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IN-DEPTH REPORT 15

Tackling mercury pollution in the EU and worldwide

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Environment

Science for Environment Policy

Tackling mercury pollution in the EU and worldwide

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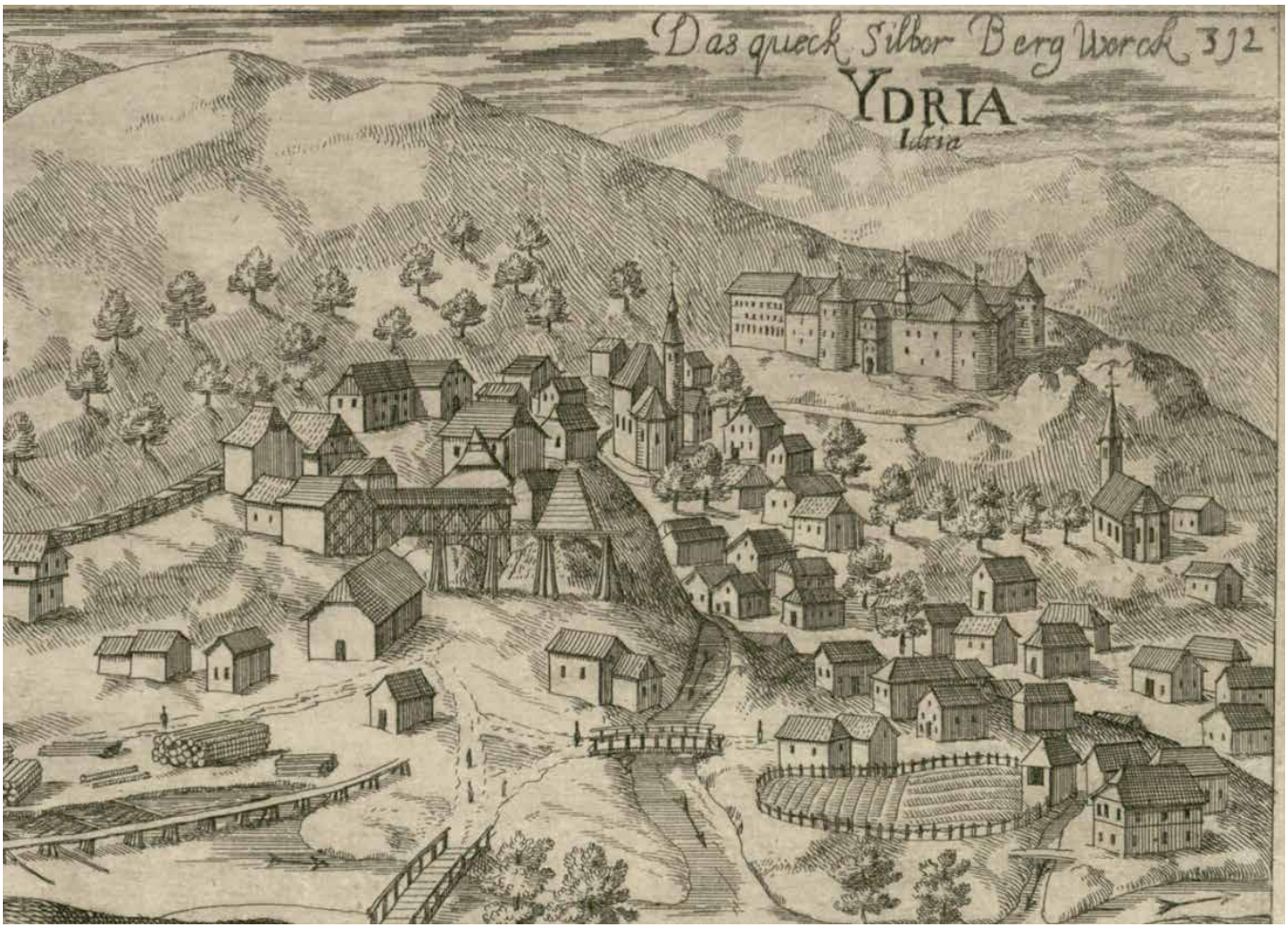
Executive summary



Mercury mine in Idrija, Slovenia, 1679, by Johann Weikhard von Valvasor (1641-1693). Wikimedia Commons. Public domain.

Mercury (**chemical symbol Hg**) is a heavy metal occurring on earth in various forms. It can be converted from one form to another by natural processes, and, once released, actively cycles in the environment for hundreds to thousands of years before being buried in sediment. It is well known for being the only metal that is liquid at room temperature and normal pressure. Mercury is also a potent neurotoxin with severe global human health impacts.

This In-Depth Report from Science for Environment Policy summarises the latest scientific studies and research results on mercury pollution in the global environment. Of the many aspects of mercury pollution, five main topics are addressed:

- Mercury sources and impacts
- Mercury cycling: movement and deposition
- Monitoring and modelling approaches
- Reduction, treatment and storage
- The Minamata Convention on Mercury and the EU mercury policy

i. Mercury emissions: sources and causes

Mercury is released into the environment from both natural and anthropogenic sources. Natural sources of mercury include volcanic eruptions, emissions from the ocean, deposits of cinnabar (where mercury is bound with sulphur) and trace amounts in coal. Volcanic eruptions over the past 270 years have contributed around 6% of the mercury emitted into the atmosphere (Krabbenhoft and Schuster, 2002). Humans have also released mercury to the environment for millennia (Amos *et al.*, 2013). Cinnabar, its main ore, was in previous centuries used widely in architecture, jewellery, alchemy, medicine and as a pigment. It was mined in Europe in places like Almadén in Spain, Idrija in Slovenia and Monte Amiata in Italy. Mercury compounds were used historically for various medical purposes: as laxatives, diuretics, antiseptics, teething powders, and as antimicrobial drugs for syphilis, typhoid and yellow fever.

There are three chemical forms of mercury:

- elemental or metallic mercury (Hg^0)
- inorganic mercury (mercurous ($Hg2^{2+}$) and mercuric (Hg^{2+}) cations)
- organic mercury (with at least one carbon bonded to a mercury atom)

We now know that doses that we thought were safe in the past are certainly not safe... We're now concerned about exposures that are highly prevalent in seafood consumers worldwide.
Philippe Grandjean, in Kessler, 2013.

Cinnabar on Dolomite. JJ Harrison, 2009. CC-BY-SA 3.0 Unported https://commons.wikimedia.org/wiki/File:Cinnabar_on_Dolomite.jpg

Once released into the environment, elemental mercury undergoes a series of complex transformations and cycles between atmosphere, ocean and land. Consequently, there is a global 'pool' of mercury circulating between air, water, sediments, soil and living organisms.

Inorganic mercury, meanwhile, can be converted to an organic compound, methylmercury, made of a 'methyl group' of hydrogen and carbon atoms plus a mercury ion. It is by far the most common form of mercury in the food chain, and is the bioaccumulative environmental toxicant responsible for the acute methylmercury poisoning seen at Minamata Bay and in a number of other historical instances of mercury poisoning.

Methylmercury can be formed from inorganic mercury by the action of anaerobic organisms that live in aquatic systems including lakes, rivers, wetlands, sediments, soils and the open ocean. This methylation process converts inorganic mercury to methylmercury in the natural environment.

In the past, methylmercury was produced directly and indirectly as part of several industrial processes

such as the manufacture of acetaldehyde, which was used in the production of various polymers useful for industry. It is also an indirect consequence of the burning of fossil fuels, particularly coal, and from the burning of wastes containing inorganic mercury.

The most significant source of methylmercury exposure for humans is via eating fish and aquatic species. Very high doses of methylmercury (not normally associated with eating fish) can be fatal to adult humans, but even relatively low doses, which could arise from the consumption of fish, can have a profound effect on the prenatal nervous system and developing foetuses.

ii. Mercury in industry

Mercury is released into the environment by humans during various activities, e.g. the burning of fossil fuels, alternative fuels and waste materials such as old tyres, and in the production of cement and some metals, such as gold (see Table 1). In 2010 alone, human activities are estimated to have released 1 960 metric tonnes of mercury into the atmosphere and at least 1 000 metric tonnes into the oceans.

According to a UNEP report (2013a), the largest source of mercury emissions from human activities is artisanal and small-scale gold mining (ASGM). This currently accounts for more than 37% of total anthropogenic emissions to the air. Mercury's continued use in this area raises issues of economic inequality and public health communication. These are issues that would benefit from further scientific and international collaboration (Zuber and Newman, 2012; Spiegel *et al.*, 2014).

The second largest emission source is coal burning, mostly for power generation and industrial use. In 2010, coal burning emitted approximately 475 tonnes of mercury. Other sources of mercury emissions are the production of ferrous (iron-containing) and non-ferrous metals such as gold, aluminium, copper, lead and zinc. Mercury is recovered from the purification of gases emitted during the production of these metals.

Mercury remains in use in scientific research applications and in dentistry, which uses some 340 tonnes per year — of which 70-100 tonnes enter the solid waste stream. Emissions resulting from dental amalgam in human remains were estimated at 3.6 tonnes in 2010.

The chlor-alkali process, cement production and mercury-added products represent further sources of environmental mercury, all of which are addressed by EU legislation and the Minamata Convention.

Asia is the largest current source of atmospheric mercury emissions, with China contributing a third of the global total (UNEP, 2013a). However, mercury tends to linger in the environment — and a recent modelling study estimated that half the mercury pollution in the surface layer of the ocean today came from emissions prior to 1950, when U.S. and European contributions exceeded those from Asia (Amos *et al.*, 2013).

iii. Mercury impacts: damage to life

Mercury is a highly toxic, naturally occurring metal that causes significant harm to both human and ecosystem health. Mercury poisoning can result from exposure to water-soluble forms of mercury (such as mercuric chloride) or inhalation of mercury vapour, or eating seafood contaminated with mercury.

When consumed, mercury produces significant adverse effects in humans and is particularly dangerous to foetuses, infants, and young children. Mercury poisoning, or hydrargyria, is poisoning caused by exposure to the metal or its compounds, which, especially the organic ones, could be more toxic than the element itself.

Effects include damage to the kidneys, liver and lungs, but mercury is primarily a neurological poison, causing tremors, extreme mood changes and eventually loss of hearing and restricted vision.

Associated diseases include acrodynia (caused by chronic exposure to mercury), Hunter-Russell syndrome (methylmercury poisoning) and Minamata disease (severe methylmercury poisoning). It is a cumulative poison, being removed from the body only very slowly; often, the effects are recognised only when it is too late.

"We now know that doses that we thought were safe in the past are certainly not safe… We're now concerned about exposures that are highly prevalent in seafood consumers worldwide." (Philippe Grandjean, in Kessler, 2013: 305)

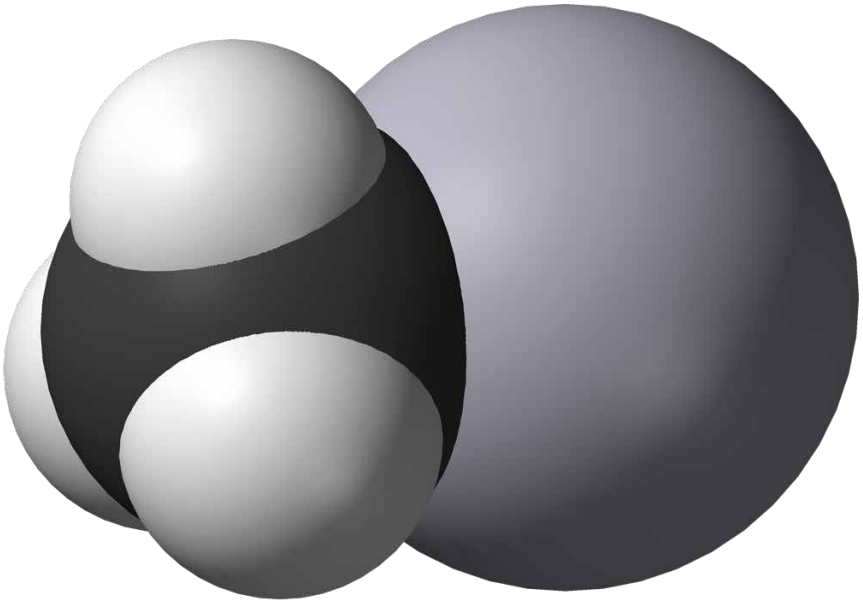
An area of rising scientific interest is how mercury builds up in the food chain, accumulating in higher species with the end result that top predators carry a substantial load of the toxin.

Even relatively low doses from the consumption of fish have been shown to have an effect on the nervous system. A report estimates that more than 60 000 children in the United States are born at risk of "adverse neurological development" due to exposure to methylmercury in the womb each year (National Research Council, 2000). The toxic metal can be passed on from mothers to unborn children by crossing the placenta, which affects the development of the embryo and growth throughout life. Moreover, mercury can also be passed to an infant through breast milk (Da Cunha *et al.*, 2013). A mother's consumption of fish and shellfish that contain methylmercury can affect a baby's growing brain and nervous system. Impacts including effects on cognitive thinking, memory, attention and language have been seen in children exposed prenatally to methylmercury.

The symptoms of poisoning are irreversible; however, they do not usually worsen unless there is new exposure. More attention has come to mercury's toxic effects via research following major public health crises and additional isolated instances of exposure to its compounds during the 20th century.

There is also evidence that mercury can increase the concentration of damaging free radicals in the body, possibly contributing to heart disease (Ercal *et al.*, 2001). Free radicals have a voracious 'appetite' for electrons that can change the structure of a molecule and therefore its ability to perform a function. They can increase the probability of a low-density lipoprotein (LDL) getting trapped in an artery wall, and potentially cause or contribute to cardiovascular disease.

Accumulation in food, particularly fish, is of major concern. People consuming a lot of fish are likely to accumulate more mercury in their bodies, but the mercury content of fish varies with type: species high in mercury include Atlantic bluefin tuna (*Thunnus thynnus*), swordfish (*Xiphias gladius*), weevers (*Trachinus*) and Atlantic bonito (*Sarda sarda*), among others. The European Food Safety Authority has used data from studies to provide advice on safe consumption levels and fish type (EFSA Scientific



Mercurous cation, Hg_2^{2+}. Wikimedia Commons. CC0.

Committee, 2015), but stresses that the applicable advice depends on the consumer, in particular on their age.

The risk to human health from dental amalgam is being addressed by new rules requiring dental practices in the EU to only use, as from 2019, dental amalgam in pre-dosed encapsulated form (the use of mercury in bulk shall be prohibited). From July 2018, the use of amalgam fillings for treatment of deciduous teeth, for children under the age of 15 and for pregnant and breastfeeding women will also be prohibited in the EU, unless deemed strictly necessary by the practitioner on the ground of special medical needs. From 2019, dentists will also be required to have amalgam separators to prevent the release of amalgam particles containing mercury, which will protect the environment and wildlife. In this respect, dental practitioners have the obligation to ensure that their amalgam waste is handled and collected by an authorised waste management establishment or undertaking. In addition, Member States shall have to set out a national plan by July 2019 on measures aiming at phasing-down the use of dental amalgam as a whole and the Commission shall report by mid-2020 on the feasibility of a phase-out of the use of dental amalgam.

Wildlife and ecosystems can also be damaged by mercury, especially through the process of bioaccumulation in the food chain. Aquatic birds and wildlife are particularly susceptible; therefore the Environmental Quality Standards Directive (2008/108/EC modified by Directive 2013/39/EU) sets environmental quality standards for mercury in both surface water and fish, with the intention of protecting higher-level predators from secondary poisoning through bioaccumulation.

iv. Movement and deposition of mercury

Human activities over the past few decades have led to **massive increases in mercury concentrations in the biosphere**, while some studies report that **re-emission of 'legacy mercury' from centuries-old deposits in surface reservoirs** may be responsible for up to 60% of emissions today (Amos *et al.*, 2013).

This mercury persists in the environment and moves around the world, cycling between atmosphere, land and water, with the atmosphere being the main transport pathway. The ease with which mercury travels means that any attempt to control it must be global in scale.

There is an increasing body of scientific evidence that recognises the potential importance of intercontinental flows of air pollutants. Mercury in its elemental, gaseous form can remain in the atmosphere for up to a year, while being transported globally. It can then be oxidised to a form that dissolves in water and is very readily deposited.

Previous work in the United States showed that while North American sources contribute only an average of 20% to domestic deposition overall, this fraction rises to 50% at locations downwind of major sources in the industrial Midwest (Selin and Jacob, 2008). European emissions contribute up to 60% of deposition to ecosystems in industrial areas of Europe. Intercontinental transport of mercury is a significant source of pollution causing up to 80% of deposition, particularly in regions with few local emission sources.

Along with these geophysical systems constraints, measurement is also difficult. Analysis of contaminated soil is complex due to uneven distribution of mercury, while meteorological effects can also distribute mercury unevenly across geographical areas. The poles are a particular area of study at present, with much research taking place into atmospheric deposition of mercury in the Arctic.

v. Monitoring and modelling mercury in the environment

A number of approaches are currently in use for monitoring levels of mercury in the environment. The satellite-based European Global Mercury Observation System (GMOS) project was designed to establish a worldwide observation system for measuring atmospheric mercury in ambient air and precipitation samples. GMOS completed its work

in October 2015; the resulting data is being used to validate regional- and global-scale atmospheric mercury modelling systems.

National data on mercury emissions have been compiled under the Convention on Long-range Transboundary Air Pollution (LRTAP), finding that emissions dropped significantly in most sectors between 1990 and 2014.

In the EU, mercury in water is measured through biota sampling, in accordance with the Environmental Quality Standards set out in Directive 2008/105/EC. Findings have shown that levels exceed the EQS in many places, though only continued monitoring will tell if improvements result from the implementation of new policies.

Studies have also looked at levels of methylmercury in fish for consumption (compared to maximum levels set out in Regulation (E.C.) 1881/2006, with mixed results. Coastal populations with high fish consumption were found to be most at risk from mercury exposure, according to a review by Višnjevec *et al.* (2014). Indeed, a human biomonitoring programme, DEMO-COPHES (CORDIS, 2013), has been implemented in the EU to look at exposure to four pollutants, including mercury. A 2013 study based on data collected indicated that economic benefits could be realised by addressing methylmercury exposure in Europe (Bellanger *et al.*, 2013). The Human Biomonitoring Initiative, HBM4EU, initiated in 2017, will build on this work and inform chemical risk assessment.

Novel sensor technology, global cooperation and networking will be a huge boon for data collection on the necessary scale. Advances in chemical analysis could help to unravel the complexities of mercury behaviour and help identify the source and fate of mercury at local, regional and global scale. Moreover, there is a need for more reliable and widespread data on levels of mercury in humans and wildlife, in order to understand fully its impact on health and ecosystems.

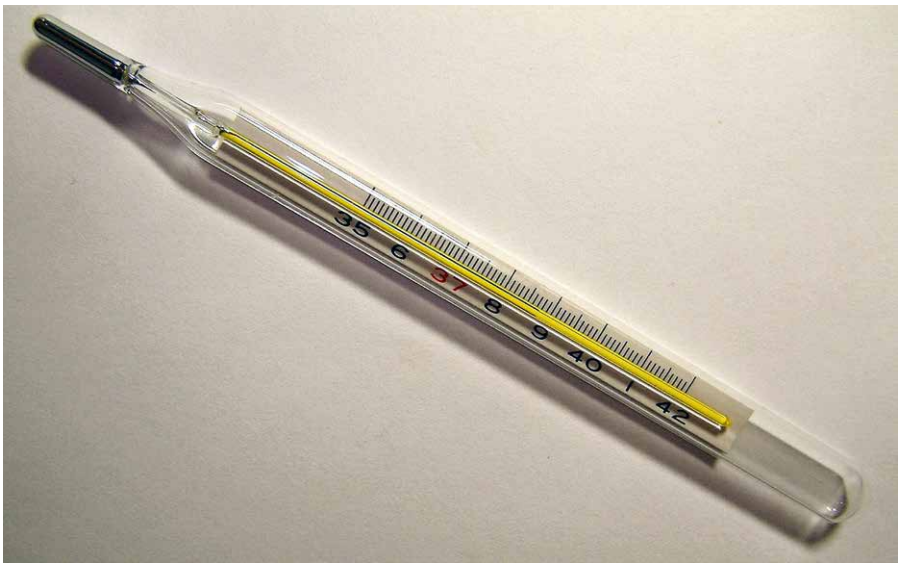
There is also a need for better models and estimates of atmospheric mercury emissions. Recent work, using the GEOS-Chem chemical transport model, has shown that there is a discrepancy between measured and modelled emissions (e.g. Song *et al.*, 2015). According to Subir *et al.* (2012), this is likely to be due to a combination of factors including (but not limited to) uncertainties in measurements, emissions inventories and mercury chemistry used in models.

There is some dispute among researchers over whether mercury has actually declined in the atmosphere since emissions controls began in the mid-1980s. Slemr *et al.* (2011) conclude that worldwide concentrations of mercury in the atmosphere decreased by 20-38% between 1996 and 2009, while Amos *et al.*'s (2013) figures show a sharp rise in anthropogenic emissions since 2000. Zhang *et al.* (2016) argue that emissions inventories underestimate the reductions in emissions resulting from the decline in atmospheric release thanks to emissions controls in the EU and North America.

vi. Reduction, treatment and storage of waste mercury

Today, mercury is still used in a number of scientific devices, although toxicity concerns have led to some being phased out in clinical environments in favour of alternatives. Mercury is also currently used in energy-efficient fluorescent light bulbs, though mercury-free LED technology is replacing these on a large scale. There remains a risk that mercury can be released to the environment when any of the mercury-containing items are broken, or if not recycled appropriately (e.g. Nance *et al.*, 2012).

The Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive) addresses the problem of hazardous substances in electronics. To comply with RoHS, items must contain no more than 1000 ppm of mercury by weight in homogenous material. Meanwhile, the Directive 2012/19/EU on



Clinical mecury thermometer. Menchi, 2005. Wikimedia Commons.

Waste Electrical and Electronic Equipment (WEEE Directive) regulates the separate collection and the treatment of electrical and electronic equipment at the end-of-life including mercury-containing equipment and mercury containing components. This includes gas discharge lamps, switches and backlighting lamps. The latter are components used in older LCD TV and computer displays, and contain an average 3.5mg of mercury (McDonnell and Williams, 2010).

Decision- and policymakers worldwide have also worked to formulate wide-ranging legal provisions for protection of human health and the environment via the Minamata Convention, which came into force in August 2017, and which requires party nations to control, reduce and in the long term eliminate emissions of mercury to the environment. So far, most countries worldwide have indicated their intention to comply with the Convention. The basis for the ensuing strategy must be accurate data on sources of the pollutant. Technology for data collection, monitoring, chemical analysis and computer modelling techniques is advancing rapidly, giving researchers tools that were unavailable even a decade ago.

Reducing industry's needs for mercury and decommissioning whole industries, such as the chlor-alkali sector, means that there will be an increasing need to store mercury waste safely without contaminating the surrounding area. Moreover, different technologies are needed to store the various forms of mercury.

The impact of reducing industry's reliance on mercury will have far-reaching effects on human health, the environment and economies. Costs of disposal as well as for remediation and cleaning of the environment will be high. One estimate of the costs of permanent disposal of mercury in Europe under sound environmental conditions is around €0.9–€2 / kg (Hagemann, 2009).

However, the costs of scaling down the use of mercury should be measured against the benefits to society in financial terms. Neurological damage and subsequent loss of intelligence quotient (IQ), for example, can result in the lowering of lifetime income and health levels. The cost of the damage and the benefit of remediation within the 2020 emission scenarios for anthropogenic emissions are in the same range according to Sundseth and Pacyna (2012).

On the biotechnology front, new techniques in genetics could harness bacteria to break down mercury compounds at specific sites where there is mercury contamination — from industrial plants to areas where mercury was, or is, being mined.

vii. The Minamata Convention and the EU

The Minamata Convention is a global treaty to protect human health and the environment from the adverse effects of mercury emissions and releases.

Box 1: The Minamata Convention

Mercury is recognised as a substance producing significant adverse neurological and other health effects, with particular concerns expressed about its harmful effects on unborn children and infants. The global transport of mercury in the environment was a key reason for the decision that global action to address the problem of mercury pollution is required.

In January 2013, the intergovernmental negotiating committee on mercury concluded its fifth session by agreeing on the text of the Minamata Convention on Mercury. The objective of the Convention is to protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds and it sets out a range of measures to meet that objective. These include measures to control the supply and trade of mercury, including setting limitations on certain specific sources of mercury such as primary mining, and to control mercury-added products and manufacturing processes in which mercury or mercury compounds are used, as well as artisanal and small-scale gold mining.

The text of the Convention includes separate articles on emissions and releases of mercury, with controls directed at reducing levels of mercury while allowing flexibility to accommodate national development plans. In addition, it contains measures on the environmentally sound interim storage of mercury and on mercury wastes, as well as contaminated sites. Provision is made in the text for financial and technical support to developing countries and countries with economies in transition, and a financial mechanism for the provision of adequate, predictable and timely financial resources is defined.

The coordinated implementation of the obligations of the Convention will lead to an overall reduction in mercury levels in the environment over time, thus meeting the objective of the Convention to protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds.

Named after the worst historical case of mercury poisoning, it details a set of measures to achieve a ban on new mercury mines; the phasing out of existing ones; control measures on air emissions; control of mercury-added products and manufacturing; measures on interim mercury storage, as well as regulation of artisanal and small-scale gold mining and of the handling of dental amalgam. The Minamata Convention's provisions are very similar to existing EU legislation on mercury; its overall goals are in line with the EU Mercury Strategy.

The Convention has been signed by 128 countries and regional economic integration organisations (127 countries plus the EU — as of October 2017) and has been ratified by at least 50 Parties, which led to its entry into force on 16 August 2017. The EU ratified it on 18 May 2017 and implemented it by means of a new mercury Regulation adopted on 17 May 2017, which complements the *acquis communautaire* on mercury and which contains provisions going beyond some of the requirements of the Convention. Countries that have so far deposited

their instruments of ratification, acceptance, approval, or accession, include China, Japan, Canada and the United States.

Ninety-six per cent of known atmospheric mercury emissions are within the scope of the Minamata Convention (Selin, 2014). The treaty addresses by-product or unintentional emissions of mercury as well as intentional uses of mercury. By-product emissions are a side effect of processes including coal burning, cement production and mercury mining. Intentional uses of mercury include uses in products (including some types of lamps, batteries, cosmetics, measuring devices, biocides and dental amalgam) and processes, such chlor-alkali production, and in activities such as artisanal and small-scale gold mining. Meetings are ongoing to discuss and determine the practical implementation of the Convention's articles. The Conference of the Parties will adopt documents to assist with implementation of the Convention.

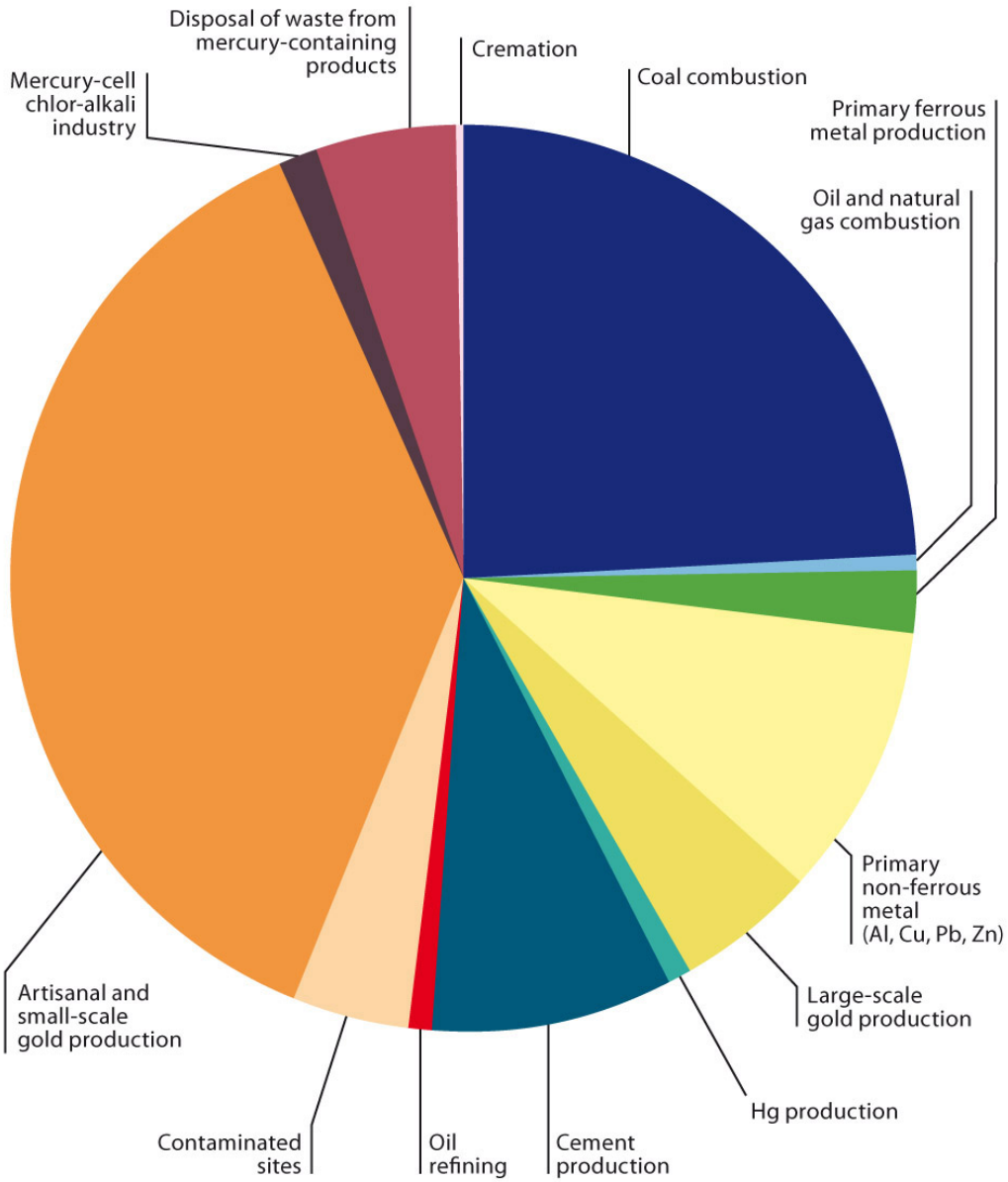
Minamata memorial. hyolee, Wikimedia Commons. CC-BY-SA 3.0.

Box 2. Articles of the Mercury Convention

The convention consists of 35 articles, which describe the obligations on party nations to reduce anthropogenic emissions and releases of mercury and mercury compounds to the environment. These articles can be grouped as follows:

- **Mercury operations:**
  - Controls on supply and on international trade in mercury (Article 3)
  - Phase-out and phase-down of mercury use in products and processes (Articles 4, 5 and 6)
  - Controls on artisanal and small scale gold mining (Article 7)
  - Control measures on air emissions and releases to water (Articles 8 and 9)
  - Storage, waste and contaminated sites (Article 10, 11 and 12)
- **Support to parties:**
  - Financial mechanism (Article 13) The Global Environment Facility Trust Fund A specific international Programme to support capacity building and technical assistance.
  - Capacity building, technical assistance and technology transfer (Article 14)
  - Implementation and Compliance Committee (Article 15)
- **Information and awareness raising:**
  - Health aspects (Article 16)
  - Information exchange (Article 17)
  - Public information, awareness and education (Article 18)
  - Research, development and monitoring (Article 19)
  - Implementation plans (Article 20)
  - Reporting – required by all Parties (Article 21)
  - Effectiveness evaluation (Article 22)
- **Administrative articles, which deal with the settlement of disputes, amendments**
- **Annexes.**

1. The global nature of the mercury cycle



Relative contributions to estimated emissions to air from anthropogenic sources in 2010.

Figure 1. Mercury emissions from man-made sources in 2010. Source: UNEP, 2013. Quantatitive data: see Table 1, next page.

1.1 Primary and secondary sources of mercury

Mercury (chemical symbol Hg) is a heavy metal occurring naturally on earth in various forms. It is known for being the only metal that is liquid at room temperature and normal pressure.

Humans have emitted and released mercury to the environment for millennia (Amos *et al.*, 2013). A major complication in estimating mercury emissions is the difficulty distinguishing between primary and secondary sources. Primary sources are from long-lived reservoirs below the surface of the Earth,

Sector	Emission (range), tonnes*	%**
By-product or unintentional emissions		
Fossil fuel burning		
Coal burning (all uses)	474 (304 - 678)	24
Oil and natural gas burning	9.9 (4.5 - 16.3)	1
Mining, smelting, & production of metals		
Primary production of ferrous metals	45.5 (20.5 - 241)	2
Primary production of non-ferrous metals (Al, Cu, Pb, Zn)	193 (82 - 660)	10
Large-scale gold production	97.3 (0.7 - 247)	5
Mine production of mercury	11.7 (6.9 - 17.8)	<1
Cement production	173 (65.5 - 646)	9
Oil refining	16 (7.3 - 26.4).	1
Contaminated sites	82.5 (70 - 95)	4
Intentional uses		
Artisanal and small-scale gold mining	727 (410 - 1040)	37
Chlor-alkali industry	28.4 (10.2 - 54.7)	1
Consumer product waste	95.6 (23.7 - 330)	5
Cremation (dental amalgam)	3.6 (0.9 - 11.9)	<1
Grand Total	**1960 (1010 - 4070)**	**100**
**Values rounded to 3 significant figures.* ***To nearest percent.*		
Sectors for which emissions are not currently quantified		
biofuel production and combustion		
vinyl-chloride monomer production, emissions during		
secondary metals production and ferro-alloys		
oil and gas extraction, transport and processing other than refinery emissions		
industrial / some hazardous waste incineration and disposal		
sewage sludge incineration		
preparation of dental amalgam fillings and disposal of removed fillings containing mercury		

Table 1. Mercury emissions from various sectors, in tonnes per year with the range of the estimate, and as a percentage of total anthropogenic emissions, from the UN 2010 assessment. Note: These numbers cannot be compared directly with those presented in the 2008 assessment. From UNEP 2013.

which can be emitted through volcano eruptions, for example. Secondary sources are those that occur when mercury is re-emitted from depositions, either through natural processes or human activity. Recent models, using a fully coupled ocean-atmosphere model and including emissions prior to 1850, indicate that **primary natural sources account for up to one half of the mercury emissions to the atmosphere**. One simulation estimates that 350 000 tonnes of mercury has been emitted as a result of human activity over all time. Of this amount, 39% was emitted before 1850 and 61% since 1850 (Streets *et al.*, 2017).

Mercury persists in the environment for a long time, meaning that previously emitted anthropogenic mercury has a large influence on the current global cycle and probably represents about one-third of present-day emissions to the atmosphere. Understanding and managing mercury already circulating in the global land surface and oceans is an ongoing, long-term challenge (Selin, 2014).

There are many natural sources of mercury, including minerals such as cinnabar, which is mined to extract mercury, but much of the current demand for mercury is met by industrial sources and stockpiles rather than mercury mining (UNEP, 2013b). Mercury is also present as an impurity in many economically valuable minerals, in particular, non-ferrous metals. In the hierarchy of human sources, artisanal and small-scale extraction of gold from ore using mercury is the main source of mercury emissions (see Figure 1), followed by coal burning and then activities that process ores or produce cement.

Figure 2 illustrates how global industrialisation is responsible for significant 20th century increases in mercury emissions. On a global level, Asia currently accounts for more than 40% of total emissions, a figure which is increasing. The contribution of volcanic activity, such as that from Krakatau, can also be seen.

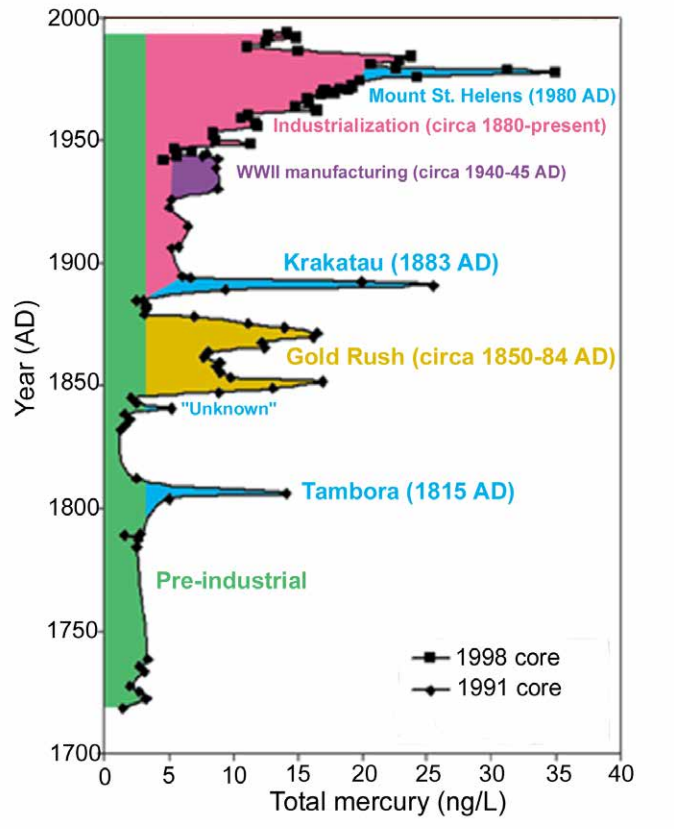


Figure 2. Mercury emissions over the last three centuries. The green area represents background mercury emissions. Source: (Krabbenhoft 2002).

1.2 The mercury cycle

The global nature of the mercury cycle, as well as the many different forms that it can take in the atmosphere, oceans, rivers, soil and living organisms, makes it difficult for policymakers or stakeholders in its related industries to address the damage it causes to health and ecosystems.

The Earth's atmosphere is not just a mixture of gases. According to Ariya *et al.* (2009), the interchange of molecules, particles and other pollutants like smoke between clouds, fog, snow and air, complicate the issue of mercury travel and pollution. In the atmosphere, mercury can exist as particulate matter, or as mercury vapour, which can circulate for up to a year, becoming widely dispersed over the surface of the Earth.

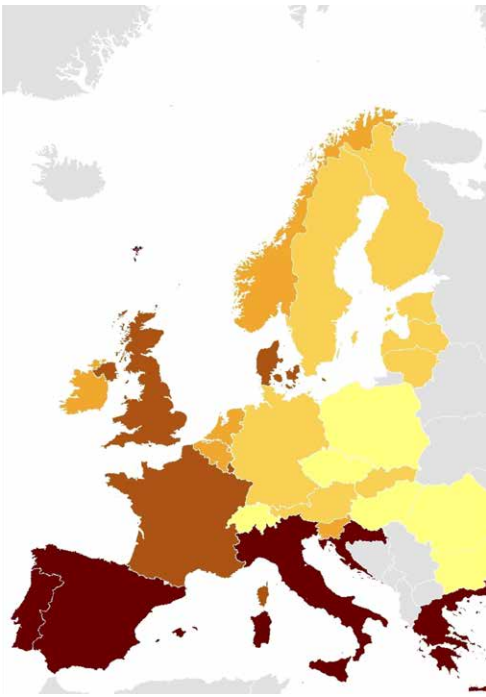
Eventually mercury in its inorganic form can combine with water vapour to fall back to the surface of the Earth as rain, ice or snow, which is then deposited into soils and water. In the absence of precipitation, mercury also reaches the ground, buildings, tree canopies or water through dry deposition of small particles. In soils, mercury will accumulate until an event causes its release, while in the oceans it tends to settle out into the sediment over time. However, in both those locations it can also be converted into methylmercury (CH_3Hg) by anaerobic organisms.

Methylmercury is particularly toxic, as it is easily absorbed in the digestive system of humans and transported freely throughout the body. It can pass across the blood-brain barrier and is of particular concern to pregnant women, since it can pass through the placenta, where it is absorbed by the developing foetus.

1.3 Mercury and the food chain

Concerns over the effects of methylmercury revolve around the fact it can enter and accumulate in food webs far more readily than other forms of mercury. As can be seen in Figure 10 (pages 36 & 37), methylmercury is taken up from plankton by small fish. As larger fish eat smaller ones, methylmercury is concentrated up the food chain, a process known as biomagnification. The end result is that humans, birds of prey, beavers, otters, bears and other top predators carry a much larger load of the toxic metal than the animals and plants at the bottom of the food chain.

High doses of methylmercury (not associated with eating fish) can be fatal to humans, but even relatively low doses from the consumption of fish can have an effect on the nervous system. Studies have also shown possible links with damage to cardiovascular, immune and reproductive systems (National Research Council, 2000).



1.4 Health effects and society

Recent research has estimated that 1.5 to 2 million children in the EU are born with exposure to methylmercury above a safe limit recommended by recent studies, of 0.1 micrograms per kilogram of body weight (equivalent to a concentration of 0.58 micrograms per gram (µg/g) in hair, when analysed) (Bellanger *et al.*, 2013). Of these, 200 000 have been exposed to levels above the World Health Organisation's recommended maximum hair concentration of 2.5 µg/g. However, not every child in Europe is equally at risk. When analysed per country, **children born in countries with high fish consumption, such as Portugal and Spain, received most exposure to methylmercury**, and Hungary the least.

The maps in Figure 3 show total mercury in children's hair throughout Europe (Višnjevec *et al.*, 2014).

1.5 Global strategy to control mercury emissions

At a global level, the Minamata Convention, named after the location of the worst-ever case of mercury poisoning, covers all aspects of the mercury life cycle. If properly implemented, it will have genuinely global effects.

Major policy changes which will result from the Minamata Convention include a ban on new mercury mines, the phasing out of existing ones, control measures on air emissions and international regulation of the informal sector for artisanal small-scale gold mining (ASGM).

1.6 EU strategy

The EU was estimated to contribute 4.5% to global anthropogenic mercury emissions to air in 2010 (AMAP/UNEP, 2013). The European Commission issued a Community Strategy Concerning Mercury (E.C., 2005) on 28 January 2005, which was subject to review in 2010 (BIO Intelligence Service, 2010; E.C., 2010). Since its launch, the EU has made significant progress in addressing the global challenges posed by mercury. The strategy addresses the bulk of the aspects presented by the mercury cycle and identifies 20 priority actions to be taken both within the EU and on a global basis. It has resulted in restrictions on the incorporation of mercury in products such as thermometers and electronic and electrical equipment (Directive 2011/65/EU on the restriction of hazardous substances in electrical and electronic equipment). Particularly important is a ban on mercury exports which came into effect in 2011 (E.C. 1102/2008), and new rules on the safe storage of mercury.

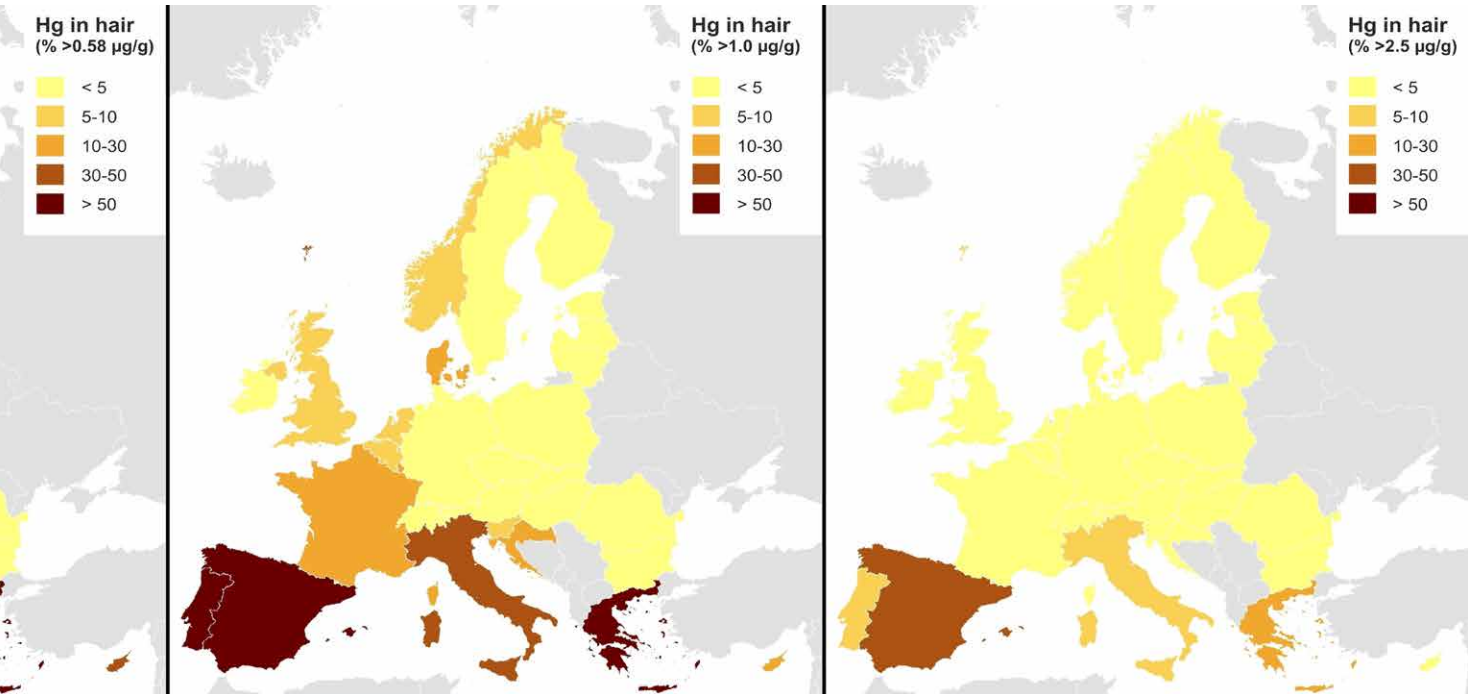


Figure 3. Total mercury in children's hair Europe-wide. Source: Višnjevec *et al.*, 2014.

In addition, as regards the treatment of waste from electrical and electronic equipment (WEEE), there is a specific requirement in Directive 2012/19/EU to remove mercury-containing components from all separately collected WEEE.

There are also restrictions on industrial processes using mercury. For example, companies using the chlor-alkali process or harvesting mercury from the cleaning of natural gas, or as a by-product from non-ferrous mining and smelting operations, need to declare the amount of mercury held each year. Overall, the measures have resulted in lower supply and demand for the element, and lower risks of exposure.

However, long-range transport of mercury means that exposure of Europe's population and environment cannot be reduced to an acceptable level through domestic policies alone, especially as regards methylmercury in fish and seafood. Coordinated international action is required to address the problem of mercury pollution on a global basis.

Map of Kumamoto Prefecture highlighting Minamata city. Borders of map as of July, 2006. Akanemoto. Wikimedia Commons

Box 3
The 'Minamata' incident

In the 1950s, one of the most serious incidents in the history of industrial pollution occurred on the Yatsushiro Sea coast in Japan. Over a period of almost 40 years, Chisso Corporation, a plastics manufacturer, released a total of 272 727 tonnes of mercury waste into the sea outside the city of Minamata. Local residents, who relied heavily on fish for food, were at high risk of exposure to methylmercury with every mouthful of fish. The high contamination levels in the people of Minamata led to severe neurological damage and killed at least 100 people, while thousands of people from the area suffered health problems or were left paralysed or permanently disabled (Kudo *et al.*, 1998). This form of mercury toxicity in humans is now called Minamata disease, after the location where the first patient of the disease was identified. In 1965, Minamata disease patients were also reported in the Agano River basin in Niigata Prefecture.

Symptoms include sensory disorders, loss of feeling or numbness in the hands and feet, muscle spasms, tunnel vision or blindness, smell and hearing impairments, and disequilibrium syndrome. More serious cases lead to convulsions, seizures, paralysis, coma and possibly death. In addition to the outbreak among adults, congenital Minamata disease was observed in babies born to affected mothers.

By the end of March 2001, 2 265 persons had been officially certified as suffering Minamata disease on the Yatsushiro Sea coast and 690 persons had been certified in the Agano River basin. Approximately 144.1 billion yen has been paid as compensation from the responsible companies.

For further details of the Minamata Incident and the effects of the disease, see Ministry of the Environment, Japan (2002), Minamata Disease: The History and Measures, and Takizawa (2005).

2. Mercury in industry

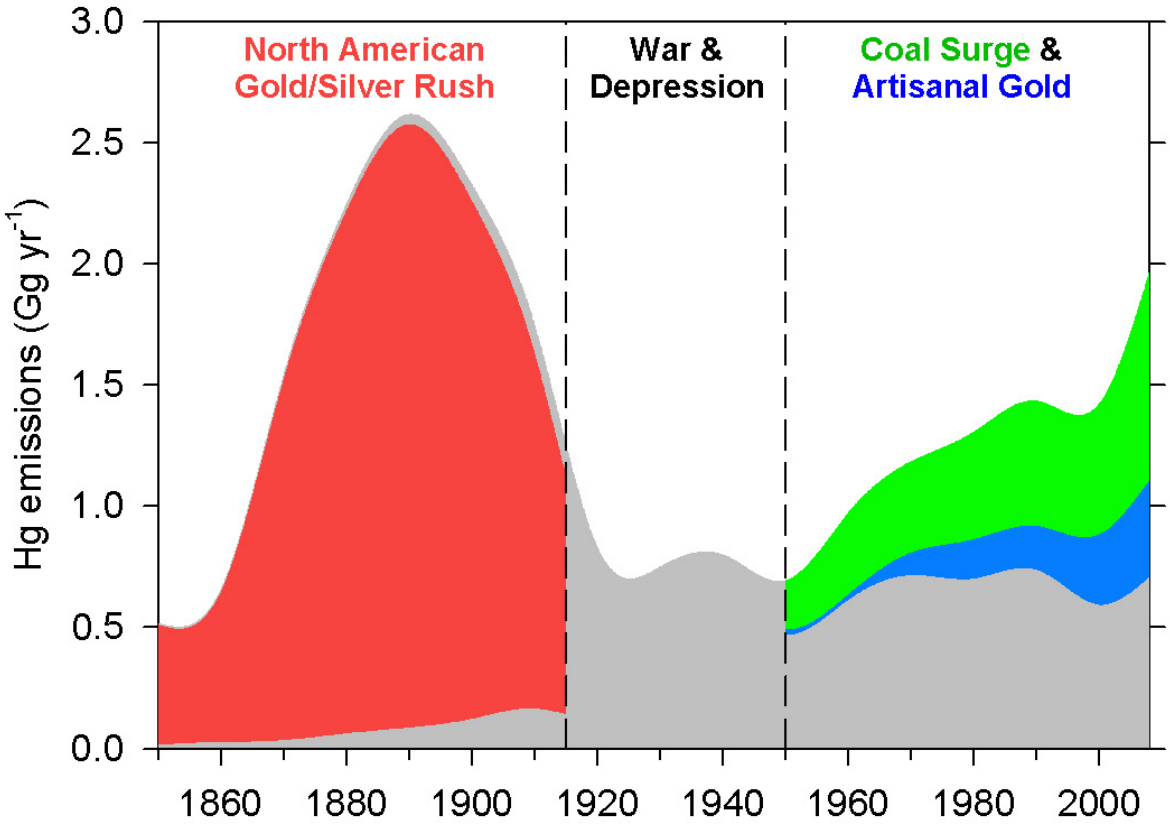


Figure 4. Three Phases of Historical Mercury Emissions. Source: Streets *et al.*, 2011. Note: Gg is gigatonne (1000 tonnes).

2.1. History and legacy

Figure 4 shows a graph developed by Streets *et al.* (2011) of the trend in global mercury emissions from 1850 to 2008. The major events — the Gold Rush, World Wars I and II and major industrialisation from around 1950 — are also shown in Figure 2 above.

As can be seen, anthropogenic emissions of mercury reached a peak of 2 600 tonnes per year in 1890 during the North American gold rush. Historically, mercury was used in mining processes to extract gold because mercury forms an amalgam with gold, whereby gold particles dissolve in the mercury. The mixture is then heated and the mercury evaporates (volatilises) into the air, leaving the gold. Small scale, 'artisanal' miners still use this process in places including the Amazon, and parts of Asia and Africa.

Between the First and Second World Wars, mercury emissions dropped to a rate of 700–800 tonnes per year. Emissions then rose steadily after 1950 to present-day levels of ca. 2000 tonnes per year. The estimate calculated by Streets *et al.* (2011 and 2017) for total mercury emissions from human activities over all time is 350 000 tonnes, of which 39% was emitted before 1850 and 61% after 1850.

For emissions due to coal, regional trends show that North America and Europe were the dominant emitting regions in the 19th century. Emphasis then shifted initially to Russia and then sharply to Asia after 1950. The study estimates that Asia was responsible for 64% of global mercury emissions in 2008.

Humans have emitted mercury to the atmosphere for millennia. When analysing data to devise a mercury strategy, legacy mercury, emitted from centuries-old surface deposits, must be taken into account. Amos *et al.* (2013) studied historic mercury emissions from Earth surface reservoirs over a period of 4 000 years. They propose that legacy mercury constitutes 60% of modern deposition, a figure backed up by figures comparing North American and European accumulated legacy mercury in the surface ocean. According to Sonke *et al.* (2013), legacy emissions from North America and Europe to global marine mercury make up 31% of the global reservoir, outweighing the 18% contributed by Asia. However, as can be seen from Figure 5, overall recent output from Asia is much larger than North American and European emissions combined.

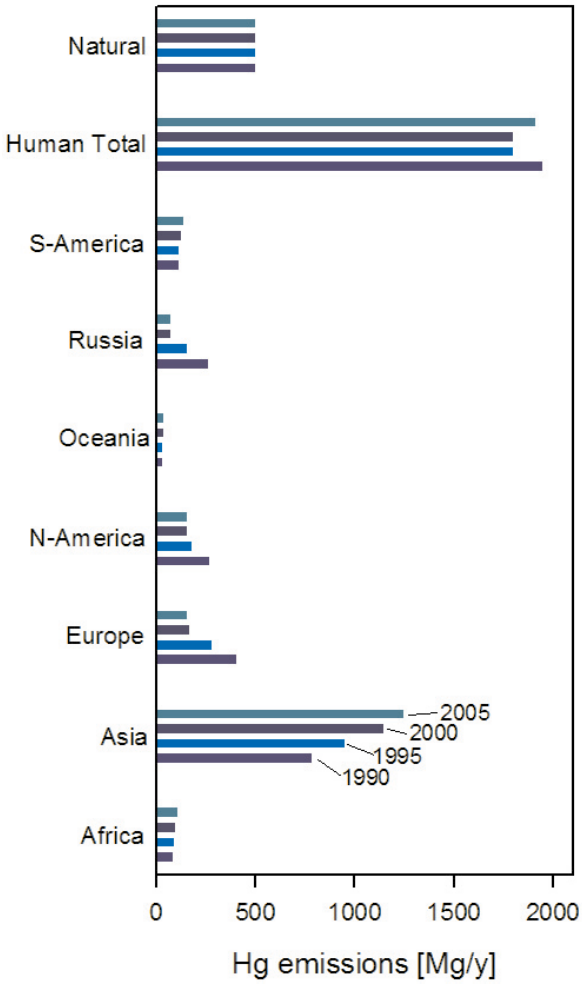


Figure 5: Revised estimates of anthropogenic mercury emissions to air (Mg/year) in 1990, 1995, 2000 and 2005 in different continents/regions. Source: Sonke *et al.*, 2013.

The implications of such research findings for decision-makers and policymakers are that new restrictions on mercury output must be hyper-stringent to offset the continuing contribution of legacy emissions.

2.2. Artisanal gold mining

Artisanal gold mining is the most significant source of mercury emissions globally (UNEP, 2011). Most artisanal gold miners are from socially and economically marginalised communities, and turn to mining in order to escape extreme poverty, unemployment and landlessness.

One study estimated that one or two grams of metallic mercury are released into the environment for every gram of gold produced using the amalgamation process (Timmins, 2001). When metallic mercury is used to dissolve and recover the gold, small amounts can also be washed out along with the unwanted tailings or sediments.

It is argued that mercury is used in artisanal mining because it is cheap, simple, fast, independent and reliable (Telmer and Veiga, 2009; Telmer and Stapper, 2012). As a first line of intervention, the researchers suggest it may be more appropriate to try to reduce mercury consumption through conservation practices like retorting, fume hoods, and mercury re-activation or cleaning (making dirty mercury usable again and thereby preventing it from being discarded into the environment), rather than immediately aiming for the total elimination of mercury use. The introduction of conservation practices can easily reduce mercury consumption by 50% to 90% and it is an easily accepted change in practice — one that can even have the powerful incentive of being profitable.

Artisanal small-scale gold mining (ASGM) takes place in more than 60 countries, mainly in Asia, South America, and Africa. Telmer and Veiga (2009) estimate that mercury amalgamation from this kind of gold mining results in releases (via water and land) of an estimated 650 tonnes of mercury per year

Madagascar: small-scale gold mining: The GEF and the Mercury challenge. Global Environment Facility. Flickr, 2008. CC-BY-NC-ND 2.0

(t/y), and emissions (via air) of an estimated 350 t/y. UNIDO (United Nations Industrial Development Organisation) estimates that ASGM constitutes more than 30% of the world's anthropogenic mercury emissions, and is the largest source of air and water mercury pollution. It has been estimated that there are between 10 and 15 million artisanal and small-scale gold miners worldwide, including 4.5 million women and 600 000 children (Main, 2013).

Recent measurements of mercury near an ASGM area along the Cikaniki River, West Java, Indonesia, were studied by Tomiyasu *et al.* (2013). Concentrations of mercury in the soil surface were up to 16.7 mg per kg (mg/kg) of soil in the village itself and up to 24.9 mg/kg in nearby paddy field soil, decreasing gradually further along the river. Such studies demonstrate the risk to human health and ecosystems in the vicinity of ASGM operations. Indeed, a number of studies have reported elevated levels of mercury in not only miners, but also in local inhabitants (Gibb and Leary, 2014).

2.2.1 Reducing emissions from the gold-mining industry

Under the Minamata Convention, parties with 'more than insignificant' ASGM and processing shall develop a national action plan outlining national objectives, reduction targets, and actions to eliminate whole ore amalgamation and open burning of amalgam as well as all burning of amalgam in residential areas.

Combined with regulations that ban new processing centres in outlying areas, there is evidence that the use of retorts led to a 10% reduction in mercury concentrations in the Segovia area of Colombia, over 2010, despite a 30% increase in gold production (Cordy 2013).

The US Environmental Protection Agency and the Argonne National Laboratory (ANL) have also released a construction manual for a low-cost, easily constructible technology called the Gold Shop Mercury Capture System (MCS). The MCS is constructed using a 55-gallon steel drum, where mercury vapour is cooled, condensed and collected as a liquid for safer management. It has been piloted by local collaborators in Brazil and Peru; data collected during site visits showed that facilities with the MCS technology installed had mean ambient mercury vapour concentrations that were five to 20 times lower than those shops that hadn't had the mercury control system installed, which suggests that the technology effectively reduces emissions.

2.3 Coal burning

Coal fired power plants are among the largest anthropogenic stationary sources of mercury emissions globally and in Europe. In 2008, UNEP reported that coal burning was the largest source of total anthropogenic emissions, and fossil fuel combustion contributed 45.6% to global anthropogenic emissions (UNEP, 2008). In 2010, the combustion of fossil fuels contributed 24.7% to global anthropogenic emissions (AMAP/UNEP, 2013).

More than 85% of these emissions are from power generation and industrial uses; power plants and industrial combustion together totalled 21.3% of anthropogenic emissions in 2010. In a previous assessment, emissions from domestic and residential coal burning were given greater prominence — but the more recent data shows that domestic coal use makes a relatively small contribution (2.9% of total in 2010).

Coal combustion is the largest source of anthropogenic emissions of mercury in the EU, North America and South Asia. Overall, coal-burning activities continue to increase, especially in China; at the same time, however, improvements are being made in the efficiency of energy production, and in the application of air-pollution-control technology at power plants. According to UNEP in 2013, these improvements are offsetting to a large extent the increase in Hg emissions that would otherwise result from the increases in coal combustion.

Coal power plant in Datteln (Germany) at the Dortmund-Ems-Kanal. Arnold Paul, 2006. Cropped by Gralo. Wikimedia Commons CC BY-SA 2.5.

2.3.1 Reducing emissions from the coal industry

Emissions of mercury from coal plants can be reduced by various methods. Washing the coal before it is fed to the boiler is one option, although this cannot remove all mercury. A study conducted in the USA showed there is a wide range of efficiency depending on the type of coal and the washing process. An advantage of washing is that there are no additional costs as these are compensated for by improved efficiency and reliability of the plant.

There are essentially three chemical forms of mercury involved in pollution and recycling: gaseous elemental mercury, oxidised mercury compounds, and the metal when it is attached to particles. An existing coal-fired power plant will normally be fitted with a device to filter out particles, an electrostatic precipitator or a fabric filter. The charged particles of mercury are soluble in water and therefore a relatively high percentage can be captured by the existing air-pollution-control devices that are used to control release of acid gases such as sulphur dioxide and nitrogen oxides.

According to the Best Available Techniques (BAT) conclusions for large combustion plants adopted in July 2017 under the 2010/75/EU Industrial Emissions Directive (Commission Implementing Decision (EU) 2017/1142), all new installations have to reduce emissions of mercury to below 3 micrograms per normal cubic metre (µg/Nm^3). Monitoring of mercury emissions to air must be carried out once every three months in plants with a thermal output under 300 MW_{th} (megawatts thermal), or continuously in plants with output higher than this. Monitoring of emissions to water should be undertaken at least monthly, and with the use of BAT should be an average of 0.2-3 µg/l (micrograms per litre), daily.

The emission standard proposed in the Aarhus Protocol on Heavy Metals is currently 30µg/Nm^3 — an easily achievable target in Europe. Although this standard includes flexibility to accommodate countries developing abatement technologies, it may be revised to be more stringent in future (UNECE, 2012).

If the standard is reduced, for example to 3 µg/Nm^3, some installations will need to take additional measures to remove mercury from stack gases, at a cost. These costs can be high, largely depending on the emission levels that have to be attained and on the number of installations requiring additional measures. However, in most cases in Europe, devices used to reduce other pollutants will coincidentally reduce mercury emissions, at no additional cost.

2.4. Mercury-cell chlor-alkali plants

The chlor-alkali industrial process uses the electrolysis of sodium chloride to produce sodium hydroxide (caustic soda) and chlorine: chemicals widely used in many industries. The process also produces hydrogen gas, which can then be used to produce hydrochloric acid or ammonia.

The process involves passing electricity through saltwater (brine), with mercury acting as the cathode to separate the sodium. This mercury-cell technology has been in use in Europe since 1892. Mercury-cell plants produce valuable, chlorine-free sodium hydroxide, but also use several tonnes of mercury within the cell. Most of this mercury is recycled through the cell, but a normal process will also emit over a hundred kilograms of mercury each year as waste product. Chlor-alkali plants currently operating with mercury technology were mostly built before the 1970s, with around 100 in operation globally (UNEP, 2012). Mercury cells are being phased out, due to concerns about their environmental impact.

Mercury used in the chlor-alkali process is required to be stored safely; in addition, chlor-alkali plants that have been closed need remediation and a method of safe storage for the large volumes of mercury removed from the plant. High levels of mercury contamination occur around decommissioned chlor-alkali plants and emissions from these contaminated sites can continue for long periods after operations have ceased (AMAP/UNEP 2013).

In 2010, mercury-cell chlor-alkali plants were responsible for 28.4 tons of mercury emissions, or

1.4% of all mercury emissions from anthropogenic sources (AMAP/UNEP 2013). This figure is falling, however, as plants are decommissioned; between 2005 and 2010 global mercury-cell chlorine capacity fell by about 30% (UNEP, 2012).

In the European Union, the amounts of mercury used in cells, temporarily or permanently stored by companies, and sent to waste facilities, needs to be reported to the European Commission each year, to track their whereabouts. In 2016, 43 chlor-alkali plants reported quantities of metallic mercury. The amount of total mercury kept on company sites (in cells or stored) has decreased since 2010, from 8 051.9 tonnes to 5 804.5 tonnes in 2016. EU legislation foresees the phase-out of this technology by the end of 2017.

2.4.1 Reducing emissions from the chlor-alkali industry

One viable alternative to mercury cells is membrane technology. As a membrane plant requires higher brine purity than a mercury-cell plant, additional treatment units are required, which means companies need access to adequate finance to invest in conversion. In addition, although the membrane technology is expensive, and every conversion is a localised case, the technology requires less electrical energy, and lower running costs. The payback period for the investment cost to replace an existing mercury-cell plant by a new membrane technology plant has been estimated at approximately 14.7 years if no particular incentive is considered (UNEP, 2012).

Emerging technologies such as a modified membrane cell using oxygen-depolarised cathodes are also under development. This technology allows for further energy savings due to their lower operating voltages (Chlistunoff, 2003). Other techniques that have been tested include a four-stage caustic evaporator, the catalytic reduction of chlorate with hydrogen, and the removal of sulphate from the brine by nanofiltration (Brinkmann *et al.*, 2014).

During the period from 1997 to 2012, the share of mercury and diaphragm cell (which uses asbestos) techniques decreased significantly in the EU and EFTA countries, from 63 % to 26% and from 24 % to 14 %, respectively, while the share of the membrane-cell technique more than quintupled from 11 % to 59 % (Brinkmann *et al.*, 2014).

Whilst the EU chlor-alkali industry had voluntarily committed to close or convert its mercury-cell plants by 2020 in view of phasing out mercury-cell technology, the Best Available Technique (BAT) conclusions applicable to chlor-alkali (Implementing Decision 2013/732/EU) adopted under the Industrial Emissions Directive (2010/75/EU) provides that the mercury-cell technology is not BAT. Read in combination with the Industrial Emissions Directive, it implies that the mercury-cell technology cannot be used after 11 December 2017. Hence, after that date, EU mercury-cell plants must be converted to BAT, i.e. bipolar membrane cell, monopolar membrane cell, or asbestos-free diaphragm cell technology, or need to be decommissioned.

In accordance with the new Mercury Regulation (2017/852), mercury from decommissioned plants is waste to be disposed of. It may be temporarily stored in above-ground facilities dedicated to and equipped for such storage. Once converted to mercury sulphide and, if required, solidified, it must be permanently stored in salt mines adapted for the disposal of metallic mercury, or in deep underground, hard rock formations or in above-ground facilities providing a level of safety and confinement equivalent to salt mines. Chapter 6.2.3 gives further information on storage techniques.

2.5. Cement production

Of the overall worldwide mercury emissions in 2010, 9% (173 tonnes) were from the cement industry. In the cement production process (Figure 6), mercury is introduced via the raw materials and the fuels used, such as coal, which contains mercury. Concentrations may vary significantly between raw materials (limestone, clay and lime marl, for example), fuels and the quarries concerned. The high temperatures used to produce calcium oxide for cement can be responsible for the release of gases and dust, rich in volatile metals including mercury, into the atmosphere.

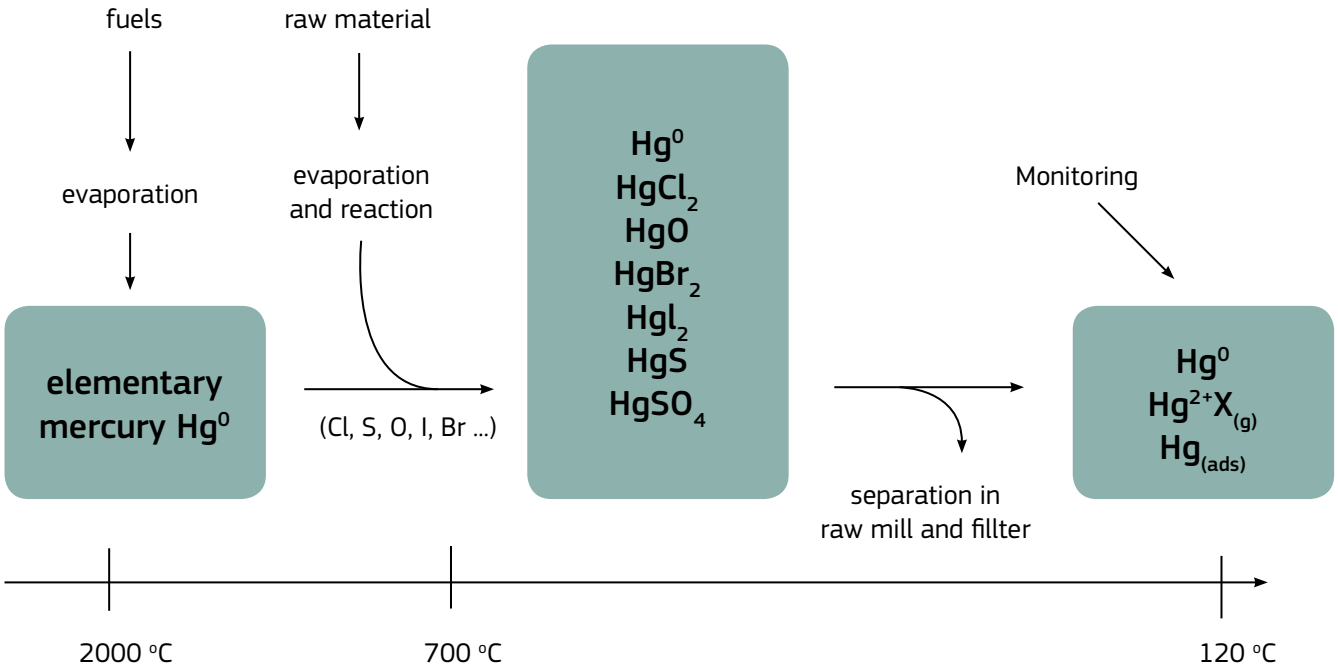


Figure 6. Mercury in the cement production process. Adapted from Hoenig, 2013.

2.5.1 Reducing emissions from the cement industry

According to the BAT conclusions (2013/163/EU, adopted under Directive 2010/75/EU) for production of cement, lime and magnesium oxide, companies should select materials with a low content of mercury, and limit the content of relevant metals in materials, especially mercury. The BAT emission levels for mercury from the flue-gases of kiln firing processes should be no higher than 0.05 mg/Nm^3 (averaged over a spot-measured sampling period of at least half an hour).

Waste-quality control processes are to be employed which analyse and guarantee the mercury content of the waste — this also applies to any waste that is to be used as fuel or raw materials. The cement industries are also recommended to use reliable effective dust-removal techniques, including electrostatic precipitators, fabric filters and hybrid filters (Schorcht *et al.*, 2013). Fabric filters are relatively simple and efficient dust collectors, suitable for many (but not all) applications. The basic principle of fabric filtration is to use a fabric membrane which is permeable to gas but which will retain the dust. As the surface layer builds up, the dust itself becomes the filter medium, and resistance to gas flow increases. Periodic cleaning of the filter medium is therefore necessary to control the gas pressure drop across the filter. The safe management of the filters, and contaminated dust, is essential to ensure that the mercury is not released elsewhere.

There are also various experimental cement-industry mercury abatement techniques in development. 'Selective dust shuttling' limits the build-up of mercury by 'bleeding' mercury-enriched dust out of the cement manufacturing process, as opposed to shuttling dust and mercury together back into the kiln. To 'bleed' the dust, activated carbon can be injected into the gas stream before the dust filter — capturing mercury on the high surface area of the sorbent. There are currently a few issues with this method — the dust is often recirculated in the cement production process and activated carbon

may also influence the cement's properties. Other methods in the research phase for mercury abatement in the cement industry include oxidising mercury so that it can be removed more easily than elemental mercury, as well as thermal treatment of dust that has been shuttled.

2.6 Soil erosion of contaminated sites

Soil erosion is one of the main causes of land degradation and, in itself, is one of the most serious ecological environmental problems facing the planet. Erosion of heavily polluted land has serious ecological consequences, particularly in the case of mercury contamination, which can potentially spread and convert to methylmercury in an aquatic environment. Researchers have found that climate change speeds up erosion and emission from soils (Llanos *et al.*, 2011).

In a study of the seriously mercury-polluted Wanshan mining area in south-western China, researchers calculated both soil and mercury erosion levels (ZhiHui *et al.*, 2013). Using the revised universal soil loss equation (RUSLE) and geographic information systems (GIS), they showed that the soil erosion rate can be as high as 600 884 tonnes per km^2 per year, and the mercury surface erosion load was predicted to be 505 kg per year. The situation is exacerbated by the steep landscape. The researchers recommend that land-use change would be the most effective way to reduce the mercury erosion load in this mining area.

Releases of mercury from historically polluted sites can be significant. Kocman *et al.* (2013) for the first time estimated the scale of the quantities involved. The researchers compiled a database with data from 3000 sites associated with mining and metal processing, including data on emissions to the atmosphere as well as releases to the water streams. Based on this work, annual global emissions and releases of mercury from the contaminated sites identified amount to, on average, 198 tonnes per year. Of this, 82 tonnes per year are emitted to the atmosphere and 116 tonnes per year are released into water sources. These sites thus represent a long-term source of mercury emissions and releases, if not carefully managed.

2.6.1 Reducing emissions from soil erosion

The ability of mercury to enter rivers and streams from old mines and industrial sites is particularly important to consider when developing methods and policies to reduce emissions. Kocman and Horvat (2011) studied emissions from the Idrijca River in Slovenia, which drains the world's second largest mercury mine. Using a newly developed model, they calculated that approximately 51 kg of mercury per year is emitted from contaminated surfaces in the catchment. These then contribute significantly to concentrations in the atmosphere in this area.

The inherent problems of mercury pollution such as persistence, and changes to its chemical form, have been studied in relation to remediation actions for contaminated sites. Llanos *et al.* (2011) carried out research in the world's largest mercury mining area, Almadén in Spain, looking at erosion prediction, weather, water and flood management in relation to mercury emissions. The researchers developed an integrated model approach to predict releases of mercury into the atmosphere, noting that larger 'plumes' were generated in warm, dry weather compared to colder periods. The model proposed by Llanos *et al.* can be used as a tool by environmental remediation managers to aid decision-making.

2.7 Mercury-added products

A number of products contain mercury. These include certain types of energy-saving fluorescent lamps, dental amalgam, batteries, electrical devices and instruments (including mercury thermometers), paints, cosmetics, and some pesticides and fungicides. Mercury can be released during their manufacture, use and disposal.

Incineration of these products during the waste treatment phase of their life-cycle may release mercury. It may also be emitted from waste products in (contained) landfills or (uncontained) dumps. It has been estimated that landfilling of consumer products was responsible for 89.4 tonnes of atmospheric mercury emissions in 2010 — accounting for 4.6%

of all atmospheric emissions from human sources (AMAP/UNEP, 2013). The same study estimates that controlled incineration of consumer products released 6.2 tonnes of atmospheric mercury emissions in 2010, representing 0.3% of emissions from all anthropogenic sources.

Emissions from the use of mercury in dental amalgam fillings can occur both during the preparation of the amalgams and their subsequent removal and disposal. Releases into the air by dental practices in the EU were estimated to have been around 19 tonnes per year in 2010 (SCHER, 2013). Emissions from dental amalgam fillings can also occur during cremation of human remains.

2.7.1 Reducing emissions from waste products

It is important to take a life-cycle approach to controlling mercury emissions from products: one that considers all stages of a product's lifetime, from reducing/avoiding mercury use in manufacture to disposal/re-use of these products. Section 6.1 considers alternatives to mercury in consumer products.

Horowitz *et al.* (2014) estimated global consumption of mercury in products and industrial processes ('commercial mercury') since 1850 (see Figure 7). The industrial processes considered were ASGM, chlor-alkali and vinyl chloride monomer (VCM) production. VCM is used in PVC, and mercury is used as part of its production process. The study shows that total usage of mercury peaked in the 1970s, and has declined since in response to regulations on its use and release in developed countries. Since 1990, developing countries have been the main consumers of commercial mercury. At the global level, products which dominated mercury consumption in 2010 are shown to be dental amalgam, wiring/measuring devices (such as switches, thermostats and barometers) and batteries.

In Europe, dental amalgam is expected to become the main use of mercury once mercury-based chlor-alkali plants have been phased out (by the end of 2017). In 2010, an estimated 75 tonnes of mercury was used in dentistry, and there were 50 tonnes of mercury in dental waste every year in 2012 (BIO Intelligence Service, 2012).

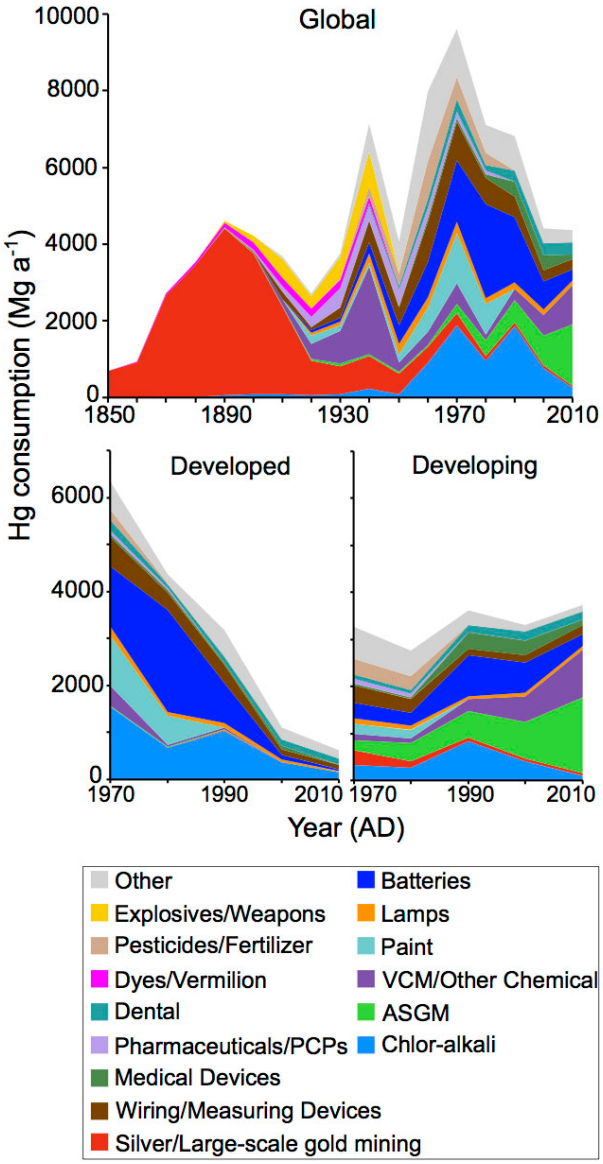


Figure 7. Global historical mercury consumption in commercial products 1850–2010. Consumption is partitioned between developed and developing countries for 1970– 2010 in the two lower tables. Source: Horowitz *et al.* 2014. (The 'other' category refers to ritual, cultural, and miscellaneous uses of mercury.)

Within the EU, the batteries Directive (Directive 2006/66/EC) originally prohibited the placing on the market of any batteries (whether or not incorporated into an appliance) that contained more than 0.0005% of mercury by weight; an exception was established at the time for button cells, which could be placed on the market with 2% mercury by weight. The legal provisions currently in force within the EU repealed that exception and establish the same level for all kind of batteries, i.e. a mercury content of no more than 0.0005% by weight (Directive 2006/66/EC, as amended).

Appropriate collection and management of waste batteries containing mercury, that were placed on the market before the prohibition, is particularly difficult in the case of small button-cell batteries; in 2009, most (88%) button-cell battery waste escaped collection for hazardous substances, and was mixed in with non-hazardous waste (BIO Intelligence Service, 2012). Collectively, this represents 3.4 tonnes of mercury.

The Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive 2011/65/EU) generally prohibits the placing on the market of any electrical and electronic equipment containing mercury whilst setting out time-limited exemptions for the use of mercury in fluorescent and discharge lamps. These types of lamp placed on the EU market contained an overall quantity of less than 3 tonnes of mercury per year (Oeko-Institut and Fraunhofer-Institut, 2016). The exemptions are under regular review with a view to their phase-out.

In addition, as regards the treatment of waste from electrical and electronic equipment (WEEE), there is a specific requirement in Directive 2012/19/EU to remove mercury-containing components from any separately collected WEEE.

Horowitz *et al.* (2014) also estimated global emissions from these products and processes for 1850–2010, directly to air, water and soil and landfill sites (Figure 8). This shows the current-day dominance of emissions from batteries and wiring/measuring devices, particularly to air, soil and landfill sites.

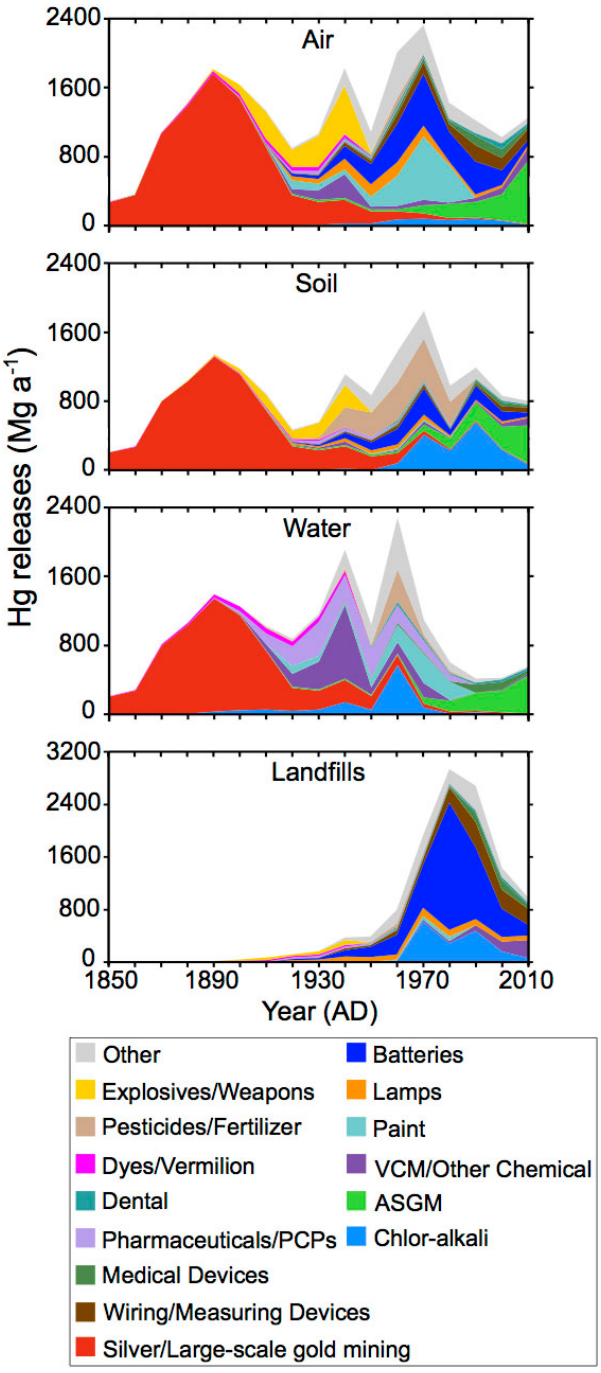


Figure 8: Global historical releases of commercial mercury to air, soil, water and landfill, 1850–2010. **Source**: Horowitz *et al.*, 2014. http://acmg.seas.harvard.edu/publications/2014/Horowitz_et_al_2014_EST.pdf

3. Mercury impacts: damage to life

3.1 Past poisoning incidents

Perhaps the most widely acknowledged incident of mercury poisoning is the case of Minamata disease in Minamata Bay, Japan. In 1956, the communities near Minamata city in Kumamoto Prefecture were reported to be suffering an unknown neurological illness, with diverse signs and symptoms — children were suffering convulsions and paralysis, and were being diagnosed with cerebral palsy. Adults were showing ataxia (loss of bodily control), numbness, muscle weakness, blindness, deafness and loss of speech, followed by convulsions, coma and death. A few years before this, effects on other species were seen: seabirds lost their ability to fly (Yorifuji *et al.*, 2013) and cats suffered convulsions labelled 'dancing disease' (Grandjean *et al.*, 2010).

After an investigation, Kumamoto University reported that the disease was a result of heavy metal poisoning. Twelve years later, the source was confirmed officially by the government: a by-product of acetaldehyde had been discharged in industrial wastewater from the Chisso Corporation's chemical factory into the sea over 35 years, from 1932 to 1968 (Yorifuji *et al.*, 2013). The poisoning occurred as a result of eating locally caught fish and shellfish contaminated with methylmercury, which can be used as a precursor to various agrochemicals, pharmaceuticals, glues, films, synthetic fibres and fabrics, food additives and other industrial chemicals (Ministry of the Environment Japan, 2002).

The official government tally of certified victims on the Yatsushiro Sea coast is 2 265, while a further 10 353 have been certified as eligible for compensation under the government's national settlement plan. It has been suggested that the actual number of victims is undoubtedly larger, because an unknown number of people died without certification or chose not to apply for certification: some estimates suggest at least several tens of thousands of people in Kumamato and Kagoshima prefectures suffered neurological effects characteristic of methylmercury poisoning, without being diagnosed (Minamata Disease Museum, 2001).

Later, a comparative study using data from a 1971 survey showed that participants from the Minamata area manifested psychiatric and neurological symptoms more frequently when compared to the surrounding areas, attesting to the long-term effects of mercury exposure, and suggesting a link between pre- or post-natal exposure and psychiatric symptoms (Yorifuji *et al.*, 2011).

In Ontario, Canada, an investigation took place into possible methylmercury poisoning in two First Nations communities where releases into a water system occurred from 1962–1970. Again, an industrial chemical plant was the source, this time operating a chlor-alkali process producing sodium hydroxide and chlorine used for bleaching paper (Rajeshwar and Ibanez, 1997).

The various signs and symptoms of mercury toxicity can be interpreted as many different ailments, leading a Japanese physician who went to study the Canadian similarities with Minamata to comment:

"If such serious cases had not been found in large numbers [in Minamata], the combination of symptoms could have been overlooked as a distinct disease. However, if one had observed carefully, various signs would have been visible. For example, fish floated to the surface, birds fell to the ground and cats went mad." (Harada, 1976: 181)

'If such serious cases had not been found in large numbers [in Minamata], the combination of symptoms could have been overlooked as a distinct disease. However, if one had observed carefully, various signs would have been visible. For example, fish floated to the surface, birds fell to the ground and cats went mad.'
Harada et al., 1976: 181

In 1971–72, a major epidemic of mercury poisoning occurred in Iraq in which almost 500 people died and 6 530 were hospitalised. In a well-intentioned humane response to famine, several nations shipped wheat grain intended for planting to Iraq. The seeds had been treated with a methylmercury-containing fungicide to suppress mould growth and preserve the viability of the seeds. The seeds were also dyed red to serve as a warning, and attempts were made to inform the population of the hazards of eating the seeds directly. Unfortunately, the warnings on the bags were in Spanish, because some of the grain had originated in Mexico, and the skull and crossbones, recognised by westerners as meaning poison, meant nothing to the Iraqi recipient. In the face of starvation many families milled the seeds directly into flour, and made and consumed contaminated bread. There would have been no danger in eating grain grown from the treated seeds, because the subsequent crop would have contained little or no methylmercury.

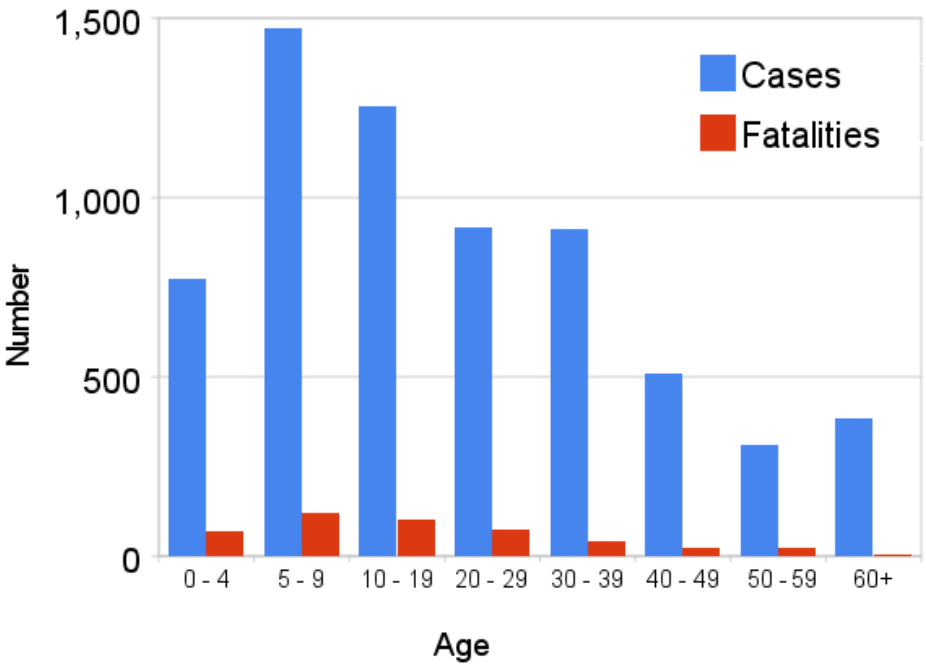


Figure 9: A bar chart showing cases of methylmercury poisoning in Iraq, 1971, as a result of the en:Basra poison grain disaster, grouped by age. Note that the two left most bars each represent groups of 5 years, the rest 10 years. Data: Bakir; Clarkson *et al.* (20 July 1973). Methylmercury poisoning in Iraq. Vol. 181. no. 4096, pp. 230–241 DOI: 10.1126. https://commons.wikimedia.org/wiki/File:Methyl_mercury_cases,_Iraq_1971.png

3.2 Humans: prenatal and neonatal exposure

Damage to organs and systems due to mercury exposure is well-documented. There are several studies that also cover the possible effects of mercury even before birth, whilst in the womb.

Pichery *et al.* (2012) looked at prenatal exposure to methylmercury and reduction in IQ in France. The research compared women of childbearing age from a national sample with women from coastal regions where more seafood is consumed. Mercury concentrations in the women's hair were measured to determine prenatal exposure to mercury. The research team calculated that for every doubling of the concentration of mercury in the women's hair, the children would lose an average of 1.5 IQ points. Sandborgh-Englund *et al.* (1998) found that children exposed to mercury in the prenatal period had defects in attention, memory, language, and motor function. These results therefore emphasise that efforts to reduce methylmercury exposure should have high social benefits.

Mercury can also reach infants through breast milk. Inorganic mercury can accumulate in breast milk and chronic exposure may cause damage to the baby's developing nervous system. A small-scale study of 18 mothers with young babies in Brazil, where environmental mercury levels are naturally high, found that a significant increase in mercury concentrations in breast milk occurred after eating a

single portion of salmon (Da Cunha *et al.*, 2013). There was also a general correlation between mercury levels in milk and mothers' consumption of grains, fat, vegetables and carbohydrate. Most infants were exposed to levels of mercury exceeding the tolerable weekly intake at least once during the first 90 days of breastfeeding following birth.

The European Food Safety Authority (EFSA) has summarised studies that analysed methylmercury concentrations in human milk from mothers with total mercury concentrations in hair above 1 mg/kg. The mean dietary exposure to methylmercury for infants with an average milk consumption ranged from 0.09 to 0.62 µg/kg body weight (bw) per week. For infants with a high milk consumption the dietary exposure ranged from 0.14 to 0.94 µg/kg bw per week. However, a study reporting only total mercury in human milk has shown higher concentrations than the studies that also provided speciation analyses. Therefore, the possibility of higher dietary exposures to methylmercury from human milk in Europe cannot be excluded.

3.3 Genetic damage

One big question surrounding mercury toxicity is whether the metal can cause damage to the set of molecular instructions for growth, development and reproduction, i.e. to the structure of DNA. DNA damage can have far-reaching harmful effects in all cells and organs of an organism, as genetic material is responsible for forming proteins, and the damage can be passed on from generation to generation.

Genotoxicity of mercury is described as 'controversial' by Crespo-López *et al.* (2009); some studies find evidence of damaging effects, but others do not. The review of four decades of research into its possible toxicity found that, since the 1990s, epidemiological studies have demonstrated increased genotoxicity in human populations exposed to mercury through diet, occupation or by carrying dental fillings. The researchers also found that very low levels of methylmercury, of just 0.1–1 µM (micromolar), may affect brain cells with genotoxic consequences for the developing central nervous system.

3.4 Organ system damage

Mercury can be found in various forms, which vary in their toxicity and effects on humans. These forms include elemental (metallic), inorganic mercury compounds, and organic mercury compounds (e.g. methylmercury). For example, elemental mercury and methylmercury are toxic to both the central and peripheral nervous systems. Certain inorganic mercury compounds dissolve in water and have a bioavailability (proportion of the substance which enters circulation and therefore has an active effect) of 7% to 15% following ingestion. Elemental mercury is poorly absorbed following ingestion with a bioavailability of less than 0.01%. However elemental mercury dissolves in fatty substances and can therefore cross the blood-brain barrier whereas inorganic mercury compounds cannot (Park and Zheng, 2012).

In its vapour form, elemental mercury is much more easily absorbed. Acute doses, via inhalation of high concentrations of mercury vapour, are rare, but can have severe effects on the respiratory and renal systems, leading to coughing, difficulty breathing, chest pain, nausea, vomiting, diarrhoea, fever, interstitial pneumonitis, necrotizing bronchiolitis, fluid accumulating in the lungs and kidney failure. Children less than 30 months of age appear to be at increased risk for pulmonary toxicity, usually following an incident of mercury vaporisation in the home. Mercury tends to accumulate in organisms, and chronic inhalation of mercury vapour by humans primarily affects the brain and central nervous system.

Studies have produced figures to estimate how long mercury remains in the brain. The measurement is called 'half-life' and refers to the time taken by the body to reduce the amount of the substance present by half.

A 2014 study suggests that previous half-life estimates of weeks to months are incorrect and are not supported by evidence from animal studies, human case studies or modelling studies based on appropriate assumptions (Rooney, 2014). Evidence from such studies point to a half-life of inorganic mercury in human brains of several years to several decades; the

SCENIHR Opinion (2015) suggests that the half-life exceeds 10 years. This finding carries important implications for estimating the concentrations of mercury in living things using computer models. It also has a bearing on assessing the adverse effects of mercury and its toxicity.

The organic mercury compound methylmercury (which is formed from the action of bacteria — mainly in aquatic systems — and as a result of certain industrial processes) is readily and completely absorbed by the digestive tract. Perhaps because it binds to proteins strongly, it bioaccumulates in tissues, and is the primary cause of neurological alterations from mercury found in humans and experimental animals. Once in the bloodstream, it can cross into the brain and accumulate there. The compound then bioaccumulates in myelin, the fatty material that coats and protects nerve fibres, the brain and spinal cord within the central nervous system, producing a variety of symptoms, including the triad of tremor, gingivitis and erethism (insomnia, excessive shyness, and emotional lability). Headache, short-term memory loss, uncoordination, limb weakness, hallucinations and death are also reported.

Some scientists suggest that neurological alterations from organic mercury seem to be related to the toxic increase of reactive oxygen species (ROS), corroborated by evidence from several animal studies (Fernandes Azevedo *et al.*, 2012). Oxidative stress is associated with neurodegenerative diseases such as amyotrophic lateral sclerosis, Parkinson's disease, and Alzheimer's disease. However, these mechanisms have yet to be fully understood.

There is evidence that the effects of methylmercury exposure from fish consumption also include neurobehavioral (Carta *et al.*, 2003; Yokoo *et al.*, 2003), neurodevelopmental (Oken *et al.*, 2008) and immunological (Nyland *et al.*, 2011) effects. Potential mechanisms of toxicity include the inhibition of protein synthesis and cell division, and interactions with cellular defences (Clarkson, 2002).

Evidence from studies of heart disease suggests a negative impact of methylmercury on cardiovascular health. In the cardiovascular system, mercury induces hypertension in humans and animals that has wide-ranging consequences, including alterations in endothelial function. Exposure to mercury by frequent consumption of fish has been shown to have a strong positive correlation with increased arterial blood pressure (Halbach, 1990). Valeraa *et al.* (2013) found an association with mercury concentrations in blood and an increased resting heart rate (a risk factor) among the Inuit of Nunavik — a population that eats high quantities of fish and marine mammals.

Inuit subsistence whaling on Hudson Bay. Polargeo, 2010. Wikimedia Commons. CC BY-SA 3.0

The range of cardiovascular consequences of mercury toxicity include hypertension,

Fish market. PaelmerPhotoArts, 2015. Pixabay. CC0.

coronary heart disease, heart attack, cardiac arrhythmias, reduced heart rate variability, increased carotid artery obstruction within the heart, stroke, and generalised hardening of the arteries (Halbach, 1990; Houston, 2011). Overall, the evidence linking realistic rates of methylmercury exposure from fish consumption to cardiovascular disease suggests an association with heart disease, particularly heart attack.

Guallar *et al.* (2002), in a case-control study conducted in eight European countries and Israel, evaluated the joint association of mercury levels in toenail clippings and docosahexaenoic acid (DHA, an omega-3 fatty acid, and primary component of the body, obtained directly from fish) — with the risk of heart attack among men. DHA levels were inversely associated with the risk of heart attack, whereas toenail mercury was directly associated with higher risk.

The mechanism by which mercury affects the cardiovascular system is not fully understood, but several pathways have been proposed. Results in Karimi *et al.* (2016) support the hypothesis that exposure to mercury via seafood is linked to increased oxidative stress. This study, along with Stern (2005), suggests that higher mercury content may diminish the cardio-protective effects of consuming fish, since the fatty acids may interact with methylmercury in an antagonistic way (however, there are varying views; see EFSA, 2012, section 3.5).

Houston (2011) states that mercury toxicity should be evaluated in any patient with hypertension, coronary heart disease, cerebral vascular disease, cerebrovascular accident, or other vascular disease to increase data on the subject.

3.5 Risk to population health: food

Fish is the main dietary source of mercury. A study of spatial distribution trends confirmed that the highest exposure levels to mercury, mostly methylmercury, are found in coastal populations, which consume more fish in their diet compared to inland populations (Višnjevec *et al.*, 2014).

In 2010, the EFSA gathered data on mercury contamination in food from 20 European countries (Benford *et al.*, 2012). Results showed that fish meat was the biggest contributor to methylmercury dietary exposure for all age groups. In particular, tuna (*Thunnus*), swordfish (*Xiphias gladius*), cod (*Gadus*), whiting (*Merlangius merlangus*) and pike (*Esox lucius*) were major sources of methylmercury exposure for adults. For children, the same species, plus hake (*Merluccius merluccius*), were the most important sources. Dominant dietary sources of inorganic mercury were fish, seafood, non-alcoholic beverages and 'composite food' (e.g. ready meals which may include fish as an ingredient).

In 2012, the EFSA Panel on Contaminants in the Food Chain (CONTAM) established a tolerable weekly intake (TWI) of 1.3 µg/kg body weight (bw)/week for methylmercury, based on prenatal neurodevelopmental toxicity. As the brain continues to develop after birth, it is undesirable that toddlers and children are exposed to methylmercury above the TWI on a regular basis. Fish meat and fish products, tuna, swordfish, cod, whiting, pike and hake were seen to be major contributors to methylmercury dietary exposure.

Susceptible individuals (children and women of childbearing age) should be discouraged from eating top predator species such as bluefin tuna, swordfish, weevers and Atlantic bonito, amongst others, given their levels of mercury contamination. Less susceptible individuals could be encouraged to limit their consumption of top predator species to no more than one or two servings per month...
from Brambilla et al., *2013*

A more recent EFSA opinion estimated how many servings of fish/seafood per week a given population group would need to reach the TWI for methylmercury, based on the varieties of fish generally consumed (EFSA, 2015). For example, they found that toddlers in Bulgaria would need to consume 1.7 servings of fish to reach the TWI; toddlers in Germany would need to consume two servings; and toddlers in Italy would need to consume 1.4 servings. They found that adults in Italy would need to consume 0.8 servings, whereas adults in Belgium would need to eat six servings to reach the TWI (EFSA, 2015).

Consuming species with a high content of methylmercury influences the number of servings that can be eaten before the TWI for methylmercury is reached. A study on Mediterranean-caught seafood (Brambilla *et al.*, 2013) recommended that susceptible individuals (children and women of childbearing age) should be discouraged from eating top predator species such as bluefin tuna (*Thunnus thynnus*), swordfish (*Xiphias gladius*), weevers (*Trachinus*) and Atlantic bonito (*Sarda sarda*), amongst others, given their levels of mercury contamination. Less susceptible individuals could be encouraged to limit their consumption of top predator species to no more than one or two servings per month, the study concludes. For toddlers, children and women of childbearing age, the EFSA recommends that the benefits of eating fish should be met by increasing the consumption of species low in methylmercury (EFSA, 2015). These species can differ between countries, but there is less chance of bioaccumulation in non-carnivorous fish.

Beyond Europe, recent research from southeastern China (Meng *et al.*, 2011) suggest that rice may accumulate elevated methylmercury if grown in soils near artisanal mercury mining areas. Studying an abandoned mercury mine in Yanwuping, Guizhou

Province, the research shows that rice consumption can be an important pathway in the exposure of humans to methylmercury. As the plant develops, most of the mercury taken up from contaminated soil is transferred to the seed.

Populations living in contaminated locations such as mining areas may also be exposed to elemental mercury through inhalation and inorganic mercury from other food sources. Therefore, further research in areas where there is multiple exposure to mercury is needed taking into account all the factors that may vary in different environments (Višnjevec *et al.*, 2014).

3.6 Risk to population health: dental amalgam

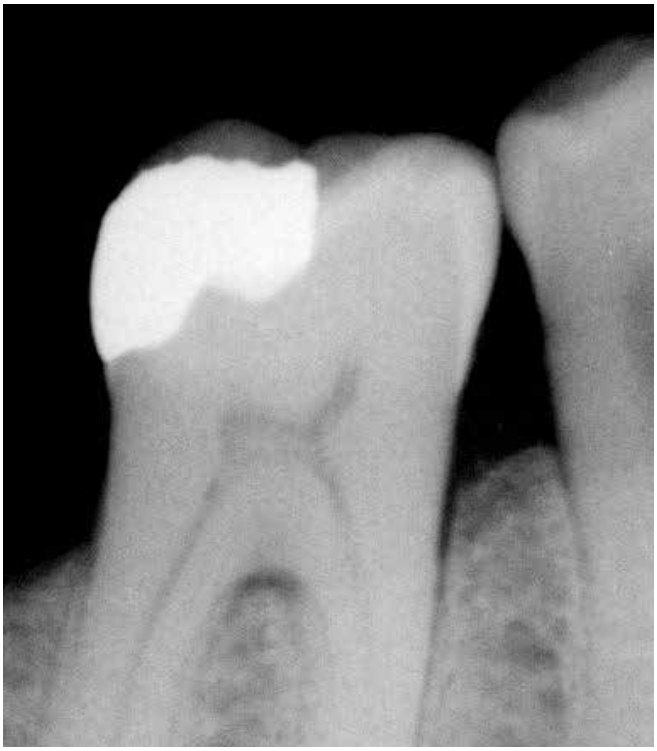
After fish consumption, the greatest exposure of the general population to mercury is generally thought to be due to dental amalgam fillings. Dental amalgam is made from mercury alloyed with silver, used for its durability.

Mercury concentration in the adult brain is associated with the number of amalgam fillings. In the foetus, mercury concentration in the kidney (but not in the foetal brain) has a tendency to be associated with the number of amalgam fillings in the mother. However, the evidence that these associations involve a causal relationship is weak. There are contradictory reports and major challenges in exposure assessment, which generally does not differentiate between organic vs. inorganic forms of mercury, or between sources (dietary vs. dental amalgam or others).

The Council of European Dentists (CED) argued in a 2014 report that research over many decades has failed to show any significant health risk posed by dental amalgam either to patient, dental staff or the public. In one study, researchers looked at the evidence from the main cohort in a Seychelles child development study (Watson *et al.*, 2011). They concluded that the results provide no support for the hypothesis that prenatal mercury exposure arising from maternal dental amalgam restorations results in neurobehavioral consequences in the child.

However, Harris *et al.* (2008) highlighted two significant pathways whereby dental mercury can enter the bloodstream. X-ray based analysis showed that mercury had migrated into areas of the tooth that had once contained an active bloodstream, as well as into hardened plaque or calculus. The researchers suggest that mercury can be dissolved by bacterial action in the saliva, after which it is deposited in calculus, and possibly ingested if this calculus is loosened.

Recently the EFSA reported that the tolerable weekly intake for inorganic mercury might be exceeded due to the additional inhalation exposure in people with a high number of amalgam fillings. However, the data are mainly derived from model-based calculations. Studies with large patient samples did not show any clear correlation between health effects and the number of dental amalgam restorations.



Amalgam filling. Bernhard bill5, 2005. Wikimedia Commons. CC-BY-SA 3.0 Unported.

In 2014, the Scientific Committee on Health and Environmental Risks (SCHER) updated its 2008 opinion on the environmental risks and indirect

health effects of mercury in dental amalgam (SCHER, 2014). SCHER concluded that, in the worst-case scenario, under extreme local conditions (maximal dentist density, maximal mercury use, absence of separator devices), a risk of secondary poisoning due to methylation cannot be excluded. These risks also depend on the methylation rate of inorganic mercury, which may differ with exposure conditions (SCHER, 2014).

Recent studies do not seem to indicate that dental personnel in general suffer from adverse effects from exposure to dental amalgam, despite somewhat higher exposures than patients. Since exposure of both patients and dental personnel could be minimised by the use of appropriate clinical techniques (SCENIHR, 2015), the new Mercury Regulation (2017/852) notably restricts the use of mercury to its encapsulated form and prohibits the use of amalgam fillings for treatment of deciduous teeth, for children under the age of 15. It also prohibits the use of amalgam fillings for pregnant and breastfeeding women, unless deemed strictly necessary by the practitioner on the ground of special medical needs.

Furthermore, given the contribution made by dental amalgam to total emissions of Hg into the environment (section 2.7), the benefits of controlling those emissions would apply indirectly to human health and to populations of wildlife affected by secondary poisoning.

3.7 Risk to wildlife and ecosystems

In common with humans exposed to mercury, wildlife affected by mercury pollution exhibits a range of symptoms indicative of serious neurological and organ damage. For example, fish show reduced reproductive success (Sandheinrich and Wiener, 2011), birds lay fewer eggs and are unable to care for their young (Heinz, 1979), while movement and hunting ability is impaired in mammals, although effects vary between species (Wolfe *et al.*, 1998).

As an animal that feeds mostly on fish, mink (*Neovison vison* and *Mustela lutreola*) are considered an indicator of environmental mercury levels. In experiments, Wobeser *et al.* (1976) found that mercury exposure caused anorexia and loss of co-ordination in mink. Fish-eating birds are also at risk; a study in the Loire River region of France found that mercury levels in 40% of cormorants (*Phalacrocorax*) exceeded toxic thresholds (Alomar *et al.*, 2016).

Exposure is not limited to fish-eating animals, but also affects those which consume insects or which inhabit environments polluted by emissions from coal-burning power plants (Evers *et al.*, 2012). For example, bats in the northeastern U.S. have been found to bioaccumulate significant levels of mercury via their main dietary food source — insects and spiders — which consume leaves contaminated with mercury deposited from the atmosphere (Nam *et al.*, 2012).

Aquatic birds and wildlife are particularly susceptible to poisoning, as mercury accumulates in freshwater and lagoons. The Environmental Quality Standards Directive (2008/105/EC as amended by Directive 2013/39/EU) sets environmental quality standards for mercury in both surface water and fish, with the intention of protecting higher-level predators from secondary poisoning through bioaccumulation. To promote consistency in monitoring methods, a Guidance Document on Biota Monitoring is available to assist stakeholders responsible for implementing the Water Framework Directive (WFD) 2000/60/EC).

According to the WFD, the concentration of mercury in fish should not exceed 20 µg/kg wet weight, and the maximum allowable concentration in inland, transitional and coastal surface waters is set at 0.07 µg per litre (µg/l). Levels of mercury should be monitored in biota to check compliance with the biota standard. A study of mercury levels in bream (*Abramis brama*), collected from six European sites from 2007–2013, showed that levels exceeded the biota EQS at most sites (Nguetseng *et al.*, 2015). In a 2014 study of Swedish waters, the EQS was exceeded in fish at all 2 881 sites (Åkerblom *et al.*, 2014). Some

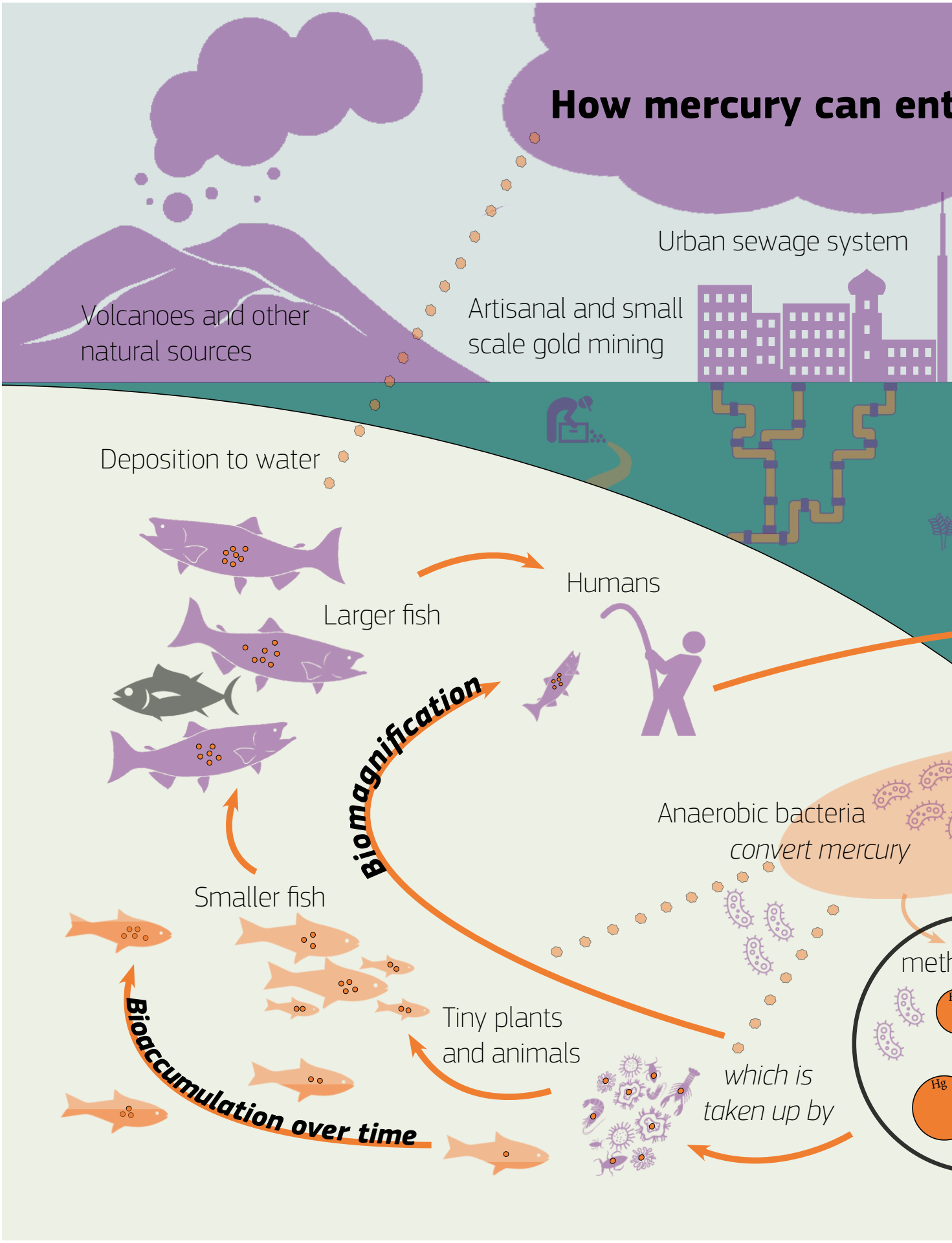
coastal waters, such as in the northern Adriatic, are severely polluted with mercury due to former mining activities and industry (Kotnik *et al.*, 2015), posing a risk to wildlife in this area.

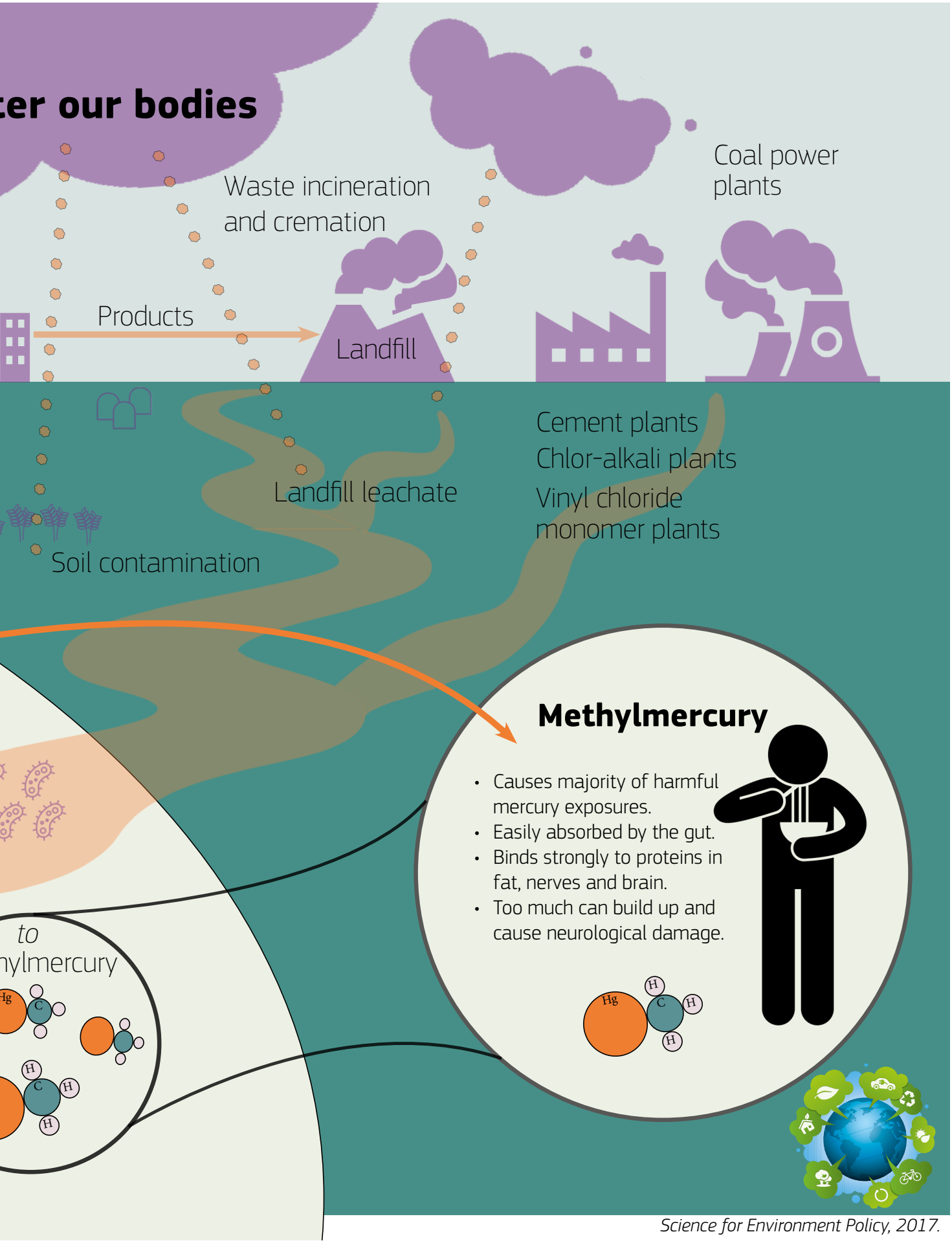
Arctic ecosystems have a prominent place in the research literature: both because the Arctic is a fragile and unstable environment, and because of the tendency of contaminants to concentrate in the polar regions. Available mercury data for both Arctic marine biota and the Inuit population (because of their high reliance on Arctic wildlife for food) have been compared with toxicity threshold values (Dietz *et al.*, 2013). In particular, top marine predators in the region exhibit concentrations of mercury in their tissues and organs that are believed to exceed thresholds for biological effects.

Species whose concentrations exceed threshold values include polar bears (*Ursus maritimus*), beluga whales (*Delphinapterus leucas*), pilot whales (*Globicephala melas*), hooded seal (*Cystophora cristata*), a few seabird species, and landlocked Arctic char (*Salvelinus alpinus*). Toothed whales appear to be one of the most vulnerable groups, with high concentrations of mercury recorded in brain tissue with associated signs of neuro-chemical effects. Evidence of increasing concentrations of mercury in some biota in Arctic Canada and Greenland is therefore a concern with respect to ecosystem health.

The fate of the polar bear is of extreme concern as a result of habitat loss from global warming, but also because it is a top predator that lives in an ecosystem where mercury is often deposited (see 4.2.3). A number of studies have shown links between mercury exposure in wild polar bears and negative neurological changes (Basu *et al.*, 2009; Newcomer *et al.*, 2000).

Polar bear in snow. robynm, 2013. Pixabay. CC0.


How mercury can ent
Urban sewage system
Volcanoes and other natural sources
Artisanal and small scale gold mining
Deposition to water
Humans
Larger fish
Biomagnification
Anaerobic bacteria convert mercury
Smaller fish
Tiny plants and animals
which is taken up by
Bioaccumulation over time
meth
Hg



Science for Environment Policy, 2017.

Figure 10. Infographic: How mercury can enter our bodies.

4. Movement and deposition of mercury

4.1. Movement of mercury globally

The atmosphere is the most important transport pathway of mercury emissions and elemental mercury can travel long distances to remote locations far from its source, such as the Arctic and Antarctic. The residence time in the atmosphere can be several months to a whole year (Basu *et al.*, 2009).

There is an increasing body of scientific evidence that now recognises the potential importance of intercontinental flows of air pollutants. Under the leadership of the European Union and the United States, the Task Force on Hemispheric Transport of Air Pollution was charged with improving understanding of the intercontinental transport of air pollutants across the Northern Hemisphere (UNECE, 2010). Figure 11 shows the major flows that transport mercury in the atmosphere and oceans.

4.1.1 Types of deposition

Mercury emissions can be deposited on very different spatial scales depending on the chemical form in which it is emitted. Mercury in its elemental, gaseous form can remain in the atmosphere for up to a year, while being transported globally. It can then be oxidised to a form that dissolves in water and is very readily deposited. Transportation from sources

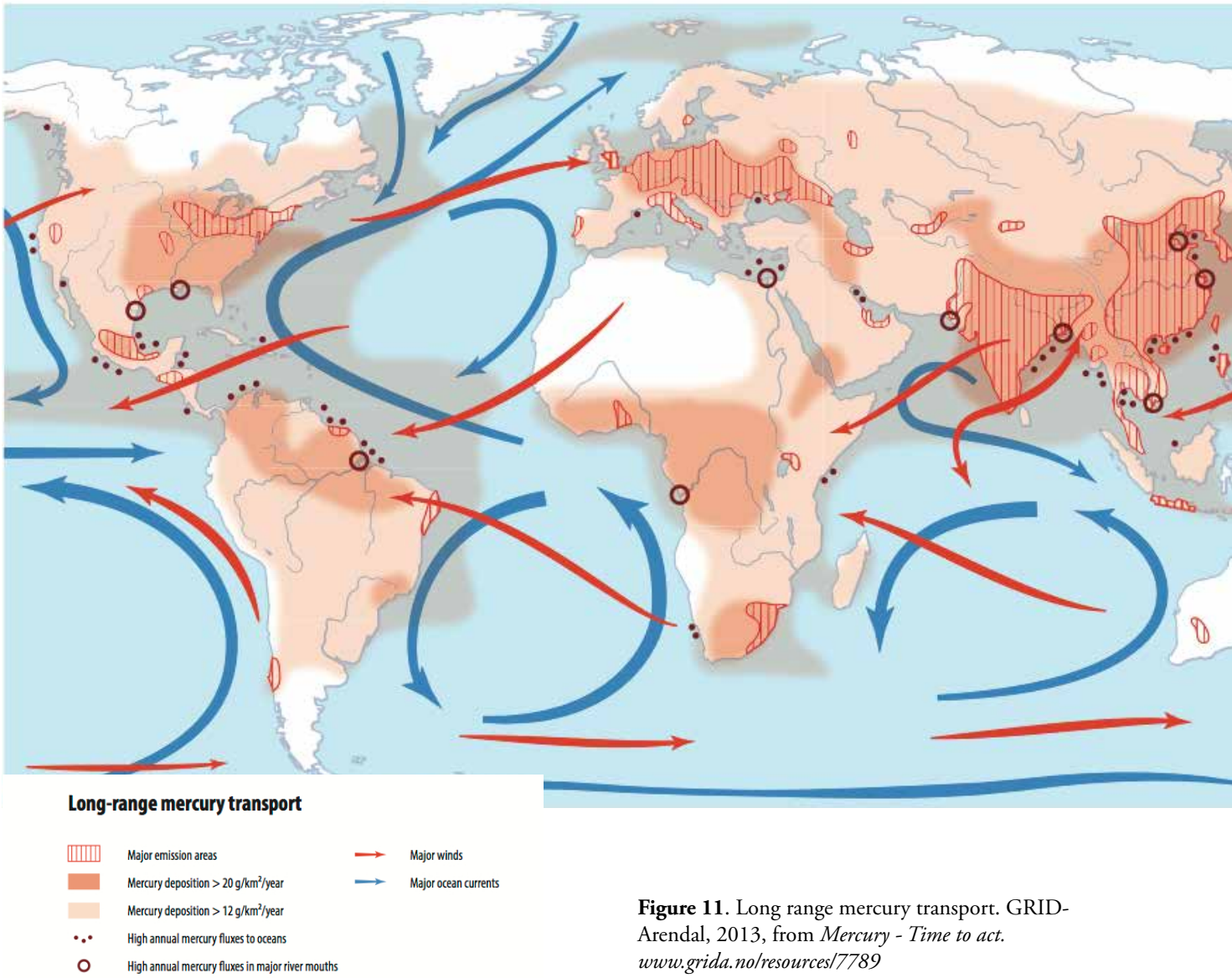


Figure 11. Long range mercury transport. GRID-Arendal, 2013, from *Mercury - Time to act. www.grida.no/resources/7789*

that release mercury compounds and mercury attached to particles is shorter-lived, resulting in localised deposition. Previous work for the United States showed that while North American sources contribute only an average of 20% to domestic deposition overall, this fraction rises to 50% at locations downwind of major sources in the industrial Midwest (Selin and Jacob, 2008).

Intercontinental transport of mercury is a significant source of pollution, particularly in regions with few local emission sources. Models providing estimates of intercontinental transport and deposition show that the contribution of foreign anthropogenic sources to annual deposition varies from 10% to 30% on average anywhere on the globe (Pirrone and Mason, n.d.). From 35% to 70% of total deposition to most regions consists of deposition contributed by global natural and secondary emissions.

Driscoll *et al.* (2013) deal with the dynamics of mercury in the atmosphere, land and the oceans, and the implications for mercury policy. They conclude that as atmospheric emissions and deposition dominate anthropogenic mercury pollution, these emissions should be the priority focus for policy measures. In addition, co-ordinated international efforts are required to monitor mercury in air, water, sediment and soils, and biota, as well as improved understanding of its movement, transformation and bioaccumulation in food webs.

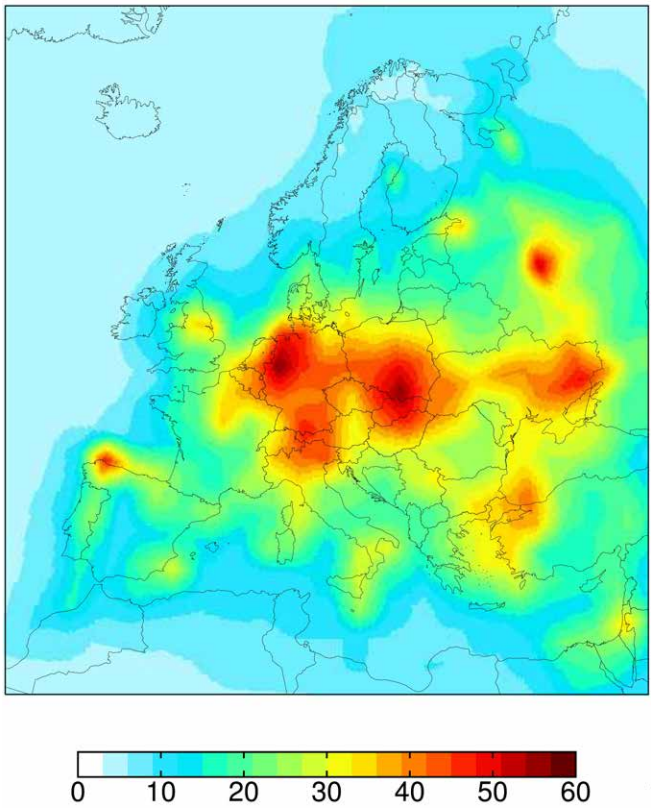


Figure 12. Percent contribution of European anthropogenic emissions to total (wet plus dry) annual mercury deposition in the GEOS-Chem model (v. 9- 01- 03). Average for meteorological years 2004–2005. Source: Sunderland and Selin, 2013.

4.1.2 Europe and mercury emissions and deposition

The model in Figure 12 shows the fraction of present day atmospheric mercury deposition in different regions of Europe from European anthropogenic sources. It is based on the GEOS-Chem global chemical transport model. European emissions contribute up to 60% of this deposition of human origin to ecosystems in industrial areas of Europe. In other areas, such as the Mediterranean, European emissions contribute 20% or less. This suggests that reducing deposition requires local, regional, and global policy actions (Sunderland and Selin, 2013).

Estimates from models of the scale of mercury intercontinental transport effects on local pollution levels depend on the availability of accurate data on anthropogenic emissions. Moreover, the accuracy of estimates relies on information on the type of mercury emitted. Mason *et al.* (2012) therefore recommends that there should be further improvements in global mercury emission inventories. The researchers stress that these should include more accurate emission quantities, type of mercury, and the timing and location of emissions.

4.2. Geophysical systems complications

4.2.1 Soil

Deciding the direction of policy requires a thorough understanding of the fate of mercury emissions. In particular, it is essential to appreciate the changes mercury may undergo during and after transport through the atmosphere and oceans.

Even within a soil, transformation of mercury depends on the chemical environment. A study by Miller *et al.* (2013) has shown that analysis of contaminated soil can be complex. The researchers analysed soil containing large deposits of elemental mercury. They found that characterisation of soils is difficult due to the uneven distribution of mercury. This problem could be exacerbated in industrial facilities where filling materials have been deposited and excavation and levelling remobilises the mercury.

4.2.2 Fog

Measurements in coastal fog in California suggest that upwelling of deep ocean water along the coast brings mercury to the surface where it enters the atmosphere and is absorbed into fog (Weiss-Penzias *et al.*, 2012). One form of methylmercury, dimethylmercury, is stable in the deep ocean, but is volatile at 200 metres depth and above, where it decomposes. Some of the resulting mercury escapes into the atmosphere where it can be transported by fog onto land. Levels in rain have always been low so the relatively high levels in fog were surprising. In California, mercury mines along the mountains running along the coast produced large amounts of mercury and land became contaminated via the fog. Watersheds were contaminated with the toxic metal, and so were sea sediments. Here, bacteria transform the mercury into methylmercury which is biologically active and poses a threat to health.

Fog in a nature reserve. 258817, 2014. Pixabay. CC0.

Arctic hare. skeeze, 2009. Pixabay. CC0 Public Domain.

4.2.3 Arctic

Atmospheric deposition of mercury in remote areas has increased threefold since pre-industrial times and this deposition is particularly pronounced in the Arctic (Point *et al.*, 2011). In the Arctic atmosphere, elemental mercury is oxidised into a form that deposits easily in the cryosphere (snow and ice). When the ice melts, this oxidised form can in turn be re-mobilised and transformed into methylmercury which can accumulate in the food chain.

Mercury moves to the Arctic from other regions of the world via the 'Grasshopper effect'. This is where a deposited compound volatises and re-enters the atmosphere. Over time, it 'hops' through the environment, transported by major air currents to the Arctic during the summer. Once in the Arctic, it cannot gain enough heat energy to hop out. Contaminants therefore become concentrated in the Arctic, despite the absence of emissions in the region (Government of Canada, 2013).

Following the discovery of atmospheric mercury deposition in polar regions, a significant research effort has been made to assess the chemical and physical mechanisms behind the rapid conversion of atmospheric mercury into reactive and water-soluble forms which are potentially bioavailable. Understanding the way in which mercury is released into the atmosphere, transformed, deposited and eventually incorporated into biota is of crucial importance not only for the polar regions but also for the marine environment in general (Sprovieri *et al.*, 2010).

4.2.3.1Mercury is pulled out of the Arctic atmosphere

Mercury depletion events from the atmosphere are often observed in the Arctic boundary layer in spring. Moore *et al.* (2014) established a link between Arctic sea ice dynamics and increased amounts of mercury deposited onto the Earth's most fragile ecosystems. Simply put, higher levels of mercury deposition are linked to a pumping effect caused by the opening and closing of large cracks on the ice (leads) that expose warmer seawater to the cold polar atmosphere. This causes 'convective forcing' of the mercury which is pulled down from a height of around 400 metres above the Arctic surface.

"The atmospheric mixing created when thinner, seasonal sea ice opens to form leads [fractures] is so strong... that it actually pulls down mercury from a higher layer of the atmosphere to near the surface."

Christopher W. Moore
Division of Atmospheric Sciences (DAS), NV, United States

Complex chemical reactions that involve sunlight deposit mercury out of the air to the surface. However, these processes normally halt once the mercury near the ground has been completely removed. Deposition can restart, fuelled by the addition of more mercury pulled down from the higher layer of the atmosphere by the effects of convective forcing. Increased deposition of mercury to the Arctic as a result of atmospheric mercury depletion events leads to more bioavailable mercury entering ecosystems during snowmelt.

4.2.3.2 Sunlight, global warming and thinning ice

After mercury is deposited to ocean surfaces and sea ice, it can be converted into methylmercury, which biomagnifies along the marine food chain, as previously discussed.

However, methylmercury can also be broken down to less biologically available forms in surface waters — a process that is accelerated by sunlight. Point *et al.* (2011) studied the different types of mercury (isotopes) in seabird eggs collected from colonies in the North Pacific Ocean, the Bering Sea and the western Arctic Ocean. The researchers anticipate that these variations may be used to estimate the extent of photochemical degradation of methylmercury in northern latitudes.

The researchers concluded that sea-ice cover impedes the photochemical breakdown of methylmercury in surface waters. They suggest that further loss of Arctic sea ice this century will accelerate sunlight-induced breakdown of methylmercury in northern surface

Arctic coastal shore. 9122 images, 2015. CC0 Public Domain. Pixabay.

waters. The effects of global warming are expected to be strongest in the Arctic bringing about the relentless retreat of glaciers, sea ice and permafrost.

4.2.3.3 Significance of global warming to Arctic life

Global emissions of mercury continue to change at the same time as the Arctic is experiencing ongoing climatic changes. Continuous monitoring of atmospheric mercury provides important information about long-term trends in the balance between transport, chemistry, and deposition of this pollutant in the Arctic atmosphere.

The research findings of Moore *et al.* (2014) have shown that events at ice level can affect levels of mercury almost half a kilometre up in the atmosphere. The researchers state that future work will need to establish the degree to which large-scale changes in sea-ice dynamics across the Arctic alter ozone chemistry and mercury deposition in fragile Arctic ecosystems.

Overall, further research is recommended to provide reliable information on the complex reactions involving mercury taking place in dynamic, vulnerable ecosystems in the Arctic. The net result, due to accelerated reactions that make mercury more bioavailable, may be an increased amount of bioavailable mercury.

5. Monitoring and modelling mercury in the environment

5.1. Approaches to monitoring

5.1.1 Satellite

Satellite observations might yet become a valuable source of information, but instruments in use are far from ready for this. The European Global Mercury Observation System (GMOS) project was designed to establish a worldwide observation system for measuring atmospheric mercury in ambient air and precipitation samples. GMOS participated in the Global Earth Observation System of Systems (GEOSS) initiative through the GEO Task HE-02 'Tracking Pollutants', received funding from the EU's 7th Framework Programme and had 23 partners across the globe. It supplied integrated information from ground-based sites, cruise and aircraft campaigns and expanded existing atmospheric monitoring capabilities to include mercury.

The mercury task group under GEOSS dealt with the sharing of data from GMOS, allowing access to comparable and long-term data from a large number of ground-based and off-shore sites, to help understand patterns of mercury transport in time and space, and possible deposition to terrestrial and aquatic ecosystems.

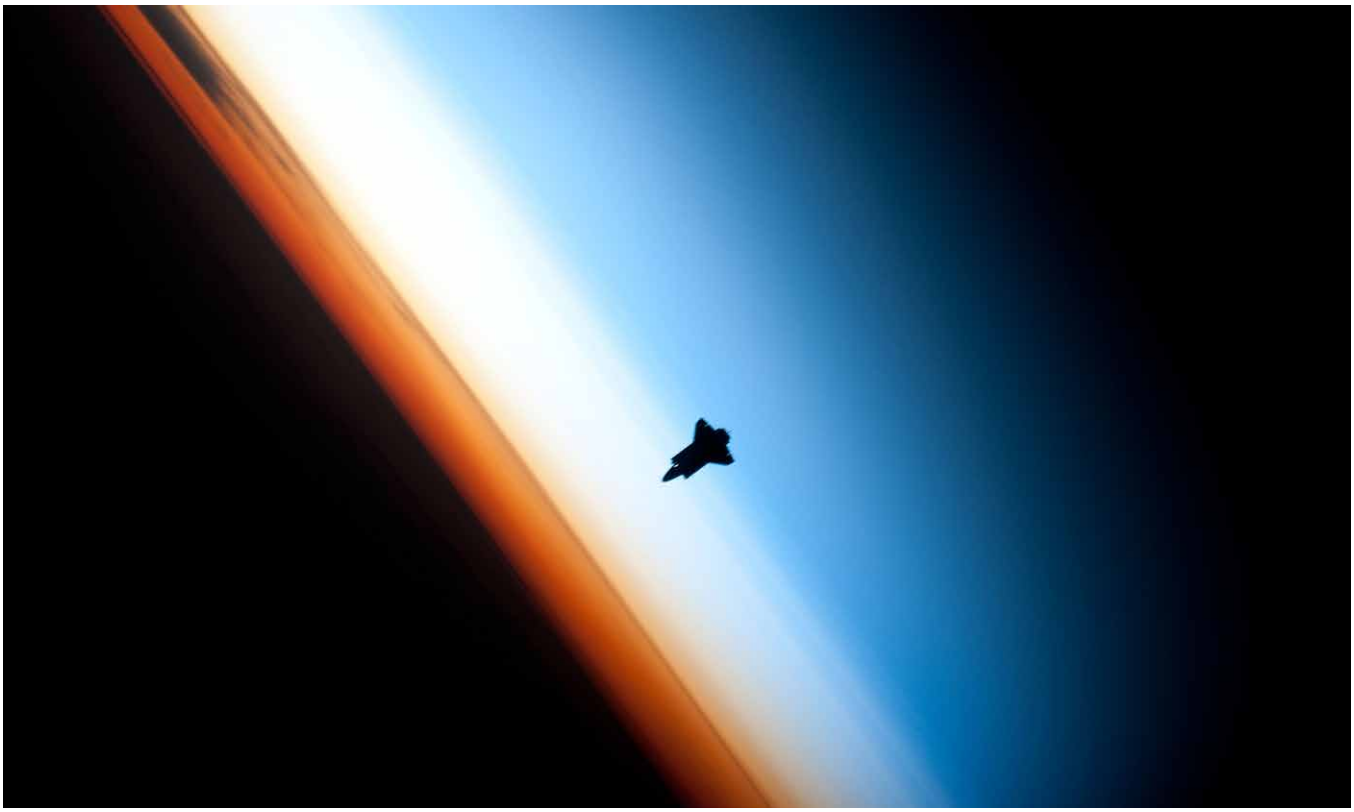
GEO data supported the evaluation of regional and global atmospheric mercury models for use in the analysis of different policy options for reducing mercury pollution impacts on human health and ecosystems and ultimately the policymaking process of the Minamata Convention.

GMOS completed its work in October 2015, publishing its major findings in 2016 (Sprovieri *et al.*, 2016). It established a global observation system for mercury, and the resulting data were used to validate regional- and global-scale atmospheric mercury modelling systems, identify source–receptor relationships and develop interoperable tools to allow the sharing of observational data. The chief finding was a clear gradient in mercury levels between the Northern and Southern hemispheres, with annual mean averages of 1.55 and 1.51 ng/m^3 in 2013 and 2014 in the North, and 0.93 and 0.97 ng/m^3 in the South. The researchers state that this finding confirms that the majority of emissions and re-emissions are in the Northern Hemisphere.

The data do not so far cover a long enough timespan to offer information on temporal trends, however it is hoped that these data will play an important role in the implementation of the Minamata Convention. Sundseth *et al.* (2017) note, though, that further work is still needed on improving emission inventory and monitoring data, predictions of future emissions and related costs and benefits.

5.1.2 Cyberinfrastructures

With the ever-increasing volume of data comes the need for an elevated level of data management. Integration of scientific data from all electronic sources, from scientific instruments to satellites, is becoming a reality due to the advent of cyber infrastructure, a term which describes advanced data-driven processes — acquisition, storage, management, integration, mining, visualisation, and other computing and information processing technologies that normally use the internet. Combined with work from multiple fields — computer science, environmental research relating to mercury, engineering and information technology — the application of data from cyber infrastructures has the potential to supply environmental managers and policymakers with relevant information for appropriate decision-making (Cinnirella *et al.*, 2012; D'Armore *et al.*, 2012).



Space Shuttle Endeavour appears to straddle the stratosphere and mesosphere in this photo. «The orange layer is the troposphere, where all of the weather and clouds which we typically watch and experience are generated and contained. This orange layer gives way to the whitish Stratosphere and then into the Mesosphere.» ISS022-E-062672 caption». (The shuttle is actually orbiting at more than 320 km (200 mi) in altitude, far above this transition layer.) NASA crew of Expedition 22, 9 February, 2010. Wikimedia Commons. Public domain.

5.1.3 Atmospheric testing

The atmosphere is a relatively minor reservoir of mercury compared to oceans or soils, but it is an important pathway of deposition in terrestrial and aquatic ecosystems. National data on mercury emissions have been compiled under the Convention on Long-range Transboundary Air Pollution (LRTAP), finding that emissions dropped significantly in most sectors between 1990 and 2014 (Figure 13). However, the most commonly used tests for measuring the extremely low concentrations of mercury in the atmosphere, involving a potassium chloride denuder device, have been shown to be inaccurate due to the effects of ozone and temperature (Gustin *et al.*, 2013; Huang *et al.*, 2014).

Likewise, the Reno Atmospheric Mercury Intercomparison Experiment (RAMIX) in 2011 assessed the performance of new and existing methods to measure atmospheric mercury (Ambrose *et al.*, 2013). Results indicated that the main substances that interfere with accuracy are ozone and water vapour, suggesting that values recorded in the past for atmospheric mercury are lower than actual concentrations. Underestimation of mercury levels could impact on the validity of risk assessment values for humans and the environment, possibly resulting in absence of implementation of measures to eliminate or reduce environmental problems.

Sampling the atmosphere usually involves taking random samples at set times, but this presents a problem as there may be considerable variation in the contents of the sample, depending on current

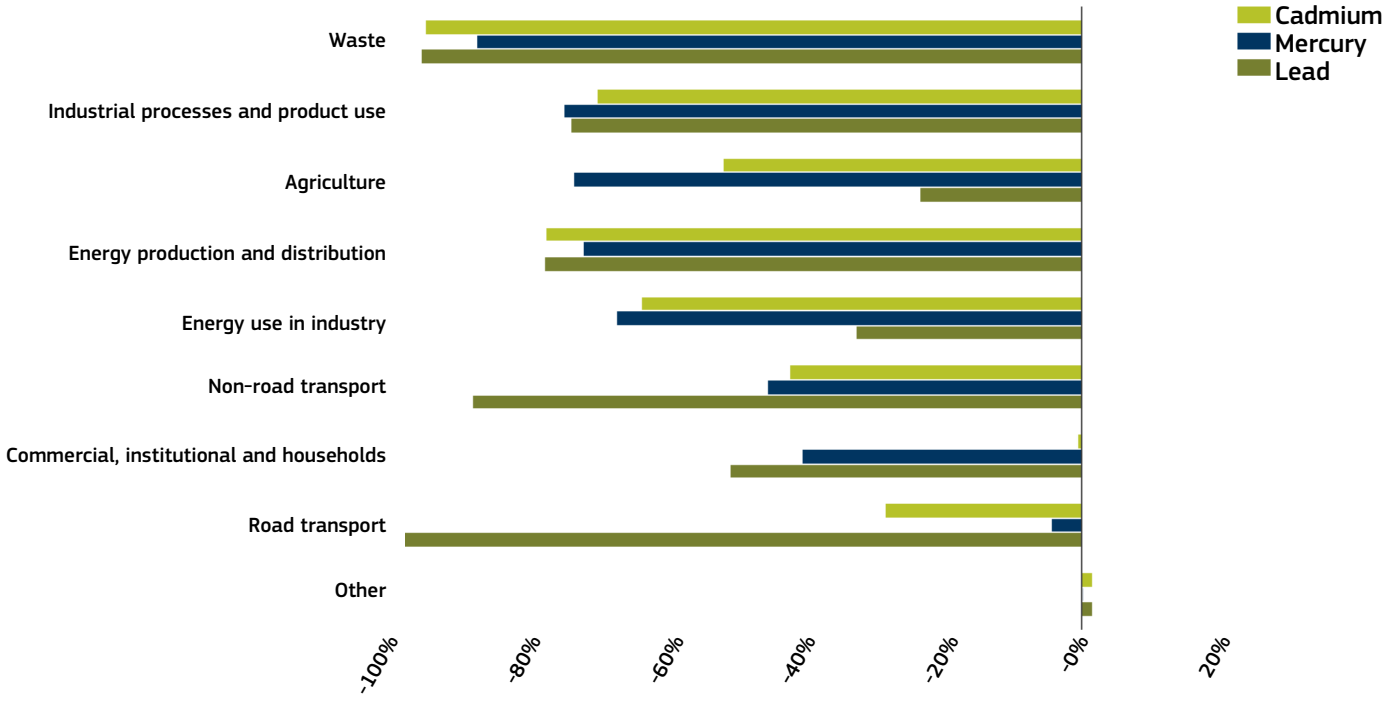


Figure 13: Bar chart - Change in cadmium, mercury and lead emissions for each sector (1990-2014). National emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention). Redrawn from European Environment Agency: https://www.eea.europa.eu/data-and-maps/daviz/change-in-cadmium-mercury-and-1#tab-used-in-indicators

conditions, and samples only represent snapshots of the situation. One way around this is to use a passive sampling system that collects samples constantly over time, offering a means of calculating an average concentration over a measurement period. For example, Lyman *et al.* (2010) developed a sampler that can collect and give data for two-week periods. The cost of current automated atmospheric mercury sampling and measuring instruments, as well as their technical requirements, are a limiting factor in large-scale deployment, however.

The GMOS initiative also includes high-altitude sampling sites. High-altitude samples are very informative about mercury transport as most movement of the toxin occurs in the troposphere, above the planetary boundary level. Analysis from an aircraft gives a 'snapshot' of the vertical distribution of mercury compounds in the atmosphere. This represents the first time that observations have been compared across high-elevation sites, for calculated mercury compound measurements and results indicate that mercury is short-lived in the stratosphere (Lyman and Jaffe, 2011).

The researchers developed a model to explain this phenomenon. In the stratosphere, mercury combines with oxygen and subsequently moves through a process called sedimentation, whereby larger particles sink. This sediment (the collection of particles) can then be transported by entrainment: that is, it can be dragged along with the moving flows of the troposphere. This moving 'river of air', the jet stream, zooms along at the top of the troposphere at some 400 km/hour.

In a review of atmospheric measurement networks, Sprovieri *et al.* (2010) argued that existing networks were insufficient to measure mercury in

the atmosphere reliably, indicating the difficulties in accurately gauging levels of gaseous mercury. In particular, less information is available in the Southern Hemisphere, and for legacy mercury fluxes. Selin and Song (2013) agree that enhancements in the capacity to measure the effectiveness of emissions reduction strategies are needed and moreover, that present knowledge is insufficient to attribute causes to changes observed. To an extent, the GMOS project aims to address these issues.

5.1.4 Monitoring mercury in water through biota

The Water Framework Directive requires biota monitoring against environmental quality standards (EQS) set out in Directive 2008/105/EC, including prescribed levels for mercury and other priority substances. In order to assess long-term trends, the EQS Directive requires a monitoring plan for concentrations of mercury and other substances that tend to accumulate in sediment and/or biota, and the development of River Basin Management Plans with measures required to reach good ecological status. The EQS is set for prey tissue (wet weight), with Member States being able to choose whether the most appropriate indicator is fish, molluscs, crustaceans or other biota. Data from existing national and regional monitoring programmes is held in the EIONET Central Data Repository.

Some countries have been regularly monitoring concentrations in marine and surface waters for many years — for example the TransNational Monitoring Network, established in 1996, works to measure levels of mercury and other hazardous substances in the Danube River. Out of 5 655 km of the river that failed to reach good chemical status in the 2015 report on the Danube's ecological status, levels of mercury in fish exceeding the EQS were to blame in 5 200 km (ICPDR, 2015). Local marine and freshwater surveys in other countries have also found levels exceeding the EQS (e.g. Åkerblom *et al.*, 2014; Jürgens *et al.*, 2013; Maggi *et al.*, 2012; Nguetseng *et al.*, 2015; Zrnčić *et al.*, 2013), indicating that work is required to meet standards.

Vignati *et al.* (2013) note that Member States can justify failure in meeting the EQS if this is due to ubiquitous persistent bioaccumulative and toxic substances (UPBTs), such as mercury, for which all possible measures have been taken, however evidence from studies highlight that the impact of mercury on European waters may be much more serious than previously thought.

5.1.5 Monitoring mercury in fish for consumption

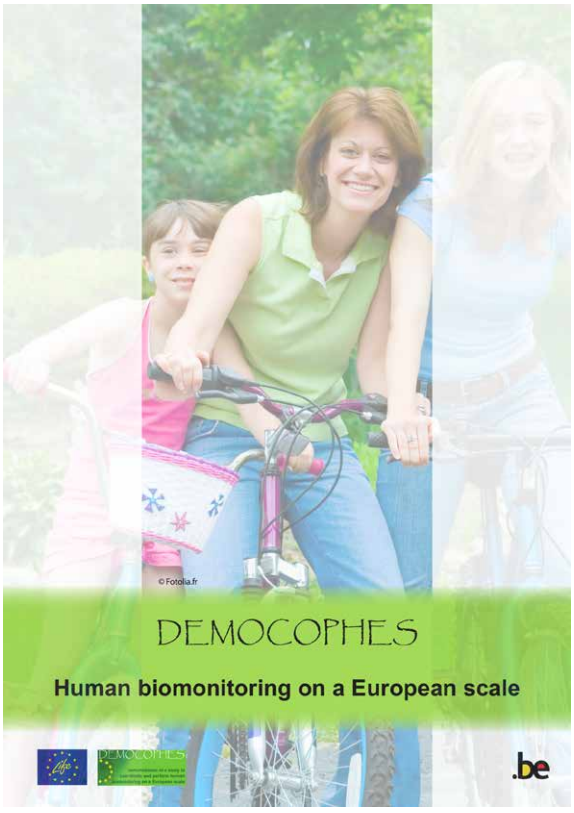
Regulation 1881/2006 sets maximum levels of 0.5 mg of mercury/kg for fish in general and 1.0 mg mercury/kg for certain larger predatory species of fish including shark, swordfish (*Xiphias gladius*), marlin (*Makaira nigricans*), tuna (*Thunnus*) and orange roughy (*Hoplostethus atlanticus*). The EFSA, meanwhile, reviewed provisional tolerable weekly intakes for methylmercury and inorganic mercury in 2012, setting these at 1.6 µg/kg body weight and 4 µg/kg body weight, respectively, based on a wide-ranging review of studies (Benford *et al.*, 2012).

In line with legislation and guidelines, a number of local surveys on mercury in fish in the consumer market have been carried out in Member States. Some studies found no significant risk to human health from levels detected (e.g. Kuballa *et al.*, 2011; García *et al.*, 2016; Zaza, *et al.*, 2015), while others have found levels that exceed recommended levels (0.5-1.0 mg/kg) for human consumption (Åkerblom *et al.*, 2014; Yusà *et al.*, 2017).

Višnjevec *et al.* (2014) carried out a comprehensive Europe-based review of exposure to mercury, looking at studies published since 2000. This review found that the highest exposure to mercury was in coastal populations, due to their higher consumption of fish compared to inland residents.

5.1.6 Human biomonitoring and Europe

Human biomonitoring (HBM) is an effective tool to assess human exposure to environmental pollutants and potential health effects of such pollutants. The European Commission's European Environment and Health Strategy (E.C., 2003) and the accompanying Environment and Health Action Plan 2004–2010 (E.C., 2004) recognised the value of HBM and the relevance and importance of coordination of HBM programmes in Europe.



A pilot study started in 2010 (known as DEMO-COPHES) (CORDIS, 2013), focused on the feasibility of a harmonised approach to HBM, restricted to four environmental pollutants, one of which was mercury.

The relevance of the data for policy aims has already been shown by the use of the DEMO-COPHES mercury data in a publication on the economic benefits of methylmercury exposure control in Europe (Bellanger *et al.*, 2013). In addition, COPHES partners supported the World Health Organisation for the development of a standardised methodology for an HBM survey in maternity wards with analysis of total mercury in maternal hair samples. The hair-mercury concentrations were highest in Southern Europe and lowest in Eastern Europe.

Using the data from the DEMO-COPHES project, the conclusions of the Environmental Health report indicate that efforts to combat mercury pollution and to reduce methylmercury exposures will have very substantial economic benefits in Europe, mainly in southern countries. Some data may not be entirely representative — some countries were not covered — and anticipated changes in mercury pollution all suggest a need for extended biomonitoring of human methylmercury exposure.

Building on COPHES and DEMO-COPHES, a new large-scale initiative — the European Human Biomonitoring Initiative, HBM4EU – was launched in January 2017. It is a joint programme of 26 countries and the European Commission, receiving an EU contribution of €50 million over 5 years and having a total budget of around €73 million, with the objective to use human biomonitoring to better assess exposures of people to chemicals in Europe, to understand the associated health impacts and to improve chemical risk assessment. Although the first set of priority substances included in the initiative does not include methylmercury, two additional rounds of prioritisation will be conducted during the five years of the project, one from 2017 to 2018 and one from 2019 to 2020, allowing for new substances to be added to the chemicals to be investigated if deemed policy relevant.

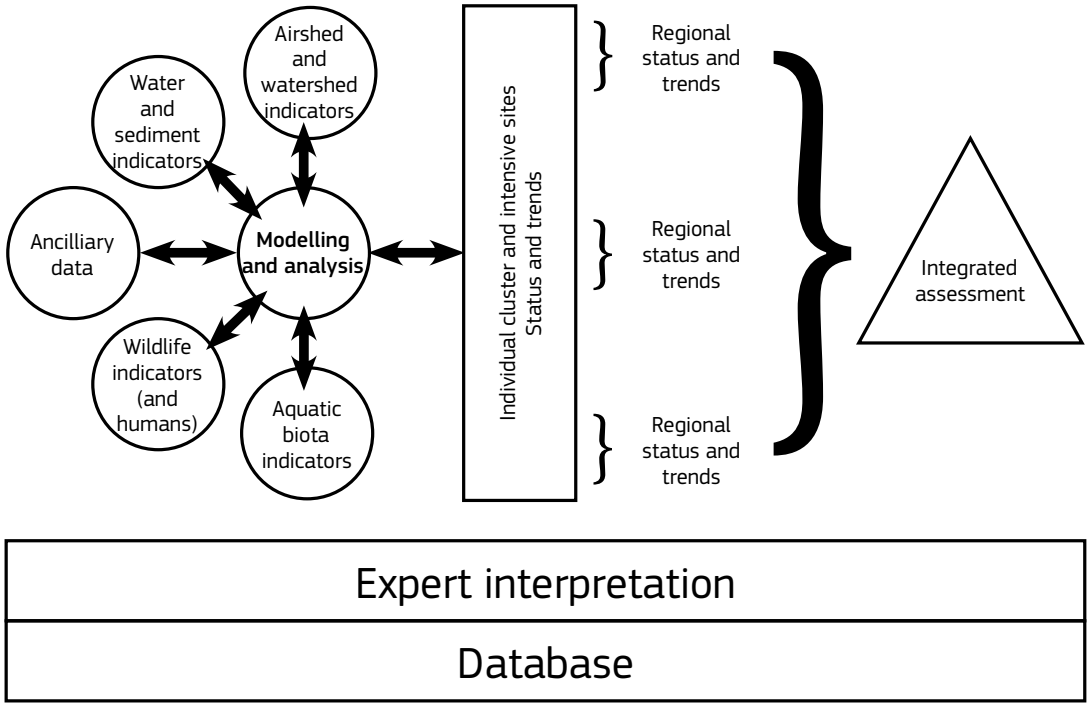


Figure 14: Integration of Indicator Framework. Redrawn from Harris *et al.*, 2007.

5.2 Modelling frameworks

Modelling mercury in the environment is complex. Figure 14, 'Integration of indicator framework' (Harris *et al.*, 2007), gives an idea of the complexity involved in producing an integrated assessment of mercury's status and trends. Each circle represents the indicators required in an analysis of impact of mercury on biota in an aquatic environment, and each poses many challenges in the areas of observation systems. Before integration of data and assessment, there is also a requirement for relevant data on regional status of the area under study together with trends in variables such as climate change.

Some local models have been developed, for example of mercury transfer from land to water and atmosphere (Llanos *et al.*, 2011, referred to in 2.6 'Soil erosion of contaminated sites'), in relation to the development of suitable remediation measures in the Las Cuevas mercury mine area in Spain. The affected region covers both terrestrial and aquatic ecosystems and is heavily degraded due to a long history of mining, the bulk of which has occurred over the last 500 years. Višnjevec *et al.* (2013) also developed a model to identify pollution hotspots in the Idrija area of Slovenia, particularly noting how mercury is transformed into the toxic, bioavailable methylmercury, in certain environments. The model incorporated factors such as local population density in order to assess the risk to human health. The results of both studies show that vulnerability of the ecosystem depends on the movement of mercury to the 'biosphere' — the ecosystems where life exists. The researchers also found that climate change speeds up erosion and emission from soils.

Currently the only accurate indicators of mercury impact on human health are methylmercury

concentrations in living organisms, and in human hair (Li *et al.*, 2014). However, recent advances in analysis, one major example being stable mercury isotopes combined with computer modelling, are shedding light on the links between deposits from the atmosphere, concentrations in water and addition of the methyl group to form methylmercury (Llanos *et al.*, 2011). The development of such regional and global mercury chemistry and transport models is making the complexities of mercury biogeochemical cycling more accessible to scientists and policymakers. Computer models can furthermore link changes in time and space — on land, in biota and in humans — quickly, efficiently and economically.

For example, anomalies in deposition, mercury movement and behaviour, plus the variably estimated contribution of legacy mercury, seem to indicate that models of the statistics of the atmospheric mercury cycle must in future include data on soil and ocean mercury pools and their dynamics to make realistic projections of future trends (Slemr *et al.*, 2011).

Slovenščina: Stopnišče v rudniku Idrija. Staircase in the Idrija mine. US Embassy Slovenia Facebook, 2013. Wikimedia commons.

Song *et al.* (2015) carried out modelling with the GEOS-Chem chemical transport model, showing that legacy mercury is more likely to reside in terrestrial ecosystems than in the ocean, long-term. Importantly, they noted that most existing estimates of mercury fluxes are based on a bottom-up approach, taking inventories from emissions and abatement efficiency, while limited direct measurements are extrapolated to larger scales. They suggest that the inverse approach, combining ground-based observations and atmospheric modelling — as has been used for greenhouse gases — can give a more accurate estimate of emissions and cycles. Under this analysis, they estimate global emissions of 5.8 Gg (gigagrams) per year (which is less than the 7.5 Gg per year estimate obtained using a bottom-up approach by Pirrone *et al.* (2010)), with emissions from global oceans accounting for 55% of this. They estimate that anthropogenic emissions from Asian sources, however, have been underestimated in bottom-up inventories. According to the researchers, future monitoring should focus on improving measurements of atmospheric mercury, in particular by extending the number of observation sites in the Southern Hemisphere, to allow more confidence in the results from such modelling.

There are also gaps in knowledge with regard to mercury chemistry in oceans, although recent work, such as the figures reported by Lamborg *et al.* (2014)

on oceanographic measurements of mercury, could be used as a benchmark for future monitoring and models. This study found 290 ± 80 million moles in the global ocean, with nearly two-thirds of this residing in the top 1 000 metres. The North Atlantic was found to be far more contaminated than the South Atlantic, Southern and Pacific Oceans, attributed to anthropogenic pollution. Other recent work, for example under the U.S. GEOTRACES project (Bowman *et al.*, 2015), is also improving knowledge of mercury concentrations and cycling in the North Atlantic.

Most mercury deposition to the North Atlantic is thought to be driven by the oxidation of mercury by bromine atoms at the surface of ocean air. However, the concentration of ozone has doubled over the North Atlantic in the past 50 years, which would cause the level of bromine to decrease. This would therefore decrease the amount of mercury deposited into the ocean — but only future monitoring will tell if this is the case.

Chen *et al.* (2015) used the GEOS-Chem model to analyse trends in atmospheric mercury in the Arctic. They found that annual declines in mercury, from 2000–2009, were lower relative to northern mid-latitudes, at about -0.67% per year. This lower annual decrease was attributed to the process of oceanic evasion, whereby oceanic mercury compounds oxidise and enters the atmosphere.

Soerensen *et al.* (2016) note that the sources and degradation pathways of methylmercury in the Arctic Ocean are also not well understood, although atmospheric deposition is probably the major source. Their geochemical model simulations indicate that mercury levels in the Arctic would fall if policy works to decrease anthropogenic emissions. Modelling carried out by Fisher *et al.* (2013), meanwhile, looked at the drivers of seasonal variation in atmospheric mercury in the Arctic, suggesting that climate change may decrease mercury levels in the surface Arctic ocean — yet another factor that must be taken into account in models.

While indicators of the impact of mercury on humans cannot be directly linked to environmental mercury measurements, these measurements, when coupled with modelling techniques, can inform estimates of mercury in ecosystems. The next step is to link these ecosystem loadings to impacts.

A major achievement would be to provide policymakers with reliable data on the relationship between anthropogenic emissions and the resulting concentrations of mercury in seafood eaten by humans. Recent work shows that estimates of mercury deposition and overall responses of ecosystems are also affected by more longstanding reservoirs in terrestrial ecosystems and the ocean (Streets *et al.*, 2011). Fully coupled biogeochemical models and their links with biological dynamics in food webs are needed for information to guide future policy analysis.

5.3. Is mercury declining in the environment?

Concern about the adverse effects of mercury on human health and ecosystems has led to control of emissions since the mid-1980s. However, there is some discussion over whether reductions achieved by some countries have been offset by the increase in emissions from rapidly industrialising countries. In addition, a key challenge for researchers is to ascertain links between mercury in the atmosphere, deposition, and ecosystem contamination (Pirrone *et al.*, 2013; Sundseth *et al.*, 2017).

According to measurements taken over the long-term at stations in the southern and northern hemisphere and combined with those from the Atlantic Ocean, worldwide concentrations of mercury in the atmosphere decreased by 20–38% between 1996 and 2009, equating to a rate of 1.4–2.7% per year (Slemr *et al.*, 2011). Zhang *et al* (2016) note that these decreases are at odds with global emissions inventories for the period, however, which indicate flat or increasing emissions.

In particular, there was a steep decline in atmospheric concentrations over the North Atlantic. This reduction is unusually large compared to other

gases also found at very small concentrations in the atmosphere (trace gases). Slemr *et al.* (2011) posit that the main reason for these falling atmospheric concentrations is reduced emissions from legacy mercury deposits. Other factors may include acidification of oceans, climate change, the input of nutrients to our rivers and oceans from fertiliser and organic waste as well as other pollution. Soerensen *et al.* (2012) put forward the theory that this was due to decreasing subsurface water mercury concentrations caused by decreasing mercury inputs into rivers and wastewater. Another possibility is that the level of oxidation of mercury in the atmosphere has increased, though not all researchers support this theory and other trace gases have not shown the same trend.

There is no consensus on the reason for apparent reductions in atmospheric mercury, and Slemr *et al.*'s 2011 results are contradicted by figures that show an increase in anthropogenic emissions over this time (Amos *et al.*, 2013; Zhang *et al.*, 2016). Amos *et al.*'s figures state that the present-day atmosphere is enriched by a factor of 2.6, relative to 1840 levels, and by a factor of 7.5, relative to 'natural' levels (in 2000 BC). Notably, this research also shows a sharp rise in anthropogenic emissions since the year 2000, with more than half of atmospheric deposition attributed to secondary re-emission of legacy mercury.

Zhang *et al.* (2016) argue that emissions inventories as used in Streets *et al.* (2011) do not tally with actual observations because they:

- do not account for the decline in atmospheric release of mercury from products;
- are biased in their estimation of emissions from gold mining;
- do not properly account for changes in mercury emissions from coal-fired utilities since emissions control targets were implemented.

In effect, the phase-out of mercury and controls targeted at coal-fired power plant emissions in North America and Europe are reaping benefits in the environment, according to recent observations. More recent inventory work by Streets *et al.* (2017) finds that emissions are indeed decreasing, in line with monitoring data, but more work is required to reduce uncertainty over observed trends. Both top-down and bottom-up models in addition to better understanding of mercury cycling are crucial for identifying real-world effects of policy.

Measuring mercury on board a Rockwell Turbo Commander at Mount Etna (3300), Sicily. National Research Council of Italy: Institute of Atmospheric Pollution Research (CNR-IIA).

6. Reduction, treatment and storage of waste mercury

6.1 Alternatives to mercury-added products

As discussed in chapter 2, whilst a number of consumer items produced in the past contained mercury, EU legislation has in the last ten years, prohibited the use of mercury in most products.

Common items on the global market that contain mercury include certain types of energy-saving discharge and fluorescent lamps, batteries, dental amalgam, electrical devices and instruments (including mercury thermometers), paints, cosmetics, and some pesticides and fungicides. It is therefore important to find safe alternatives to mercury in these products, and/or reduce their mercury content. This is particularly challenging given the wide range of products that contain mercury, but the potential for reduction in use is significant since alternatives are often available. Table 2 provides a summary of mercury-containing products and their mercury-free alternatives. Mercury-free prospects for just some of these products are considered in more detail in the following sections.

6.1.1 Dental amalgam

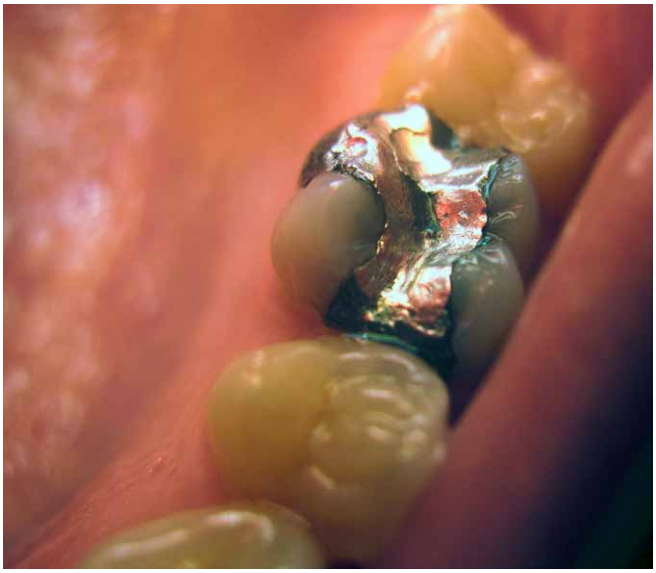
Mercury released during placement and removal of dental fillings results in temporary exposure to patients and also to dental personnel. Based on available evidence, however, there is no justification for removing clinically satisfactory amalgam fillings as a precaution, except where an allergic reaction occurs. From an environmental perspective, though, alternatives to new mercury fillings would reduce emissions.

Mercury-free alternatives to amalgam fillings are available but not widely used across all EU Member States, partly due to their higher costs. Alternatives include mercury-free 'composite' fillings and Atraumatic Restorative Treatment (ART). ART uses a type of glass polymer called ionomers and is widely used in developing countries. Laser, ultrasound and drug-based therapies that stimulate the regeneration of the tooth material dentine, are also being developed (e.g. Cass, 2016).

BIO Intelligence Service (2012) considered the potential to reduce mercury usage in dental amalgam as part of an EU-commissioned study. The study considered the high costs of mercury-free alternatives a market failure, as the external costs of mercury amalgam (e.g. waste management) are not factored into its purchase cost, concluding that there is a strong need to improve waste management of dental amalgam through improved enforcement of EU waste legislation.

Not all dentists are trained in conducting mercury-free work or may be reluctant to change their practices — either due to the cost, scepticism about the alternatives, or a lack of awareness of mercury's environmental impacts.

The SCENIHR (2015) notes that current alternative materials to amalgam are chemically very complex, also have clinical limitations and may present toxicological risks — and that data are very limited



Mercury filling on first molar, shown upsidedown. Kauzio, 2009. Wikimedia Commons.

Product category	Specific use/application	Mercury-free alternatives
Batteries	Button cell, silver oxide	Mercury-free units
	Button cell, zinc air	
	Alkaline manganese (manganese dioxide)	
	Mercuric oxide	
	Button cell, mercuric oxide	
	Button cell, zinc carbon	
Electrical/electronic devices	Tilt/vibration switch	Capacitive, electrolytic, mechanical, metallic ball, potentiometer, solid-state
	Float switch	Alloy, capacitance, conductivity, magnetic dry reed, mechanical, metallic ball, optical, pressure transmitter, sonic,/ultrasonic, thermal
	Pressure switch	Mechanical, solid-state
	Temperature switch	Mechanical, solid-state
	Displacement relay	Dry magnetic reed, electromechanical, hybrid (electromechanical & solid-state), silicon controlled rectifier, solid-state
	Wetted reed relay	
	Contact relay	
	Flame sensor	Electronic ignition system
	Thermostat	Digital, snap-switch
Measuring devices	Sphygmomanometer	Aneroid, oscillometrics
	Fever thermometer	Digital, liquid-in-glass
	Non-fever thermometer	Bi-metal, digital, infrared, liquid-in-glass
	Hygrometer/Psychrometer	Digital, spirit-filled
	Barometer	Aneroid, digital
	Manometer	Aneroid, digital, meedle/bourdon
	Flow Meter	Ball-actuated, digital
	Pyrometer	Digital, optical
	Hydrometer	Spirit-filled
Lamps/lighting	Linear fluorescent	Linear LED
	Compact fluorescent	LED, LED downlight
	High intensity discharge	Halogen, LED, mercury-free units
	Backlight units for LCD displays	LED
	Mercury short arc	No known mercury-free alternatives
	Neon	
Dental amalgam	Dental cements and fillings	Composite, glass ionomer, resin ionomer
Paints	Interior/exterior paints (phenylmercuric acetate, biocide)	Non-mercury preservative/microbial
Pesticides	Agricultural applications (organomercurial compounds, biocide)	Non-mercury based pesticides
Cosmetics	Skin care products (creams, soaps, lotions)	Non-mercury preservative/microbial

Table 2: Summary list of alternatives to mercury-containing products. Redrawn from UNEP (2008) http://www.unep.org/chemicalsandwaste/Portals/9/Mercury/Products/flyer%20final1%20%20mercury-free%20alternatives.pdf

regarding their exposure effects. Some of these materials may undergo chemical reactions within the tooth cavity and adjacent soft tissues during placement and may also degrade *in situ*.

To reduce the use of mercury-added products in line with the intentions of the Minamata Convention, SCENIHR recommend that, for primary teeth, alternative materials to amalgam should be the first choice. Also, as with any other medical or pharmaceutical intervention, caution should be taken when considering the placement of any dental restorative material in pregnant women. The new EU Mercury Regulation sets out short and longer term measures to reduce use of and pollution from dental amalgam (EC, 2017). It will:

- prohibit the use of amalgam in vulnerable populations (pregnant/breastfeeding women and children under the age of 15);
- require the use of pre-dosed encapsulated amalgam;
- require dental clinics to be equipped with amalgam separators, to prevent mercury being released into sewage systems.

In addition, the Commission is due to present a report on the feasibility of ending the use of amalgam by 2030. The development of alternative restorative materials and therapies is therefore of utmost importance.

6.1.2 Batteries

Very small amounts of mercury are still added to most zinc air, alkaline and silver oxide miniature batteries in order to prevent the formation of internal gases that can cause leakage. According to the EU Batteries Directive (2006/66/EC) no battery with a content of mercury higher than 0.0005% by weight can be placed on the EU market. This also includes button cells that, although they do not pose a health risk in use, have to be properly collected and treated as they reach the end of their active use period. If incinerated, the mercury can end up back in the air; if inadequately landfilled, it could end up in ground water, and potentially in sources of drinking water.

In mercuric oxide batteries, mercury is used as an electrode rather than an additive to control gas buildup. These are still produced for hospitals, military and commercial applications globally, where a stable current and long life is required.

A 2014 study found batteries on the market in Germany with levels of mercury exceeding EU limits (Recknagel *et al.*, 2014), indicating that attention to compliance is needed. The study found that only four out of 69 button cells were completely mercury free.

A number of mercury-free alternatives (e.g. lithium, silver and alkaline) have been available for several years. They are considered to perform as well as mercury batteries, but were 10% more expensive in 2012, according to reports (BIO Intelligence Service, 2012). However, as technologies develop, the prices of these alternatives are expected to decrease.

Li-ion battery from a laptop computer. Kristoferb, 2010. CC BY-SA 3.0 Wikimedia Commons.

6.1.3 Healthcare equipment

Safe, accurate and practical alternatives to mercury-based equipment are available for many healthcare applications (Danasekaran *et al.*, 2013). For instance, alternatives to mercury thermometers include digital thermometers and infrared thermometers. Electronic sphygmomanometers (blood pressure meters) are also available.

There are several policy initiatives that aim to move the market towards such alternatives. For instance, UNEP's Global Mercury Partnership has set the goal of reducing demand for mercury-containing fever thermometers and sphygmomanometers by at least 70% by 2017. In 2013, the WHO and Health Care Without Harm launched a joint initiative to completely remove mercury from all measuring devices by 2020.[3] Practical guides for healthcare workers on how to substitute non-mercury thermometers and sphygmomanometers in health-care settings are available from the WHO (Shimek *et al.*, 2011) and Health Care Without Harm.[4]

6.1.4 Lamps

Certain energy efficient lighting, such as compact fluorescent bulbs (CFLs), is currently exempt from the RoHS Directive, which restricts the use of mercury and other hazardous substances in electrical and electronic equipment.

Great progress has been made in recent years in reducing reliance on mercury-containing energy-efficient lamps (linear fluorescent bulbs, compact fluorescent bulbs, and high-intensity discharge lighting) altogether. Solid state lighting (SSL), based on light-emitting diodes (LEDs), has emerged as a viable alternative, now widely available and affordable.

The Ecodesign Preparatory Study on Light Sources commissioned by the EC demonstrated that although LED bulbs initially cost the consumer more than traditional bulbs, savings are realised after a few years thanks to lower energy costs (VITO and VHK, 2015), making LED lighting an attractive option from more than one perspective. The price of LEDs has also dropped remarkably in recent years as production has been upscaled.

Even ultraviolet lamps, used in a variety of applications such as disinfection and curing, have been revolutionised with LED technology, though further optimisation is required (Martín-Sómer *et al.*, 2017). The outlook for mercury-free lighting

Some of the LED lightbulbs available to the consumer as screw-in replacements for standard incandescent bulbs. Geoffrey A. Landis, 2012. CC BY-SA 3.0 Wikimedia Commons.

3 http://www.who.int/mediacentre/news/notes/2013/mercury-medical-devices-20131011/en/
4 https://noharm-global.org/issues/global/switching-alternatives

is therefore good, but treatment of end-of-life lamps and other mercury-containing products is a challenge in the coming years.

6.2 Dealing with waste mercury: treatment and storage

6.2.1 Waste mercury in the EU

In accordance with the Industrial Emissions Directive, the Waste Framework Directive and the WEEE Directive, Member States must ensure that all waste mercury is safely disposed of. This includes mercury waste from the following industrial activities:

- the chlor-alkali industry (which will cease to use mercury from 11 December 2017);
- the cleaning of natural gas;
- non-ferrous smelting and mining operations.

In 1995, it was estimated that mercury waste in the EU amounted to 990 metric tonnes (Mukherjee *et al.*, 2004), while a more recent study suggests that around 11 000 tonnes of metallic mercury will need to be disposed of in the next 40 years in the EU (Hagemann *et al.*, 2014). The new Mercury Regulation, meanwhile, notes that more than 6 000 tonnes of liquid mercury waste, from the mandatory decommissioning of mercury cells in the chlor-alkali industry in the EU, will have been generated by the end of 2017.

It has been a requirement for mercury in all end-of-life goods to be safely and efficiently extracted for specialist disposal within the EU since the restrictions on mercury in measuring and control devices (Directive 2007/51/EC) and in other items (e.g. Directive 94/62/EC), and this continues under the new mercury Regulation.

Liquid mercury is particularly hazardous, therefore the new mercury regulation requires that it undergoes appropriate conversion before permanent storage (see 6.2.2) and solidification if it is to be stored above-ground. However, given the limited capacity for undertaking conversion, liquid mercury waste may be temporarily stored in dedicated above-ground facilities before conversion, in compliance with storage requirements set out in Council Directive 1999/31/EC.

Appropriate treatment of mercury prior to permanent storage depends on correct separation of waste. A recent study quantified environmental impacts from the incineration of unseparated household waste products including mercury, finding that mercury from lamps and batteries accounted for 96% of the toxic impacts of such misplaced waste (Bigum *et al.*, 2017). Overall, misplaced special waste only made up 0.5% of the household waste in the study, carried out in Denmark, but this figure is likely to vary across Member States.

Technical guidelines on management of mercury waste have been published under the Basel Convention.

6.2.2 Treatment methods

A large number of treatment technologies are available which extract mercury from contaminated substances (e.g. soil) then transform or stabilise it, so that it can be 'locked away' and will not contaminate the surrounding environment when stored. Rodríguez *et al.* (2012) outline the most representative methods, which include the following.

- Liquid mercury can be dissolved with a solid metal, such as zinc or copper, to form an **amalgam**. However, Rodríguez *et al.* caution that it can still evaporate from the amalgam, and do not consider this to be a valid method in itself. However, it can be used in combination with other methods.
- Liquid mercury can also be converted into **mercury sulphide** by mixing or reacting it with sulphur. This method may also benefit from combination with other stabilisation methods (e.g. sulphur polymerisation, see below), in order to prevent mercury from escaping to the atmosphere.
- **Thermal treatment** of mercury solid waste allows mercury to be extracted as a vapour, which can then be converted to liquid mercury. This is then further treated, usually through amalgamation, for disposal. This technology is still in development.

- Mercury can also be turned into a glassy material, in a process called **vitrification**. This is also achieved through heating: either an electrical current can be passed through a contaminated material (often soil) or the material can be placed in a furnace or melter. A major disadvantage of both thermal treatment and vitrification is that they consume large amounts of energy.
- **Soil washing** is a method used as part of soil remediation. Mercury tends to bind to smaller particles of soil; these can be separated from larger particles and then further processed using another treatment technology. An advantage of soil washing is that it can reduce the volume of material that needs treatment, but may not be cost-effective for small quantities of contaminated material.
- Through chemical techniques, mercury can be incorporated into hard materials, in a process called solidification, which stabilises the contaminant. For instance, it can be incorporated into a sulphur polymer or a phosphate ceramic. Although less commonly applied, it is also possible to bind mercury into cement, asphalt or resin. **Stabilisation/solidification** treatment appears to be one of the most effective and safest technologies, but increases the volume of waste.

Another method of treating mercury contamination is **phytoremediation**, a relatively new technology that uses plants to degrade, extract, contain or immobilise contaminants from soil and water. Su *et al.* (2009) researched the use of suitable plants to extract and accumulate mercury from contaminated soils. Out of Indian mustard (*Brassica juncea*), beard grass (*Polypogon*) and Chinese brake fern (*Pteris vittata*), the fern showed the fewest stress symptoms from the mercury exposure and also had the highest accumulation rate in the roots. Phytoremediation could be advantageous for treatment of mercury-polluted soils, especially in developing countries where artisanal gold mining has left a legacy of polluted soil (Moreno *et al.*, 2009). The mercury in the plants could then be recovered or stored in an area where it does not pose a threat to the environment.

Phytoremediation at Cunha Baixa mine, Viseu, Portugal. Daniela, 2014. CC BY-SA 2.0 Flickr.

'Mercury disposal, mercury recycling centre'. Enzo Carretta, 2011. CC BY-SA 3.0 Wikimedia Commons.

Phytostabilisation uses plant roots to limit the mobilisation of mercury and bioavailability in soil. However, disadvantages are that the mercury remains in the soil, therefore this is only applicable in cases where rapid immobilisation is needed to protect ground and surface waters.

6.2.3 Storage methods

Permanent storage facilities include above-ground warehouse-style storage facilities and underground storage facilities, such as abandoned or repurposed salt mines, or deep underground hard rock formations. In accordance with the new mercury regulation, mercury must be stored separately from other waste, in sealed storage chambers, and certificates must be issued to confirm the placing of shipments of mercury into permanent storage. Above-ground permanent storage facilities can also be used, provided they ensure at least an equivalent level of safety and confinement as underground storage facilities.

Salt mines are one of the best places to store mercury, offering large spaces that do not require special buttresses and cannot be easily penetrated by liquid and gas. Both abandoned and operating salt mines can be suitable, but they must provide low humidity conditions and not be subject to threat of natural disasters, such as earthquakes and volcanic activity. In some cases, where only a small amount of waste needs to be managed, it may be more economically feasible to export mercury waste to another EU country for storage than establish new storage facilities (Lee and Lee, 2012).

Liquid mercury waste is to be stored in dedicated and equipped temporary storage facilities before being transferred to underground or above-ground facilities for permanent storage. Operators of temporary storage facilities must keep records on origins, destinations and volumes of waste received and shipped out, for purposes of traceability. Records must also be kept by operators of conversion facilities.

6.2.4 Bacterial remediation

The biologically active form of mercury, methylmercury, is produced by the action of a bacterium that lives in conditions without oxygen. Formation of this most toxic form of mercury therefore tends to occur in deep sea conditions, river beds, wetlands, sediments and soils (Ullrich *et al.*, 2001). Researchers have identified genes in bacteria that allow them to methylate mercury, opening up the possibility of removing these genes to destroy their ability to make methylmercury from mercury, while retaining their ability to stabilise mercury in less toxic, volatile forms, for collection and storage (Parks *et al.*, 2013). A recent review by Mahbub *et al.* (2017) suggested that this type of bioremediation could be used to remove mercury from soil, as well as from water.

Volatile mercury produced in this way can be collected in inert porous materials such as activated carbon, or in a bioreactor it can be recovered through distillation. It is also possible for it to be immobilised in the bacteria itself (Sinha and Khare, 2012).

This points to the potential to use bacteria in treatment plants, or in small contaminated areas. Although there are many examples of pilot-scale applications of this biotechnology (e.g. Velásquez-Riaño and Benavides-Otaya, 2015; Wagner-Döbler, 2013), it is not widely employed, currently. One of the difficulties is the contamination of sites with multiple substances, which can affect the efficacy of bacteria. Mahbub *et al.* (2017) suggest, therefore, that future research efforts should be focussed on producing bacteria resistant to multiple contaminants.

7. The Minamata Convention and the EU

7.1 The Minamata Convention

The Governing Council of the United Nations Environment Programme agreed in 2009 that voluntary actions to date had not been sufficient to address the concerns on mercury, and decided it was necessary to prepare a globally binding instrument on mercury. The aim of the resulting, global Minamata Convention is to sustain an overall reduction in mercury levels in the environment over time thus protecting human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds.

The Convention entered into force in August 2017, after the fiftieth instrument of ratification, acceptance, approval or accession had been deposited by Romania, in May 2017. **As the first new multilateral treaty in over a decade, it is notable that the Convention addresses the problems raised by mercury over the whole of its complicated cycle.**

It is undeniable that the challenges confronting developing countries will be tough to reconcile with the progress made by more developed continents with available financial resources and more technically qualified researchers. Under the Convention, financial and technical assistance as well as capacity-building and technology transfer are encouraged for developing countries, those with economies in transition and small island developing states (UNEP, 2013c).

Minamata memorial. hyolee2, 2011. CC BY-SA 3.0 Unported. Wikimedia Commons.

Where bans on activities resulting in mercury releases are not possible, plans to phase out and reduce emissions have been devised. The Convention has set phase-out dates for specific mercury-added products and manufacturing processes in which mercury is used. For each of these categories, there may be an exemption if a Party requests. Rules for registration and exemptions available to a Party on request are covered under Article 6 of the Convention. For example, "No Party may have an exemption in effect at any time after 10 years after the phase-out date for a product or process listed in Annex A or B" (Article 6.9).

7.2 The EU and the Minamata Convention

The goals of the Minamata Convention on Mercury are in line with the EU's Community Strategy concerning Mercury. Global action and international cooperation through the Convention will bring further health and environment benefits within the EU; it is seen as the best, most cost-effective opportunity available to realise this goal for the EU, while also substantially reducing mercury's harmful impacts at a global level (COWI *et al.*, 2014).

Following a public consultation in 2014, the Commission proposed a ratification package in February 2016, which resulted in the adoption *inter alia* of a Council Decision on the ratification by the EU of the Convention. Thanks to the ratification of the Convention by the EU, several Member States, and Afghanistan and Norway in May 2017, the Convention entered into force on 16 August 2017. Certain legislative gaps were identified in EU legislation, which required amending the *acquis communautaire* to ensure full implementation of the Convention. These were in the following areas:

- import of metallic mercury;
- export of certain mercury-added products;
- mercury use in new products and processes;
- use of mercury in certain manufacturing processes;
- mercury use in artisanal and small-scale gold mining (ASGM);
- use of dental amalgam.

As part of this process, a new mercury Regulation, (EU) 2017/852, repealing Regulation (EC) No 1102/2008 was adopted in May 2017, amending and complementing the *acquis* by, *inter alia*:

- prohibiting within the EU any future new uses of mercury in products and industry, unless significant environmental and health benefits are demonstrated and provided that there are no mercury-free alternatives;
- addressing the issue of dental amalgam, by restricting its use to its encapsulated form; by requiring the use of amalgam separators and by banning the use of amalgam fillings for the treatment of deciduous teeth, for children under 15 and for pregnant and breastfeeding women.

The first Conference of the Parties to the Minamata Convention (COP1) took place on 24–29 September 2017 in Geneva.

"The new global treaty on mercury will help protect millions of people all over the world from exposure to this toxic heavy metal. With ratification the EU has delivered the decisive bit and triggered its entry into force. This is a great success of EU green diplomacy. It highlights Europe's commitment to strong and concerted international action.»

Karmenu Vella, Commissioner for Environment, Fisheries and Maritime Affairs, 2017

For materials developed by the Interim Secretariat of the Minamata Convention on Mercury in support for the ratification and effective implementation of the Convention, see UNEP Minamata Convention Resource materials, or Fact sheet in English.

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Mercury levels exceed safety standards for fish in six European freshwater and estuary sites (May 2016)

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Mercury-resistant bacteria useful for studying toxic metal cycling (January 2016)

Mercury-resistant bacteria could help scientists to understand more about mercury cycling in the environment. In a new study, researchers identified one particular strain of soil bacterium that could serve as a model for the conversion of the toxic metal into less toxic forms. They also discovered a new gene involved in the conversion process. **http://ec.europa.eu/environment/integration/research/newsalert/pdf/mercury_resistant_bacteria_useful_for_studying_toxic_metal_cycling_442na5_en.pdf**

Minamata Convention will help China and India avoid mercury emissions in 2050 (July 2015)

Under the United Nations Minamata Convention on mercury, China and India could avoid a combined 242 tonnes of mercury emissions in 2050 from coalfired power plants, a new study predicts. This amount is equal to approximately 12% of total emissions in 2010. While the benefits will be mostly regional, lower mercury deposition in surrounding oceans is good news for Europeans who eat fish sourced from those waters. **http://ec.europa.eu/environment/integration/research/newsalert/pdf/minamata_convention_will_help_china_and_India_avoid_mercury_emissions_in_2050_419na4_en.pdf**

Albatrosses' survival seriously threatened by mercury and pollutants (September 2014)

Mercury and persistent organic pollutants (POPs) reduce albatrosses' chances of successfully breeding, a recent study finds. These pollutants add to the list of environmental pressures, including climate change, disease and fishery bycatch, affecting this highly threatened species. **http://ec.europa.eu/environment/integration/research/newsalert/pdf/mercury_albatrosses_pollution_387na4_en.pdf**

Thematic Issues

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Ship recycling: reducing human and environmental impacts (June 2016)

The ship recycling industry — which dismantles old and decommissioned ships enabling the re-use of valuable materials — is a major supplier of steel and an important part of the economy in many countries, such as Bangladesh, India, Pakistan and Turkey. The recycling of scrap metals from ships also reduces the need for mining, an environmentally damaging practice. In this way, it is a vital part of the circular economy — which purports to minimise waste and recycle some materials infinitely.
http://ec.europa.eu/environment/integration/research/newsalert/pdf/ship_recycling_reducing_human_and_environmental_impacts_55si_en.pdf

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