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Measurement Report: The effects of SECA regulations on the atmospheric SO_2 concentrations in the Baltic Sea, based on long-term observations at the Finnish Utö Island.

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Abstract. The designation of the Baltic Sea as a Sulphur Emission Control Area (SECA) in May 2006, with subsequent tightening of regulations in 2010 and 2015 has reduced the sulphuric emission from shipping traffic. This study, focusing on impacts of SECA on observed SO_2 concentrations, provides a long-term analysis of 1–minute time resolution air quality data from 2006 to 2020 at Utö island (Baltic Sea), supported by the predictions from the Ship Traffic Emission Assessment Model (STEAM). Additionally, hourly data from 2003 to 2005 is utilized to investigate changes due to the SECA limits set in 2006. The observed SO_2 concentrations at Utö have continuously decreased since 2003 due to an overall decrease in SO_2 emissions in Northern Europe, combined with reduced emissions from shipping traffic due to SECA regulations. Three–year average SO_2 concentrations dropped from pre–SECA (2003–2005) to post–SECA periods (2007–2009, 2011–2013, 2016–2018) by 38 %, 39 %, and 67 %, respectively. No clear trends were observed in the concentrations of other pollutants measured. In addition to time series analysis, we investigated wind direction resolved SO_2 concentrations for two selected years and studied the changes in ship plumes of one vessel regularly passing by Utö. This study brings out the importance of long–term, high time-resolution air quality observations at remote marine research stations, in the vicinity of a heavily trafficked ship lane, providing possibility for both quantitative and qualitative analyses of the impacts of regulatory environmental legislation.

1 Introduction

In recent years, international maritime trade has seen sustained growth, primarily due to its recognized economic efficiency, accounting for over 90 % of global trade (IMO, 2016). This growth has been projected to continue. Projections from the United Nations Conference on Trade and Development (UNCTAD, 2019) indicated a prospective annual growth rate of 2.6 % to 3.4 % until 2024. In 2019, 11.08 billion tons of goods were shipped, and the global commercial fleet, consisting of 98 140 vessels exceeding 100 gross tons, had a total capacity of 2.06 billion deadweight tonnage (UNCTAD, 2020). In the Baltic Sea, the shipping activity has increased fairly steadily during 2006–2020 (HELCOM, 2021). For example, in 2020 the total number of

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vessel fleet was increased by 271 %, 140 % and 46 % in comparison to 2006, 2010 and 2015, respectively.

Johansson et al. (2017) reported that on a global scale, shipping emissions contribute annually to 20.8×10^6 tons NO_x, 9.7×10^6 tons SO_2 and 1.5×10^6 tons $PM_{2.5}$, whereas Smith et al. (2015) evaluated that global shipping is responsible for approximately 13 % and 12 % of total global anthropogenic emissions of NO_x and SO_x, respectively. On European scale, the European Environment Agency (EEA, 2017) evaluated that 90 % of SO_2 emissions from transport were attributed to maritime transport, while $PM_{2.5}$, PM_{10} and NO_x transport-associated emissions accounted for 45 %, 28 %, and 35 %, respectively.

In some locations within the Baltic Sea region, the emissions of SO_2, NO_x, and NO_2 from international shipping were estimated to account for as much as 80 % of the overall concentrations of these pollutants in the near-surface environment (Haglund et al., 2016). Jonson et al. (2015) reported that shipping emissions in the Baltic Sea could deteriorate the air quality in coastal areas. These emissions had also the potential to cause acidification and eutrophication of marine waters and surrounding terrestrial ecosystems, significantly impacting the Baltic Sea environment (HELCOM, 2009; Hunter et al., 2011; Raudsepp et al., 2013).

The impacts of shipping emissions are not limited to sea areas. In fact, around 70 % of ship emissions occur within 400 km of land (Corbett et al., 1999) while more than one-third of the world's population lives within 100 km from the coast (UNEP, 2024). Pollution from shipping can reach the inhabited land areas and have a severe impact on human health. Shipping emissions have been shown to negatively impact the air quality, especially on coastal regions and portside (Chen et al., 2019; Donateo et al., 2014; Liu et al., 2017), the climate (Contini et al., 2015; Merico et al., 2016; Sofiev et al., 2018) and the economy (Jalkanen et al., 2014). Andersson et al. (2009) and Brandt et al. (2013) evaluated that international shipping was responsible for approximately 50 000 premature deaths annually in Europe. Furthermore, Barregard et al. (2019) showed that shipping in the Baltic Sea and the North Sea alone may have resulted in approximately 14 000 premature deaths in Europe in 2011.

As international maritime trade and shipping emissions are increasing, measures to limit and monitor their adverse impacts are necessary. To mitigate shipping emissions, the International Maritime Organization (IMO) has implemented a series of regulations aimed at reducing emissions from ships. These regulations include the establishment of Sulphur Emission Control Areas (SECAs), which require ships to use low-sulphur fuel in designated areas, or, alternatively, reduce the sulphuric emission to air with exhaust gas cleaning system. In May 2006, the Baltic Sea was designated as a SECA region along with the North Sea and the English Channel. SECA regions have also been set up along the North American East and West Coast and the U.S Caribbean. The maximum allowed sulphur content of fuel in the SECA areas was decreased in 2006 from 2.7 to 1.5 %. Since 1 of July 2010, the International Maritime Organization (IMO) implemented a rule that required ships sailing in SECA regions to use fuel with a sulphur content no higher than 1.0 % (Van Aardenne et al., 2013). This rule was further tightened in 2015,

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reducing the sulphur limit to 0.1 %.

However, while the SECA regulations aim at improving human health, it should be kept in mind that reducing sulphuric emissions from shipping may also have significant adverse impacts on climate and marine ecosystems. The impact on climate, due to decrease in the cooling effect of ship-emitted aerosols (Partanen et al., 2013) is likely leading to an increase in global sea surface temperatures (Hausfather and Forster, 2023). For instance, Lauer et al. (2009) estimated that limiting fuel sulphur content (FSC) of ships globally to 0.5 % would decrease the negative radiative forcing (less cooling) of shipping emissions from -0.6 W m^{-2} to -0.3 W m^{-2}, potentially accelerating global warming. In addition, Hausfather and Forster (2023) argued that transition to low-sulphur marine fuels has intensified global warming, as sulphur particles in ship emissions have been mitigating greenhouse gas-induced warming. Furthermore, the authors claimed that estimates by Carbon Brief indicated that the 2020 regulations could contribute to a temperature increase of approximately 0.05 °C by 2050, equivalent to two additional years of emissions. The impacts of SECA on marine ecosystems include concentrated aquatic phase pollutant emissions from the exhaust gas cleaning systems as discussed in Picone et al. (2023) and Hermansson et al. (2024).

In this study, we will present unique fine temporal resolution data of SO_2, NO_x, NO, $PM_{2.5}$ and O_3 concentrations measured on Utö island at the outer edge of the Archipelago Sea in the Baltic Sea during the period 2003-2020, covering the period with three separate changes in SECA limits. Additionally, hourly data from 2003 to 2005 has also been utilized. The focus of the study is on the impacts of SECA regulations on SO_2 concentrations. A qualitative case study is also presented on the changes due to the SECA regulations based on an analysis of pollution plumes originating from an individual Ro-Ro cargo ship.

2 Measurement location and site characteristics

The observations utilized in this study have been carried out in Utö (59º 46’ 50 N, 21º 22’ 23 E), a small island in the Baltic Sea (Fig. 1a) with an area less than 1 km^2. It is located 70 km from the coast of the mainland of Finland and surrounded only by the open sea and a few smaller islands. The vegetation between the bare rocky areas consists mainly of different shrubs and a few trees. The island is flat, the highest point is less than 15 m above the sea surface. Less than 40 inhabitants live in Utö during the winter. Population including tourists during the summer months varies between 100 and 200. Ships that pass Utö are pilot, passenger, military, fishing, cargo, commercial and tanker vessels. An important shipping lane to or from Finland is located at a distance of approximately 1 km west of the island (Fig. 1b).

Meteorological observations at Utö started in 1881. Since the beginning of observations, there has been a gradual increase in measured atmospheric, air quality, marine and electromagnetic parameters (Ahlnäs, K., 1961, Laurila and Hakola, 1996, Komppula et al., 2007, Kyllönen et al., 2009, Kilkki et al. 2015, Laapas and Venäläinen, 2017, Laakso et al. 2018, Honkanen et al., 2018; 2021, Grönholm et al., 2021, Kraft et al., 2021, Seppälä et al., 2021, Rautiainen et al., 2023, Honkanen et al., 2024,

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Hellén et al., 2024). As the island is sparsely populated and there is very little land traffic, there are no local sources of NO_x and SO_2. Consequently, Utö is an ideal location for plume tracking.

The long-term marine and meteorological observations and other characteristics of Utö Atmospheric and Marine Research Station are discussed in Laakso et al. (2018) and the references listed above, and thus only few results relevant for shipping plume dispersion are summarized here. The prevailing meteorological conditions in the area are characterized by high wind speeds, with monthly averages ranging from 5.6 m s^{-1} in July to 8.9 m s^{-1} in December, resulting in an annual average of 7.1 m s^{-1}. The prevailing wind is from the southwest, while the sector from south (clockwise) to northwest dominates, accounting for approximately 60 % of the observed wind patterns (Honkanen et al., 2018). An examination of the wind time series from 1959 to 2016 (Laapas and Venäläinen, 2017) indicated no substantial alterations in wind direction or wind speed, aligning with a recent investigation covering the period of 1979 to 2008.

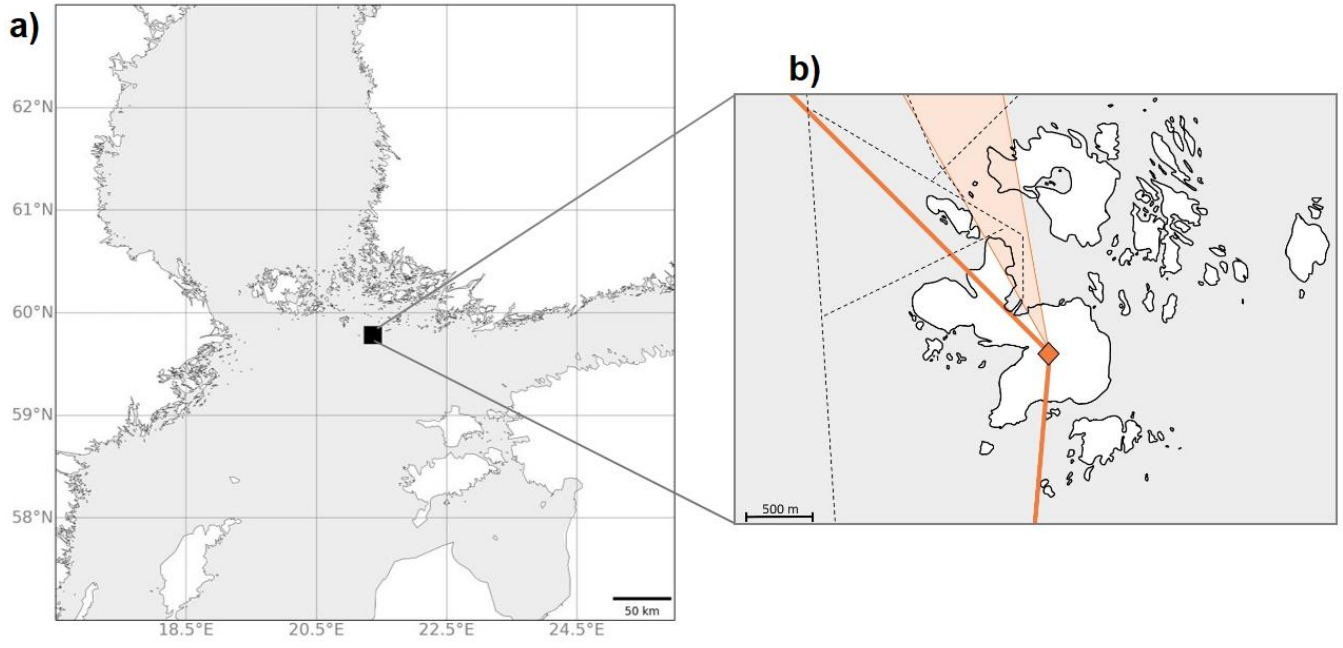

Figure 1: a) The location of the Utö island in the Baltic Sea and b) Utö air quality station (orange diamond) and the shipping lanes adjacent to the island (black dashed lines). Major ships operate on the north-south shipping lane at a distance of approximately 500 m west of Utö (or 1 km from air the quality station). The wind sector representing the directions from the main shipping lane (185°–315°), is indicated by the orange lines. The ship traffic to and from the harbour of the island is presented by the shaded orange sector.

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3 Measurements and methods

3.1 Air quality and wind observations

To study the effects of SECA regulations on air quality, observations of SO_2, $PM_{2.5}$, NO, NO_x and O_3 were analysed. The period of the study spanned 15 years, from 2006 to 2020 (supporting hourly data from 2003 to 2005). During this time, some of the instruments were changed (Table 1). The data has gone through normal quality control procedures as defined by EMEP and World Meteorological Organization (WMO) standards (see e.g. Anttila and Tuovinen, 2010 and references therein). In addition to the air quality observations, wind data on site was used. The temporal resolution of the wind data was 10 minutes and therefore it was interpolated linearly for intervals of 1 minute to match the air quality data.

Table 1. Air quality observations.

Observation	Device	Start	End	Notes
SO_2	Thermo 43i-TLE	09/09/2011		
	Thermo 43s	01/01/1996	08/09/2011	
PM_{25}	5030 Sharp	22/11/2017		
	Thermo FH62 I-R	01/06/2003	22/11/2017	
NO_X	Thermo 42i-TL	07/02/2014		
	Horiba APNA-370	18/08/2007	07/02/2014	
	TEI 42CTL		18/08/2007	Data gap 2006-2007
O_3	Thermo 49i	12/02/2015		
	Horiba Ltd APOA-360	03/10/2003	11/02/2015	

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3.2 Automatic Identification System (AIS) data

The Automatic Identification System (AIS) is a mechanism for the automated generation and transmission of vessel-related information to both other vessels and coastal authorities (IMO, 2020). The AIS data encompassed main ship attributes, including Maritime Mobile Service Identity (MMSI), latitude, longitude, true heading, course over ground, and speed over ground. Based on the HELCOM AIS data, vessels were categorized into six distinct types that best characterized their specific roles: cargo ships, large passenger ships, medium-sized passenger vessels, large work vessels, small vessels, and others. In the vicinity of Utö, cargo and large passenger ships constituted the majority of vessels.

In our study, AIS data was utilized to calculate emissions using the STEAM model and to monitor ship movements of one Ro-Ro cargo in the vicinity of Utö. Data collection for the studied ship comprised AIS data sourced from the Helsinki Commission (HELCOM) for the period from 2013 to 2015 and from the AIS receiver at the Utö marine station for the period from 2016 to 2019.

3.3. The STEAM model

The STEAM model integrates AIS-derived data alongside technical insights into the global fleet and fundamental naval architecture principles (Jalkanen et al., 2009, 2012, 2014; Johansson et al., 2017). The model is subsequently used to predict vessel water resistance and instantaneous engine power of the main and auxiliary engines. The STEAM model facilitates the prediction of instantaneous fuel consumption and the emissions of specific pollutants (Jalkanen et al., 2016).

The input data for the STEAM model concerning ship properties, encompasses, among other factors, measured emission factors (when available), shaft generators, specific fuel oil consumption, and fuel type and sulphur content for main and auxiliary engines, along with installed abatement techniques (Jalkanen et al., 2009). The computed emissions for NO_x used in this study encompass the International Maritime Organization (IMO) registered traffic. The assessment includes all vessel traffic equipped with AIS transceivers while specifically excluding those navigating in inland waterways from the dataset.

4 Results and discussion

The results are divided in subsections addressing the changes in long-range transport and shipping, investigating (i) the air quality time series, (ii) wind-direction dependence of observations and (iii) a qualitative case study based on one regular Ro-Ro ship that has passed by the Utö Island.

4.1 Changes of long-range transport and shipping emissions

The SO_2 emissions in the Northen Europe have shown a decreasing trend in most of the emission sectors. Figure 2 illustrates the combined emissions in each emission sector from countries that have a major impact on the considered area during the

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period 2003−2020. The dominant emissions originate from the energy (indicated as "public power" in Fig. 2) and industry sectors, exceeding the emissions from shipping by more than an order of magnitude. The typical lifetime of SO_2 in the atmosphere is of the order of a few days. Part of the SO_2 observed at Utö is therefore originated from long-range transport of regional background pollution, while another portion is attributed to shipping traffic in the vicinity of Utö (e.g., Lee et al., 2011). Long-range transported background pollution is well-diluted, whereas local emissions tend to manifest as short-term, high-concentration peaks.

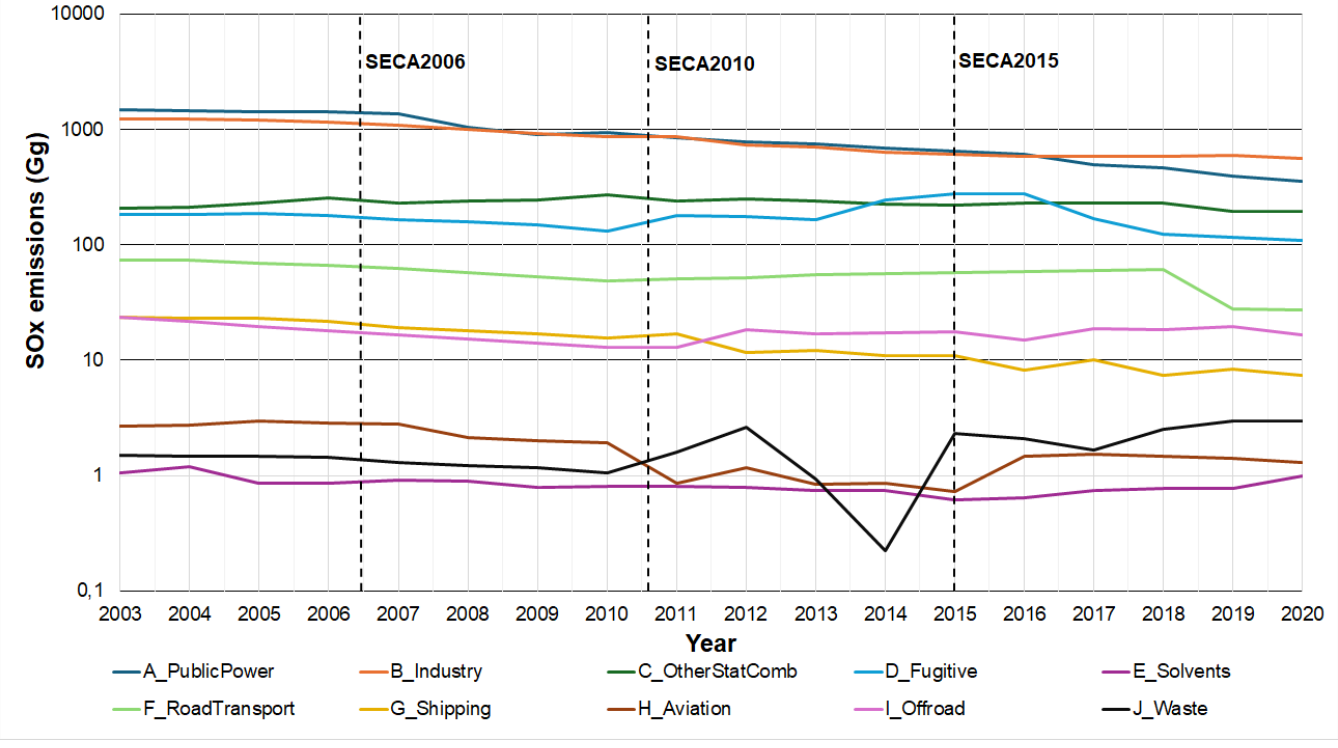

Figure 2: The combined annual SO_x emissions of Estonia, Finland, Lithuania, Latvia, Sweden, Russia and Poland divided in source sectors during the period 2003-2020. The implementation of subsequent SECA regulations is indicated with vertical lines.

Figure 3 displays the monthly shipping emissions in the Baltic Sea calculated using the STEAM model. The changes in SO_2 emissions are a combination of changes in emissions due to the implementation of SECA regulations, and changes in shipping traffic density. The maximum allowed sulphur content of fuel was decreased from 2.7 to 1.5 % in May 2006, and it was further reduced to 1.0 % in July 2010, and finally, to 0.1 % in January 2015. The shipping activity in the Baltic Sea, both in terms of the total number of ships and the transport work, has increased steadily during 2006–2020, except for a few minor exceptions such as the economic recession, which started in 2008 and continued until 2009 in most areas of the neighbouring countries of the Baltic Sea (Jalkanen et al., 2014) and the COVID–19 pandemic in 2019 (HELCOM, 2021). According to emission model

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computations from STEAM (Fig. 3), there has been a gradual decrease of SO_x and $PM_{2.5}$ emissions originating from shipping in the Baltic Sea since 2006.

This gradual decline in the modelled SO_x emissions continued until 2014, followed by a sharp decrease from 2014 till 2015; the latter decrease aligns with the implementation of limiting the maximum allowed sulphur content of fuel in 2015. The magnitude of the relative reduction of $PM_{2.5}$ emissions attributed to shipping is smaller than that of the SO_x emissions. The predicted annual NO_x emissions during the period between 2006 and 2020 have remained relatively stable.

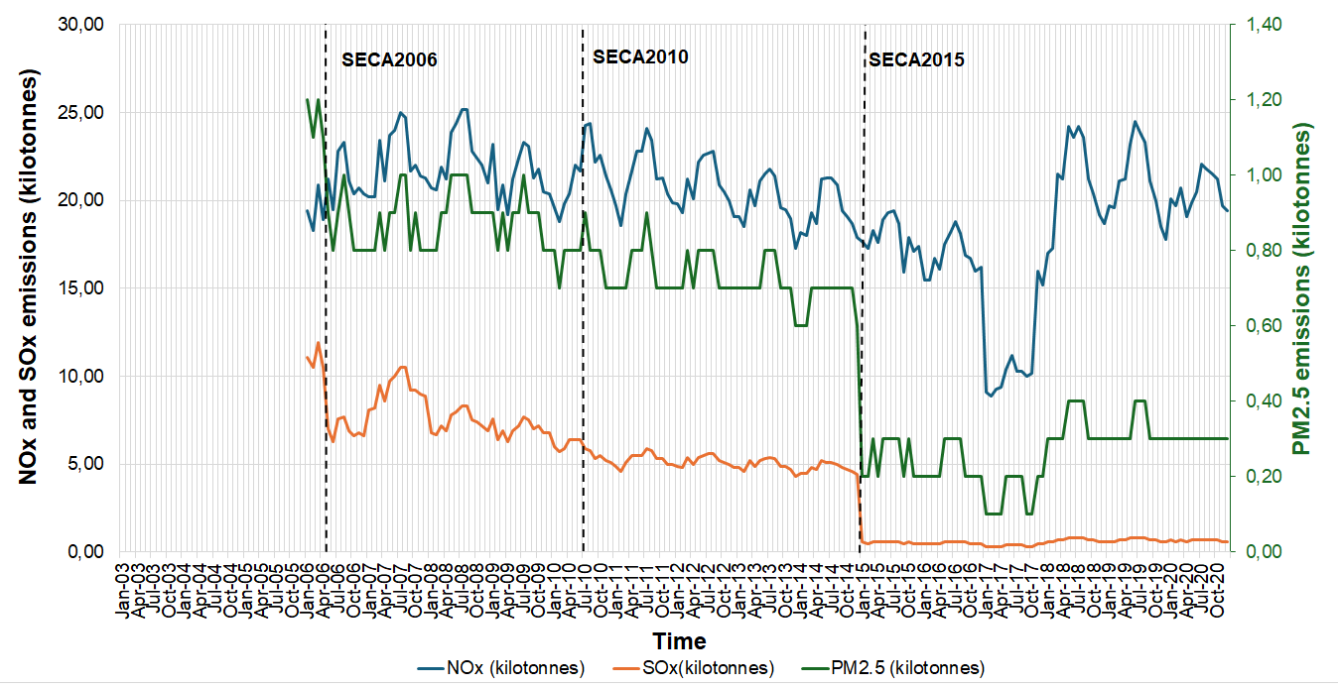

Figure 3: Predicted emissions of NO_x, SO_x, and $PM_{2.5}$ attributed to maritime traffic in the Baltic Sea from January 2003 to December 2020, computed using the STEAM model. The SECA regulations were introduced in 2006, 2010 and 2015 (indicated with vertical lines).

4.2 Observed changes in ship traffic and concentrations of SO_2 and other air quality parameters at Utö

At Utö, local marine traffic typically consists of a few larger vessels per day. We have analysed the AIS data of the number of ships passing the island of Utö per day at distances closer than 5 km (Fig. 4). On average, around 5–10 ships passed the island daily. The number of ships per day did not experience either an increasing or decreasing trend during 2013–2020. The amount of ship traffic has been fairly constant during this period. There have been a few local maxima, in particular during the summers of 2013 and 2014. Currently, we do not have access to the AIS data before 2013.

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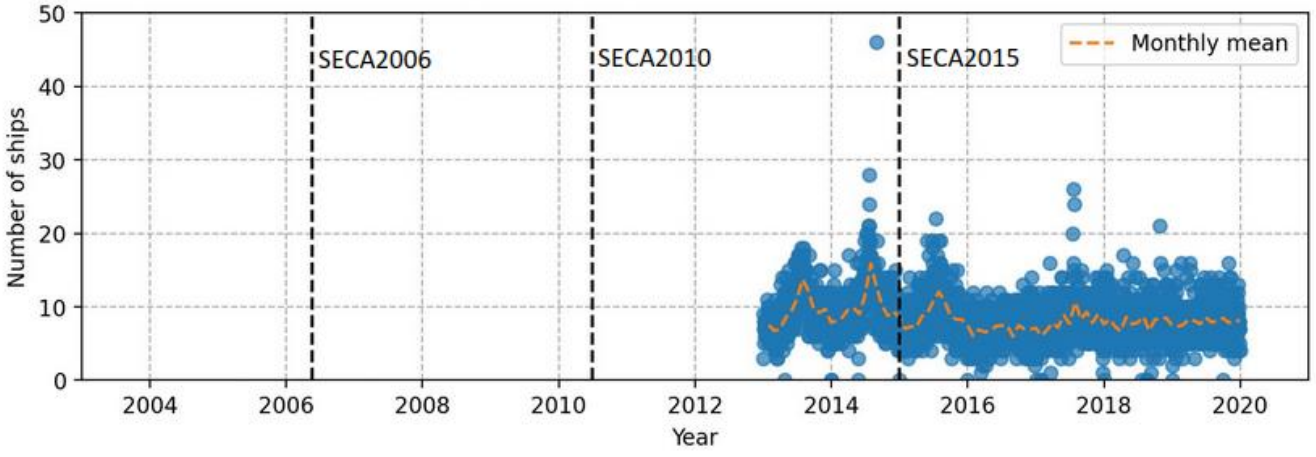

Figure 4: The number of ships per day that have passed the island of Utö at distances closer than 5 km (blue circles). The orange dashed line presents the monthly mean of daily values.

The observed 30–day moving averages and moving percentiles of the concentration data for SO_2, $PM_{2.5}$, NO, NO_x and O_3 from 2006 to the end of 2020 are presented in Fig. 5. The dashed vertical lines represent the introduction of SECA regulations in 2006, 2010 and 2015, corresponding to 1.5 %, 1.0 % and 0.1 % sulphur fuel content limits, respectively. The effects of the sulphur cap in 2006 and 2015 are clearly visible, while the impact of 2010 is negligible. The change in 2015 is apparent in the shifts of the 1st and 99th percentiles corresponding to short–duration local ship plumes. Additionally, the mean and median values after 2015 are closer to each other, indicating that the higher peaks in the data occur less frequently.

Table 2: Annual average and median concentrations of SO_2 at Utö. Values for the period 2003–2005 are based on hourly averages, while for the period 2006-2020, 1–minute time resolution data has been used.

SO_2	Mean [µg m^{-3}]	Median [µg m^{-3}]	STD	N (%)
2003	1.38	0.70	2.15	TBA
2004	1.17	0.80	1.13	TBA
2005	1.32	0.80	1.45	TBA
2006	0.93	0.55	1.51	55.7
2007	0.97	0.56	1.58	99.8
2008	0.70	0.40	1.19	98.9
2009	0.73	0.42	1.07	98.4
2010	1.12	0.58	1.80	89.0

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2011	1.00	0.57	1.81	93.0
2012	0.78	0.45	1.18	96.1
2013	0.58	0.39	0.81	84.4
2014	0.75	0.46	1.08	99.5
2015	0.37	0.29	0.47	99.4
2016	0.45	0.32	0.68	99.5
2017	0.34	0.27	0.54	98.3
2018	0.50	0.37	0.60	99.3
2019	0.41	0.36	0.50	99.1
2020	0.34	0.32	0.35	99.1

In general, the reduction in the release of SO_2 emissions attributed to shipping could also result in a decline in the production of particulate matter originating from precursor compounds from shipping. However, as the results (Fig. 5 and Appendix A) demonstrate, there were no step changes in the $PM_{2.5}$ concentration during the considered period. This does not mean that the emissions of particulate matter from ships were at the same level as before SECA regulations, but rather that the measurement of $PM_{2.5}$ is not sensitive enough to show the changes in the ultrafine particle size range. Seppälä et al. (2021) studied the impact of SECA on particle number size distribution (size range 7–537 nm) at Utö and found that the main changes due to SECA in particle number were on sizes between 33 and 144 nm, and thus the impact on particle mass, resulting mainly from larger particles, is minor. Similarly to $PM_{2.5}$, no decreases were observed in the NO_x, NO and O_3 concentrations. The year–to–year temporal variation of $PM_{2.5}$, NO, NO_x and O_3 (yearly mean and median values and standard deviation) are presented in Appendix A.

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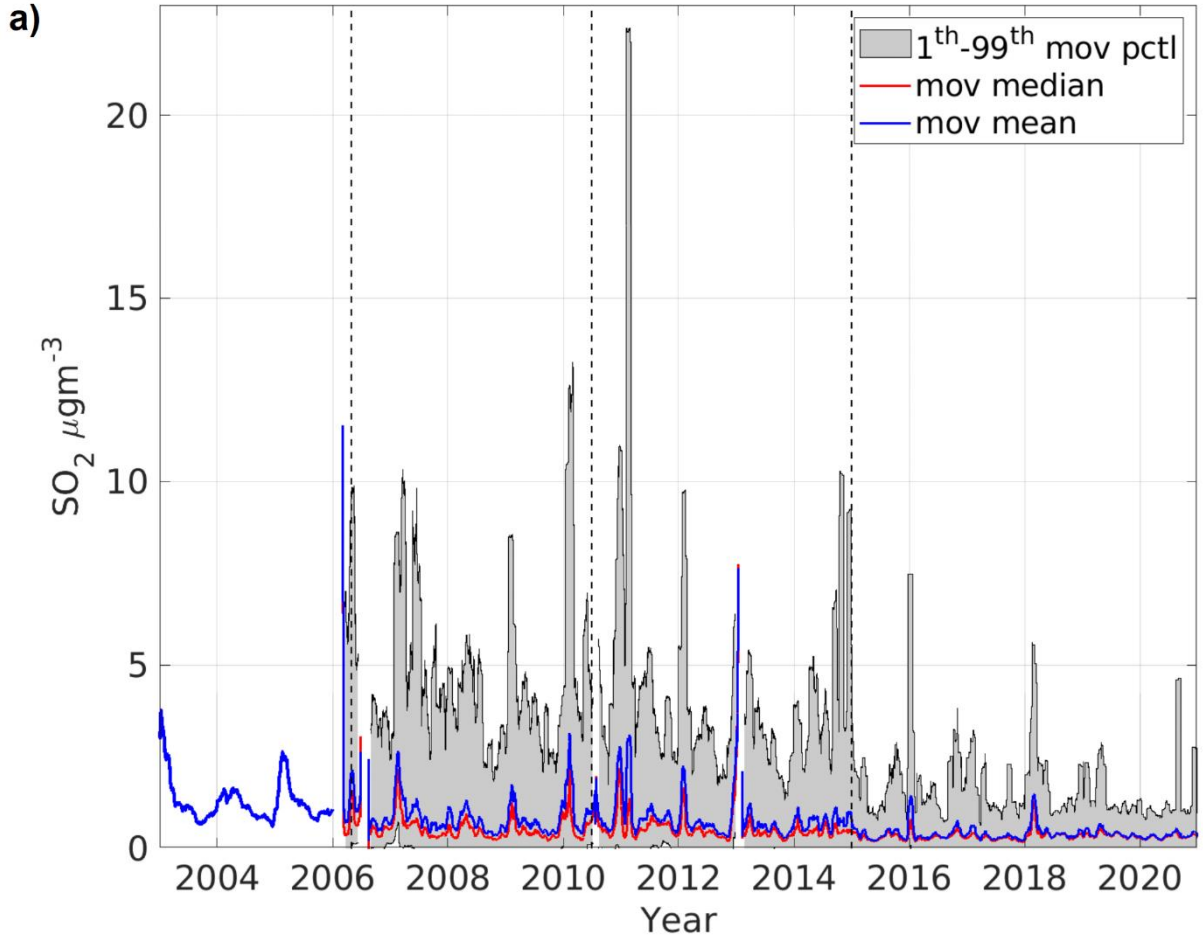

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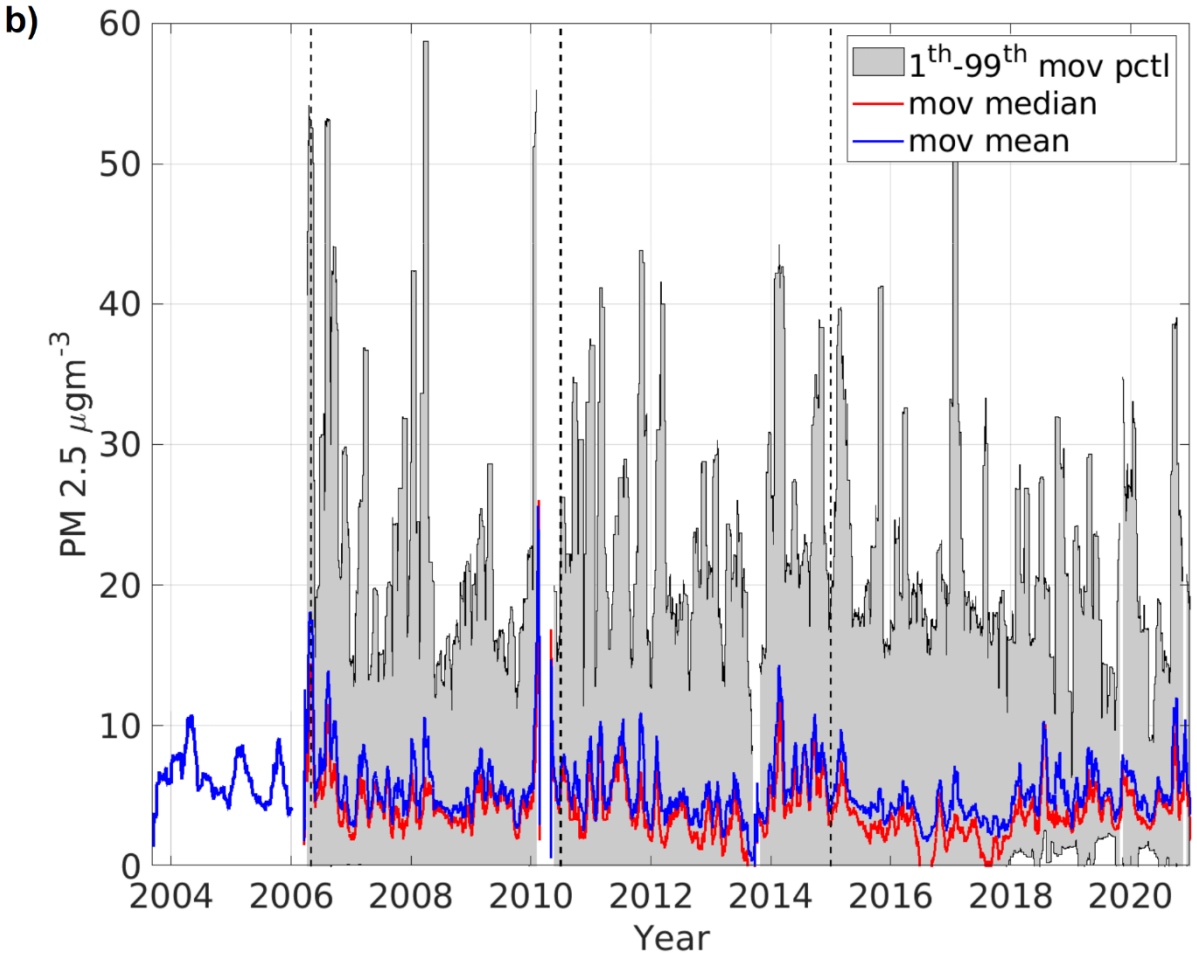

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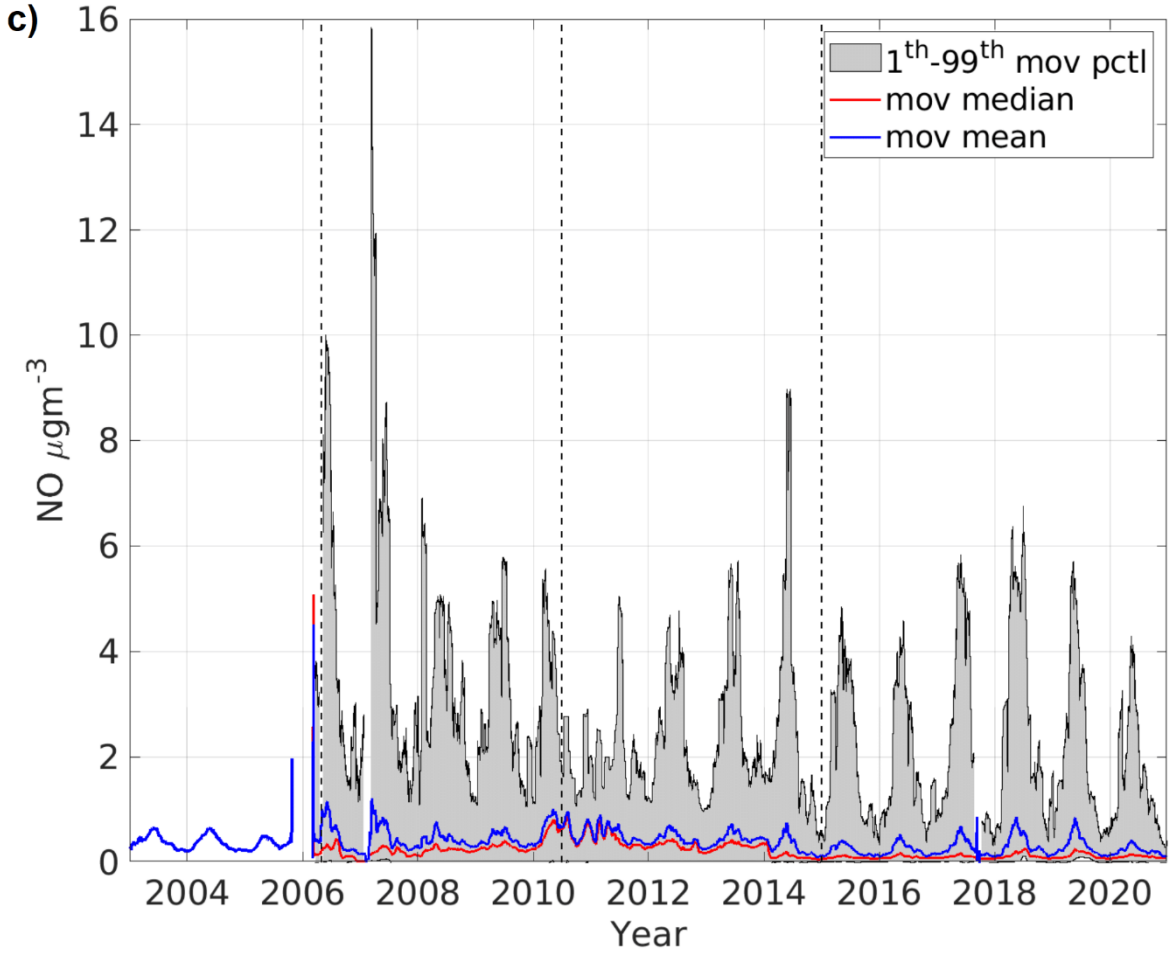

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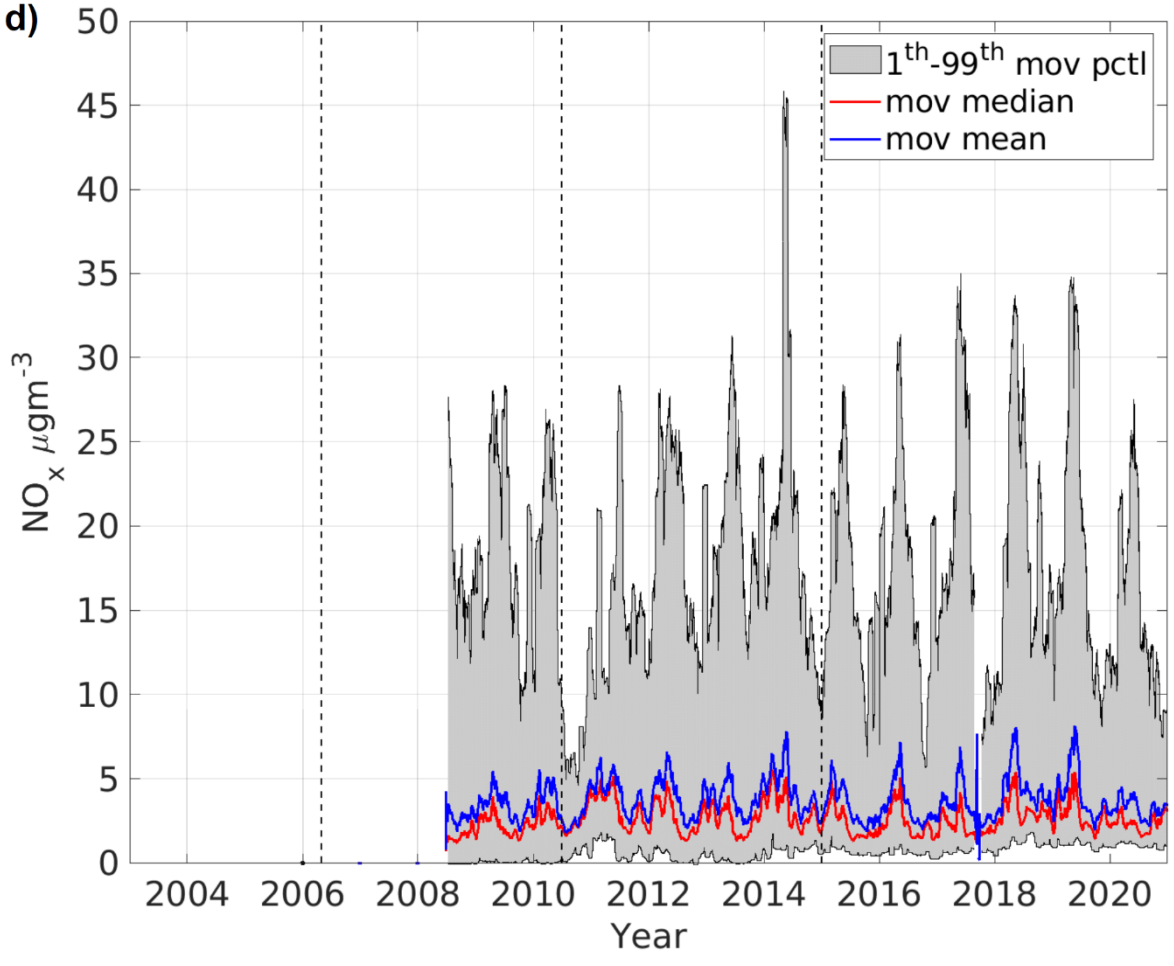

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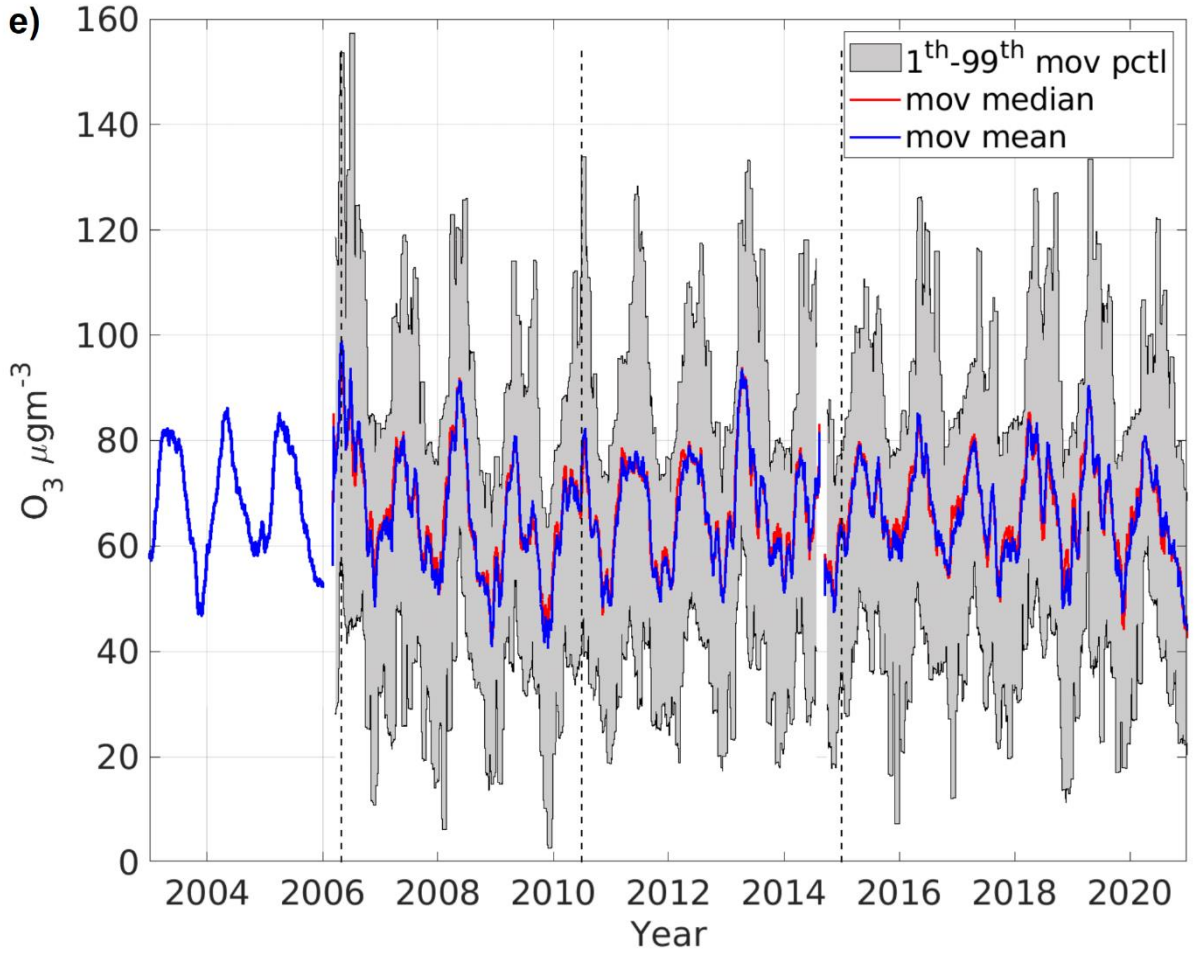

Figure 5: Time series of measured concentrations presented as moving percentiles based on 1-minute temporal resolution in 30 days window for a) SO_2, b) $PM_{2.5}$, c) NO, d) NO_x and e) O_3 from 2003 to the end of 2020 at the air quality station in Utö. The implementation of the SECA regulations in 2006, 2010 and 2015 have been presented by three vertical dashed lines.

Since the years of 2006, 2010 and 2015 marked significant milestones, as they represented the introduction of the new SECA regulations, we decided to focus on the periods that occurred before and after the implementation of SECAs: 2003–2005, 2007–2009, 2011–2013 and 2016–2018. Specifically, we compared the three-year average of SO_2 concentrations before the SECA introduction (2003–2005) to those following each SECA enactment (2007–2009, 2011–2013, and 2016–2018). Our findings revealed notable reductions in three-year average SO_2 concentrations during these periods: 38% (after SECA 2006), 39% (after SECA 2010), and 67% (after SECA 2015), respectively.

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As indicated in the previous section, SO_2 emissions have been widely reduced across various industrial sectors. To estimate the local effect of shipping, we utilized NO, which is highly reactive and has a short lifetime in the air. Since it is one of the main gases in ship exhaust, it can serve as a marker for ship plumes originating near Utö. Therefore, we selected periods when SO_2 and NO both showed clear peaks simultaneously in the data, and when the wind was blowing from the western sector (180–360 degrees). Figure 6 depicts the SO_2 concentration normalized by NO concentration during these plumes. There is a clear difference before and after January 1, 2015. Prior to the implementation of the strictest SECA regulation (i.e. SECA 2015), the SO_2 concentrations during local pollution plumes were of the same magnitude as NO. However, after the SECA 2015 regulation was enacted, the SO_2 concentrations decreased significantly during these near-source plumes.

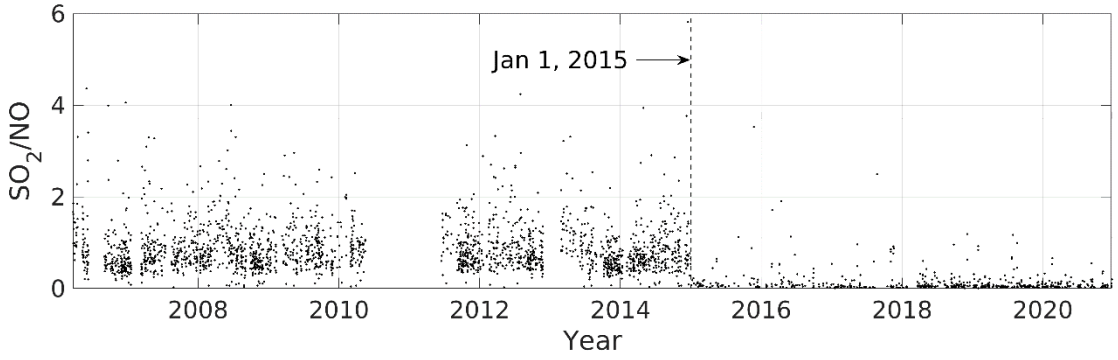

Figure 6: Time series of the observed SO_2/NO concentration ratio, when the wind was blowing from the westerly directions (wind direction 180-360º) and the plume from the passing ships was transported over the Utö island. Only the periods with simultaneous peaks in both SO_2 and NO signals were included into the analysis.

4.3. Dependence of concentrations on local wind direction

To study the impacts of the ships passing by Utö, we selected the SO_2 concentration data based on the wind direction. First, we separated the datapoints that were measured during the wind was blowing from the shipping lane (includes the wind directions from 185° to 315°) towards the measurement site from the rest of the data.

All data, as well as data when wind was blowing from the direction of shipping lane, and data from the background sector (wind directions excluding the shipping lane sector) are shown in Figs. 7a–c. Similarly to the previously presented results, there is an evident decrease of the SO_2 concentrations after the SECA in 2015, and a slight decrease after the SECA in 2010. The decreasing trend can be seen in all three plots, but the strongest decrease is after 2015 when only wind directions of shipping lane were selected.

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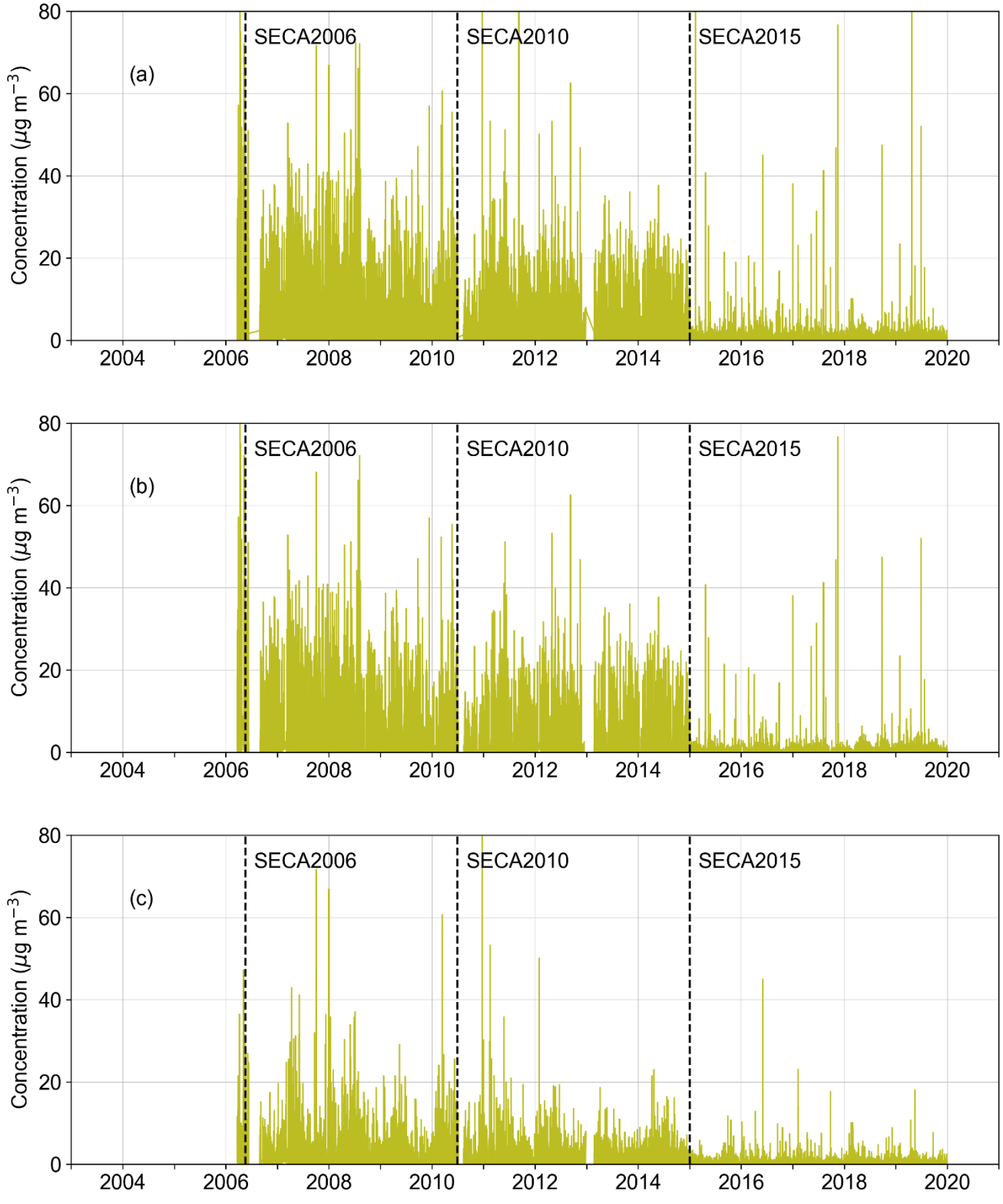

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Figure 7: The time series of SO_2 concentrations with a) all the data points included (unstratified), b) data only from 130º wide wind sector from direction of shipping lane, extending from 185º to 315º and c) data only from background wind sectors excluding shipping lane, less than 185º and over 315º. The temporal resolution of the SO_2 concentration data was 1 minute on average.

To analyse the effect of wind direction in more detail, we generated concentration rose plots in finer 10–degree intervals (Fig. 8). To assess the effects of the implementation of SECA regulation in 2015, we chose two years: one immediately preceding the new regulation, 2014, and the other representing the 5–year period after, 2019. The measured annual distribution of wind directions is determined by the local climate at the site and potentially by local factors affecting wind measurements. The most common wind directions in this region are southwesterly with relatively high contributions also from northwesterly directions, at angles from 320º to 350º (Fig. 8a and Fig. 8c). This northwesterly sector coincidentally corresponds to the routes of shipping to and from the harbor and wharf area of the island. The shipping traffic to the island typically consists of smaller vessels on average compared to the average marine transport in the neighboring ship lane. The upper panels in Figs. 8a–b include all measured concentrations. The observed SO_2 concentrations were systematically and substantially higher in 2014 compared to the values in 2019. Furthermore, if only peak concentrations during the plumes are considered (lower panels, Figs. 8c–d), it is evident that the numbers of the highest concentrations were drastically higher in 2014 compared to the corresponding values in 2019 and originated from the direction of the adjacent shipping lane (i.e., from the westerly directions).

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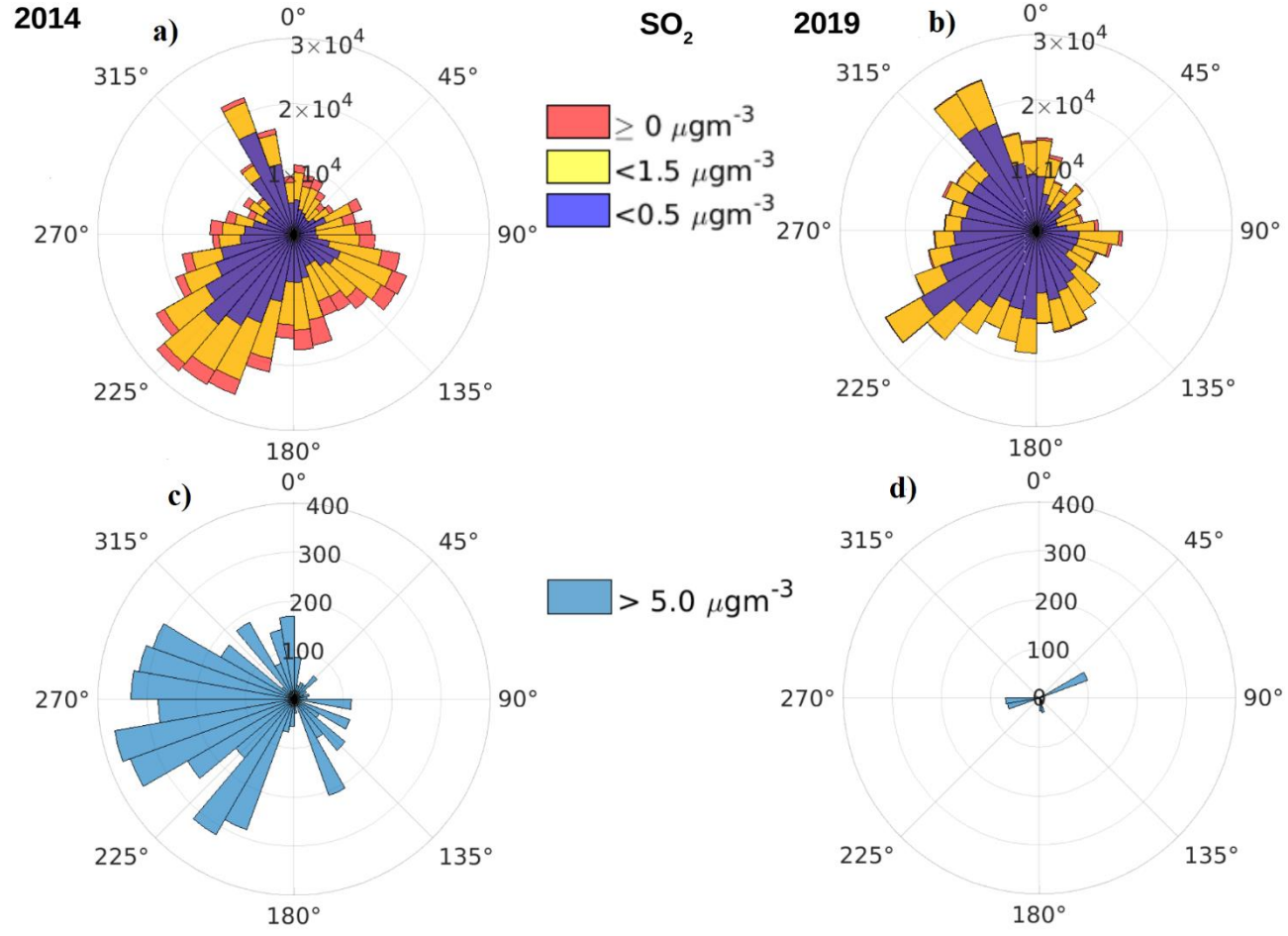

Figure 8: The measured concentrations of SO_2 at the island of Utö as a function of the wind direction, as polar histograms with 1-minute resolution. The panels a) and c) correspond to the data in 2014 and the panels b) and d) to those in in 2019. These two years were selected to represent the situation before and after the SECA regulation in 2015. The upper panels (a and b) include all datapoints, whereas the lower panels (c and d) include only the data, for which the concentrations were higher than a selected threshold value (5 µg m^{-3}). The radial axis represents the number of measured cases for each wind direction sector. The red colour in the legend refers to all data, except for the regimes shown by the yellow and blue colours.

4.5. Case study: Analysis of individual ship plumes of a selected ship prior and post the SECA regulation in 2015

We also analysed individual ship plumes of one Ro-Ro cargo ship that has regularly transited the sea route in the vicinity of the Utö island. The chosen vessel was classified as a Hazardous Category A cargo ship, with dimensions of 188 m in length, 26 m in width, and a draught of 6.6 m. Table 3 presents detailed information of the wind speed and direction, plume direction and the distance between the Ro-Ro cargo ship and the measurement tower, along with other parameters. The ship's speed

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during all passes was approximately 19 knots. The study provides only qualitative results, as the data shown has not been processed to take into account dilution of the ship plume.

Table 3: Wind and plume parameters, and ship location data recorded during its passing in the vicinity of the Utö island for the selected case study. The ship was equipped with a scrubber in June 2015.

Time (date and time)*	Window (TOA)**	Wind speed (m s^{-1})	Wind direction (°)	Plume direction (°)	Ship latitude (°)	Ship longitude (°)	Distance (m)***
2/11/2013 2:11	2/11/2013 2:17	10.2	251	71	59.75	21.35	3490
24/4/2014 21:48	24/4/2014 21:58	2.8	275	95	59.77	21.35	1690
23/10/2015 7:23	23/10/2015 7:31	7.8	283	103	59.74	21.34	4090
15/2/2017 22:16	15/2/2017 22:20	6.5	249	69	59.77	21.35	1580

* Time is the AIS file timestamp.

** Window (TOA= Time Of Arrival) is when the plume is estimated to reach the measurement tower located in Utö.

*** Distance is the distance between the ship and the measurement tower.

First, we identified the time periods, during which the plume originating from the Ro-Ro cargo ship was detectable at the measurement station at the island, i.e., the so-called plume windows. This analysis was done for selected recorded passage of the vessel during the years 2013–2017. The AIS data for this ship was not available during 2006–2012 and in 2016.

Second, we compiled and examined the temporal variations of the SO_2 and NO_x concentrations, which were measured at 1–minute intervals. The considered passages occurred approximately three and four years after the implementation of SECA regulations in 2010 (2.11.2013 and 24.4.2014), and at ten months and two years after the enforcement of the latest SECA regulations in 2015 (23.10.2015 and 15.2.2017). The temporal evolution of the concentrations of SO_2 and NO_x during these plume windows have been presented in Figs. 9a–d.

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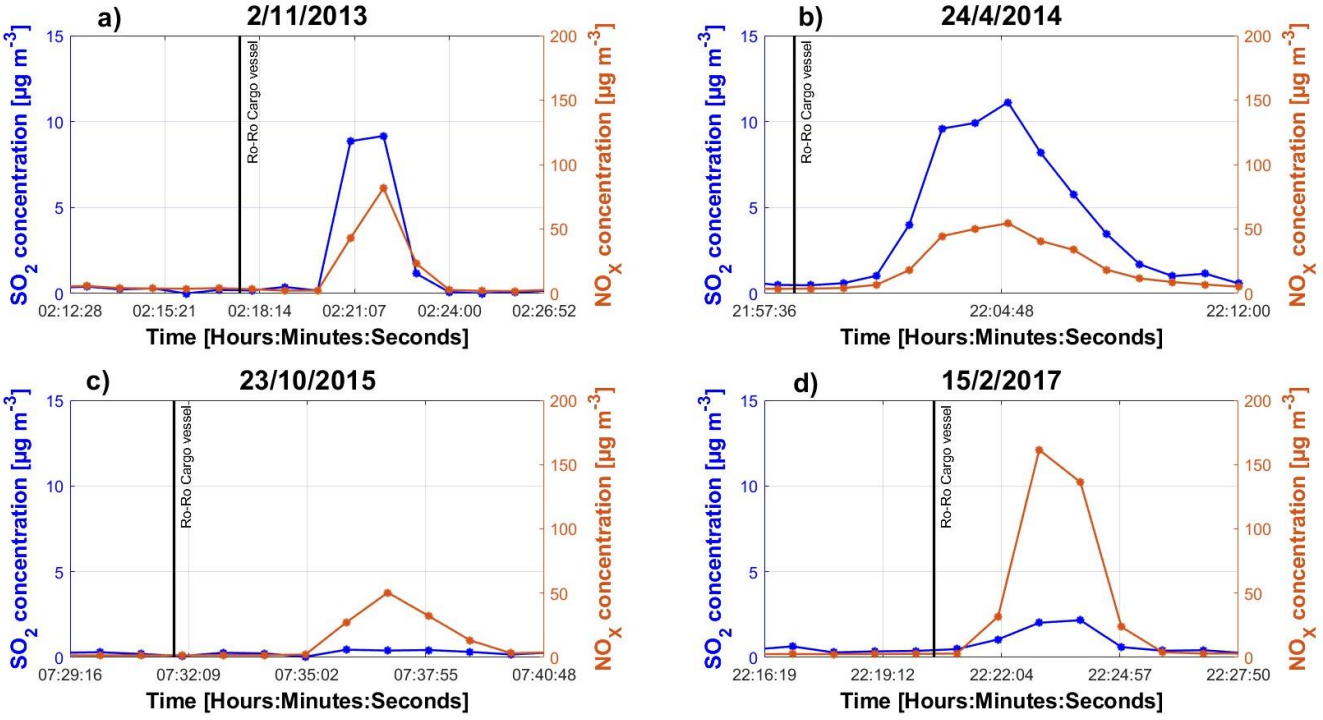

Figure 9: Temporal variation of the measured concentrations of SO_2 and NO_x at the Utö island before and after the passage of a Ro-Ro cargo ship along a shipping lane located west of the island. The concentrations are presented at two times before the implementation of SECA regulation on 1 January 2015, presented in panels (a) and (b) and at two times post this regulation presented in panels (c) and (d). Solid black vertical line indicates the ship's passing time, i.e., the time, during which the ship is closest to the measurement station. The time series of the concentrations of SO_2 (blue curves, left vertical axis) and NO_x (dark orange curves, right vertical axis) were measured at 1–minute intervals. The durations of the horizontal scales range from 9 to 15 minutes.

Prior to the passage of the Ro-Ro cargo vessel past Utö island, the concentrations of both NO_x and SO_2 consistently remained below the regional background values of approximately 6 µg m^{-3} and 1 µg m^{-3}, respectively. However, after some time from the moment, at which the ship had travelled past the closest point of the measurement station of Utö, there was a significant short-term rise in NO_x concentrations for all four considered cases, from a few tens to up to approximately 160 µg m^{-3} (Figs. 9a–d).

In contrast to the increases of the NO_x concentrations, there was a systematic difference in the rise of the SO_2 concentrations after the passing of the ship, when one considers the cases before and after the latest SECA regulations. After the studied vessel's transit past Utö before the SECA regulation in 2015, the SO_2 concentrations increased to approximately 9 µg m^{-3} and 11 µg m^{-3}, respectively (Figs. 9a–b). The corresponding increases of the SO_2 concentrations after the 2015 SECA (and

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installation of a scrubber to the ship studied) were approximately 0.45 μg m^{-3} and 2.20 μg m^{-3}, respectively (Figs. 9c–d). These observations provide evidence on the efficacy of the SECA regulation implemented in 2015.

5 Conclusions

In this study, we have presented and analysed a high temporal resolution dataset that covers the data on air quality and wind for one and a half decades at the island of Utö in the Baltic Sea. The period of the study includes three, consecutive revisions of the SECA regulations.

The findings derived from the analysis of the air quality and meteorological datasets and STEAM modelling indicated that the SECA regulations, introduced in 2006, tightened in 2010 and further strengthened in 2015, have been successful in reducing the observed SO_2 concentrations at Utö during the studied period 2003-2020. In fact, comparing three–year average SO_2 concentrations pre–SECA (2003–2005) to post–SECA periods (2007–2009, 2011–2013, 2016–2018) revealed reductions of 38 % (SECA 2006), 39 % (SECA 2010), and 67 % (SECA 2015), respectively. During the target period, there were no clear decreasing trends for the concentrations of NO_x, NO and O_3, or $PM_{2.5}$. The year–to–year variations of the concentrations were substantial for all pollutants and may be attributed to differences in regional meteorology.

We also analysed polar histograms of SO_2–concentration during two representative years, 2014 and 2019, i.e., before and after the implementation of the SECA regulations in 2015. This analysis was done both for the whole dataset and for selecting only the highest measured concentrations, above a specified threshold. The numbers of the cases with the highest SO_2 concentrations were drastically higher in 2014 compared to the corresponding values in 2019. The highest concentrations were mostly originating from the direction of the adjacent shipping lane. This analysis therefore indicates that the highest measured concentrations attributed to shipping have substantially decreased after the SECA regulations in 2015.

The present study highlights the importance of good quality, high temporal resolution, long–term air quality data to support the evaluation of the impacts of changes in environmental regulations and legislation, in this study impacts of SECA.

Appendix A

Table A1: Annual average and median concentrations of $PM_{2.5}$ at Utö. Values for year 2004 and 2005 are based on hourly averages and for the period 2006-2020 on 1-minute time resolution.

$PM_{2.5}$	Mean [μg m^{-3}]	Median [μg m^{-3}]	STD	N (%)
2003	5.97	4.30	5.57	TBA

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2004	6.82	5.20	6.07	TBA
2005	6.07	4.50	6.13	TBA
2006	8.35	5.55	9.43	70.3
2007	5.28	3.93	5.49	99.9
2008	5.26	3.88	6.00	98.8
2009	5.30	4.37	4.84	98.0
2010	6.39	4.67	7.18	69.2
2011	6.35	4.67	7.28	93.8
2012	4.51	3.05	5.58	96.0
2013	3.85	2.24	5.29	86.7
2014	7.35	5.73	7.56	99.5
2015	4.97	3.48	6.21	98.9
2016	3.85	2.19	5.25	98.7
2017	3.66	1.96	5.91	95.9
2018	5.58	3.83	4.94	97.9
2019	5.49	4.09	4.54	90.6
2020	5.42	3.93	5.02	87.5

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Table A2: Annual average and median concentrations of NO at Utö. Values for year 2004 and 2005 are based on hourly averages and for the period 2006-2020 on 1-minute time resolution.

NO	**Mean [µg m^{-3}]**	**Median [µg m^{-3}]**	**STD**	**N(%)**
2003	0.40	0.10	0.76	
2004	0.39	0.20	0.60	TBA
2005	0.35	0.10	0.57	TBA
2006	0.47	0.14	1.87	71.2
2007	0.50	0.19	1.70	86.9
2008	0.43	0.23	1.42	99.1
2009	0.43	0.28	1.09	97.9
2010	0.66	0.56	0.87	97.0
2011	0.53	0.41	0.81	95.0
2012	0.44	0.31	1.10	98.1

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2013	0.46	0.31	1.23	98.0
2014	0.30	0.09	1.10	99.5
2015	0.22	0.08	1.09	98.7
2016	0.23	0.09	1.20	99.5
2017	0.29	0.09	1.86	86.0
2018	0.34	0.11	1.76	99.3
2019	0.31	0.12	1.73	99.1
2020	0.22	0.10	1.41	95.9

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Table A3: Annual average and median concentrations of NO_x at Utö. Values for year 2004 and 2005 are based on hourly averages and for the period 2006-2020 on 1-minute time resolution.

NO_x	**Mean [µg m^{-3}]**	**Median [µg m^{-3}]**	**STD**	**N (%)**
2003	-	-	-	-
2004	-	-	-	-
2005	-	-	-	-
2006	-	-	-	-
2007	-	-	-	-
2008	2.73	1.62	4.50	46.3
2009	3.37	2.15	4.47	97.8
2010	3.34	2.42	3.82	96.4
2011	4.13	3.33	3.64	94.9
2012	3.93	2.64	4.86	97.7
2013	3.76	2.50	4.76	97.5
2014	4.32	2.99	4.97	99.4
2015	3.31	2.13	4.35	98.7
2016	3.47	2.25	4.92	99.5
2017	3.50	2.13	5.97	86.0
2018	4.49	3.01	5.92	99.3
2019	4.06	2.59	5.91	99.1
2020	3.27	2.30	4.78	95.9

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Table A4: Annual average and median concentrations of O_3 at Utö. Values for year 2004 and 2005 are based on hourly averages and for the period 2006-2020 on 1-minute time resolution.

O_3	Mean [µg m^{-3}]	Median [µg m^{-3}]	STD	N (%)
2003	67.04	68.00	19.97	
2004	69.73	69.00	16.47	TBA
2005	68.71	67.00	18.20	TBA
2006	74.95	74.08	22.23	77.6
2007	65.66	65.87	16.46	99.8
2008	65.01	63.53	20.41	98.8
2009	60.12	59.91	16.87	98.3
2010	64.42	64.48	16.36	99.1
2011	66.17	66.11	16.43	95.1
2012	65.62	66.24	16.02	97.5
2013	70.28	68.93	18.05	98.4
2014	62.36	62.42	15.98	82.0
2015	67.57	68.12	13.66	99.3
2016	66.70	66.58	15.88	99.5
2017	65.61	66.83	14.53	98.7
2018	67.63	67.59	17.67	99.3
2019	67.24	67.71	17.91	99.1
2020	64.59	65.41	15.55	99.1

Code availability

Codes for the analysis of long-term pollutant concentrations and of individual ship plumes in case of one selected ship prior and post SECA are available upon request from Androniki Maragkidou (androniki.maragkidou@fmi.fi). Codes for the concentration analyses are available from Tiia Grönholm (Tiia.Gronholm@fmi.fi).

Data availability

The measured data are available from FMI Open Data (https://en.ilmatieteenlaitos.fi/open-data).

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Author contributions

AM conducted part of the analyses, wrote the first draft of the manuscript, and lead the processing of the manuscript to its final format. TG performed most of the data analysis and part of the writing. LR, LL, and JK contributed to the planning of the study and the writing of the article. TM and TA were responsible for the measurements at the Utö island and contributed to the analysis of the measurements. J-PJ has done the computations on the emissions of shipping using the STEAM model. JN is responsible of the computer analyses underlying Fig. 7. All authors commented on the manuscript and provided feedback.

Competing interests

The authors declare that they have no conflict of interest.

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