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Article

Ship Based Measurements of Seasonal Atmospheric Mercury Concentrations over the Baltic Sea

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Abstract: Mercury is a toxic pollutant emitted from both natural sources and through human activities. A global interest in atmospheric mercury has risen ever since the discovery of the Minamata disease in 1956. Properties of gaseous elemental mercury enable long range transport which can cause pollution even in pristine environments. Total gaseous mercury (TGM) was measured from winter 2016 to spring 2017 over the Baltic Sea. A Tekran 2357A mercury analyser was installed aboard the research and icebreaking vessel Oden for the purpose of continuous measurements of gaseous mercury in ambient air. Measurements were performed during a campaign along the Swedish east coast and in the Bothnian Bay near Lulea during the icebreaking season. Data was evaluated from Gothenburg using a plotting software and back trajectories for air masses were calculated. The TGM average of 1.365 ± 0.054 ng/m^3 during winter and 1.288 ± 0.140 ng/m^3 during spring was calculated as well as a total average of 1.362 ± 0.158 ng/m^3. Back trajectories showed a possible correlation of anthropogenic sources elevating the mercury background level in some areas. There were also indications of depleted air, i.e., air with lower concentrations than average, being transported from the Arctic to northern Sweden resulting in a drop in TGM levels.

Keywords: atmospheric mercury; Baltic Sea; mapping of TGM levels; long range transport

1. Introduction

Mercury is a toxic pollutant which is naturally abundant in the earth's crust. It can be released to the atmosphere through volcanic and geothermal activities and the weathering of rocks. Emissions of mercury from anthropogenic sources come from mining, coal combustion, cement production and oil refining among other sources. Globally, the largest source of anthropogenic mercury emissions to the atmosphere is artisanal small-scale gold mining and another major source is the combustion of coal [1]. In Sweden the major mercury emission sources are combustion, chemical industry on the west coast and metal and mining companies in northern Sweden [2]. In gaseous elemental form, also known as GEM or Hg0, mercury is very stable and can therefore be transported long distances from its source of emission. For that reason GEM is the most abundant mercury species in the troposphere, having a residence time between 6 – 24 months [3, 4]. An issue deriving from GEM's stable nature is that the long range transports can cause even pristine environments to be polluted [1, 4].

While natural and anthropogenic sources make up 10% and 30% of total Hg-emissions respectively, the remaining part come from re-emissions which is placed in a category of its own because the original source may have been either natural or anthropogenic. Once in the atmosphere, mercury circulates between air, earth and water. When mercury enters the ocean or fresh water it has two possible paths other than being re-emitted. It can either be methylated by microorganisms and bio-accumulate in the food chain. The other path, which is the only way for the circulation to stop, is for it to get buried deep in bottom sediments or get trapped in stable mineral compounds [1].

In the environment mercury exists most commonly in oxidation states 0 or +II [5]. Oxidised mercury species are more soluble and can therefore easily fall down with precipitation and be deposited on vegetation and in oceans and fresh waters [4, 5, 6]. Oxidation from GEM to gaseous oxidised mercury (GOM) is suggested to be caused by ozone or halogens such as bromine. The sum of GEM and GOM is called total gaseous mercury (TGM). Since Hg0 has low solubility in water most

aqueous mercury is therefore present in inorganic or organic form as Hg2+ or methylated mercury (MeHg) [5].

There are several studies that have found occasions in the Polar regions where GEM is extensively oxidised into GOM or particulate mercury (HgP) in reactions with halogen radicals. The mechanism has yet to be confirmed but it is thought to involve halogen species that are released when open water areas refreeze and absorb UV-radiation [7]. These events are called atmospheric mercury depletion events (AMDE) and result in a sudden drop of GEM. They occur during springtime in Arctic and Antarctic regions but there is evidence suggesting that mercury depleted air masses may travel with the winds and be discoverable away from the polar areas [8].

Mercury is a neurotoxin and can damage a human's central and peripheral nervous system. It is toxic both in inorganic and organic form. Different species of mercury have different harmful effects on the human body with MeHg being most toxic and harmful to human health and wildlife [9, 10]. MeHg-poisoning or the Minamata disease was officially discovered in 1956 in Minamata, Japan. Some symptoms of the disease include brain damage and paralysis [11]. Pregnant women showing minor symptoms gave birth to infants with congenital Minamata disease with symptoms such as great neurological problems and deformed limbs [9, 11]. MeHg has a far greater impact on the foetal brain than on an adult's brain. Children's brains are therefore more sensitive to lower exposures of MeHg, especially during brain development for foetuses still in the womb [9, 10, 11]. As MeHg bioaccumulates in the aquatic food chain, humans consuming large amounts of fish and shellfish are thought to be at the highest risk for MeHg-poisoning [10, 12].

1.1 Current State of Research

There has been extensive research on the subject of atmospheric mercury distribution ever since the discovery of the Minamata disease [13, 14, 15 and references therein]. As of 2013, the Minamata convention works toward protecting humans and the environment from mercury. It is a global treaty with as many as 128 countries having signed and 42 countries have ratified the treaty [16]. To understand the nature of mercury, how it travels and how it is transformed, it is important to map the concentrations at different locations around the world. A global observation network was created by the European Union called Global Mercury Observation System (GMOS) to support the Minamata convention and to facilitate the cooperation between countries. The GMOS programme collected data on mercury concentrations at different monitoring sites as well as during cruise campaigns. These data are used for research such as the Mercury Air Transport and Fate Research run by United Nations Environment Programme (UNEP) [17]. UNEP has also released several Global Mercury Assessments which present the latest research discoveries related to global emissions and distribution of mercury [1].

A previous study of mercury concentrations in and over the Baltic Sea was performed during the summer of 1997 and winter of 1998. Measurements were taken at various locations during two expeditions with results reflecting the normal background concentrations in winter but slightly higher during the summer expedition [18]. Seasonal variations were observed by Kentisbeer et. al. in a monitoring study in the United Kingdom in 2005-2008. The results showed a higher average concentration of mercury during the summer and could be explained by contaminated air masses coming with the southerly winds from continental Europe [19]. More commonly, winter and spring maxima have been found and are probably due to the increased burning of fossil fuels during the cold months [20, 21, 22]. In 1995 sudden drops in mercury levels were discovered during the spring at an Arctic monitoring site. Several other monitoring studies were able to confirm this phenomenon at other Polar regions. AMDE's occur when GEM is oxidised into GOM or HgP resulting in a drop in TGM levels – these species are more reactive and therefore more likely to be transferred to the surroundings through reactions or deposition [7].

1.2 Aim and Conclusion

The aim of this study was to evaluate concentrations of TGM in ambient air in different parts of the Baltic Sea and to look for seasonal variations while comparing the results to other studies in the same and other areas. Reasons for varying TGM concentrations in different locations and the occurrence of AMDE's during spring in Lulea was investigated. The collected data was compared and evaluated for seasonal variations of mercury levels in the air. It was found that during the winter cruise, the average value was higher than the measured average value for the cruise south in late spring. Indications of depleted air coming from the Arctic were also discovered. The calculated average TGM levels were 1.365±0.054 ng/m^3 during winter and 1.288±0.140 ng/m^3 during spring with a total average of 1.362±0.158 ng/m^3.

2. Method

The Tekran 2537A used for taking measurements was installed aboard IB Oden on the fourth deck, approximately 20 meters above sea level. IB Oden, owned by the Swedish Maritime Administration, is not only an icebreaking vessel but also works as a platform for polar research and has thus far made seven research expeditions to the North Pole and worked six seasons in Antarctica. IB Oden being a research vessel was made possible by a contract between the Swedish Maritime Administration and the Swedish Polar Research Secretariat, which is another government ruled organisation focusing on promoting polar research [23].

Continuous TGM measurements in ambient air above the surface of the Baltic Sea were conducted during a campaign aboard the Swedish icebreaker IB Oden. The Baltic Sea is a young sea with brackish water which makes it a challenging environment for organisms to inhabit. The environmental conditions become increasingly harmful due to heavy pollution and eutrophication from the many residential areas on the coastlines [24]. The geographical location of the Baltic Sea in the northern latitudes results in great variations in temperature and hours of daylight during different seasons. The proximity to the Arctic also makes it possible for AMDEs to travel south with the winds and be discoverable in this area [8].

2.1 Mercury Analyser

A Tekran model 2537A, stationed at the bow of the icebreaker vessel Oden (IB Oden), was used for all the measurements of TGM. Continuous measurements were taken every ten minutes. Tekran utilises CV-AFS for determining mercury concentrations in the air. The air inlet was placed at the same level as Tekran at 20 meters in a direction opposite of the ship's funnel as to avoid getting exhaust gas in the inlet. As Tekran 2357A operated almost completely unattended during this study, the input method was set to auto-calibration at a 24 hour interval via the internal permeation source to control the data quality.

The detection compartment of the instrument consists of a hollow-cathode lamp, emitting light at 253.7 lambda which is mercury's absorbance line, as well as a photomultiplier tube. According to the Tekran manufacturers the detection limit of Tekran 2537A is 0.1 ng/m^3 [25, 26].

As air enters the inlet and is carried towards the instrument it passes a soda-lime trap which scrubs the incoming air from unwanted substances such as hydrocarbons, dirt and moist. Thereafter it also passes a PTFE-filter which in turn filters out HgP from entering the system [26]. By using two gold traps continuous measurements are enabled. As one trap samples air the other is heated and desorbed to the detector and then they switch tasks. Inside the cartridges the mercury is trapped by the amalgamation technique where mercury is adsorbed onto the gold and then desorbed as GEM. Argon gas carries the gaseous elemental mercury to the detector [26]. Obs två 26

2.2 Softwares

The ocean data view (ODV) program, version 4.7.10, was used for plotting and analysing data. In this study the ship coordinates were combined with the Tekran data to visualise the concentrations along the ship's track [27]. Other parameters such as wind speed and wind direction were plotted to

indicate whether they influenced the fluctuating concentrations. The National Oceanic and Atmospheric Administration's Hybrid Single-Particle Lagrangian Integrated Trajectory (NOAA HYSPLIT) online trajectory model was used to produce back trajectories of air masses. In this study HYSPLIT was used to calculate back trajectories to see where air masses originated from before they reached the coordinate of interest. These calculations were used as an aid to find possible explanations as to why an area had lower or higher concentrations than the average background mercury levels. Four day backward trajectories of air masses were produced at three different vertical levels (0, 20 and 100 m), for the coordinate interest. HYSPLIT was also used to look at solar flux, precipitation, temperature and humidity [28].

3. Results and Discussion

Continuous measurements of TGM were carried out during the ship's cruise north from Helsingborg to Luleå, during icebreaking season in the Bothnian Bay (BB) and during the ship's cruise south from Luleå to Landskrona. The average concentrations are presented in Table 1 divided into five intervals according to location and time. The icebreaking season in Bothnian Bay was split into three sections to facilitate the reading of the plots. The measured average values were comparable to normal background concentrations of TGM in the northern hemisphere which is approximately 1.5-1.7 ng/m^3 [19]. Most of the data however show lower values, particularly the measurements from BB1. The fluctuations between different intervals may be due to calibration issues as the instrument seemed to get slightly varying concentration spans after the calibrations were performed.

Table 1. Results from the measurements performed in the Baltic Sea. Average values are presented.

Site	Season	TGM (ng/m^3)	Range (low-high, ng/m^3)
Cruise North	Winter (Dec 2-6)	1.365±0.054	1.161-1.508
Bothnian Bay (1)	Spring (Mar 13-22)	1.164±0.105	0.821-1.595
Bothnian Bay (2)	Spring (Mar 23-Apr 5)	1.509±0.115	1.100-2.675
Bothnian Bay (3)	Spring (Apr 6-27)	1.364±0.110	0.817-1.703
Cruise South	Spring (Apr 28-May 5)	1.288±0.140	0.797-1.839
All cruises	Dec 2016 – May 2017	1.362±0.158	0.817-2.675

During this study calibrations were performed manually using the Tekran internal calibration source on the following occasions namely 2nd of December which was the first day of this study's measurements and on the 10th of March. The last calibration was performed on the 23rd of March. Few calibrations and relatively long intervals between calibrations may cause uncertainties in the measurements. However, the calibrations looked satisfactory in terms of showing similar areas. Furthermore, the data and the standard deviation were not unusual in comparison to the background level of TGM in the northern hemisphere.

A comparison, between calibration data from this study and from a previous measurement campaign during summer 2016 using the same instrument and the same internal hollow-cathode lamp, was performed to determine how much the lamp possibly could have aged between calibrations. By comparing the area responses from different calibrations an indication of the lamp's degradation is obtained. Calibration data from the summer campaign indicated that there was no major change in response [5]. However, on the 10th of March 2017 a new hollow-cathode lamp was installed inside the instrument and between the calibrations on the 10th of March and on the 23rd of March a 23% decline in area response was calculated and corrected for.

3.1 Anthropogenic Sources

When evaluating the data and looking at back trajectories for low or elevated concentrations, possible anthropogenic emission sources for elevated levels were searched for. Air masses that had passed through Norrbotten in northern Sweden often resulted in elevated levels. In 2016, Norrbotten was the largest contributor of mercury emissions to the air, followed by Östergötland and then Västra

Götaland. In northern Sweden mining and metal industry are the predominant atmospheric mercury emission sources and in mid and southern Sweden combustion and chemical industry are the main sources of atmospheric mercury. However, there seems to be a declining trend in the overall anthropogenic mercury emissions to the atmosphere in Sweden when comparing emission data sheets from the last ten years [2]. On a few occasions back trajectories showed winds that had passed through areas in Finland where there are gold mines and also a chlor-alkali industry [29, 30]. These are also mercury emission sources that have possibly impacted the elevated levels observed in this study.

3.2 Observations from the Plots

Each cruise was plotted on a map using ODV software. Coordinates of significantly high or low concentrations were investigated by calculating back trajectories. The most important events are presented in chapter 3.2.1, 3.2.2 and 3.2.3 and possible anthropogenic sources are discussed.

3.2.1 Cruise North

On the cruise north from Helsingborg to Luleå the measured average concentration reflected normal background levels. There were areas with higher TGM levels near the Danish islands, south of Sweden and Stockholm (see figure 1). For these events it was expected that the winds would originate in more populated areas such as the nearby urban areas or continental Europe. However, back trajectories showed consistent northerly winds for most of the cruise. There was no exceptionally high value measured and even the slightly higher values did not deviate far from normal background levels.

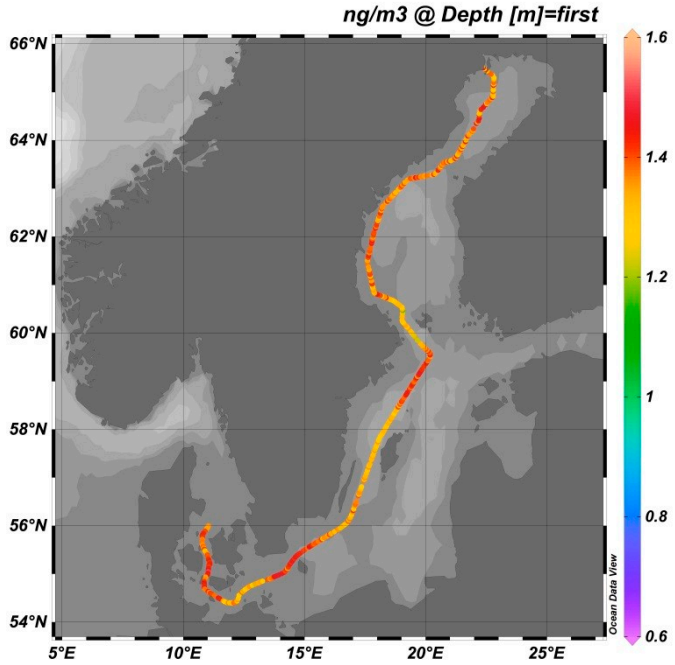

Figure 1. Plot showing the measured concentrations during the transit north from Helsingborg to Lulea.

As can be seen in figure 1 Oden's transit north appears to start between the Danish Islands. One reason for this is that the measurements in Helsingborg and a few hours after Oden left port were unreasonably low and thus excluded from the results. The other reason was the blackout. It was decided to calibrate Tekran and after the calibration was performed the data appeared normal.

The somewhat elevated TGM levels near the Danish islands were investigated. Back trajectories showed northern winds passing through Denmark, Norway and in some cases all the way from Iceland, before reaching Oden. A low point was also investigated (see figure 2) and showed similar trajectory patterns with winds coming from the north. However, for some elevated levels the winds

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had passed over the North Sea and were potentially carrying re-emitted gaseous mercury from the water.

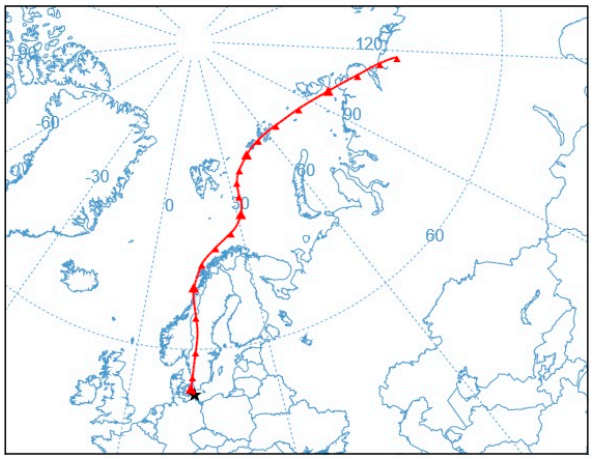


Figure 2. Back trajectory for low level found on the 2nd of December. Vertical level 20 m.

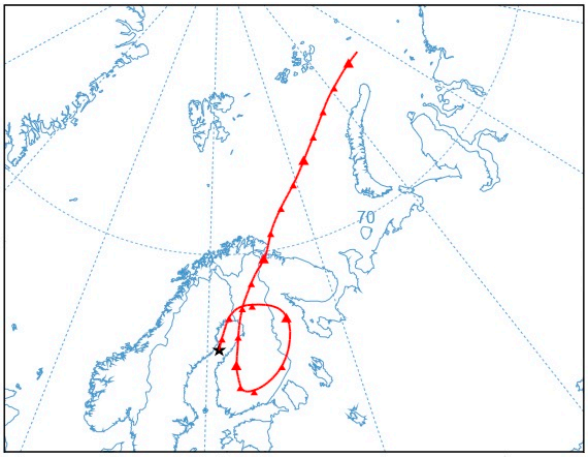


Figure 3. Back trajectory for elevated level found on the 5th of December. Vertical level 20 m.

In the northern parts of Sweden there were generally higher TGM levels compared to southern part (see figure 1). Using HYSPLIT to investigate some high level coordinates, winds were observed to have passed through Finland before reaching Sweden. In figure 3 back trajectory winds pass over areas in Finland where there are both gold mines and chemical industry emitting mercury to the air [29, 30]. Contaminated air from these anthropogenic sources is a possible reason as to why there were areas of elevated TGM levels seen in the plot. Winds reaching the areas of lower concentrations can be assumed to have bypassed these sources but it is difficult to see the exact trajectory path in the HYSPLIT diagrams.

3.2.2 Bothnian Bay

Data was also collected during icebreaking season in the Bothnian Bay and were divided into three separate groups: BB1, BB2 and BB3. Plots are presented for BB1 (figure 4) and BB2 (figure 5) but not for BB3 as the vessel was stationed at port in Lulea for this time period. The lowest average TGM was calculated for the BB1 icebreaking cruise. This might be due to the calibration made on the 10th of March causing these values to be lower overall. Back trajectories of air masses did not correlate with the levels of TGM measured. In some cases there were low concentrations with winds passing by known anthropogenic sources of atmospheric mercury. In other cases this was reversed.

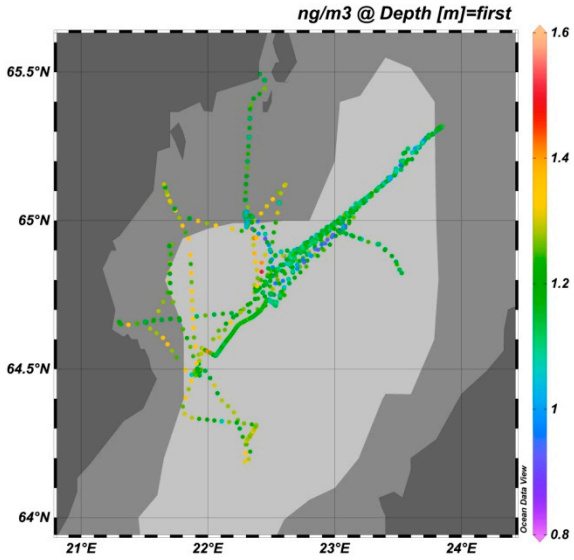


Figure 4. Plot showing the measured concentrations during the first part of the icebreaking season, BB1.

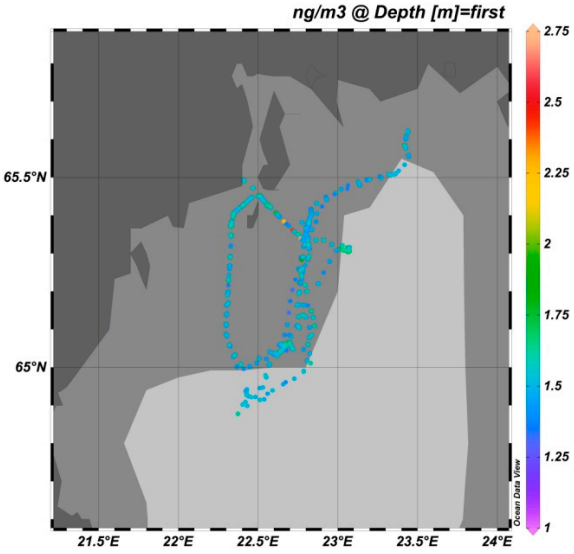


Figure 5. Plot showing the measured concentrations during the second part of the icebreaking season, BB2.

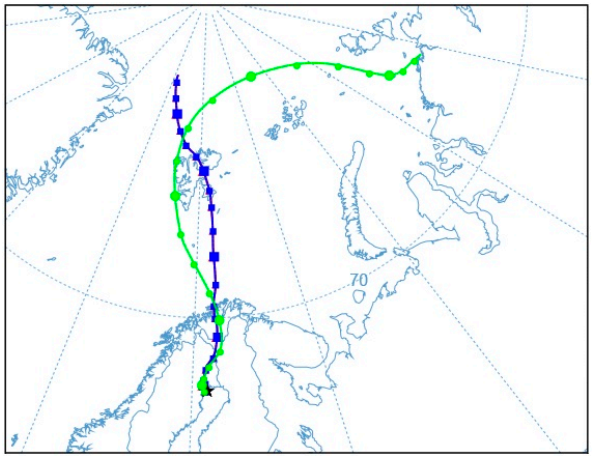


Figure 6. Back trajectory for possible AMDE found on the 28th of March. Blue line represents vertical level 20 m, green represents 100m.

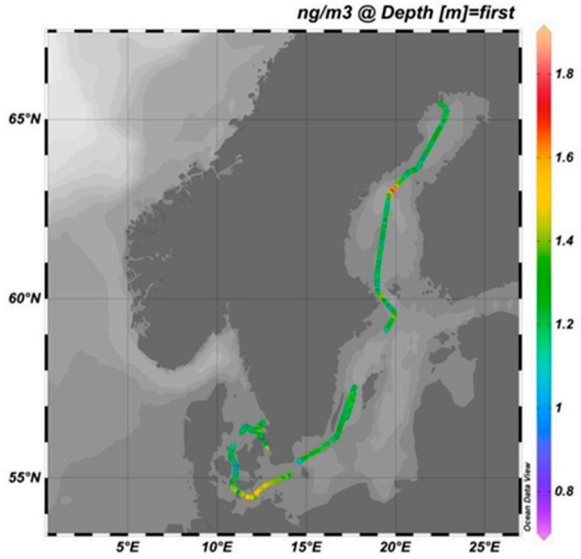
During the icebreaking season and BB2 the highest value of mercury 2,675 ng/m^3 was measured. One explanation is possible contamination from the ship's exhaust since it greatly differs from the

other measured values. The average value for BB2 was higher than for all the other groups, especially high values were measured during the last week of March where the mercury levels at multiple occasions approached 2.0 ng/m^3. Towards the end of this cruise the values seem to drop towards more normal background levels.

During the evaluation of data from Bothnian Bay two possible AMDE's was discovered on the 28th of March and 18th of April. The first was found on BB2 where a dip in the concentrations was observed with the lowest measured value at 1.100 ng/m^3 found on the 28th of March. Back trajectory showed winds coming from the Arctic, possibly carrying depleted air to the Bothnian Bay. The other possible indication of an AMDE was found on the 18th of April when the ship was stationed in the Luleå harbour. The concentration dropped suddenly to 0.817 ng/m^3 and as can be seen in figure 6 back trajectories showed that winds originated in the Arctic, passing through Svalbard. Since the winds did not pass through any apparent anthropogenic mercury sources this suggests a potential AMDE.

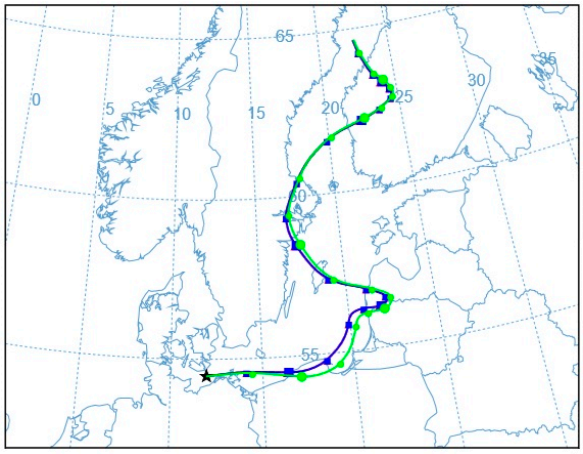
3.2.3 Cruise South

On the cruise south to Landskrona the measurements were comparable to normal background concentrations. The calculated average was lower compared to the winter average. There was missing or faulty ship location data causing a few gaps in the ODV-plot for the cruise south (see figure 7). This is because of a problem with the ship's coordinate data storing but it did not affect the calculation of the average concentration.



Figur 7. Plot showing the measured concentrations during the transit south from Lulea to Landskrona.

Elevated levels of TGM were measured in the Gulf of Bothnia, near Örnsköldsvik in Sweden. According to back trajectories the winds passed through or near gold mines and chemical industry in western and northern Finland, possibly carrying mercury rich air causing higher TGM levels in this area [29, 30]. Another occasion where the concentrations were greater than the average was found between Denmark and Germany. Back trajectories showed winds coming from the east passing through Stockholm, Latvia and Lithuania and then passing by the coast of Poland and Germany (see figure 8). As these countries have higher mercury emissions compared to the Nordic countries it was expected to find higher levels of TGM with eastern winds [31].



Figur 8. Back trajectory for elevated level found on the 2nd of May. Blue line represents vertical level 20 m, green represents 100 m.

3.3 Comparisons and other Observations

Comparing figures 9 and 10, depicting the cruise to northern Sweden during winter and the cruise to southern Sweden during spring, it can be seen that during winter the TGM concentrations are higher. The measured data peaks in March-April during BB2 and if the average value for BB1 is excluded a rising trend can be seen from December to March as well as a declining trend starting at the beginning of April. This corresponds to other studies in the northern hemisphere measuring TGM in the atmosphere where winter or spring maxima were found [20, 21, 22]. However, the amount of data and the timeframe of this project is insufficient to safely evaluate the seasonal trends.

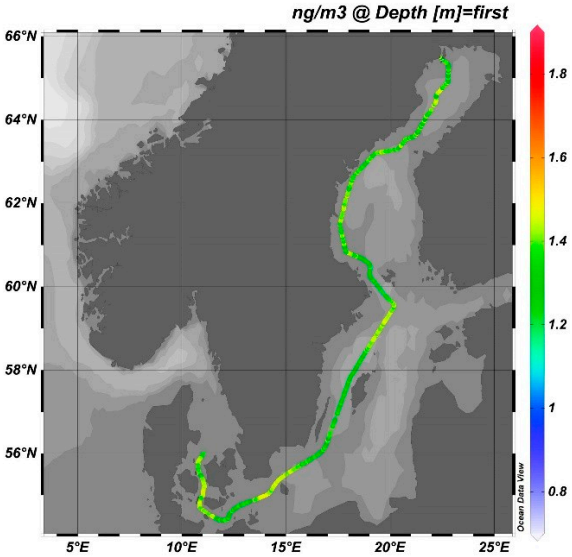


Figure 9. Plot showing the north cruise.

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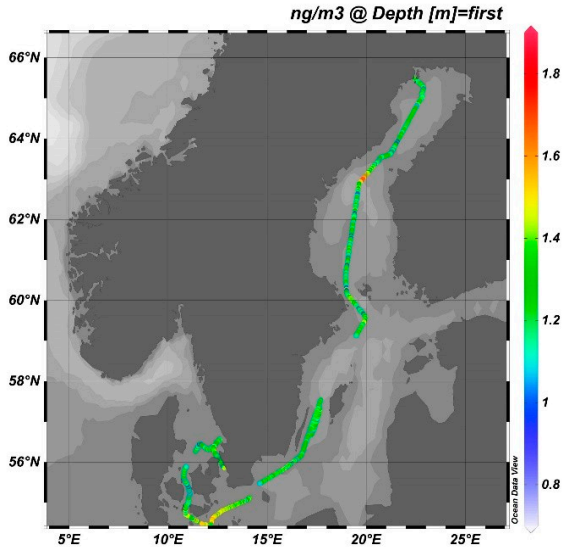

Figure 10. Plot showing the south cruise.

The higher average measured during the cruise north might have been caused by the increased burning of fossil fuels for domestic heating in the winter. Another possible explanation for this trend is that a higher abundance of atmospheric oxidants in summer causes Hg to oxidise and deposit onto surfaces, resulting in decreased TGM levels [20, 32]. The opposite trend – a summer maximum – has also been observed in the United Kingdom and in the Baltic [18, 19]. This is probably due to a larger influence of southerly winds carrying contaminated air from continental Europe [19].

On average the levels for both cruises are similar to what earlier studies of background levels have found, with some exceptions of elevated levels in certain areas (see table 2). On both transits, north and south, mercury concentrations were elevated near the Danish Islands. For the north cruise no obvious anthropogenic sources were found to be the cause. On one occasion, air masses passed through the Swedish west coast near known mercury emission sources. Conversely, during other occasions, air masses passed through Denmark, Norway and Iceland where no specific sources were found. On the cruise south during spring the elevated levels were most likely caused by atmospheric mercury being transported from continental Europe and the Baltic, as previously mentioned.

Air mass trajectories originating in mercury rich areas mostly correlated with elevated measurements. However, there were instances where back trajectories did not always give a clear answer as to why a certain measurement was either elevated or not. In several cases of elevated levels air masses passed through areas where no known source of emission could be found. The reverse was also observed for some low measurements.

Table 2. TGM levels from other studies where TGM was measured, in the northern hemisphere and around the world.

Location	Time Period	TGM (ng/m³)	Reference
Baltic Sea	Summer 1997	1.70±0.20	Wängberg et. al. Ref: 18
Baltic Sea	Winter 1998	1.38±0.13	Wängberg et. al. Ref: 18
Råö, Sweden	2012 – 2015	1.42±0.20	Wängberg et. al. Ref: 34
Ny-Ålesund, Norway	2015	1.49±0.21	Angot et. al. Ref: 14
Arctic	2011 – 2014	1.46±0.33	Angot et. al. Ref: 14
Harwell, England	2013	1.45±0.24	Kentisbeer et. al. Ref: 35
South China	May 2008 – May 2009	2.80±1.51	X.W.Fu et. al. Ref: 4
Pallas, Finland	1996 – 1997	1.26± -	Berg et.al. Ref: 36
Ny-Ålesund, Norway	1996 – 1997	1.43± -	Berg et.al. Ref: 36
Hoburg, Sweden	1979 – 1980	3.91±1.15	Brosset C. Ref: 22
Mace Head, Ireland	Summer 1995 – 2001	1.6±	Ebinghaus et. al. Ref: 20
Mace Head, Ireland	Winter, 1995 – 2001	1.9±	Ebinghaus et. al. Ref: 20

A declining trend has been observed the last 10-30 years in sub-Arctic and mid-latitude sites [3, 21, 33]. This trend is corroborated by comparing the measured values in this study with measurements from previous studies. Measurements were performed in Hoburg on the Swedish east coast as early as in 1979-1980 resulting in an average of 3.91 ng/m^3 which is nearly 300% higher than the average from this study [22]. A later study was performed in 1997-1998 where measurements were taken at various locations over the Baltic Sea. During summer in 1997 an average of 1.70 ng/m^3 was found which is about 30% higher than the south cruise average of this study. During winter 1998 the calculated average was 1.38 ng/m^3 which does not differ significantly from the winter average of this study [18].

During the cruise north a diurnal variation pattern was observed with elevated levels during the day and lower levels at night. This pattern was not consistent once IB Oden had passed Stockholm and was neither observed again on the other cruises.

4. Conclusion

Data was evaluated with the aid of the programs ODV and HYSPLIT. Average concentrations, for the transits north and south as well as during the icebreaking season, were 1.365 ng/m^3 (north), 1.288 ng/m^3 (south), 1.164 (BB1), 1.509 ng/m^3 (BB2) and 1.364 ng/m^3 (BB3). The total average was 1.362 ng/m^3. When IB Oden was heading north during the winter, the average value was found to be higher than the measured average value for the cruise south in late spring. These seasonal differences coincided with other studies suggesting that average TGM levels in ambient air during winter were elevated compared to spring. Over the past 10-30 years a declining trend in atmospheric mercury concentrations has been observed [3, 21, 33]. When comparing the average values of this study with measurements from previous studies made in the Baltic, this observation was supported.

Elevated levels were found near the Danish islands during both winter and spring. In winter there were elevated levels near and above Stockholm and during the spring cruise an area of high levels was found near Örnsköldsvik, Sweden. Using HYSPLIT to calculate air mass trajectories, some winds were observed to have passed through places of known mercury sources such as continental Europe or mining and metal companies in Sweden and Finland. However, during other occasions of elevated levels back trajectories did not give sufficient indications of possible anthropogenic sources. In many of these cases the winds had instead travelled over the North Sea indicating that the elevated levels were possibly caused by re-emission of gaseous mercury from the water. Low or lower values compared to normal background levels were also of interest when calculating back trajectories as particularly low values could be indications of AMDE's. On two occasions during spring the levels clearly dropped while oncoming winds came from the Arctic region. This result suggests that depleted air masses had reached the site of measurement.

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