Atmospheric deposition of Mercury on the Baltic Sea

HELCOM Baltic Sea Environment Fact Sheet (BSEFS), 2023

Authors: Ilia Ilyin, Olga Rozovskaya, Alexey Gusev, EMEP MSC-E

Key message

Levels of annual total atmospheric deposition of mercury to the Baltic Sea have decreased in period from 1990 to 2021 by 41%. The rate of decrease was almost uniform throughout the whole considered period.

Results and Assessment

Relevance of the BSEFS for describing developments in the environment

This BSEFS shows the levels and trends in mercury atmospheric deposition to the Baltic Sea. The deposition of mercury represents the pressure of the emission sources on the Baltic Sea aquatic environment as described in the BSEFS “Atmospheric emissions of mercury in the Baltic Sea region”.

Policy relevance and policy reference

The updated Baltic Sea Action Plan states the ecological objectives that concentrations of hazardous substances in the environment are to be close to background values for naturally occurring substances. HELCOM Recommendation 31E/1 identifies the list of regional priority substances for the Baltic Sea.

The relevant policy to the control of emissions of heavy metals to the atmosphere on European scale is set in the framework of UN ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). The CLRTAP Protocol on Heavy Metals (1998) targets three particularly harmful metals: cadmium, lead and mercury. According to one of the basic obligations emissions of these three metals must be reduced below the emission levels in 1990. The Protocol entered into force in 2003 and was signed and/or ratified by 41 countries.

Assessment

Model assessment of mercury long-range transport and deposition within the Baltic Sea region in period 1990-2021 was carried out taking into account anthropogenic emissions officially reported by HELCOM and other EMEP countries. In addition, natural and legacy emissions (re-emission) from terrestrial and seawater compartments were considered. Besides, fast re-emission of Hg deposited during Arctic Mercury Depletion Events (AMDEs) in high latitudes is also taken into account.

Model simulations indicate that atmospheric input of mercury to the Baltic Sea declined by 41% in the period from 1990 to 2021 (Figure 1, Table 1). The decline of Hg deposition in particular sub-basins ranged from 11% to 60% for the considered period (Figure 2). The strongest decline (60%) was noted for the Sound sub-basin. The lowest deposition decrease (11%) took place in the Bothnian Bay sub-basin.

The decline of mercury deposition to the Baltic Sea in the period 1990-2021 was almost uniform through the entire period and made up around 50 kg per year. Deposition trend in the considered period was analysed using Mann-Kendall test [*Gilbert*, 1987; *Connor et al*, 2012]. Mann-Kendall test reveals that the decreasing trend was significant at $\alpha = 0.05$.

Temporal variations of total mercury depositions are affected by changes of anthropogenic emissions of countries as well as changes of non-EMEP emissions. It should be noted also that only a fraction of mercury, emitted by the sources of particular country, deposits to the Baltic Sea. This fraction depends on the location of the country, speciation of Hg emissions and prevailing atmospheric transport pathways. In particular, the largest fraction of total national emissions, deposited to the Baltic Sea, is estimated for Denmark (14%) while the lowest one for Russia (about 0.1%).

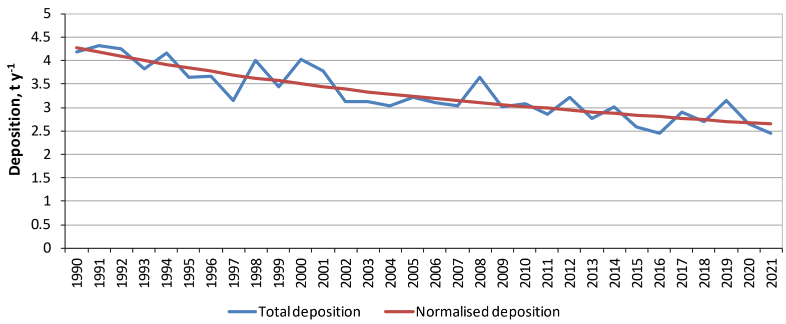
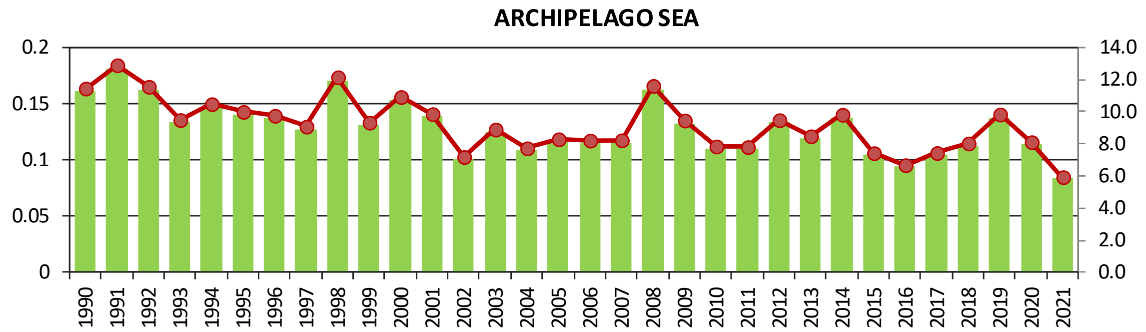
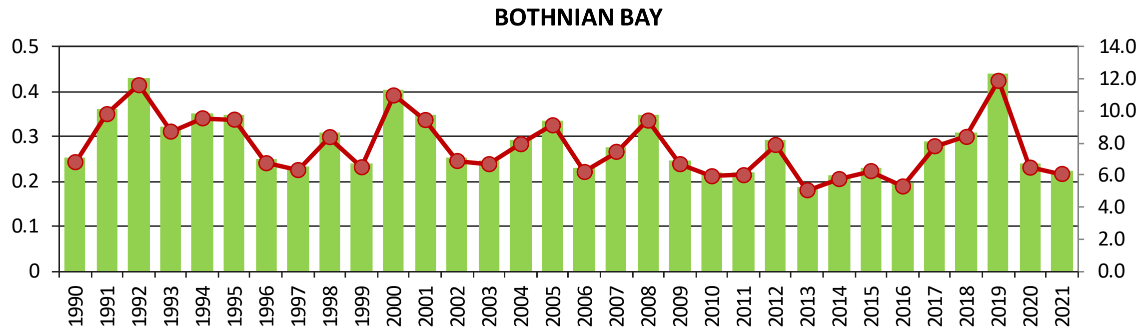


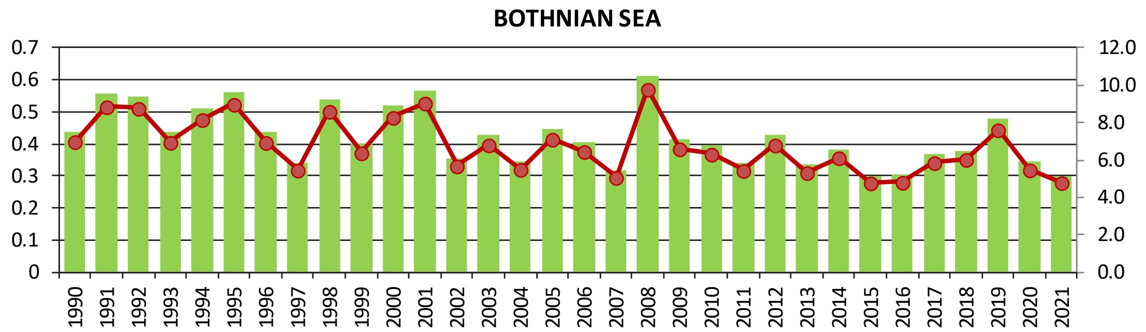
Figure 1. Changes of modelled (blue line) and normalized (red line) total annual atmospheric deposition of mercury to the Baltic Sea for the period 1990-2021, (t y^{-1}). Normalized depositions were obtained using the methodology described below in the metadata section 5.

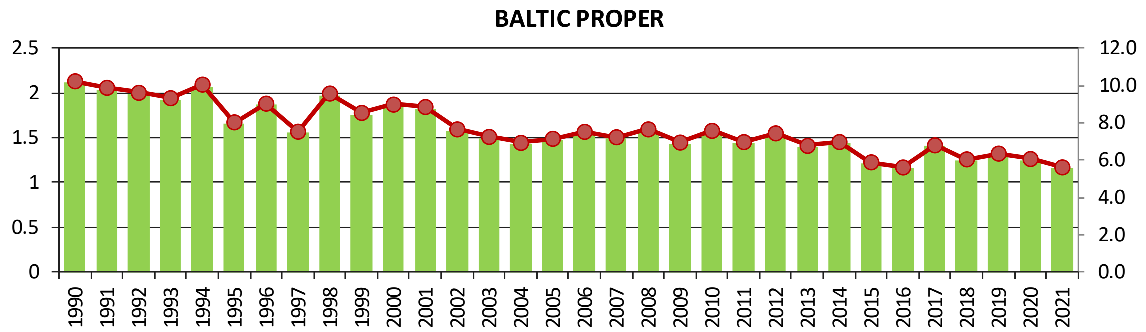
Spatial distributions of annual total deposition fluxes of mercury in 1990 and 2021 within the Baltic Sea region are shown in Figure 3. Total deposition fluxes of Hg vary significantly among the sub-basins. The highest spatially averaged total deposition flux in 2021 among the Baltic Sea sub-basins is noted for the Gulf of Finland and Sound sub-basins. The Bothnian Sea sub-basin is characterized by the lowest Hg deposition flux that is explained by its relatively large area and low levels of emissions in the surrounding areas.

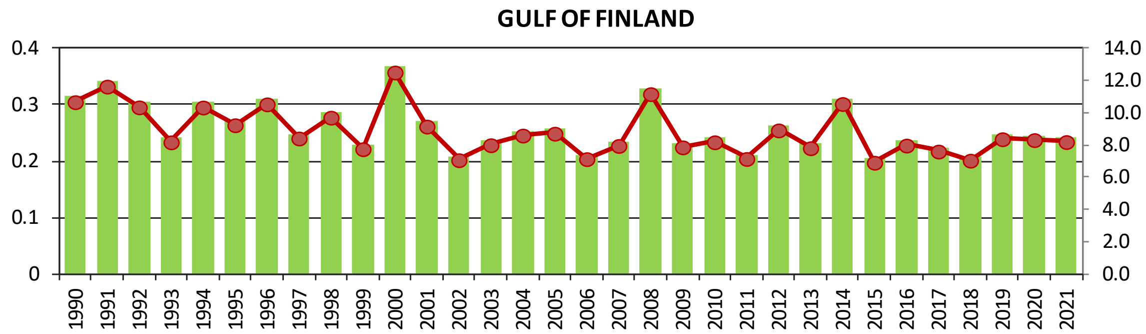
The HELCOM Contracting Parties contributed almost 22% to total deposition of mercury to the Baltic Sea in 2021 (Table 2). The largest contribution is made by Poland (8.3%) and Germany (6.4%) (Figure 4, Table 2). It is important to note that contributions of emissions of the Contracting Parties to deposition in particular sub-regions differ significantly. Reduction of atmospheric input of mercury from anthropogenic sources to the Baltic Sea is a result of various activities including abatement measures, economic contraction, and industrial restructuring, which took place in the HELCOM countries as well as other EMEP countries during the considered period.


ARCHIPELAGO SEA
0.2
0.15
0.1
0.05
0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021


BOTHNIAN BAY
0.5
0.4
0.3
0.2
0.1
0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021


BOTHNIAN SEA
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021


BALTIC PROPER
2.5
2
1.5
1
0.5
0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021


GULF OF FINLAND
0.4
0.3
0.2
0.1
0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021

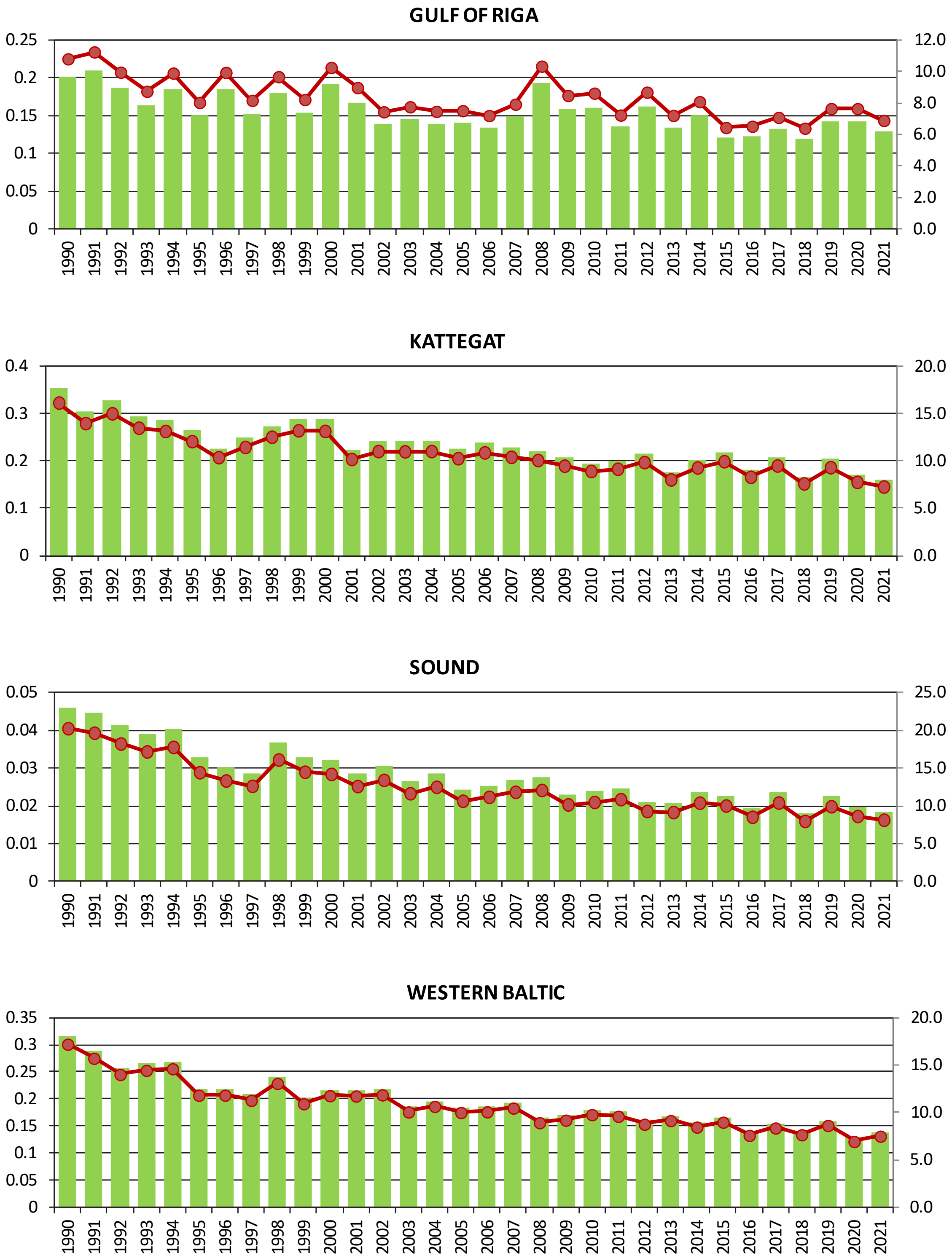


Figure 2. Time-series of computed total annual atmospheric deposition of mercury to nine sub-basins of the Baltic Sea for the period 1990-2021 in t y^{-1} as green bars (left axis) and total deposition fluxes in g km^{-2} y^{-1} as red lines (right axis).

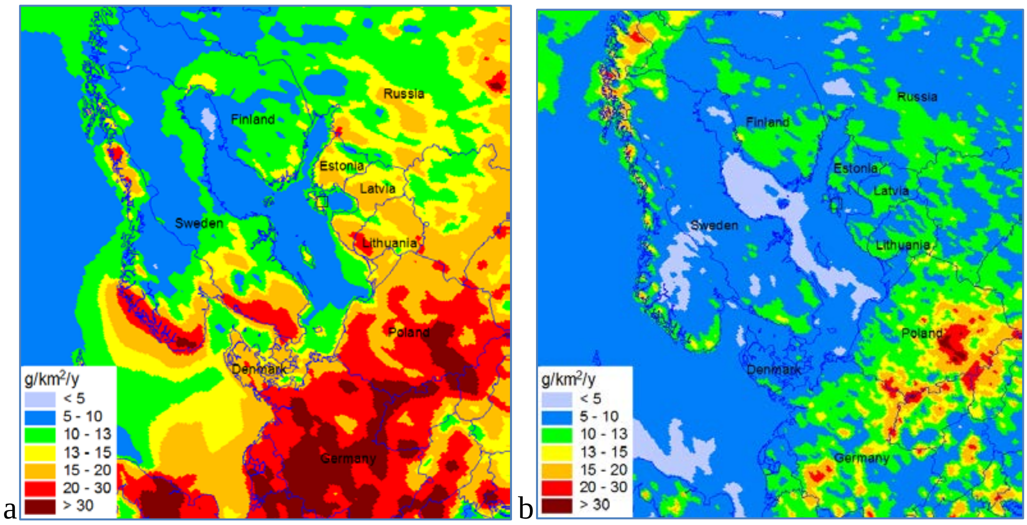


Figure 3. Spatial distribution of modelled annual total mercury deposition fluxes in the Baltic Sea region for 1990 (a) and 2021 (b), g km^{-2} y^{-1}.

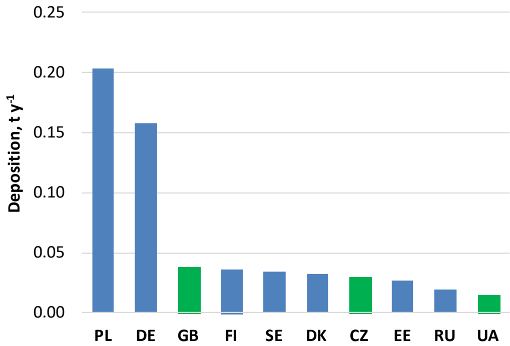


Figure 4. Ten countries with the highest contribution to annual total deposition of mercury to the Baltic Sea estimated for 2021, t y^{-1}. Green bars indicate non-HELCOM countries.

Data

Numerical data on computed mercury depositions to the Baltic Sea are given in the following tables.

Table 1. Computed total annual deposition of mercury to nine Baltic Sea sub-basins, the whole Baltic Sea (BAS) and normalized deposition* to the Baltic Sea (Norm) for the period 1990-2021. Units: t y^{-1}.

	ARC	BOB	BOS	BAP	GUF	GUR	KAT	SOU	WEB	BAS	Norm
1990	0.161	0.252	0.439	2.109	0.315	0.202	0.353	0.046	0.316	4.193	4.284
1991	0.181	0.363	0.555	2.037	0.343	0.210	0.306	0.045	0.289	4.329	4.185
1992	0.162	0.429	0.550	1.982	0.305	0.186	0.328	0.041	0.258	4.242	4.092
1993	0.133	0.322	0.436	1.923	0.242	0.163	0.295	0.039	0.266	3.819	4.004
1994	0.147	0.353	0.513	2.073	0.305	0.185	0.287	0.040	0.269	4.172	3.921
1995	0.140	0.350	0.564	1.656	0.273	0.150	0.264	0.033	0.218	3.647	3.842
1996	0.137	0.249	0.436	1.863	0.311	0.186	0.227	0.030	0.218	3.656	3.768
1997	0.127	0.234	0.343	1.553	0.249	0.153	0.250	0.029	0.208	3.145	3.697
1998	0.171	0.310	0.540	1.974	0.286	0.181	0.274	0.037	0.240	4.013	3.629
1999	0.131	0.240	0.401	1.760	0.229	0.154	0.289	0.033	0.201	3.438	3.565
2000	0.153	0.406	0.520	1.852	0.369	0.192	0.288	0.032	0.217	4.027	3.504
2001	0.138	0.349	0.568	1.825	0.270	0.168	0.223	0.029	0.216	3.786	3.446
2002	0.101	0.255	0.357	1.578	0.209	0.139	0.241	0.030	0.218	3.129	3.390
2003	0.125	0.247	0.428	1.495	0.236	0.145	0.240	0.026	0.185	3.128	3.337
2004	0.108	0.293	0.346	1.429	0.254	0.139	0.241	0.028	0.196	3.036	3.286
2005	0.116	0.337	0.447	1.474	0.257	0.140	0.225	0.024	0.184	3.205	3.237
2006	0.115	0.229	0.406	1.551	0.211	0.135	0.238	0.025	0.185	3.095	3.190
2007	0.115	0.276	0.319	1.492	0.235	0.148	0.228	0.027	0.193	3.032	3.144
2008	0.163	0.348	0.614	1.578	0.329	0.193	0.220	0.027	0.164	3.638	3.101
2009	0.133	0.247	0.415	1.433	0.232	0.158	0.207	0.023	0.169	3.018	3.059
2010	0.110	0.219	0.397	1.562	0.242	0.161	0.195	0.024	0.180	3.090	3.019
2011	0.110	0.222	0.342	1.438	0.211	0.135	0.200	0.025	0.177	2.859	2.980
2012	0.133	0.292	0.427	1.535	0.263	0.162	0.216	0.021	0.162	3.210	2.942
2013	0.119	0.187	0.335	1.396	0.231	0.135	0.175	0.021	0.169	2.768	2.906
2014	0.138	0.213	0.385	1.439	0.311	0.151	0.203	0.024	0.156	3.019	2.871
2015	0.104	0.231	0.301	1.215	0.204	0.120	0.218	0.023	0.165	2.581	2.836
2016	0.094	0.196	0.303	1.158	0.236	0.122	0.181	0.019	0.140	2.449	2.803
2017	0.104	0.289	0.368	1.402	0.225	0.132	0.208	0.024	0.154	2.906	2.771
2018	0.113	0.310	0.379	1.248	0.208	0.119	0.166	0.018	0.141	2.703	2.739
2019	0.138	0.439	0.478	1.311	0.247	0.143	0.204	0.023	0.159	3.142	2.709
2020	0.114	0.239	0.344	1.251	0.246	0.143	0.170	0.020	0.128	2.654	2.679
2021	0.083	0.225	0.302	1.159	0.242	0.129	0.159	0.018	0.138	2.455	2.650

* - normalized depositions were obtained using the methodology described below in the metadata section 5.

Table 2. Computed contributions by country to annual total deposition of mercury to nine Baltic Sea sub-basins for the year 2021. Units: t y^{-1}. HELCOM: contribution of anthropogenic sources of HELCOM countries; EMEP: contribution of anthropogenic sources in other EMEP countries; Other: contributions of sources other than primary anthropogenic emissions (natural, secondary (re-suspension), and non-EMEP sources).

	ARC	BOB	BOS	BAP	GUF	GUR	KAT	SOU	WEB	BAS
DK	3.87E-04	4.67E-04	1.09E-03	1.28E-02	6.69E-04	7.41E-04	8.82E-03	1.56E-03	6.12E-03	3.27E-02
EE	9.06E-04	1.14E-03	2.18E-03	7.47E-03	1.17E-02	2.86E-03	1.55E-04	1.39E-05	9.66E-05	2.66E-02
FI	2.11E-03	1.42E-02	7.28E-03	4.68E-03	7.07E-03	8.18E-04	1.80E-04	1.26E-05	1.02E-04	3.64E-02
DE	3.67E-03	3.48E-03	1.00E-02	9.08E-02	6.81E-03	5.39E-03	1.49E-02	2.07E-03	2.10E-02	1.58E-01
LV	2.76E-04	1.74E-04	6.66E-04	4.34E-03	7.99E-04	2.05E-03	5.36E-05	8.08E-06	5.38E-05	8.42E-03
LT	3.68E-04	2.16E-04	9.43E-04	7.62E-03	7.96E-04	1.39E-03	1.05E-04	1.80E-05	9.00E-05	1.15E-02
PL	4.90E-03	5.03E-03	1.71E-02	1.40E-01	1.06E-02	9.34E-03	7.90E-03	9.75E-04	7.44E-03	2.03E-01
RU	6.28E-04	3.49E-03	2.67E-03	7.01E-03	4.50E-03	9.49E-04	3.18E-04	2.66E-05	1.74E-04	1.98E-02
SE	1.39E-03	4.82E-03	7.70E-03	1.47E-02	1.42E-03	1.06E-03	2.44E-03	3.49E-04	6.49E-04	3.45E-02
AL	5.30E-06	9.68E-06	2.27E-05	1.05E-04	1.11E-05	5.06E-06	2.42E-06	3.92E-07	2.55E-06	1.64E-04
AM	5.75E-07	3.71E-06	3.03E-06	1.20E-05	3.29E-06	1.70E-06	4.13E-07	4.05E-08	2.01E-07	2.50E-05
AT	1.47E-04	2.42E-04	5.57E-04	2.81E-03	3.84E-04	1.76E-04	3.58E-04	3.65E-05	3.53E-04	5.06E-03
AZ	2.70E-06	2.10E-05	1.79E-05	4.30E-05	2.73E-05	8.17E-06	2.43E-06	1.80E-07	1.12E-06	1.24E-04
BA	2.01E-04	3.67E-04	8.93E-04	3.31E-03	3.54E-04	1.84E-04	1.67E-04	2.02E-05	1.45E-04	5.64E-03
BE	1.95E-04	1.85E-04	4.54E-04	3.39E-03	3.59E-04	2.51E-04	9.72E-04	1.18E-04	1.10E-03	7.02E-03
BG	5.07E-05	9.96E-05	1.93E-04	6.64E-04	1.54E-04	6.37E-05	2.48E-05	2.49E-06	1.69E-05	1.27E-03
BY	1.19E-04	1.49E-04	3.54E-04	1.66E-03	4.35E-04	2.84E-04	3.95E-05	5.80E-06	2.73E-05	3.07E-03
CH	1.12E-04	1.99E-04	4.49E-04	1.84E-03	2.72E-04	1.17E-04	3.67E-04	3.38E-05	3.79E-04	3.77E-03
CY	5.57E-08	3.41E-07	3.33E-07	9.06E-07	8.52E-07	1.47E-07	3.56E-08	3.78E-09	2.11E-08	2.69E-06
CZ	7.62E-04	9.61E-04	2.59E-03	1.72E-02	1.70E-03	1.17E-03	2.28E-03	2.64E-04	2.25E-03	2.92E-02
ES	2.42E-04	3.91E-04	8.05E-04	2.92E-03	4.29E-04	2.14E-04	7.01E-04	7.04E-05	7.13E-04	6.48E-03
FR	3.46E-04	4.82E-04	1.02E-03	5.56E-03	7.26E-04	4.39E-04	1.58E-03	1.66E-04	1.64E-03	1.20E-02
GB	1.28E-03	1.47E-03	3.46E-03	1.88E-02	1.88E-03	1.42E-03	5.52E-03	5.78E-04	4.08E-03	3.85E-02
GE	4.44E-06	2.58E-05	2.23E-05	1.08E-04	2.06E-05	1.23E-05	2.95E-06	3.33E-07	1.40E-06	1.98E-04
GR	1.50E-05	4.65E-05	8.39E-05	2.87E-04	7.31E-05	2.14E-05	1.07E-05	1.27E-06	8.68E-06	5.48E-04
HR	3.34E-05	6.32E-05	1.51E-04	5.37E-04	6.42E-05	3.03E-05	5.48E-05	5.76E-06	4.99E-05	9.90E-04
HU	1.22E-04	2.46E-04	5.82E-04	2.39E-03	2.82E-04	1.61E-04	1.64E-04	2.08E-05	1.91E-04	4.16E-03
IE	6.37E-05	9.79E-05	1.99E-04	8.34E-04	1.01E-04	7.24E-05	2.51E-04	2.43E-05	1.50E-04	1.79E-03
IS	1.85E-06	7.49E-06	6.92E-06	3.02E-05	3.46E-06	2.38E-06	4.93E-06	4.79E-07	3.96E-06	6.17E-05
IT	2.68E-04	5.54E-04	1.23E-03	4.18E-03	5.80E-04	2.44E-04	6.31E-04	5.81E-05	5.72E-04	8.32E-03
KY	5.24E-07	2.46E-06	3.48E-06	6.53E-06	1.55E-06	6.85E-07	3.91E-07	3.56E-08	2.77E-07	1.59E-05
KZ	1.17E-04	6.60E-04	6.81E-04	1.26E-03	6.87E-04	2.30E-04	1.36E-04	8.11E-06	4.63E-05	3.83E-03
LI	5.28E-08	1.02E-07	2.14E-07	9.28E-07	1.65E-07	5.37E-08	1.55E-07	1.62E-08	1.71E-07	1.86E-06
LU	1.28E-05	1.62E-05	3.52E-05	2.43E-04	2.76E-05	1.92E-05	6.46E-05	6.99E-06	6.93E-05	4.95E-04
MC	4.16E-08	1.10E-07	1.98E-07	6.32E-07	1.11E-07	4.53E-08	1.37E-07	1.07E-08	1.20E-07	1.41E-06
MD	1.52E-05	3.51E-05	4.36E-05	1.72E-04	3.71E-05	2.97E-05	3.30E-06	4.77E-07	2.51E-06	3.39E-04
ME	5.71E-06	9.83E-06	2.21E-05	9.36E-05	1.47E-05	7.63E-06	2.83E-06	4.07E-07	2.85E-06	1.60E-04
MK	1.42E-05	2.76E-05	5.68E-05	2.42E-04	3.73E-05	1.70E-05	7.82E-06	9.67E-07	6.26E-06	4.10E-04
MT	1.88E-08	7.96E-08	1.42E-07	4.12E-07	9.23E-08	2.99E-08	3.25E-08	4.09E-09	3.23E-08	8.43E-07
NL	1.77E-04	1.50E-04	4.09E-04	3.45E-03	3.01E-04	2.24E-04	9.55E-04	1.21E-04	1.09E-03	6.88E-03
NO	1.53E-04	4.68E-04	7.26E-04	1.50E-03	2.58E-04	1.70E-04	4.79E-04	2.62E-05	1.60E-04	3.94E-03
PT	3.59E-05	5.38E-05	1.20E-04	5.13E-04	6.41E-05	3.70E-05	1.31E-04	1.44E-05	1.41E-04	1.11E-03
RO	2.26E-04	5.06E-04	9.00E-04	3.07E-03	5.12E-04	3.19E-04	8.50E-05	1.22E-05	8.46E-05	5.72E-03
RS	1.65E-04	3.32E-04	7.95E-04	2.61E-03	2.77E-04	1.54E-04	1.22E-04	1.51E-05	1.10E-04	4.58E-03
SI	3.38E-05	6.27E-05	1.51E-04	5.70E-04	6.94E-05	3.51E-05	6.25E-05	6.87E-06	6.16E-05	1.05E-03
SK	9.83E-05	1.78E-04	4.26E-04	2.24E-03	2.67E-04	1.57E-04	1.59E-04	1.95E-05	1.81E-04	3.73E-03
TJ	3.07E-07	1.55E-06	2.03E-06	4.50E-06	8.41E-07	4.71E-07	2.68E-07	2.43E-08	2.02E-07	1.02E-05
TM	1.53E-06	1.32E-05	1.13E-05	2.21E-05	2.52E-05	5.01E-06	1.85E-06	1.26E-07	7.98E-07	8.12E-05
TR	1.27E-04	6.86E-04	6.89E-04	2.60E-03	8.77E-04	3.00E-04	7.21E-05	7.88E-06	3.89E-05	5.40E-03
UA	5.90E-04	1.43E-03	1.95E-03	7.42E-03	1.69E-03	1.04E-03	1.82E-04	2.66E-05	1.32E-04	1.45E-02
UZ	5.68E-06	3.57E-05	3.79E-05	7.90E-05	3.53E-05	1.17E-05	5.28E-06	4.16E-07	3.13E-06	2.14E-04
HELCOM	0.015	0.033	0.050	0.290	0.044	0.025	0.035	0.005	0.036	0.531
EMEP	0.006	0.010	0.020	0.093	0.013	0.008	0.016	0.002	0.014	0.181
Other	0.063	0.181	0.232	0.777	0.185	0.096	0.109	0.012	0.089	1.743
Total	0.083	0.225	0.302	1.159	0.242	0.129	0.159	0.018	0.138	2.455

Metadata

Technical information

1. Source:

Meteorological Synthesizing Centre East (MSC-E) of EMEP.

2. Description of data:

Atmospheric deposition of mercury to the Baltic Sea for the period from 1990 to 2021 were estimated using the latest version of GLEMOS model developed at EMEP/MSC-E (http://msceast.org/index.php/j-stuff/glemos). Annual Hg emissions, officially reported by EMEP countries in 2020, were used in model computations for the years 1990-2018. Pollution levels of Hg in 2019 were evaluated using emission data, reported for the previous year 2021, the results for 2020 are based on emissions submitted in 2022 and emissions reported in 2023 were used to calculate Hg levels for 2021. These data are available from the EMEP Centre on Emission Inventories and Projections (CEIP) (http://www.ceip.at/). Detailed description of reported emission data, gap-filling methods, and expert estimates can be found in the CEIP Technical report [*Poupa*, 2022].

3. Geographical coverage:

Atmospheric depositions of mercury were estimated for the European region and surrounding areas covered by the EMEP modelling domain.

4. Temporal coverage:

Time-series of annual Hg atmospheric deposition were estimated for the period 1990 – 2021.

5. Methodology and frequency of data collection:

Atmospheric input and source allocation budget of mercury deposition to the Baltic Sea were computed using the latest version of GLEMOS model over the new EMEP domain (https://www.ceip.at/ms/ceip_home1/ceip_home/new_emep-grid/). Model estimates describe regional scale distribution of pollution levels and source-receptor relationships.

GLEMOS modelling framework is a multi-scale multi-pollutant simulation platform developed for operational and research applications within the EMEP programme [*Tarrason and Gusev*, *2008; Travnikov et al.*, 2009*; Jonson and Travnikov*, 2010; *Travnikov and Jonson*, 2011]. The framework allows simulations of dispersion and cycling of different classes of pollutants (e.g. heavy metals and persistent organic pollutants) in the environment with a flexible choice of the simulation domain (from global to local scale) and spatial resolution. In the vertical the model domain covers the height up to 10 hPa (ca. 30 km). The current vertical structure consists of 20 irregular terrain-following sigma layers. Among them 10 layers cover the lowest 5 km of the troposphere and height of the lowest layer is about 75 m.

Anthropogenic Hg emission data for modelling have been prepared based on the gridded emissions fields provided by CEIP for the EMEP longitude-latitude grid system with spatial resolution 0.1x0.1 degree. Gridded emissions are complemented by additional emission parameters required for model runs (e. g. intra-annual variations and vertical distribution). Boundary conditions for model simulations over EMEP domain were estimated using the global scale GLEMOS model simulations [*Ilyin et al.*, 2022].

Meteorological data used in the calculations for 1990-2021 were obtained using WRF meteorological data pre-processor [*Skamarock et al*., 2008] on the basis of meteorological data of European Centre for Medium-Range Weather Forecasts (ECMWF).

Mercury presents in the atmosphere in three forms, such as elemental, gaseous oxidized and particulate mercury. Atmospheric properties of these three forms differ markedly. Elemental mercury is relatively inert. It slowly oxidized in the atmosphere, characterized by low wet and dry deposition removal, and thus can travel over global scale. Gaseous oxidized and particulate forms of mercury more readily deposit to the underlying surface and are considered as regional-scale pollutants. Ability of Hg to travel over the global distances determines significant contribution of emission sources located outside EMEP countries to mercury pollution levels in the Baltic region.

Mercury is naturally occurring element with mean content in the Earth's crust 0.085 ppm [*CRC*, 2008]. Beside anthropogenic emissions, Hg is released to the atmosphere through secondary sources such as natural sources and processes (volcanoes, weathering, geothermal activities), and re-emission of previously deposited Hg [GMA, 2018, AMAP/UNEP, 2013]. In the current work secondary emissions of Hg from the territories of the HELCOM countries (except for Russia) and the Baltic Sea area were estimated at the level of about 11 t, remaining almost the same through the considered period.

Normalized deposition values for the period 1990-2021 were obtained on the basis of results of model simulations using bi-exponential approximation [*Colette et al.,* 2016].

Quality information

6. Strength and weakness:

Strength: annually reported data on mercury emissions to the atmosphere.

Weakness: uncertainties in the officially submitted mercury emission data, estimates of secondary emissions, and speciation of mercury in emissions.

7. Uncertainty:

Discrepancies between the modelled and observed values can be caused by a number of reasons. One of them is uncertainties of officially reported emission data. In addition to this, uncertainties of spatial distribution as well as distribution along the vertical also contributes to the emission-related uncertainties.

Another source of the discrepancies is uncertainties of the model parameterizations and input data. Most of parameterizations of physical processes used in GLEMOS were transferred from previous model MSCE-HM used in operational modelling under EMEP [*Travnikov and Ilyin*, 2005]. The MSCE-HM model has been verified in a number of intercomparison campaigns with other regional HM transport models [*Gusev et al*., 2006; *Ryaboshapko et al.,* 2001, 2005] and has been qualified by means of sensitivity and uncertainty studies [*Travnikov*, 2000]. It was concluded that the results of heavy metal airborne transport modelling were in satisfactory agreement with the available measurements and the discrepancies did not exceed on average a factor of two [*UNEP*, 2010a,b]. The model was thoroughly reviewed at the workshop held in October, 2005 under supervision of the EMEP Task Force of Measurements and Modelling (TFMM). It was concluded that "MSC-E model is suitable for the evaluation of long-range transboundary transport and deposition of HMs in Europe" [*ECE/EB.AIR/GE.1/2006/4*].

Finally, the discrepancies can be contributed by the uncertainties of measurements. Information on quality of Hg measurements is limited. Field intercomparison study carried out in 2005 revealed that deviation of Hg concentrations in precipitation and total deposition measured by various laboratories ranged within ±40% [*Aas*, 2006]. More modern studies on assessment of Hg measurement quality are needed.

8. Further work required:

Further work is required to reduce uncertainties in Hg modelling approaches applied in the GLEMOS model. It can be reached through joint efforts of measurement, emission and modelling communities.

References

Aas W., [2006]. Data quality 2004, quality assurance, and field comparisons. EMEP/CCC-Report 4/2006. 95p.

AMAP/UNEP, [2013]. Technical Background Report for the Global Mercury Assessment 2013. Arctic Monitoring and Assessment Programme, Oslo, Norway / UNEP Chemicals Branch, Geneva, Switzerland.

CCC [2022] EMEP laboratory intercomparison. Heavy metals in precipitation 2021 - % deviation from expected value. https://projects.nilu.no/ccc/intercomparison/index.html. Site visited 10.08.2023

Colette et al. [2016]. Air pollution trends in the EMEP region between 1990 and 2012. EMEP: CCC-Report 1/2016. 105 p.

Connor J.A., Farhat S.K., Vanderfort M. [2012]. GSI Mann-Kendall toolkit for constituent trend analysis. User's manual, version 1.0. GSI Environmental Inc., (https://www.academia.edu/26179389/GSI_MANN-KENDALL_TOOLKIT_For_Constituent_Trend_Analysis_USERS_MANUAL?auto=download).

CRC [2008] Handbook of Chemistry and Physics, 89th Edition. CRC Press, 2736 p.

Gilbert R.O. [1987]. Statistical methods for environmental pollution monitoring. Van Nostrand Reinhold Company Inc., ISBN 0-442-23050-8, 320 p.

GMA [2018]. Technical background report to the Global Mercury Assessment 2018. UN Environment.

Gusev A., Ilyin I., Mantseva L., Rozovskaya O., Shatalov V. and Travnikov O. [2006] Progress in further development of MSCE-HM and MSCE-POP models (implementation of the model review recommendations). EMEP/MSC-E Technical Report 4/2006. 148 p.

Ilyin I., Batrakova N., Gusev A., Kleimenov M., Rozovskaya O., Shatalov V., Strizhkina I., Travnikov O., Vulykh N., Breivik K., Bohlin-Nizzetto P., Pfaffhuber K. A., Aas W., Poupa S., Wankmueller R., Ullrich B., Vivanco M. G., Theobald M. R., Garrido J. L., Gil V., Couvidat F., Collette A., Mircea M., Adani M., Delia I., Kouznetsov R. D., Kadancev E. V., [2022] Assessment of heavy metal and POP pollution on global, regional and national scales. EMEP Status Report 2/2022.

Jonson J. E. and Travnikov O. (Eds.). [2010] Development of the EMEP global modeling framework: Progress report. Joint MSC-W/MSC-E Report. EMEP/MSC-E Technical Report 1/2010.

Poupa S. [2022] Methodologies applied to the CEIP GNFR gap-filling 2022. Part II: Heavy Metals (Cd, Hg, Pb) and Persistent Organic Pollutants (Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Indeno(1,2,3-cd)pyrene, Total polycyclic aromatic hydrocarbons, Dioxin and Furan, Hexachlorobenzene, Polychlorinated biphenyls) of the year 2020. Technical report CEIP 04/2022.

Ryaboshapko A., Ilyin I., Bullock R., Ebinghaus R., Lohman K., Munthe J., Petersen G., Seigneur C., Wangberg I. [2001] Intercomparison study of numerical models for long-range atmospheric transport of mercury. Stage I: Comparison of *chemical modules for mercury transformations in a cloud/fog environment. EMEP/MSC-E Technical report 2/2001, Meteorological Synthesizing Centre – East, Moscow, Russia. (http://www.msceast.org/reports/2_2001.pdf).*

Ryaboshapko A., Artz R., Bullock R., Christensen J., Cohen M., Draxler R., Ilyin I., Munthe J., Pacyna J., Petersen G., Syrakov D., and Travnikov O. [2005] Itercopmparison study of numerical models for long-range atmospheric transport of mercury. Stage III. Comparison of modelling results with long-term observations and comparison of calculated items of regional balances. EMEP/MSC-E Technical Report 1/2005, Meteorological Synthesizing Centre – East, Moscow, Russia. (http://www.msceast.org/reports/1_2005.pdf).

Salminen R. (Chief-editor) [2005] Geochemical Atlas of Europe. Part 1 - Background Information, Methodology and Maps. A contribution to IUGS/IAGC Global Geochemical Baselines. ISBN 951-690-913-2 (electronic version). http://weppi.gtk.fi/publ/foregsatlas/index.php.

Skamarock W.C., Klemp J.B., Dudhia J., Gill D.O., Barker D.M., Duda M.G., Huang X-Y., Wang W. and Powers J.G. [2008] A Description of the Advanced Research WRF Version 3. NCAR/TN–475+STR NCAR technical note.

Tarrasón L. and Gusev A. [2008] Towards the development of a common EMEP global modeling framework. MSC-W Technical Report 1/2008.

Travnikov O. [2000] Uncertainty analysis of heavy metals long-range transport modelling. EMEP/MSC-E Technical note 9/2000, Meteorological Synthesizing Centre - East, Moscow, Russia. (http://www.msceast.org/reports/9_2000.pdf).

Travnikov O., J.E. Jonson, A.S Andersen, M. Gauss, A. Gusev, O. Rozovskaya, D. Simpson, V. Sokovykh, S. Valiyaveetil and P. Wind [2009] Development of the EMEP global modelling framework: Progress report. Joint MSC-E/MSC-W Report. EMEP/MSC-E Technical Report 7/2009.

Travnikov O. and Jonson J. E. (Eds.). [2011] Global scale modelling within EMEP: Progress report. EMEP/MSC-E Technical Report 1/2011.

Travnikov O. and Ilyin I. [2005] Regional Model MSCE-HM of Heavy Metal Transboundary Air Pollution in Europe. EMEP/MSC-E Technical Report 6/2005. (http://www.msceast.org/reports/6_2005.pdf).

UNEP [2010a] Final review of scientific information on lead. UNITED NATIONS ENVIRONMENT PROGRAMME. Chemicals Branch, DTIE. 255 p. + annexes.

UNEP [2010b] Final review of scientific information on cadmium. UNITED NATIONS ENVIRONMENT PROGRAMME. Chemicals Branch, DTIE. 201 p.+ annexes.