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Identifying and characterizing major emission point sources as a basis for geospatial distribution of mercury emissions inventories

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HIGHLIGHTS

- Investigation of the use of publicly available data resources.
- Characterization of point-source emissions of mercury.
- Elaboration of a method to integrate reported and calculated emission estimates.
- Improved geospatial distribution of global anthropogenic mercury emissions to air.

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ABSTRACT

Mercury is a global pollutant that poses threats to ecosystem and human health. Due to its global transport, mercury contamination is found in regions of the Earth that are remote from major emissions areas, including the Polar regions. Global anthropogenic emission inventories identify important sectors and industries responsible for emissions at a national level; however, to be useful for air transport modelling, more precise information on the locations of emission is required. This paper describes the methodology applied, and the results of work that was conducted to assign anthropogenic mercury emissions to point sources as part of geospatial mapping of the 2010 global anthropogenic mercury emissions inventory prepared by AMAP/UNEP. Major point-source emission sectors addressed in this work account for about 850 tonnes of the emissions included in the 2010 inventory. This work allocated more than 90% of these emissions to some 4600 identified point source locations, including significantly more point source locations in Africa, Asia, Australia and South America than had been identified during previous work to geospatially-distribute the 2005 global inventory. The results demonstrate the utility and the limitations of using existing, mainly public domain resources to accomplish this work. Assumptions necessary to make use of selected online resources are discussed, as are artefacts that can arise when these assumptions are applied to assign (national-sector) emissions estimates to point sources in various countries and regions. Notwithstanding the limitations of the available information, the value of this procedure over alternative methods commonly used to geo-spatially distribute emissions, such as use of 'proxy' datasets to represent emissions patterns, is illustrated. Improvements in information that would facilitate greater use of these methods in future work to assign emissions to point-sources are discussed. These include improvements to both national (geo-referenced) emission inventories and also to other resources that can be employed when such national inventories are lacking.

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1. Introduction

Mercury is a highly toxic element with both natural and anthropogenic sources (UNEP, 2013a). The recognition by the international community that mercury is a global pollutant that poses serious threats to ecosystem and human health resulted in the agreement of the Minamata Convention in October 2013 (UNEP,

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2013b). An important part of the work supporting the negotiation and future implementation of the Minamata Convention is the development of global inventories documenting emissions to air from anthropogenic sources. Typically, such inventories report emissions as national totals for defined emission sectors (AMAP/UNEP, 2013). The work to compile global mercury emission inventories has also been associated with assessments, such as those produced by the Arctic Monitoring and Assessment Programme (AMAP) (AMAP, 1998; Macdonald et al., 2003; AMAP, 2005, 2011), where these inventories are used as a basis for understanding the role of air transport pathways in determining Arctic mercury contamination from various source regions.

In order to use these inventories in modelling applications designed to simulate air transport from source to receptor regions, it is important to geo-spatially distribute the emissions in a realistic manner. This involves identifying the locations of the sources and assigning emissions to these sources (Pacyna et al., 2010). For many contaminants, including mercury, major point sources are responsible for a significant part of the emissions; however identifying the locations of these point sources is not straight-forward, and obtaining information on their emissions even less-so. For this reason, (modelling) studies that associate mercury emissions with major point-sources have tended to focus on the regional level (Streets et al., 2005; Nelson, 2007; Nelson et al., 2012; Ye et al., 2015).

Geospatial distribution involves assigning emissions to specific locations (point sources), or areas in the case of diffuse sources, as accurately as possible, see Wilson et al. (2006) and Pacyna et al. (2010). When the first geospatially-distributed global mercury emission inventory was prepared (Pacyna et al., 2003), the need for reliable information on point sources of emissions was evident; however, almost no point source information was available at the time. Therefore the geospatial distribution had to be performed using proxy data, for example using global population as a surrogate to represent mercury emission intensity.

Geospatial distribution using both point sources and proxy data was first introduced when mapping the 2005 global mercury emissions inventory (Pacyna et al., 2010; AMAP/UNEP, 2008). The availability of point source information created a better defined picture of actual emission locations; however, the global distribution of these point sources was very uneven between regions/countries (see Section 3). It was apparent that more information on well-defined point sources was needed to improve the global geospatial distribution of mercury emissions.

This paper describes the results of work that was conducted to assign anthropogenic mercury emissions to point sources as part of gridded geospatial distribution of the 2010 global inventory prepared by AMAP/UNEP (AMAP/UNEP, 2013); it also discusses limitations of the applied methodology and possible ways to address some of these limitations in future work.

2. Methodology

The overall goal of the work described here was to assign the total national estimated emissions (for a given emission-sector) to relevant point sources, in order to appropriately locate the emissions in the global $0.5 \times 0.5^\circ$ latitude/longitude grid.

The national emission estimates produced for the 2010 global mercury emissions inventory (AMAP/UNEP, 2013; Annex 8) are quantified for 17 aggregated emission sectors (listed in the footnote to Table 1). Major point sources are associated primarily with heavy industry and power generation sectors. Many other point sources exist, including landfill sites, crematoria, etc. While most of these are likely to be relatively insignificant in terms of emissions from individual sources their cumulative contribution to total global

emissions is not insignificant.

In the current study the main focus was placed on power plants (in particular coal-burning power plants), cement manufacturing plants, and ferrous and non-ferrous metal smelters, especially in countries not covered by a national emissions reporting system. In addition, point sources associated with oil refineries and chlor-alkali plants were addressed. According to the global inventory (AMAP/UNEP, 2013), these sectors account for ca. 50% of anthropogenic mercury emissions to air in 2010.

A further 37% of the total emission to air in 2010 were attributed to artisanal and small-scale gold mining (ASGM); this source sector is however not addressed in the current work because the production sites are too numerous to individually identify, often transient over time and therefore almost impossible to geo-locate as 'point sources' in any comprehensive manner. A similar situation exists for wastes from mercury-containing products disposed of in landfill (4.6% of global emissions).

The most basic requirements for point source information for use in emissions geo-spatial distribution work are (i) the plant/facility geographical location (i.e. its latitude and longitude coordinates, to an appropriate precision) and (ii) a quantification of the mercury emission from the plant/facility concerned. If quantified emissions are not available, national emission estimates for a particular sector can be assigned to relevant point sources by employing a suitable surrogate that reflects relative emissions.

As a first step, relevant information on point-sources of potential interest was compiled. Several countries maintain 'pollution release and transfer' (PRT) registers, generally based on facility-level reporting by plant operators. Examples include the US EPA's national emissions inventory (US-EPA, 2012) and the European Pollution Release and Transfer Register (E-PRTR, 2012). These registers are subject to different reporting requirements as well as different levels of audit determined by applicable legislative and regulatory systems. The advantage of such systems, in the context of this work, is that they include quantified facility level mercury emissions (in the publicly available data resources these are generally annual total emissions) together with information on the location of the plant. Location is, however, not always presented as geographical coordinates (or coordinates with adequate precision for geo-location). Often, public domain (online) PRT registers identify facilities by plant name and town/city (in some cases with an address) only. Using these data therefore required application of reverse geo-coding.

For countries without facility based national reporting systems it is much more difficult to obtain relevant information on point source emissions. The current work utilised a range of public domain information sources to attempt to fill this gap. These resources are of varying quality in terms of the information they contain (Table 1). Point sources which are identified this way seldom have an associated mercury emission value, so emission levels have to be inferred using methods detailed below.

For any given country-sector, the compiled dataset of point sources may include plants with reported emissions, plants without reported emissions but including some other relevant information (e.g. plant capacity, production, or consumption of fuels or raw materials), and plants with no information other than their coordinates, or a combination of the above. In some cases more detailed information, including e.g. installed technology may be available, however this is not generally the case and it was beyond the scope of this work to try to incorporate that level of detail in the (facility based) emission distribution procedure. It should however be noted that emission control technology is taken into account at a generic level when deriving national emissions estimates (AMAP/UNEP, 2013).

The workflow and approach used to assign emissions to

Table 1

Available data resources used in the current work, and their characteristics in relation to data requirements discussed in Section 2.

Resource	Coordinates (latitude, longitude)	Sector(s) ^a	Regional coverage	Reported Hg emissions	Emission surrogate	Other information/remarks
US NEI	Yes	CEM, CREM, CSP, NFMP, NFMP_AL, NFMP_AU, OR, OTH, PISP, PP_COAL, PP_OIL, PP_GAS, SC_IND, WASOTH, WI	USA	Yes	n/a	Emission as annual total, lbs
E-PRTR	http://www.epa.gov/ttn/chief/net/2008inventory.html Yes	CEM, NFMP, NFMP_AL, OR, OTH, PISP, PP_COAL, PP_GAS, PP_OIL, SC_DR, SC_IND, WASOTH, WI	European Union	Yes	n/a	Emission as annual total, optional when <10 kg/a
Canadian NEI	http://prtr.ec.europa.eu/ Yes	CEM, NFMP, NFMP_AL, OR, OTH, PISP, PP_COAL, PP_OIL, WASOTH, WI	Canada	Yes	n/a	Emission as annual total, >5 kg/a ^b
Australian NEI	http://www.ec.gc.ca/inrp-npri/ Yes	NFMP, NFMP_AL, NFMP_AU, OR, OTH, PISP, PP_COAL, PP_GAS	Australia	Yes	n/a	Emission as annual total
CemNet	http://www.npi.gov.au/npidata/action/load/summary-result/criteria/year/2011/destination/ALL/substance/55/source-type/ALL/subthreshold-data/Yes/substance-name/Mercury%2B%2526%2Bcompounds No	CEM	Global	No	Production capacity	Fuel type, plant technology, street address
CARMA	http://www.cemnet.com/gcr/ Yes	PP_COAL, PP_OIL, PP_GAS	Global	No	CO2 emission	Intensity
Global energy Obs.(power plants, oil-refineries)	http://carma.org/ Yes	PP_COAL, PP_OIL, PP_GAS, OR	Global	No	CO2 emission/	
Electrical cap, production cap.	Fuel type					
Wikipedia (China, India PP's)	http://globalenergyobservatory.org/ Yes/No	PP_COAL	China, India	No	Electrical capacity	Data for other countries available (not used)
USGS additional sources data.gov	http://en.wikipedia.org/wiki/List_of_power_stations_in_Asia Yes	NFMP	Global	No	Production capacity	Data hosted at USGS, initial source unknown
USGS minerals report	https://catalog.data.gov/dataset/global-trade-world-copper-smelters Yes/No	NFMP	Global	No	Production capacity	Commodity
ACAP report 2005, Russian PP's	http://mrddata.usgs.gov/mineral-operations/ No (too imprecise)	PP_COAL	Russia	Yes (2008)	n/a	Fuel type, plant technology
OSPAR (Chor-alkali)	Yes	CSP	Europe	Yes		
UNEP report (Chor-alkali)	No	CSP	Global	No	Production capacity	
Chlorine council (Chor-alkali)	No	CSP	Global	No	No	
National expert submissions to UNEP/AMAP inventory activity		Argentina, Australia, Brazil, Japan, Mexico, Republic of Korea, South Africa				

^a Stationary combustion at power plants (separately for coal, oil and gas; PP_COAL, PP_OIL, PP_GAS, respectively); industrial stationary combustion (SC_IND); other stationary combustion (SC_DR); primary non-ferrous (NFMP (includes Cu, Pb, Zn)); aluminium production (NFMP_AL); mercury production (NFMP_HG); large-scale gold production (NFMP_AU); artisanal and small-scale gold production (ASGM); primary iron and steel production (PISP); cement production (CEM); (mercury process) chlor-alkali industry (CSP); oil refining (OR); waste incineration (WI); other waste disposal (WASOTH); crematoria emissions (CREM).

^b Canada Gazette, Vol. 144, No. 50, Part 1, p3128; <http://www.gazette.gc.ca/rp-pr/p1/2010/2010-12-11/pdf/g1-14450.pdf>.

individual point sources is described in Fig. 1. The starting point for this work was the national emission estimates for a given sector as derived from the AMAP/UNEP 2010 inventory results (AMAP/UNEP, 2013).

The first two steps in this workflow take account of situations where national-sector emissions estimates include an amount that is explicitly assigned to diffuse (i.e. non-point) sources, or where there are no relevant point sources, in which case point source emissions also need to be treated in the same way as diffuse source emissions. The methods used to geo-spatially distribute 'diffuse source' emissions (including emissions without known point sources) are described in other publications (Wilson et al., 2006; Pacyna et al., 2010).

After this, the decision tree in Fig. 1 illustrates how emissions were assigned to point sources that have associated reported

emissions, and those that do not – either using other available information to proportionally assign emissions, or where even this is lacking, assigning emissions equally between the listed point sources.

A key step in the process involves comparing the total emissions to be distributed (i.e. total national estimate for the sector concerned) with the total emissions assigned to point sources using the approach detailed above. In most cases these will not match and a further decision step involves resolving this difference by further adjusting the point source emissions or the 'diffuse' emissions component until the numbers converge.

In a few cases, where most locations have reported emissions and only one (or a very few) did not, the applied method can result in anomalously high emissions being assigned to the latter. A situation can also arise where some points have reported emissions

Fig. 1. Workflow scheme for assigning emissions to point-sources.

and others do not, and at the same time the reported emissions exceed the national total for the sector concerned. In this case various options exist: the first is to use the reported emissions and ignore any other identified point sources; this option was not employed due to the desire to retain consistency with national estimates. A second option would be to downscale reported emissions (so that their total matches the national estimate) and ignore

any other identified point locations; this was also not employed. Instead, a third option, assigning an average of the reported facility emissions to plants lacking reported emissions and thereafter downscaling facility estimates until these matched the national sector estimate was applied. This ensured that all identified point sources were represented in the distributed emissions.

The resulting dataset is a list of point source locations each with

an associated emission value (either reported or estimated) that is assigned to a given grid cell in the global ($0.5 \times 0.5^\circ$) geospatial distribution grid. The total emissions thus assigned to individual point sources are consistent with the national-sector-based estimates derived in the 2010 AMAP/UNEP global mercury emission inventory (AMAP/UNEP, 2013).

3. Results/discussion

The product of this work – that is a geo-spatially distributed global mercury emissions dataset for point-source emissions in 2010 (AMAP/UNEP, 2013) – is ‘operationally defined’ (by the methodological assumptions described above and in Section 3.2). Nevertheless, the approach is considered to result in a better representation of the real world emissions patterns than the alternatives (see Section 3.3).

3.1. Improvements in point source coverage

Previously, the available dataset of emissions linked to specific ‘point sources’ was essentially limited to those (few) countries that maintain facility-based PTR inventories. These countries include Canada, the United States and EU member countries. Similar information was also available from work conducted to collect information on point source emissions for specific sectors (e.g. Russia coal-fired power plants (ACAP, 2005; UNEP, 2011)).

Differences between the numbers of point sources used in the geospatial distribution of the 2005 (Pacyna et al., 2010) and 2010

global emissions inventories (this work) are shown in Table 2. Table 2 also compares the amount of emissions allocated to point sources as opposed to ‘diffuse emissions’ (and therefore subject to proxy distribution) for different sectors in the respective years. The considerable increase in the number of identified point sources associated with coal/oil-fired power stations and cement production plants is apparent. For other sectors, such as chlor-alkali production, the information on point sources has also improved through the identification of facilities in regions not represented in the 2005 distribution; the total number of chlor-alkali plants included is lower in 2010 than 2005 but this is due to plant closures or changes from mercury process to membrane process in the intervening period (UNEP, 2012).

3.2. Consideration of assumptions involved in the applied methods

The applied methods involve a number of assumptions that need to be appreciated. For example, the implied assumption, when using capacity or production (volume or amount) to proportionally distribute emissions, that the larger the plant (in terms of capacity or production) the greater its emissions. This assumption is clearly compromised in cases where, for example, plants do not operate at their nominal capacity. Also, in some cases, in particularly in advanced countries, it is likely that the larger the plant (in terms of capacity or production) the better the installed emission control technology. Here, therefore, smaller plants may be responsible for more, not less of the total emissions relative to their size. Thirdly, with the exception of the PTRs, it is not possible to gauge the extent

Table 2

The increase in the number of point-source locations included in the procedure to geospatially distribute emissions for 2010 compared with 2005 (see also Fig. 4), for different sectors in different regions. The table also shows the percentage of total emissions for that sector in the indicated region that are treated as ‘diffuse’ emissions and distributed using proxy data distributions. Country membership of different regions is as specified in AMAP/UNEP (2013); EU group 1 refers to the EU27 countries apart from Bulgaria, Latvia, Lithuania and Romania; these four countries constitute EU group 2.

	Cement production				Chlor alkali (Hg process)				Pig iron and steel (primary)			
	2005		2010		2005		2010		2005		2010	
	n	d (%)	n	d (%)	n	d (%)	n	d (%)	n	d (%)	n	d (%)
Central America and Caribbean	0	100	44	11.0	0	100	3	0	0	100	10	0
EU (group 1)	211	2.0	322	0	61	0	29	32.0	136	7.7	166	0
EU (group 2)	11	16.4	13	0	0	100	1	0	15	0	10	0
Middle East	0	100	133	0.4	0	100	10	0	0	100	15	0
North Africa	0	100	41	0	0	100	4	0	0	100	8	0
North America	96	0	228	0	26	2.7	7	0	90	0	43	30.9
Oceania	0	100	33	1.5	0	100	9	0.2	0	100	4	0
CIS and non EU European	58	58.1	60	11.5	8	63.4	13	0	58	15.9	76	0
South America	2	96.6	99	0	4	89.8	9	0	1	96.5	28	0.6
South Asia	0	100	142	0	9	9.5	13	0	0	100	15	0
South East Asia	1	99.9	172	0.6	0	100	1	0	1	99.9	50	0
Sub-Saharan Africa	0	100	64	3.8	0	100	1	0	0	100	27	0
Total	379		1351		108		99		301		452	
	Non-ferrous metal (primary)				Large- scale gold production				Power plants (coal/oil fired)			
	2005		2010		2005		2010		2005		2010	
	n	d (%)	n	d (%)	n	d (%)	n	d (%)	n	d (%)	n	d (%)
Central America and Caribbean	5	41.1	5	0	0	100	3	32.0	0	100	65	4.6
EU (group 1)	55	0	53	0	0	100	3	32.9	502	4.9	245	15.3
EU (group 2)	10	0	14	0	0	100	0	100	65	9.2	23	0.2
Middle East	0	100	10	0	0	100	1	97.0	0	100	89	3.0
North Africa	2	0	4	0	0	100	0	100	0	100	25	2.1
North America	21	0	11	13.1	7	99.6	25	0	849	0	879	0
Oceania	3	0	11	0	0	100	5	3.3	0	100	96	0
CIS and non EU European	21	48.5	30	0	9	100	3	93.7	140	51.3	174	5.7
South America	17	21.8	20	0	0	100	4	84.4	1	97.7	29	9.1
South Asia	5	55.1	10	1.2	0	100	0	100	0	100	192	0
South East Asia	20	91.3	70	0	0	100	16	12.0	1	99.6	542	0.1
Sub-Saharan Africa	5	100	12	0	0	100	7	55.2	10	1.7	36	0.1
Total	164		250		16		67		1568		2395	

n = number of point sources, d(%) = diffuse emission (%)pg. 1.

to which most public-domain point-source information resources are routinely updated; it is therefore very likely that the information they contain is at least partially outdated, for example listing plants that are no longer operational. However, in the absence of a better alternative, the authors considered the approach employed to be justified given that:

- for several countries where the approach used is most likely to be compromised by the above listed circumstances, large point sources do have associated emissions which were generally used as reported; and
- for many less developed countries, where point sources lack reported emissions, and production volume or capacity surrogates were employed to allocate emissions, the installed control technologies are likely to be less effective – and therefore emissions more likely mirror plant size.

3.3. Influence of point source emission assignment on spatial distribution

The influence of allocating emissions to point-source locations in the geospatial distribution process can be illustrated by considering the results of this approach in comparison to the alternative, namely treating point source emissions as ‘diffuse emissions’ for the purposes of geo-spatial distribution. The latter typically involves either:

- (i) Geo-spatially distributing point-source emissions ‘uniformly’ across national territories;
- (ii) Using population distribution as a proxy to mirror point-source emissions distributions; or
- (iii) Applying a more sophisticated approach involving the use of different proxies for different sectors.

The third option is the approach employed previously by the authors and others to geo-spatially distribute emissions in countries lacking any characterized point sources (AMAP/UNEP, 2008; Pacyna et al., 2010; Muntean et al., 2014). It was also used to distribute the 2010 inventory for (a much lower number of) countries (see Section 3.1) where no point sources were identified. The proxies employed to different sectors were population, urban population, carbon emission intensity, gold exploitation, and artisanal gold deposits/activity.

Fig. 2 shows an example of the use of these different approaches in distributing emissions within a $0.5 \times 0.5^\circ$ grid. Fig. 2(a) shows the gridded distribution of emissions from UK coal-fired power plants as reported to the E-PRTR in 2010 (totalling 1227 kg). This reported total is somewhat lower than the UK national total for this sector of 2078 kg estimated under the AMAP/UNEP 2010 work (AMAP/UNEP, 2013). Fig. 2(b) illustrates the emissions pattern obtained distributing the estimated national total (2078 kg) using population density as a proxy (surrogate) for mercury emissions intensity. This method was applied previously in geospatially distributing the 1995 and 2000 global mercury emissions inventories (Wilson et al., 2006). It shows how what are essentially point source emissions are spread over large areas (204 grid cells) rather than being restricted to grid cells in which power plants are located. Fig. 2(c) illustrates the results of using the power plant emissions ‘proxy mask’ developed based on CARMA data on carbon emissions (see Wheeler and Ummel, 2008; Ummel, 2012). This method was originally developed and applied to distribute the 2005 global inventory for countries lacking point source information (AMAP/UNEP, 2008; Pacyna et al., 2010). Power plant emissions are still attributed to (68) cells covering much of the country,

but the main emissions are concentrated in relatively few cells. Fig. 2(d) presents the results of the current work, using the scheme detailed in Fig. 1 to distribute the UK national emissions estimate for the power plant sector. This assigns emissions to 17 cells and includes some power plants identified in the current work that are not included in the E-PRTR.

3.4. Sector discussion

In the methodology applied to derive the 2010 global inventory (AMAP/UNEP, 2013) total national emissions estimates for a given sector are dependent on three main factors:

- i. The ‘activity’ level (the amount of production of cement, metal, or fuel consumed etc.)
- ii. The unabated emission factor applied, that is the amount of mercury emitted per unit of activity, in the absence of any emission controls (e.g. the mercury content of the fuels or raw materials consumed)
- iii. The applied emission control (degree of application of particular types of controls within a country and their effectiveness at reducing mercury emissions)

In the methodology applied to derive the 2010 global inventory and assign total national emissions estimates for different sectors, countries were allocated to one of (five) ‘regional groups’ considered to reflect similar technological capacity in terms of application of emissions control technologies for the sector concerned. These groupings were used to define the technology profiles (item iii) for countries lacking specific information of their national applied control technologies.

Fig. 3 presents the results of point-source emissions assignments produced using the methodology described in Section 2 above, for selected countries for four sectors.

3.4.1. Coal-fired power plants

Fig. 3(a) shows the distribution of emissions assigned to coal-fired power plant point sources, for some of the major emitting countries/regions. South Africa stands out as having (coal-fired) power plants with higher emission rates (kg/a from individual facilities) than those of other countries. The reasons for this relates back to the original estimates of total national emissions from the coal-AMAP/UNEP inventory work (mercury content of coal ca. 0.3 g/t; from Masekoameng et al., 2010). This was considerably higher than that for most other countries, including the global default values (0.06–0.15 g/t) applied in the AMAP/UNEP inventory work in the absence of specific national factors. As a result, the national total emissions from this sector for South Africa is relatively high compared with other countries with similar levels of activity. Since the national total forms the basis for the emissions allocated to individual facilities for that sector, these facilities are assigned a per plant annual emission that is correspondingly high (in the case of South Africa, which is a country that is highly reliant on coal for energy production, a factor of ca. five more than might be expected taking account of application of control technology alone).

Fig. 3(a) also reflects the influence of ‘technology profile’ (factor iii in the list above) on the per facility emissions levels. The countries in the top of the graphic (USA, Canada, Japan, Republic of Korea, most EU27 countries, China and Australia) are associated with the country groups operating coal-fired power stations with more effective emission control technologies. In general, these countries have lower per facility emission levels than countries assigned to regions that are assumed to have a lesser degree of application or less efficient emission control technologies (the

Fig. 2. Example of different approaches to geo-spatial distribution of power plant emissions: (a) emissions reported in the European Pollution Release and Transfer Register (E-PRTR); (b) AMAP/UNEP 2010 emissions estimate distributed using population distribution as a proxy; (c) as (b) but using the power plant emissions 'proxy mask'; (d) as (b) but using the scheme developed under this work.

latter also include some EU countries (labelled *EU27 tc 2–4*)).

Under the assumptions made regarding applied emission control technology in different country groups (AMAP/UNEP, 2013) it might be expected that per facility emission rates would generally be higher for those countries with less (effective) applied emission control technology. This would be reflected in the graphic by higher values for countries at the bottom of the graphic than those at the top of the graphic. This of course does not take into account other factors such as differences in the mercury content of fuels burned, etc.). On this basis, the per plant emissions in Russia (mainly based on values reported in a recent UNEP study (UNEP, 2011)) appear comparatively low; but these low values are consistent with the assignment of the total mercury emissions for this sector in Russia (ca. 8200 kg) between a relatively large number (128) of identified coal-fired power plants.

The (methodology dependent) emission rates for power-plants in China (bar labelled China) can be compared with measured/estimated plant emissions reported in literature (Zhang et al., 2008; Wang et al., 2010) (bar labelled China lit). The median and range of the latter (median 57.8, range 6.4–487) are somewhat lower than the median and range (median 180, range 9–990) represented by the plant emissions assigned in this work, however the values are not incompatible and the ranges overlap. It is likely that the higher values assigned in this work are, at least in part a result of the existence of a number of coal-fired power plants in China that are not included in the (public domain) resources used to identify Chinese power plants in this work. New coal-fired power stations are being built in China at an unprecedented rate, many of which are equipped with advanced emissions control systems (Zhao and Chen, 2014). It is therefore likely that a number of these are not

Fig. 3. Box-and-whisker plots of per facility emission rates inferred from assignment of national emissions to point sources in (a) the coal-fired power sector; (b) cement production sector; (c) (primary) ferrous metal production sector; (d) (primary) non-ferrous metal production sector. The mean emission value is represented by the small circle. The whiskers extend to the most extreme data point within the inner-quartile range * 3. Values outside this range plotted as + symbols.

represented in the list of Chinese coal-fired power plants identified in this work. The effect of incomplete identification of relevant point sources will be that the total emissions from the sector will be distributed between too few point sources, and therefore emissions for individual plants that have been identified will be exaggerated. In terms of the geo-spatial distribution of emissions produced in this work, this effect may be mitigated if the spatial distribution (and relative emission levels) of the point sources that are identified and those that are ‘missing’ are reasonably consistent. That is, the effect will be one of scaling on individual plants rather than a systematic bias in the spatially gridded emissions.

The distribution of assigned emissions for the United States is also worth considering. Here the distribution shown in Fig. 3(a) essentially reflects the reported point source emissions that are registered in the US-NEI, for more than 2400 individual ‘sources’. Here it is necessary to appreciate that (unlike other countries) the total emissions from a single site/facility may be split between

individual ‘point sources’ (e.g. individual boilers, release points, etc.). Consequently, single reported emission values tend to be lower than the (combined plant) emission values for other countries. This has no effect on the geo-spatial distribution work, but does introduce an inconsistency in the statistical representation of facility level emissions in Fig. 3(a).

3.4.2. Cement production plants

Fig. 3(b) presents a summary of the assigned (per facility) emission rates for cement production plants. In this figure, again there is a tendency towards higher rates of emissions from plants in countries that, on the basis of available information or related-assumptions are considered to apply less effective emission control technology (for example cement plants in Egypt and India). The relatively high values assigned to cement plants in China are likely due to the incomplete identification of relevant facilities in China (leading to an over-estimation of the emissions for those facilities

that have been identified, as discussed above).

The available information on cement production facilities obtained from CemNet (see Table 1) includes an indication of fuels used as well as plant production capacity, but not (annual) mercury emission estimates. However, for a number of cement plants in North America, Europe and Australia, it was possible to associate facilities listed in the CemNet resource with those listed in national PTRs. On this basis, it was possible to combine plant fuel and capacity information with reported emission estimates and calculate corresponding (abated) emission factors for plants using different fuels. Resulting emission factors were 8.4 kg/Mt (range 6.8–10), 18.7 kg/Mt (range 3.3–71.7) and 35.5 kg/Mt (range 0.02–132) for facilities using gas, coke and coal, respectively; and 28 kg/Mt (range 0.1–176) for plants co-combusting waste (with conventional fuel undefined). The majority of the plants included in these calculations have capacities of between 0.5 and 2.5 Mt/a, implying corresponding plant emission rates of the order of 10–100 kg/a. The fact that these values are consistent with the results presented in Fig. 3(b) for this group of countries supports the use of plant capacity as a surrogate for use in assigning emissions to individual cement plants.

3.4.3. Ferrous and non-ferrous metal (primary) production plants and smelters

With some exceptions, the distributions of (per facility) emission rates for ferrous and non-ferrous metal production facilities in different countries/regions (examples in Fig. 3(c) and (d), respectively) generally conform to an expected pattern of lower emission rates in countries with more advanced emission controls (typically applied to a few larger plants). This can be compared with the situation in other countries, especially those where a significant part of the non-ferrous metal smelting may still be conducted using practises lacking any significant emission controls. In the case of ferrous metal plants, China again stands out with plants with anomalously high inferred emission rates, likely due to an under-identification of relevant point-sources for this country (see discussion of coal-fired power plants, above). This reinforces the justification for applying a maximum (per facility) emission rate in any repeat of this work to ‘cap’ the possible emissions from an individual point source. However, as discussed previously, this was not done in the current work as no practical method was identified for establishing such a cap. In terms of the geo-spatial distribution, application of an arbitrary maximum facility emission rate would mean that a greater amount of the national sector emissions estimates would need to be treated as ‘diffuse emissions’ and distributed using some relevant surrogate rather than assigning them to specific point sources.

3.5. Reporting thresholds

Most of the available national PTRs that report emissions (some derived from measurements) for individual facilities apply a reporting threshold, i.e., a threshold below which facilities are not obliged to report their emissions. The E-PRTR, for example specifies a reporting threshold of 10 kg/a (reporting from facilities with lower annual emissions is voluntary), and the Canadian PRT ca. 5 kg/a (with other criteria also applied, such as the number of people employed at a given plant). The application of such thresholds means that smaller point sources may not be accounted for in the PTR datasets. A consequence for the applied methodology is that emissions that should be associated with smaller plants may be attributed to larger facilities.

The US-NEI does not apply a reporting threshold (it includes sites with mercury emissions estimated at less than 1 g/a). Some 4% and 6.9% of the emissions included in the US-NEI are associated

with individual reported emissions less than 5 kg/a or 10 kg/a, respectively. If these observations are extrapolated to other PTRs (such as the E-PRTR) it might be assumed that these PTRs could be missing some 5–10% of the actual emissions that occur within the countries covered by this PTR.

4. Conclusions and future work

The fundamental purpose of this work was to investigate the utility of (publicly) available information on emission point-sources as a basis for improving the geospatial distribution of mercury emissions at the global scale.

The results illustrate that a number of relevant information resources exist and that these can be used for the purpose described. At the same time the work identifies a number of considerations and limitations that need to be taken into account. These include several assumptions that are necessary in order to employ the available information in a useful manner with respect to assigning emissions to specific point sources or (grid cell) locations.

Most web-based resources and national PTR inventories include latitude/longitude coordinates that proved sufficiently accurate that these could be used directly to associate point sources with a particular grid cell in the ($0.5 \times 0.5^\circ$) grid used for the geo-spatial distribution work. By contrast, cement plants/kilns extracted from the CemNet database (see Table 1) lacked coordinate information; however, most did include address information, and reverse geo-coding (identifying coordinates from addresses) was used to assign coordinates.

Using these approaches, it is still likely that a (small) number of plants will be incorrectly located, and this has to be accepted. Large industrial facilities and power stations are relatively easy to locate on satellite imagery and a number of plants were checked using, e.g., Google Earth to correct or make their coordinates more precise where necessary. For the intended geo-spatial distribution work it is only necessary to place a plant within the correct grid cell; however point sources were located as accurately as possible so that they could be reassigned if the resolution of the distribution grid is changed at some point in the future.

In the work to geospatially distribute the 2010 global mercury emissions inventory, the procedures developed substantially increased the proportion of the global emissions that could be assigned to sources at known locations, as opposed to emissions that have to be treated as ‘diffuse’ emissions (i.e. emissions associated with non-point sources or, more pertinently, sources associated with point sources where the locations of these sources are not known).

The improvements in identification of relevant point-sources were particularly notable with respect to continental regions of South America, Africa, South and Eastern Asia, and Oceania when compared with similar activities used to geo-spatially distribute the 2005 global emissions inventory. This is illustrated in Fig. 4, which shows the point-source data coverage available when distributing the 2005 global inventory (left panel), and (right panel) that used in the current work to geo-spatially distribute the 2010 global mercury emissions inventory. As well as the work described in this paper, these improvements reflect contributions by national experts to identify point sources in several countries (including Australia, Brazil, Japan, Mexico, Republic of Korea) in support of the preparation of the 2010 global inventory.

Major point-source emission sectors addressed in this paper account for about 850 tonnes of mercury emissions included in the 2010 inventory. Based on the work reported here, more than 90% of this total was allocated to point locations that were then used in the geospatial distribution. This can be compared with less than 20% of (a similar total amount of) emissions assigned to point sources in

Fig. 4. Improvement in point-source coverage available for use in distribution of the 2005 (left) and 2010 (right) global mercury emission inventories.

the geospatial distribution of the previous (2005) global inventory.

Using point source attribution to associate national emissions estimates with actual facilities results in an emissions distribution that reflects actual emission patterns to a better extent than can be achieved by treating (point source) emissions as 'diffuse emissions' for the purposes of geo-spatial distribution for the reasons discussed in Section 3.3.

It is difficult to validate individual plant emissions against estimates derived using the methods described here as this would involve comparison of assigned emissions with reported values that are themselves a component of the emission attribution process. Some limited comparisons have been made for Chinese coal-fired power plants as discussed in Section 3.4.1. It was recognized that one artefact of the procedure applied was the potential to over-attribute emissions at individual point sources under certain conditions. This can occur when, as suggested in the case of Chinese coal and cement plants, the number of point sources identified within a country is probably incomplete. It can also occur where reported emissions are available for most but not all facilities in a country where the total reported emissions are lower than the national inventory estimate. The authors considered applying a maximum possible emission value for any given point source to avoid this situation, but decided not to do so because it was beyond the scope of this work to identify the appropriate maxima for the various countries and sectors concerned, and a globally applied 'cap' would have been too arbitrary. In future applications, this part of the workflow may be revised to address potential anomalies.

This paper describes the latest developments in activities to geospatially distribute mercury emissions inventories compiled under AMAP and UNEP. The resulting geospatially distributed datasets are available from <http://www.amap.no/mercury-emissions>. These activities have, however not been continuous but rather follow the periodicity of work to compile global mercury emissions inventories (approximately once every five years). If inventories were produced at more frequent intervals then more systematic approaches to the work to compile relevant point source information and use it to geospatially distribute these inventories could be envisaged.

Much information exists for individual facilities; however, in order to use this information in a global or large regional scale context, initiatives are needed that compile and organize this information in a compatible and usable manner, and preferably also make it freely-available in the public domain. Ideally, these information compilations should include information that:

- Characterizes the facility in terms of its production, technology (including control technology), fuels and raw materials, etc.;
- Accurately geo-locates the facility (latitude/longitude co-ordinates with a precision of better than a few kilometres);

- Where possible, provides facility-level (mercury) emissions, and if available at better than annual resolution to support, e.g. seasonal air transport modelling work;
- Is updated to reflect the current operational status of the facility (in terms of its production, installed technology, etc.)

Lack of systematic maintenance of information of this type is the primary obstacle to application of the type of methods described in this paper to spatially distribute previously compiled global emission inventories in a comparable manner. Some such initiatives are conducted at the national level, in those countries/regions that maintain geo-located PTRs, however these initiatives are currently largely restricted to Europe, North America and a few other countries. Hopefully such initiatives will be established or expanded in more countries as part of their (voluntary) activities to implement the Minamata Convention.

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