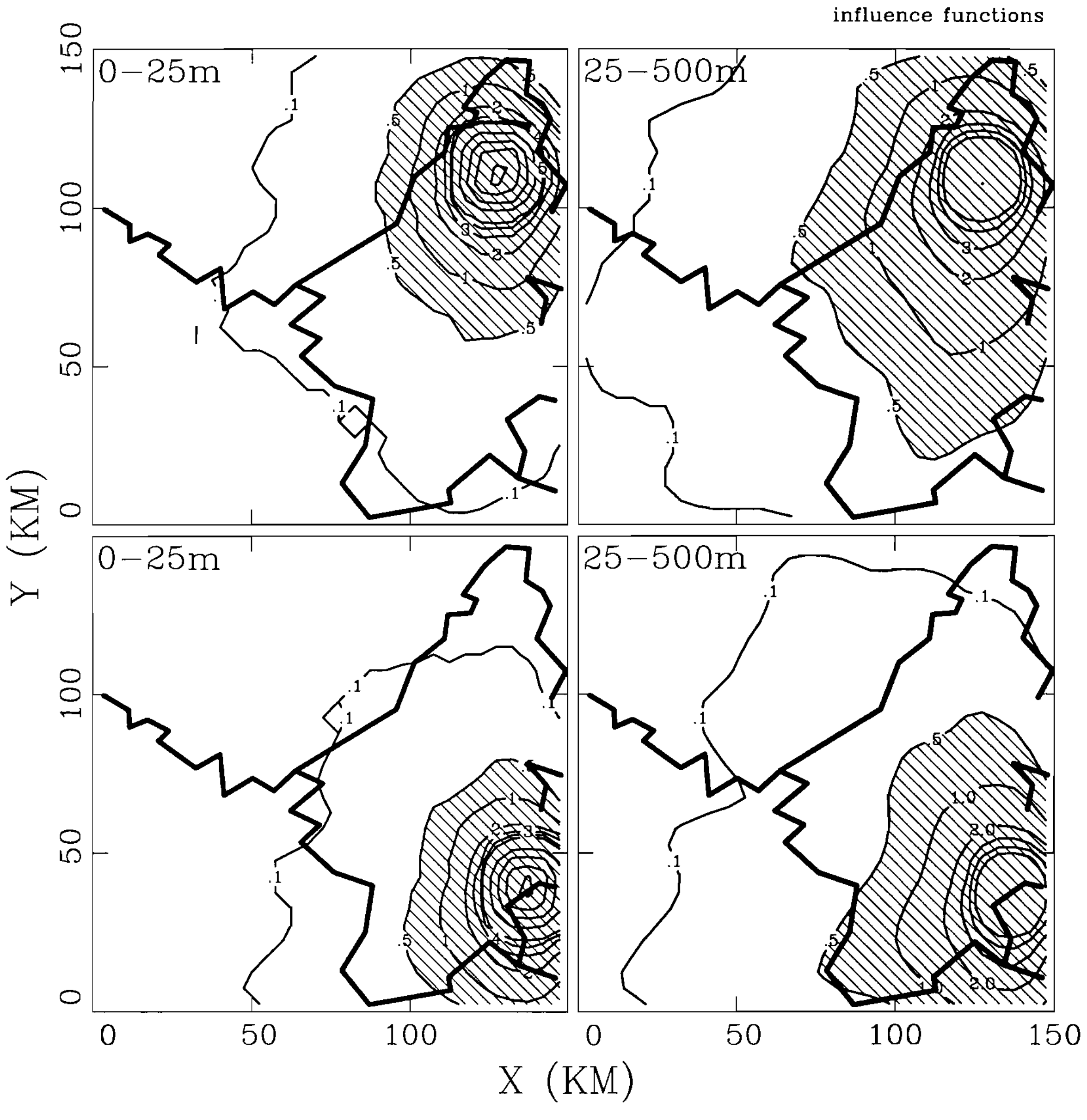

Figure 18: Influence function calculated for the average air concentration of Cd at the receptors located in the Olkusz mining region (top) and the Goczalkowice Reservoir (bottom). These influence function shows the potential impact from the low emission sources located within the layer 0-25 m (left) and within the layer 25-500 m (right).

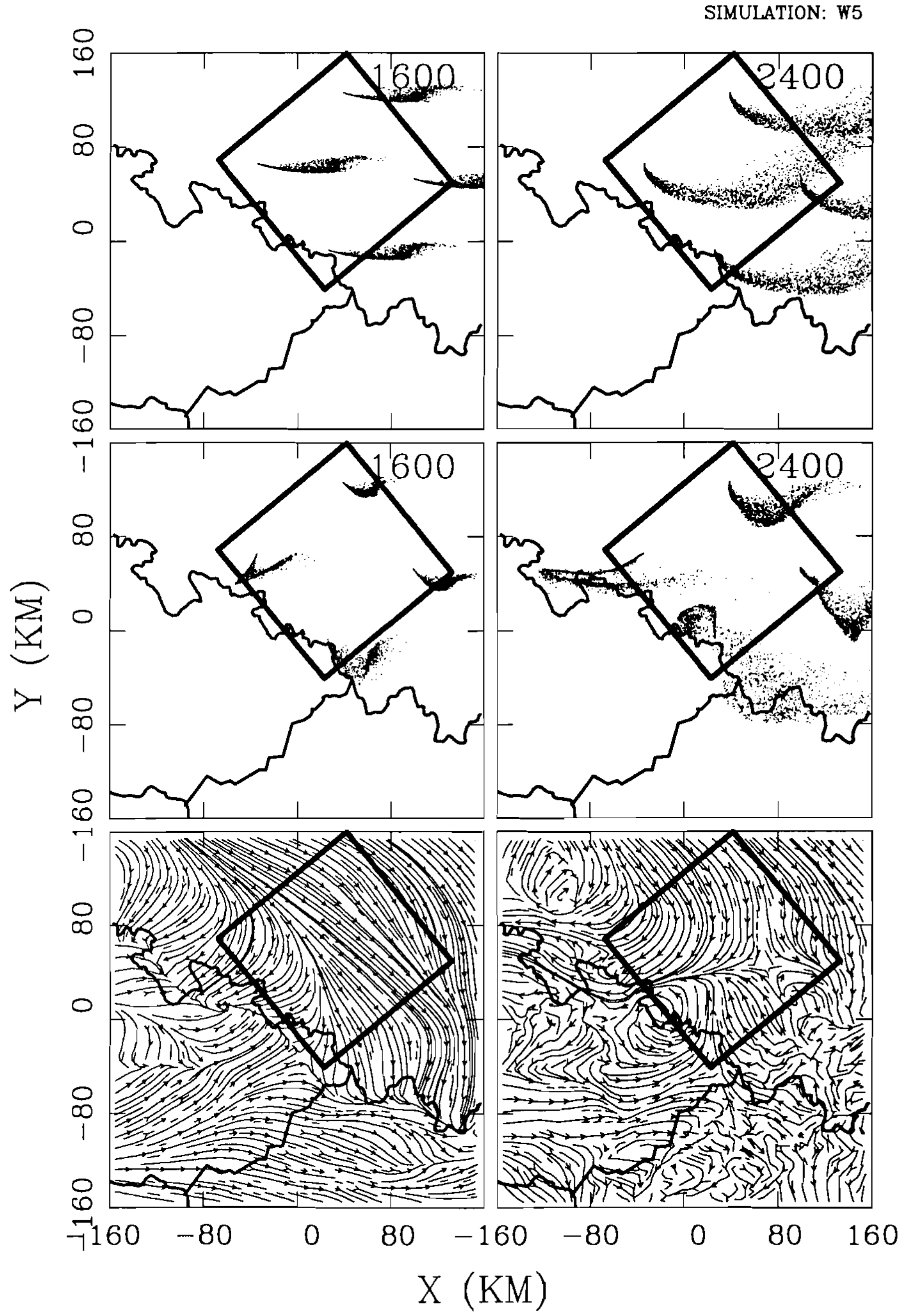

Figure 19: Plumes of passive tracer simulated using 1-dimensional (top) and 3-dimensional meteorological fields ($\Delta x = 5$ km), and streamlines (bottom) at 200 m model level derived from the same 3-dimensional meteorological simulation at 16:00 (left) and 24:00 (right) GMT for $U_g = 5\ m/s$ and $V_g = 0\ m/s$.

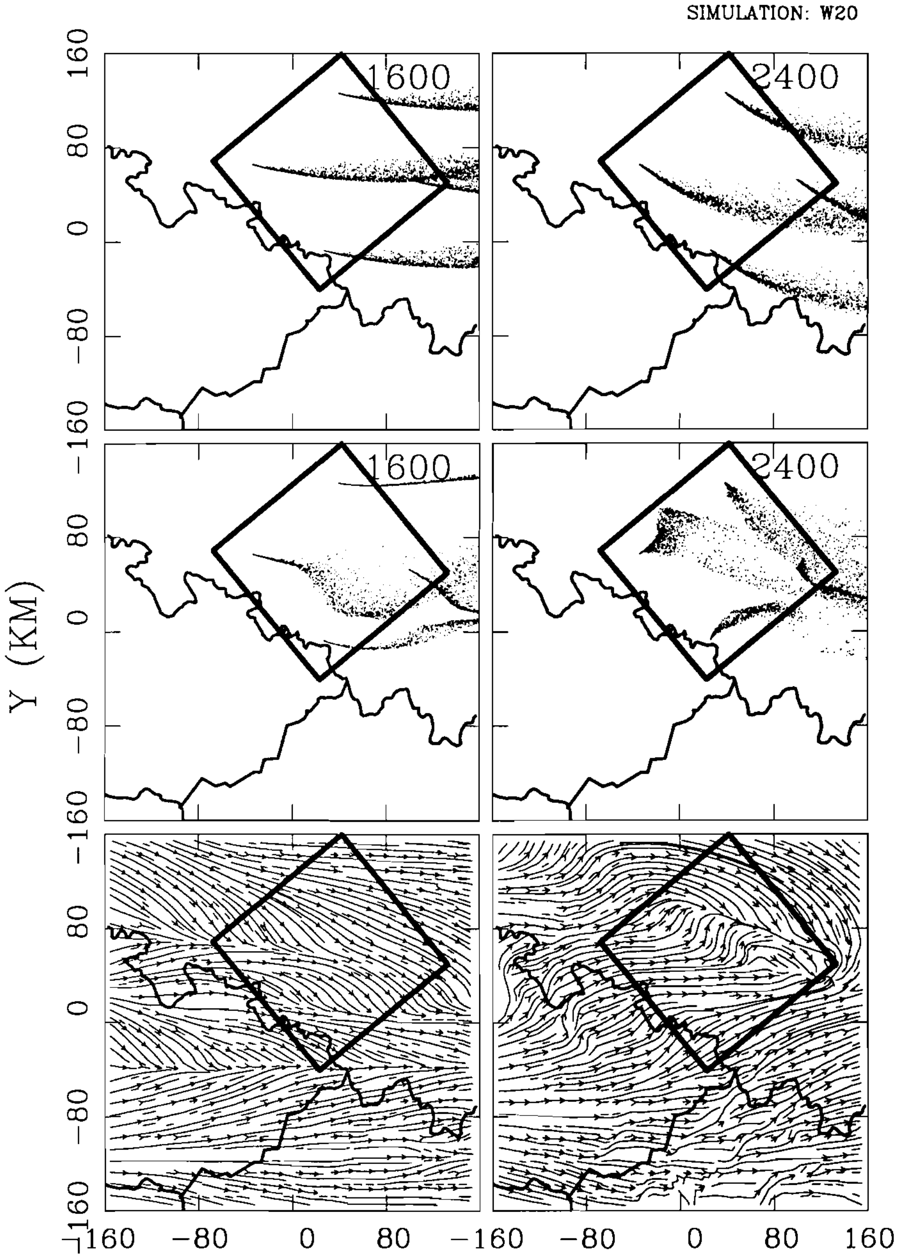

Figure 20: Same as Fig. 19 but for $U_g = 20$ m/s, $V_g = 0$ m/s

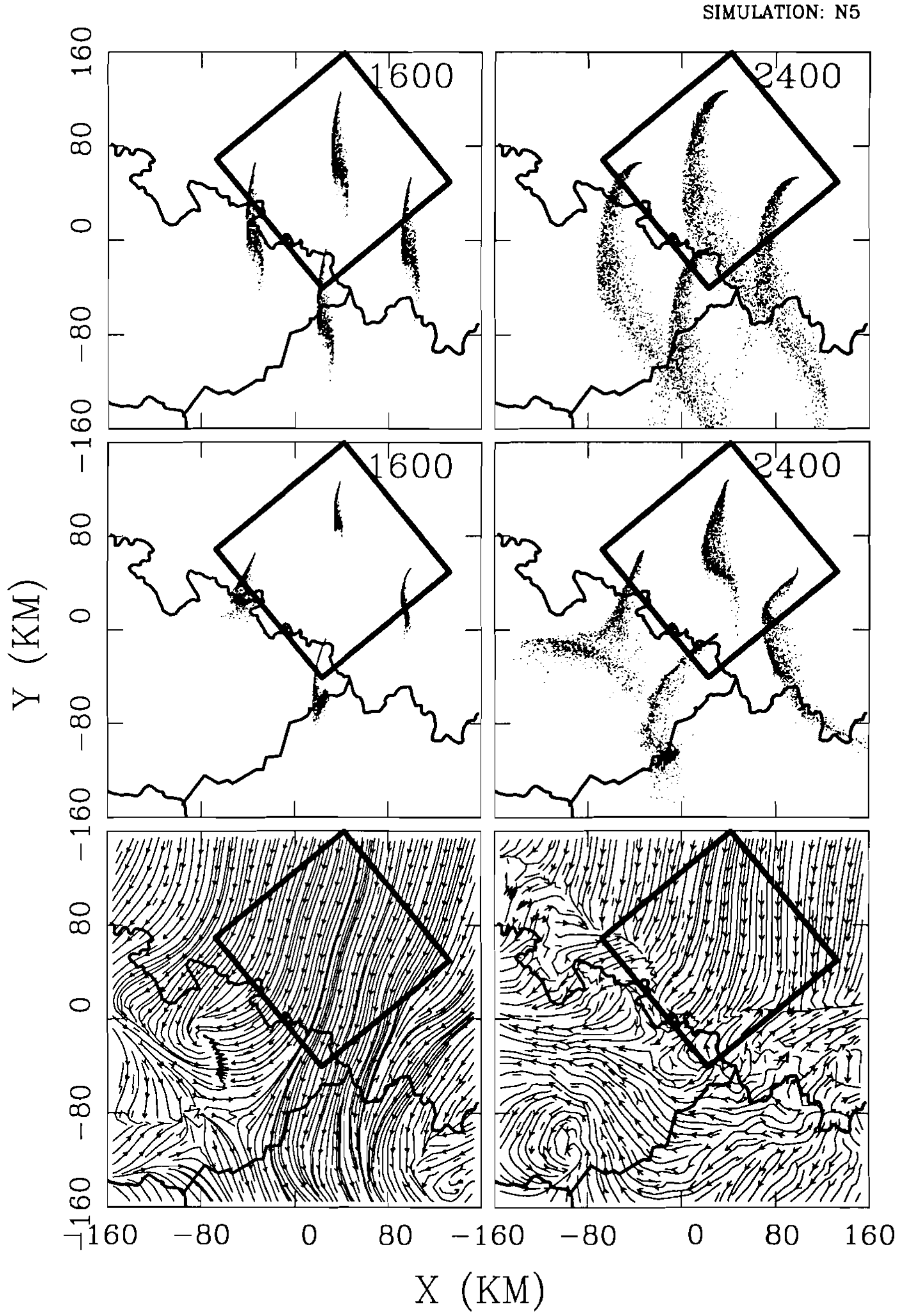

Figure 21: Same as Fig. 19 but for $U_g = 0$ m/s, $V_g = -5$ m/s

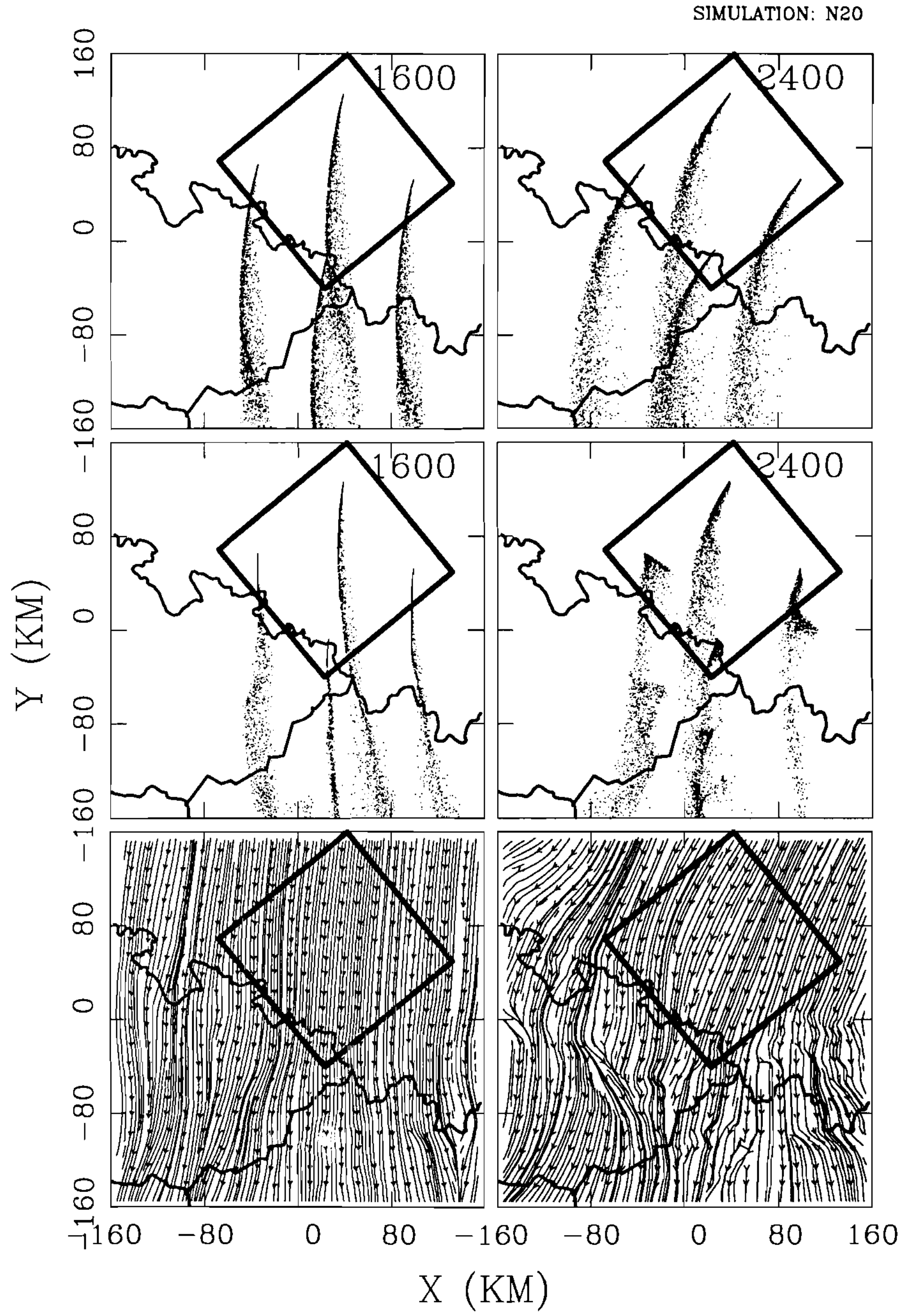

Figure 22: Same as Fig. 19 but for $U_g = 0$ m/s, $V_g = -20$ m/s

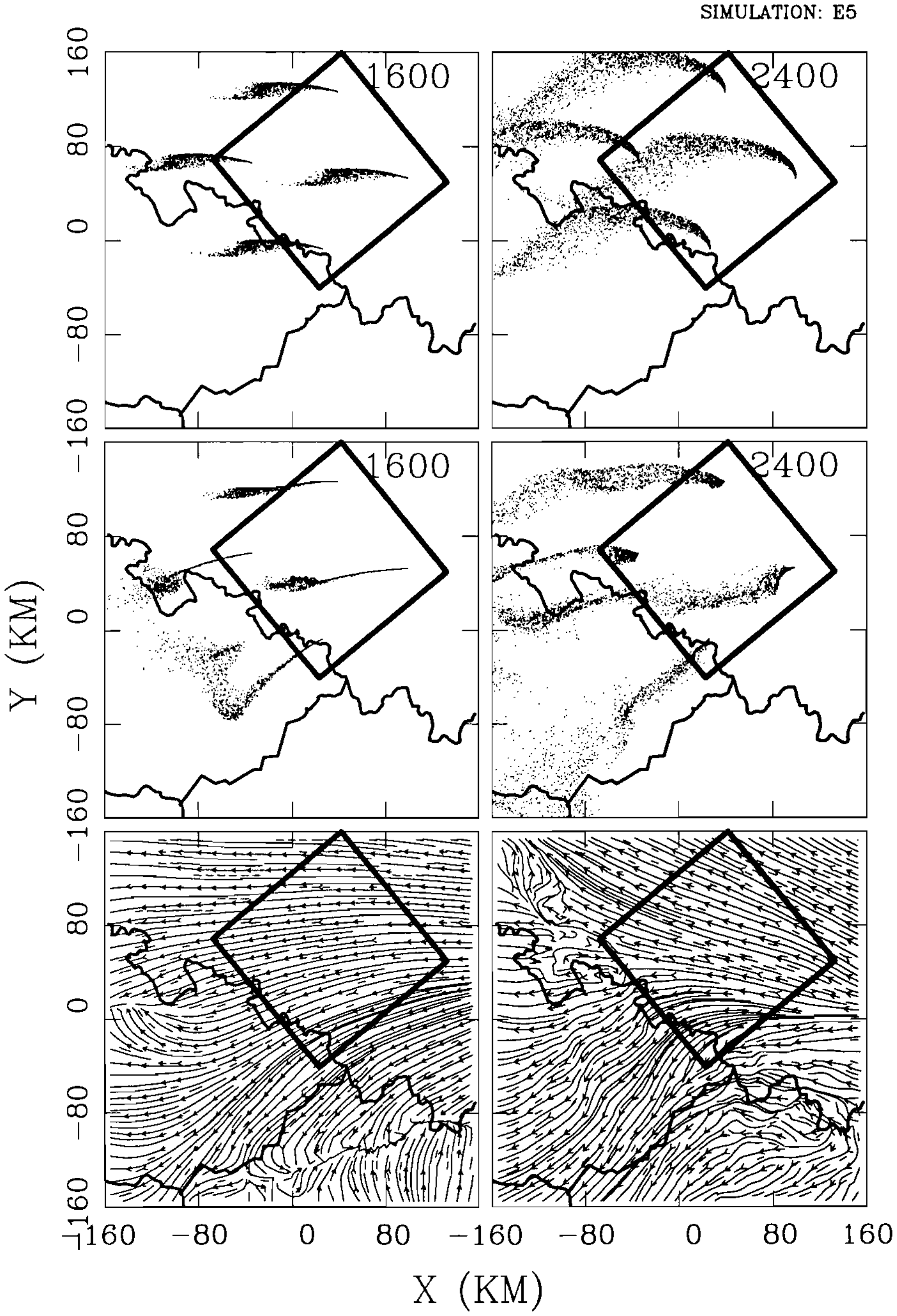

Figure 23: Same as Fig. 19 but for $U_g = -5$ m/s, $V_g = 0$ m/s

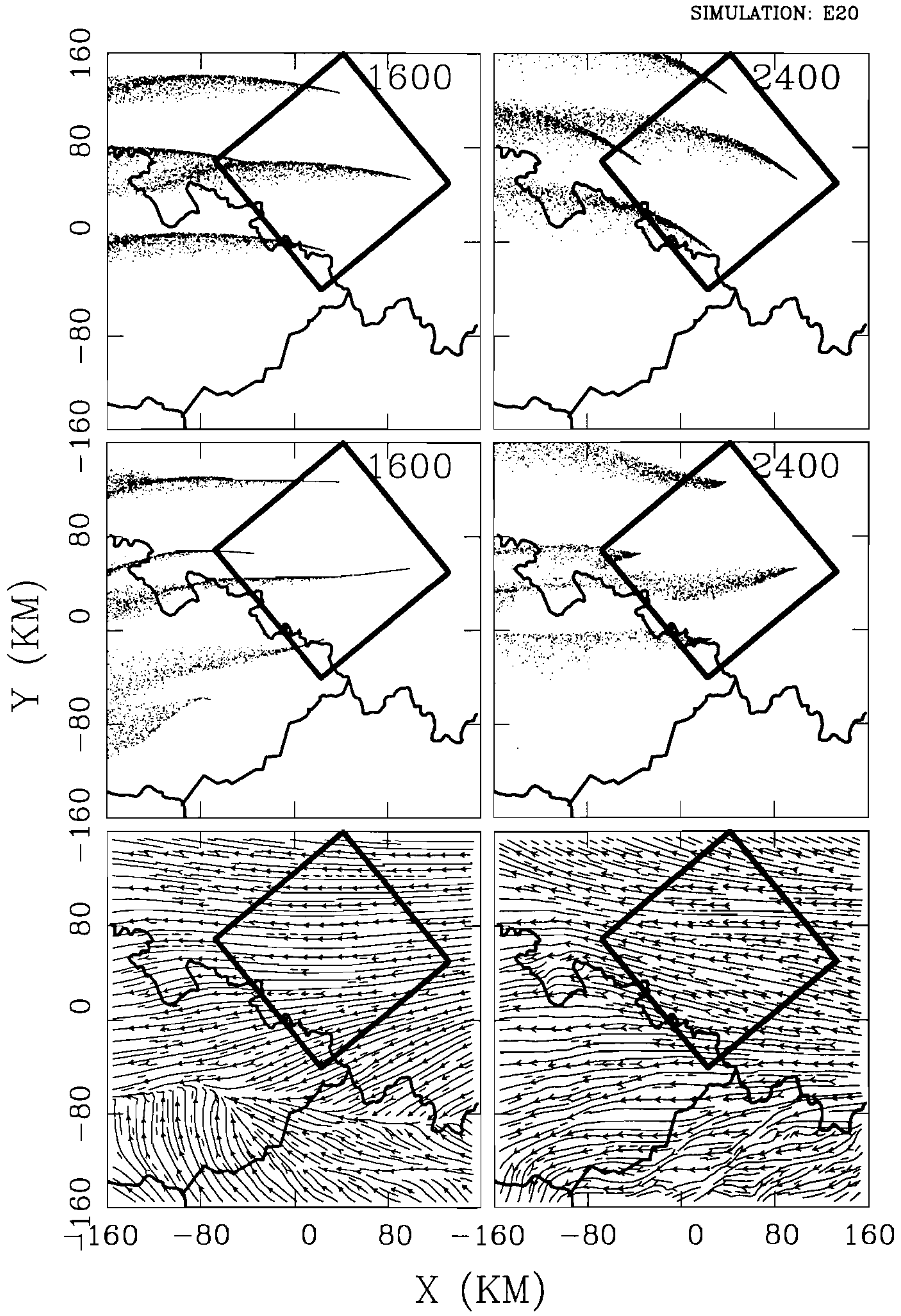

Figure 24: Same as Fig. 19 but for $U_g = -20$ m/s, $V_g = 0$ m/s

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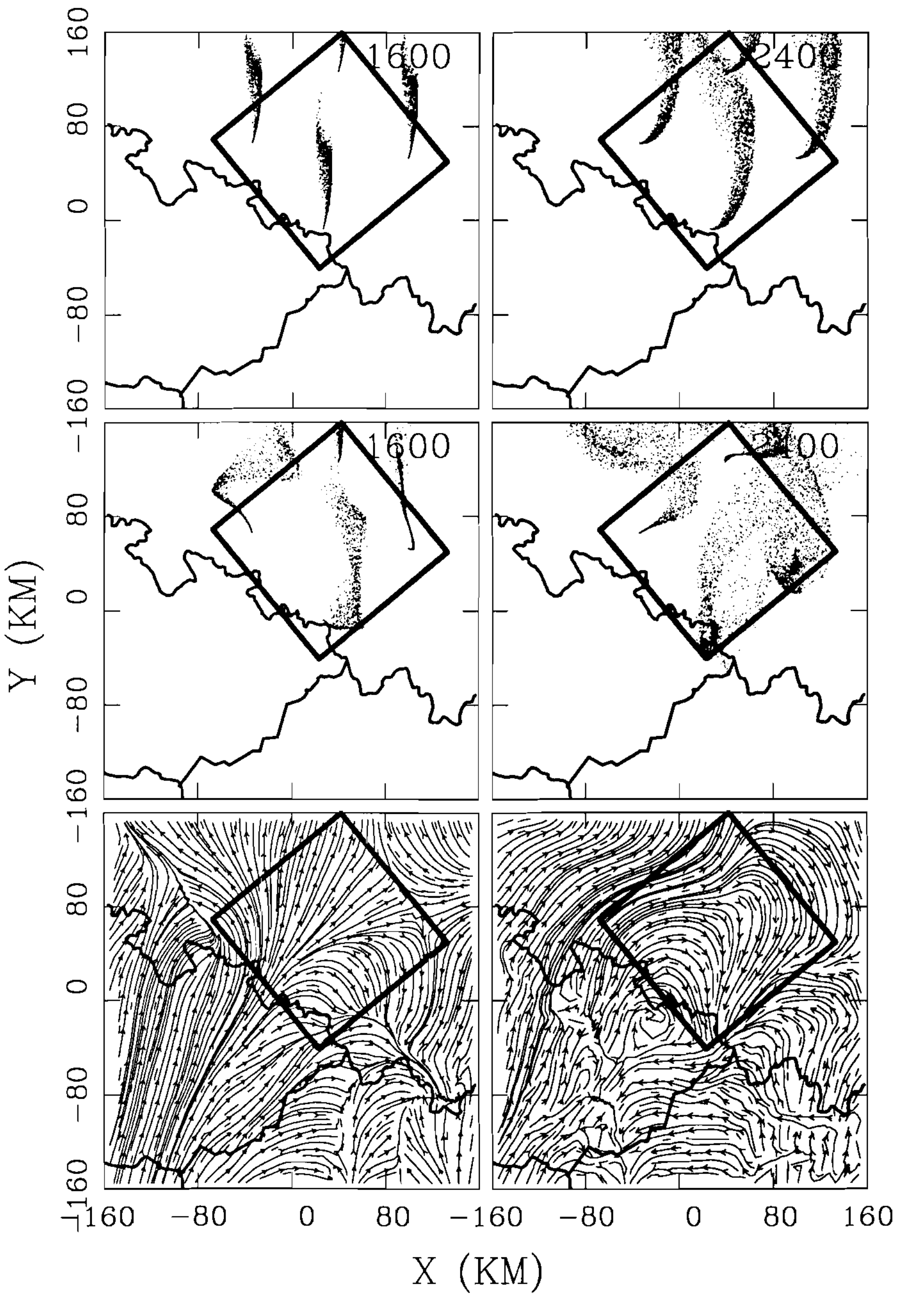

Figure 25: Same as Fig. 19 but for $U_g = 0$ m/s, $V_g = 5$ m/s

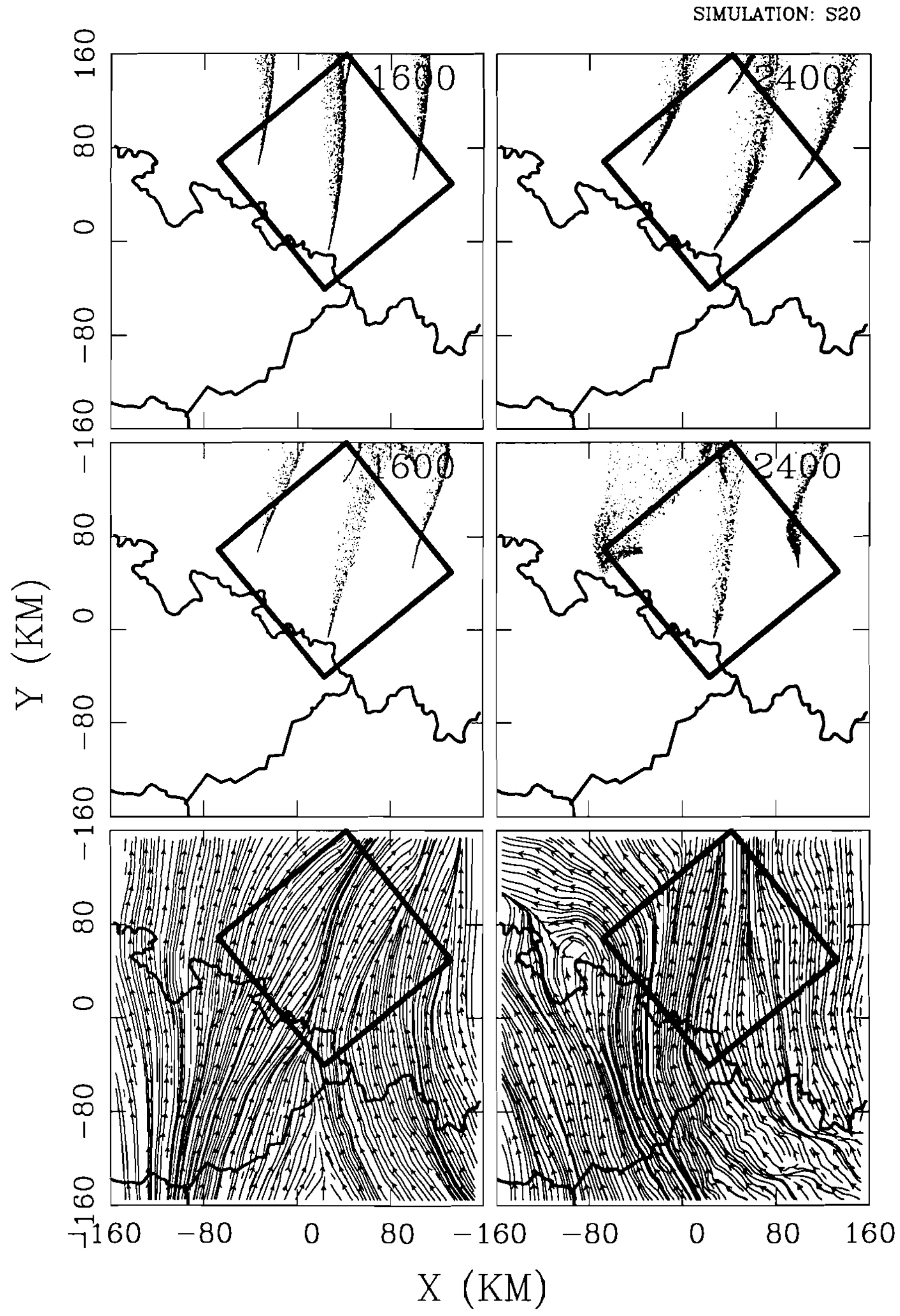

Figure 26: Same as Fig. 19 but for $U_g = 0$ m/s, $V_g = 20$ m/s

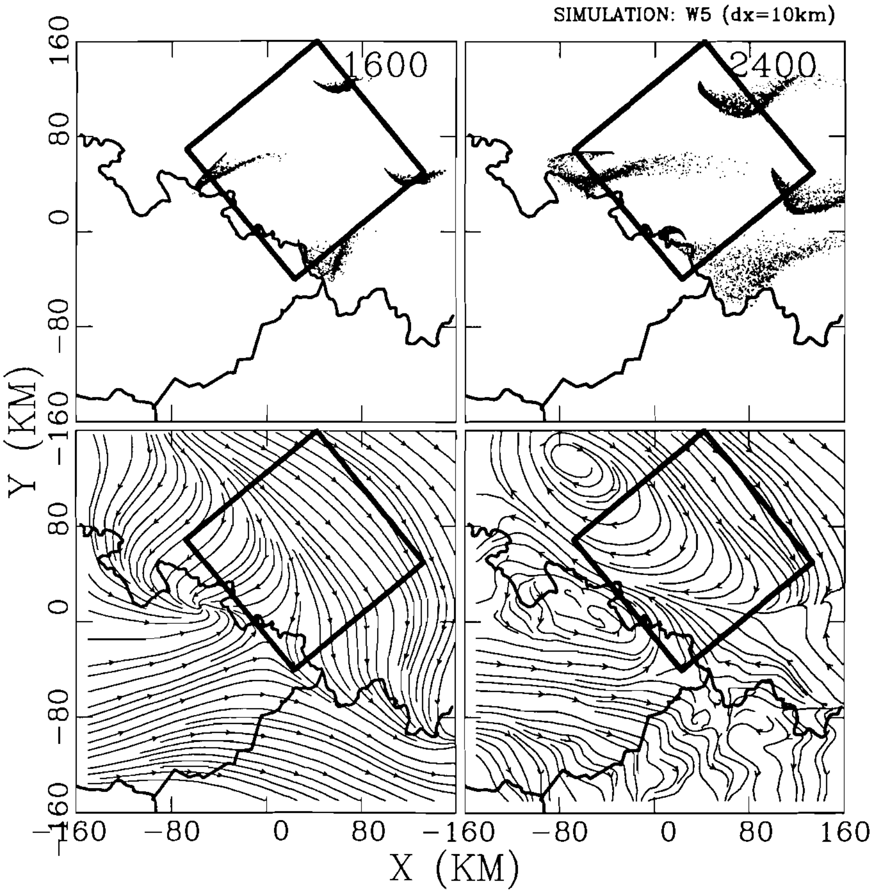

Figure 27: Plumes of passive tracer (top) and streamlines at 200 m model level (bottom) calculated with the aid 3-dimensional meteorological fields with a coarser horizontal resolution ($\Delta x = 10$ km) at 16:00 (left) and 24:00 (right) GMT for $U_g = 5$ m/s and $V_g = 0$ m/s.

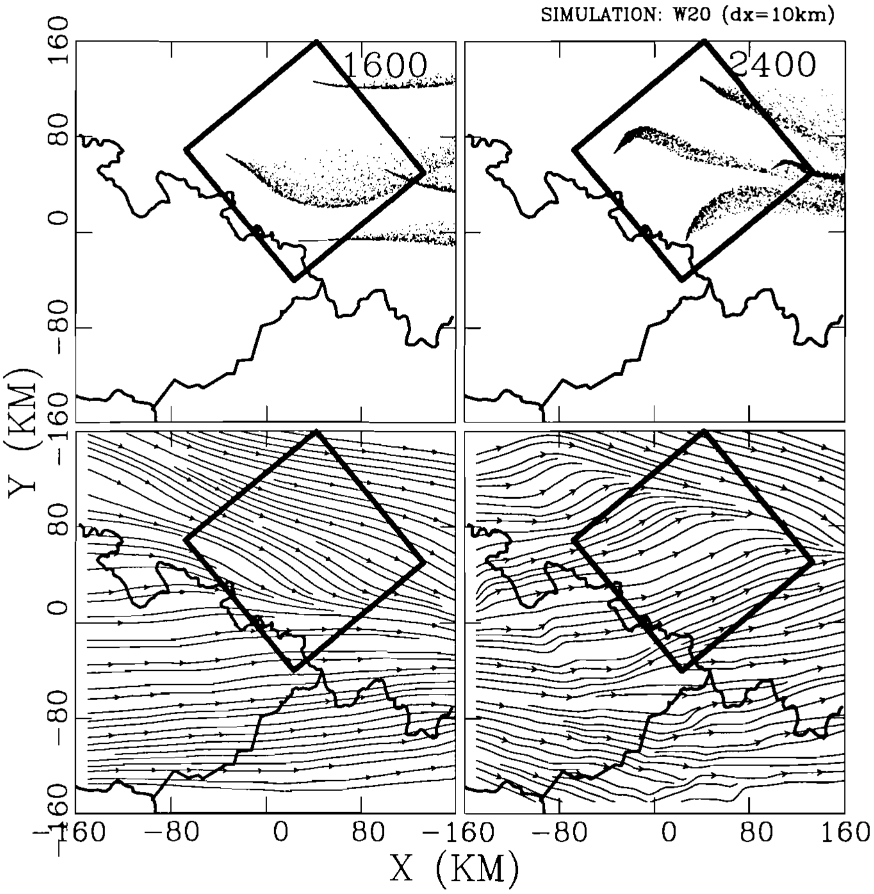

Figure 28: Same as Fig. 27 but for $U_g = 20\ m/s$, $V_g = 0\ m/s$

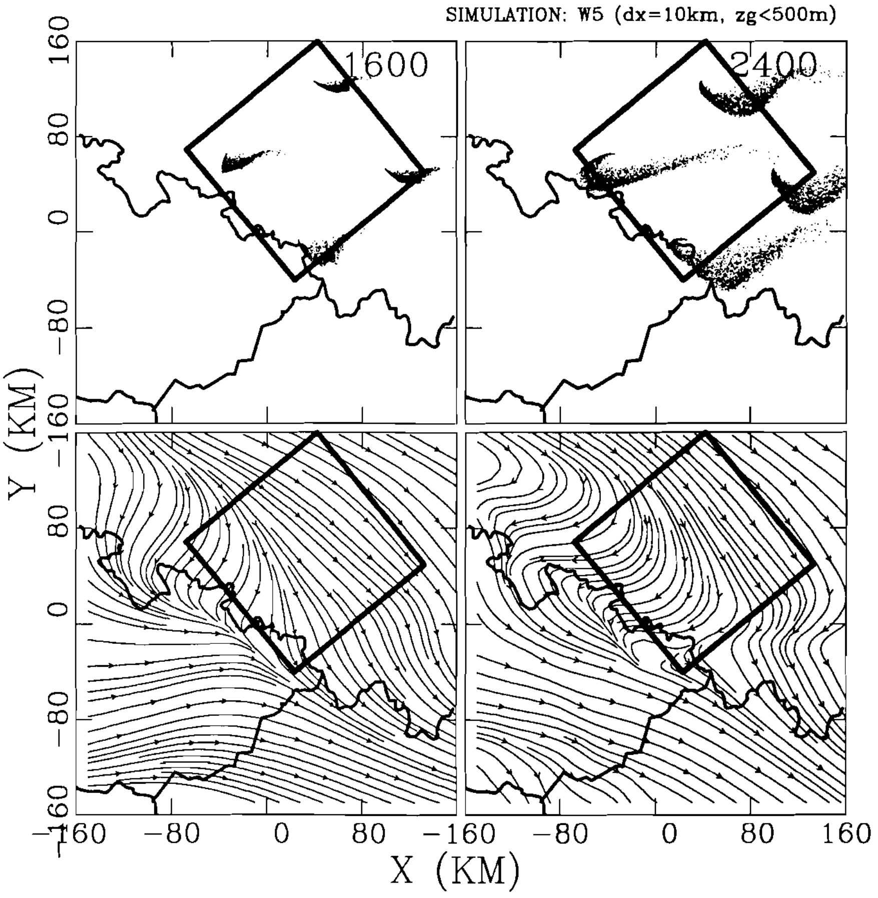

Figure 29: Plumes of passive tracer (top) and streamlines at 200 m model level (bottom) calculated with the aid 3-dimensional meteorological fields with a coarser horizontal resolution ($\Delta x = 10\ km$) and terrain elevation reduced to 500 m above sea level at 16:00 (left) and 24:00 (right) GMT for $U_g = 5\ m/s$ and $V_g = 0\ m/s$.

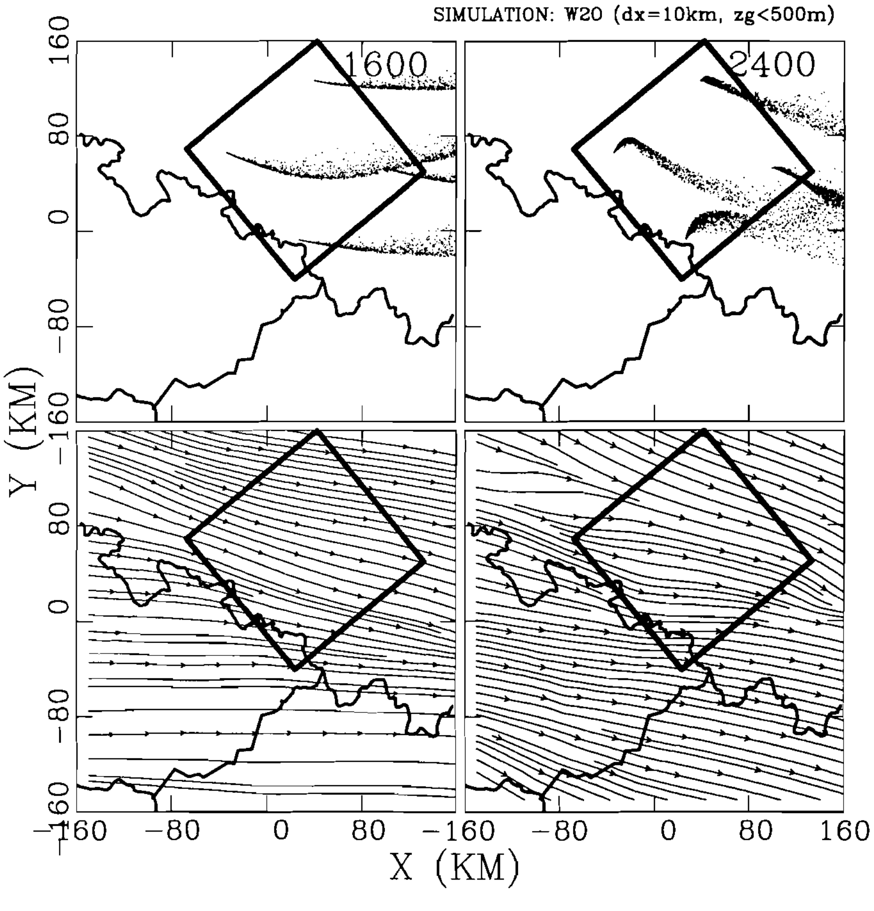

Figure 30: Same as Fig. 29 but for $U_g = 20\ m/s$, $V_g = 0\ m/s$