EMEP Status Report 2/2007

June 2007

Heavy metals:
transboundary pollution of the environment

METEOROLOGICAL SYNTHESIZING CENTRE - EAST

I. Ilyin, O. Rozovskaya, O. Travnikov

CHEMICAL CO-ORDINATING CENTRE

W. Aas

ccc

Norwegian Institute for Air
Research (NILU)
P.O.Box 100
N-2027 Kjeller
Norway
Phone: +47 63 89 81 58
Fax: +47 63 89 81 58
E-mail: kjetil.torseth@nilu.no
Internet: www.nilu.no

ciam

International Institute for
Applied Systems Analysis
(IIASA)
A-2361 Laxenburg
Austria
Phone: +43 2236 80 70
Fax: +43 2236 71 31
E-mail: amann@iiasa.ac.at
Internet: www.iiasa.ac.at

msc-e

Meteorological Synthesizing
Centre - East
Leningradsky prospekt, 16/2
125040 Moscow
Russia
Tel.: +7 495 614 39 93
Fax: +7 495 614 45 94
E-mail: msce@msceast.org
Internet: www.msceast.org

msc-w

Norwegian Meteorological
Institute (met.no)
Postboks 43 Blindren
N-01313 Oslo
Norway
Phone: +47 22 96 30 00
Fax: +47 22 96 30 50
E-mail: emep.mscw@met.no
Internet: www.emep.int

EXECUTIVE SUMMARY

In accordance with the EMEP Workplan for 2007 [*ECE/EB.AIR/ 2006/10*] Meteorological Synthesizing Centre – East (MSC-E) and Chemical Co-ordinating Centre (CCC) continued their research activities in the field of heavy metal (HMs) atmospheric pollution assessment. The major goal of this work is to assess regional-scale levels of pollution in Europe of lead, cadmium and mercury by means of monitoring and atmospheric modelling. Particular attention was paid to implementation of the recommendations formulated by the the EMEP Task Force of Measurements and Modelling aimed at evaluation and further improvement of the MSC-E heavy metal model. Furthermore, MSC-E contributed to the Task Force on Heavy Metals and the Task Force on Hemispheric Transport of Air Pollution. The report summarizes the results of scientific work achieved by MSC-E and CCC in 2007.

At present the EMEP monitoring network contains 64 stations reported data on lead and cadmium concentrations in air and in precipitation. There were 19 stations where at least one form of mercury was reported. Nevertheless, spatial coverage with measurements of the southern and eastern parts of Europe is unsatisfactory. Results achieved in the annual analytical intercomparison of national laboratories clearly indicate data quality improvement of the EMEP measurements since 1995. However, problems with analytical processing of measurement data were indicated for some countries.

Measurements of heavy metal concentrations in 2005 demonstrated that the lowest concentrations of lead, cadmium and mercury were observed in Northern Scandinavia. The highest concentrations were measured in the central part of Europe.

In 2007 as much as 30 EMEP Parties submitted official emission data on lead, cadmium and mercury for 2005 reporting year. Information on gridded emissions was presented by 24 countries at least for one year in the period 1990-2005. Among them 17 EMEP countries have changed previously reported national emission data for the period 1990–2004. Emissions of some metals in some countries changed due to the revision by more than 100%. Analysis of the emissions data by source categories has shown manufacturing industries and construction is the largest contributor to the total lead and cadmium emissions in Europe (41% and 45%, respectively), whereas public electricity and heat production is the prevailing source of mercury emissions (42%).

In accordance with the recommendations of TFMM MSC-E continues further development and improvement of the heavy metal transport model and input data required for modelling. The scheme of wind re-suspension of mineral dust and particle-bound heavy metals from soil and seawater has been further developed. Particularly, an effect of soil characteristics on dust production and suspension were taken into account. Another activity aimed at improvement of the model formulation was connected with evaluation of input meteorological data. The system of meteorological data quality control has been applied to evaluation of the pre-processed meteorological fields against those from independent datasets.

Evaluation of the modeling results against observations has shown that calculated concentrations of heavy metals well correlate with measured values. In general, the modelled levels of lead underestimate measurements by 20-30%, of cadmium – 30-50%. The most significant underestimation was obtained at sites located in Central Europe and Northern Scandinavia. The reasons of the underestimation the most probably connected with uncertainties of spatial distribution of emissions in these regions or with missed local sources. Mercury levels are well reproduced by the model: the difference between modelled and measured values does not exceed 15% for air concentrations and commonly within ±45% for concentration in precipitation.

Evaluation of lead, cadmium and mercury depositions, concentrations and source-receptor relationships for 2005 was carried out on the basis of officially reported emission data. According to the modelling results depositions of lead, cadmium and mercury in 2005 varied significantly across Europe. The highest atmospheric pollution levels were indicated for countries of Central, Eastern and South-Eastern Europe and in some regions of the Western Europe.

Estimated contribution of the wind re-suspension of particle-bound heavy metals to atmospheric depositions over Europe is comparable or even exceeds contribution of anthropogenic sources in a number of countries, particularly, for lead. However, the current estimates of wind re-suspension are subject of significant uncertainty because of developing status of the model dust suspension scheme.

The influence of the transboundary transport on heavy metal depositions in Europe is significant. Contribution of transboundary transport to depositions from anthropogenic sources exceeds 50% in 37, 32 and 32 countries for lead, cadmium and mercury, respectively. On the other hand, fraction of national emissions contributing to the transboundary transport in Europe ranges from 60% to 80% for lead and cadmium. In case of mercury, this fraction is commonly higher than 80%.

Pilot calculations of transboundary pollution of the Central Asian countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan and Tajikistan) have been performed for lead. It was obtained that contribution of the transboundary transport from the EMEP and Central Asian sources to anthropogenic depositions was the highest among these countries for Kyrgyzstan (80%) and Turkmenistan (74%), the lowest contribution – for Kazakhstan (33%).

Mercury hemispheric transport and depositions were evaluated at the hemispheric scale. Sensitivity of mercury deposition in the Northern Hemisphere to emission reduction in different regions was evaluated. The most significant decrease of mercury deposition in the Northern Hemisphere is caused by emission reduction in Eastern Asia because of large relative contribution of sources located in this region. Depositions in Europe are most sensitive to reduction of anthropogenic emissions from its own sources but also in Eastern Asia and North America.

Along with the estimates of the intercontinental transport, the hemispheric model was applied for implementation of the one-way nesting to the regional modelling of mercury pollution. For this purpose monthly mean concentrations of three mercury forms (elemental, reactive gaseous and particulate) were calculated with the hemispheric model at the EMEP domain boundaries and were assimilated by the regional model.

The EMEP Centres were also involved in cooperation with subsidiary bodies to the Convention (TFMM, TFHM, TF HTAP) as well as international organizations and national programmes (European Commission, HELCOM, OSPAR, UNEP). The main results were discussed at a number of scientific conferences, workshops and expert meetings.

CONTENTS

INTRODUCTION

Environmental pollution by heavy metals is the subject of concern of a number of national and international organizations. Heavy metals and their compounds are known as toxics capable causing adverse effects on human and biota. Besides, most heavy metals can be accumulated in the environmental compartments and/or tissues of living organisms increasing the risk of the harmful effects in future. In order to take control over the atmospheric emissions of heavy metals 36 Parties to the Convention on Long-Range Transboundary Air Pollution (CLRTAP, hereinafter the Convention) signed the Protocol on Heavy Metals. Heavy metals targeted by the Protocol are lead (Pb), cadmium (Cd) and mercury (Hg).

According to the Protocol, Cooperative Programme for Monitoring and Evaluation of Long-range Transmission of Air Pollutants in Europe (EMEP) provides the Executive Body for the Convention with information on depositions, and transboundary transport of heavy metals within the geographical scope of EMEP. Measurements of heavy metal concentrations in the air and precipitation are carried out at the EMEP monitoring network under the methodological guidance of the Chemical Coordinating Centre (CCC). Along with that Meteorological Synthesizing Centre – East (MSC-E) performs the model assessment of depositions and air concentrations of heavy metals over the EMEP region as well as the transboundary fluxes between the EMEP countries. The aim of this report is to overview the results of the EMEP activities in 2007 in the field of heavy metal pollution.

Pollution levels of heavy metals and their temporal and spatial trends in the environment are assessed by means of monitoring and modelling. By the moment monitoring of heavy metal levels in air and/or in precipitation was carried out at more than 60 sites over Europe. However, the measurements cover only limited territory of Europe (mostly the western and northern parts) and it is hardly possible to deduce information about source-receptor relationships from the measured data. Therefore, modelling is used to assess heavy metal pollution levels providing information about pollution levels over the entire EMEP region with identification of individual source countries.

Model assessment of heavy metal concentrations, depositions and transboundary fluxes within EMEP is carried out by means of the MSCE-HM atmospheric transport model. Recently the model underwent extensive review procedure, supervised by the EMEP Task Force of Measurements and Modelling (TFMM). The main outcome of the review was confirmation that "MSC-E model is suitable for the evaluation of long-range transboundary transport and depositions of HMs in Europe" [*ECE/EB.AIR/GE.1/2006/4*]. The TFMM also formulated a number of recommendations aimed at further improvement of MSCE-HM model. The progress in model development following these recommendations is, particularly, reflected in this report.

Main directions of EMEP activity in 2007 concerning heavy metals are outlined in the EMEP Workplan [*ECE/EB.AIR/ 2006/10*]. According to the workplan, MSC-E carried out assessment of pollution levels of lead, cadmium, and mercury in the EMEP region and mercury over the northern hemisphere. Source-receptor relationships for the atmospheric transport of lead, cadmium and mercury between the EMEP countries were evaluated. Besides, pilot calculations of transboundary pollution of Central Asian countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan and Tajikistan) were performed. Particular attention was paid to evaluation of modelling results against available measurements from the EMEP monitoring network. The progress in the field of heavy metals, achieved by CCC and MSC-E is summarized in this status report. Content of the report is briefly described below.

Chapter 1 is focused on the EMEP monitoring activities in the field of heavy metals. Measured concentrations in air and in precipitation are characterized from viewpoint of their levels, spatial variability and spatial coverage. Quality of measurement data is overviewed and most uncertain measurements are discussed. The results of the recent laboratory intercomparison study are summarized.

Chapter 2 describes emission of heavy metals within the EMEP region. The information about official reporting of emission data in 2005 and revisions of data submitted in previous year is presented along with analysis of the reported data by source categories. Besides, officially reported national emissions are compared with available non-official estimates. In addition, the emission datset prepared for the modelling activity is described.

Chapter 3 considers the progress in the MSCE-HM model development and evaluation. Brief description of development and application of a system of meteorological data quality control is presented. Further improvement of the heavy metal wind re-suspension scheme is characterized. A special attention was paid to the model evaluation against measurements and to comparison with another chemical transport model (CMAQ).

Chapter 4 summarizes information on modelled pollution levels and transboundary transport of lead, cadmium and mercury in Europe in 2005. Concentrations and depositions of lead, cadmium and mercury in Europe and their transboundary transport to European countries are described along with atmospheric loads to the regional seas. Results of mercury modelling at the hemispheric scale are discussed.

Chapter 5 is focused on cooperation of MSC-E with the subsidiary bodies to the Convention, national and international organizations. MSC-E contribution to the Task Force of Measurements and Modelling, the Task Force on Heavy Metals and Task Force on Hemispheric Transport of Air Pollution is overviewed. Cooperation of the Centre with HELCOM and the European Commission is described.

The main outcomes of EMEP activities concerning heavy metals are summarized in *Conclusions*. Important supplementary information is given in the *Annexes*.

1. MONITORING OF HEAVY METALS IN EMEP

1.1. Measurement network

Heavy metals were included in EMEP's monitoring program in 1999. However, earlier data has been available and collected, and the EMEP database thus also includes older data, even back to 1987 for a few sites. A number of countries have been reporting heavy metals within the EMEP area in connection with different national and international programmers such as HELCOM, AMAP and OSPAR.

The locations of the measurement sites, which have delivered data on heavy metals for 2005, are found in Fig. 1.1. Detailed information about the sites and the measurement methods are found in EMEP/CCC's data report on heavy metals and POPs [*Aas and Breivik*, 2007]. In the figure, the sites are divided in those measuring both concentrations in air and in precipitation, and those measuring only one of them. In 2005 it was 28 sites measuring heavy metals (Pb and Cd) in both compartments, and altogether it was 64 measurement sites. It was 19 sites measuring at least one form of mercury. In addition two sites from AMAP (Alert in Canada and Amderma in Russia) are included for mercury air measurements. These sites in addition to Nuuk at Greenland are outside the map.

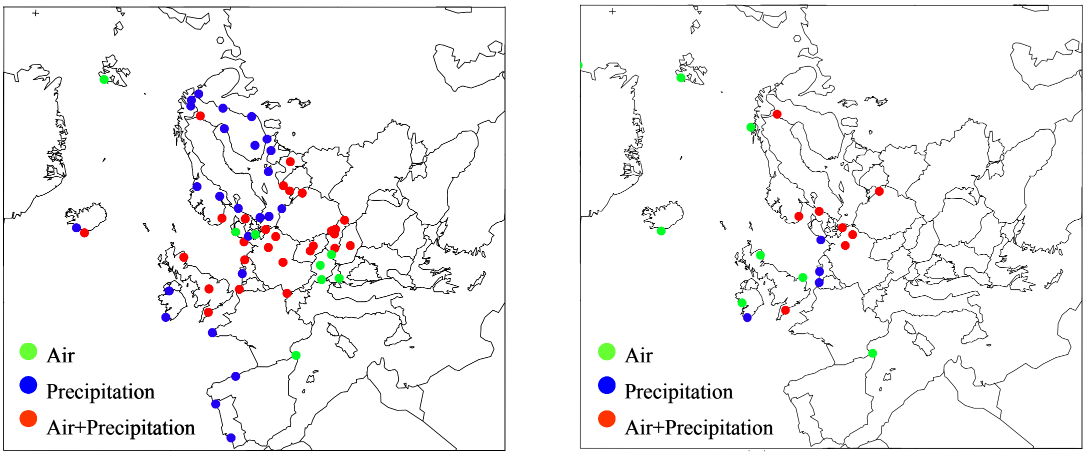


Fig. 1.1. *Measurement network of lead, cadmium (left) and mercury (right) in 2005*

From Fig.1.1 one can see that the spatial coverage in east and southern Europe is unsatisfactory, especially for mercury. In addition, it is too few sites measuring concentrations both in air and precipitation. The adopted EMEP monitoring strategy for 2004-2009 (EB.AIR/GE.1/2004/5) and the EUs daughter directive on heavy metals and PAH will expectantly improve this situation.

1.2. Monitoring of Pb, Cd and Hg in 2005

Annual averages of Pb, Cd and Hg concentrations in precipitation and in air in 2005 are presented in Fig. 1.2-1.7. The lowest concentrations for all elements in air as well as precipitation are found in northern Scandinavia. An increasing gradient can in general be seen southeast, but the concentration levels are not evenly distributed, there are some "hotspots" for some elements.

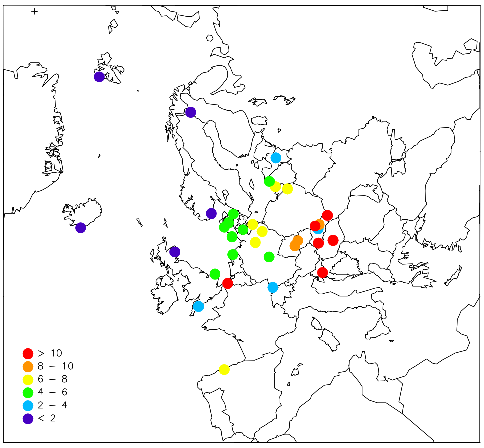


Fig. 1.2. *Pb in aerosol, ng/m*^{3}

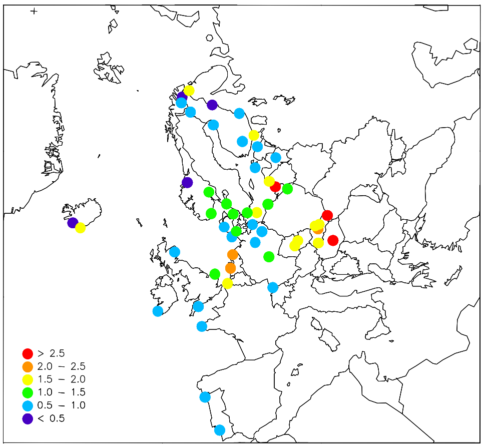


Fig. 1.3 *Pb in precipitation, µg/L*

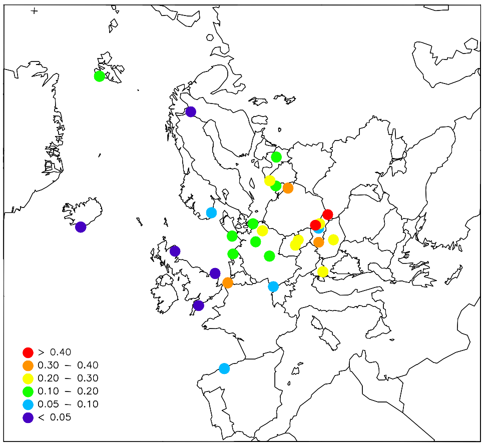


Fig. 1.4. *Cd in aerosol, ng/m*^{3}

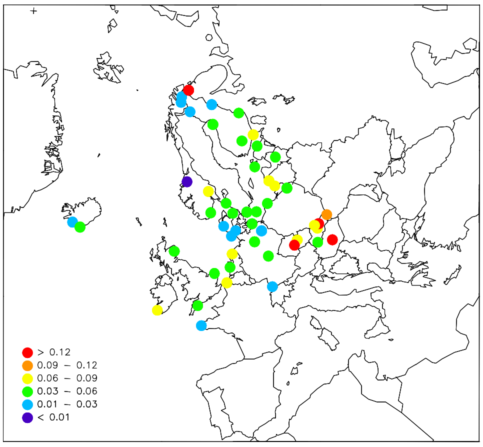


Fig. 1.5. *Cd in precipitation, µg/L*

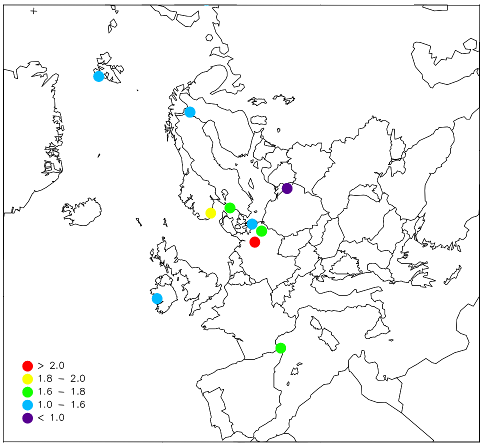


Fig. 1.6. *Hg in air, ng/m*^{3}

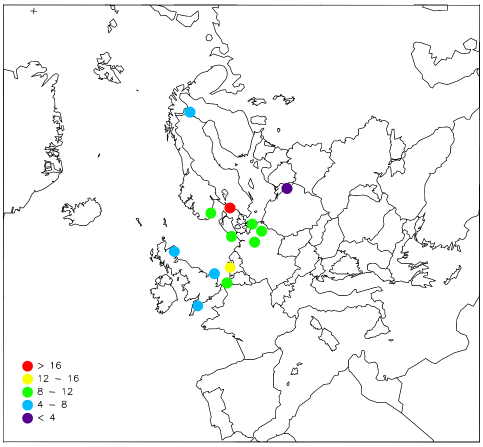


Fig. 1.7. *Hg in precipitation, ng/L*

The highest concentrations of heavy metals in both air and precipitation are seen in Hungary and Slovakia. High levels are also seen in the Czech Republic and Slovenia. For the latter one should notice that much of the data is under the detection limit. Elevated levels are also in northern Scandinavia, Poland, Lithuania, and in the Benelux countries.

There are only a few stations measuring mercury in Europe, and most of them are related to the OSPAR program CAMP. The concentrations of mercury at the different sites are decreasing from north to south, but these differences are quite small.

1.3. Data quality

Portugal has very high detection limit for Cd so these data are not shown in Fig 1.4. This is also the case for the mercury measurements in precipitation in Ireland, not included in Fig 1.7. More than 75% of the Portuguese, Irish and Estonian precipitation data are under the detection limit and these concentration levels should be looked upon as max values. At ES08 the concentrations in precipitation were reported as wet deposition, these measurements are therefore not included in the report. At GB6 more than half the year is missing, so these data are neither included in the figures. At PT10 only one 1% of the precipitation data is analysed and is not included here. The data capture is otherwise above 90% for most of the precipitation measurements. There are some data, which are unexpectedly high or low. The Polish PL05 Hg data in both precipitation and air are unreasonably low. In air the data are half of the general concentration level and in precipitation 15 times lower. It is recommended not to use these data in the model verification. On the opposite side is the Icelandic site IS91, which has 5 times higher level of heavy metals in precipitation than the neighbouring site IS90. Therefore, the data from IS91 should be considered with caution. The IS91 data for aerosol data seems reasonable. The NO47 site is part of the Norwegian monitoring network and not EMEP, the site is located close to the Nickel smelters at Kola and influence from these is clearly seen on the concentration level. These data are not used for model verification

The data quality objectives (DQO) in EMEP states that the accuracy in the laboratory should be better than 15% and 25% for high and low concentrations of heavy metals, respectively. One important measure to check the data quality is laboratory ring test. There is a marked improvement in the laboratory performance for both lead and cadmium since the beginning of the laboratory comparison in 1995. The intercomparison completed last year [*Aas and Breivik*, 2007] is representative for the 2005 data. In Table 1.1, there is a summary of the results from this laboratory intercomparison. There are some countries reporting measurements data without participation in the laboratory intercomparison: Belgium, the Czech Republic, Ireland, Portugal, and Spain. Data from these countries are of unknown quality; and it is therefore strongly recommended that they take part in the annual laboratory intercomparison. Sweden and Iceland were not participating because these measurements were analysed in Norway. As can be seen from the table, Estonia and Hungary has analytical problems, France has very high detection limit for most of the elements. Otherwise, the performance for most elements and laboratories are satisfactory.

Table 1.1. *Average per cent error (absolute) in low and high concentration samples, results from the laboratory intercomparison. DQO is EMEPs data quality objectives*

	As		Cd		Cr		Cu		Pb		Ni		Zn	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high
DK	33	11	0	6	8	5			25	3	47	2		
FI	2	2	1	2	22	9	5	6	6	1	15	8	4	7
FR	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	12	<DL	<DL	<DL	12
DE	2	2	4	2	2	2	2	3	3	5	5	5	9	1
HU			54	15					203	6				
NL	10	1	0	4	40	8	0	1	7	2	13	1	15	2
NO	0	2	4	1	0	8	5	0	2	2	5	9	10	3
PL05				6		1	8	7			21	6	3	3
GB	8	8	29	7	47	5	9	4	7	9	10	11	16	16
SK		6	0	2	2	4	3	4	4	3		3		2
LT	0	3	6	4	0	5	18	2	4	2	6	3	6	3
LV	11	0	0	3	13	0	15	13	6	1	7	2	11	3
SI	5	5	23	1	115	3	8	4	2	5	8	1	2	11
EE	<DL	33	<DL	6	<DL	22	23	12	31	36	163	28	29	4

🟩 1/2 - 1 DQO 🟪 1 - 2 DQO 🟥 > 2 DQO

2. EMISSIONS OF HEAVY METALS IN EUROPE

This Chapter provides information on heavy metal official emission data submitted by Parties to the LRTAP Convention by April 2007. Particularly, trends of anthropogenic emission reduction of lead, cadmium and mercury in the EMEP region are presented for the period 1990-2005 along with information on emission reduction in individual countries and specification of emission data by source categories. Emission changes caused by backward recalculations of emission data are also analyzed. Besides, officially submitted emission data are compared with available non-official estimates in order to reveal possible uncertainties and encourage national experts in improvement of heavy metal emission inventories.

2.1. Official submissions of emission data

In 2007, national totals on lead, cadmium and mercury emissions for 2005 reporting year were submitted to the UNECE Secretariat by 30 European countries. These countries are Austria, Belarus, Belgium, Bulgaria, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Latvia, Lithuania, Malta, Monaco, the Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, the Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom. Among them 17 countries recalculated previously reported emission data on Pb, Cd and Hg for all or for selected years from the period of 1990-2004.

Emission trends in the EMEP region (1990-2005)

Changes of Pb, Cd and Hg anthropogenic emissions in the EMEP region in the period of 1990-2005 are shown in Fig. 2.1. Emission trends were assessed on the base of the reported emission data. In the absence of official emission data non-official estimates [*Berdowski et al.,* 1997; *Denier van der Gon et al.,* 2005] were used. Between 1990 and 2005 total anthropogenic emissions in the EMEP region decreased for all the three metals: for lead by about 87%, for cadmium by about 50% and for mercury by about 48%.

Fig. 2.1. *Total anthropogenic emissions of lead, cadmium and mercury in the EMEP region in the period 1990-2005 according to the official data combined with non-official estimates, t/y*

Emission reductions from 1990 to 2005 in individual countries

The extent of emission reductions varies significantly from country to country. The relative emission reduction was estimated as $100*(E_{1990}-E_{2005})/E_{1990}$ (%), where E_{1990} and E_{2005} are emissions in 1990 and 2005, respectively. Figure 2.2 shows the relative reductions of lead, cadmium and mercury emissions between 1990 and 2005 in the 28 countries of the EMEP region, which reported their emissions both for 1990 and 2005. Emissions of lead decreased in all the countries varying from about 18% (Latvia) to 99% (Monaco). The lowest reduction of cadmium is in Belarus (4%), the highest

– in Republic of Moldova (94%). In Cyprus emissions of cadmium have increased about 2 times. The reductions of mercury emissions vary from about 10% (Russian Federation) to 93% (Republic of Moldova). In Portugal mercury emissions have increased by about 10%. In Cyprus, emissions of mercury have increased almost 1.5 times, and in Lithuania – almost 23 times.

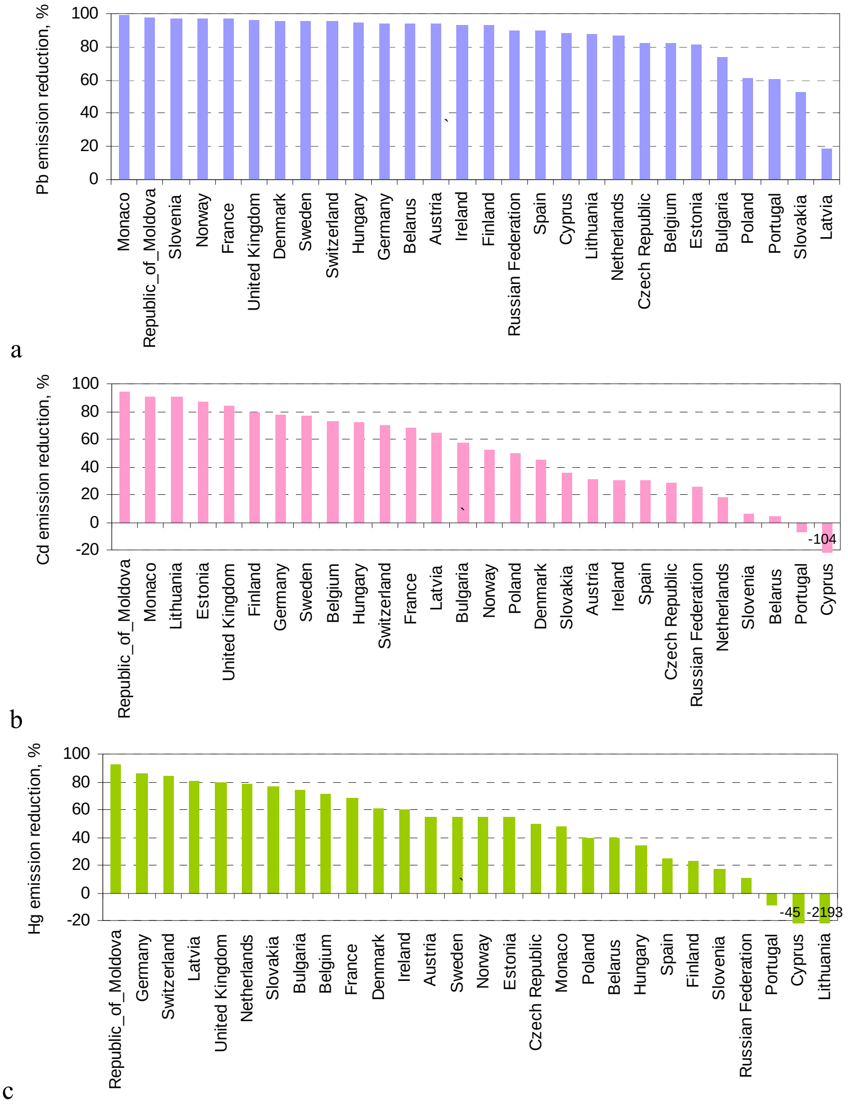


Fig. 2.2. *Reductions of lead (a), cadmium (b) and mercury (c) emissions in the 28 countries of the EMEP region for the period of 1990-2005 based on data reported for both 1990 and 2005, %*

Changes of national emission estimates

In 2007 changes of previously submitted data on Pb, Cd and Hg emissions for the period 1990-2004 were reported by 17 countries (Austria, Belgium, Cyprus, Denmark, Estonia, France, Germany, Ireland, Latvia, the Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom). Relative changes of national estimates of total heavy metals emission in these countries for the period 1990-2004 are given in Annex B.

The changes of lead, cadmium and mercury emissions in each country are expressed as 100*(E_{curr} – E_{prev})/E_{prev} (%), where E_{curr} and E_{prev} are current and previous total emissions in the each particular year, respectively. Maximum changes are presented in Figs. 2.3 – 2.5. Negative values indicate decrease in emissions after the recalculations, whereas positive values illustrate increase in emissions.

Lead. For Austria, Belgium, Estonia, Ireland, Norway, Spain and the United Kingdom the changes of emission estimates did not exceed ±10% (Fig. 2.3). For Germany the changes were more than 100%: Lead emissions were increased about 5 times for 1999. The maximum emission decrease after the recalculation was 93% (Latvia for 2003).

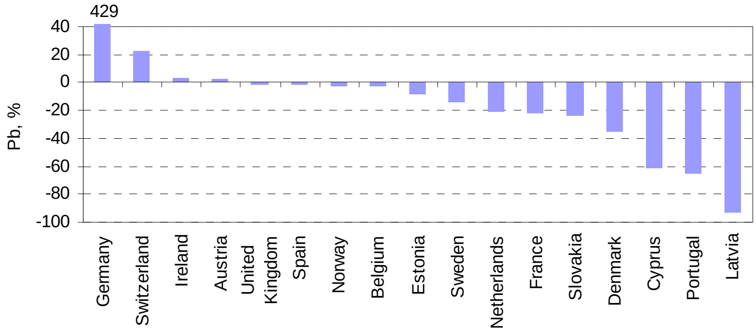


Fig. 2.3. *Maximum relative changes in lead official emissions after the recalculations, %*

Cadmium. For Austria, Denmark, Ireland, Latvia, Norway and Portugal the changes of emission estimates were less than ±10% (Fig. 2.4). In Germany, Cyprus and the Netherlands the changes exceeded 100%. In Germany emissions were increased about 10 times for 1990, in Cyprus and the Netherlands – about 3 and 2 times for 1990 and 2003, respectively. The maximum emission decrease after the recalculation was 47% for Slovakia in 2004.

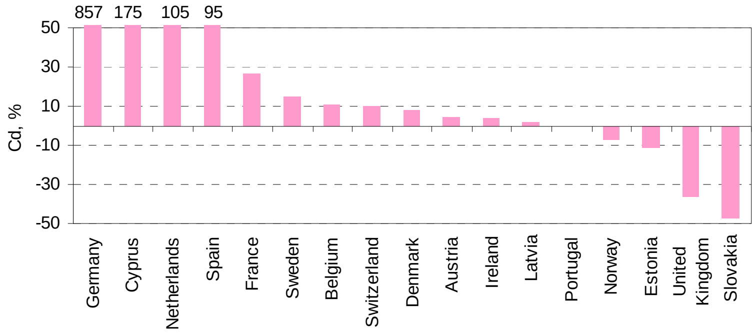


Fig. 2.4. *Maximum relative changes in cadmium official emissions after the recalculations, %*

Mercury. For Austria, Belgium, Estonia, Latvia, Norway, Portugal and Slovakia the changes of emission estimates were less than ±10% (Fig. 2.5). For Germany and Cyprus the changes exceeded 100%. German and Cyprian emissions of mercury for 1990 were increased by about 4 and 3 times, respectively. The highest decrease of emissions after recalculations was about 66% for Sweden in 1990.

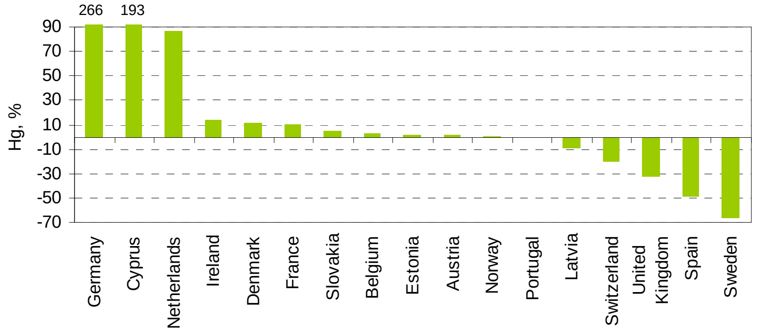


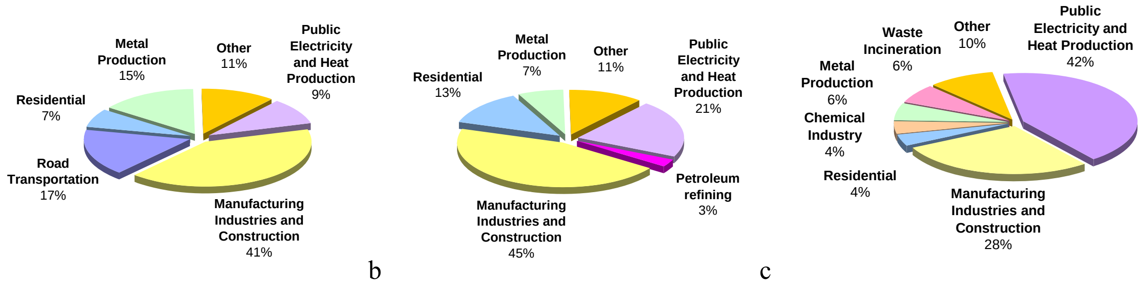
Fig. 2.5. *Maximum relative changes in mercury official emissions after the recalculations, %*

Emissions of heavy metals by source categories

Official data on heavy metals emissions by source categories in 2005 are available for 30 countries. Detailed information on relative contribution of different source categories to national emission totals for all countries is presented in Annex C. Below the emission splitting by sectors was aggregated for Europe as a whole (based on the data from 30 countries).

Figure 2.6 shows relative contribution of different source categories to total emission of lead, cadmium and mercury from 30 European countries in 2005. *Manufacturing industries and construction* is the largest contributor (41%) to lead emissions in Europe (Fig. 2.6a). This sector is the largest source of lead for Belarus, Bulgaria, the Czech Republic, Finland, France, Hungary, Republic of Moldova, Poland, the Russian Federation, Slovakia, Spain and the United Kingdom. The next important emission sectors are *road transportation* (17%) and *metal production* (15%).

The largest contribution to the total cadmium emissions is also made by *manufacturing industries and Construction* (45%; Fig. 2.6b). This sector is the largest source of cadmium for Belarus, Bulgaria, Finland, France, Hungary, Ireland, Republic of Moldova, Norway, Portugal, the Russian Federation, Slovakia, Spain, Switzerland and the United Kingdom. The second most important sector for cadmium emissions is *public electricity and heat production* (21%) which is followed by *residential combustion* (13%).



a b c

Fig. 2.6. *Relative contribution of source categories to total emission of lead (a), cadmium (b) and mercury (c) from European countries in 2005*

Public electricity and heat production the most significantly contribute (42%) to the total mercury emissions in Europe (Fig. 2.6c). This sector is the most important for Bulgaria, Cyprus, Denmark, Estonia, France, Germany, Malta, Monaco, the Netherlands, Portugal, Romania, the Russian Federation, Slovenia, Spain, Switzerland and the United Kingdom. The second largest contributor is *manufacturing industries and construction* (28%). This sector is the largest source of mercury in Belarus, the Czech Republic, Hungary, Ireland, Poland and Slovakia.

2.2. Comparison of heavy metal emission inventories

In order to analyze consistency and reveal possible uncertainties of emission data the officially reported emissions of lead and cadmium has been compared with available non-official emission estimates prepared by TNO [*Denier van der Gon et al*., 2005] and within the EU ESPREME project [http://espreme.ier.uni-stuttgart.de]. Detailed comparison of these emission datasets including analysis of key source categories is available in [*Ilyin et al*., 2007]. The comparison of national emission totals of lead and cadmium officially reported to the Convention with non-official emission estimates is illustrated in Figs. 2.7.

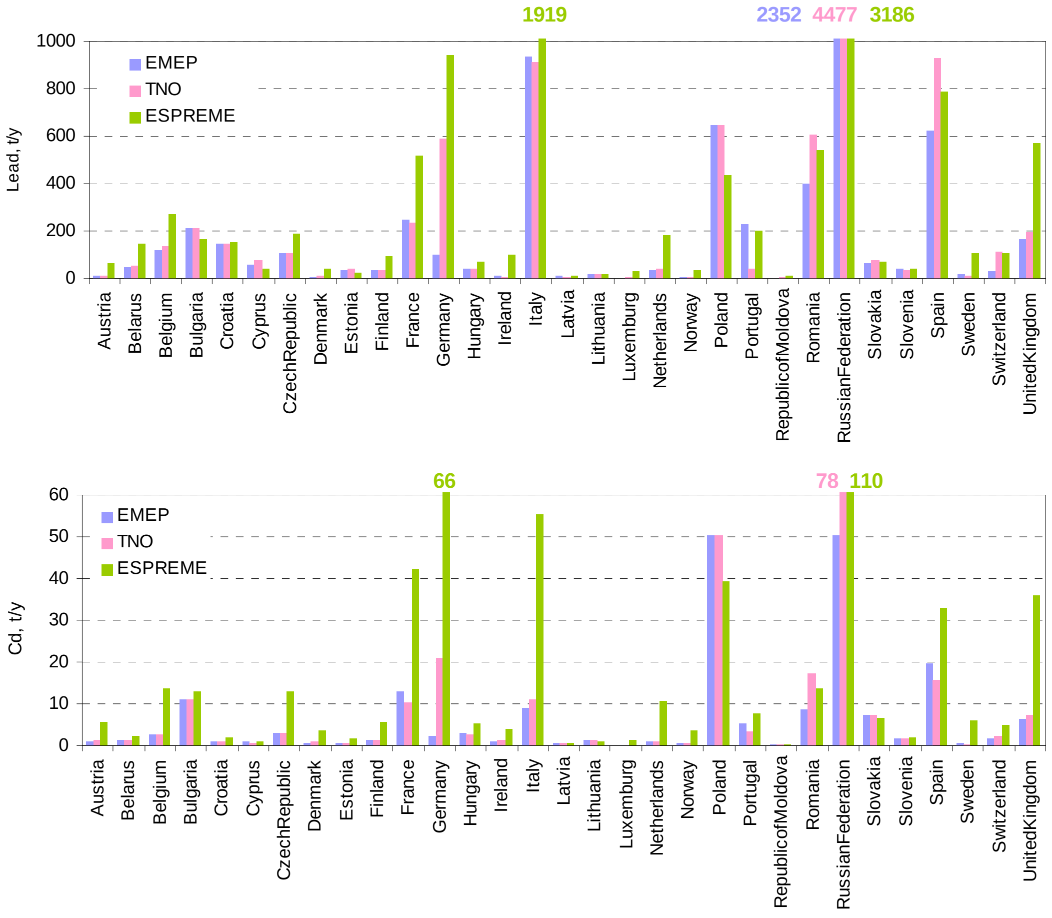


Fig. 2.7. *Comparison of official EMEP emissions data with TNO and ESPREME emission estimates for lead (a) cadmium (b) in 2000, t/y*

Based on the performed analysis it has been summarized that although different emission inventories for lead and cadmium well correlate with each other, significant differences are observed for many countries, particularly, between the EMEP and ESPREME datasets. In general the ESPREME inventory presents higher emission estimates than two other datasets. The deviation is more pronounced for cadmium emissions. Significant discrepancies take place also in contribution of key source categories to national emissions.

2.3. Input emission data for modelling

In order to provide European countries with data on depositions, concentrations and source-receptor relationships, MSC-E needs emission data from all EMEP countries. The emission data used for modelling of 2005 were based on officially reported information from WEBDAB (*http://webdab.emep.int*). For countries, which official data are not available, emission totals for 2005 were estimated by interpolation between 2000 and 2010 of non-official estimates and projections made by the Dutch TNO institution [*Denier van der Gon et al.,* 2005]. Total emissions of lead, cadmium and mercury for 2005, derived through this combination of official data and non-official estimates were around 4700, 245 and 170 t/y, respectively.

The information about spatial distribution of heavy metals emissions at least for one year of the period 1990-2005 was provided by 24 countries (Austria, Belarus, Belgium, Bulgaria, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, Monaco, the Netherlands, Norway, Poland, the Russian Federation, Slovakia, Spain, Sweden, Switzerland, the United Kingdom). Among them 19 countries (underlined) have submitted gridded emission data by sectors. For the first time, the gridded emission data have been reported by Germany, Ireland and Italy. Besides, three countries – Denmark, Norway and Sweden – have presented information on spatial distribution of heavy metals emissions from sea transport.

Inclusion of the Central Asian countries that are Parties (Kazakhstan, Kyrgyzstan) or candidates (Uzbekistan, Tajikistan, and Turkmenistan) to the LRTAP Convention in the routine EMEP model calculations of transboundary fluxes has become an important priority within the CLRTAP. Therefore, pilot calculations of transboundary transport of lead have been performed this year at the extended EMEP grid covering these countries. To fill in part of the extended model domain outside the standard EMEP grid with emissions data TNO expert estimates [*Denier van der Gon et al.,* 2005] were used along with GEIA global lead emission inventory [http://www.geiacenter.org/]. Particularly, lead emission totals for Kazakhstan and Kyrgyzstan for 2005 were derived from the TNO inventory using mentioned above interpolation between 2000 and 2010. Lead emissions from other Central Asian countries (Uzbekistan, Tajikistan, and Turkmenistan) were obtained from the GEIA global inventory for 1990 expecting the same emission reduction in these countries between 1990 and 2005 as in the Russian Federation according to the EMEP official data. Emissions from the Asian part of Russia was assessed using official emission data for the European part of the country and keeping ratio between the European and Asian parts derived from the GEIA inventory. Besides, the GEIA emissions data were used for other Asian and African countries expecting the same emission reduction between 1990 and 2005 as for Turkey. Spatial distribution of lead emissions from all these countries was obtained by interpolation of GEIA gridded emissions with 1°×1° spatial resolution into the model grid.

Spatial distributions of lead, cadmium and mercury emissions used in the modelling are shown in Fig. 2.8. Temporal and vertical distribution of the emission data and speciation of mercury emissions, employed in MSCE-HM model, are described in [*Travnikov and Ilyin*, 2005].

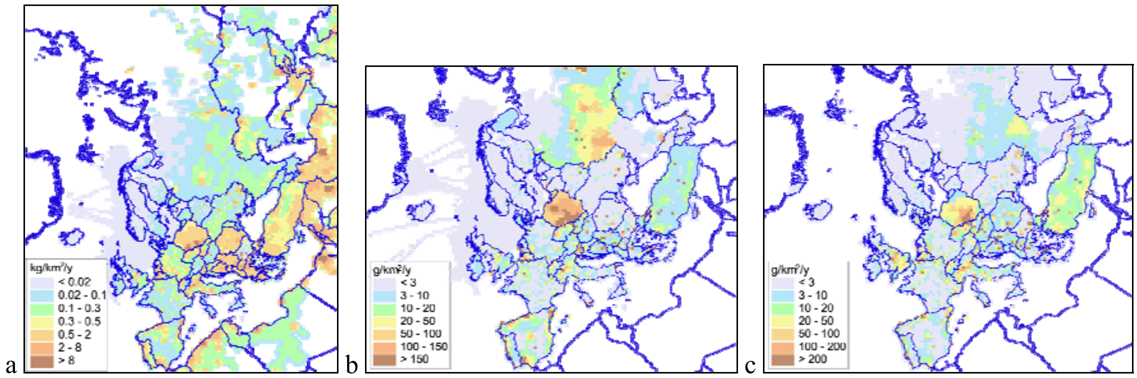


Fig.2.8. *Spatial distribution of anthropogenic emissions of lead (a), cadmium (b) and mercury (c) in 2005*

3. MODEL DEVELOPMENT AND EVALUATION

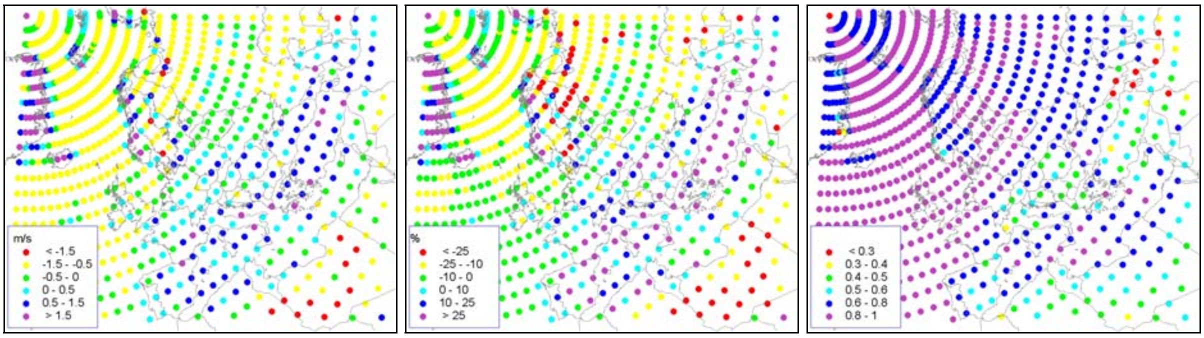
This Chapter is focused on MSC-E activities on further development and evaluation of the regional heavy metal model MSCE-HM. Particularly, development and application of the meteorological data quality control system is considered, further development of the mineral dust and heavy metal wind re-suspension scheme is described. A special attention is paid to evaluation of the modelling results against measurements and in comparison with another chemical transport model (CMAQ).

3.1. System of meteorological data quality control

Quality of atmospheric transport model results strongly depends on quality of input data, in particular, on gridded meteorological fields. Meteorological input for the MSCE-HM regional-scale transport model is generated by the MM5 model [*Grell et al.*, 1995], using NCEP/DOE Reanalysis-II or ECMWF analyses as driving meteorological fields. Following the recommendations of the TFMM [ECE/EB.AIR/GE.1/2006/4], MSC-E started development of a system of meteorological data quality control. This section presents some results of the developed system application and outlines plans of MSC-E future activities in this field. More detailed information about this system is available in [*Ilyin et al.*, 2007].

The main idea of the quality control system operation is evaluation of pre-processed meteorological fields against those from an independent dataset in an automated regime. There are several options for the reference dataset including ERA-40 re-analysis of ECMWF [http://www.ecmwf.int/research/era/], precipitation data prepared in the framework of GPCP project [http://cics.umd.edu/~yin/GPCP/], direct meteorological observations at synoptic stations etc. Currently the system was tested with the ERA-40 and GPCP data for the period 1990–2004. Some results are illustrated below.

Figure 3.1 shows spatial distribution of statistical parameters characterizing absolute and relative deviation between MM5 generated wind velocity and that from ERA-40. As seen from Figs 3.1a and 3.1b difference between these datasets mostly does not exceed 25%. However, MM5 tends to generate somewhat lower wind velocities (by 0.5-1.5 m/s or 10-25%) compared to ERA-40 over the Atlantic and Eastern Europe. Over southern part of Europe, Turkey, and west of Scandinavia wind velocities computed by MM5 are higher than those from ERA-40. The temporal correlation coefficient in most cases exceeds 0.6 except some areas in Southern Europe, Africa and Central Asia.



a b c

Fig. 3.1. *Absolute bias (a), relative bias (b) between MM5 and ERA-40 near-surface wind velocities and temporal correlation coefficient (c, 6-hour time step) for near-surface wind velocity over EMEP domain in 2000*

Figure 3.2 presents temporal variation of the spatial correlation coefficient between monthly sums of precipitation from MM5 and from the reference datasets for the period 1990-2004. Spatial correlation between the generated and the reference precipitation fields was evaluated at 0.75 on average for the whole period and demonstrated strong seasonal variations (Fig. 3.2). Higher correlation coefficients (0.8–0.9) were obtained for winter seasons; whereas in summer they were somewhat lower (0.55–0.7). It can be partly explained by more complicated and uncertain character of modelling summertime convective precipitation.

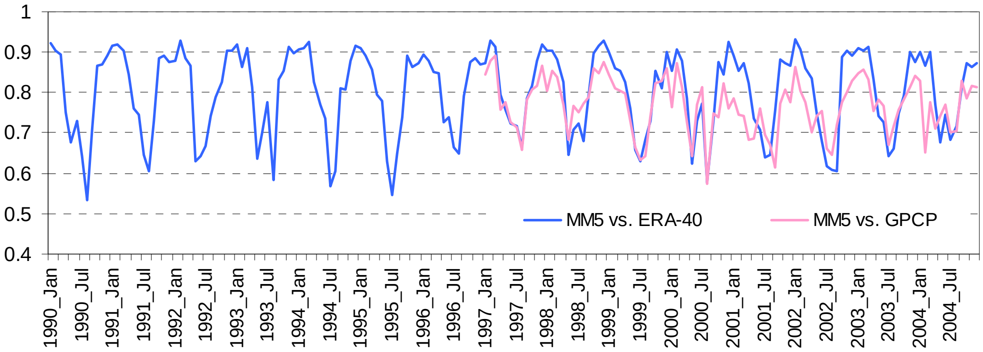
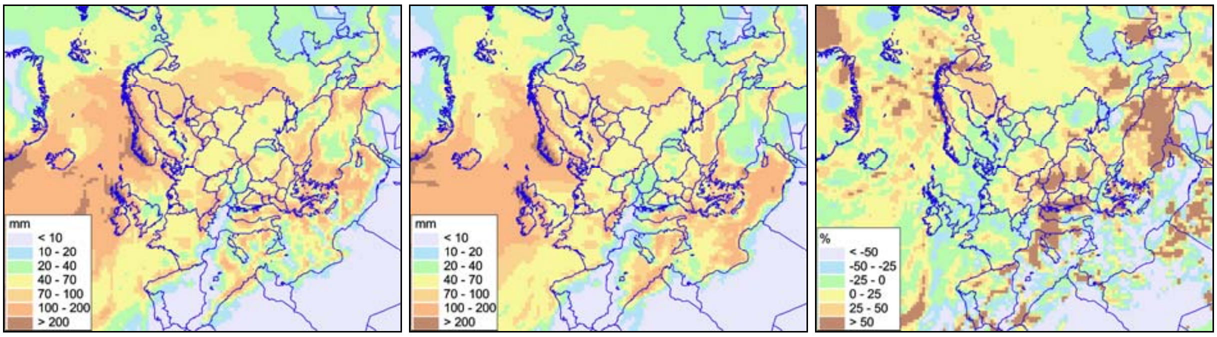


Fig. 3.2. *Spatial correlation coefficients between monthly-mean near-surface precipitation sums provided by MM5 and the reference datasets*

Following the recommendations of TFMM [ECE/EB.AIR/GE.1/2006/4], MSC-E has also started movement to use of the ECMWF analysis data as driving information for the meteorological pre-processing. In this framework the global analysis data with 1°x1° spatial resolution have been retrieved from ECMWF data storage system and pre-processed. A primary analysis of meteorological fields derived from the ECMWF dataset was performed. More detailed analysis is planed for the future.

An example demonstrating comparison of precipitation fields generated MM5 based on the NCEP/DOE and ECMWF datasets is shown in Fig. 3.3. As seen the relative difference between the two fields is within ±25% over most European territory. However, precipitation based on ECMWF are significantly (more than 50%) lower than that based on NCEP/DOE data over Mediterranean region. The opposite situation takes place over some areas in Scandinavia, Southern Europe and Turkey. Besides, the precipitation based on ECMWF data are characterized by higher spatial variability. This can be connected with finer spatial resolution of ECMWF data compared to NCEP/DOE re-analysis.



a b c

Fig. 3.3. *Precipitation amounts in January, 2005 computed by MM5 on the base of ECMWF(a), NCEP/DOE Reanalysis-II (b), and relative difference between them (c)*

Further activities regarding the supply of MSC-E with regional-scale meteorological data include (1) complete transition from NCEP/DOE Re-analyses to ECMWF analyses data; (2) carrying out detailed comparison of pre-processed meteorological data based on NCEP/DOE Re-analysis and ECMWF data; (3) performing quality control of input meteorological information on the routine basis; (4) where possible, make use of meteorological observations for the purposes of meteorological data quality control.

3.2. Further development of heavy metals wind re-suspension scheme

Wind re-suspension of particle-bound heavy metals (like lead and cadmium) from soil and seawater appears to be important process affecting ambient concentration and deposition of these pollutants, particularly, in areas with low direct anthropogenic emissions. Recent data demonstrate significant decrease of lead and cadmium emissions in Europe during last decade [ECE/EB.AIR/WG.5/2006/2]. However, long-term historic emissions of these metals during previous century from industrial processes, fuel combustion, road transport etc. followed by atmospheric dispersion and deposition to the ground resulted in their accumulation in the surface soils all over Europe. Aeolian erosion of bare soils or human disturbed areas leads to suspension of dust particles containing heavy metals into the atmosphere. This process supplements current anthropogenic emissions and can partly explain discrepancy between sharp trends of emission reduction and moderate decrease of measured heavy metal concentrations in precipitation [*Ilyin and Travnikov*, 2005].

Pilot parameterization of heavy metal re-suspension developed for the MSCE-HM model along with tentative estimates of the re-suspension effect on pollution levels in Europe were described in [*Gusev et al.*, 2006]. This section contains a short summary of further development and improvement of the heavy metal re-suspension scheme. Particularly, effect of soil characteristics (soil texture, size distribution of soil grains etc.) on dust production and suspension are taken into account. Besides, some special effects influencing dust mobilization (such as wind drag partition, inhibition by soil moisture, the Owen effect) are introduced or revised in the model. More detailed description of the modified scheme can be found in [*Ilyin et al*., 2007].

In general dust suspension flux strongly depends on size distribution of soil grains. To derive spatially resolved data of soil size distribution we utilized global soil characteristics dataset from the International Satellite Land-Surface Climatology Project (ISLSCP), Initiative II (http://islscp2.sesda.com). Particularly, we extracted soil texture classification according to content of three major components (sand, silt, and clay). Different soil types were classified according to the classic sand/silt/clay triangle of texture composition [*Hillel*, 1982]. Resulting spatial distribution of different soil types in Europe is presented in Fig. 3.4. As seen, according to this data, loam soils prevail over Central and Eastern Europe, whereas Southern Europe is dominated by clay loam. Sandy soils are characteristics of Africa and Central Asia. It should be noted that this approach allows only rough information on soil composition and texture. Soil characteristics of natural surfaces are much more variable in reality. Therefore, soil properties data with higher spatial resolution should be used in future.

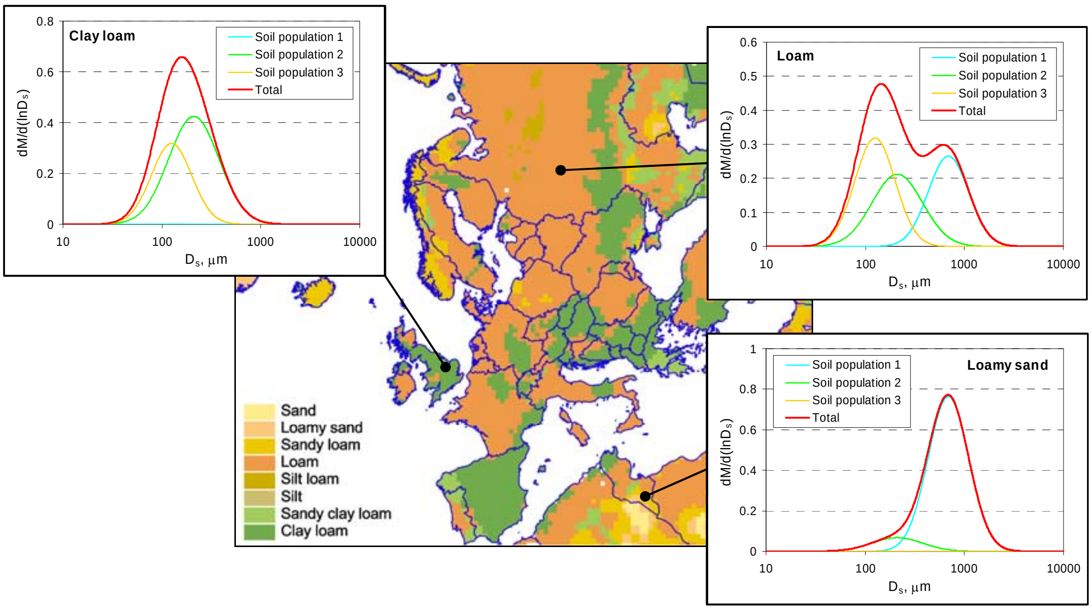


Fig. 3.4. *Spatial distribution of soil texture types in Europe and size distributions of soil aggregates for different soil types*

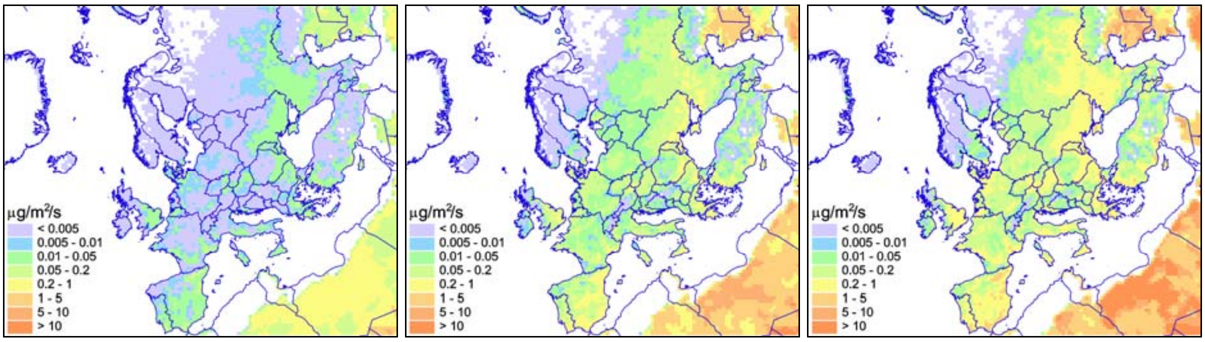
Each soil type was associated with certain size distribution of soil aggregates based on the dry sieving technique measurements by *Chatenet et al.* [1996]. We used definitions of soil size distribution derived for major arid soil types by *Marticorena et al.* [1997]. According to this work size distribution of soil aggregates can be presented as a combination of three soil populations with definite lognormal distribution function. Resulting size distributions of tree different soil types (clay loam, loam, and loamy sand) is illustrated in Fig. 3.4. As seen sandy soils are characterized by relatively large soil grains up to a few millimetres. Whereas clay containing soils are dominated by smaller grains of 1-2 hundreds micrometers.

These soil characteristics data have been utilised for evaluation of size-segregated dust suspension flux applying parameterizations [*Marticorena and Bergametti*, 1995; *Alfaro and Gomes*, 2001; *Gomes et al.*, 2003] widely used in mineral dust production models. Particularly, suspension of dust aerosol from soil is considered as combination of two major processes – *saltation* and *sandblasting* – presenting horizontal movement of large soil aggregates driven by wind stress and ejection of fine dust particles, respectively.

Under natural conditions wind stress is commonly shared between erodible and non-erodible surfaces. Extend of the stress sharing depends both on size and density of non-erodible roughness elements. To take into account this sharing effect we have applied the drag partition scheme developed by *Shao and Yang* [2005]. Another process affecting wind erosion and saltation of soil particles is the Owen effect [*Owen*, 1964] responsible for positive feedback of saltation on wind shear stress. Saltating soil grains interact with underlying surface and transfer part of wind momentum to the ground. It leads to increase of the wind shear stress, which can be expressed in increase of the wind friction velocity. An empirical parameterisation developed by *Gillette et al.* [1998] has been introduced to the dust suspension scheme to describe this effect.

The calculated mean annual flux of dust suspension from soil in 2005 is shown in Fig. 3.5 for different ranges of particle size (PM2.5, PM10 and PM20). As seen high suspension fluxes are characteristics of deserts in Northern Africa and Central Asia. Elevated fluxes were also obtained for Southern Europe and agricultural regions of Southeastern and Eastern Europe. Comparison of Figs. 3.5a and

3.5b demonstrates that major part of wind dust suspension flux over Europe consists of coarse particles (with particles size greater than 2.5 μm).

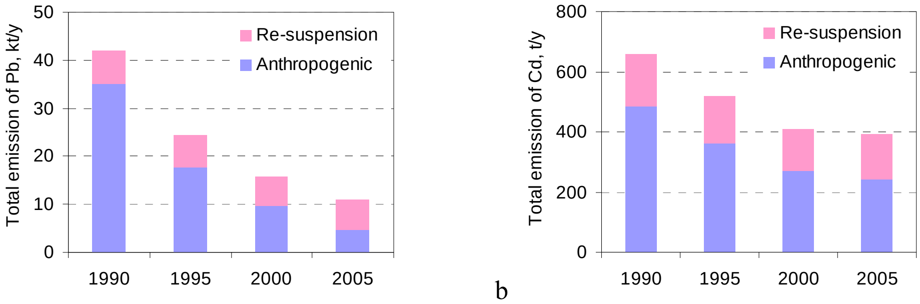


a b c

Fig. 3.5. *Spatial distribution of calculated mean annual dust suspension flux of different particle size in 2005: (a) – PM2.5; (b) – PM10; (c) – PM20, μg/m²/s*

For estimation of heavy metal emission with dust suspension from soils detailed measurement data on heavy metals concentration in topsoil from the Geochemical Atlas of Europe developed under the auspices of the Forum of European Geological Surveys (FOREGS) [*Salminen et al*., 2005; *www.gtk.fi/publ/foregsatlas/*] were used. The data cover most parts of Europe (excluding Eastern European countries) with more than 2000 measurement sites. Besides, conditional enrichment factors were used for lead and cadmium content in suspended dust to take into account accumulation of these metals in the upper skin layer of soil due to long-term atmospheric depositions. In order to estimate heavy metal re-suspension from seawater with sea-salt aerosol the empirical Gong-Monahan parameterization was applied [*Gong*, 2003] along with the emission factors derived from the literature. More detailed description of heavy metal re-suspension from soil and seawater is available in [*Ilyin et al*., 2007].

The described above scheme has been applied for estimates of heavy metal re-suspension in the European region for selected years of the period 1990-2005. Changes of heavy metal content in soil were not taken in to account in this study. Figure 3.6 illustrates comparison of lead and cadmium wind re-suspension with total anthropogenic emissions from European countries in different years. As seen absolute amount of lead and cadmium re-suspension slightly varies from year to year depending on particular meteorological conditions. On the other hand, its relative contribution changes significantly. According to the current estimates, relative contribution of lead re-suspension did not exceed 20% in 1990 but its contribution increased up to 60% in 2005 due to drastic reduction of anthropogenic emissions. Contribution of cadmium re-suspension increased from about 30 to 40% during this period.



a b

Fig. 3.6. *Total anthropogenic emission and re-suspension of lead (a) and cadmium (b) from European countries*

Spatial distribution of wind re-suspension fluxes of lead and cadmium from European soils and seawater in 2005 are presented in Figs. 3.7 and 3.8, respectively, in comparison with anthropogenic emissions. Heavy metal re-suspension from soil is presented for dust particles size below 10 μm (PM10). As seen the obtained re-suspension fluxes from soil are comparable or even higher those from anthropogenic sources officially reported by some European countries (Germany, France, Spain, the United Kingdom, Ukraine etc.) These elevated fluxes are resulted from combination of relatively high concentration in soil and significant dust suspension from agricultural and urban areas. Besides, high re-suspension fluxes were obtained for desert areas of Africa and Central Asia because of significant dust production in these regions.

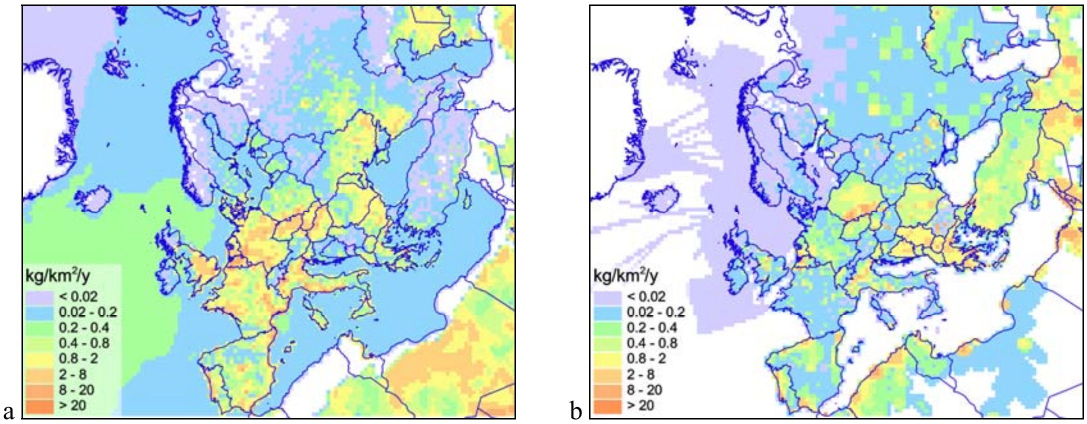


Fig. 3.7. *Spatial distribution of wind re-suspension flux (a) and anthropogenic emissions (b) of lead in Europe in 2005, kg/km^2/y*

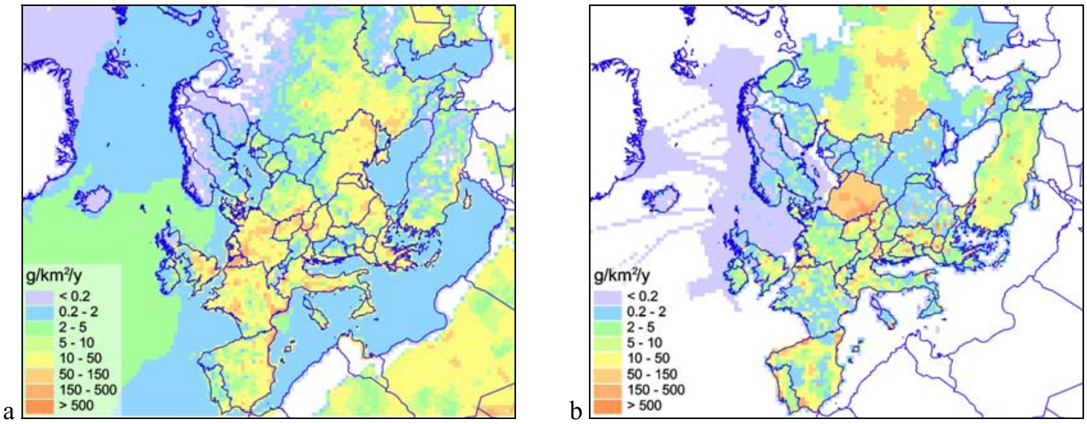


Fig. 3.8. *Spatial distribution of wind re-suspension flux (a) and anthropogenic emissions (b) of cadmium in Europe in 2005, g/km^2/y*

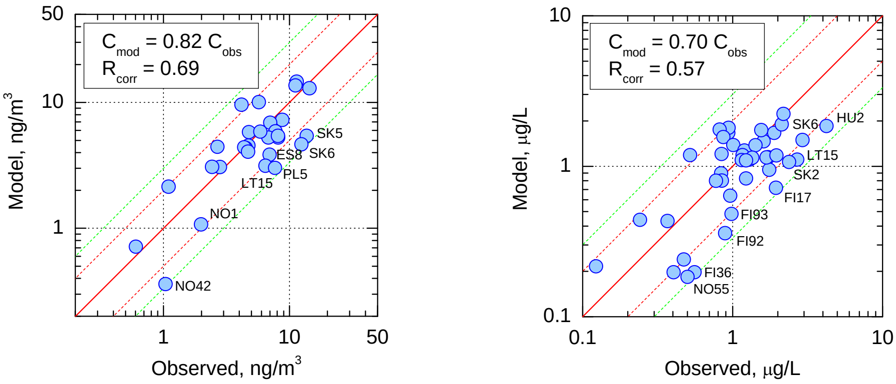
To address the most significant uncertainties of the described above heavy metal re-suspension scheme it is planed to perform comparative analysis of different soil properties datasets and to utilize soil data with much finer resolution. Besides, in depth analysis of the literature data is required to evaluate critical parameters of the scheme. And finally, a comprehensive sensitivity analysis of the dust suspension scheme is to be performed with regard to selected parameterization along with extensive evaluation against measurement data.

3.3. Evaluation of modelling results

Evaluation of modelling results against observations is a routine procedure allowing assessment of the model performance and supporting improvement of the model parameterization. This section contains the comparison of modelled concentrations of lead, cadmium and mercury in air and in precipitation with measurements from the EMEP monitoring network in 2005. Model ability to reproduce both annual mean and short-term (daily or weekly) measurements is analysed. Besides, the model results are compared with results of one of the well-developed contemporary transport models (CMAQ).

Lead

Comparison of modelled and measured annual mean lead concentrations in air and precipitation for 2005 is presented in Fig. 3.9. In general the model underestimates observations by 20-30%. Correlation coefficients are significant and amount to about 0.7 and 0.6 for concentrations in air and precipitation, respectively. In 80% of cases difference between modelled and measured concentrations does not exceed a factor of two. Modelled air concentrations well match the observed values at sites located in Western Europe and Southern Scandinavia (Belgium, Germany, Denmark, the Netherlands, Norway, Sweden). However, at some sites in Central Europe (the Czech Republic, Slovakia, Poland) and Northern Scandinavia (Norway, Finland) the model tends to underestimate observations.



a b

Fig. 3.9. *Comparison of modelled annual mean lead concentrations in air (a) and precipitation (b) with measurements from the EMEP monitoring network in 2005. Red solid line delineates 1:1 ratio, red and green dashed lines show deviation by a factor of two and three, respectively*

To evaluate the model ability to reproduce atmospheric transport and short-term variations of lead air concentrations we performed comparison of modelling results with daily or weekly observations using raw measured data provided by EMEP/CCC. Figure 3.10 illustrates an example of the comparison of daily mean data at Danish site DK8. As seen the model successfully capture most observed peaks of lead concentrations at site DK8, particularly, in April, September, October, November, December, and in the beginning of February (Fig. 3.10). The use of wind re-suspension favours better agreement between the modelled and measured concentrations. However, some peaks (e.g. the episode in the end of February) were not captured by the model. It can be partly explained by effect of emission sources (anthropogenic or re-suspension) not covered by current emissions dataset used in the modelling.

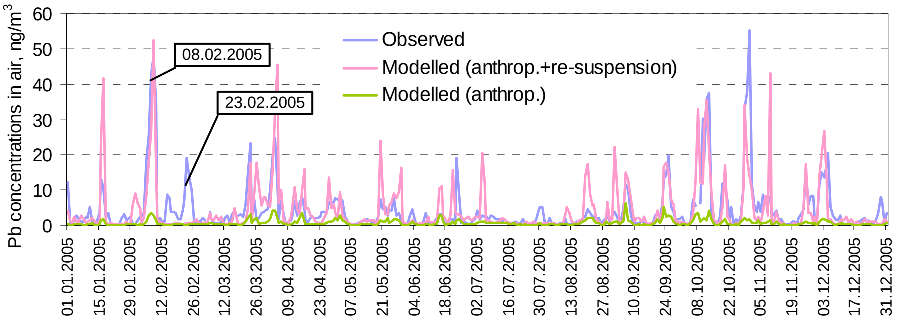


Fig. 3.10. *Comparison of modelled lead concentrations in air with daily measurements at station DK8 (Anholt, Denmark) in 2005, ng/m*^{3}

To illustrate this idea backward trajectories of the atmospheric transport have been generated for two episodes of elevated lead concentrations at site DK8 (Fig. 3.11). As it was mentioned above the first episode (08 Feb 2005) was successfully reproduced by the model. Backward trajectories for this episode went over Southern Poland, where strong emission sources are located (Fig. 11a). On the other hand, the model failed to reproduce the second considered peak (23 Feb 2005). Appropriate backward trajectories for this episode went over Southern Sweden, Baltic countries and Russia (Fig. 11b). As seen from the figure, there is no significant emission sources located along the trajectory (according to the utilised emissions data), which could cause the observed concentration peak. Therefore, it is quite possible that some sources are lost in the emissions inventory.

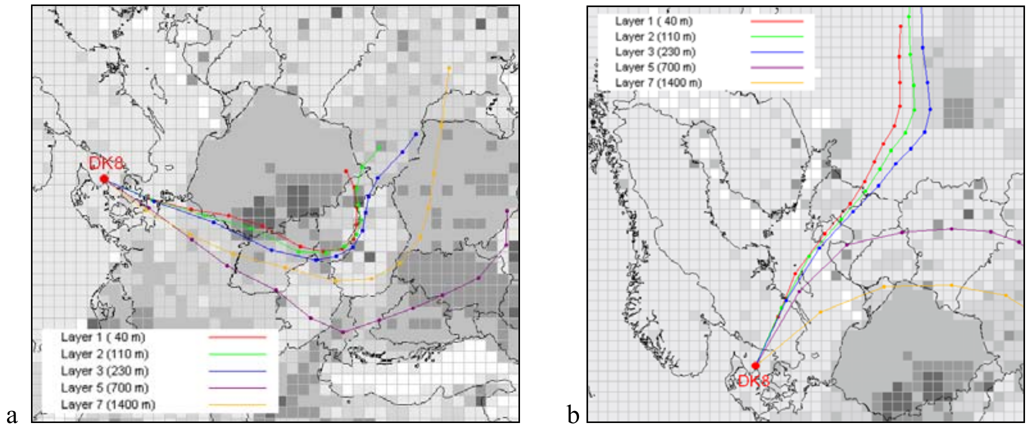


Fig. 3.11. *Backward trajectories of the atmospheric transport to site DK8 (Anholt, Denmark) for two episodes of high lead air concentration: 08 Feb 2005 (a) and 23 Feb 2005 (b). Distance between dots corresponds to 6-hours period. Background map presents spatial distribution of lead anthropogenic emissions*

As it was mentioned above the model tends to underestimate observations at a number of monitoring sites, particularly, in Central Europe. Figure 3.12a illustrates the typical situation at the Slovakian site SK5 (Liesek) for lead concentration in air. The model evaluation at site DE2 (Langenbrügge) is given for comparison (Fig. 3.12b) because it characterizes typical pollution levels in the continental part of Western Europe. As seen from the figures, lead concentrations measured at the mountain site SK5 (892 m a.s.l.) located at the Slovakian-Polish border are almost twice higher those at the site DE2, which is situated in central Germany. The model failed to reproduce these high concentrations at the Slovakian site. Possible reasons for that include unaccounted local emission sources, underestimation of wind re-suspension contribution, or peculiarities of the atmospheric transport in the mountain region unsuccessfully simulated by the model.

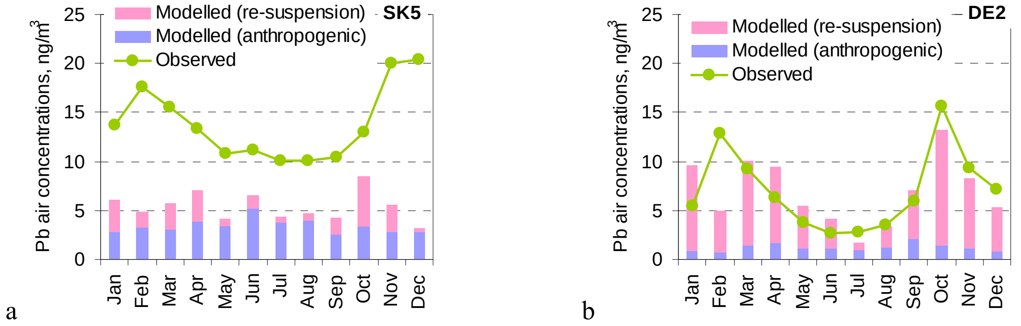


Fig. 3.12. *Comparison of modelled and measured monthly mean lead concentrations in air at stations SK5 (Liesek, Slovakia) (a) and DE2 (Langenbrügge, Germany) (b) in 2005, ng/m^3*

Besides, as one can see the underestimation is the most pronounced in the cold season (late autumn, winter, early spring) when the observed concentrations are significantly higher. This seasonal cycle is typical for measured air concentrations of heavy metals in Western and Central Europe. Figure 3.13 shows seasonal variation of lead air concentration measured at 20 sites in this region. As seen wintertime concentrations are commonly significantly higher than those in summer. It can be explained by the seasonal cycle of anthropogenic emissions and/or more stable conditions of the atmospheric boundary layer in the cold season. In some cases the model successfully reproduces this cycle (Fig. 3.12b) but at some other sites it fails (Fig. 3.12a). It should be noted that the current official anthropogenic emission dataset does not contains information on seasonal variation of emissions, which could improve the modelling results.

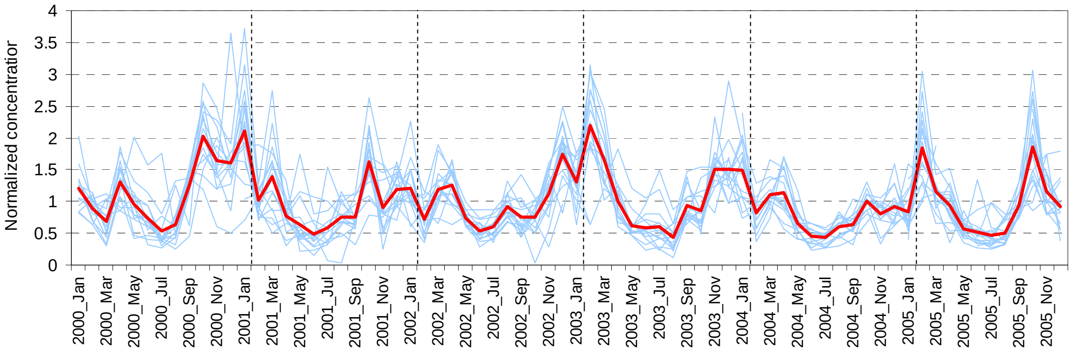
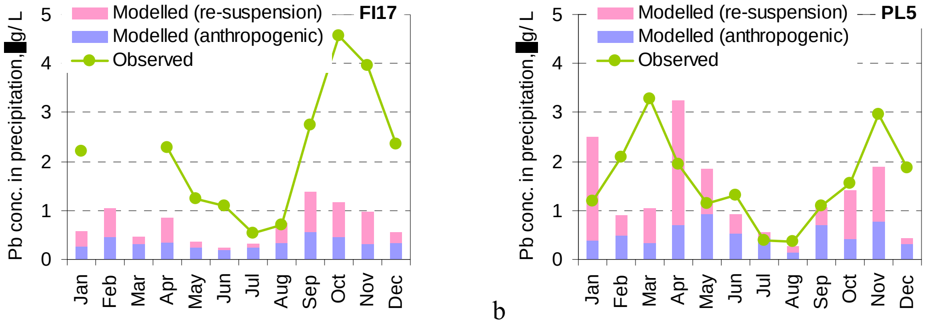


Fig. 3.13. *Seasonal variation of normalized monthly mean air concentrations of lead measured at 20 sites of Western and Central Europe (Austria, Belgium, the Czech Republic, Germany, Denmark, Hungary, Lithuania, the Netherlands, Poland, and Slovakia). Blue lines show variation at individual sites, red line – the ensemble average*

Another region where the model tends to underestimate observed values is Northern Scandinavia (Finland, Norway). An example of this sort of underestimation is shown in Fig. 3.14a for lead concentration in precipitation at site FI17 (Virolahti II, Finland). This site is located at the Baltic coast close to the Finnish-Russian boundary. As seen the measurements demonstrate quite large concentrations, which are even higher levels measured at sites in Central Europe (measurements at Pollish site PL5, Diabla Gora, are presented in Fig. 3.14b for comparison). On the other hand, the available emissions inventory does not report any significant emission sources in this region (see Fig. 2.8). One can hardly explain these high concentration levels by long-range transport from remote sources located in Central Europe. Therefore, among the possible reasons of them are uncertainties in spatial distribution of emissions in Finland or neighbouring countries and/or unaccounted local sources.

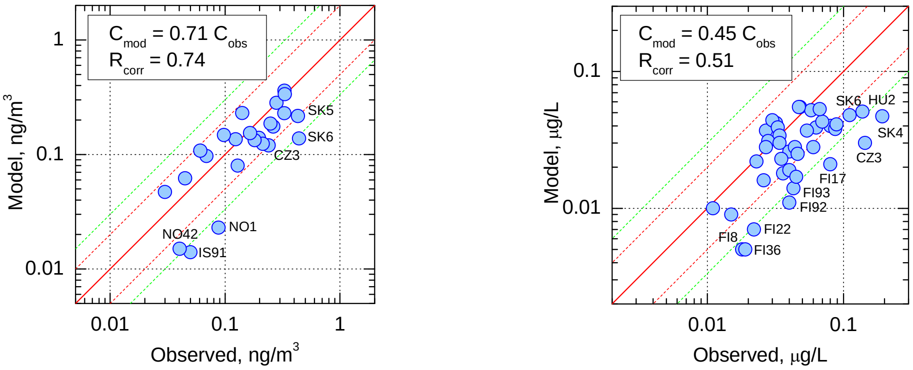


a b

Fig. 3.14. *Comparison of modelled and measured monthly mean lead concentrations in precipitation at stations FI17 (Virolahti II, Finland) (a) and PL5 (Diabla Gora, Poland) (b) in 2005, µg/L*

Cadmium

Figure 3.15 presents comparison of modelled and measured annual mean concentrations of cadmium in air and precipitation in 2005. In general the model underestimation of observations is somewhat larger than in the case of lead – 30% for concentrations in air and more than 50% for concentrations in precipitation. However, this statistics is significantly affected by large underprediction of the observed values at Central European (Slovakia, the Czech Republic, Hungary) and Scandinavian sites (Finland, Norway), whereas the model-to-measurement correspondence at other sites is much better. Nevertheless, the correlation coefficients are significant and amount to 0.74 and 0.51 for concentrations in air and precipitation, respectively. In 80% of cases for concentrations in air and in 65% – concentrations in precipitation – the difference between modelled and measured valuess does not exceed a factor of two.



a b

Fig. 3.15. *Comparison of modelled annual mean cadmium concentrations in air (a) and precipitation (b) with measurements from the EMEP monitoring network in 2005. Red solid line delineates 1:1 ratio, red and green dashed lines show deviation by a factor of two and three, respectively*

Similar to lead, the model ability to reproduce short-term variations of measured concentrations was evaluated using measurements data with higher temporal resolution (daily or weekly). An example of the analysis for air concentration of cadmium at site CZ1 (Svratouch, the Czech Republic) is presented in Fig. 3.16. As seen most measured peaks along the year were reproduced by the model except for three very high concentration episodes in October and November. Besides, one can conclude that contribution of the wind re-suspension to cadmium concentrations at this site is not large with the exception of some episodes (e.g. on 29 Oct 2005), when it significantly improves the comparison with observations.

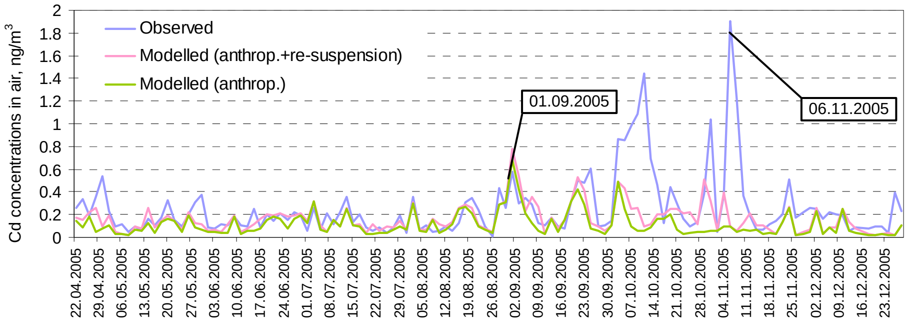


Fig. 3.16. *Comparison of modelled cadmium concentrations in air with daily measurements at station CZ1 (Svratouch, Czech Republic) in 2005, ng/m^3*

In order to analyse possible reasons of the model success or failure to reproduce short-term episodes we generated backward trajectories for two episodes of elevated cadmium concentrations at site CZ1 (Fig. 3.17). The first episode (01 Sep 2005) was successfully reproduced by the model (see Fig. 3.16). Appropriate backward trajectories went over industrial regions of Poland, which are characterized by high emissions (Fig. 3.17a). The model failed to capture the second considered peak (06 Nov 2005). The backward trajectories analysis shows that air mass containing such high cadmium concentrations came from France, crossed Belgium and Germany. However, there were no significant emission sources on its pathway according to the utilized emissions data. Thus, one can expect that some strong emissions sources are missed in the inventory.

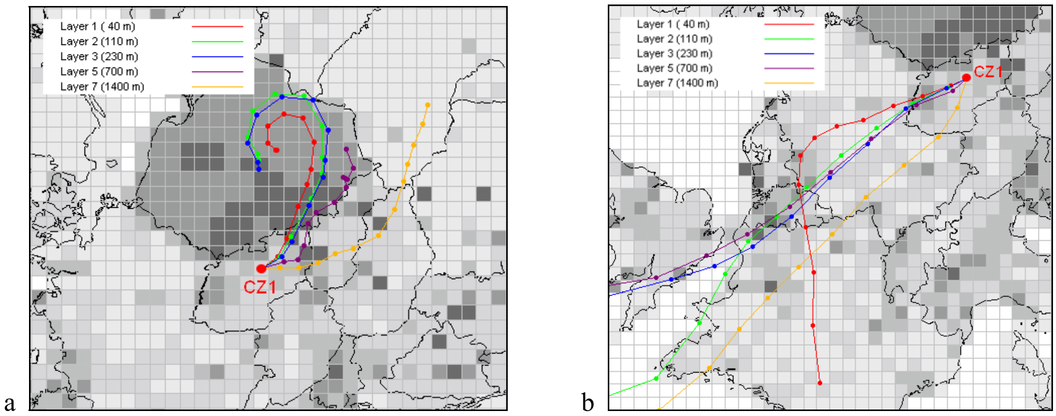


Fig. 3.17. *Backward trajectories of the atmospheric transport to site CZ1 (Svratouch, Czech Republic) for two episodes of high cadmium air concentration: 01 Sep 2005 (a) and 06 Nov 2005 (b). Distance between dots corresponds to 6-hours period. Background map presents spatial distribution of cadmium anthropogenic emissions*

As it was mentioned above the comparison statistics (Fig. 3.18) is significantly affected by large underestimation of observed concentration by the model at a number of sites in Central Europe and Scandinavia. Figure 3.18a presents an example of this kind of underestimation at Slovakian site SK6 (Starina). This site is located in the mountain area in the eastern part of Slovakia not far from the boundary with Poland. According to the available emissions data there is no large emission sources in the vicinity of the site. Nevertheless, it reports very high cadmium concentrations both in air and in precipitation (Fig. 3.18a) in comparison with other monitoring sites in Europe (Fig. 3.18b). As seen from the figure, estimated contribution of wind re-suspension is insignificant in this area. Besides, similar to lead the observations demonstrate well pronounced seasonal cycle with elevated cadmium concentrations in the cold season (late autumn, winter, early spring) and relatively low in summer.

This seasonal cycle was not reproduced by the model, probably, because of absence of seasonal variation of emissions data and/or uncertainties of meteorological data (particularly, stability conditions of the atmospheric boundary layer in winter).

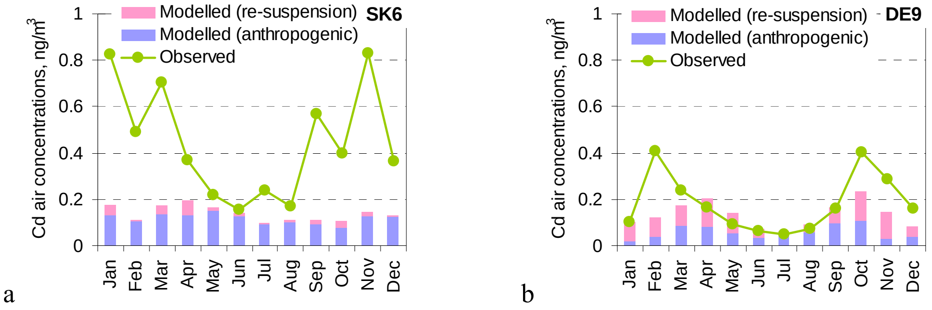


Fig. 3.18. *Comparison of modelled and measured monthly mean cadmium concentrations in air at stations SK6 (Starina, Slovakia) (a) and DE9 (Zingst, Germany) (b) in 2005, ng/m*^{3}

As seen in Fig. 3.18b the model significantly underestimates cadmium concentrations in precipitation at most Finnish sites. It should be noted that concentrations measured at these sites are unexpectedly high in comparison with observations in other parts of Europe. Particularly, concentrations measured at site FI17 (Virolahti II, Finland) are among the highest in Europe. But a number of other Finnish sites also demonstrate quite significant levels of cadmium. This is particularly surprising taking in account absence if any significant emission sources in this region (Fig. 2.8). Figure 3.19 shows comparison of modelled and measured cadmium concentrations in precipitation at site FI93 (Kotinen) located in Southern Finland and at German site DE7 (Neuglobsow). The model successfully reproduces cadmium levels at the German site but it fails simulating very high concentrations at the Finnish one. This fact can be partly explained by missed emission sources in Finland or in the neighbouring countries. It should be noted that measurement data with higher temporal resolution could significantly improve analysis of the model-measurements discrepancies.

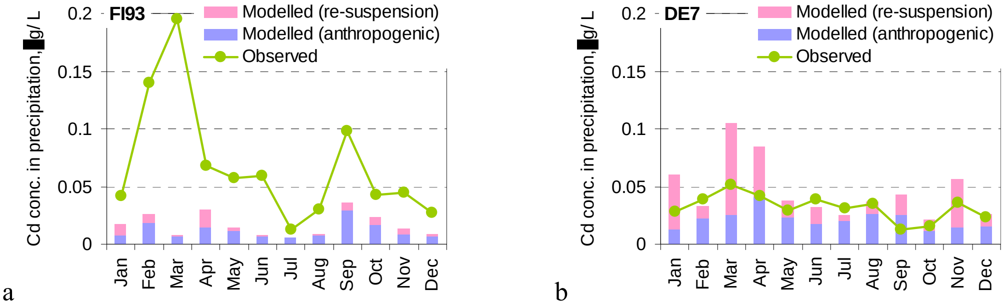
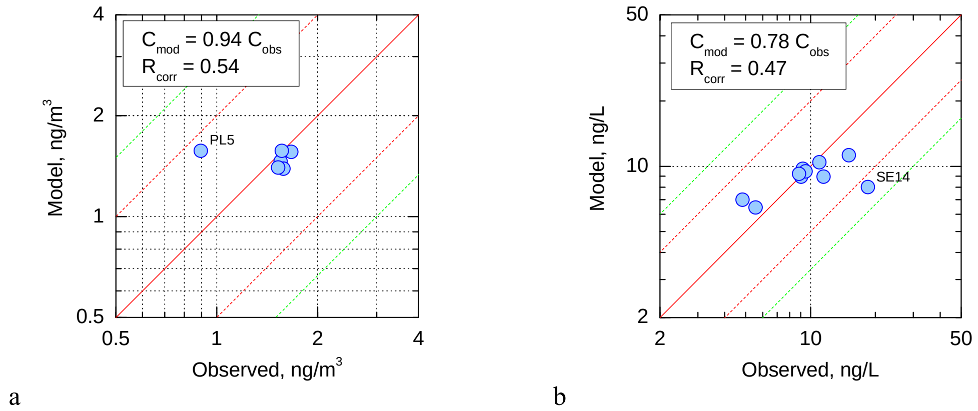


Fig. 3.19. *Comparison of modelled and measured monthly mean cadmium concentrations in precipitation at stations FI93 (Kotinen, Finland) (a) and DE7 (Neuglobsow, Germany) (b) in 2005, µg/L*

Mercury

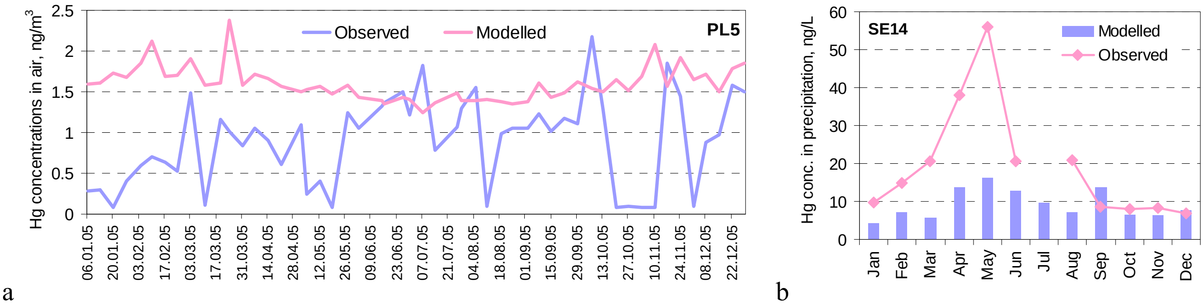
Comparison of modelled and measured mean annual mercury concentrations in air and precipitation for 2005 is presented in Fig. 3.20. Both modelled mercury concentration in air and precipitation well agree with observations. With the exception of one site (PL5), the difference between modelled and observed air concentrations does not exceed 15%. For concentration in precipitation the difference does not exceed 50% for all but one site.



a b

Fig. 3.20. *Comparison of modelled annual mean concentrations of gaseous elemental mercury in air (a) and total mercury in precipitation (b) with measurements from the EMEP monitoring network in 2005. Red solid line delineates 1:1 ratio, red and green dashed lines show deviation by a factor of two and three, respectively*

Figure 3.21a shows comparison of modelling results with weekly measurement data at site PL5 (Diabla Gora, Poland), which reported suspiciously low concentrations of mercury (0.9 ng/m^3). Analysis of the raw data revealed very untypical behaviour of measured gaseous elemental mercury concentrations: they vary significantly (up to 100%) and often drop down to 0.08 ng/m^3 that is considerably below the background level (about 1.5 ng/m^3). Therefore, quality of these measurement data gives major concern and they were not used in the comparison statistics. Another site, where significant discrepancies between modelled and observed mercury concentrations in precipitation were obtained, is SE14 (Råö, Sweden). As seen from Fig. 3.21b, both modelled and measured values demonstrate similar seasonal pattern with higher concentrations in spring-summer and with lower ones in autumn-winter. However, the model significantly underestimates observed concentrations in spring, whereas it fits them well in autumn.



a b

Fig. 3.21. *Comparison of modelled and measured weekly gaseous elemental mercury concentrations in air at site PL5 (Diabla Gora, Poland) (a) and mercury concentration in precipitation at site SE14 (Råö, Sweden) (b) in 2005*

Similar to lead and cadmium, modelled concentrations of mercury were compared with high temporally resolved observations. An example showing the comparison of mercury concentrations in air at site DE9 (Zingst, Germany) is illustrated in Fig. 3.22. The measurements were carried out on daily basis. Most of peak locations along with their magnitudes were captured by the model. It can also be seen that seasonal variability, i.e., lower concentrations in summer and higher concentrations in winter, we reproduced by the model.

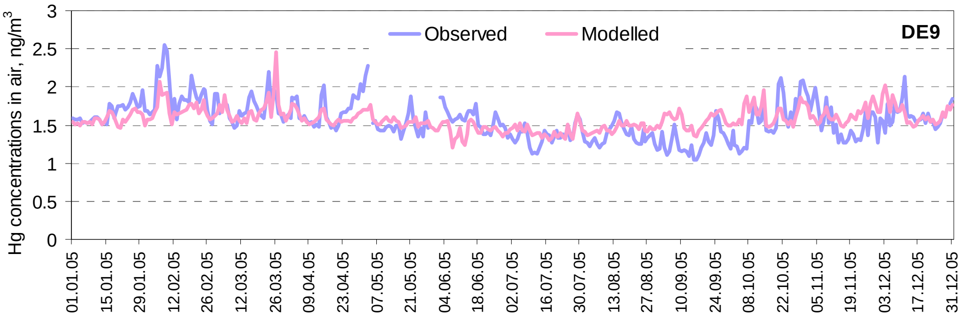


Fig. 3.22. *Comparison of modelled gaseous elemental mercury concentrations in air with daily measurements at site DE9 (Zingst, Germany) in 2005, ng/m*^{3}

Another example (Fig. 3.23) demonstrates comparison of observed and modelled concentrations in precipitation at site DE1 (Westerland, Germany). Measurements were performed on weekly basis. Most minimums and maximums of mercury concentrations in precipitation were successfully captured by the model. Seasonal pattern, characterized by higher concentrations in summer and lower concentrations in winter, was also reproduced.

Fig. 3.23. *Comparison of modelled total mercury concentrations in precipitation with weekly measurements at site DE1 (Westerland, Germany) in 2005, ng/L*

Comparison of MSCE-HM and CMAQ modelling results

To analyse peculiarities of the MSCE-HM model performance its modelling results were compared with calculations performed by the CMAQ model under similar conditions. For this purpose both models were applied to calculate the atmospheric transport and depositions of lead and cadmium for the year 2000 using both the official emissions data and the ESPREME estimates. Besides, both models utilized a tentative parameterisation of heavy metal re-suspension from soil and seawater and the same meteorological dataset generated by the MM5 pre-processor. Some results of the comparison are presented below, whereas more detailed analysis is available in [*Ilyin et al.*, 2007].

Total annual depositions of cadmium in Europe calculated by MCSE-HM and CMAQ are compared in Fig. 3.24. Spatial patterns of deposition fluxes in Europe calculated by both models are very similar. MSCE-HM predicts somewhat larger depositions, particularly, in remote regions and over the Atlantic Ocean. It can be explained by more significant atmospheric dispersion, larger dry deposition to vegetation and higher boundary concentrations imposed in the MSCE-HM model. CMAQ estimates higher cadmium dry depositions over African deserts.

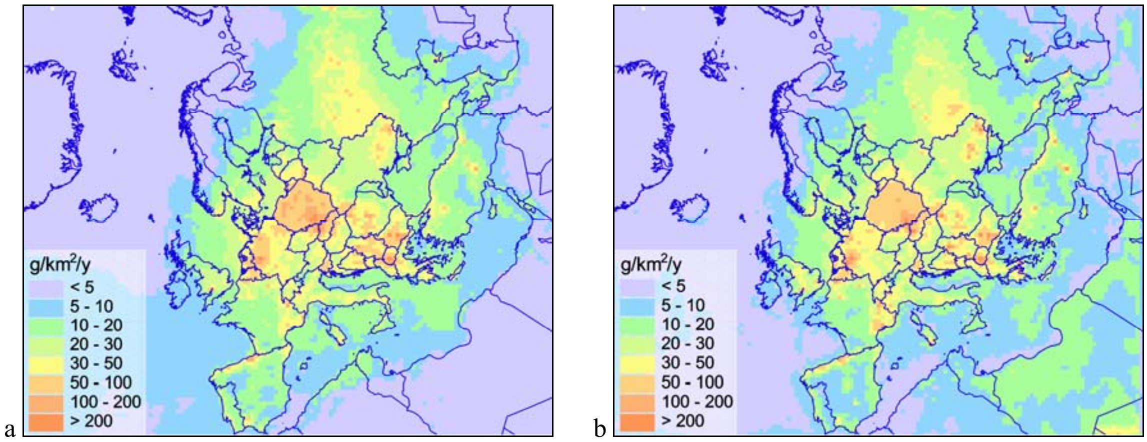


Fig. 3.24. *Spatial distribution of cadmium total (dry and wet) annual deposition in 2000 calculated with MSCE-HM (a) and CMAQ (b) models based on EMEP official emissions data, g/km^2/y*

Comparison of cadmium concentrations in air and precipitation modelled with MCSE-HM and CMAQ with measurements is illustrated in Fig. 3.25. Modelling results correlate well with the measurement data: the correlation coefficients are around 0.7 for both models. However, both MCSE-HM and CMAQ significantly underestimate observations (by 60-70%). Particularly, both models tend to underestimate lower concentrations in precipitation corresponding to Scandinavian sites, and the underestimation is larger for the CMAQ model.

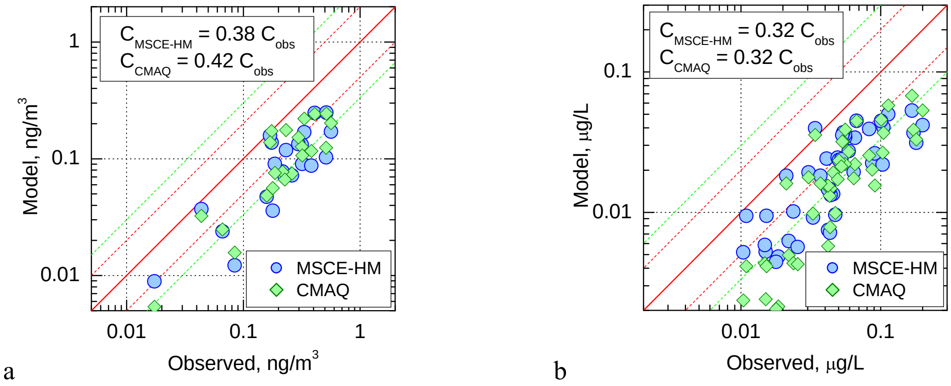


Fig. 3.25. *Scatter plots of comparison of cadmium concentrations in air (a) and precipitation (b) calculated by MSCE-HM and CMAQ models based on the official emissions data for 2000 with observations. Red solid line delineates 1:1 ratio, red and green dashed lines show deviation by a factor of two and three, respectively*

Thus, from the performed analysis it was concluded that both considered models demonstrate quite similar results both for lead and cadmium. Calculated concentration and deposition fields are in good agreement with each other, however, some discrepancies take place because of differences of the models parameterizations of dry deposition. Besides, both models tend to underestimate observations, particularly, for cadmium when the official emissions data were used.

4. MODEL ASSESSMENT OF HEAVY METAL POLLUTION

This Section is devoted to the model assessment of the long-range transport of heavy metals in the atmosphere of Europe and the Northern Hemisphere. The first section contains analysis of lead, cadmium and mercury pollution levels in Europe in 2005, information on transboundary fluxes between European countries, and heavy metal atmospheric loads to the regional seas. Particular attention is paid to transboundary pollution of Central Asian countries that are Parties (Kazakhstan, Kyrgyzstan) or candidates (Uzbekistan, Turkmenistan and Tajikistan) to the Convention. The second section includes evaluation of mercury atmospheric transport and depositions in the Northern Hemisphere. Detailed information on source-receptor relationships for all countries is presented in Annex D.

4.1. Heavy metal pollution levels in Europe in 2005

Lead

According to official emissions data total anthropogenic emissions of lead in the EMEP countries in 2005 were 4590 tonnes. It is lower by 14% than those estimated for 2004. Besides, according to utilized unofficial emission estimates about 970 tonnes were emitted in 2005 from Central Asian countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan and Tajikistan). Total deposition of lead from anthropogenic sources to the EMEP countries in 2005 was estimated at 3330 tonnes, which is about 13% lower than that for 2004 [*Iyin et al*., 2006]. Lead depositions to the EMEP countries from all sources (anthropogenic, wind re-suspension and non-EMEP) made up 10665 tonnes. Depositions to four Central Asian countries consisted of about 535 tonnes from their own sources and the EMEP countries and 960 tonnes from all other sources including emissions from other Asian countries and re-suspension. One should note that the parameterization of wind re-suspension applied in the study is still under development and, therefore, estimates of its contribution to total deposition are to be taken with caution.

Spatial distribution of lead depositions over Europe and adjacent areas to significant extent corresponds to the anthropogenic and natural emissions patterns (Fig. 4.1). In general, annual deposition fluxes in Europe in 2005 ranged from 0.2 to 2.5 kg/km^2/y. In the most pollution loaded areas of such countries as Belgium, Germany, Portugal, Poland, Greece etc. deposition fluxes often exceed 2 kg/km^2/y. In the northern part of Europe (north of Scandinavia Peninsula) deposition fluxes of lead are typically less than 0.5 kg/km^2/y. In countries of Central Asia the depositions mostly ranged between 0.2 and 0.8 kg/km^2/y. However, in some areas the depositions can exceed 1.7 kg/km^2/y.

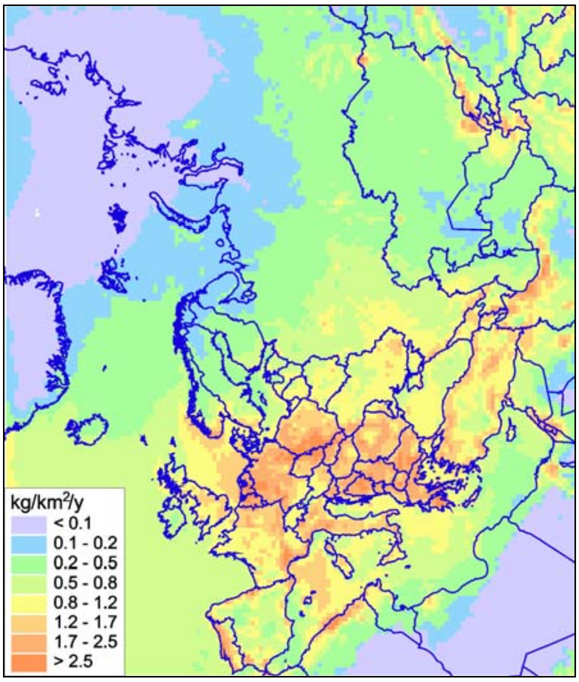


Fig. 4.1. *Spatial distribution of lead depositions in Europe in 2005, kg/km^2/y*

The largest country-averaged total deposition flux took place in the Netherlands, followed by Belgium, Bosnia and Herzegovina and the FYR of Macedonia (Fig. 4.2). As seen from the figure, the contribution of wind re-suspension to total depositions is comparable to the anthropogenic one for the majority of countries. This contribution consists of two fractions, which cannot be separated: purely natural emission, and re-suspension of long-term (historic) depositions from anthropogenic sources. It is also important to stress that current estimates of natural and historical emissions are subject of significant uncertainty. The contribution of non-EMEP sources (both natural and anthropogenic) varies from 5-6% in Central European countries (Poland, the Czech Republic, Slovakia) to about 70% in Armenia. However, for the majority of countries their contribution is less than 25%. The contribution of these non-EMEP sources was estimated via prescribed observation-based air concentrations of lead at the EMEP region boundaries. Besides, lead emissions from African and Asian countries were also taken into account as mentioned above.

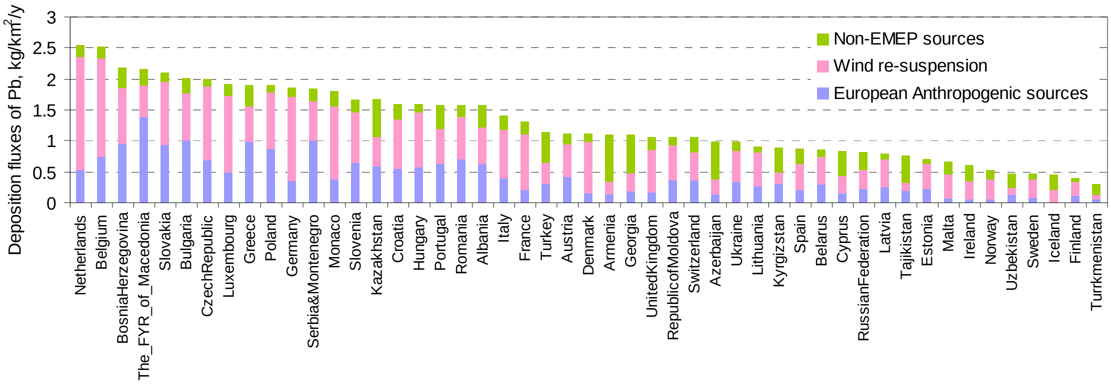


Fig. 4.2. *Country-averaged deposition fluxes of lead from European anthropogenic, natural/historical and non-EMEP sources in 2005, kg/km^2/y*

Relative contribution of the transboundary transport from European sources to anthropogenic depositions in such countries as Malta, Monaco, Iceland, Republic of Moldova, Denmark exceeds 90% (Fig. 4.3). In 37 countries this contribution exceeds 50% and in 14 countries - 80%. Contribution of the transboundary transport to depositions is relatively low for countries which are characterized by high emission, and hence, high depositions from national sources (e.g., Poland, Greece, Italy), or countries remote from main anthropogenic sources (e.g., Spain, United Kingdom, Portugal). Among countries of Central Asia the highest contribution of transboundary transport from EMEP and Central Asian anthropogenic sources was estimated for Kyrgyzstan (about 80%) and Turkmenistan (74%). The lowest contribution took place for Kazakhstan (33%).

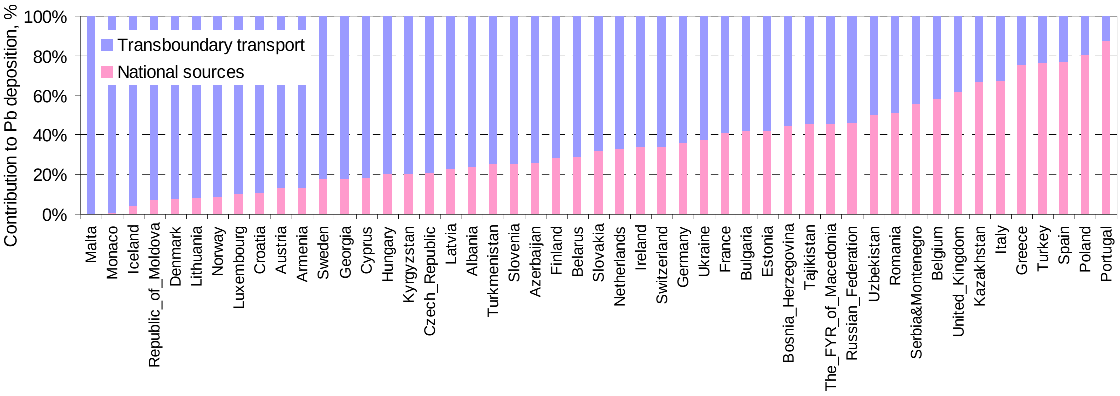


Fig. 4.3 *Relative contribution of the transboundary transport and national sources to anthropogenic lead depositions in European countries in 2005, %*

Contribution of countries to transboundary pollution was evaluated as mass of the pollutant, emitted by national sources and transported outside country's territory. This contribution depends on magnitude of national emissions, area and configuration of a country territory, predominant meteorological conditions etc. In 2005 this contribution ranged between about 400 tonnes (Kazakhstan) to some few kg (Monaco) (Fig. 4.4). Other countries contributing significantly to the transboundary transport are Greece, Turkey, Poland, and Portugal. Fractions of lead mass, emitted by national sources and involved in transboundary transport, are mostly between 60% and 90%. For Russia (part of the country within the extended EMEP domain) this fraction is around 20%, for Cyprus, Luxembourg and Monaco this fraction exceeds 90%.

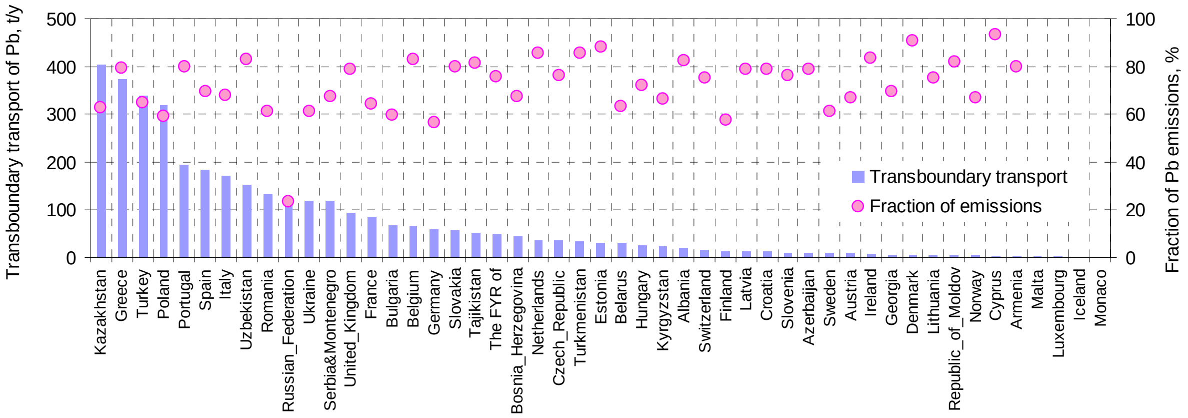
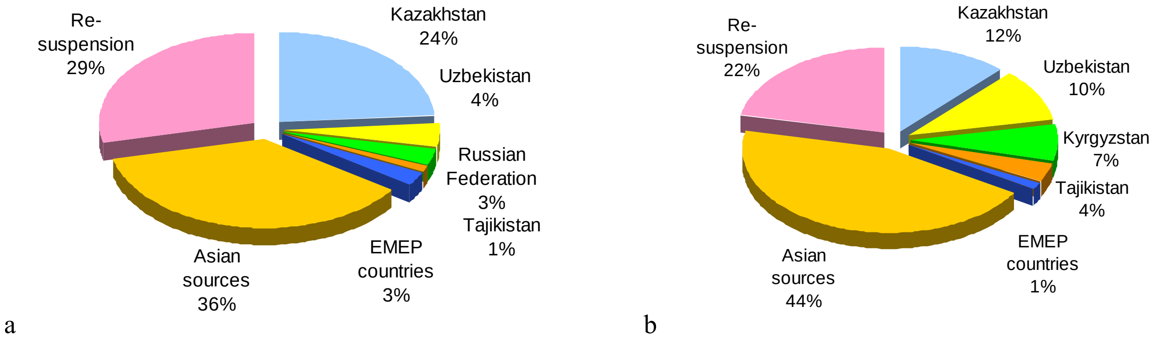


Fig. 4.4. *Absolute contribution of European countries to lead transboundary transport in Europe in 2005 and relative fraction of national emissions in this contribution, t/y*

Estimates of transboundary pollution of the selected Central Asian countries are illustrated in Fig. 4.5. The figure shows relative contribution of different countries and regions to lead deposition over Kazakhstan and Kyrgyzstan. The major anthropogenic contributors to lead depositions to these countries are sources located on their own territories and on territories of neighbouring countries (Uzbekistan and Tajikistan, the Russian Federation). Contribution of other EMEP countries does not exceed several percents. On the other hand, contribution of other Asian sources (both anthropogenic and natural) is quite significant – 36% and 44% for Kazakhstan and Kyrgyzstan respectively. However, one should notice that estimates for these sources contain significant uncertainty because of absence of reliable up to date emissions data for Asian countries.



a

b

Fig. 4.5. *Relative contribution of different countries to lead depositions to Kazakhstan (a) and Kyrgyzstan (b) in 2005*

Cadmium

According to official emissions data total anthropogenic emissions of cadmium in European countries in 2005 were about 245 tonnes. It is almost equal to the official emission estimates for 2004. Total deposition of cadmium to European countries from anthropogenic sources in 2005 was estimated at 180 tonnes. It is almost the same value as that obtained in calculations for 2004 [*Ilyin et al.*, 2006] based on official emissions data. Total depositions from all sources (European anthropogenic, re-suspension and non-EMEP) amounted to 345 tonnes. Again, similar to lead, estimates of contribution of wind re-suspension should be taken with certain caution because of pilot character of this process parameterization used in the study.

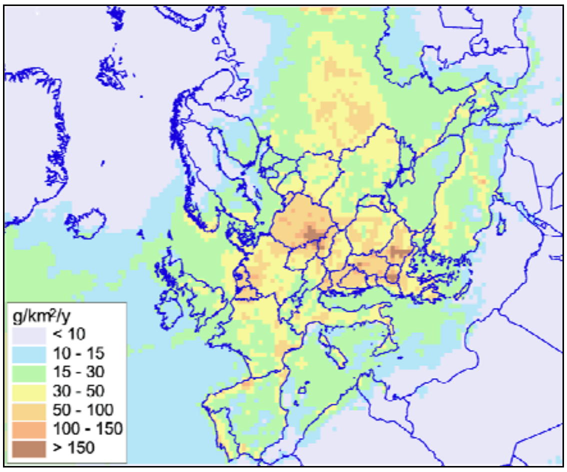


Fig. 4.6. *Spatial distribution of cadmium depositions in Europe in 2005, g/km^2/y*

Spatial distribution of cadmium depositions over the EMEP region is shown in Fig. 4.6. Over most territory of Europe depositions of cadmium in 2005 varied between 15 and 200 g/km^2/y. In Poland, Belgium, the Netherlands, some Balkan countries the depositions often exceed 100 g/km^2/y. The lowest depositions occurred in the northern regions of Europe – Iceland, north of Finland, Norway, Sweden and Russia.

Country-averaged deposition fluxes from anthropogenic, natural/historical and non-EMEP sources are demonstrated in Fig. 4.7. As seen, among 45 countries as much as in 31 countries the depositions from anthropogenic sources dominate over those caused by wind re-suspension. The highest anthropogenic depositions were obtained for the FYR of Macedonia, then Poland, Bulgaria and Slovakia. High depositions in these countries are mainly caused by significant national emissions. The contribution of non-EMEP sources to European countries ranges from 3% in Poland to almost 70% in Iceland. However, in the majority of countries this contribution is less then 25% of total deposition.

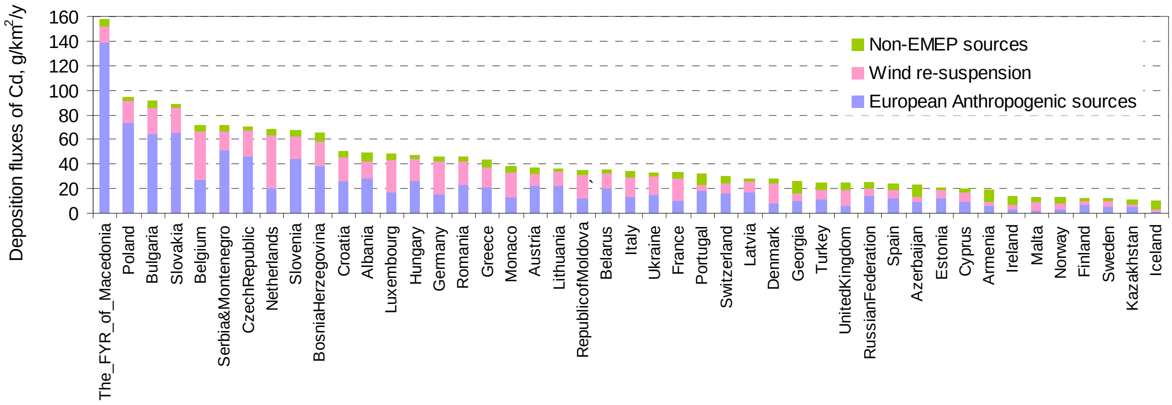


Fig. 4.7. *Country-averaged deposition fluxes of cadmium from European anthropogenic, natural/historical and non-EMEP sources in 2005, g/km^2/y*

Contribution of the transboundary transport to cadmium anthropogenic depositions in European countries in 2005 varied in wide range (Fig. 4.8). Almost 100% of depositions from anthropogenic sources in Malta are originated from the transboundary transport. In Monaco, Lithuania and Albania this contribution exceeded 95%. The lowest contribution took place in Spain, Poland and the FYR of Macedonia (12-14%). Relatively low contribution of transboundary transport in these countries is explained by either their remoteness from main pollution sources (Spain), or by high national emissions (Poland, Macedonia). In 32 of 45 countries the contribution of transboundary transport exceeded 50%, in 18 countries it is higher than 80%.

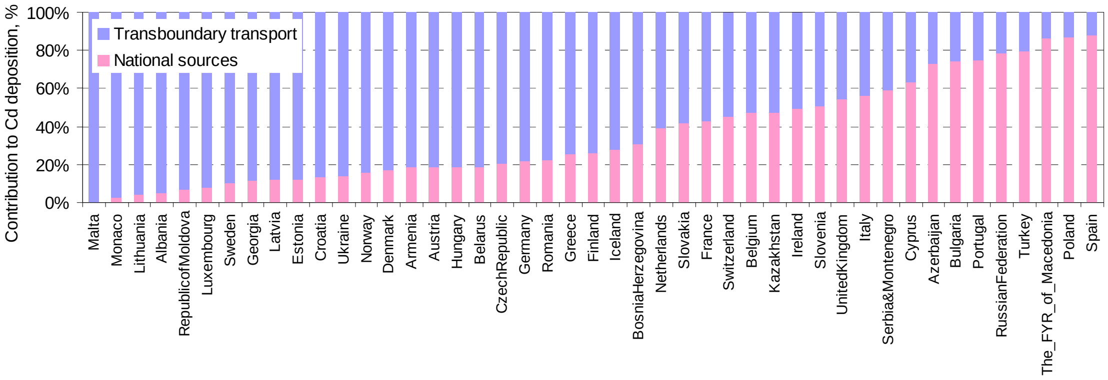


Fig. 4.8. *Relative contribution of the transboundary transport and national sources to anthropogenic cadmium depositions in European countries in 2005, %*

Contribution of each country to the atmospheric transboundary transport of cadmium was also estimated (Fig. 4.9). The largest absolute contribution to the transboundary transport of cadmium in 2005 was made by Poland (about 26 t/y), followed by Russia (17 t/y), Spain (12 t/y) and Turkey (10 t/y). The main reason for this high amount of atmospheric cadmium is high national emissions, compared to other countries of Europe. Similar to lead, the fraction of national emission involved into transboundary transport mostly ranges from 60% to 80%. The relative fraction in Russia is around 30%, whereas in Monaco, Cyprus, Malta and Luxembourg it is higher than 90%.

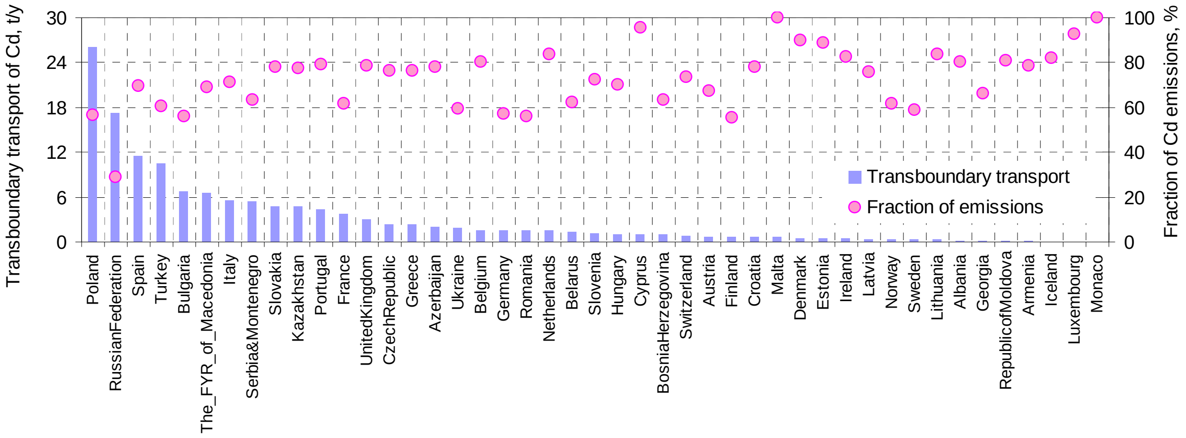


Fig. 4.9. *Absolute contribution of European countries to cadmium transboundary transport in Europe in 2005 and relative fraction of national emissions in this contribution, t/y*

Mercury

Total anthropogenic emissions of mercury in European countries in 2005 according to official emissions data were 172 tonnes. It is by 6% lower than official emission estimates for 2004. Total deposition of mercury to European countries from European anthropogenic sources in 2005 made up as much as 55 tonnes. It is 3% lower as compared to 2004 [*Iyin et al.*, 2006]. Total depositions of mercury to Europe, caused by all sources (anthropogenic, global, and natural) in 2005 were 145 tonnes, which is almost the same as that computed for 2004.

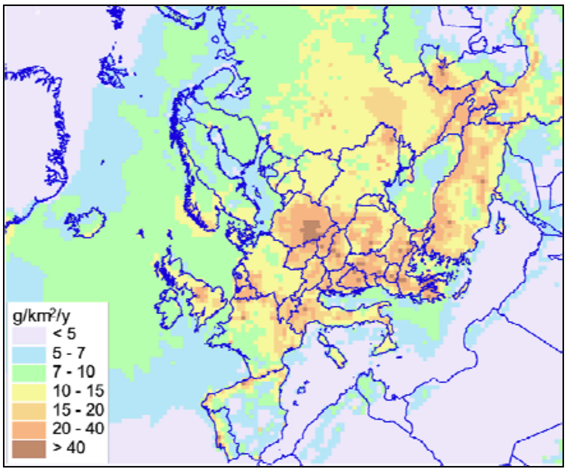


Fig. 4.10. *Spatial distribution of mercury depositions in Europe in 2005, g/km^2/y*

Generally, mercury depositions in Europe in 2005 were higher than 5 g/km^2/y but rarely exceeded 40 g/km^2/y (Fig. 4.10). The highest deposition fluxes took place in Poland, Hungary and a number of Balkan countries, where depositions were as large as 20 g/km^2/y and higher. Over central parts of the Scandinavia Peninsula and the Arctic the depositions did not exceed 10 g/km^2/y.

Country-averaged deposition fluxes and contribution of different types of emission sources to mercury deposition to European countries in 2005 is presented in Fig. 4.11. The highest average fluxes (25 – 30 g/km^2/y) were obtained for Slovakia, the FYR of Macedonia, Poland, Greece, Bosnia and Herzegovina. In 16 European countries anthropogenic emissions made up the major contribution to mercury depositions, whereas in the other 29 countries contribution of global emissions prevails over the anthropogenic ones. This fact emphasizes the need to use the global/hemispheric approach along with the regional one when evaluating mercury pollution in Europe. The contribution of natural emissions and re-emissions from the EMEP region is comparatively small. It is expected that mercury is emitted from natural sources and re-emitted in the elemental gaseous form. This mercury form is characterized by very long residence time in the atmosphere. As a result the most part of these emissions is transported behind the model domain not being deposited.

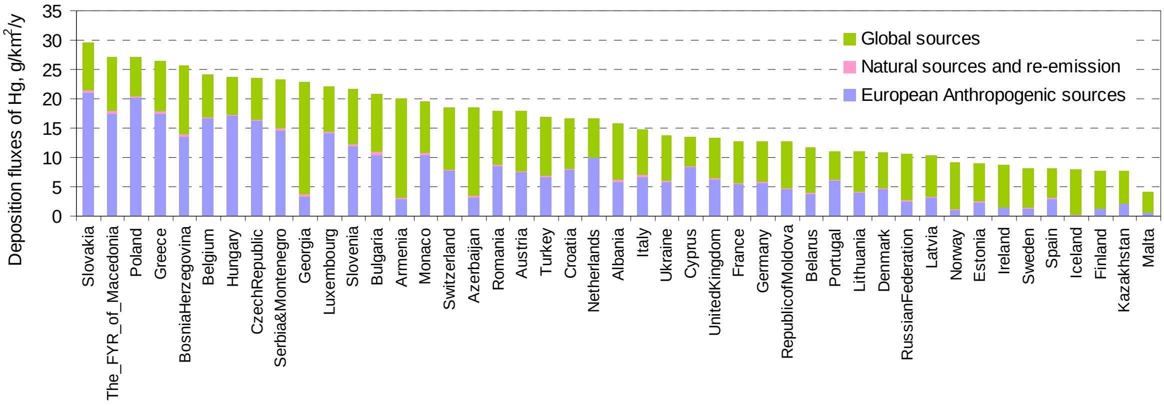


Fig. 4.11. *Country-averaged deposition fluxes of mercury from European anthropogenic, natural/historical and global sources in 2005, g/km^2/y*

The contribution of the transboundary transport in mercury pollution from anthropogenic sources in Europe varies essentially from country to country (Fig. 4.12). The highest contribution of the transboundary transport to anthropogenic mercury deposition took place in Malta, Iceland and Latvia (more than 95%). In 23 European countries this contribution exceeds 50% and in 8 countries – 80%. The lowest contribution of transboundary transport (and, hence, the highest role of national sources) was estimated for Portugal, Spain, Turkey, the United Kingdom, and Poland. Similar to other metals, relatively small influence of transboundary transport is explained by high national emissions and by their location far from major anthropogenic sources.

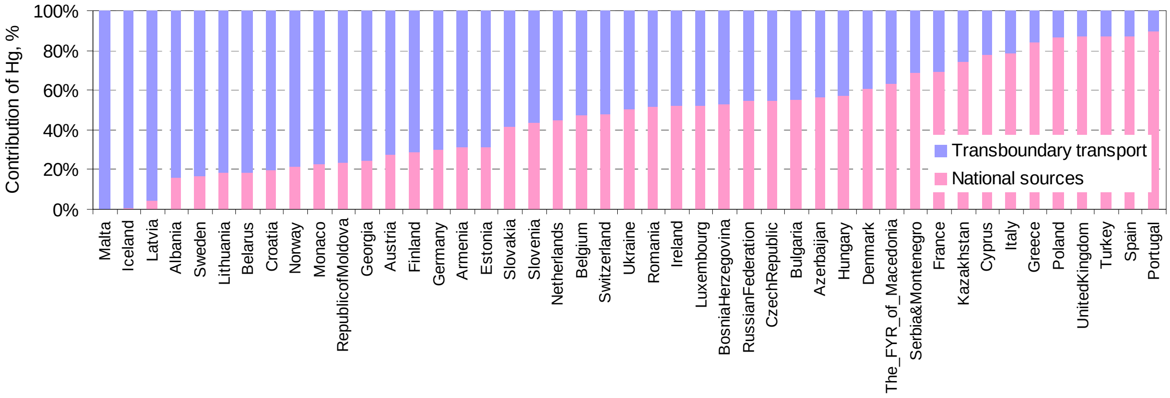


Fig. 4.12. *Relative contribution of the transboundary transport and national sources to anthropogenic mercury depositions in European countries in 2005, %*

Contribution of different countries to mercury transboundary transport in Europe in 2005 is demonstrated in Fig. 4.13. As seen from the figure Turkey was the largest contributor of mercury to long-range transport (17 tonnes), followed by Poland (15 tonnes) and Greece (11 tonnes). Significant transboundary transport from these countries is mainly caused by their large national emissions. The fraction of mercury emissions contributed to the transboundary transport was typically higher than that of lead and cadmium and commonly exceeds 80%. The exception is Russia for which this fraction is about 60%.

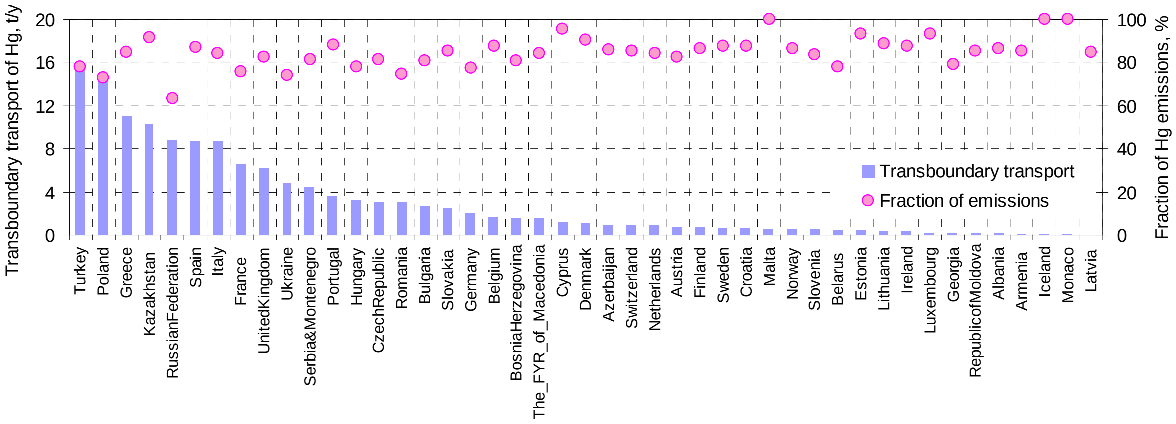


Fig. 4.13. *Absolute contribution of European countries to mercury transboundary transport in Europe in 2005 and relative fraction of national emissions in this contribution, t/y*

Depositions to regional seas

According to the working plan MSC-E estimates atmospheric loads to seas surrounding Europe (Black, Azov, North, Mediterranean, Baltic and Caspian). As seen in Fig. 4.14 the highest average deposition fluxes of lead and cadmium in 2005 were obtained for the North Sea (1.1 kg/km^2/y and 24 g/km^2/y, respectively). This is caused by atmospheric transport from the countries with significant emission sources located nearby. The lowest depositions are to the Caspian Sea since it is located far from the major European sources. The most significant depositions of mercury occurred over the Caspian Sea (10 g/km^2/y)

Contribution of different countries to depositions of lead, cadmium and mercury to each marginal sea was also evaluated (see Annex D). Figure 4.15 shows an example of the analysis for lead deposition from anthropogenic sources to the Caspian and North Seas in 2005. The highest atmospheric load to the North Sea (Fig. 4.15a) from European anthropogenic sources was made by the United Kingdom (32%). Other important contributors are France, Belgium, Poland and the Netherlands with similar contribution about 10%. Around one half of lead depositions to the Caspian Sea (Fig 4.15b) was contributed by Kazakh emission sources. Other main contributors are Russia (10%), Turkey (8%), Uzbekistan (7%) and Turkmenistan (7%).

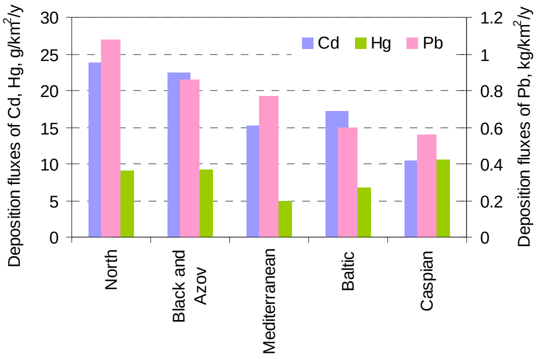


Fig. 4.14. *Averaged deposition fluxes of lead, cadmium and mercury to regional seas in 2005*

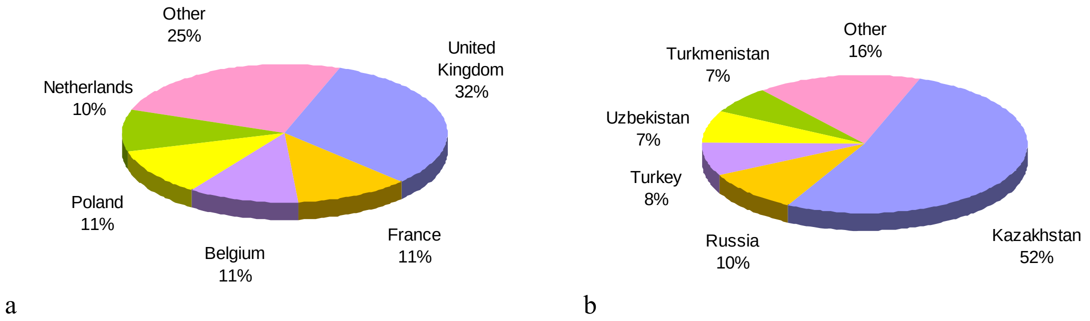


Fig. 4.15. *Contribution of different countries to lead depositions from anthropogenic sources to the North Sea (a) and the Caspian Sea (b) in 2005*

4.2. Hemispheric modelling of mercury pollution

Mercury is well recognized by the environmental community as a global pollutant capable of dispersing all over the globe. Because of its very long residence time in the atmosphere it can be easily transported by air masses between the continents and can significantly affect regional depositions both in industrially developed and in remote regions. Therefore mercury pollution levels in Europe cannot be assessed without consideration of the intercontinental transport.

Within the framework of the Task Force on Hemispheric Transport of Air Pollution (TF HTAP) MSC-E participates in the intercomparison study of hemispheric models [http://www.htap.org/activities/Model_Evaluation.htm]. The aim of the study is assessment of intercontinental source-receptor relationships, evaluation of current models variability and uncertainties, and guidance of future model developments. The first set of the model experiments includes evaluation of mercury hemispheric transport in 2001 and estimates of sensitivity of mercury concentration and deposition levels to emission reduction in major source regions.

Global mercury anthropogenic emissions dataset for 2000 [*Pacyna et al.,* 2006; *Wilson et al.,* 2006] was utilized for the modelling along with estimates of mercury natural emission and re-emission [*Travnikov and Ryaboshapko*, 2002]. Two-years model spin-up was performed prior to the calculations in order to fill in the model domain with mercury. Patterns of gaseous elemental mercury (GEM) concentration in air and total mercury deposition calculated with MSCE-HM-Hem model are shown in Fig. 4.16. Long-lived elemental mercury more or less evenly distributed in the Northern Hemisphere with concentrations varied within the range 1.3-2.5 ng/m^3 (Fig. 4.16a). On the other hand, spatial distribution of depositions well corresponds to the emission field (Fig. 4.16b): Elevated depositions (more than 20 g/km^2/y) are in Europe, North America, Eastern and Southern Asia. It can be explained by the fact that mercury depositions are defined to a greater extent by short-lived mercury forms (oxidized gaseous and particulate mercury). Considerable depositions (up to 12 g/km^2/y) are also predicted over the oceans as a result of oxidation of long-lived elemental mercury in the atmosphere by ozone, hydroxyl radical and reactive halogens.

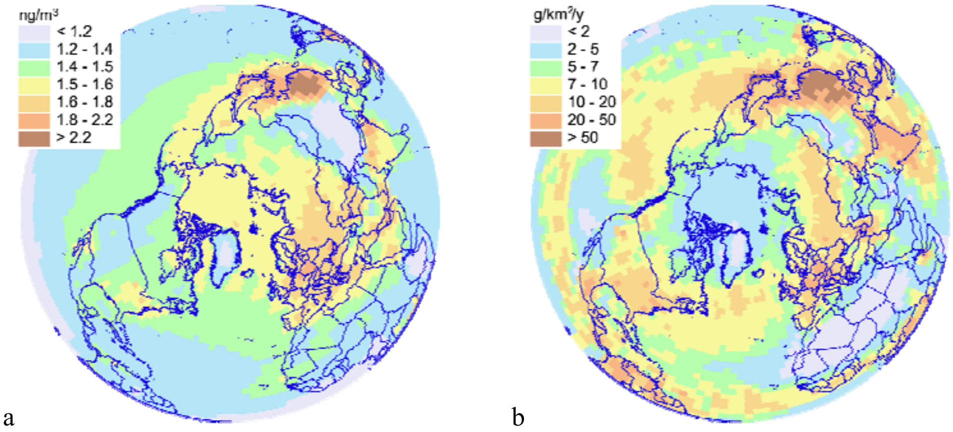
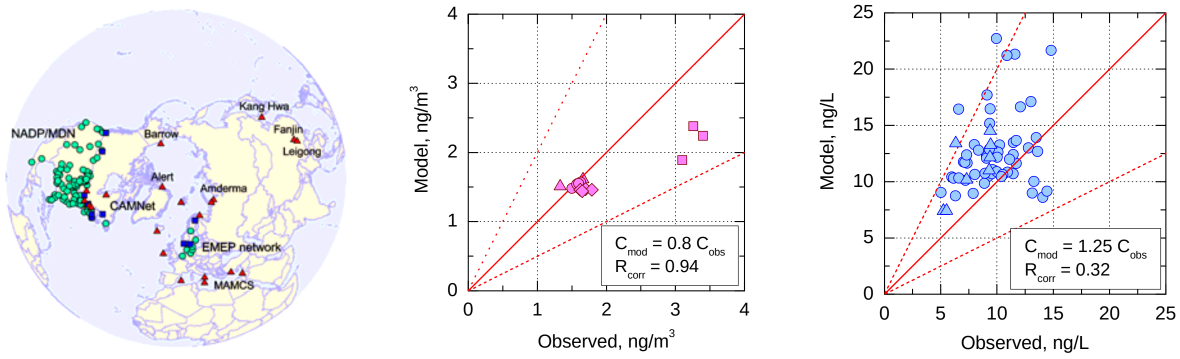


Fig. 4.16. *Spatial distribution of gaseous elemental mercury concentration in air, ng/m^3 (a) and total mercury deposition, g/km^2/y (b) in the Northern Hemisphere in 2001*

In order to evaluate the modelling results calculated mercury concentrations in air and precipitation were compared with available measurements. For this purpose we used long-term observations from the EMEP monitoring network in Europe as well as the NADP/MDN and CAMNet networks in North America. Besides, measurements at the Arctic stations Barrow, Alert and Amderma were involved in the comparison. Location of monitoring sites used in the model evaluation is shown in Fig. 4.17a. Results of the comparison are presented in Figs. 4.17b and 4.17c. As seen, modelled concentrations of gaseous elemental mercury well agree with observed ones. Discrepancy between calculated and measured values does not exceed 20% with the exception of high values at Chinese and Korean sites which are somewhat underestimated by the model. On the other hand, the model tends to overestimate observed mercury concentration in precipitation. Besides, scattering of modelled and observed concentration in precipitation is more significant than in the case of GEM concentration.

Nevertheless, difference between the calculated and measured values does not exceed a factor of two.



a b c

Fig. 4.17. Location of monitoring sites used in the model evaluation (a), calculated vs. measured values of mean annual concentration of gaseous elemental mercury (b) and mercury concentration in precipitation (c). Dashed lines depict two-fold difference interval

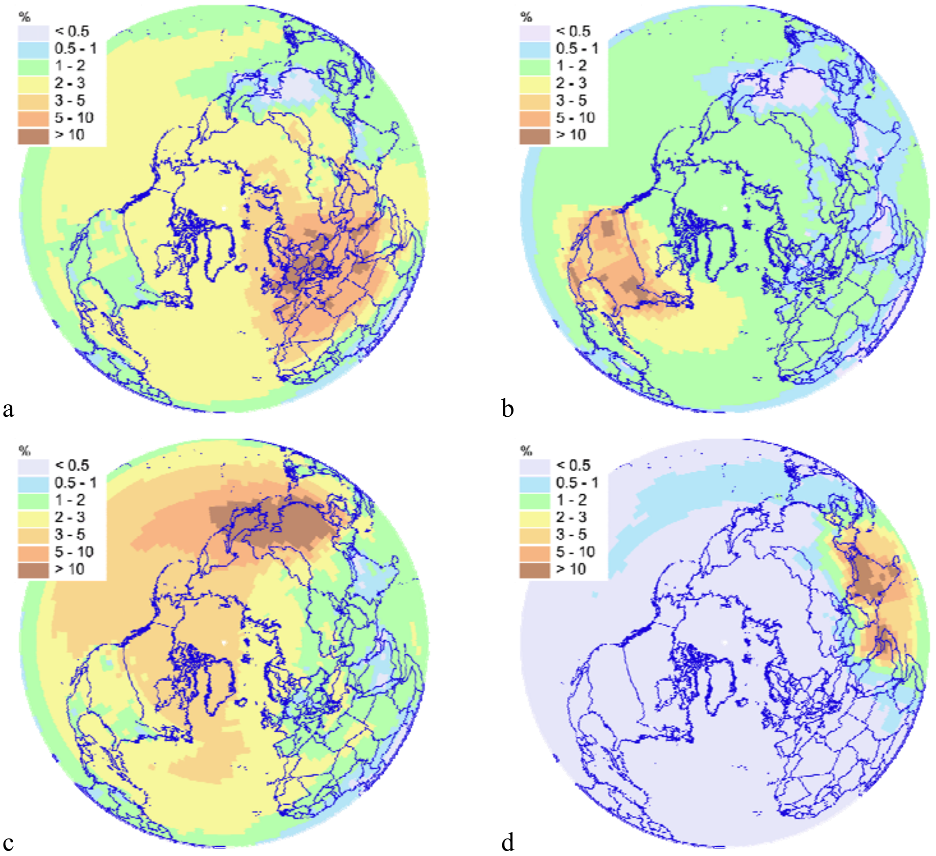


Fig. 4.18. *Spatial distribution of mercury deposition decrease in the Northern Hemisphere due to emission reduction by 20% in Europe (a), North America (b), Eastern Asia (c), and Southern Asia (d), %*

Sensitivity of mercury deposition in the Northern Hemisphere to emission reduction has been evaluated by performing model runs with anthropogenic emissions decreased by 20% in four major source regions - Europe, North America, Eastern Asia and Southern Asia. Obtained deposition fields were compared with the base case simulation for 2001 described above. Figure 4.18 illustrates calculated response of mercury deposition in the Northern Hemisphere to 20% emission reduction in the mentioned above regions. The most significant reduction of mercury deposition in the Northern Hemisphere is caused by emission reduction in Eastern Asia (Fig. 4.18c) because of large relative contribution of sources located in this region to the global mercury emissions. Depositions decrease considerably not only in Eastern Asia but also over the Pacific, North America and the Arctic. Emission reduction in Europe also results in considerable depositions decrease (apart from Europe itself) in the North Atlantic, the Arctic and Northern Africa (Fig. 4.18a). Emission reduction in Southern Asia has the lowest effect on decrease of mercury depositions in the Northern Hemisphere (Fig. 4.18d).

Quantitative analysis of sensitivity of mercury depositions in different regions of the Northern Hemisphere to emission reduction is illustrated in Fig. 4.19. For this purpose the sensitivity coefficient of mercury deposition has been calculated as follows for four major receptor regions (Europe, North America, Asia, and the Arctic):

$$S.c. = \frac{\Delta D_i}{\Delta E_j}, \tag{4.1}$$

where ΔD_i and ΔE_j are deposition changes in i^{th} receptor region to emission reduction in j^{th} emission region, respectively. As seen from Fig. 4.19b depositions in Europe are most sensitive to reduction of anthropogenic emissions from its own sources but also in Eastern Asia and North America. Reduction of depositions in Asia mostly depends on emission reduction from Eastern and Southern Asian sources. On the other hand, mercury depositions in North America only partly depend on emissions from own sources but also to great extent on those from Eastern Asian and European sources.

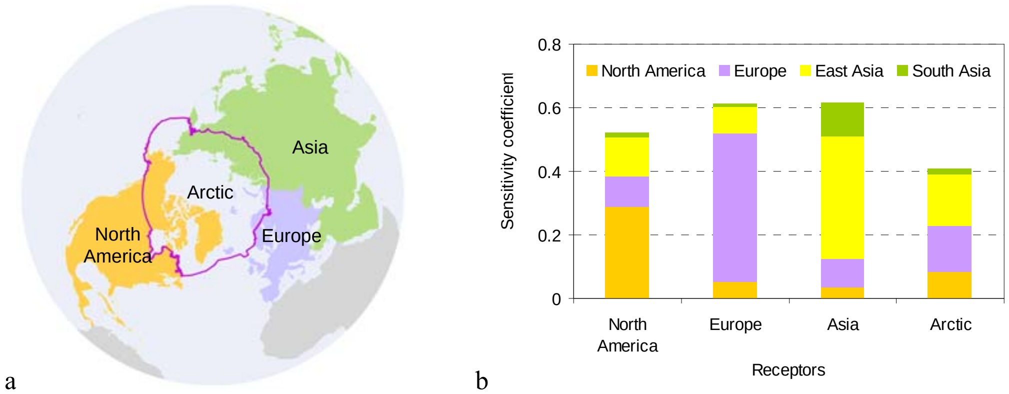


Fig. 4.19. *Selected receptor regions of the Northern Hemisphere (a) and coefficient of mercury deposition sensitivity to emission reduction in different source regions (b)*

Along with the estimates of the intercontinental transport, the hemispheric model was applied for implementation of the one-way nesting to the regional modelling of mercury pollution. For this purpose daily mean concentrations of three mercury forms (elemental, reactive gaseous and particulate) were calculated with the hemispheric model at the EMEP domain boundaries and were assimilated the regional model.

5. CO-OPERATION

5.1. Task Force on Measurements and Modelling

MSC-E took part in the 8th meeting of the Task Force on Measurements and Modelling (Dessau, April 2007) and presented information on results of the joint MSC-E and MSC-W technical meeting (Moscow, February 2007). The meeting was held in accordance with the recommendation of the EMEP Steering Body Bureau to discuss possibilities for further streamlining the work at MSC-E and MSC-W with respect to hemispheric/global modelling. Centres recognized limitation of hemispheric modelling approach and noted that the development of a global scale model especially for ozone, mercury and some POPs was required. Work-plan elements for the elaboration of a common modular system for modelling of different pollutants on global level were presented. Centres suggested a step-wise approach for the development of a global Unified EMEP model, beginning with the unification of model geometry, input data, meteorological drivers and driving meteorological input, and harmonization of physical/chemical modules and numerical techniques. The work had been already started in 2007 and it was planned to be completed in 2010-2012.

Taking into account that the extension of the geographical scope of EMEP in order to include EECCA countries had become an important priority within CLRTAP, Centres had a detailed discussion on this issue. It was proposed two-step approach. As interim decision (step1) it was suggested to extend current EMEP 50x50 km grid eastward to cover Central Asian countries. This approach would allow including Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan in the routine model calculations of EMEP.

Final version of an extended EMEP grid (step 2) was planned to be based on the application of a new Unified EMEP global model. (Minutes of the joint MSC-W and MSC-E technical meeting are given in the Annex E).

5.2. Task Force on Heavy Metals

MSC-E participated in the 4th meeting of the Task Force on Heavy Metals (TF on HMs) held in Vienna, Austria, in June 2007. MSC-E presented an overview of recent activities under EMEP related to heavy metals.

In particular it was noted that number of countries reporting the data on HM emissions increased considerably during recent years. Nevertheless, official emissions continued to have significant uncertainties. Submission of the emission data remained insufficient and official emissions were still underestimated for some countries.

The Centre informed the meeting of the development of a dust re-suspension scheme and demonstrated that wind re-suspension of dust particles could make considerable contribution to heavy metals pollution levels, especially for lead. Application of this process into modelling system gave better agreement between modelled and measured concentrations in air and precipitations.

Contribution of global mercury sources to pollution levels in Europe was demonstrated by MSC-E. According to the modelling results, this contribution could be dominant for a number of EMEP countries. It was stressed that global/hemispheric approaches should be used alongside regional approach for further progress in the evaluation of mercury pollution levels.

5.3. Task Force on Hemispheric Transport of Air Pollution

MSC-E continued cooperation with the EMEP Task Force on Hemispheric Transport of Air Pollution (TF HTAP). Particularly, the Centre participates in the intercomparison study of hemispheric models organised in the framework of TF HTAP. The aim of the study is assessment of intercontinental source-receptor relationships for different pollutants including mercury and selected POPs, evaluation of current models variability and uncertainties, and guidance of future model developments.

The first set of the model experiments for mercury included evaluation of the hemispheric transport in 2001 and estimates of sensitivity of mercury concentration and deposition levels to emission reduction in major source regions. Major modelling results obtained by MSC-E at the current stage of the study are briefly discussed in Section 4.2 of the current report. Besides, these results were presented at the TF HTAP Workshop in Geneva, Switzerland, in February 2007.

5.4. European Commission and national experts

ESPREME project

MSC-E in 2007 participated in the EU ESPREME project (SSPI-CT-2003-502527), which has been finished this year. The project aimed to develop methods and tools to support European environmental policy making in the specific case of reducing the harmful impacts of heavy metals in a harmonised way across Europe. The role of MSC-E in the project was to assess by means of its chemical transport models the atmospheric dispersion of selected heavy metals (Hg, Pb, Cd, As, Ni and Cr) and their deposition to water and soil.

The main activities carried out by MSC-E during the last year were connected with application of the regional chemical transport model MSCE-HM to extensive calculations of heavy metal atmospheric dispersion in Europe both for the base year 2000 and 2010 scenarios. Particularly, the following modelling activities have been performed:

- Calculations of As, Cd, Cr, Hg, Ni, and Pb concentration and depositions fields in Europe for the base year 2000. Spatial patterns of the pollution levels have been analysed and the modelled values have been compared with available measurements. It was obtained that discrepancies between modelled and observed values mostly do not exceed a factor of two. Besides, the model uncertainty was estimated to be not higher than 50%.

- Calculations of As, Cd, Cr, Hg, Ni, and Pb concentration and depositions fields for BAU+Climate and MFTR scenarios of 2010. Reduction of heavy metal deposition in Europe between 2000 and 2010 has been estimated. Comparison of the estimated total deposition of heavy metals to European countries in 2000 and two emission scenarios for 2010 is illustrated in Fig. 5.1. It was obtained that the reduction varies both for different heavy metals and in different parts of Europe. The highest deposition reduction was predicted for Cd, Pb and Ni (about 20% and 30% for BAU and MFTR, respectively); the lowest – for As and Cr (below 8% and 15% for BAU and MFTR, respectively). The value of deposition reduction depends on reduction of anthropogenic emissions, contribution of natural sources and wind re-suspension, and influence of the intercontinental atmospheric transport.

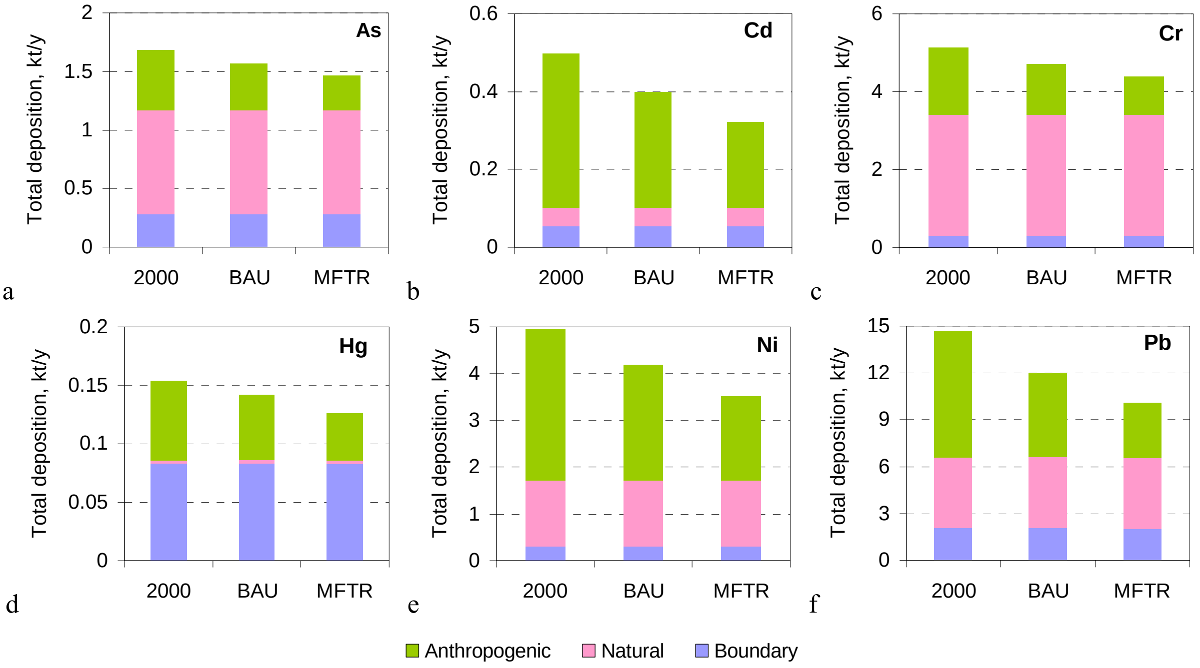


Fig. 5.1. *Estimated total deposition of heavy metals to European countries in 2000 and 2010 according to BAU and MFTR emission scenarios, kt/y*

- Calculations of country-to-grid source-receptor matrices of As, Cd, Cr, Hg, Ni, and Pb concentration and deposition sensitivity to emission reduction in different European countries for BAU+Climate and MFTR scenarios of 2010. This kind of matrices define a link between emission reduction in each European country and heavy metal deposition to each grid cell (or even to each land use type within a grid cell) of the model domain. Thus, they allow estimating sensitivity of heavy metal deposition in Europe to emission reduction in each European country. An example of this analysis is presented in Fig. 5.2.

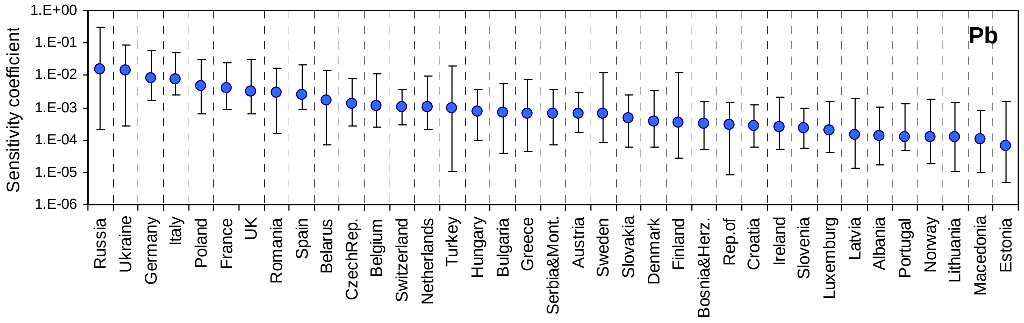


Fig. 5.2. *Sensitivity of Pb deposition in Europe to emission reduction in different European countries. Dots present medians of the frequency distribution functions; ranges show 90%-confidense intervals over the European territory*

HEIMTSA project

MSC-E also takes part in the HEIMTSA project launched in 2007 under the 6th Framework Programme of the EC. The project aims to support the Environment and Health Action Plan (EHAP) by extending health impact assessment (HIA) and cost benefit analysis (CBA) methods and tools so that environment and health impacts of policy scenarios in key sectors can be evaluated reliably at the European level. The role of MSC-E in the project is to assess by means of its chemical transport models the atmospheric dispersion of selected heavy metals and POPs and their concentration in different environmental media.

5.5. Helsinki Commission

During 2006 MSC-E in co-operation with EMEP Centres prepared contribution to the joint annual report for HELCOM devoted to the evaluation of airborne pollution load to the Baltic Sea in 2004 [*Bartnicki et al*., 2006]. MSC-E was responsible for providing the information on atmospheric transport and depositions of lead, cadmium, and mercury to the Baltic Sea. The depositions and atmospheric transport were assessed on the base of EMEP officially submitted emission data. Besides, this report provides detailed information about emissions of heavy metals in HELCOM countries and comparison of modelling results against measurement data collected in the HECLOM region in 2004.

In addition to the joint annual report, MSC-E prepared environmental indicator reports with the updated information on atmospheric emissions of heavy metals and their depositions to the Baltic Sea for 1990 – 2004 period. These reports are available in the Internet at the web site of Helsinki Commission [*www.helcom.fi*].

According to the officially reported emission data, cadmium emissions in HELCOM countries declined by 44%, mercury – by 42% and lead by 87% for period from 1990 to 2004 (Fig. 5.3). Generally, the reduction of heavy metal emissions in this area is caused by extensive use of unleaded gasoline and application of cleaner production technologies. Besides, it is partly connected with economic re-structuring which has taken place in Poland, Estonia, Latvia, Lithuania, and Russia since early 1990s. The highest decrease of cadmium emissions took place in Estonia (87%) and Lithuania (86%). Germany was noted as a leader of lead emission reduction. For the considered period its emissions dropped by almost 80 times. The most substantial decrease of mercury emissions was in Sweden (83%). The abrupt decrease of lead emissions in HELCOM countries between 2003 and 2004 is mostly caused by emission changes in the Russian Federation.

Following the reduction of atmospheric emissions, depositions of heavy metals decreased for the period 1990 – 2004 (Fig. 5.4). Depositions of lead are characterized by the most significant decline (69%). The decrease of cadmium depositions made up 51%, and mercury – 44%. When considering individual sub-basins of the Baltic Sea the highest decrease of cadmium depositions was revealed for the Gulf of Finland (68%). Over the Gulf of Bothnia and the Gulf of Finland the largest decrease (73%) of lead depositions occurred. For mercury, the most significant decline in depositions was obtained for the Belt Sea (60%).

In 2004 the highest modelled depositions of heavy metals were indicated for the southern-western part of the Baltic Sea (the Belt Sea and the Baltic Proper). Among other regions characterized by significant pollution levels it is worth mentioning the Gulf of Riga. Poland, Germany and Russia are the major contributors to atmospheric depositions of heavy metals to the Baltic Sea in 2004 among HELCOM countries.

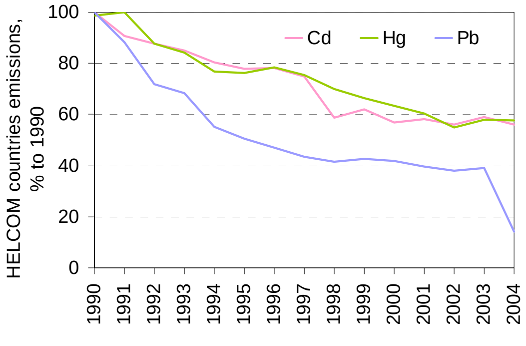


Fig. 5.3. Trend of anthropogenic emissions of cadmium, mercury, and lead from HELCOM countries in 1990-2004 according to official emissions data

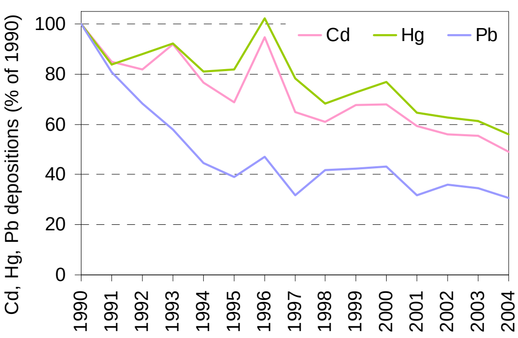


Fig. 5.4. Temporal variations of cadmium, mercury, and lead depositions to the Baltic Sea in 1990-2004

5.6. Publications and scientific meetings

In 2007 three papers with co-authors of MSC-E regarding heavy metals were published in peer-reviewed journals. Two of these papers summarizes the results of mercury intercomparison study, coordinated by MSC-E from 2000 to 2006. The third paper deals with preliminary evaluation of critical load exceedances of lead, cadmium and mercury on the base of deposition data computed by MSCE-HM model. Full references to these papers are listed below:

1. Ryaboshapko A, Bullock Jr O.R,.Christensen J., Cohen M., Dastoor A., Ilyin I., , Petersen G., Syrakov D., Artz R.S., Davignon D., Draxler R. R. and Munthe J. (2007). Intercomparison study of atmospheric mercury models: 1. Comparison of models with short-term measurements. Science of the Total Environment 376, 228–240.

2. Ryaboshapko A, Bullock Jr O.R,.Christensen J., Cohen M., Dastoor A., Ilyin I., , Petersen G., Syrakov D., Travnikov O., Artz R.S., Davignon D., Draxler R. R., Munthe J., Pacyna J. (2007). Intercomparison study of atmospheric mercury models: 2. Modelling results vs. long-term observations and comparison of country deposition budgets. Science of the Total Environment 377, 319–333.

3. Slootweg J., Hettelingh J.-P., Posch M., Schütze G., Spranger T., de Vries W., Reinds G. J., van ’t Zelfde M., Dutchak S. and Ilyin I. (2007). European Critical Loads of Cadmium, Lead and Mercury and their Exceedances. Water Air Soil Pollut: Focus 7:371–377.

Representatives of MSC-E took part in Eighth International Conference on Mercury as a Global Pollutant, held in Madison, the USA in August, 2006. MSC-E presentation included information on modelled hemispheric-scale depositions of mercury for the period 1990 – 2005. The presented pollution trends were verified via comparison of modelled and observed concentrations of mercury in air and in precipitation. In addition to this, intercontinental transport was characterized. Special attention was paid to analysis of seasonal variability of mercury depositions to different continents.

6. FUTURE ACTIVITIES

In order to further improve the quality of modeling results of lead, cadmium and mercury pollution over EMEP region, the following activities are proposed for 2008:

1. Model development
   - 1.1. Improve the Hg hemispheric/global model in accordance with recent scientific findings.
   - 1.2. Improve the regional heavy metal model with respect to size-segregated description of aerosol atmospheric transport and removal processes.
   - 1.3. Further develop and evaluate heavy metal re-suspension scheme for the regional heavy metal model.
   - 1.4. Initiate work for a global modelling system by testing new meteorological drivers. Start testing GEM and PUM meteorological weather prediction models.
2. Input data preparation
   - 2.1. Prepare gridded anthropogenic emission data for modelling based both on official and unofficial data.
   - 2.2. Start preparation of input data for global modelling (land cover, sources, global data on soil properties, etc).
   - 2.3. Employ ECMWF analyses for meteorological data processing
3. Evaluation of pollution
   - 3.1. Prepare information on lead, cadmium and mercury for 2006: air concentrations and ecosystem-dependent depositions over Europe and estimates of country-to-country matrices; estimates of depositions to regional seas (Mediterranean, Baltic, Black and North Sea).
   - 3.2. Evaluate ecosystem-dependent depositions of heavy metals and contribute to development of the effect-based approach.
   - 3.3. Prepare information on mercury dispersion at the hemispheric scale for the evaluation of boundary conditions for the regional modeling.
   - 3.4. Complement EMEP monitoring data with quality-checked data from other international programmes. Compare modeling results (concentrations in air and in precipitation, deposition fluxes) with monitoring data.
   - 3.5. Continue to co-operate with EU, HELCOM, UNEP, etc.

CONCLUSIONS

The main activities of EMEP Centres CCC and MSC-E in the field of monitoring and modelling of heavy metals in 2007 were focused on evaluation of pollution levels in Europe in 2005. Particular attention was paid to implementation of the recommendations formulated by TFMM aimed at evaluation and further improvement of the MSC-E heavy metal model. Besides, MSC-E co-operated with the Task Force on Measurements and Modelling and contributed to the Task Force on Heavy Metals and the Task Force on Hemispheric Transport of Air Pollution. The main conclusions on the activities, undertaken by CCC and MSC-E, are presented below.

Monitoring of heavy metals

1. For 2005 as much as 64 stations reported data on lead and cadmium concentrations in air and in precipitation. Among them there are 28 sites which reported the concentrations in both media. There were 19 stations where at least one form of mercury was reported. Nevertheless, spatial coverage with measurements of the southern and eastern parts of Europe is unsatisfactory.
2. Measurements of heavy metal concentrations in 2005 demonstrated that the lowest concentrations of lead, cadmium and mercury were observed in Northern Scandinavia. The highest concentrations were measured in the central part of Europe (Slovakia, the Czech Republic, Slovenia and Hungary).
3. Results achieved in the annual analytical intercomparison of national laboratories clearly indicate data quality improvement of the EMEP measurements since 1995. However, problems with analytical processing of measurement data were indicated for some countries. Besides, not all of the countries participate in the annual laboratory intercomparison and, hence, data from these countries are of unknown quality.

Emissions

1. In 2007 as much as 30 EMEP parties submitted official emission data on lead, cadmium and mercury for 2005 reporting year. Information on gridded emissions was presented by 24 countries at least for one year in the period 1990-2005. Among them 19 countries have submitted the gridded emission data by sectors.
2. Seventeen EMEP countries have changed previously reported national emission data for the period 1990–2004. The changes of the emissions due to the revision reached 10 times in Germany, 3 times in Cyprus, and almost 100% in some other countries.
3. Official data on heavy metals emissions by source categories in 2005 is available for 30 countries. The data analysis has shown that contribution of key source categories varies for different metals. Particularly, the source category “Manufacturing Industries and Construction” is the largest contributor to the total lead and cadmium emissions in Europe (41% and 45%, respectively), whereas “Public Electricity and Heat Production” is the prevailing source of mercury emissions (42%).

4. Officially reported emission data on lead and cadmium were compared with the available non-official expert estimates (TNO, ESPREME). It was concluded that different emission inventories for lead and cadmium well correlate with each other, however, significant differences are observed for many countries. The deviation is more pronounced for cadmium emissions. Significant discrepancies take place also in contribution of key source categories to national emission totals.

Model development and evaluation

1. In accordance with recommendations of TFMM MSC-E continues further development and improvement of the heavy metal transport model. Particularly, a system of meteorological data quality control has been developed and applied and the heavy metal wind re-suspension scheme has been improved. A special attention was paid to the model evaluation against measurements and in comparison with another chemical transport model (CMAQ).

2. The system of meteorological data quality control has been applied to evaluation of the pre-processed meteorological fields against those from independent datasets (ECMWF ERA-40, GPCP). Results of the comparison demonstrate that the meteorological data used for the modelling process reasonably well agree with reference data. MSC-E has also started movement to use of data with higher spatial resolution (1°x1°) from the ECMWF analysis as driving information for the meteorological pre-processing.

3. The scheme of wind re-suspension of mineral dust and particle-bound heavy metals from soil and seawater has been further developed. Particularly, an effect of soil characteristics (soil texture, size distribution of soil grains etc.) on dust production and suspension are taken into account. Besides, some special effects affecting dust mobilization (such as wind drag partition, inhibition by soil moisture, the Owen effect) are introduced or revised in the model.

4. Evaluation of the modeling results against observations has shown that calculated concentrations of heavy metals well correlate with measured values. In general, the modelled levels of lead underestimate measurements by 20-30%, of cadmium – 30-50%. The most significant underestimation was obtained at sites located in Central Europe and Northern Scandinavia. The reasons of the underestimation the most probably connected with uncertainties of spatial distribution of emissions in these regions or with missed local sources. Mercury levels are well reproduced by the model: the difference between modelled and measured values does not exceed 15% for air concentrations and commonly within ±45% for concentration in precipitation.

5. Comparison of modelling results obtained with MSCE-HM and CMAQ models demonstrates that the models predict quite similar ambient levels of lead and cadmium. Calculated concentration and deposition fields are in good agreement with each other, however, some discrepancies take place because of differences of the models parameterizations of dry deposition. Besides, both models tend to underestimate observations, particularly, for cadmium when the official emissions data were used.

Model assessment of pollution levels

1. According to the modelling results depositions of lead, cadmium and mercury in 2005 varied significantly across Europe. The highest atmospheric pollution levels were indicated for countries of Central, Eastern and South-Eastern Europe (the Czech Republic, the FYR of Macedonia, Slovakia, Poland, Bulgaria) and in some regions of the Western Europe (e.g. the Benelux region).

2. Estimated contribution of the wind re-suspension of particle-bound heavy metals to atmospheric depositions over Europe is comparable or even exceeds contribution of anthropogenic sources in a number of countries, particularly, for lead. However, the current estimates of wind re-suspension are subject of significant uncertainty because of developing status of the model dust suspension scheme.

3. The influence of the transboundary transport on heavy metal depositions in Europe is significant. Contribution of transboundary transport to depositions from anthropogenic sources exceeds 50% in 37, 32 and 32 countries for lead, cadmium and mercury, respectively. On the other hand, fraction of national emissions contributing to the transboundary transport in Europe ranges from 60% to 80% for lead and cadmium. In case of mercury, this fraction is commonly higher than 80%.

4. Pilot calculations of transboundary pollution of Central Asian countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan and Tajikistan) have been performed for lead. It was obtained that contribution of the transboundary transport from the EMEP and Central Asian sources to anthropogenic depositions was the highest among these countries for Kyrgyzstan (80%) and Turkmenistan (74%), the lowest contribution – for Kazakhstan (33%).

5. Mercury hemispheric transport and depositions were evaluated at the hemispheric scale. Sensitivity of mercury deposition in the Northern Hemisphere to emission reduction in different regions has been evaluated. The most significant decrease of mercury deposition in the Northern Hemisphere is caused by emission reduction in Eastern Asia because of large relative contribution of sources located in this region. Depositions in Europe are most sensitive to reduction of anthropogenic emissions from its own sources but also in Eastern Asia and North America.

Co-operation

1. In the framework of co-operation with the Task Force on Heavy Metals (TFHM) MSC-E presented information about recent developments in the field of heavy metals pollution assessment within the EMEP. In particular, situation with emission reporting and emission uncertainties was described. The development of wind re-suspension scheme was presented and the effects of introduction of this scheme on modelled pollution levels were demonstrated. Besides, the TFHM was informed about influence of intercontinental transport of mercury on European pollution levels.

2. MSC-E reported to the Task Force on Measurements and Modelling (TFMM) results of joint meeting of MSC-E and MSC-W, devoted to elaboration of a common global modelling system. Particularly, detailed working plan to develop this system was discussed. In addition, a two-steps approach was suggested to include Central Asian countries that are Parties (Kazakhstan,

Kyrgyzstan) or candidates (Uzbekistan, Turkmenistan and Tajikistan) to the Convention in the routine EMEP modelling activity.

3. MSC-E also contributed to the Task Force on Hemispheric Transport of Air Pollution (TF HTAP). It participates in the intercomparison study of hemispheric models organised within the framework of TF HTAP and devoted to assessment of intercontinental source-receptor relationships for different pollutants, evaluation of current models variability and uncertainties, and guidance of future model developments.

4. The EMEP Centres were also involved in cooperation with other subsidiary bodies to the Convention as well as international organizations and national programmes (HELCOM, EC, OSPAR, UNEP). The main results were discussed at a number of scientific conferences, workshops and expert meetings and published in scientific journals.

REFERENCES

Aas W. and Breivik K. [2007] Heavy metals and POP measurements, 2005. EMEP/CCC-Report 6/2007.

Alfaro S.C. and L. Gomes [2001] Modeling mineral aerosol production by wind erosion: Emission intensities and aerosol size distributions in source areas. *Journal of Geophysical Research*, vol. 106, No. D16, pp.18,075 – 18,084.

Bartnicki J., A. Gusev, W. Aas, H.Fagerli [2006] Atmospheric Supply of Nitrogen, Lead, Cadmium, Mercury and Dioxins/Furans to the Baltic Sea in 2006. MSC-W Technical Report 3/2006.

Berdowski J.J.M., Baas J., Bloos J.P.J., Visschedijk A.J.H. and P.Y.J.Zandveld [1997] The European Emission Inventory of Heavy Metals and Persistent Organic Pollutants for 1990. TNO Institute of Environmental Sciences, Energy Research and Process Innovation, UBA-FB report 104 02 672/03, Apeldoorn, 239 p.

Denier van der Gon D. H.A.C., van het Bolscher M., Visschedijk A.J.H. and Zandveld P.Y.J. [2005]. Study to the effectiveness of the UNECE Heavy Metals Protocol and costs of possible additional measures. Phase I: Estimation of emission reduction resulting from the implementation of the HM Protocol. TNO-report B&O-A R 2005/193.

Chatenet B.B., Marticorena B.B., Gomes L. and G. Bergametti [1996] Assessing the size distribution of desert soils erodible by wind. *Sedimentology*, vol. 43, pp. 901 – 911.

Gillette D. A., Marticorena B., Bergametti G. [1998] Change in the aerodynamic roughness height by saltaiting grains: Experimental assessment, test of theory, and operational parameterization. *Journal of Geophysical Research*, vol. 103, No. D6, pp. 6203-62-09.

Gong S.L. [2003] A parameterization of sea-salt aerosol source function for sub- and super-micron particles. *Global Biogeochemical Cycles*, vol. 17, No. 4, p. 1097.

Gomes L., Rajot J.L., Alfaro S.C. and A. Gaudichet [2003] Validation of a dust production model from measurements performed in semi-arid agricultural areas of Spain and Niger. *Catena*, vol. 52, pp. 257 – 271.

Grell, G. A., J. Dudhia, and D. R. Stauffer [1995] A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR/TN-398+STR. NCAR Technical Note. Mesoscale and Microscale Meteorology Division. National Center for Atmospheric Research. Boulder, Colorado. Pp. 122.

Gusev A., Ilyin I., Mantseva L., Rozovskaya O., Shatalov V. and Travnikov O. [2006]. Progress in further development in MSCE-HM and MSCE-POP models (implementation of the model review recommendations). EMEP/MSC-E Technical report 4/2006. 114 p.

Hillel D. [1982] Introduction to soil physics. Academic, San Diego, California, 364 pp.

Ilyin I., Rozovskaya O., Sokovykh V., and Travnikov O. [2007] Atmospheric modelling of heavy metal pollution in Europe: Further development and evaluation of the MSCE-HM model. EMEP/MSC-E Technical Report 2/2007., 52 p.

Ilyin I. and O. Travnikov [2005] Modelling of heavy metal airborne pollution in Europe: Evaluation of the model performance. EMEP/MSC-E Technical report 8/2005. June 2005

Ilyin I., Travnikov O. and Aas W. [2006] Heavy metals: transboundary pollution of the environment. EMEP Status Report 2/2006, 60 p.

Marticorena B. and G. Bergametti [1995] Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. *Journal of Geophysical Research*, vol. 100, No. D8, pp. 16,415 – 16,430.

Marticorena B., Bergametti G, and B. Aumont [1997] Modeling the atmospheric dust cycle: 2. Simulation of Saharan dust sources. *Journal of Geophysical Research*, vol. 102, No. D4, pp. 4387 – 4404

Owen P.R. [1964] Saltation of uniform sand grains in air. *Journal of Fluid Mechanics*, vol. 20, pp.225-242

Pacyna E. G., Pacyna J. M., Steenhuisen F. and Wilson S. [2006] Global anthropogenic mercury emission inventory for 2000. *Atmos. Environ.* vol. 40, No. 22, pp.4048-4063.

Salminen, R. (Chief-editor), Batista, M. J., Bidovec, M., Demetriades, A., De Vivo, B., De Vos, W., Duris, M., Gilucis, A., Gregorauskiene, V., Halamic, J., Heitzmann, P., Lima, A., Jordan, G., Klaver, G., Klein, P., Lis, J., Locutura, J., Marsina, K., Mazreku, A., O'Connor, P. J., Olsson, S.Å., Ottesen, R.-T., Petersell, V., Plant, J.A., Reeder, S., Salpeteur, I., Sandström, H., Siewers, U., Steenfelt, A., Tarvainen, T. [2005] Geochemical Atlas of Europe. Part 1: Background Information, Methodology and Maps. Espoo, Geological Survey of Finland, 526 pages, 36 figures, 362 maps.

Shao Y. and Yang Y. [2005] A scheme for drag partition over rough surfaces. *Atmospheric Environment*, vol. 39, pp.7351-7361

Travnikov O. and I.Ilyin [2005] Regional Model MSCE-HM of Heavy Metal Transboundary Air Pollution in Europe. EMEP/MSC-E Technical Report 6/2005, 59 pp.

Travnikov O. and A. Ryaboshapko [2002] Modelling of Mercury Hemispheric Transport and Depositions. MSC-E Technical Report 6/2002, 67 p., www.msceast.org.

Wilson S. J., Steenhuisen F., Pacyna J. M. and Pacyna E. G. [2006] Mapping the spatial distribution of global anthropogenic mercury atmospheric emission inventories. Atmos. Environ. vol. 40, No. 24, pp.4621-4632.

Annex A

EMEP work-plan for HMs in 2007

2.2. Atmospheric measurements and modelling

Description/objectives

To support the implementation of protocols to the Convention; provide the measurement and modelling tools necessary for further abatement policies; compile and evaluate information on transboundary air pollution; and implement the EMEP monitoring strategy adopted in 2004. The Task Force on Measurements and Modelling, led by the United Kingdom and co-chaired by WMO, reviews and assesses the scientific and operational activities of EMEP related to monitoring and modelling, evaluates their contribution to the effective implementation and further development of the protocols, and reviews national activities related to measurement, modelling and data validation.

Main activities and time schedule for monitoring:

(b) Review, store and make available the 2006 monitoring data (CCC, MSC-W, MSC-E); assess uncertainties relating to, and the representativeness of, monitoring data on heavy metals and POPs (CCC, MSC-E);

(i) Review heavy metals monitoring data (mosses, forests, etc.) generated in the framework of the Working Group on Effects and make recommendation for their use in model validation (CCC, MSC-E);

(j) Consider nationally available measurements on dry deposition of mercury to forests to evaluate measurement uncertainties and improve model parameterization (CCC, MSC-E, Parties);

(l) Evaluate the POP passive measurements campaign and compare with modelling; evaluate the EMEP monitoring strategy in relation to the outcome of this campaign as well as UNEP’s global monitoring strategy; report conclusions to the Task Force (MSC-E, CCC);

Main activities and time schedule for atmospheric modelling in general:

(c) Further develop the MSC-E models and report on progress, taking into account the recommendations of the model review (MSC-E);

(e) Complement EMEP data with data from other international programmes and make a comprehensive comparison of observations with model results (CCC, MSC-E, MSC-W, Parties).

Main activities and time schedule for atmospheric modelling for HMs:

(a) Prepare information on lead, cadmium, mercury, arsenic, chromium and nickel for 2005: air concentrations and ecosystem-dependent depositions over Europe; comparison of modelling results (concentration in air and precipitation, deposition fluxes) with monitoring data; country-to-country deposition matrices; estimates of depositions on regional seas (Mediterranean, Baltic, Black and North Seas) (MSC-E, CCC);

(b) Improve model description of heavy metal deposition processes; develop a model for the second-priority metals (Cu, Zn, Se) and make pilot calculations of the atmospheric transport and depositions of these metals in Europe (MSC-E);

(c) Prepare input data for the model application; employ the ECMWF reanalysis for data pre-processing; prepare mapped anthropogenic emission data for regional modelling based both on official and expert estimates (MSC-E);

(d) Evaluate ecosystem-dependent depositions of heavy metals and contribute to the development of the effect-based approach (MSC-E, CCC).

2.4. Hemispheric transport of air pollution

Description/objectives:

Description/objectives: To develop a fuller scientific understanding of the hemispheric transport of air pollution and estimate the hemispheric transport of specific air pollutants, the Task Force on the Hemispheric Transport of Air Pollution, led by the United States and the European Community, coordinates activities, including collaboration with other international bodies, programmes and networks, both within and outside the UNECE region, with related interests.

Main activities and time schedule:

(c) Continue the model intercomparison and evaluation exercise and the development of intercomparison tools and information infrastructure begun at Workshop on Intercontinental Transport Modelling Intercomparison held on 30-31 January 2006 (Task Force; CCC, MSC-E, MSC-W).

Annex B

PERCENTAGE CHANGES IN THE TOTAL NATIONAL EMISSIONS OF Pb, Cd AND Hg AFTER THE RECALCULATIONS

[100*($E_{current}$-$E_{previous}$)/$E_{previous}$, %]

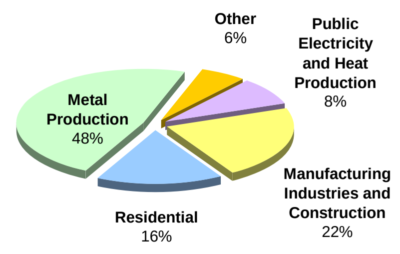
The highest changes are flagged.

		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Austria	Pb	0.012	0.013	0.015	0.014	0.012	0.002	-0.009	-0.006	0.016	0.8	-0.2	2.2	2.1	-0.8	0.8
	Cd	3.0	3.4	1.9	1.8	1.8	3.2	2.7	2.1	0.8	3.3	2.1	3.5	4.4	0.6	-2.2
	Hg	-0.0004	-0.0002		-0.0003	0.0002	0.013	0.013	0.009	-0.005	0.9	0.1	1.1	1.3	-0.9	0.3
Belgium	Pb															-2.6
	Cd															10.9
	Hg															2.5
Cyprus	Pb	-61	-51	-50	-52	-51	-50	-51	-56	-56	-61	-20	12		-0.02	
	Cd	175														
	Hg	193													-0.7	
Denmark	Pb	0.00004	0.0001	0.0002	0.0006	-32	-34	-36	0.006	0.007	0.007	2.7	2.3	4.7	1.6	3.9
	Cd	-0.007	-0.006	-0.004	-0.002	-0.001	-0.001	0.0004	0.001	0.002	0.003	2.82	3.0	5.2	4.6	8.3
	Hg	0.001	0.002	0.003	0.004	0.007	0.008	0.008	0.011	0.012	0.013	7.1	5.5	10	4.0	12
Estonia	Pb											-8.7	-7.2	-7.5		
	Cd											-11	-10	-10		
	Hg											-0.5	-2.0	2.0		
France	Pb	-0.4	-0.6	-0.9	-0.9	-1.2	-1.4	-1.5	-1.8	-2.3	-3.1	-10	-12	-12	-18	-22
	Cd	10	11	13	15	21	22	21	25	26	26	26	24	26	8	-21
	Hg	11	10	10	10	10	9.3	8.4	10	9.2	8.9	7.5	6.4	5.6	5.3	8.8
Germany	Pb	9.0	6.9	10	13	22	28	49	342	414	429	306	325	357	358	423
	Cd	857	22	38	87	302	206	195	190	172	230	-18	-15	-6.7	-5.6	-3.6
	Hg	266	3.5	3.3	6.3	12	-2.1	1.1	2.8	2.5	1.9	0.1	-0.2	-1.2	2.8	9.3
Ireland	Pb	-0.09					0.3	1.3	0.1	0.4	0.7	-0.2	1.0	0.4	3.8	0.7
	Cd	0.05					2.1	3.3	1.9	1.6	2.5	4.0	-0.4	-0.7	-0.9	-0.8
	Hg	-2.7					-4.8	1.4	-2.3	-4.0	-4.5	-1.2	5.1	3.7	10	13
Latvia	Pb	-87	-85	-89	-55	-27	-80	-81	-59	-69	-75	-72	-78	-92	-93	-90
	Cd	-0.6	-0.3	2.0	-0.6	-0.5	-0.3	-0.4	-0.4	-0.2	-0.08	0.4	0.2	-0.001	-0.3	0.3
	Hg	-1.8	-1.4	2.2	-1.1	-0.9	-0.8	-0.9	-0.8	-0.8	-0.8	0.4	-0.3	-5.1	-9.5	-5.8
Nether-lands	Pb	1.5					3.2					-21	-11	-1.8	-9.0	-0.5
	Cd	0.2					0.5					-12	42	91	105	53
	Hg	36					8.7					58	34	29	21	86
Norway	Pb	-0.10		-0.14	-0.2	-0.7	-0.8	-1.8	-1.8	-1.8	-2.0	-1.8	0.02		-0.02	-0.09
	Cd	-1.4	-1.5	-2.1	-1.6	-1.2	-1.4	-1.3	-1.4	-1.3	-1.4	-1.5	-0.1	-0.3	-5.1	-7.4
	Hg							-0.0003	-0.001	-0.001	-0.28	-0.5	-0.6	1.1	0.3	0.6
Portugal	Pb	-35	-35	-33	-33	-35	-37	-37	-40	-40	-51	-65	-61	-64	-62	-62
	Cd	0.0001	0.0001	0.0001	0.0001	0.0001	-0.0002	-0.0002	-0.0003	-0.0002	-0.0002	-0.0003	-0.0002	-0.0002	-0.0002	-0.0003
	Hg	0.0001	0.0001	0.0001	0.0001	0.0001	-0.001	-0.002	-0.14	-0.003	-0.033	-0.2	-0.04	-0.13	-0.01	-0.2
Slovakia	Pb						-12	-7.4	-7.6	3.9	5.2	-9.8	4.3	5.0	5.1	-24
	Cd						-0.09	-0.11	-0.10		0.15	-0.06	0.03	0.04	-0.60	-47
	Hg						-0.6	-0.6	-0.3	0.2	0.3	-0.4	0.2	0.2	-0.4	4.7
Spain	Pb	0.3	0.2	0.1	0.1	0.3	0.4	0.7	1.1	0.7	0.5	0.04	-0.6	-0.1	-0.8	-1.4
	Cd	95	79	60	57	58	55	52	47	39	31	24	21	19	19	15
	Hg	-29	-30	-27	-28	-29	-29	-30	-38	-42	-43	-45	-47	-46	-49	-49
Sweden	Pb	-14	-14	-13	-13	-5.5	-4.6	-9.0	-7.4	-3.2	-5.9	-3.5	-3.4	-4.0	-3.7	-4.1
	Cd	-11	14	-0.7	-4.7	-4.9	-3.9	-8.1	-8.8	-8.4	-4.1	0.06	0.02	-0.04	-0.14	-0.13
	Hg	-66	1.9	1.1	1.0	-0.02	0.7	1.4	-0.9	-0.6	-0.7	-0.8	-0.1	0.2	-0.14	0.03
Switzer-land	Pb	-2.7	-1.0	-0.3	-2.2	3.3	-3.3	-2.3	7.3	22	-19	-7.2	-8.3	-9.5	-10	0.4
	Cd	-6.1	-5.3	-2.2	-2.9	-1.1	-4.0	-1.4	1.5	10	-2.8	0.9	-0.1	-4.4	-4.7	7.4
	Hg	-2.1	-2.1	1.5	4.3	6.6	-0.1	2.5	6.3	14	-2.7	0.8	-3.8	-12	-20	1.6
United Kingdom	Pb	-0.04	-0.04	-0.05	-0.06	-0.06	-0.08	-0.09	-0.06	-0.11	-0.10	0.96	-1.31	-1.31	-0.26	-0.13
	Cd	-6.0	-6.6	-6.8	-10	-11	-13	-15	-17	-21	-19	-16	-23	-27	-36	-31
	Hg	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.5	-0.5	0.1	6.8	-1.2	1.2	4.6	-32

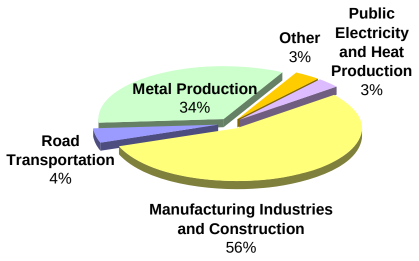
CONTRIBUTION OF SOURCE CATEGORIES TO THE TOTAL NATIONAL EMISSIONS OF Pb, Cd AND Hg in 2005

Lead

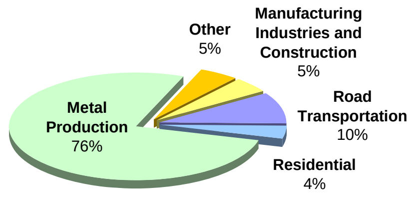
Austria



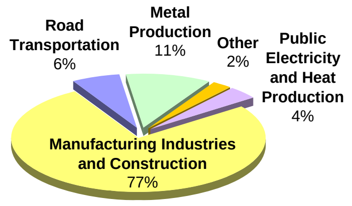
Belarus



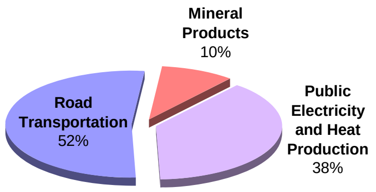
Belgium



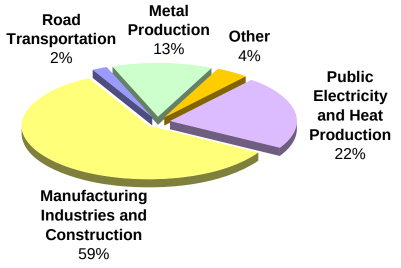
Bulgaria



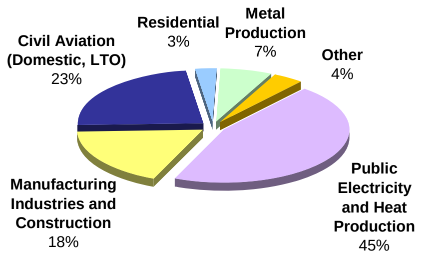
Cyprus



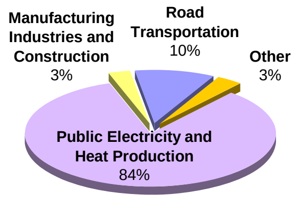
Czech Republic



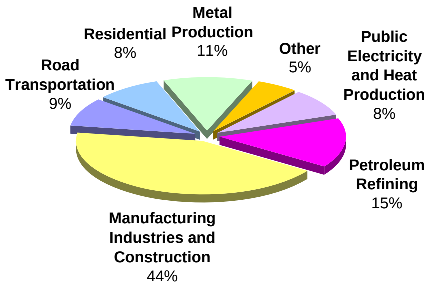
Denmark



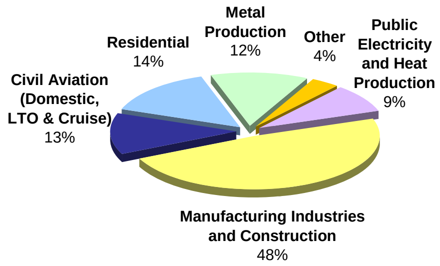
Estonia



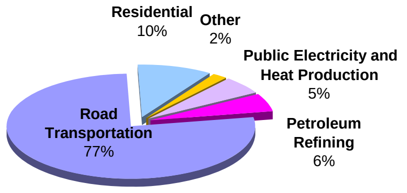
Finland



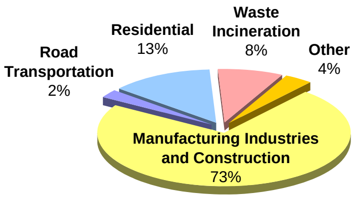
France



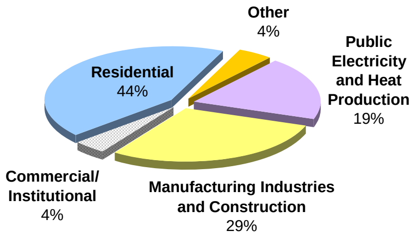
Germany



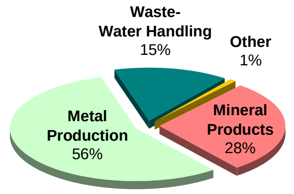
Hungary



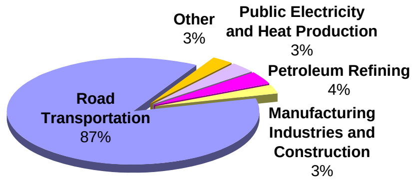
Ireland



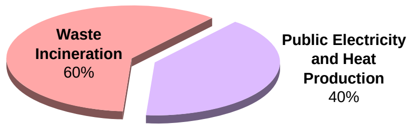
Latvia



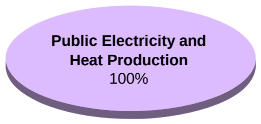
Lithuania



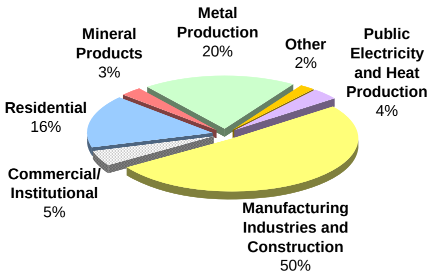
Malta



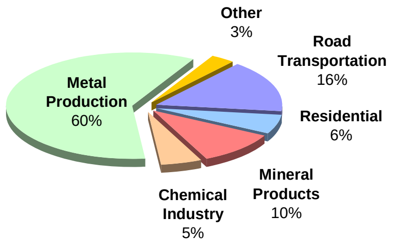
Monaco



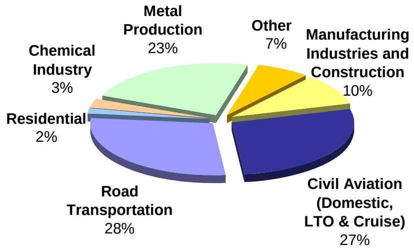
Republic of Moldova



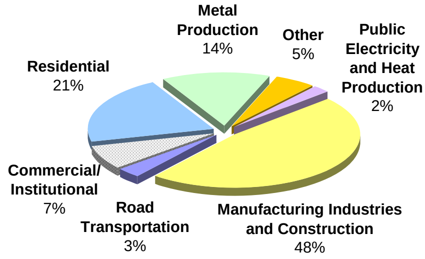
Netherlands



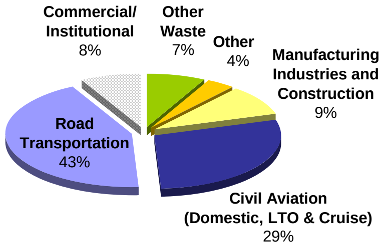
Norway



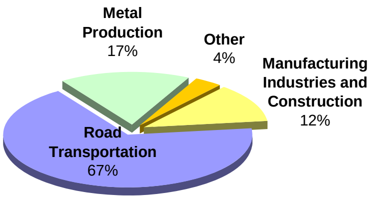
Poland



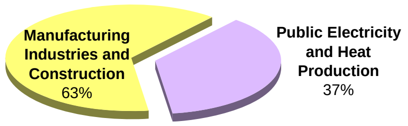
Portugal



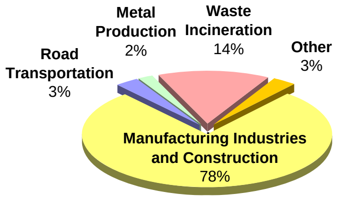
Romania



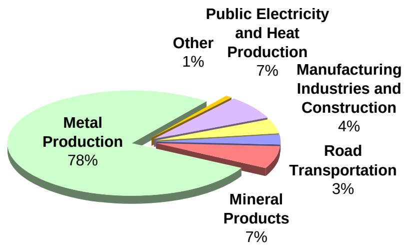
Russian Federation



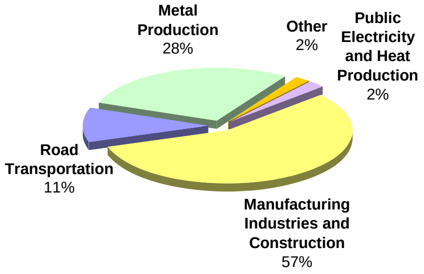
Slovakia



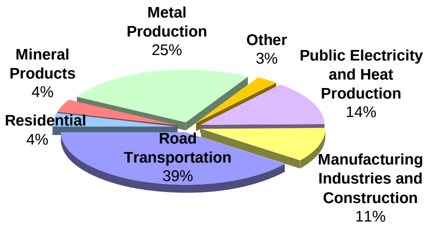
Slovenia



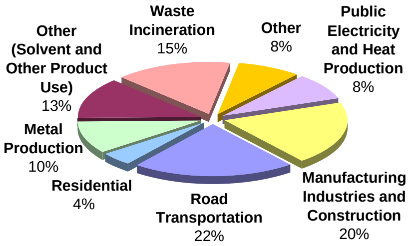
Spain



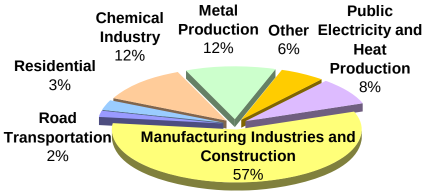
Sweden



Switzerland

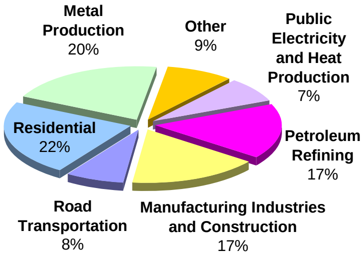


United Kingdom

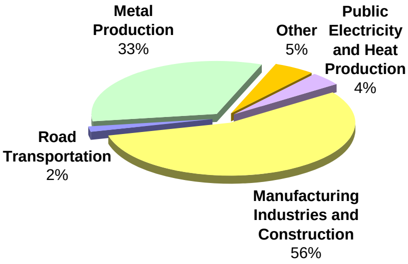


Cadmium

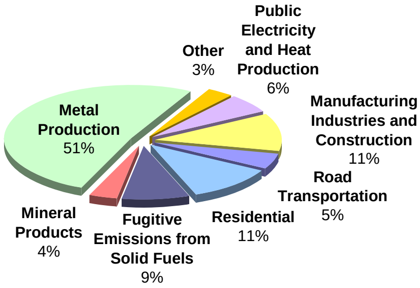
Austria



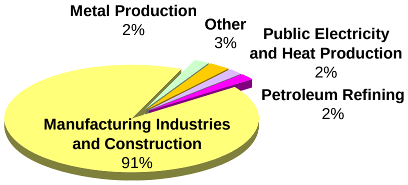
Belarus



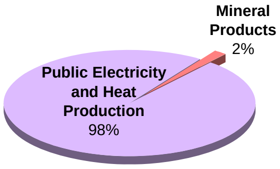
Belgium



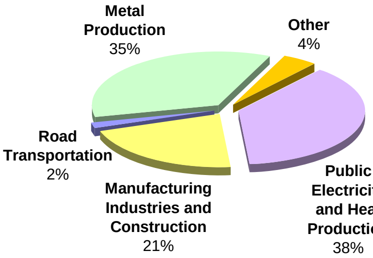
Bulgaria



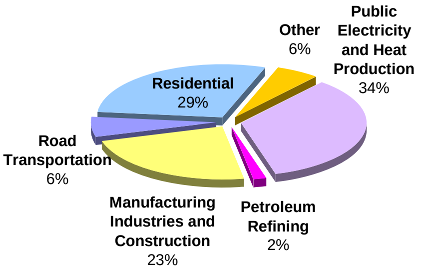
Cyprus



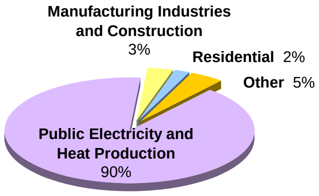
Czech Republic



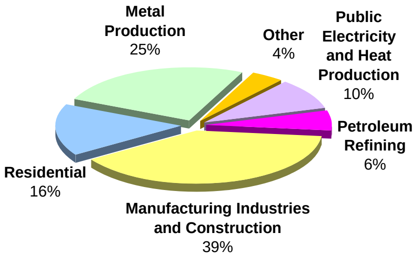
Denmark



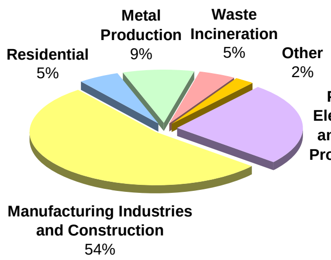
Estonia



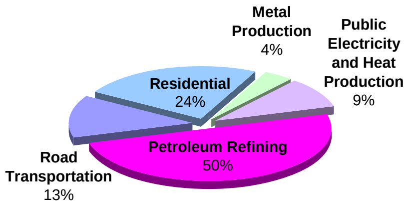
Finland



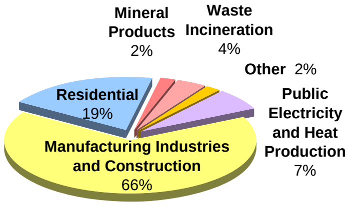
France



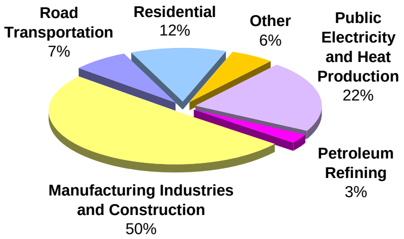
Germany



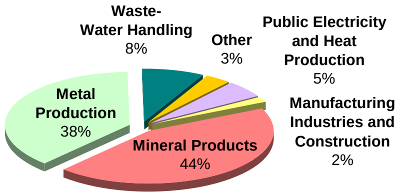
Hungary



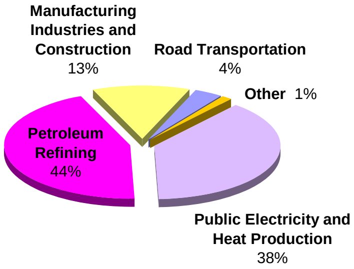
Ireland



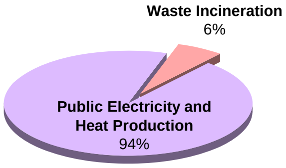
Latvia



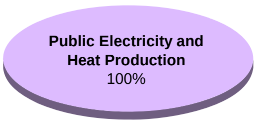
Lithuania



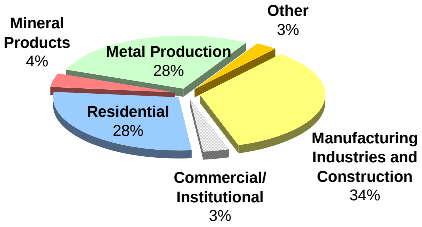
Malta



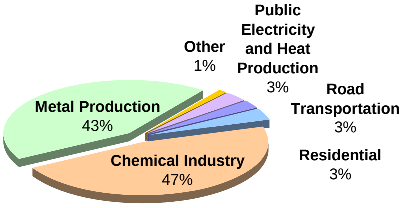
Monaco



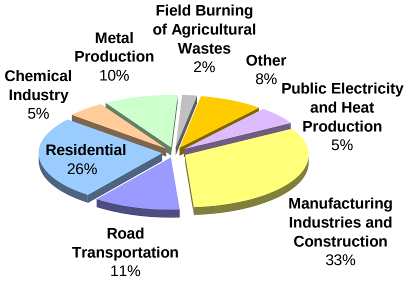
Republic of Moldova



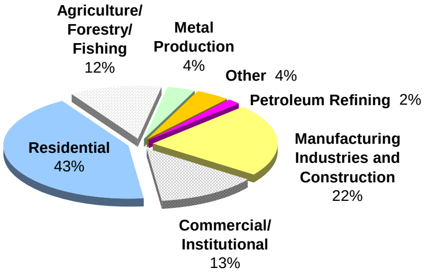
Netherlands



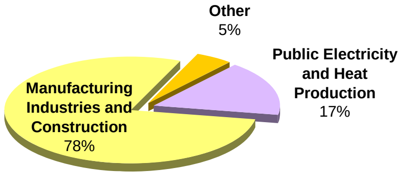
Norway



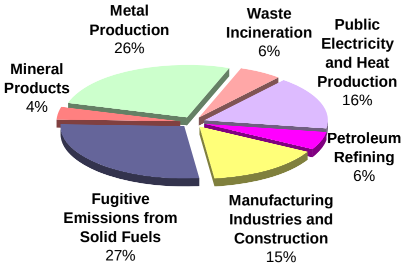
Poland



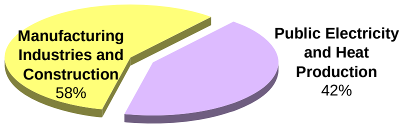
Portugal



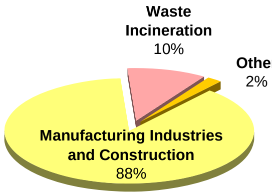
Romania



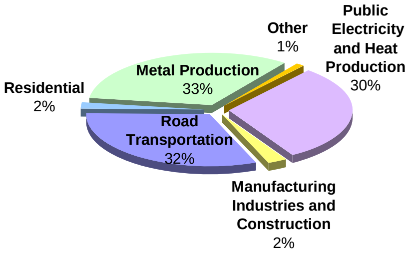
Russian Federation



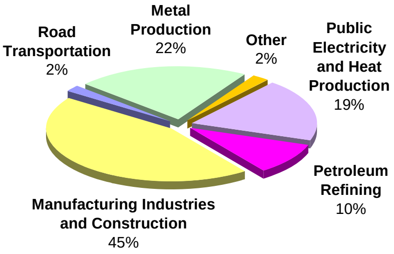
Slovakia



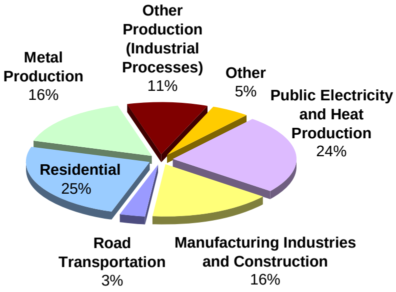
Slovenia



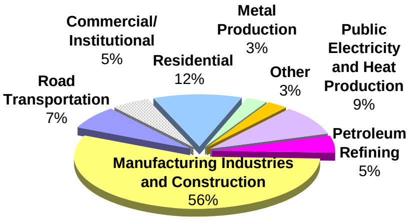
Spain



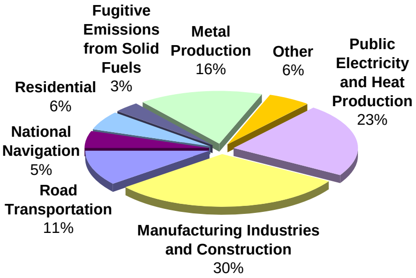
Sweden



Switzerland

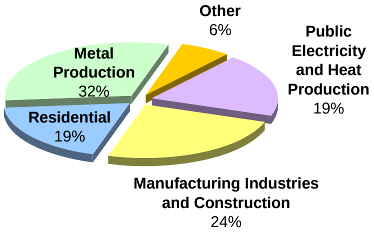


United Kingdom

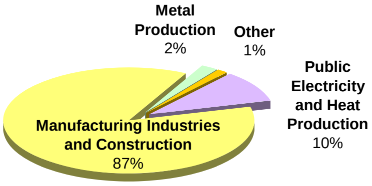


Mercury

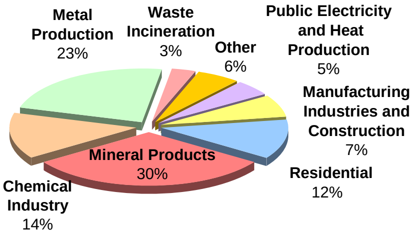
Austria



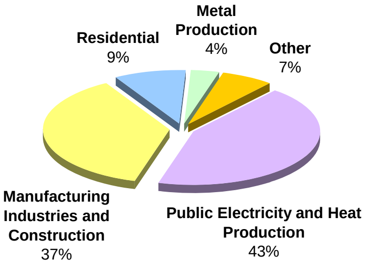
Belarus



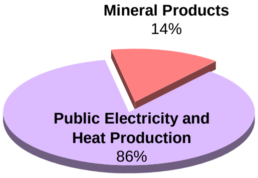
Belgium



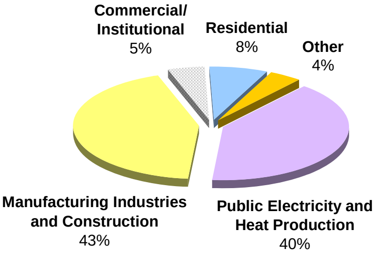
Bulgaria



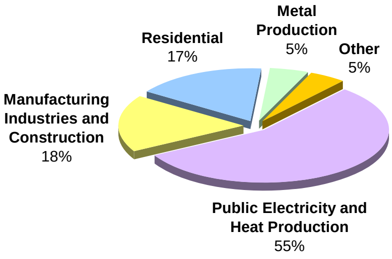
Cyprus



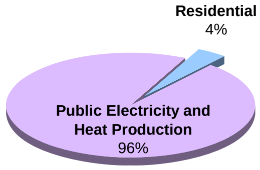
Czech Republic



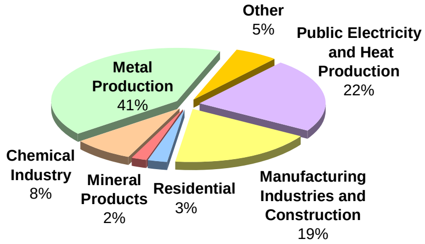
Denmark



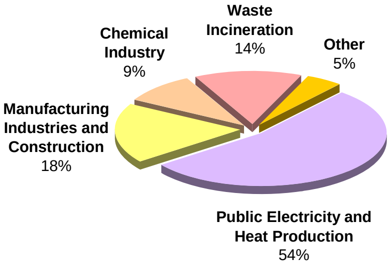
Estonia



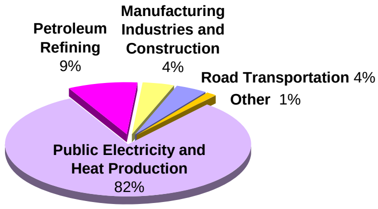
Finland



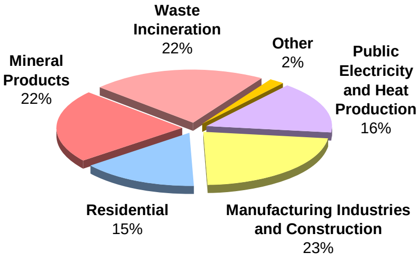
France



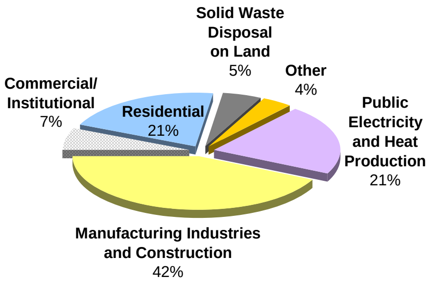
Germany



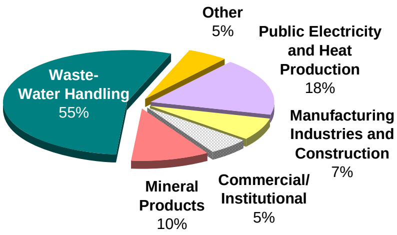
Hungary



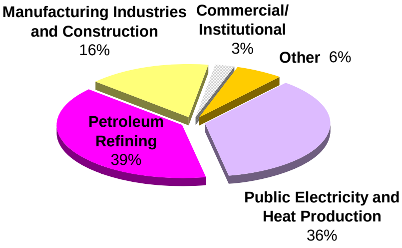
Ireland



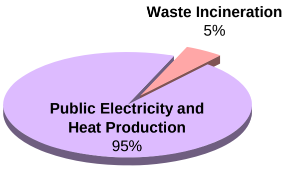
Latvia



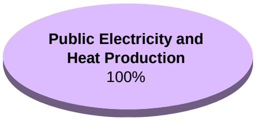
Lithuania



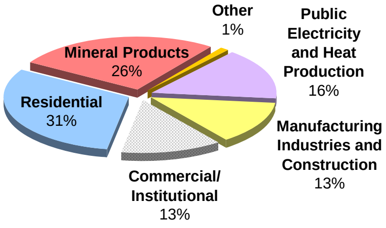
Malta



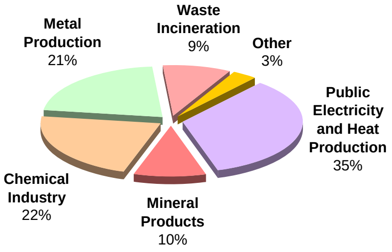
Monaco



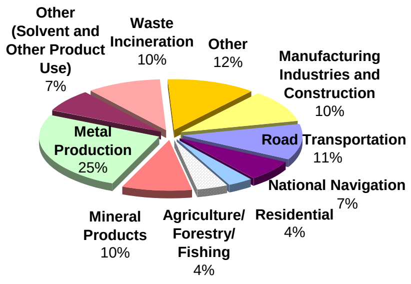
Republic of Moldova



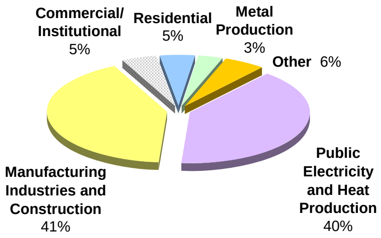
Netherlands



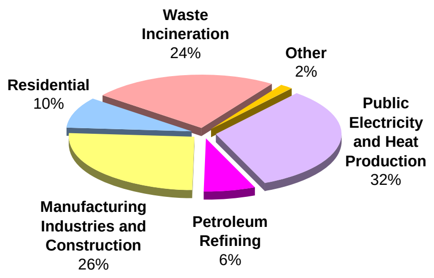
Norway



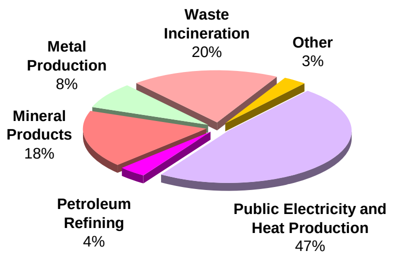
Poland



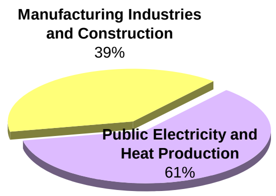
Portugal



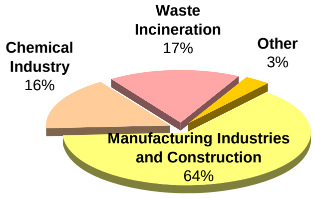
Romania



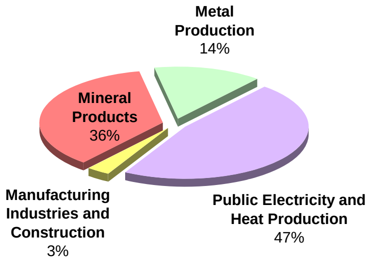
Russian Federation



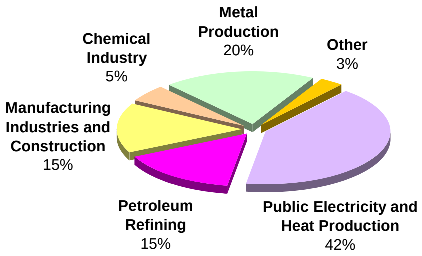
Slovakia



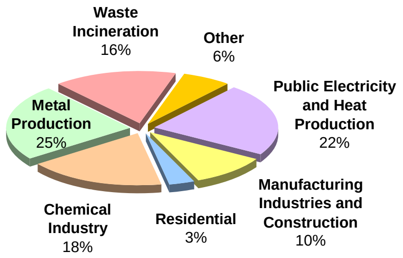
Slovenia



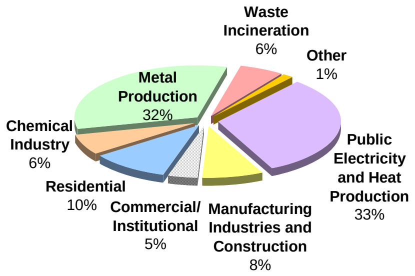
Spain



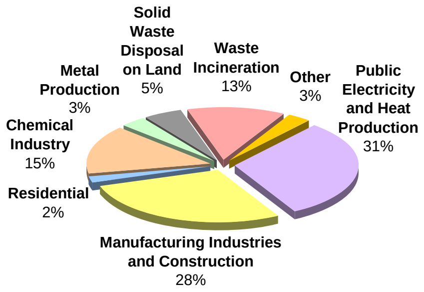
Sweden



Switzerland



United Kingdom



Annex D

COUNTRY-TO-COUNTRY DEPOSITION MATRICES FOR 2005

Table D.1. *Codes of countries, regions and seas*

Country/Region/Sea	Code	Country/Region/Sea	Code
Albania	AL	Malta	MT
Armenia	AM	Monaco	MC
Austria	AT	Netherlands	NL
Azerbaijan	AZ	Norway	NO
Belarus	BY	Poland	PL
Belgium	BE	Portugal	PT
Bosnia and Herzegovina	BA	Republic of Moldova	MD
Bulgaria	BG	Romania	RO
Croatia	HR	Russian Federation (European part)	RU
Cyprus	CY	Serbia and Montenegro	CS
Czech Republic	CZ	Slovakia	SK
Denmark	DK	Slovenia	SI
Estonia	EE	Spain	ES
Finland	FI	Sweden	SE
France	FR	Switzerland	CH
Georgia	GE	The Former Yugoslav Republic of Macedonia	MK
Germany	DE	Tajikistan	TJ
Greece	GR	Turkey	TR
Hungary	HU	Turkmenistan	TU
Iceland	IS	Ukraine	UA
Ireland	IE	United Kingdom	GB
Italy	IT	Uzbekistan	UZ
Kazakhstan	KZ	Baltic Sea	BAS
Kyrgyzstan	KY	Black Sea	BLS
Latvia	LV	Caspian Sea	CAS
Lithuania	LT	North Sea	NOS
Luxembourg	LU	Mediterranean Sea	MDT

***Table D.2**. Matrix of lead country-to-country depositions from anthropogenic sources in 2005, kg/y*

Receptors ↓ Emitters ⟶

	AL	AM	AT	AZ	BA	BE	BG	BY	CH	CS	CY	CZ	DE	DK	
AL	**4242**	0.2	11.3	0.9	302.8	12.4	628.0	8.9	13.9	2800	0.5	30.3	27.9	0.9	**AL**
AM	5.6	**500.4**	0.9	406.7	8.3	1.7	20.4	4.5	1.3	22.9	6.9	2.5	3.6	0.1	**AM**
AT	46.5	0.3	**4471**	1.2	613.0	575.6	332.8	105.6	755.0	1441	0.3	1891	2953	18.1	**AT**
AZ	12.2	119.9	2.4	**2878**	18.6	5.5	49.0	16.6	3.5	53.0	12.3	7.4	11.3	0.5	**AZ**
BA	507.2	0.4	163.8	1.2	**21636**	86.9	780.7	38.5	62.6	8067	1.3	462.3	276.2	10.4	**BA**
BE	3.0	0.0	17.9	0.0	11.8	**13266**	9.4	10.2	74.5	22.9	0.0	41.3	902.4	11.8	**BE**
BG	598.7	4.0	67.1	19.9	746.4	71.2	**46349**	185.1	42.2	8284	3.7	246.4	188.7	7.2	**BG**
BY	101.4	6.2	133.8	31.6	408.6	274.9	924.3	**18518**	87.3	1320	1.9	849.0	762.1	62.3	**BY**
CH	7.2	0.0	75.7	0.3	51.0	333.5	19.6	13.4	**5033**	70.5	0.1	86.1	793.8	3.8	**CH**
CS	1587	1.1	170.5	3.9	5103	112.3	4707	76.2	69.4	**56989**	2.4	587.9	342.1	13.1	**CS**
CY	6.5	0.3	0.5	0.4	6.7	0.6	15.0	0.6	0.6	18.4	**250.3**	1.1	1.4	0.0	**CY**
CZ	19.2	0.2	803.7	1.3	284.6	596.9	182.7	153.5	282.7	856.5	0.1	**11178**	3149	41.3	**CZ**
DE	30.4	0.4	1217	2.8	212.1	13048	152.8	336.1	3595	490.2	0.4	3446	**46535**	299.3	**DE**
DK	1.3	0.0	16.6	0.1	5.6	661.4	6.3	47.9	33.1	15.5	0.0	126.9	861.3	**523.3**	**DK**
EE	2.8	0.2	17.9	1.3	23.0	99.0	26.6	300.0	18.1	64.1	0.1	112.6	217.7	35.4	**EE**
ES	36.5	0.1	32.3	0.3	140.7	507.5	59.0	10.1	145.3	180.4	0.1	46.1	318.4	8.7	**ES**
FI	9.7	0.8	74.4	3.7	70.4	446.5	91.2	760.3	92.5	232.4	0.3	493.9	858.8	126.2	**FI**
FR	135.4	0.2	210.0	0.9	592.5	7502	235.0	78.1	2366	766.9	0.5	387.5	4390	61.7	**FR**
GB	4.3	0.1	47.7	0.3	22.9	2725	15.2	24.1	151.4	49.0	0.0	170.9	1351	43.9	**GB**
GE	16.6	210.0	5.2	805.6	32.2	10.8	109.1	32.8	5.7	107.3	18.9	17.9	21.9	0.9	**GE**
GR	1185	2.4	35.4	11.2	540.5	51.4	5097	79.9	38.0	3138	11.8	115.1	112.0	3.8	**GR**
HR	327.4	0.3	266.2	0.9	4395	75.8	675.6	35.6	71.9	5066	0.9	466.3	253.6	6.8	**HR**
HU	161.4	0.4	423.3	1.3	2136	123.4	1073	96.2	91.5	7529	0.6	1019	456.4	13.0	**HU**
IE	0.5	0.0	2.4	0.0	2.1	149.3	1.1	1.0	16.7	3.8	0.0	6.3	93.9	2.6	**IE**
IS	0.6	0.0	1.3	0.2	1.6	39.4	2.8	3.6	7.6	3.3	0.1	7.1	45.2	7.0	**IS**
IT	1097	0.8	486.4	3.9	3348	296.4	1103	68.3	1094	3852	2.5	546.1	816.6	11.6	**IT**
KY	10.0	11.7	3.3	56.7	19.4	8.6	42.6	15.4	5.5	50.5	5.3	10.4	17.3	0.8	**KY**
KZ	96.0	136.2	55.4	927.4	219.2	144.5	716.5	541.8	66.8	718.3	32.9	216.0	301.2	17.6	**KZ**
LT	16.5	0.5	62.3	2.9	108.7	163.2	132.8	1261	47.1	304.4	0.2	372.8	449.1	59.9	**LT**
LU	0.3	0.0	2.5	0.0	1.3	296.7	0.9	1.1	13.3	2.3	0.0	4.6	128.5	0.8	**LU**
LV	10.0	0.6	41.7	3.5	75.4	166.7	88.1	790.6	36.4	205.6	0.2	246.1	412.9	59.0	**LV**
MC	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	**MC**
MD	33.2	1.1	10.5	5.0	89.4	19.1	524.0	121.5	8.3	370.4	0.9	51.0	45.4	2.3	**MD**
MK	1005	0.3	12.7	1.4	225.2	12.8	2206	13.8	10.2	3759	0.6	42.6	33.1	1.2	**MK**
MT	0.6	0.0	0.1	0.0	0.8	0.1	0.6	0.0	0.1	1.3	0.0	0.1	0.2	0.0	**MT**
NL	2.6	0.0	18.7	0.1	11.4	5976	7.5	14.8	47.8	22.3	0.0	58.5	1270	17.9	**NL**
NO	8.3	0.2	82.1	1.3	40.1	1354	66.6	155.0	129.5	144.3	0.1	439.7	1759	310.4	**NO**
PL	86.9	1.0	632.8	4.7	789.5	1545	708.6	2417	420.7	2387	0.8	8632	5996	353.2	**PL**
PT	0.8	0.0	1.2	0.0	4.1	45.8	1.1	0.6	8.4	4.2	0.0	2.1	23.1	0.8	**PT**
RO	645.4	6.4	264.0	29.7	2748	243.0	9617.0	469.1	130.2	14578	4.4	1065	693.9	25.0	**RO**
RU	643.0	445.2	556.9	3141	1922	1809	5366	14446	566.0	6052	118.1	2879	3975	392.0	**RU**
SE	12.5	0.4	99.2	2.4	52.3	1548	104.6	465.0	153.1	219.8	0.2	688.0	2616	826.2	**SE**
SI	49.7	0.1	296.3	0.5	668.8	46.6	219.8	18.5	52.9	1110	0.1	177.3	162.9	2.3	**SI**
SK	61.5	0.2	275.0	1.0	635.6	137.6	428.8	121.7	77.6	2063	0.2	1953	479.7	16.0	**SK**
TJ	3.1	5.4	1.0	24.8	6.2	2.6	13.1	5.0	1.7	15.8	2.1	3.0	5.1	0.2	**TJ**
TR	433.9	262.5	65.5	268.3	590.3	96.3	2691.7	316.5	70.3	2139	487.4	209.4	223.5	9.2	**TR**
TU	6.0	16.4	2.5	136.0	12.0	7.6	33.7	25.0	3.4	35.6	5.1	9.5	15.2	0.7	**TU**
UA	374.2	36.4	265.9	170.2	1379	493.8	4517	4043	177.3	5133	22.3	1484	1237	67.7	**UA**
UZ	8.5	17.2	3.5	106.8	17.3	9.7	45.6	33.6	4.8	49.6	4.9	12.0	19.0	1.0	**UZ**
BAS	15.1	0.6	146.2	3.6	110.4	1815	132.8	843.7	211.1	365.3	0.2	1050	3889	824.4	**BAS**
BLS	271.7	50.4	74.6	166.5	578.7	116.3	4031	571.3	57.3	2695	56.7	286.3	270.0	12.8	**BLS**
CAS	21.2	92.1	9.7	1488	44.0	23.6	160.9	84.7	10.6	152.4	14.8	33.7	44.7	2.1	**CAS**
MDT	4836	11.7	595.5	32.3	7354	766.0	7203	184.7	1069	11325	677.2	950.3	1436	32.1	**MDT**
NOS	22.9	0.5	215.6	2.7	116.6	9856	128.6	190.9	430.5	281.9	0.4	991.0	6471	654.6	**NOS**
	AL	**AM**	**AT**	**AZ**	**BA**	**BE**	**BG**	**BY**	**CH**	**CS**	**CY**	**CZ**	**DE**	**DK**	

***Table D.2**. Matrix of lead country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors ↓ Emitters ⟶

	EE	ES	FI	FR	GB	GE	GR	HR	HU	IE	IS	IT	KY	KZ	
AL	2.6	143.3	1.4	84.7	16.2	0.6	4184	49.6	65.7	0.9	0.01	1491	0.03	33.4	**AL**
AM	1.7	14.1	0.7	5.2	1.9	144.3	167.0	1.6	2.7	0.1	0.0	30.6	0.7	454.8	**AM**
AT	23.1	433.1	9.7	893.7	351.9	1.1	313.0	387.0	1064	12.2	0.1	5100	0.04	53.5	**AT**
AZ	8.0	33.5	3.1	13.5	6.2	239.8	346.4	3.6	6.7	0.3	0.0	68.0	9.3	2922	**AZ**
BA	10.2	297.4	6.5	260.6	76.1	1.2	2174	1313	1196	3.4	0.02	3515	0.03	41.0	**BA**
BE	7.6	466.9	3.2	4452	1220	0.1	25.3	4.6	7.1	29.5	0.1	183.6	0.0	1.1	**BE**
BG	45.6	326.7	17.5	174.8	70.2	21.8	17211	138.1	480.2	3.3	0.03	1508	0.4	796.4	**BG**
BY	660.5	310.7	197.2	310.9	268.1	22.6	1171	111.8	548.3	9.6	0.1	808.1	1.2	687.5	**BY**
CH	4.0	539.1	1.7	1664	264.8	0.2	62.8	31.1	31.0	12.0	0.04	4678	0.01	4.2	**CH**
CS	19.1	337.0	10.1	266.8	96.9	4.7	4899	648.1	2116	4.3	0.03	3369	0.1	127.8	**CS**
CY	0.2	5.5	0.1	2.8	0.7	0.5	315.6	1.2	1.6	0.04	0.0	26.6	0.0	4.8	**CY**
CZ	35.8	276.8	14.7	651.7	413.9	1.0	131.3	165.2	999.4	13.1	0.1	1101	0.1	44.9	**CZ**
DE	178.1	2925	70.4	12054	5603	2.1	241.1	95.6	374.9	149.9	0.9	3076	0.1	54.0	**DE**
DK	33.2	238.1	16.3	529.7	779.7	0.1	11.0	2.2	14.8	22.8	0.2	74.7	0.01	4.5	**DK**
EE	**4307**	59.4	371.7	96.4	133.4	0.8	27.7	7.8	39.4	4.9	0.04	73.3	0.1	47.8	**EE**
ES	9.0	**81023**	4.3	2935	737.8	0.2	247.3	54.3	34.1	58.7	0.2	1812	0.02	5.9	**ES**
FI	3277	285.6	**9959**	472.8	587.3	2.8	101.7	22.0	170.1	24.8	0.3	324.0	0.6	194.3	**FI**
FR	48.1	22363	21.1	**48086**	6412	0.7	843.1	248.8	175.0	276.7	0.7	11216	0.1	22.8	**FR**
GB	23.9	2007	16.7	3251	**25166**	0.3	38.0	10.8	27.1	899.4	1.4	312.8	0.04	5.4	**GB**
GE	8.1	48.4	3.3	21.8	13.1	**2338**	555.1	7.2	19.0	0.6	0.0	113.6	1.0	867.4	**GE**
GR	16.4	378.4	7.1	206.6	58.4	10.3	**96985**	94.8	205.1	3.1	0.02	1933	0.2	353.1	**GR**
HR	10.6	269.8	5.9	259.2	61.8	1.2	1506	**3383**	1670	2.6	0.02	3980	0.04	35.1	**HR**
HU	26.5	219.4	13.3	251.0	99.0	1.9	1021	1000	**10517**	3.6	0.03	2608	0.1	48.7	**HU**
IE	2.5	417.6	1.6	348.2	1108	0.0	4.0	0.7	1.1	**1321**	0.3	29.2	0.01	0.6	**IE**
IS	14.3	143.7	8.3	61.0	136.5	0.3	12.0	0.5	0.7	14.8	**37.6**	22.9	0.01	1.8	**IS**
IT	21.6	2364	11.4	2405	307.4	2.5	7376	1347	782.7	15.6	0.1	**80777**	0.1	153.4	**IT**
KY	9.7	75.0	4.8	24.1	11.8	18.5	213.5	4.3	8.5	0.6	0.01	87.6	**12370**	21070	**KY**
KZ	282.8	490.5	119.0	253.4	188.6	297.9	2170	54.1	178.1	9.4	0.1	755.3	6982	**241029**	**KZ**
LT	279.0	139.8	115.1	177.2	163.9	1.8	136.9	37.1	139.6	6.3	0.1	331.2	0.1	70.6	**LT**
LU	1.0	50.0	0.4	462.4	56.6	0.01	2.3	0.5	0.9	1.6	0.01	25.8	0.0	0.1	**LU**
LV	925.5	102.5	214.5	158.7	192.0	1.9	77.0	24.1	89.5	7.5	0.1	220.6	0.2	94.9	**LV**
MC	0.0	0.1	0.0	0.6	0.02	0.0	0.1	0.03	0.02	0.0	0.0	3.3	0.0	0.0	**MC**
MD	21.9	48.1	7.5	31.6	18.2	7.2	775.5	16.0	65.0	0.7	0.01	179.2	0.2	169.0	**MD**
MK	3.6	88.9	1.8	48.5	13.3	1.1	9228	35.4	97.0	0.7	0.0	600.6	0.03	48.1	**MK**
MT	0.0	1.3	0.0	0.7	0.1	0.0	11.5	0.2	0.1	0.0	0.0	5.5	0.0	0.1	**MT**
NL	10.7	396.2	4.4	2346	1526	0.1	19.0	4.5	9.8	33.4	0.2	128.6	0.0	1.8	**NL**
NO	163.8	793.4	168.1	1304	3260	0.9	71.5	12.0	93.4	138.6	1.8	299.2	0.1	78.7	**NO**
PL	398.6	1149	181.7	1660	1200	5.2	769.0	367.9	1854	39.8	0.4	2477	0.3	153.3	**PL**
PT	0.6	6316	0.3	172.5	72.3	0.03	7.0	1.6	1.4	6.8	0.03	63.0	0.0	0.6	**PT**
RO	121.6	538.4	47.5	432.6	213.6	35.8	7535	533.8	2681	8.9	0.1	3446	0.6	1022	**RO**
RU	18751	3004	5548	2348	2561	2051	12243	458.0	1752	115.0	1.8	5541	1541	199504	**RU**
SE	736.5	739.8	1491	1339	1957	1.5	109.0	16.9	164.1	71.9	0.7	380.6	0.4	127.0	**SE**
SI	5.0	117.0	2.2	131.9	34.2	0.4	272.1	756.0	429.5	1.4	0.01	2724	0.0	26.0	**SI**
SK	31.2	135.9	16.7	190.5	116.1	1.0	451.5	275.8	2645	3.9	0.04	1213	0.1	37.5	**SK**
TJ	2.5	22.8	1.2	7.3	3.4	7.2	69.8	1.3	2.4	0.2	0.0	28.4	1042	3227	**TJ**
TR	78.4	703.8	29.1	291.5	109.4	448.5	24124	120.6	287.7	5.6	0.04	2240	2.1	2073	**TR**
TU	11.8	33.0	4.9	15.0	8.2	27.0	153.9	2.6	6.5	0.4	0.0	44.2	147.3	5296	**TU**
UA	509.2	776.8	183.8	656.5	446.5	214.3	8285	353.2	1976	17.0	0.2	2740	9.0	5110	**UA**
UZ	16.5	44.6	6.7	19.8	12.1	28.1	207.4	3.9	9.2	0.6	0.01	66.5	1597	16458	**UZ**
BAS	3379	992.4	2718	1627	1711	2.1	148.6	44.1	256.1	57.5	0.4	625.6	0.4	131.0	**BAS**
BLS	128.2	322.9	48.5	196.3	131.1	544.2	10938	121.9	391.3	6.0	0.04	1337	2.3	4767	**BLS**
CAS	31.0	65.8	10.9	41.0	29.0	200.2	580.2	10.3	33.3	1.4	0.01	149.7	107.9	18439	**CAS**
MDT	52.2	16823	26.4	7632	981.2	38.5	119373	2052	1285	47.2	0.3	56996	1.1	936.3	**MDT**
NOS	238.6	4977	145.4	10100	27848	2.5	200.6	48.2	164.8	780.4	5.7	1210.2	0.2	78.0	**NOS**
	EE	**ES**	**FI**	**FR**	**GB**	**GE**	**GR**	**HR**	**HU**	**IE**	**IS**	**IT**	**KY**	**KZ**	

Table D.2*. Matrix of lead country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors ↓ Emitters ⟶

	LT	LU	LV	MC	MD	MK	MT	NL	NO	PL	PT	
AL	0.8	0.4	2.4	0.1	4.5	2480	0.02	6.4	0.4	241.4	32.7	**AL**
AM	0.3	0.1	0.7	0.0	0.8	15.9	0.02	1.0	0.1	26.4	4.8	**AM**
AT	10.7	25.3	25.6	0.5	9.9	144.3	0.2	274.1	7.6	7496	129.2	**AT**
AZ	1.2	0.2	3.0	0.01	2.1	35.7	0.05	3.2	0.5	81.8	11.8	**AZ**
BA	5.8	2.7	17.0	0.3	11.0	609.0	0.1	50.3	3.0	2984	81.2	**BA**
BE	2.8	104.8	11.5	0.1	0.3	6.1	0.1	1313	4.0	347.7	132.0	**BE**
BG	12.0	1.9	25.3	0.2	170.6	4596	0.2	42.9	3.2	2295	99.6	**BG**
BY	531.0	6.2	555.7	0.1	127.4	342.8	0.9	200.8	24.7	17210	111.8	**BY**
CH	1.8	16.7	4.1	0.8	0.7	13.1	0.05	121.7	1.8	525.1	123.7	**CH**
CS	9.1	3.3	24.3	0.3	38.9	4591	0.1	63.3	4.2	4121	92.3	**CS**
CY	0.05	0.02	0.1	0.0	0.3	15.9	0.0	0.3	0.02	9.2	1.2	**CY**
CZ	18.0	18.9	46.7	0.2	8.9	64.1	0.3	397.7	13.3	27587	81.7	**CZ**
DE	76.1	543.6	268.8	0.8	10.2	73.6	1.3	8475	76.6	22275	854.2	**DE**
DK	11.7	7.7	46.8	0.03	0.5	3.1	0.2	567.3	18.8	1642	113.5	**DK**
EE	109.9	1.9	620.7	0.02	3.5	9.8	0.4	80.9	17.7	2045	18.1	**EE**
ES	3.1	13.6	11.9	0.5	0.8	61.8	0.2	190.6	3.6	335.1	16161	**ES**
FI	181.7	8.6	821.3	0.1	12.4	34.1	5.9	315.1	173.0	8135	61.8	**FI**
FR	17.7	362.2	67.1	11.3	4.9	224.8	0.7	2066	20.8	2899	3555	**FR**
GB	6.8	34.8	30.6	0.1	0.6	9.0	1.2	1483	24.0	1603	894.2	**GB**
GE	1.8	0.3	3.8	0.01	8.7	52.7	0.1	6.5	0.5	204.5	15.6	**GE**
GR	5.6	1.4	12.2	0.2	45.8	5407	0.1	28.0	1.6	1015	77.7	**GR**
HR	5.2	2.7	15.1	0.4	10.7	414.2	0.1	41.1	2.2	2790	63.2	**HR**
HU	12.4	4.1	31.4	0.3	20.9	497.8	0.1	73.9	4.3	6256	58.6	**HU**
IE	0.4	3.3	2.2	0.01	0.0	0.8	0.2	74.4	2.0	69.0	232.5	**IE**
IS	1.0	0.8	4.7	0.01	0.1	1.5	2.6	22.0	8.4	92.8	117.0	**IS**
IT	7.8	12.0	21.4	7.1	17.6	1327	0.2	132.7	4.9	3475	447.4	**IT**
KY	1.2	0.3	3.4	0.02	1.7	29.8	0.1	4.8	1.0	111.7	27.1	**KY**
KZ	38.2	3.8	99.2	0.1	66.0	345.2	2.8	86.5	17.9	2749	170.7	**KZ**
LT	**1418**	3.4	1020	0.05	15.5	53.5	0.4	120.4	18.4	7633	52.0	**LT**
LU	0.3	**132.4**	1.1	0.01	0.0	0.6	0.0	37.5	0.2	33.7	13.5	**LU**
LV	540.8	3.1	**3525**	0.04	11.1	33.9	0.5	133.9	21.6	4532	33.8	**LV**
MC	0.0	0.0	0.0	**0.03**	0.0	0.01	0.0	0.01	0.0	0.1	0.0	**MC**
MD	6.8	0.5	13.4	0.02	**906.9**	139.7	0.1	12.0	1.0	780.0	13.3	**MD**
MK	1.3	0.4	3.3	0.1	7.8	**16015**	0.02	7.1	0.5	339.8	24.3	**MK**
MT	0.0	0.0	0.0	0.0	0.0	0.8	**0.0**	0.04	0.0	0.6	0.2	**MT**
NL	3.6	19.0	15.4	0.05	0.3	4.9	0.2	**6307**	7.2	537.6	117.4	**NL**
NO	34.6	22.3	148.1	0.1	4.9	27.7	281.8	957.2	**1940**	5062	224.0	**NO**
PL	342.7	37.2	678.2	0.4	63.1	271.8	1.5	1092	75.8	**218973**	380.1	**PL**
PT	0.2	1.1	0.8	0.02	0.04	1.2	0.02	17.4	0.3	17.4	**48738**	**PT**
RO	38.9	6.4	89.2	0.4	805.8	2616	0.5	145.9	10.0	10145	161.7	**RO**
RU	1081	40.6	2959	0.8	560.2	2318	112.0	1277	401.6	45355	997.5	**RU**
SE	131.3	26.6	754.4	0.1	13.1	42.4	5.4	1168	753.0	10662	264.6	**SE**
SI	2.0	1.8	4.9	0.2	4.1	114.1	0.02	22.6	0.8	1044	28.3	**SI**
SK	15.1	4.1	37.5	0.1	11.9	191.0	0.1	88.8	4.8	15905	39.8	**SK**
TJ	0.4	0.1	1.0	0.0	0.5	9.0	0.04	1.4	0.3	32.3	8.3	**TJ**
TR	19.0	2.7	40.1	0.2	132.0	1363	0.4	57.4	5.0	2237	189.5	**TR**
TU	1.6	0.2	4.1	0.0	1.6	19.9	0.1	4.2	0.8	116.0	11.6	**TU**
UA	194.2	12.5	367.3	0.3	1094	1462	1.8	315.1	28.5	27624	239.4	**UA**
UZ	2.1	0.3	5.4	0.0	2.4	27.6	0.1	5.5	1.1	146.7	15.9	**UZ**
BAS	397.1	32.8	3055	0.2	15.8	51.0	2.0	1399	164.7	18957	344.4	**BAS**
BLS	32.3	2.7	66.8	0.1	410.0	1099	0.5	74.6	6.8	3636	92.2	**BLS**
CAS	4.9	0.6	12.0	0.0	12.6	72.6	0.2	14.0	1.6	408.0	20.8	**CAS**
MDT	17.8	27.4	55.9	7.8	96.5	7054	0.8	360.8	17.9	6110	2065	**MDT**
NOS	56.9	94.7	245.4	0.4	6.0	61.9	7.0	8466	459.7	9794	1682	**NOS**
	LT	**LU**	**LV**	**MC**	**MD**	**MK**	**MT**	**NL**	**NO**	**PL**	**PT**	

***Table D.2**. Matrix of lead country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors ↓ Emitters ⟶

	RO	RU	SE	SI	SK	TJ	TR	TU	UA	UZ	Total, t	
AL	324.3	37.2	1.4	20.1	89.1	0.03	270.6	0.6	112.3	0.7	**17.8**	AL
AM	29.2	116.2	0.4	1.3	4.8	1.6	1646	95.7	41.9	69.0	**3.9**	AM
AT	937.8	119.6	17.2	1166	2352	0.04	181.4	1.3	356.4	1.6	**35.1**	AT
AZ	72.2	664.5	1.5	2.9	12.9	21.6	1953	633.4	142.1	489.7	**11.0**	AZ
BA	1861	71.2	10.6	247.2	1168	0.04	513.7	1.0	311.0	1.0	**48.9**	BA
BE	16.5	9.5	7.9	6.3	15.4	0.0	13.5	0.0	11.8	0.1	**22.8**	BE
BG	13800	1228	12.3	80.8	722.0	0.5	7049	16.3	3283	17.5	**111.1**	BG
BY	3360	3429	141.7	104.3	1610	2.5	1169	27.3	6473	38.4	**64.1**	BY
CH	48.6	17.9	3.4	56.2	47.3	0.01	27.2	0.1	29.3	0.2	**14.8**	CH
CS	6868	203.1	15.3	209.2	2056	0.1	1277	3.3	857.3	3.3	**102.1**	CS
CY	15.5	8.0	0.1	0.7	2.6	0.01	617.5	0.2	9.2	0.2	**1.3**	CY
CZ	835.6	130.8	35.3	229.7	2618	0.1	92.1	1.2	345.6	1.7	**53.9**	CZ
DE	594.9	334.5	186.2	162.9	973.1	0.2	195.7	1.8	483.1	2.5	**129.8**	DE
DK	23.4	45.6	87.5	3.6	54.6	0.01	8.0	0.1	36.8	0.2	**6.7**	DK
EE	154.6	663.0	132.8	10.4	111.6	0.2	31.2	1.5	211.3	2.2	**10.3**	EE
ES	62.9	18.5	7.8	64.8	46.6	0.02	31.7	0.2	28.2	0.3	**105.5**	ES
FI	651.7	2692	1747	32.3	503.3	1.0	133.1	4.7	732.2	9.1	**34.9**	FI
FR	365.9	102.4	46.6	298.2	262.5	0.1	166.3	0.8	176.7	1.2	**117.1**	FR
GB	45.7	30.5	34.3	15.9	66.3	0.04	26.3	0.3	29.6	0.5	**40.7**	GB
GE	276.8	1051	1.8	6.3	36.2	2.2	5577	168.5	437.1	113.7	**13.4**	GE
GR	2570	460.0	5.8	51.3	295.9	0.3	7319	6.8	1118	7.9	**129.1**	GR
HR	1647	66.9	7.7	916.1	1466	0.04	508.2	0.8	293.0	0.9	**31.1**	HR
HU	5427	130.1	15.5	564.1	9244	0.07	444.6	1.3	785.4	1.5	**52.5**	HU
IE	3.0	2.6	2.3	0.9	2.7	0.0	2.0	0.03	1.6	0.1	**3.9**	IE
IS	4.0	13.3	12.3	0.7	1.9	0.01	22.5	0.1	7.8	0.1	**0.9**	IS
IT	1409	208.1	13.8	1578	985.7	0.1	1144	3.3	534.9	3.8	**119.6**	IT
KY	68.1	627.8	2.7	3.7	17.0	6355	850.1	637.9	97.2	17757	**60.8**	KY
KZ	2118	30585	61.0	51.2	406.9	9753	6887	4453	4758	42265	**361.9**	KZ
LT	577.9	633.3	115.6	44.1	389.1	0.3	114.4	2.9	617.2	4.3	**17.4**	LT
LU	2.0	1.2	0.6	0.8	2.1	0.0	1.2	0.01	1.2	0.01	**1.3**	LU
LV	413.5	778.4	153.9	28.7	249.5	0.4	85.8	3.4	496.5	5.2	**15.3**	LV
MC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	MC
MD	3785	526.6	4.8	11.1	131.9	0.2	1020.6	4.2	2379	5.1	**12.4**	MD
MK	594.2	61.9	1.8	17.0	132.5	0.04	434.7	1.0	185.3	1.1	**35.3**	MK
MT	0.6	0.2	0.01	0.1	0.2	0.0	2.4	0.0	0.3	0.0	**0.03**	MT
NL	15.8	13.0	10.8	5.9	22.9	0.0	10.6	0.1	16.1	0.1	**19.0**	NL
NO	263.1	325.0	490.6	18.1	241.5	0.2	63.6	1.6	217.4	2.3	**21.2**	NO
PL	3478	1105	359.4	448.1	6579	0.5	462.7	4.9	3187.3	7.2	**271.8**	PL
PT	2.3	1.2	0.6	1.9	2.2	0.0	1.4	0.0	1.0	0.0	**55.5**	PT
RO	**84726**	2232	40.4	301.2	3988	0.7	5648	29.0	8145	31.4	**166.3**	RO
RU	16445	**408786**	1901	439.2	4629	2341	39869	3837	45110	11684	**887.9**	RU
SE	493.2	962.0	**6437**	27.9	464.6	0.6	111.8	2.4	588.2	4.2	**36.8**	SE
SI	438.8	38.5	2.4	**3368**	498.0	0.02	96.8	0.5	122.6	0.6	**13.1**	SI
SK	2051	119.1	19.5	273.9	**14438**	0.1	138.7	1.1	603.4	1.3	**45.3**	SK
TJ	20.0	183.8	0.7	1.2	4.9	**11781**	330.0	614.3	26.7	8463	**26.0**	TJ
TR	5545	4069	16.5	85.0	501.6	4.0	**184984**	147.3	4443	131.2	**242.4**	TR
TU	58.1	716.5	2.5	2.4	14.4	1612	610.7	**5851**	149.9	7512	**22.7**	TU
UA	21050	13928	133.5	266.7	5247	16.1	14669	167.0	**75982**	232.7	**203.7**	UA
UZ	86.8	1099	3.6	3.6	19.8	7034	728.0	2611	173.4	**31302**	**62.1**	UZ
BAS	727.2	1787	2344	66.5	728.2	0.7	133.0	3.4	863.7	5.7	**52.2**	BAS
BLS	11894	8946	26.8	91.8	748.9	3.4	38821	117.4	15148	144.0	**109.5**	BLS
CAS	410.7	3407	5.6	9.4	69.3	269.0	2748	2334	1010	2647	**35.3**	CAS
MDT	5944	1258	37.5	1464	1806	1.1	41729	21.7	2614	26.8	**313.4**	MDT
NOS	342.6	292.6	450.5	70.5	455.2	0.2	167.5	2.8	293.7	3.9	**88.1**	NOS
	RO	RU	SE	SI	SK	TJ	TR	TU	UA	UZ	Total, t	

Table D.3. *Matrix of cadmium country-to-country depositions from anthropogenic sources in 2005, kg/y*

Receptors ↓ Emitters ⟶

	AL	**AM**	**AT**	**AZ**	**BA**	**BE**	**BG**	**BY**	**CH**	**CS**	**CY**	**CZ**	**DE**	**DK**	**EE**	**ES**	
AL	**39.18**	0.01	0.97	0.17	7.59	0.30	57.86	0.34	0.76	134.5	0.13	2.01	0.68	0.10	0.03	9.29	**AL**
AM	0.04	**31.05**	0.06	54.35	0.18	0.03	1.85	0.14	0.06	0.85	1.90	0.13	0.07	0.01	0.02	0.77	**AM**
AT	0.38	0.01	**353.6**	0.22	14.05	14.60	30.49	4.02	41.11	72.13	0.07	104.5	82.8	1.97	0.30	26.15	**AT**
AZ	0.09	7.37	0.15	**562.5**	0.39	0.09	4.46	0.48	0.15	1.96	3.47	0.33	0.18	0.03	0.07	1.71	**AZ**
BA	4.02	0.02	14.16	0.21	**599.3**	2.04	76.19	1.46	3.27	469.1	0.31	29.32	6.69	1.13	0.14	18.62	**BA**
BE	0.02	0.00	1.22	0.01	0.24	**389.7**	0.83	0.39	4.08	1.01	0.01	2.36	26.52	1.38	0.11	26.57	**BE**
BG	4.90	0.21	5.72	3.71	18.85	1.69	**5307.1**	6.99	2.27	400.9	0.83	15.99	4.55	0.76	0.62	20.45	**BG**
BY	0.78	0.32	9.98	5.82	9.21	6.51	90.04	**785.7**	4.45	58.20	0.46	58.51	18.74	6.93	10.28	17.89	**BY**
CH	0.05	0.003	7.60	0.07	1.03	8.90	1.80	0.48	**294.0**	3.25	0.02	4.86	17.35	0.38	0.06	33.66	**CH**
CS	13.34	0.06	15.05	0.68	132.9	2.69	450.0	2.89	3.70	**3122.7**	0.53	38.10	8.40	1.39	0.26	21.35	**CS**
CY	0.05	0.02	0.04	0.07	0.17	0.02	1.56	0.03	0.03	0.78	**53.3**	0.07	0.03	0.005	0.002	0.36	**CY**
CZ	0.16	0.01	62.67	0.25	6.29	14.19	17.14	6.21	14.89	40.54	0.03	**733.6**	73.95	4.70	0.49	15.93	**CZ**
DE	0.23	0.02	85.14	0.59	4.51	350.3	14.01	12.98	203.2	21.55	0.09	219.41	**1170.5**	37.04	2.57	167.6	**DE**
DK	0.01	0.00	1.13	0.03	0.12	15.41	0.55	1.81	1.73	0.66	0.003	7.83	25.18	**63.7**	0.45	13.34	**DK**
EE	0.02	0.01	1.33	0.23	0.49	2.32	2.35	11.23	0.96	2.65	0.02	7.59	5.66	3.72	**65.9**	3.33	**EE**
ES	0.29	0.004	2.60	0.05	3.00	13.38	5.57	0.39	7.92	8.42	0.02	2.63	7.77	0.98	0.13	**5129.2**	**ES**
FI	0.08	0.04	5.43	0.65	1.59	10.38	8.18	27.73	4.78	9.52	0.06	32.82	21.56	12.97	47.87	15.54	**FI**
FR	1.04	0.01	15.64	0.16	12.16	221.3	20.72	2.89	136.9	34.60	0.12	22.01	109.5	7.01	0.68	1330.9	**FR**
GB	0.03	0.004	2.99	0.05	0.46	66.27	1.32	0.84	7.94	2.09	0.01	9.61	34.59	5.07	0.32	117.0	**GB**
GE	0.13	13.31	0.37	169.1	0.71	0.23	10.48	1.16	0.28	4.68	5.25	1.02	0.46	0.08	0.10	2.86	**GE**
GR	10.31	0.13	2.81	2.10	13.19	1.17	620.3	2.93	2.00	123.3	3.08	6.86	2.51	0.39	0.21	23.87	**GR**
HR	2.59	0.02	24.44	0.16	90.25	1.84	66.58	1.34	3.80	312.6	0.23	29.86	6.43	0.75	0.14	17.07	**HR**
HU	1.25	0.02	42.60	0.23	49.69	3.02	100.6	3.81	4.86	369.4	0.14	68.72	11.60	1.50	0.35	13.62	**HU**
IE	0.004	0.00	0.14	0.005	0.04	3.68	0.09	0.03	0.84	0.16	0.00	0.34	2.29	0.30	0.03	24.68	**IE**
IS	0.004	0.003	0.09	0.04	0.03	0.92	0.24	0.12	0.40	0.13	0.02	0.44	1.11	0.71	0.18	8.78	**IS**
IT	8.86	0.04	47.24	0.71	73.88	7.38	102.1	2.49	58.67	179.8	0.58	32.83	19.88	1.22	0.28	154.0	**IT**
KZ	0.26	2.61	1.66	88.49	1.90	1.21	30.61	10.66	1.17	12.97	2.56	5.69	2.58	0.61	1.71	6.85	**KZ**
LT	0.12	0.03	4.74	0.58	2.26	3.93	12.04	50.79	2.45	12.66	0.05	25.06	11.79	6.35	3.96	7.86	**LT**
LU	0.00	0.00	0.17	0.00	0.03	10.57	0.08	0.04	0.74	0.10	0.00	0.26	3.21	0.09	0.02	2.84	**LU**
LV	0.07	0.03	3.11	0.71	1.52	3.87	7.67	30.17	1.91	8.33	0.05	16.37	10.83	6.38	13.26	5.82	**LV**
MC	0.00	0.00	0.001	0.00	0.001	0.00	0.001	0.00	0.004	0.003	0.00	0.001	0.00	0.00	0.00	0.01	**MC**
MD	0.26	0.06	0.78	1.00	2.07	0.43	51.01	4.80	0.42	15.44	0.23	3.27	1.04	0.24	0.32	2.84	**MD**
MK	9.30	0.02	1.05	0.26	5.64	0.30	179.7	0.50	0.55	123.4	0.13	2.67	0.78	0.13	0.05	5.71	**MK**
MT	0.004	0.00	0.01	0.00	0.02	0.002	0.05	0.001	0.01	0.05	0.00	0.01	0.004	0.00	0.00	0.08	**MT**
NL	0.02	0.001	1.22	0.02	0.23	133.3	0.68	0.53	2.58	0.99	0.01	3.5	39.47	2.20	0.15	22.65	**NL**
NO	0.06	0.01	5.30	0.24	0.85	32.10	5.30	5.53	6.42	5.48	0.03	24.82	44.79	34.08	2.28	43.80	**NO**
PL	0.68	0.06	50.10	0.91	17.87	37.48	69.22	109.6	21.69	115.2	0.18	652.3	160.2	42.27	5.80	64.53	**PL**
PT	0.01	0.001	0.10	0.01	0.08	1.16	0.10	0.02	0.44	0.18	0.001	0.12	0.54	0.08	0.01	394.3	**PT**
RO	5.34	0.35	21.39	5.58	67.56	5.61	982.11	17.64	6.79	670.9	1.03	68.44	16.32	2.66	1.67	33.03	**RO**
RU	4.02	20.81	33.68	554.4	34.16	34.42	437.1	570.3	22.33	210.1	24.96	158.4	80.53	34.89	303.7	120.6	**RU**
SE	0.09	0.02	6.75	0.45	1.11	36.94	8.65	17.33	7.79	8.05	0.04	42.38	69.89	88.31	10.08	41.14	**SE**
SI	0.41	0.01	32.36	0.08	15.28	1.16	21.06	0.70	2.82	62.23	0.04	11.40	4.38	0.24	0.07	7.37	**SI**
SK	0.48	0.01	25.78	0.19	14.97	3.38	40.74	5.03	4.17	103.6	0.05	161.25	12.25	1.86	0.45	8.25	**SK**
TR	3.41	15.02	5.03	40.02	13.70	2.22	279.5	12.39	3.67	94.77	134.78	12.76	5.10	0.91	1.09	43.91	**TR**
UA	2.96	1.98	20.18	34.28	31.91	11.42	452.6	169.9	9.02	230.9	5.78	100.91	29.23	7.44	7.54	45.26	**UA**
BAS	0.11	0.03	10.21	0.69	2.34	42.17	11.92	32.76	10.71	14.98	0.06	66.37	102.50	94.72	51.17	54.16	**BAS**
BLS	2.15	2.76	5.50	31.55	13.11	2.51	399.1	21.19	2.82	120.4	14.62	17.03	5.95	1.27	1.71	19.21	**BLS**
CAS	0.16	4.99	0.63	313.1	0.90	0.46	14.74	2.76	0.46	6.03	3.96	1.77	0.86	0.17	0.37	3.30	**CAS**
MDT	38.49	0.61	48.04	5.51	164.7	18.17	738.3	6.70	55.47	464.9	227.4	53.59	31.88	3.20	0.65	1223.2	**MDT**
NOS	0.18	0.03	13.85	0.49	2.36	221.7	10.93	6.77	22.15	11.77	0.08	56.18	183.36	74.43	3.12	281.1	**NOS**
	AL	**AM**	**AT**	**AZ**	**BA**	**BE**	**BG**	**BY**	**CH**	**CS**	**CY**	**CZ**	**DE**	**DK**	**EE**	**ES**	

Table D.3. *Matrix of cadmium country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors↓ Emitters ⟶

	FI	FR	GB	GE	GR	HR	HU	IE	IS	IT	KZ	LT	LU	LV	MC	
AL	0.06	3.25	0.52	0.02	32.69	2.92	2.73	0.07	0.003	54.97	0.65	0.05	0.01	0.07	0.01	**AL**
AM	0.02	0.18	0.05	4.92	0.98	0.08	0.09	0.01	0.00	0.85	7.94	0.01	0.001	0.02	0.00	**AM**
AT	0.46	39.37	11.25	0.03	1.93	19.06	39.36	0.85	0.03	111.9	0.87	0.54	0.63	0.74	0.07	**AT**
AZ	0.08	0.42	0.14	9.63	2.06	0.17	0.21	0.02	0.001	1.84	53.38	0.04	0.003	0.05	0.001	**AZ**
BA	0.32	10.20	2.39	0.03	13.75	69.34	44.07	0.23	0.01	102.9	0.73	0.35	0.06	0.48	0.04	**BA**
BE	0.17	228.1	43.22	0.001	0.15	0.24	0.25	2.20	0.04	5.11	0.02	0.22	3.03	0.35	0.01	**BE**
BG	0.76	6.95	2.22	0.57	89.65	7.12	20.02	0.23	0.01	49.26	13.89	0.55	0.04	0.74	0.02	**BG**
BY	9.21	12.88	8.49	0.63	6.98	5.27	23.03	0.69	0.04	20.50	12.59	18.39	0.15	19.04	0.01	**BY**
CH	0.08	88.34	8.97	0.005	0.38	1.80	1.03	0.85	0.02	116.6	0.08	0.08	0.41	0.11	0.09	**CH**
CS	0.48	10.68	3.07	0.12	34.69	30.74	81.01	0.30	0.01	105.1	2.27	0.51	0.08	0.70	0.04	**CS**
CY	0.00	0.12	0.02	0.02	2.03	0.07	0.06	0.003	0.00	0.95	0.09	0.002	0.00	0.003	0.00	**CY**
CZ	0.72	27.35	13.06	0.03	0.82	7.61	37.42	0.91	0.04	25.86	0.70	1.04	0.44	1.42	0.02	**CZ**
DE	3.45	524.9	185.5	0.06	1.47	4.59	13.55	10.89	0.36	76.57	0.95	5.54	14.41	8.37	0.10	**DE**
DK	0.79	23.50	25.08	0.003	0.07	0.11	0.53	1.66	0.06	2.03	0.07	0.87	0.19	1.39	0.003	**DK**
EE	16.05	4.07	4.13	0.02	0.17	0.34	1.46	0.35	0.02	1.69	0.75	10.88	0.05	22.07	0.002	**EE**
ES	0.22	110.1	25.27	0.01	1.63	3.26	1.27	4.29	0.08	64.32	0.09	0.24	0.34	0.36	0.07	**ES**
FI	**582.3**	19.92	17.53	0.08	0.62	0.96	6.41	1.72	0.12	7.24	2.67	14.59	0.20	25.40	0.01	**FI**
FR	1.04	**2288**	232.6	0.02	5.26	14.41	6.10	20.48	0.28	342.9	0.35	1.27	9.52	1.97	1.49	**FR**
GB	0.84	146.9	**820.5**	0.01	0.22	0.53	0.92	67.70	0.58	7.89	0.06	0.53	0.87	0.86	0.01	**GB**
GE	0.12	0.82	0.37	**79.9**	3.45	0.34	0.69	0.04	0.001	3.33	17.18	0.08	0.01	0.10	0.002	**GE**
GR	0.31	7.97	1.78	0.28	**706.3**	5.09	7.66	0.21	0.01	67.54	6.41	0.26	0.03	0.34	0.03	**GR**
HR	0.29	10.33	1.96	0.03	9.36	**194.8**	62.95	0.18	0.01	111.6	0.62	0.31	0.06	0.43	0.05	**HR**
HU	0.66	10.44	3.18	0.04	6.53	47.50	**457.8**	0.25	0.01	65.58	0.76	0.71	0.10	0.97	0.04	**HU**
IE	0.08	16.05	37.98	0.001	0.02	0.03	0.04	**101.2**	0.14	0.82	0.01	0.03	0.08	0.06	0.001	**IE**
IS	0.35	2.49	4.18	0.01	0.07	0.03	0.02	1.02	**14.9**	0.74	0.02	0.08	0.02	0.13	0.001	**IS**
IT	0.54	100.1	9.75	0.07	45.86	86.77	28.70	1.09	0.03	**2261**	2.65	0.42	0.29	0.61	0.92	**IT**
KZ	1.69	3.36	1.85	4.35	4.85	1.04	3.18	0.20	0.01	6.54	**1367.6**	0.79	0.03	1.14	0.005	**KZ**
LT	5.63	7.51	5.26	0.06	0.82	1.67	5.47	0.45	0.02	7.44	1.21	**60.3**	0.08	36.78	0.01	**LT**
LU	0.02	14.77	2.00	0.00	0.01	0.03	0.03	0.12	0.002	0.70	0.002	0.02	**3.56**	0.03	0.001	**LU**
LV	9.94	6.71	6.10	0.06	0.47	1.06	3.40	0.53	0.02	4.88	1.65	79.26	0.08	**130.3**	0.004	**LV**
MC	0.00	0.03	0.00	0.00	0.00	0.002	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	**0.004**	**MC**
MD	0.34	1.23	0.55	0.19	4.61	0.77	2.69	0.05	0.003	4.90	3.20	0.33	0.01	0.41	0.003	**MD**
MK	0.08	1.89	0.42	0.03	73.34	1.86	3.74	0.05	0.002	20.80	0.89	0.07	0.01	0.09	0.01	**MK**
MT	0.00	0.03	0.004	0.00	0.07	0.01	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	**MT**
NL	0.21	108.6	53.06	0.00	0.11	0.22	0.34	2.45	0.07	3.47	0.03	0.29	0.51	0.46	0.01	**NL**
NO	9.52	55.94	99.64	0.02	0.41	0.53	2.94	9.97	0.69	7.09	0.92	2.64	0.53	4.21	0.01	**NO**
PL	9.30	70.00	39.09	0.14	4.75	17.46	77.20	2.91	0.15	58.90	2.58	18.27	0.89	22.12	0.05	**PL**
PT	0.02	7.04	2.47	0.00	0.05	0.09	0.05	0.50	0.01	2.40	0.01	0.01	0.03	0.02	0.003	**PT**
RO	2.16	17.39	6.61	0.94	47.01	26.00	118.7	0.61	0.03	94.97	17.78	1.96	0.15	2.65	0.05	**RO**
RU	252.8	75.30	60.67	57.95	63.88	17.52	59.26	5.98	0.43	112.2	1828.7	56.32	0.77	86.17	0.08	**RU**
SE	94.27	57.82	61.35	0.04	0.64	0.70	5.66	5.20	0.28	9.31	1.46	12.14	0.64	21.65	0.01	**SE**
SI	0.11	5.55	1.09	0.01	1.73	42.70	16.05	0.10	0.003	70.04	0.44	0.11	0.05	0.15	0.03	**SI**
SK	0.86	8.15	3.75	0.02	2.87	13.27	115.5	0.28	0.01	29.05	0.59	0.88	0.10	1.19	0.02	**SK**
TR	1.27	11.40	3.38	10.27	148.9	6.07	11.06	0.40	0.02	71.55	37.73	0.91	0.06	1.19	0.03	**TR**
UA	8.49	26.49	13.80	5.69	50.72	17.36	97.08	1.19	0.06	71.30	96.74	9.10	0.29	11.46	0.04	**UA**
BAS	163.6	67.89	53.44	0.06	0.90	1.90	9.05	4.05	0.15	14.67	1.94	42.64	0.78	92.60	0.02	**BAS**
BLS	2.03	7.53	3.83	13.30	66.76	5.68	14.71	0.40	0.02	36.78	85.91	1.37	0.06	1.83	0.02	**BLS**
CAS	0.37	1.39	0.74	6.67	3.44	0.45	1.13	0.08	0.003	3.82	402.6	0.20	0.01	0.29	0.002	**CAS**
MDT	1.19	293.6	30.99	1.02	732.6	125.5	45.06	3.30	0.13	2165.3	15.41	0.99	0.62	1.49	1.00	**MDT**
NOS	6.76	439.3	921.2	0.07	1.15	2.34	5.75	56.45	2.25	29.79	1.17	4.16	2.33	6.72	0.05	**NOS**
	FI	**FR**	**GB**	**GE**	**GR**	**HR**	**HU**	**IE**	**IS**	**IT**	**KZ**	**LT**	**LU**	**LV**	**MC**	

Table D.3*. Matrix of cadmium country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors ↓ Emitters ⟶

	MD	**MK**	**MT**	**NL**	**NO**	**PL**	**PT**	**RO**	**RU**	**SE**	**SI**	**SK**	**TR**	**UA**	**Total**	
AL	0.13	396.5	0.004	0.23	0.03	18.09	0.72	4.24	4.62	0.04	2.28	6.84	7.08	1.78	**794.6**	**AL**
AM	0.02	2.11	0.002	0.03	0.01	1.62	0.09	0.28	8.82	0.01	0.12	0.30	47.49	0.62	**168.1**	**AM**
AT	0.25	16.98	0.05	10.40	0.70	478.9	2.78	14.62	19.64	0.50	141.2	218.8	5.17	3.72	**1887.2**	**AT**
AZ	0.06	4.77	0.01	0.08	0.02	4.43	0.21	0.68	43.33	0.03	0.27	0.74	61.86	2.30	**770.3**	**AZ**
BA	0.29	80.86	0.02	1.80	0.27	206.7	1.72	29.02	11.65	0.31	27.61	99.65	13.72	3.69	**1948.2**	**BA**
BE	0.01	0.76	0.03	60.26	0.39	26.60	2.90	0.23	1.99	0.23	0.68	1.68	0.37	0.13	**833.8**	**BE**
BG	5.01	457.07	0.04	1.56	0.28	173.5	2.15	133.7	136.8	0.35	9.68	49.96	159.2	52.69	**7169.5**	**BG**
BY	3.35	43.40	0.25	7.34	2.37	1827.3	2.36	36.69	771.9	4.59	11.66	112.2	34.16	72.22	**4151.6**	**BY**
CH	0.02	1.66	0.01	4.62	0.17	32.98	2.67	0.71	2.98	0.09	5.94	4.31	0.77	0.32	**649.6**	**CH**
CS	1.07	544.34	0.03	2.32	0.39	286.9	2.00	95.32	31.33	0.44	25.19	144.0	34.70	11.66	**5263.6**	**CS**
CY	0.01	2.48	0.00	0.01	0.002	0.68	0.03	0.17	0.57	0.002	0.08	0.20	19.90	0.15	**84.2**	**CY**
CZ	0.23	7.60	0.07	14.65	1.28	1593.6	1.72	14.08	25.08	1.04	26.84	804.9	2.93	3.62	**3606.1**	**CZ**
DE	0.27	8.92	0.37	318.0	7.52	1617.2	18.62	9.54	70.43	5.56	17.54	115.0	6.17	5.26	**5340.8**	**DE**
DK	0.01	0.38	0.06	21.34	1.98	136.3	2.41	0.34	9.29	2.46	0.38	7.67	0.24	0.40	**371.6**	**DK**
EE	0.08	1.14	0.10	2.92	1.63	208.3	0.39	2.31	127.4	4.36	1.12	11.22	0.95	2.36	**534.1**	**EE**
ES	0.02	8.89	0.06	7.90	0.36	25.36	386.6	0.91	3.07	0.23	7.37	4.17	0.83	0.38	**5840.0**	**ES**
FI	0.31	4.10	1.85	11.28	13.49	763.1	1.32	10.58	442.7	56.65	3.32	51.85	4.26	8.14	**2251.9**	**FI**
FR	0.13	29.70	0.20	89.45	2.08	202.7	78.98	4.99	18.22	1.36	32.55	25.03	4.41	2.10	**5332.7**	**FR**
GB	0.02	1.13	0.36	61.95	2.27	115.1	19.77	0.70	5.55	0.98	1.66	7.68	0.75	0.30	**1515.3**	**GB**
GE	0.25	7.51	0.01	0.21	0.04	14.59	0.33	2.53	129.6	0.04	0.65	2.39	198.9	7.20	**680.9**	**GE**
GR	1.29	771.8	0.02	0.96	0.14	73.25	1.69	27.22	46.97	0.16	5.60	20.41	176.1	17.69	**2762.6**	**GR**
HR	0.27	53.27	0.02	1.54	0.20	197.5	1.36	26.43	11.00	0.23	103.8	115.9	13.25	3.24	**1479.0**	**HR**
HU	0.52	60.40	0.03	2.76	0.40	470.5	1.27	106.1	23.97	0.48	67.54	406.4	12.77	7.46	**2426.7**	**HU**
IE	0.001	0.10	0.07	2.95	0.18	5.38	5.20	0.04	0.38	0.07	0.08	0.26	0.05	0.02	**204.0**	**IE**
IS	0.00	0.18	0.84	0.81	0.75	7.82	2.64	0.03	1.74	0.34	0.07	0.29	0.77	0.10	**53.7**	**IS**
IT	0.47	186.6	0.05	4.88	0.45	236.2	9.77	19.76	26.60	0.40	180.6	87.51	28.18	7.06	**4017.3**	**IT**
KZ	1.16	18.12	0.14	1.11	0.39	97.69	0.84	11.13	1070.2	0.55	2.20	12.14	79.87	56.19	**2919.9**	**KZ**
LT	0.36	6.08	0.11	4.43	1.69	876.8	1.10	7.77	230.0	3.71	4.94	37.41	3.38	6.49	**1461.6**	**LT**
LU	0.00	0.07	0.002	1.65	0.02	2.47	0.30	0.03	0.23	0.02	0.08	0.21	0.04	0.01	**44.6**	**LU**
LV	0.25	3.79	0.14	4.82	2.05	477.2	0.73	5.21	185.4	5.14	3.13	23.79	2.72	5.48	**1074.4**	**LV**
MC	0.00	0.002	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.002	0.00	0.00	**0.2**	**MC**
MD	**27.48**	18.67	0.02	0.42	0.09	69.15	0.28	20.94	94.47	0.14	1.19	8.19	25.63	33.37	**403.6**	**MD**
MK	0.22	**3037.4**	0.004	0.25	0.04	24.22	0.53	7.06	7.41	0.05	1.92	9.10	10.04	2.83	**3534.5**	**MK**
MT	0.00	0.12	**0.00**	0.001	0.00	0.04	0.003	0.01	0.01	0.00	0.01	0.02	0.05	0.004	**0.9**	**MT**
NL	0.01	0.63	0.05	**278.9**	0.70	41.68	2.59	0.23	2.63	0.33	0.62	2.82	0.33	0.18	**709.1**	**NL**
NO	0.12	2.97	100.15	36.11	**195.6**	382.6	4.83	3.41	50.00	14.68	1.76	26.05	1.96	2.39	**1228.9**	**NO**
PL	1.59	33.90	0.42	40.25	7.54	**19969**	8.27	59.05	339.2	11.72	52.10	714.6	14.22	29.85	**22953.9**	**PL**
PT	0.001	0.15	0.01	0.71	0.03	1.26	**1200**	0.03	0.15	0.02	0.21	0.19	0.05	0.01	**1612.5**	**PT**
RO	21.39	345.6	0.12	5.18	0.91	764.5	3.47	**1206**	349.2	1.17	34.50	246.3	139.2	112.0	**5473.4**	**RO**
RU	13.79	260.5	15.97	38.00	24.40	3623.6	14.81	146.0	**42143**	49.77	38.32	298.3	1213.1	704.0	**53905.4**	**RU**
SE	0.33	4.64	1.68	42.82	61.78	983.8	5.65	6.80	172.4	**218.6**	2.87	51.79	3.53	6.63	**2173.5**	**SE**
SI	0.11	14.24	0.01	0.87	0.07	74.02	0.62	6.50	5.67	0.07	**462.1**	43.25	2.60	1.45	**909.3**	**SI**
SK	0.30	23.75	0.04	3.37	0.46	1159.8	0.86	42.13	24.85	0.61	32.10	**1329.9**	4.29	5.61	**3187.0**	**SK**
TR	3.94	195.7	0.10	2.00	0.42	173.1	4.10	52.04	262.6	0.45	9.02	34.43	**6826.9**	74.73	**8612.1**	**TR**
UA	33.32	197.1	0.48	11.38	2.66	2671.0	5.07	226.6	2323.5	4.15	29.65	251.9	435.3	**1261.4**	**9024.5**	**UA**
BAS	0.41	5.94	0.58	50.12	14.97	1938.4	7.23	10.93	376.1	76.78	6.88	78.82	4.03	9.80	**3529.5**	**BAS**
BLS	12.25	154.2	0.13	2.51	0.55	273.5	1.94	93.81	576.9	0.72	9.51	45.50	1103.4	253.1	**3429.1**	**BLS**
CAS	0.34	9.89	0.04	0.42	0.11	27.38	0.38	3.72	242.2	0.13	0.89	3.98	82.34	17.32	**1165.1**	**CAS**
MDT	2.62	946.6	0.23	12.83	1.61	386.4	47.34	65.78	120.5	1.02	161.8	147.0	1142.2	39.76	**9574.6**	**MDT**
NOS	0.15	7.18	2.08	337.2	45.56	709.0	36.32	4.88	48.60	12.26	7.30	53.33	5.21	3.28	**3640.4**	**NOS**
	MD	**MK**	**MT**	**NL**	**NO**	**PL**	**PT**	**RO**	**RU**	**SE**	**SI**	**SK**	**TR**	**UA**	**Total**	

Table D.4. *Matrix of mercury country-to-country depositions from anthropogenic sources in 2005, kg/y*

Receptors ↓ Emitters →

	AL	AM	AT	AZ	BA	BE	BG	BY	CH	CS	CY	CZ	DE	DK	EE	ES	
AL	**26.88**	0.005	0.29	0.03	3.04	0.11	3.99	0.04	0.25	33.98	0.03	0.79	0.19	0.07	0.01	1.22	**AL**
AM	0.02	**26.25**	0.03	11.82	0.09	0.03	0.24	0.02	0.04	0.23	0.70	0.10	0.04	0.02	0.01	0.18	**AM**
AT	0.16	0.01	**171.7**	0.04	5.61	5.19	1.69	0.48	17.30	13.53	0.03	69.10	17.32	1.81	0.10	5.19	**AT**
AZ	0.04	4.97	0.08	**154.7**	0.22	0.07	0.58	0.06	0.09	0.57	1.33	0.27	0.11	0.05	0.03	0.44	**AZ**
BA	1.44	0.01	4.25	0.04	**365.9**	0.68	3.33	0.16	1.06	104.8	0.08	11.59	1.65	0.86	0.04	3.02	**BA**
BE	0.01	0.00	0.37	0.002	0.10	**240.4**	0.08	0.04	1.41	0.22	0.005	1.15	15.43	1.27	0.03	4.15	**BE**
BG	1.48	0.07	1.64	0.37	6.32	0.58	**641.2**	0.56	0.76	69.14	0.26	6.19	1.21	0.55	0.16	3.25	**BG**
BY	0.27	0.12	2.86	0.80	3.57	2.06	6.76	**144.1**	1.53	10.92	0.18	20.71	5.43	6.26	4.02	3.33	**BY**
CH	0.03	0.002	2.18	0.02	0.49	3.38	0.18	0.08	**152.4**	0.85	0.01	3.24	4.70	0.37	0.02	6.31	**CH**
CS	5.52	0.02	4.64	0.09	59.95	0.88	20.08	0.31	1.18	**1022.6**	0.13	15.04	2.04	0.99	0.08	3.51	**CS**
CY	0.01	0.01	0.01	0.01	0.05	0.01	0.17	0.00	0.01	0.13	**59.8**	0.04	0.01	0.005	0.001	0.07	**CY**
CZ	0.05	0.01	24.60	0.04	2.09	4.57	0.81	0.67	5.14	6.37	0.02	**696.6**	22.43	4.23	0.14	2.78	**CZ**
DE	0.10	0.01	32.47	0.10	2.10	107.2	1.30	1.35	84.98	5.16	0.05	139.9	**595.2**	41.92	0.68	25.95	**DE**
DK	0.004	0.001	0.35	0.01	0.06	4.16	0.06	0.19	0.56	0.18	0.00	3.39	7.92	**124.0**	0.15	1.92	**DK**
EE	0.01	0.01	0.35	0.04	0.20	0.67	0.20	1.37	0.31	0.48	0.01	2.66	1.43	3.39	**34.35**	0.66	**EE**
ES	0.07	0.002	0.60	0.01	0.77	3.36	0.34	0.06	2.02	1.24	0.01	1.16	2.08	0.80	0.05	**1282.9**	**ES**
FI	0.04	0.02	1.45	0.13	0.70	2.99	0.72	2.83	1.55	1.83	0.04	10.90	5.58	11.03	17.91	3.17	**FI**
FR	0.31	0.01	4.26	0.05	3.63	95.97	1.49	0.39	54.78	5.62	0.06	11.02	45.71	6.21	0.24	216.8	**FR**
GB	0.01	0.00	0.72	0.01	0.20	18.53	0.16	0.08	2.27	0.48	0.01	3.28	8.74	3.91	0.09	20.17	**GB**
GE	0.06	7.08	0.17	30.46	0.35	0.13	1.23	0.13	0.15	0.99	2.14	0.61	0.22	0.09	0.04	0.71	**GE**
GR	4.00	0.04	0.79	0.23	4.39	0.39	92.61	0.23	0.64	20.70	0.87	2.58	0.72	0.29	0.07	3.36	**GR**
HR	0.87	0.005	7.44	0.02	37.22	0.60	2.57	0.15	1.11	64.76	0.06	12.85	1.50	0.56	0.04	2.67	**HR**
HU	0.40	0.01	15.61	0.03	21.08	1.10	4.16	0.50	1.50	80.77	0.04	36.11	3.24	1.31	0.12	2.45	**HU**
IE	0.002	0.00	0.04	0.00	0.02	1.03	0.02	0.00	0.22	0.05	0.00	0.13	0.56	0.23	0.01	4.11	**IE**
IS	0.002	0.001	0.04	0.00	0.02	0.24	0.05	0.02	0.13	0.05	0.01	0.27	0.31	0.59	0.05	1.37	**IS**
IT	3.34	0.02	12.92	0.14	25.49	2.56	6.06	0.29	22.32	28.77	0.16	14.47	4.64	0.93	0.10	21.90	**IT**
KZ	0.12	1.47	0.62	16.67	0.90	0.62	3.43	1.15	0.50	2.59	0.97	2.82	1.08	0.69	0.62	1.78	**KZ**
LT	0.04	0.01	1.22	0.10	0.74	1.07	0.65	9.14	0.76	1.92	0.02	9.05	3.03	5.98	1.64	1.34	**LT**
LU	0.001	0.00	0.05	0.00	0.01	3.45	0.01	0.00	0.23	0.02	0.00	0.13	1.57	0.09	0.00	0.41	**LU**
LV	0.03	0.01	0.82	0.11	0.58	1.05	0.52	4.13	0.62	1.47	0.02	5.81	2.65	5.75	5.34	1.14	**LV**
MC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.002	**MC**
MD	0.09	0.02	0.25	0.12	0.81	0.17	5.53	0.57	0.15	2.86	0.08	1.47	0.36	0.24	0.10	0.55	**MD**
MK	4.22	0.01	0.31	0.03	2.11	0.11	14.24	0.05	0.20	37.83	0.03	1.03	0.22	0.09	0.01	0.89	**MK**
MT	0.00	0.00	0.00	0.00	0.005	0.001	0.003	0.00	0.001	0.006	0.00	0.002	0.00	0.00	0.00	0.008	**MT**
NL	0.01	0.001	0.34	0.00	0.09	58.00	0.06	0.05	0.83	0.20	0.003	1.71	24.20	2.41	0.04	3.29	**NL**
NO	0.04	0.01	1.55	0.07	0.49	8.90	0.63	0.68	2.04	1.38	0.02	10.81	11.74	30.65	0.89	8.06	**NO**
PL	0.22	0.02	13.79	0.14	6.00	10.21	3.58	19.90	6.37	19.03	0.08	289.4	65.25	38.69	1.75	9.50	**PL**
PT	0.00	0.00	0.03	0.00	0.03	0.26	0.02	0.00	0.11	0.05	0.00	0.05	0.13	0.06	0.00	49.80	**PT**
RO	1.64	0.12	6.63	0.72	25.89	1.89	78.89	2.00	2.20	131.6	0.31	30.27	4.68	2.20	0.52	5.96	**RO**
RU	1.69	10.09	11.91	89.36	15.42	13.37	40.66	78.67	9.60	43.02	10.64	67.01	26.31	32.85	141.1	28.05	**RU**
SE	0.05	0.02	1.87	0.12	0.58	9.69	0.87	1.88	2.55	1.82	0.03	16.71	18.37	99.11	3.58	7.89	**SE**
SI	0.13	0.00	11.52	0.01	4.72	0.38	0.86	0.07	0.79	9.32	0.01	5.83	0.92	0.19	0.02	1.21	**SI**
SK	0.15	0.01	8.87	0.03	5.56	1.08	1.74	0.58	1.22	18.93	0.02	79.19	3.22	1.55	0.14	1.42	**SK**
TR	1.19	9.23	1.87	6.14	5.15	1.15	51.13	1.23	1.61	16.72	53.95	6.60	2.08	0.94	0.39	8.20	**TR**
UA	0.96	0.75	5.86	4.37	11.98	3.85	39.79	22.85	3.01	40.77	2.29	38.75	8.72	6.62	2.75	7.91	**UA**
BAS	0.05	0.02	2.85	0.16	0.90	11.38	0.99	4.29	3.41	2.52	0.04	27.53	30.52	148.1	26.37	8.71	**BAS**
BLS	0.62	0.91	1.41	3.32	3.58	0.82	54.84	1.87	0.98	13.94	5.18	6.19	1.74	1.08	0.48	3.42	**BLS**
CAS	0.08	2.73	0.25	81.51	0.47	0.23	1.65	0.33	0.23	1.31	1.78	0.91	0.37	0.21	0.15	0.89	**CAS**
MDT	17.23	0.23	11.56	0.78	51.55	4.66	78.44	0.69	12.94	65.52	156.6	20.15	7.00	2.39	0.26	255.2	**MDT**
NOS	0.07	0.02	3.66	0.10	0.95	73.72	1.00	0.75	6.75	2.44	0.05	21.55	54.10	82.00	0.90	46.72	**NOS**
	AL	**AM**	**AT**	**AZ**	**BA**	**BE**	**BG**	**BY**	**CH**	**CS**	**CY**	**CZ**	**DE**	**DK**	**EE**	**ES**	

***Table D.4**. Matrix of mercury country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors ↓ Emitters ⟶

	FI	FR	GB	GE	GR	HR	HU	IE	IS	IT	KZ	LT	LU	LV	MC	
AL	0.01	1.56	0.37	0.01	34.58	0.89	2.00	0.02	0.001	14.61	0.43	0.02	0.02	0.00	0.03	**AL**
AM	0.01	0.16	0.07	2.67	1.52	0.03	0.13	0.00	0.00	0.44	8.44	0.01	0.00	0.00	0.00	**AM**
AT	0.08	25.27	9.55	0.01	3.05	4.97	41.49	0.32	0.007	62.28	0.67	0.22	1.66	0.02	0.23	**AT**
AZ	0.03	0.42	0.22	6.08	3.38	0.07	0.32	0.01	0.002	1.05	60.89	0.03	0.01	0.00	0.01	**AZ**
BE	0.04	5.51	1.83	0.01	13.23	22.13	45.42	0.07	0.004	33.67	0.46	0.11	0.15	0.01	0.12	**BE**
BG	0.02	169.3	31.78	0.00	0.20	0.07	0.27	0.59	0.003	1.75	0.04	0.07	10.85	0.01	0.02	**BG**
BA	0.10	3.77	1.61	0.16	107.6	1.55	14.75	0.07	0.006	14.16	5.88	0.20	0.11	0.03	0.06	**BA**
BY	1.12	7.39	6.55	0.22	9.68	1.29	17.40	0.24	0.02	8.87	10.84	10.52	0.35	1.15	0.05	**BY**
CH	0.02	53.14	7.80	0.00	0.74	0.54	1.23	0.31	0.003	64.86	0.17	0.03	1.12	0.00	0.31	**CH**
CS	0.07	5.57	2.29	0.03	27.30	9.19	82.00	0.09	0.01	32.15	1.04	0.18	0.18	0.02	0.10	**CS**
CY	0.00	0.06	0.02	0.01	2.71	0.02	0.06	0.00	0.00	0.23	0.10	0.00	0.00	0.00	0.00	**CY**
CZ	0.10	15.23	8.82	0.01	1.02	1.66	35.16	0.26	0.01	11.07	0.61	0.38	1.04	0.04	0.06	**CZ**
DE	0.43	309.0	121.77	0.03	2.48	1.33	12.90	3.06	0.04	30.88	1.34	1.71	38.62	0.20	0.27	**DE**
DK	0.10	11.47	17.96	0.00	0.12	0.04	0.50	0.49	0.004	0.70	0.11	0.33	0.38	0.04	0.01	**DK**
ES	2.00	2.14	3.09	0.01	0.30	0.07	0.87	0.11	0.004	0.77	0.75	5.02	0.10	1.85	0.01	**ES**
EE	0.05	48.79	17.81	0.00	1.27	0.55	0.77	1.19	0.01	13.82	0.13	0.09	0.66	0.01	0.13	**EE**
FI	**114.1**	10.34	12.79	0.04	1.39	0.25	4.22	0.54	0.03	3.48	2.30	5.57	0.45	1.08	0.03	**FI**
FR	0.20	**2078.6**	186.1	0.02	5.77	3.18	4.94	5.88	0.04	124.6	0.60	0.45	36.42	0.06	7.40	**FR**
GB	0.11	80.68	**1340.9**	0.00	0.42	0.14	0.74	23.16	0.03	2.69	0.14	0.14	1.65	0.02	0.03	**GB**
GE	0.03	0.73	0.43	**58.36**	5.98	0.12	0.76	0.02	0.002	1.72	19.70	0.04	0.02	0.01	0.01	**GE**
GR	0.06	3.70	1.23	0.09	**1947.8**	1.39	5.52	0.06	0.005	18.36	4.03	0.10	0.08	0.01	0.06	**GR**
HR	0.04	5.52	1.51	0.01	8.72	**86.62**	73.67	0.06	0.003	44.27	0.33	0.10	0.15	0.01	0.14	**HR**
HU	0.09	6.13	2.78	0.02	5.97	15.43	**903.0**	0.09	0.005	27.09	0.51	0.29	0.25	0.03	0.11	**HU**
IE	0.01	8.41	29.66	0.00	0.06	0.01	0.04	**51.58**	0.01	0.32	0.02	0.01	0.15	0.00	0.00	**IE**
IS	0.05	1.11	2.14	0.00	0.16	0.01	0.05	0.24	**0.06**	0.33	0.07	0.03	0.04	0.00	0.00	**IS**
IT	0.11	53.01	7.00	0.04	52.04	25.42	21.35	0.32	0.01	**1595.1**	2.07	0.17	0.74	0.02	4.11	**IT**
KZ	0.33	2.61	2.11	2.26	7.29	0.32	2.88	0.10	0.01	3.61	**917.7**	0.39	0.11	0.06	0.02	**KZ**
LT	0.58	3.78	3.66	0.02	0.98	0.31	3.62	0.14	0.01	2.80	1.52	**46.60**	0.18	1.68	0.02	**LT**
LU	0.00	8.28	1.47	0.00	0.02	0.01	0.03	0.04	0.00	0.23	0.00	0.01	**19.06**	0.00	0.00	**LU**
LV	1.02	3.48	4.19	0.03	0.68	0.22	2.30	0.16	0.01	2.13	2.02	52.72	0.17	**8.91**	0.01	**LV**
MC	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	**0.03**	**MC**
MD	0.05	0.79	0.49	0.06	6.03	0.21	2.43	0.02	0.002	1.91	2.21	0.16	0.03	0.02	0.01	**MD**
MK	0.01	1.05	0.34	0.01	74.57	0.53	2.79	0.02	0.001	6.23	0.52	0.03	0.02	0.00	0.02	**MK**
MT	0.00	0.01	0.002	0.00	0.07	0.002	0.003	0.00	0.00	0.07	0.001	0.00	0.00	0.00	0.00	**MT**
NL	0.03	57.52	34.09	0.002	0.15	0.05	0.32	0.63	0.004	1.08	0.06	0.10	1.15	0.01	0.01	**NL**
NO	1.97	26.98	66.52	0.02	1.08	0.20	2.51	2.88	0.05	3.33	1.14	1.08	1.08	0.14	0.03	**NO**
PL	0.98	33.15	25.76	0.05	5.60	3.51	61.00	0.82	0.03	21.46	2.15	8.02	1.73	0.67	0.12	**PL**
PT	0.00	2.45	1.36	0.00	0.05	0.02	0.04	0.12	0.002	0.49	0.01	0.01	0.04	0.00	0.00	**PT**
RO	0.31	9.92	5.12	0.29	51.77	6.74	126.3	0.20	0.02	35.36	11.15	0.79	0.36	0.10	0.14	**RO**
RU	33.86	52.12	54.20	25.99	97.00	5.26	50.71	2.29	0.24	56.89	1543.9	25.41	2.21	4.67	0.32	**RU**
SK	24.94	28.23	43.35	0.03	1.48	0.24	4.29	1.56	0.05	4.29	2.01	4.81	1.37	0.64	0.04	**SK**
SI	0.02	2.94	0.79	0.00	1.86	13.10	14.29	0.03	0.001	41.02	0.23	0.04	0.10	0.00	0.08	**SI**
SE	0.09	4.17	2.60	0.01	3.08	3.26	173.0	0.08	0.004	10.90	0.49	0.33	0.22	0.04	0.04	**SE**
TR	0.27	7.80	3.59	4.50	230.6	1.72	10.56	0.16	0.02	24.68	37.27	0.42	0.22	0.05	0.11	**TR**
UA	1.16	14.97	11.07	2.06	65.02	4.01	72.06	0.41	0.04	28.07	100.7	4.36	0.68	0.52	0.13	**UA**
BAS	29.58	33.42	38.78	0.04	1.63	0.40	6.06	1.27	0.03	5.90	3.06	22.63	1.61	5.70	0.05	**BAS**
BLS	0.27	4.34	2.87	6.06	93.88	1.10	9.51	0.12	0.01	13.15	71.70	0.57	0.15	0.08	0.06	**BLS**
CAS	0.08	1.10	0.83	3.49	5.50	0.16	1.04	0.04	0.005	2.26	1629.5	0.12	0.04	0.02	0.01	**CAS**
MDT	0.27	162.86	18.45	0.38	1456.7	42.66	28.95	0.83	0.04	761.6	10.86	0.40	1.10	0.05	3.28	**MDT**
NOS	0.81	261.4	735.6	0.04	2.03	0.57	4.48	16.63	0.09	9.93	1.58	1.34	4.63	0.16	0.11	**NOS**
	FI	**FR**	**GB**	**GE**	**GR**	**HR**	**HU**	**IE**	**IS**	**IT**	**KZ**	**LT**	**LU**	**LV**	**MC**	

***Table D.4**. Matrix of mercury country-to-country depositions from anthropogenic sources in 2005, kg/y (continued)*

Receptors ↓ Emitters →

	MD	**MK**	**MT**	**NL**	**NO**	**PL**	**PT**	**RO**	**RU**	**SE**	**SI**	**SK**	**TR**	**UA**	**Total**	
AL	0.06	32.12	0.003	0.07	0.02	2.87	0.12	1.90	0.46	0.02	0.29	1.08	2.30	0.92	**167.7**	**AL**
AM	0.02	0.17	0.002	0.01	0.01	0.46	0.03	0.24	0.80	0.01	0.03	0.09	28.31	0.46	**83.9**	**AM**
AT	0.15	0.98	0.02	3.50	0.25	90.27	0.63	5.96	1.43	0.17	17.03	34.04	2.89	3.68	**620.1**	**AT**
AZ	0.04	0.40	0.01	0.04	0.02	1.22	0.07	0.55	4.67	0.02	0.06	0.22	29.14	1.54	**274.1**	**AZ**
BA	0.12	3.71	0.01	0.52	0.09	32.63	0.35	9.79	0.76	0.09	3.36	14.33	3.72	2.72	**693.8**	**BE**
BE	0.01	0.04	0.01	26.07	0.12	3.39	0.46	0.13	0.13	0.07	0.09	0.20	0.24	0.13	**510.6**	**BG**
BG	2.57	29.50	0.02	0.43	0.10	24.82	0.42	100.6	11.15	0.12	1.02	8.83	74.67	26.80	**1165.0**	**BA**
BY	1.58	2.47	0.09	2.09	0.82	294.2	0.55	17.08	62.37	1.34	1.38	20.02	12.99	69.76	**775.3**	**BY**
CH	0.02	0.14	0.01	1.65	0.07	6.48	0.57	0.46	0.37	0.04	0.96	0.75	0.45	0.50	**317.0**	**CH**
CS	0.44	41.90	0.02	0.65	0.13	46.79	0.42	47.39	2.05	0.13	3.01	28.06	9.77	7.10	**1485.2**	**CS**
CY	0.01	0.12	0.00	0.004	0.002	0.15	0.01	0.11	0.09	0.002	0.01	0.04	12.67	0.12	**76.9**	**CY**
CZ	0.12	0.38	0.02	4.57	0.40	361.3	0.36	5.24	1.65	0.31	2.77	44.36	1.58	3.46	**1272.5**	**CZ**
DE	0.17	0.66	0.12	153.77	2.36	236.7	3.09	4.20	4.22	1.66	2.23	11.69	3.43	4.99	**1991.7**	**DE**
DK	0.01	0.03	0.02	5.69	0.89	18.92	0.33	0.18	0.59	1.25	0.05	0.64	0.14	0.39	**204.3**	**DK**
EE	0.04	0.08	0.03	0.74	0.53	28.57	0.12	0.90	9.64	1.23	0.12	1.18	0.45	2.18	**109.0**	**ES**
ES	0.01	0.34	0.03	1.88	0.14	3.89	80.26	0.35	0.32	0.09	0.62	0.45	0.42	0.30	**1469.8**	**EE**
FI	0.15	0.34	0.44	2.90	4.77	96.24	0.44	3.93	32.31	17.50	0.40	5.46	2.34	7.42	**392.2**	**FI**
FR	0.09	1.40	0.09	29.08	0.72	30.77	13.04	2.20	1.70	0.45	3.86	3.07	2.74	1.97	**2992.1**	**FR**
GB	0.01	0.09	0.08	14.98	0.66	11.40	3.87	0.31	0.42	0.26	0.18	0.58	0.52	0.31	**1543.1**	**GB**
GE	0.16	0.60	0.01	0.08	0.03	3.05	0.11	1.69	6.77	0.03	0.11	0.57	86.99	4.56	**237.3**	**GE**
GR	0.56	73.61	0.01	0.25	0.06	10.42	0.33	13.02	3.81	0.07	0.68	3.08	85.78	7.85	**2313.9**	**GR**
HR	0.10	2.10	0.01	0.45	0.07	33.04	0.29	9.32	0.63	0.07	14.38	19.34	3.32	2.39	**439.1**	**HR**
HU	0.26	2.99	0.02	0.90	0.14	95.50	0.30	46.04	1.70	0.16	8.39	283.2	4.40	9.60	**1583.8**	**HU**
IE	0.00	0.01	0.02	0.68	0.06	0.59	1.07	0.03	0.05	0.02	0.01	0.04	0.05	0.03	**99.4**	**IE**
IS	0.00	0.02	0.17	0.17	0.22	1.12	0.47	0.04	0.18	0.11	0.02	0.04	0.33	0.10	**10.4**	**IS**
IT	0.24	8.72	0.04	1.56	0.18	37.91	1.72	7.42	2.30	0.16	35.30	11.13	9.94	4.53	**2026.8**	**IT**
KZ	0.66	1.34	0.07	0.44	0.21	17.23	0.32	6.41	168.2	0.27	0.34	2.56	33.20	32.65	**1239.6**	**KZ**
LT	0.14	0.31	0.03	1.14	0.53	118.7	0.21	2.79	13.60	0.99	0.48	4.39	1.42	6.55	**253.9**	**LT**
LU	0.001	0.004	0.001	0.71	0.01	0.34	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.01	**36.3**	**LU**
LV	0.12	0.23	0.04	1.19	0.63	64.22	0.19	2.22	12.60	1.34	0.32	2.79	1.20	5.20	**200.4**	**LV**
MC	0.00	0.00	0.00	0.00	0.00	0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.1**	**MC**
MD	35.49	1.03	0.01	0.14	0.04	14.86	0.07	23.40	6.11	0.06	0.16	2.20	10.85	31.96	**154.2**	**MD**
MK	0.10	282.9	0.00	0.08	0.02	3.81	0.10	3.54	0.63	0.02	0.25	1.58	3.96	1.40	**445.9**	**MK**
MT	0.00	0.004	0.00	0.00	0.00	0.006	0.00	0.002	0.001	0.00	0.001	0.002	0.02	0.00	**0.2**	**MT**
NL	0.01	0.04	0.01	158.8	0.22	5.59	0.38	0.12	0.18	0.11	0.07	0.28	0.18	0.18	**352.6**	**NL**
NO	0.08	0.29	77.12	9.18	93.77	49.55	1.24	1.52	4.60	4.94	0.27	2.60	1.46	2.49	**436.1**	**NO**
PL	0.64	1.74	0.12	11.38	2.38	5407.8	1.47	21.48	18.98	3.25	5.16	102.7	5.53	39.91	**6271.6**	**PL**
PT	0.00	0.01	0.00	0.14	0.01	0.20	487.2	0.02	0.02	0.01	0.02	0.03	0.03	0.02	**542.9**	**PT**
RO	12.23	18.54	0.05	1.51	0.33	140.5	0.81	1032.9	24.51	0.40	4.31	71.02	56.00	94.13	**2001.4**	**RO**
RU	7.42	17.71	3.93	11.72	9.65	548.1	4.74	76.26	5174.8	16.14	5.56	52.31	473.2	519.6	**9495.8**	**RU**
SE	0.20	0.42	0.40	10.58	26.17	127.0	1.40	2.96	13.50	94.88	0.37	4.77	2.37	6.26	**573.8**	**SK**
SI	0.04	0.58	0.00	0.26	0.03	13.07	0.13	2.39	0.35	0.03	104.0	6.39	1.02	1.01	**239.8**	**SI**
SK	0.16	1.11	0.01	0.96	0.16	247.2	0.19	16.41	1.60	0.18	3.47	428.3	1.85	7.46	**1031.2**	**SE**
TR	2.40	12.31	0.07	0.75	0.25	33.01	1.09	34.62	34.00	0.27	1.39	7.49	4474.4	47.96	**5139.5**	**TR**
UA	27.61	10.74	0.17	3.33	1.02	522.2	1.24	118.0	250.6	1.38	3.47	92.20	171.9	1723.9	**3434.2**	**UA**
BAS	0.20	0.45	0.17	13.79	5.94	303.1	1.40	4.55	29.46	36.16	0.70	8.17	2.44	9.58	**834.2**	**BAS**
BLS	8.75	8.23	0.05	0.68	0.22	42.91	0.47	61.73	85.15	0.26	0.97	8.08	592.0	160.2	**1274.0**	**BLS**
CAS	0.20	0.83	0.02	0.15	0.07	5.18	0.16	2.31	31.26	0.08	0.16	0.82	36.43	10.00	**1824.9**	**CAS**
MDT	1.19	46.36	0.12	3.09	0.57	56.00	6.39	28.86	10.74	0.42	22.87	16.71	663.7	19.37	**4050.1**	**MDT**
NOS	0.10	0.50	0.45	104.6	19.57	81.52	6.99	2.00	3.68	4.76	0.82	4.43	3.02	2.82	**1569.4**	**NOS**
	MD	**MK**	**MT**	**NL**	**NO**	**PL**	**PT**	**RO**	**RU**	**SE**	**SI**	**SK**	**TR**	**UA**	**Total**	

MINUTES of the Joint MSC-West and MSC-East technical meeting (1-2 February 2007)

The meeting was attended by Anna Benedictow, Jan Eiof Jonson, Leonor Tarrasón and Svetlana Tsyro from MSC-West and by Sergey Dutchak, Alexey Gusev, Ilia Ilyin, Oleg Travnikov and Marina Varygina from MSC-East.

The aim of the meeting was the discussion and harmonization of EMEP Centres activities in the field of the development of hemispheric/global modelling, preprocessing of meteorological data, model description of dust suspension and preparation of emission data for model runs.

Another important topic for the meeting was consideration of a possible assistance of the EMEP Centres to EECCA countries in raising the capacity of air quality management within the institutions in these countries and in implementing selected LRTAP Convention protocols.

These minutes of the meeting include:

1) Short summary of the discussions
2) Annex EI: Agenda of the meeting
3) Annex EII: Proposal for the development of a common EMEP global modeling system
4) Annex EIII: Proposal for transboundary pollution calculations for EECCA countries

The proposals in Annex EII and Annex EIII are to be presented at the forthcoming EMEP Bureau meeting on 26-28 March for consideration and evaluation by the EMEP Bureau members.

Short summary of the discussions

Hemispheric/global modelling

The meeting participants considered in depth possibilities for further streamlining the work at both modelling Centres with regard to hemispheric/global modeling. MSC-E and MSC-W discussed experience in approaches to hemispheric/global modeling currently used by the Centres.

It was recognized that specially for ozone, mercury, and some POPs, there is a clear need to consider their transport at the global scale rather than on hemispheric scale. Application of hemispheric modelling approach leads to the uncertainties in the description of pollution levels near the equator due to necessity of definition of boundary conditions. This is particularly important for the Southeast Asia which growing economic development and increase of emission levels in recent years makes it an important source of pollution for other regions of the globe. For long-lived components, like mercury, the inter-hemispheric exchange of pollution becomes relevant and even for ozone, convection in the Tropics becomes relevant process to take into account for an accurate description of the pollution levels in the free troposphere. For POPs which require the description of pollutant transport within seawater it is also of importance to include southern Atlantic in the model domain. Furthermore, the vertical extension of a global model needs also to be increased in order to take into account troposphere-stratosphere exchange.

With the growing importance of intercontinental pollution transport, the meeting agreed that the development of hemispheric scale models in EMEP is not satisfactory and recommended the extension of the modeling domain to cover global scale.

MSC-W and MSC-E discussed possible ways of streamlining of hemispheric/global model development. It was recognized that there could be three different options of the development of common hemispheric/global modelling system. One of them implies the joint development of such a single modelling system from the beginning. This option could the most fully fit EMEP needs but it is likely very time- and resource consuming. Additional drawback is that this system as a new one will require thorough validation. The second possible option is the adaptation of a hemispheric/global model already developed outside the EMEP. This is possibly the easiest way that, however, also contains some negative aspects. First, one can hardly expect that an external model will completely fit the needs of EMEP modelling or will not require significant modifications. Second, updates and development of such a model could be connected with undesirable dependence on the “third party”. Additionally, such model should be well recognized by the community, validated, and efficient enough to permit operative computations of transboundary fluxes of acidifying pollutants, photooxidants, HMs, and POPs. The third option is gradual unification of the existing MSC-E and MSC-W hemispheric/global approaches starting from unification of the model geometry, meteorological drivers and input information. It was agreed to recommend this option as most appropriate and realistic, as it does not neglect existing EMEP modelling systems.

Following this discussion, a work plan was defined to allow for the gradual unification of MSC-E and MSC-W models and elaboration of the common modular system for modelling of different pollutants on global level. The summarized draft work-plan of elaboration of common unified modelling system for global scale is given in Annex EII. MSC-E and MSC-W have agreed to implement some of these practical steps in 2008 and reflect this activity in their work-plans for 2008.

Computation of transboundary pollution of the EECCA countries

In order to support EECCA countries with information required for air quality management in these countries and implementation of the selected LRTAP Convention protocols MSC-E and MSC-W considered possibility to include these countries into EMEP routine calculations of pollution levels and transboundary fluxes.

A long-term perspective solution of this task implies application of the hemispheric/global model with fine enough spatial resolution or possibility of nesting. An interim solution could include combination of the available EMEP regional and hemispheric models. For this aim the current EMEP 50x50 km grid should be extended eastward to cover EECCA countries and the hemispheric model is to be used for calculation of boundary conditions for this region. As an interim solution, the regional EMEP model could be applied for routine calculations of transboundary pollution on this extended area. For the future, an in-depth reconsideration of the EMEP grid domain, projection and resolution is required. A draft of the suggested interim extensions of the EMEP grid is presented in Annex EIII. MSC-E and MSC-W have agreed to implement calculations of transboundary fluxes in the interim extended EMEP grid in their routine calculations starting from 2008.

Dust suspension

MSC-W and MSC-E discussed modeling approaches to assessing wind suspension of dust from natural and agricultural surfaces applied by the Centres. The two centers presently use very similar parametrisation approaches for modeling of the dust suspension, especially after the last developments at MSC-E. Large uncertainties remain still on the requirements for information on soil types and their morphology and moisture. Additional efforts are also needed to compile observational data to validate the model estimates.

It was agreed to cooperate in order to improve the input information to the wind driven dust suspension modeling. It was agreed to start compiling a common input data for land use, extending it afterwards to include soil types and morphology and if possible also information on soil chemical composition. Efforts would also be addressed to compile available measurements for the validation purposes. This work should be carried out at global scale.

Taking into account the developing status of contemporary dust mobilization models and significant uncertainty of major input parameters it was recognized that final selection of the unified parameterization requires common efforts by MSC-E and MSC_W, with coordinated sensitivity studies and evaluation against measurements. A proposal for such research effort is to be included already in the work plan for EMEP in 2008 and supports the development of the unified global model as identified in Annex EII.

Preprocessing of meteorological data for regional modelling

MSC-E and MSC-W also discussed current activities and future plans on preparation of meteorological data for the regional-scale modeling. Both MSC-E and MSC-W gave overview of meteorological drivers used to prepare meteorological information for transport models. Both Centres use similar approaches for generation of meteorological data, but while MSC-E uses primarily MM5 data, MSC-W uses primarily HIRLAM data.

MSC-W shared its experience in adapting and testing different meteorological drivers (HIRLAM, ALADIN, WRF) and summarized their advantages and drawbacks. Plans for further MSC-W activities in preparation of meteorological data were presented including improvement of the operational set of meteorological input data, moving towards finer spatial resolution and developing meteorological data for national-scale applications.

MSC-E discussed possible approaches to quality control and validation of data produced by meteorological drivers as an input for transport models. It was agreed to share experience and harmonize approaches of MSC-E and MSC-W to quality control of meteorological data for the purposes of air pollution modelling.

MSC-E also presented ideas on evaluation of the effects of meteorological variability and climate change on modelled pollution levels. Their possible approaches to treat the meteorological variability in model calculations (e.g. assessment of future scenarios) included averaging of modeled pollution levels over long time period (decades); selecting of one or a few years based either on similarity of pollution levels in these years to the long-term average or on the meteorological statistics (atmospheric circulation indices, similarity of meteorological fields to climatic means etc.); adoption of a single meteorological year based on political principles (e.g. formulated in CLRTAP Protocols, EU directives etc). The Centers did not agree on a common position. Different approaches are valid and require further evaluation and discussion. Such discussion is especially relevant also for scenario analysis within EMEP for 2020 and beyond and the question on how EMEP should account for meteorological variability and climate change in the future.

Emission data

MSC-W presented an overview of the needs on emission related activities within EMEP, their status and need for changes. In particular, MSC-E and MSC-W discussed the need for emission data as input to atmospheric transport modeling. Both Centres agreed that the activities dedicated to the gap filling and the elaboration and review of gridded sector data for modeling need to be strengthened and coordinated, especially as we intend to extend the domain of the EMEP transboundary calculations and in future years, also increase the resolution of the model results.

Currently, MSC-E is dependent on gridded emission data from expert estimates. MSC-W has improved their methodology in the preparation of gridded emissions from ancillary information, but it is still far from satisfactory. Gridded sector official data reported by countries is still so sparse that further efforts are necessary in the elaboration of input emissions for modelling.

The extension of the modeling activities to global scale imposes additional requirements on the preparation of emission data. It is important to recognize the need for consistent, complete and accurate data in global scale to support the development of the EMEP global model. In some cases, this goes beyond the competence area of EMEP and experts estimates would have to be used instead. The meeting agreed to invite the EMEP Bureau to identify and share responsibilities with respect to expert estimates of emissions in relation to the Bureaus evaluation of a new organization of emission work under EMEP.

Additionally, the work planned at MSC-W on nested models, down to finer resolution scales imposes also new requirements on emission data. To what extent such requirements should be extended also to the official reported data is a matter for discussion first by the EMEP Bureau, and eventually also by the EMEP Steering Body.

Annex EI. Agenda of Joint MSC-W/MSC-E meeting

The aim of the meeting is harmonization of the MSC-W and MSC-E activities in the field of global/hemispheric modeling, meteorology, dust suspension, and emissions

Thursday, 1 February

9.00 Hemispheric/global modeling

- Approaches to hemispheric/global modeling (concepts of the hemispheric/global transport model considered in MSC-W and MSC-E)
- Unification of input data (meteorological data, preprocessing, land-use, LAI, soil properties etc.)
- Unification of hemispheric/global model parameters from the point of view of output results (coverage, spatial resolution, nesting etc.)

(Alexey Gusev, Jan Eiof Jonson)

11.00 Coffee break

11.15 Continuation of hemispheric/global modeling topic.

Discussion of approaches for the evaluation of source-receptor relationships for EECCA countries

(*Leonor Tarrason, Ilia Ilyin*)

13.00 **Lunch**

14.00 Preparation of a draft common discussion paper on hemispheric/global issues that should be considered at the next EMEP SB Bureau meeting in March 2007

15.45 Coffee break

16.00 Dust suspension

- Approaches to parameterization of wind suspension in air quality models (possibility of harmonization of dust mobilization schemes)
- Unification of input data on (soil size distribution, clay content etc.)

(*Oleg Travnikov, Svetlana Tsyro*)

18.00 Adjourn

Friday, 2 February

9.00 Meteorology

- Preprocessing of meteorological data for regional modeling (pre-processor, data assimilation, technical questions about the use of ECMWF data) in both Centres
- Validation procedure and quality control of the output of meteorological data (meteorology criteria)
- Effects of meteorological variability on assessment of pollution levels. How to harmonize these effects when evaluating effectiveness of long-term emission reduction measures and future pollution scenarios
- Effects on climate change on pollution transport and depositions

(*Leonor Tarrason, Anna Benedictow, Ilia Ilyin*)

10.30 Coffee break

10.45 Continuation of the discussion on meteorological issues

12.45 **Lunch**

13.40 Emissions

- Further development of the emission database (two options proposed by the meeting of the Core Bureau of the EMEP Steering Body)
- Emission data preparation for model runs, as a work-element of item “Modelling” of EMEP work-plan for 2007
- Emission compilation at finer spatial resolution then the present 50x50km.

(*Leonor Tarrason, Oleg Travnikov*)

14.40 The end of the meeting and departure.

Annex EII. PROPOSAL “Draft work-plan of agreed activities on streamlining the development of common global modeling system within EMEP”

This appendix responds to the invitation of the EMEP core Bureau from November 2006 for the EMEP chemical modelling centers to discuss the possibilities for further streamlining the work at MSC-E and MSC-W with respect to hemispheric/global modelling.

MSC-E and MSC-W welcome the recommendation from the EMEP Bureau to consider the development of a common global modelling framework that includes traditional main pollutants, particulate matter, heavy metals and POPs.

The main reason to develop a global modelling system is that many of the pollutants considered within EMEP undergo significant intercontinental transport. The increased importance of intercontinental transport and the existence of significant pollution sources in areas susceptible for inter-hemispheric transport, advise the extension of hemispheric approaches to use of global scale models instead.

After considering different alternatives for the development of such global system, the Centres recommend to streamline the existing parallel hemispheric model developments both at MSC-E and MSC-W towards a common global development. Synergies with other (global) modelling groups should be used under way, but a main focus for the next 3-5 years would be to strengthen the cooperation between the two EMEP chemical transport modelling centers.

A stepwise approach, involving the present capabilities at both centers, is suggested in the following tasks and is summarized in Table E1:

1. Unification of geographical coverage and parameters of the model domains including type of projection, spatial resolution, type of the vertical coordinate, number of vertical layers etc.

2. Unification of the input data (land-use, leaf area index, soil properties), spatial distribution of common anthropogenic emission sources, climatological data (sea surface temperature, snow cover, etc.)

3. Unification of the meteorological drivers and driving meteorological input (e.g. ECMWF meteorological analysis data).

4. Harmonization and development of physical processes modules including atmospheric advection, eddy diffusion, convection, dry and wet deposition, dust suspension, troposphere-stratosphere exchange, etc. Application of common physical and chemical modules as far as possible.

5. Unification of modeling system code with possibility of plugging different pollutant specific modules (Unification of input/output routines, identification of subroutines which needs to be rewritten, integration of modular subroutines, paralellisation and support of different platforms).

The work involved in this harmonization is time and resource demanding but can be completed in a period of 5 years, without jeopardizing the operationality of the EMEP project and securing routine results from the EMEP centers during this period. To trace progress in this task, annual joint deliverables from MSC-W and MSC-E have been identified in Table E1.

Task 1 on the unification of the physical domain of the model can be completed already in 2007. For 2008, work should be addressed both to Task 2 and Task 3 on the unification of input data and meteorological drivers.

In 2008, we expect to be able to identify an agreed input dataset for land use, soil properties, emission data, and climatological properties. These tasks have been assigned between MSC-E and MSC-W as expressed in Table E1.

Work for the unification of meteorological drivers needs to begin as soon as possible, in order to ensure an informed decision in 2009. The requirements for the selected meteorological drivers are as follow: a) the system should be capable to provide necessary set of parameters for the global scale, b) should be flexible enough to permit usage of different input data and c) should generate meteorological information with different spatial resolution (2.5˚x2.5˚, 1˚x1˚, etc.). Along with that additional features like data assimilation, nesting capabilities, availability of source code and support, possibility of selection of different parameterizations of physical processes are also considered important. Above all, the meteorological data should be easily accessible for both Centers. It is proposed that MSC-E and MSC-W will investigate possibilities of four different candidate meteorological drivers. The drivers to be implemented and tested by MSC-E are GEM from Environment Canada and PUM from the UK Met Office. The drivers to be tested by MSC-W are the IFS at ECMWF and the hemispheric WRF from US EPA. Experience on the use of these drivers is to be compiled for two years and then inform a common decision on which system should be used by the two modelling centres.

It is proposed to initiate the harmonization of physical and chemical modules and numerical techniques through a common development of an improved parametrisation of dust suspension. The work is to be initiated in 2008 with the compilation of information on soil properties and the compilation of observational data for model validation. The work is to be finalized in 2009, with a common report on an improved and validated common methodology for modelling soil emissions, tested both for HM and PM.

Further harmonization of physical processes modules and unification of common modelling system code, should proceed from 2009. MSC-E and MSC-W are willing to continue this work and coordinate their work plans up to 2012 when the common global modelling system should be fully tested and implemented.

Table E1. *Proposed work plan for the development of a common EMEP global model*

Activity	**Deliverable**	**Period**
Unification of input data ***Land-use*** – MSC-W will compile the global 0.1° x 0.1° land use from MM5 consistent as much as possible with the EMEP land-use – MSC-E will identify independent land-use sources and compare these sets if appropriate	Agreed land-use dataset	2008
Soil properties – MSC-E will start compile the global data on soil properties – MSC-W and MSC-E will start to compile soil chemical composition data for European region for validation purposes, if possible, for calcium, HMs, silicates, iron, and aluminum	Agreed soil properties dataset	2008
Other input data – Leaf area index (LAI) – Climatological data (sea surface temperature, snow cover etc.) – Spatial distribution of emission sources and population	Agreed datasets on LAI, climatological data, spatial distribution of emissions, population	2008
Unification of the meteorological driver – Common evaluation of meteorological drivers and processed meteorological data for modelling by both Centres – MSC-E will implement GEM and PUM meteorological weather prediction models – MSC-W will implement ECMWF IFS and WRF meteorological weather prediction models	Joint report on the comparison of meteorological drivers; decision for unification	2009
Harmonization of physical and chemical modules and numerical techniques – Parametrisation of dust suspension (sensitivity and validation) – Atmospheric transport (advection, diffusion, convection) – Dry and wet deposition – Troposphere-stratosphere exchange – Transpolar transport – Mass conservation filters	Joint report on improved and verified soil resuspension Agreed procedures to include parameterizations of common physical processes; agreed numerical techniques	2009
Unification of common modelling system code – Unification of input/output routines and formats – Identification of subroutines which needs to be rewritten – Integration of modular subroutines – Parallelization and support of different platforms	Common global modelling system	2010 - 2012

Annex EIII. PROPOSAL
Extension of the EMEP grid to include EECCA countries

The extension of the geographical scope of EMEP in order to include Eastern Europe, Caucasus and Central Asian countries has become an important priority within the Convention. At the Steering Body session in 2006, representatives from Central Asian countries that are Parties to the CLRTAP raised the question as to when the operational EMEP results on transboundary fluxes could be presented also for Central Asian countries.

This appendix considers the requirements on the extension of the EMEP grid in order to include EECCA countries in the routine EMEP model calculations. The goal is that EECCA countries should receive information on transboundary fluxes with the same level of accuracy as other EMEP countries. A two-step approach is proposed here.

Step 1: Extension of the existing EMEP grid to the East

A first step solution could include combination of the available EMEP regional and hemispheric models. For this aim the current EMEP 50x50 km^2 grid should be extended eastward to cover EECCA countries and the hemispheric model is to be used for calculation of boundary conditions for this region. As an interim solution, the regional EMEP model could be applied for routine calculations of trasboundary pollution on the extended area as tentatively indicated in Fig. C1. This solution has the advantage that it can be easily implemented. MSC-E and MSC-W would be willing to implement calculations of transboundary fluxes in the interim extended EMEP grid in their routine calculations starting from 2008. The main disadvantage is that important sources in Asia, India and the Middle East are outside the modelling domain, and only considered through boundary conditions to the hemispheric models.

Step 2: Future change of the EMEP grid projection to LONG-LAT

In the long-term, source-receptor analysis for EECCA countries should involve global simulations providing the boundary conditions to the EMEP regional domain. The development of the global model advocates for a change of projection of the EMEP grid. Instead of using the traditional polar stereographic projection, adequate for studies of transport to northern areas and the Arctic, it is proposed to change to geographical coordinates that support better global scale applications. For the future, by 2012, MSC-W proposes to change the projection of the EMEP grid to a longitude-latidude grid, with the regional domain covering a similar domain as in Step 1. A tentative extension and projection of the new EMEP domain is presented in Fig. C.2. It is at the moment an open question whether the resolution of the new EMEP calculations is still 50 x 50km^2 or if it should be more refined. MSC-Ws preference would be a finer resolution, down to 10 x 10km^2, but this is indeed a matter for future discussions.

The extension of the EMEP domain has consequences for the requirements on the compilation of official emissions. It has also consequences for the definition of the geographical scope of EMEP and the compliance with Protocols. An analysis of such consequences is beyond the purpose of this note. The EMEP Bureau is invited to consider the proposed changes in the EMEP domain, projection and resolution and forward a recommendation to the Steering Body on how to proceed further with the proposed changes in the EMEP grid.

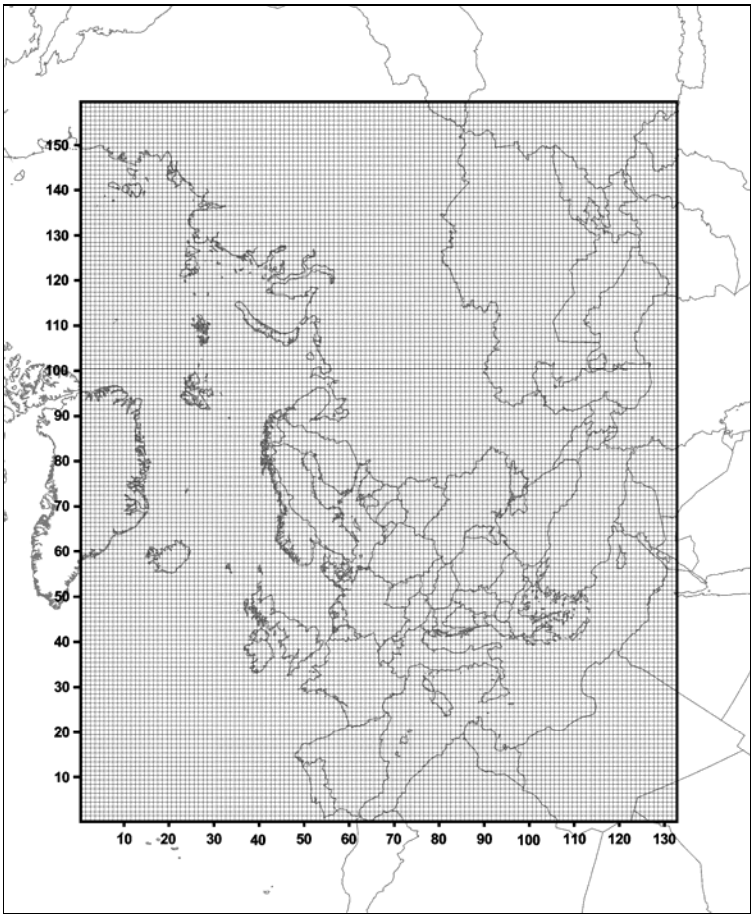


Fig. C1. *Extended EMEP 50×50 km grid (132×159 gridcells) suggested to include EECCA countries. (Step 1, operational from 2008)*

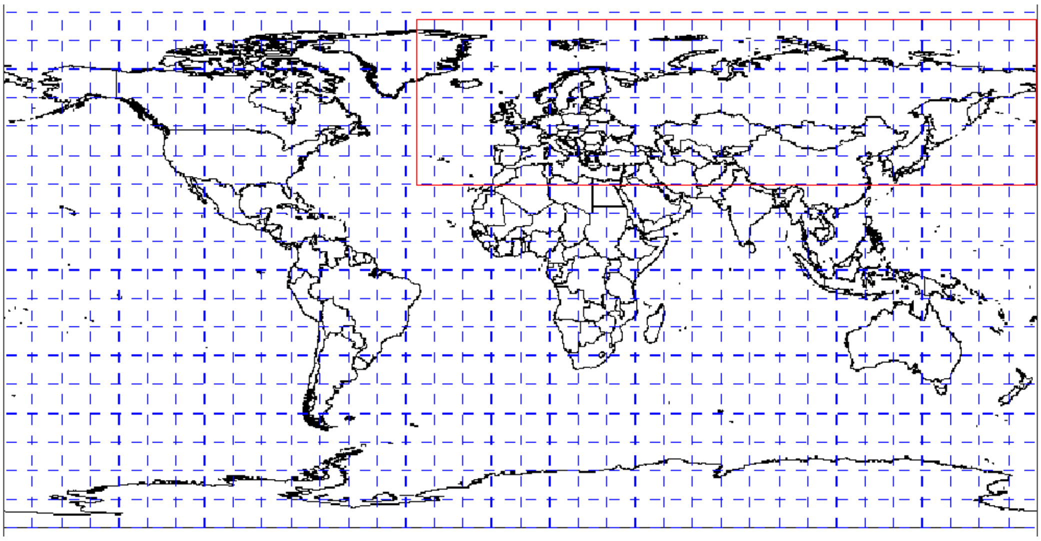


Fig. C2. *Tentative future EMEP grid in geographical LONG-LAT coordinates by 2012. The proposal in red is for the EMEP domain for routine calculations (extending from 40W, 180E - 25N, 90N). Both Centres agree that this is only a tentative proposal and needs to be further discussed*