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Effect of sea ice on fuel consumption and carbon intensity of shipping in the Baltic Sea area in 2009 - 2019

Elisa Majamäki, Jukka-Pekka Jalkanen and Lasse Johansson

Finnish Meteorological Institute, Atmospheric Composition, Erik Palmenin aukio 1, FI-00560 Helsinki, Finland

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Executive summary

The Finnish Meteorological Institute has made using the Ship Traffic Emission Assessment Model (STEAM) a theoretical estimate of the effect of sea ice on fuel consumption and carbon intensity of shipping in the Baltic Sea area in 2009 - 2019. Chapter 2 gives estimates on the annual total number of ships sailing in ice conditions in the Baltic Sea area, the distance sailed in ice conditions and additional fuel consumed in ice conditions for years 2009 - 2019. In chapter 3, the impact of sea ice on the annual carbon intensity of ships, which had sailed in ice conditions in 2009 - 2019, was analyzed by comparing the carbon intensity of shipping in open water with the carbon intensity in ice conditions. Finally, in chapter 4, the impact of sea ice on the total annual fuel consumption of all ships that have sailed in the Baltic Sea area in 2009 - 2019 was also analyzed including also e.g. ships having sailed only in open water.

Key Messages

1. **During 2009 – 2019, on the average 1475 ships with 5000 gross tonnage and above were sailing in ice conditions in the Baltic Sea area each year.** The number ships affected annually by ice conditions during this period ranges from 972 in 2015 to 1900 in 2019. This includes, on the average, 85 ro-ro passenger ships, 27 vehicle carriers, 67 ro-ro cargo ships, 7 cruise passenger ships, 320 bulk carriers, 258 general cargo ships, 161 container ships, 63 refrigerated cargo carriers, 3 LNG carriers, 16 gas tankers and 430 tankers.

2. **On the average, 31.7% of all ships with 5000 gross tonnage and above sailing in the Baltic Sea area were affected by sea ice each year during 2009 - 2019.** The average annual percentage of ships sailing in ice conditions during this period ranges from 20.7 % in 2015 to 41.7 % in 2010, which is due to varying ice extent in these years. Largest annual impact can be seen on ro-ro passenger ships of which on the average 57.6 % have operated in ice conditions during this period. Small passenger ships and cruise passenger ships have the smallest fraction of ships effected by sea ice as less than on the average 10 % of these ships had traveled annually in ice conditions.

3. **On the average, sea ice increases the total annual fuel consumption of ships with 5000 gross tonnage and above sailing in ice conditions by 7.81 % in the Baltic Sea.** The total annual average increase for all ships ranges from 1.79 % in 2019 to 14.85 % in 2013. With regard to average annual increase of fuel consumption of different ship types, the largest average effect can be seen for general cargo ships of which fuel consumption has increased on the average by 23.56 % due to sailing in ice conditions in 2013. The lowest average increase is for LNG tankers with 0.27 % increase in fuel consumption caused by sea ice in 2017.

4. **During years 2009 – 2019, ships with 5000 gross tonnage and above have travelled annually on the average 1 058 794 nautical miles in ice conditions which corresponds to 7.57 % of the total distance sailed by all ships in the Baltic Sea area**. Tankers, ro-ro passenger ships and container ships have sailed the longest distances in ice contributing to 24 %, 18 % and 14

% of the total distance, respectively. Cruise passenger ships have the smallest contribution as they have sailed less than 0.5 % of the total distance in ice.

5. **For all ship types, including the operation in ice conditions in the calculation increases the annual average Carbon intensity indicator (CII) by an average of 9.99 % for ships with 5000 gross tonnage and above during years 2009 – 2019.** The average annual increase of the average carbon intensity indicator for all ships ranges from 3.52 % in 2019 to 16.61 % in 2013 depending on the annual maximum ice extent in the Baltic Sea area. With regard to average annual increase of CII of different ship types, largest average annual increase of the indicator is for general cargo ships with over 14.23 % difference between the CII values with and without sailing in ice conditions included in the calculation of the indicator. Cruise passenger ships have the lowest annual change with only an increase of 1.22 % when including operation in ice in the calculation of the indicator.

1 Material and method

Ship's fuel consumption, distance sailed, and CO_2 emissions are generated using the Ship Traffic Emission Assessment Model STEAM (Jalkanen et al., 2009, 2012, 2021; Johansson et al., 2013, 2017) that combines AIS messages and ship technical data obtained from IHS Markit to estimate the ship's power consumption and emissions.

The coverage of AIS data used in this study varies over the years and has improved especially after year 2016. This will affect the absolute total values calculated for each year and should be considered when e.g. the annual total fuel consumption between different years is compared. *Table 1* shows the number of AIS messages in the datasets used in this study for ships of 5000 gross tonnage and above in years 2009 – 2019.

Table 1 Total number of AIS messages and AIS messages per ship of ships with 5000 gross tonnage and above in the Baltic Sea in years 2009-2019.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
AIS messages	1.25 E+07	1.17 E+07	1.33 E+07	1.12 E+07	1.2 1E+07	1.95 E+07	2.97 E+07	5.09 E+07	1.44 E+09	1.49 E+08	1.20 E+08
AIS messages / ship	48390	38548	44148	35844	40897	63532	94122	181679	6236253	546260	462080

The additional required engine power caused by sea ice is calculated using the channel resistance method described in Juva and Riska (2002). It is assumed that icebreakers are assisting ships sailing in ice conditions, if required. Ships, other than icebreakers, are assumed to sail in broken ice in an ice channel. However, because there is only very limited number of icebreakers relative to merchant vessels, icebreaker assistance and related broken channel can only be provided in ice covered waters where merchant vessels cannot sail independently in a safe manner. Therefore, the actual resistance in ice conditions might be higher than what this model predicts, e.g. in cases when a merchant ships sails in an ice covered area with high ice concentration. Coverage and thickness of the ice are obtained from Copernicus Marine Services. The used CMEMS Baltic Sea Physical Reanalysis -product has a spatial resolution of 4 x 4 km and a temporal resolution of one hour. In this study, the ice fields are updated every 3 hours.

2 Ships affected by sea ice

In this chapter, the total number of ships sailing annually in ice conditions in the Baltic Sea area, distance sailed in ice conditions for these ships and their additional fuel oil consumption when sailing in ice conditions is estimated for years 2009 - 2019.

The number and percentage of ships in size class of 5000 gross tonnage and above that have been affected by sea ice, when sailing in the Baltic Sea, have been estimated for each year for years 2009 – 2019. Numbers are estimated based on the distance ships have travelled in ice conditions according to the STEAM model that uses AIS data collected by HELCOM and sea ice data from Copernicus marine services.

Table 2 shows the number of ships that have operated within an area of ice coverage each year and *table 3* shows the percentage of each ship type that have travelled in sea ice. In total, 16226 ships and an average of 31.7 % of ships have operated annually in ice conditions between years 2009 and 2019. Bulk carriers, general cargo ships and tankers are the most common ship types to have operated in ice conditions. Largest impact can be seen on ro-ro passenger ships of which 57.6 % have travelled in ice conditions and ro-ro cargo ships of which 57.1 % were affected by sea ice. Small passenger ships and cruiser passenger ships have the smallest fraction of ships effected by sea ice. Results show that there has been some variation between different years; highest percentages of ships effected was in years 2010 (41.7 %) and 2013 (39.4 %), and the lowest in 2015 (20.7 %).

Table 2 Number of ships with 5000 gross tonnage and above that have travelled within the area of sea ice coverage in the Baltic Sea during 2009-2019.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	TOTAL
RoPax ships	60	130	121	64	120	102	43	93	74	88	40	**935**
Vehicle carriers	23	44	30	33	41	19	14	24	23	23	23	**297**
RoRo cargo ships	67	91	83	65	77	56	54	66	60	65	57	**741**
Cruise ships	1	2	1	1	1	1	1	2	8	4	55	**77**
Bulk carriers	146	303	249	220	341	256	193	349	426	507	525	**3515**
General cargo	173	294	254	229	279	221	184	253	290	320	341	**2838**
Container	117	190	180	154	182	158	121	165	176	187	145	**1775**
Reefers	87	89	81	55	66	50	38	50	61	62	52	**691**
LNG tankers	0	2	0	1	3	2	0	5	3	7	6	**29**
Gas tankers	4	23	9	9	20	11	12	21	19	21	25	**174**
Other tankers	310	533	443	341	496	334	297	429	450	511	581	**4725**
Passenger ships	0	0	0	0	0	0	0	0	1	1	0	**2**
Fishing vessels	17	13	7	2	5	3	1	4	1	0	0	**53**
Service ships	0	1	1	2	10	0	0	0	5	1	2	**22**
Miscellaneous	12	35	31	21	35	29	14	39	42	46	48	**352**
TOTAL	**1017**	**1750**	**1490**	**1197**	**1676**	**1242**	**972**	**1500**	**1639**	**1843**	**1900**	**16226**

Table 3 Percentage (%) of ships with 5000 gross tonnage and above that have travelled within the area of sea ice coverage in the Baltic Sea during 2009-2019.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	TOTAL
RoPax ships	40.0	79.8	70.3	40.5	79.5	68.9	29.1	71.0	54.0	63.8	31.5	**57.6**
Vehicle carriers	13.8	25.7	17.3	21.4	29.1	13.2	9.8	15.8	14.9	14.5	13.9	**17.2**
RoRo cargo ships	49.6	73.4	66.9	53.7	70.6	54.9	49.5	56.9	49.6	58.0	45.6	**57.1**
Cruise ships	1.4	2.8	1.3	1.2	1.2	1.3	1.4	2.7	10.7	4.5	61.1	**8.9**
Bulk carriers	15.4	30.2	22.1	18.6	28.8	16.8	12.5	21.7	25.9	29.9	30.4	**23.2**
General cargo	28.8	45.4	39.0	35.2	42.6	31.3	25.6	34.8	41.8	46.2	48.4	**38.1**
Container	35.2	59.2	47.5	41.0	56.2	45.0	34.6	48.0	37.5	39.0	30.9	**42.3**
Reefers	39.9	39.7	42.9	32.0	48.5	47.6	36.2	46.7	55.5	60.8	56.5	**44.3**
LNG tankers	0.0	25.0	0.0	12.5	30.0	13.3	0.0	26.3	10.0	16.7	10.3	**13.4**
Gas tankers	6.6	37.1	14.5	13.2	26.3	14.3	16.9	21.4	21.8	28.8	27.5	**21.1**
Other tankers	23.6	42.2	34.4	26.8	39.3	25.9	23.1	32.5	33.3	36.4	39.7	**32.6**
Passenger ships	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.1	12.5	0.0	**4.3**
Fishing vessels	54.8	50.0	33.3	22.2	62.5	75.0	14.3	40.0	10.0	0.0	0.0	**37.9**
Service ships	0.0	8.3	10.0	10.5	40.0	0.0	0.0	0.0	22.7	3.2	6.7	**10.8**
Miscellaneous	20.3	38.9	33.0	23.9	39.8	27.9	12.3	27.7	24.7	26.1	28.1	**27.2**
TOTAL	**24.8**	**41.7**	**34.0**	**27.4**	**39.4**	**26.6**	**20.7**	**30.8**	**32.2**	**35.4**	**35.7**	**31.7**

Figure 1 shows the contribution of different ship types to the total distance ships have sailed in ice in the Baltic Sea. During years 2009 – 2019, ships have travelled each year on the average in total 1 058 794 nautical miles in ice conditions which corresponds to 7.57 % of the average total distance sailed annually by all ships with 5000 gross tonnage and above in the Baltic Sea area. Tankers, ro-ro passenger ships and container ships have travelled longest distances in ice contributing to 24 %, 18 % and 14 % of the total distance, respectively. Cruise passenger ships have the smallest contribution as they have travelled less than 0.5 % of the total distance in ice.

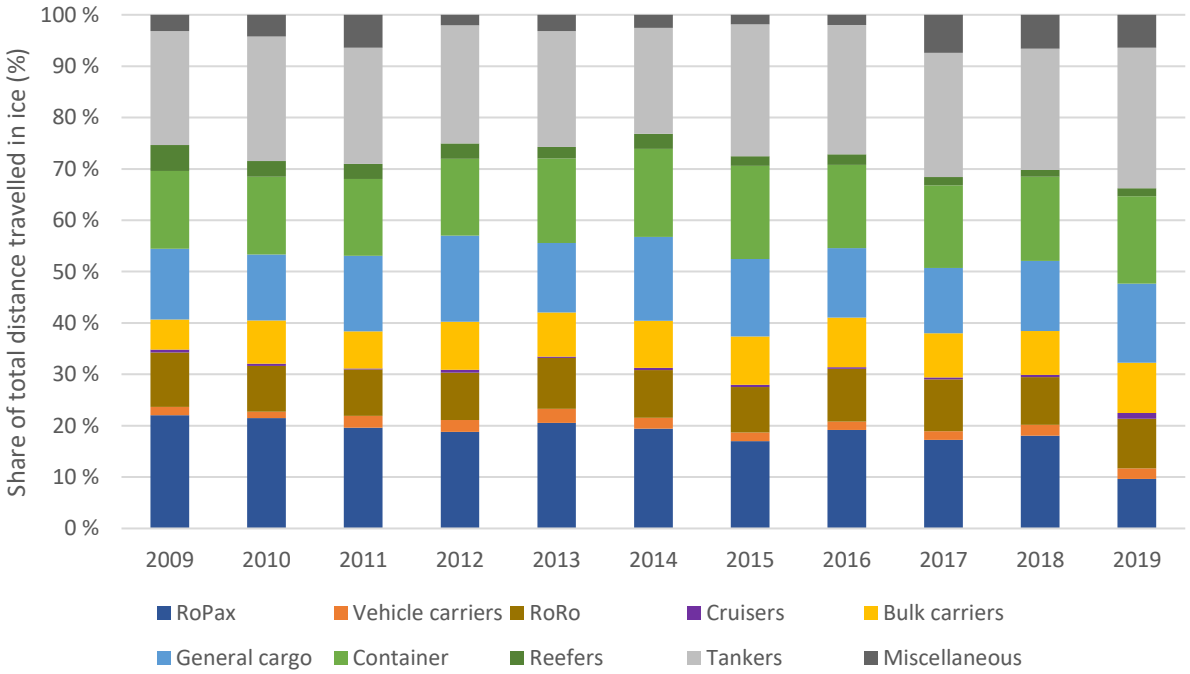

Figure 1 Share (%) of the total distance travelled in ice conditions by different ship types in the Baltic Sea during 2009 – 2019. Different colors indicate different ship types.

Figure 2 shows the percentage of the total distance that ships have been sailed in ice conditions in comparison to the total distance sailed for each ship type. Until 2016, ro-ro passenger ships and ro-ro cargo ships have operated the highest percentage of the distance in ice conditions. In 2017, 2018 and 2019 general cargo ships have the highest

share, but the differences between different ship types are decreasing in comparison to the previous years.

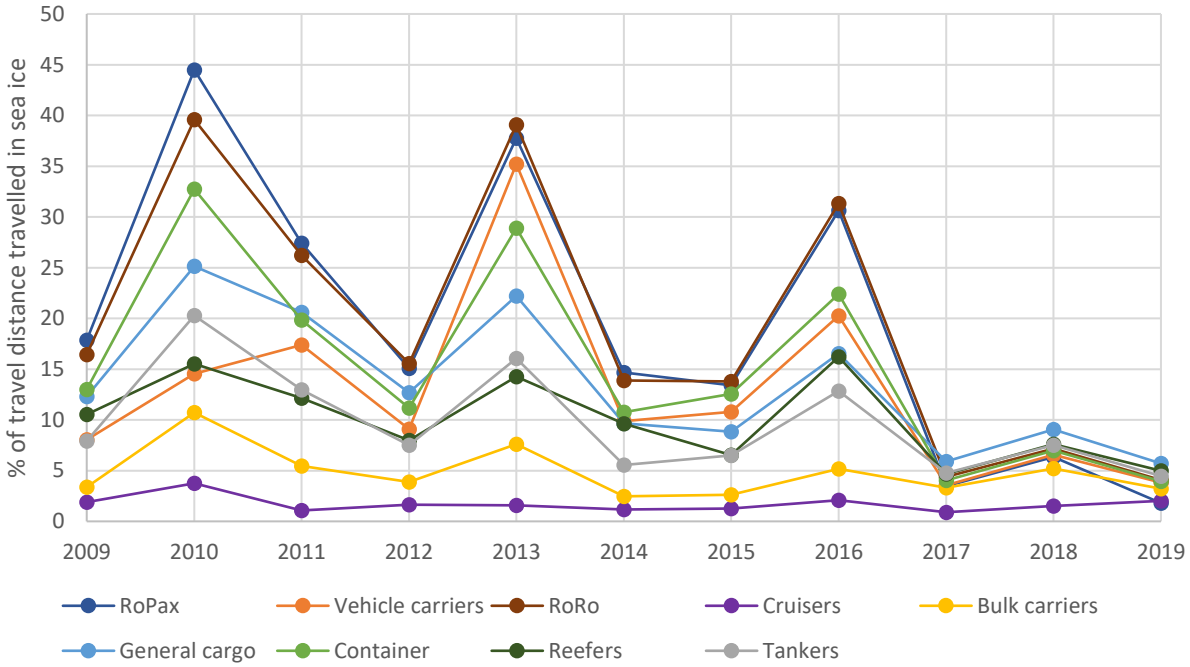

Figure 2 Percentage of the total distance ships have sailed in sea ice conditions for different vessel types in the Baltic Sea during 2009 – 2019. Only ships with 5000 gross tonnage and above are included.

Model runs were done separately with and without the effect of sea ice to estimate the increase in fuel consumption caused by ice conditions. *Tables 4 and 5* show the total fuel consumption of all ships with 5000 gross tonnage and above that have sailed in ice conditions with and without the impact of sea ice. It should be noted that the total fuel consumption is affected by the annual changes in the coverage of AIS data (see *table 1*) and therefore, relative changes in the fuel consumption of different years should be compared instead of the absolute values.

Table 6 shows the increase in the fuel consumption due to operation in ice conditions in percentages of the total fuel consumed annually. The total annual average increase for all ships ranges from 1.79 % in 2019 to 14.85 % in 2013, which indicates the effect of varying ice conditions each year, see figures 6 - 11. On the average, in years 2009 - 2019, sea ice increased the annual total fuel consumption of ships that have sailed in ice by 7.81 % in the Baltic Sea area. With regard to the average annual increase of fuel consumption of different ship types, the largest average effect can be seen for general cargo ships of which fuel consumption has increased on the average by 23.56 % due to sailing in ice conditions in 2013. With regard to the other ship types, high increase of the annual average fuel oil consumption can also be observed in 2013. In year 2013 the ice coverage in the Baltic Sea area was quite large as can be seen in figure 8. It should be noted, that these are average values for ships that have sailed in ice conditions during these years. In addition to varying ice conditions, the sailing area of the ship has a big effect on the additional annual fuel oil consumption. The increase of annual fuel oil consumption in percentage for an individual ship, which regularly sails in the northern Baltic Sea area, e.g. to the ports in the Bay of Bothnia or to the ports in the eastern Gulf of Finland, can be on a much higher level compared to these average values.

Table 4 Total annual fuel consumption (tons) of ships with 5000 gross tonnage and above that have sailed in sea ice in the Baltic Sea in 2009 – 2019 without the effect of sea ice.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
RoPax ships	57922	97543	90186	60687	90405	85149	41941	80995	820248	977584	570062
Vehicle carriers	4301	3779	5510	6449	6420	4379	3072	3390	56164	58802	56623
RoRo cargo ships	28781	28274	28338	24261	26468	26189	23935	26063	346202	340694	324754
Cruise ships	1111	1196	542	1147	687	1099	1184	762	46081	18944	160092
Bulk carriers	16692	28153	21538	23851	33903	28814	23506	38315	145247	160018	160913
General cargo	14765	19789	16998	16480	17410	16186	13097	18082	113913	123537	122728
Container	36227	45657	45598	41234	45124	42198	33380	41214	417398	432115	384785
Reefers	8203	6526	5937	4694	5872	4737	3961	4503	30951	24491	26361
LNG tankers	0	33	0	47	125	260	0	517	2653	5230	8124
Gas tankers	170	1364	623	459	1380	1630	1801	2793	31362	30306	30112
Other tankers	59536	78743	69009	61277	73254	56632	58810	79786	450371	442102	475097
TOTAL	**227708**	**311057**	**284280**	**240586**	**301046**	**267273**	**204688**	**296420**	**2460591**	**2613824**	**2319650**

Table 5 Total annual fuel consumption (tons) of ships with 5000 gross tonnage and above that have sailed in sea ice in the Baltic Sea in 2009 – 2019 including the effect of sea ice.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
RoPax ships	61793	106954	99369	63691	101185	88005	45707	88802	834244	1003664	574784
Vehicle carriers	4423	4016	5875	6590	7054	4519	3201	3663	56979	59901	57065
RoRo cargo ships	30386	31852	31968	25491	31578	27429	25364	29967	353935	350277	328451
Cruise ships	1236	1340	609	1233	770	1156	1357	885	46467	19535	161584
Bulk carriers	17768	31936	24318	25566	38131	30540	25441	42291	154514	171239	165864
General cargo	16376	23605	20741	18325	21511	17845	14845	21407	120107	133413	126833
Container	37982	50500	49975	43215	51949	44492	36265	46713	430944	450494	392199
Reefers	9041	7633	6890	5091	6708	5168	4224	5045	32453	25841	27021
LNG tankers	0	37	0	48	187	267	0	536	2660	5272	8246
Gas tankers	174	1454	642	483	1471	1665	1862	2954	31840	31092	30389
Other tankers	62908	88526	77553	65473	85222	60252	64118	89898	472430	471624	488647
TOTAL	**242087**	**347854**	**317940**	**255205**	**345766**	**281337**	**222383**	**332160**	**2536574**	**2722352**	**2361083**

Table 6 Increase in the total annual fuel consumption (%) due to operation in sea ice for ships with 5000 gross tonnage and above that have sailed in sea ice in the Baltic Sea in 2009 – 2019.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	MEAN
RoPax ships	6.68	9.65	10.18	4.95	11.92	3.35	8.98	9.64	1.71	2.67	0.83	**6.41**
Vehicle carriers	2.85	6.27	6.61	2.19	9.86	3.19	4.19	8.05	1.45	1.87	0.78	**4.30**
RoRo cargo ships	5.57	12.66	12.81	5.07	19.31	4.73	5.97	14.98	2.23	2.81	1.14	**7.93**
Cruise ships	11.18	12.04	12.30	7.47	12.12	5.21	14.57	16.12	0.84	3.12	0.93	**8.72**
Bulk carriers	6.45	13.44	12.90	7.19	12.47	5.99	8.23	10.38	6.38	7.01	3.08	**8.50**
General cargo	10.91	19.28	22.02	11.19	23.56	10.25	13.35	18.39	5.44	7.99	3.34	**13.25**
Container	4.84	10.61	9.60	4.80	15.13	5.44	8.64	13.34	3.25	4.25	1.93	**7.44**
Reefers	10.22	16.97	16.05	8.45	14.24	9.10	6.63	12.02	4.85	5.51	2.50	**9.69**
LNG tankers	N/A	12.43	N/A	0.68	50.12	2.62	N/A	3.80	0.27	0.81	1.51	**9.03**
Gas tankers	2.54	6.61	3.11	5.13	6.61	2.11	3.42	5.78	1.52	2.59	0.92	**3.67**
Other tankers	5.66	12.42	12.38	6.85	16.34	6.39	9.02	12.67	4.90	6.68	2.85	**8.74**
MEAN	**6.31**	**11.83**	**11.84**	**6.08**	**14.85**	**5.26**	**8.64**	**12.06**	**3.09**	**4.15**	**1.79**	**7.81**

3 Carbon intensity

The impact of sea ice on the annual carbon intensity of ships, which had sailed in ice conditions in 2009 - 2019, was analyzed by modelling the CO_2 emissions from shipping with the STEAM model and comparing the carbon intensity of shipping in open water with the carbon intensity in ice conditions. This comparison was performed only for ships with 5000 gross tonnage and above and that had sailed at least 10 kilometers both in ice conditions and open water. The minimum sailing distance of 10 km is set to reduce the impact of ships that have only been at berth or anchoring. Carbon intensity indicator is calculated as defined in resolution MEPC.336(76):

$$attained\ CII_{ship} = \frac{M}{W}$$

where:

M= total mass of CO_2 (g),

W = transport work (ton nm).

The transport work is calculated as a product of ship's capacity (in tons) and the distance sailed (in nautical miles). For bulk carriers, LNG carriers, gas tankers, tankers, container ships, general cargo ships, ro-ro cargo ships and refrigerated cargo carriers the deadweight tonnage is used to represent the capacity, and for cruise passenger ships, vehicle carriers and ro-ro passenger ships, gross tonnage is used to represent the capacity. Number of ships included in the analysis of carbon intensity is given in *table 7* below. For cruise passenger ships, LNG carriers and gas tankers, the number of ships that could be included in the analysis is low, which might affect the reliability of the results with regard to these ship types.

Table 7 Number of ships included in the analysis of Carbon intensity indicator (CII).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	TOTAL
RoPax ships	55	111	105	58	107	88	42	90	67	82	39	**844**
Vehicle carriers	22	36	27	26	32	17	14	19	23	23	22	**261**
RoRo cargo ships	63	76	79	63	74	52	52	62	59	65	57	**702**
Cruise ships	1	2	1	1	1	1	1	1	7	3	54	**73**
Bulk carriers	141	285	240	207	331	244	188	339	408	483	490	**3356**
General cargo	170	286	252	222	267	213	179	249	287	318	331	**2774**
Container	117	182	173	149	173	156	121	161	175	181	142	**1730**
Reefers	83	84	73	50	64	48	38	48	61	62	52	**663**
LNG tankers	0	2	0	1	1	2	0	4	3	4	6	**23**
Gas tankers	4	18	9	7	16	11	12	19	19	21	23	**159**
Other tankers	303	514	428	327	478	318	286	421	432	497	547	**4551**
TOTAL	**959**	**1597**	**1387**	**1111**	**1544**	**1150**	**933**	**1413**	**1541**	**1739**	**1763**	**15136**

The attained CII values have been calculated for each ship first by including all of the ship's activity in the calculation and then by leaving out the sailed distance and the consumed fuel when the ship has been operating in ice conditions. The average annual Carbon intensity indicator CII for each ship type and their average values were then calculated. Results are shown in *tables 8 and 9* and the differences between these values are shown in *table 10*. Including the operation in ice condition increases the average annual CII for all ship types by an average of 9.99 % during years 2009 – 2019. The average annual increase of the average CII for all ship types has large annual variation,

from 3.52 % in 2019 to 16.61 % in 2013, which is due to different maximum ice extent in these years, see figures 8 and 11. When comparing the results for different ship types, the largest average annual increase takes place for general cargo ships with 14.23 % difference between the CII values. Cruise passenger ships have the lowest change with only an increase of 1.22 % from including operation in ice in the CII value. The obvious reason for this is that different ship types have different sailing areas in the northern Baltic Sea area. Cruise passenger ships usually sail in the Baltic Sea area only during summertime.

There are a few cases when the CII calculated including the operation in ice have been lower than the CII value calculated by leaving the ice operation out (e.g. cruise passenger ships and LNG carriers in 2010). Negative values in *table 6* occur for vessel types with a low number of ships included in analysis and therefore, already one ship, for example with high hoteling or berthing emission, might affect the results.

Table 8 The average annual Carbon intensity indicator CII (g-CO_2 ton^{-1} nm^{-1}) for each ship type and their average values calculated including both the operation in ice conditions and in open water. Mean values (last row and column) are weighted by the number of ships included in the analysis (see table 7).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	MEAN
RoPax ships	22.17	24.86	27.29	20.56	26.36	18.76	22.29	21.11	17.67	19.96	16.93	**22.30**
Vehicle carriers	15.14	17.18	15.58	14.56	19.58	14.44	14.11	14.92	13.00	13.67	13.53	**15.38**
RoRo cargo ships	32.69	37.16	33.88	30.16	34.83	29.42	31.23	33.66	29.51	45.47	34.42	**34.10**
Cruise ships	22.11	21.97	24.13	20.69	22.05	19.04	23.38	21.03	9.26	15.84	11.89	**13.03**
Bulk carriers	7.82	8.48	8.28	6.81	6.58	6.22	5.90	6.10	5.13	6.00	5.36	**6.38**
General cargo	16.48	18.41	16.33	14.22	15.65	13.16	12.94	13.68	11.83	12.60	11.82	**14.19**
Container	22.21	23.90	22.56	18.32	20.22	17.10	17.27	17.41	13.51	16.38	14.76	**18.53**
Reefers	27.36	28.96	24.31	21.72	22.87	20.97	21.17	21.31	17.90	20.98	19.87	**23.06**
LNG tankers	0.00	34.57	N/A	27.11	44.81	23.76	N/A	26.84	19.21	21.45	19.45	**24.18**
Gas tankers	21.09	19.15	22.34	22.14	16.68	15.67	16.90	18.17	17.07	17.74	16.51	**17.92**
Other tankers	10.09	11.16	10.72	8.81	9.14	8.07	8.01	8.34	7.05	8.02	7.00	**8.76**
MEAN	**16.21**	**16.83**	**16.26**	**13.44**	**14.28**	**12.37**	**12.43**	**12.42**	**10.16**	**11.83**	**9.96**	**13.15**

Table 9 The average annual Carbon intensity indicator CII (g-CO_2 ton^{-1} nm^{-1}) for each ship type and their average values calculated by leaving out the operation in ice conditions. Mean values (last row and column) are weighted by the number of ships included in the analysis (see table 7).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	MEAN
RoPax ships	20.88	23.86	24.44	19.13	24.68	17.78	20.73	19.45	16.94	19.44	16.65	**20.94**
Vehicle carriers	14.08	16.63	14.64	13.43	19.14	14.02	13.36	13.59	12.79	13.29	13.23	**14.71**
RoRo cargo ships	30.56	33.50	30.54	28.17	29.18	27.41	28.60	28.66	28.73	44.24	33.84	**31.35**
Cruise ships	18.86	24.47	23.07	18.90	21.41	18.57	20.65	21.24	9.13	15.50	11.80	**12.87**
Bulk carriers	7.14	7.12	6.98	6.19	5.78	5.76	5.37	5.37	4.73	5.66	5.14	**5.76**
General cargo	14.68	15.79	13.21	12.50	12.45	11.57	10.99	11.41	11.11	11.70	11.34	**12.39**
Container	21.29	23.14	20.83	17.28	17.47	16.12	15.71	15.22	12.91	15.75	14.44	**17.30**
Reefers	25.06	27.28	21.65	20.31	20.53	19.26	19.96	19.29	17.01	19.83	19.48	**21.37**
LNG tankers	0.00	44.18	N/A	26.13	26.62	23.16	N/A	25.53	19.13	20.92	19.15	**23.72**
Gas tankers	20.64	15.36	22.13	22.15	15.24	15.21	15.66	16.85	16.55	17.24	16.17	**16.86**
Other tankers	9.39	10.35	9.22	8.02	7.79	7.41	7.25	7.24	6.65	7.47	6.75	**7.96**
MEAN	**15.02**	**15.40**	**14.23**	**12.33**	**12.31**	**11.41**	**11.22**	**10.84**	**9.63**	**11.22**	**9.66**	**12.01**

Table 10 The average annual change in Carbon intensity indicator CII (%) for each ship type and their average values when operation in ice is included (%). Mean values (last row and column) are weighted by the number of ships included in the analysis (see table 7).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	MEAN
RoPax ships	6.17	4.18	11.66	7.51	6.82	5.51	7.52	8.53	4.28	2.64	1.66	**6.32**
Vehicle carriers	7.53	3.31	6.40	8.38	2.30	3.01	5.58	9.84	1.60	2.80	2.25	**4.66**
RoRo cargo ships	6.96	10.95	10.95	7.06	19.36	7.35	9.21	17.44	2.69	2.77	1.70	**9.10**
Cruise ships	17.22	-10.21	4.56	9.50	2.97	2.54	13.22	-0.98	1.40	2.14	0.82	**1.22**
Bulk carriers	9.43	19.08	18.72	9.97	13.87	7.86	9.85	13.60	8.38	6.03	4.26	**10.34**
General cargo	12.25	16.61	23.58	13.77	25.75	13.73	17.72	19.98	6.49	7.65	4.26	**14.23**
Container	4.31	3.27	8.32	6.03	15.72	6.08	9.95	14.41	4.63	4.00	2.24	**7.22**
Reefers	9.18	6.17	12.30	6.92	11.35	8.87	6.07	10.44	5.26	5.79	1.97	**7.83**
LNG tankers	N/A	-21.75	N/A	3.76	68.32	2.58	N/A	5.15	0.41	2.52	1.57	**3.26**
Gas tankers	2.16	24.69	0.97	-0.04	9.45	3.02	7.90	7.78	3.09	2.92	2.13	**6.65**
Other tankers	7.45	7.80	16.23	9.82	17.32	8.90	10.48	15.07	6.09	7.32	3.60	**9.91**
MEAN	**8.24**	**10.72**	**15.86**	**9.62**	**16.61**	**8.70**	**11.18**	**14.83**	**6.22**	**6.10**	**3.52**	**9.99**

Additionally, CII values were calculated only for the operation in ice conditions and the results are shown in *table 11* below. For all ship types, the CII values calculated for the operation in ice conditions are higher than the CII values for open water operation or CII including both open water and ice operation. Average difference between the CII values for operation in ice and in open water is 58.68 %.

Table 11 The average annual Carbon intensity indicator CII (g-CO_2 ton^{-1} nm^{-1}) for each ship type and their average values calculated for the time ship sailed in ice conditions. Mean values (last row and column) are weighted by the number of ships included in the analysis (see table 7).

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	MEAN
RoPax ships	28.99	30.87	33.69	42.72	30.33	24.21	28.05	31.33	44.00	25.55	24.74	**31.30**
Vehicle carriers	22.73	21.02	18.16	17.66	23.86	16.34	17.36	21.54	20.36	17.78	18.25	**19.84**
RoRo cargo ships	39.64	42.07	43.56	38.28	44.45	39.08	42.55	45.48	44.26	55.77	41.32	**43.44**
Cruise ships	24.43	23.41	24.49	22.55	22.26	20.00	28.51	20.94	20.20	36.25	14.94	**17.36**
Bulk carriers	12.84	12.41	14.08	10.72	10.36	10.64	9.95	10.20	9.91	9.11	8.35	**10.38**
General cargo	23.44	24.39	24.85	19.88	22.96	22.15	21.46	20.10	20.39	21.07	18.68	**21.65**
Container	27.69	26.00	28.26	23.60	26.51	24.72	24.50	23.63	23.17	23.46	20.49	**24.74**
Reefers	37.26	33.71	33.88	28.46	31.84	33.08	30.34	27.42	29.99	29.64	25.40	**31.53**
LNG tankers	0.00	23.61	N/A	57.45	90.94	28.86	N/A	43.47	28.83	30.63	36.00	**37.05**
Gas tankers	27.29	27.62	24.53	26.06	19.17	19.42	25.91	23.12	29.01	23.71	25.59	**24.64**
Other tankers	14.17	14.22	16.60	13.13	13.49	13.42	13.01	12.53	14.06	13.42	11.26	**13.54**
MEAN	**22.05**	**20.90**	**22.94**	**19.33**	**19.65**	**18.92**	**18.78**	**18.08**	**18.60**	**17.66**	**14.75**	**19.05**

Figure 3 shows the difference between CII values in ice, open water and including both, for different ship types, and *Figure 4* shows the differences between the average of these CII values during years 2009 – 2019. The difference between the CII values including all operation and only operation in open water has high values in 2011 (15.86 %) and in 2013 (16.61 %), and low values for example in 2019 (3.52 %). The obvious reason for this variation is due to changes in the maximum ice extent in the Baltic Sea area, see *figures 7, 8 and 11*. Annual average CII indicator values for operation only in ice conditions are at least 46 % higher than the indicator values for operation only in open water.

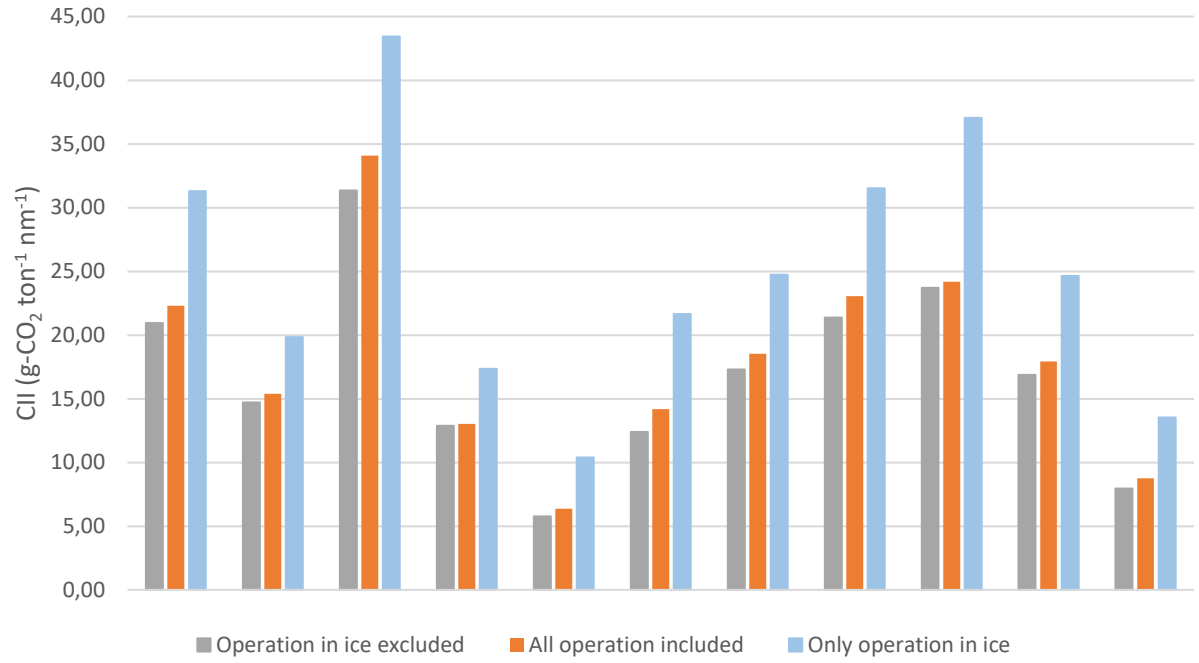

Figure 3 Average Carbon intensity indicator CII (g-CO_2 ton^{-1} nm^{-1}) in Baltic Sea 2009-2019 for ships with 5000 gross tonnage and above calculated for operation during the whole year including operation in ice (orange), operation only in open water (grey) and operation only in ice conditions (blue).

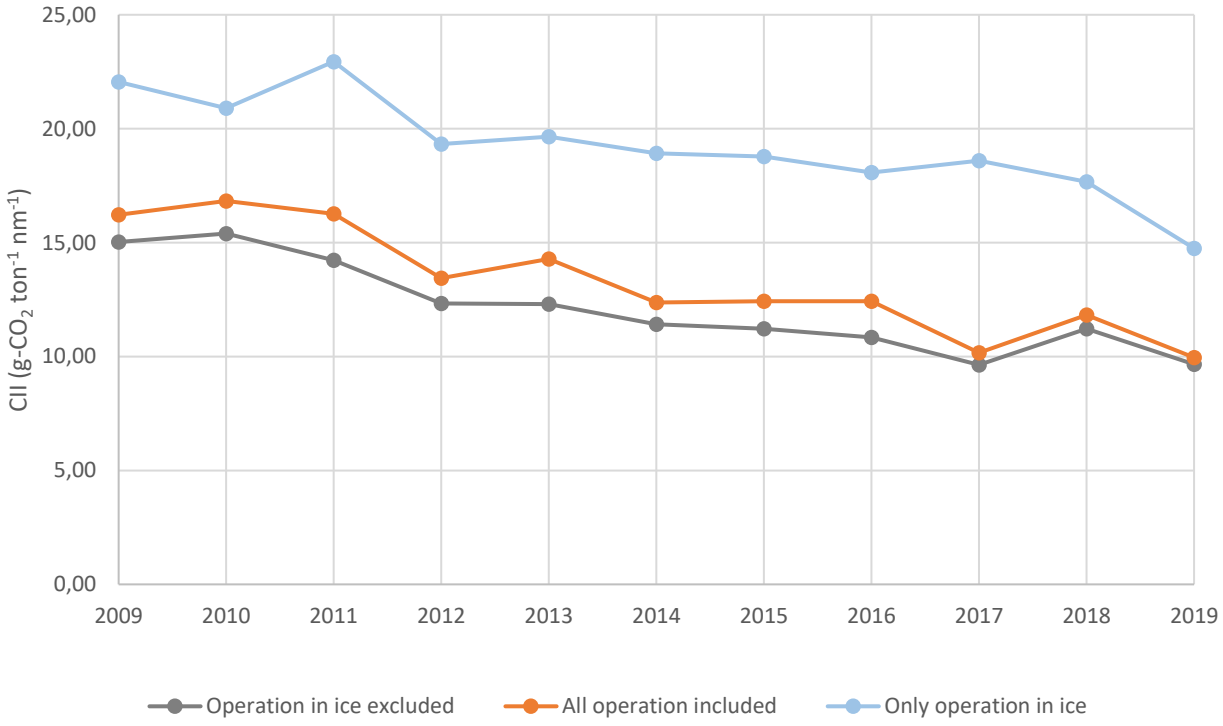

Figure 4 Average Carbon intensity indicator CII (g-CO_2 ton^{-1} nm^{-1}) in the Baltic Sea 2009-2019 for ships with GRT 5000 and above calculated for operation during the whole year (orange), operation only in open water operation (grey) and operation only in ice condition (blue).

4 Total fuel consumption

The impact of sea ice on the total annual fuel consumption of all ships that have sailed in the Baltic Sea area was also analyzed, i.e. in addition of ships, which had sailed in ice conditions, also ships having sailed only in open water were included in the analysis. Model runs were done separately with and without the effect of sea ice to estimate the increase in annual fuel consumption caused by ice conditions in the Baltic Sea during 2009 – 2019. All ships with 5000 gross tonnage and above were included in the analysis. The total annual fuel consumption in the Baltic Sea without and with the effect of sea ice are shown in *tables 12 and 13*, respectively. It should be noted that the total fuel consumption is affected by changes in the coverage of AIS data (see *table 1*) and therefore, relative changes in the fuel consumption of different years should be compared instead of absolute values. The increase in the total fuel consumption in percentages of the total fuel consumed annually due to ice conditions is shown in *table 14.*

Table 12 Total annual fuel consumption (tons) of the Baltic Sea shipping (GT>=5000) in 2009 – 2019 without the effect of sea ice.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
RoPax ships	104162	100076	102719	103521	96585	92531	91954	89092	1182143	1117451	1117856
Vehicle carriers	12433	11495	12190	13012	9672	10107	7505	8060	66820	69129	65017
RoRo cargo ships	33861	29533	30439	28952	28205	28673	26847	29190	379190	355113	354756
Cruise ships	32245	29166	31905	32157	30831	33524	32714	23483	163739	187210	187407
Bulk carriers	76553	82726	98044	105226	105205	132851	129733	141042	331255	331526	325003
General cargo	32034	35521	31808	33902	32710	35835	36325	36788	155383	163623	151710
Container	55604	61620	69617	66613	59100	68776	66966	69975	546426	551074	558081
Reefers	15941	14893	12843	12045	11111	8689	8040	7451	37395	29353	31646
LNG tankers	42	58	56	85	151	484	1047	1918	10511	15970	19429
Gas tankers	2404	2800	2967	2442	4551	3753	4149	4970	37763	33711	34076
Other tankers	155113	150050	154139	154090	147684	151348	163302	172702	660281	634265	638212
TOTAL	**520390**	**517937**	**546727**	**552046**	**525806**	**566572**	**568581**	**584672**	**3570905**	**3488427**	**3483193**

Table 13 Total annual fuel consumption (tons) of the Baltic Sea shipping (GT>=5000) in 2009 – 2019 including the effect of sea ice.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
RoPax ships	108033	109486	111902	106525	107366	95387	95720	96899	1196139	1143531	1122578
Vehicle carriers	12555	11732	12554	13154	10305	10247	7634	8333	67634	70228	65458
RoRo cargo ships	35466	33111	34070	30182	33315	29912	28275	33094	386923	364696	358453
Cruise ships	32369	29310	31972	32243	30915	33581	32886	23606	164125	187800	188900
Bulk carriers	77628	86509	100824	106942	109433	134577	131668	145018	340521	342747	329955
General cargo	33645	39337	35550	35747	36811	37494	38073	40113	161577	173499	155814
Container	57359	66463	73993	68594	65926	71070	69851	75474	559971	569453	565495
Reefers	16779	16000	13796	12442	11947	9120	8302	7993	38897	30703	32306
LNG tankers	42	62	56	86	214	491	1047	1938	10518	16013	19552
Gas tankers	2408	2890	2987	2465	4642	3788	4210	5131	38241	34497	34354
Other tankers	158485	159834	162684	158286	159652	154968	168609	182814	682341	663787	651762
TOTAL	**534770**	**554734**	**580387**	**566665**	**570526**	**580636**	**586276**	**620412**	**3646888**	**3596955**	**3524626**

Table 14 Increase in annual fuel consumption (%) of the Baltic Sea shipping (GT>=5000) caused by sea ice.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	MEAN
RoPax ship	3.72	9.40	8.94	2.90	11.16	3.09	4.10	8.76	1.18	2.33	0.42	**5.09**
Vehicle carriers	0.99	2.06	2.99	1.09	6.55	1.38	1.71	3.39	1.22	1.59	0.68	**2.15**
RoRo cargo ships	4.74	12.12	11.93	4.25	18.12	4.32	5.32	13.37	2.04	2.70	1.04	**7.27**
Cruise ships	0.39	0.49	0.21	0.27	0.27	0.17	0.53	0.52	0.24	0.32	0.80	**0.38**
Bulk carriers	1.41	4.57	2.83	1.63	4.02	1.30	1.49	2.82	2.80	3.38	1.52	**2.53**
General cargo	5.03	10.74	11.77	5.44	12.54	4.63	4.81	9.04	3.99	6.04	2.71	**6.98**
Container	3.16	7.86	6.29	2.97	11.55	3.34	4.31	7.86	2.48	3.34	1.33	**4.95**
Reefers	5.26	7.44	7.42	3.29	7.53	4.96	3.27	7.27	4.02	4.60	2.08	**5.19**
LNG tankers	0.00	7.10	0.00	0.38	41.30	1.41	0.00	1.02	0.07	0.27	0.63	**4.74**
Gas tankers	0.18	3.22	0.65	0.97	2.00	0.92	1.48	3.25	1.27	2.33	0.81	**1.55**
Other tankers	2.17	6.52	5.54	2.72	8.10	2.39	3.25	5.86	3.34	4.65	2.12	**4.24**
MEAN	**2.46**	**6.50**	**5.32**	**2.36**	**11.19**	**2.54**	**2.75**	**5.74**	**2.06**	**2.87**	**1.29**	**4.10**

On the average, sea ice increases the total fuel consumption of all ships sailing in the Baltic Sea area by 4.1%. The annual average increase ranges from 1.29 % in 2019 to 11.19 % in 2013. Regarding the different ship types, the largest average annual effect can be seen for ro-ro cargo ships of which fuel consumption has increased on the average by 7.27 % due to sailing in ice conditions. The lowest annual average increase is for cruise passenger ships with a 0.38 % increase in the fuel consumption caused by sea ice. *Figure 5* shows the trend over the years 2009 – 2019 in the impact of sea ice on annual total fuel consumption of different ship types in the Baltic Sea.

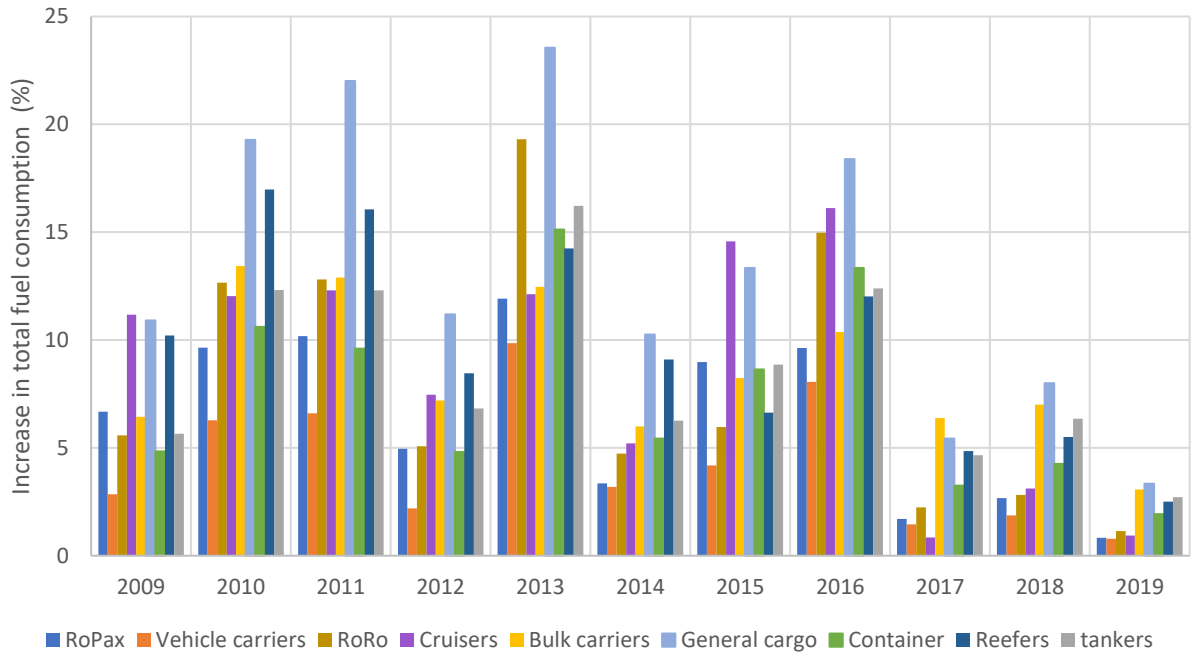

Figure 5 *Effect of sea ice on the total fuel consumption in the Baltic Sea 2009-2019 for ships with 5000 gross tonnage and above.*

Figures 6 – 11 below show the total main engine fuel consumption in ice condition during years 2009 – 2019 in the Baltic Sea. Unlike in the tables and figure presented previously in the chapter, *figures 6-11* do not include the fuel consumed by the auxiliary machinery. These figures include all ship types and size classes that have sailed in the Baltic Sea. Figures show that as the extent of sea ice cover varies over the years, only shipping in the Gulf of Finland, Gulf of Bothnia and Gulf of Riga have been affected by ice every year between 2009 and 2019. In each figure, the maximum ice extent has been depicted for each year.

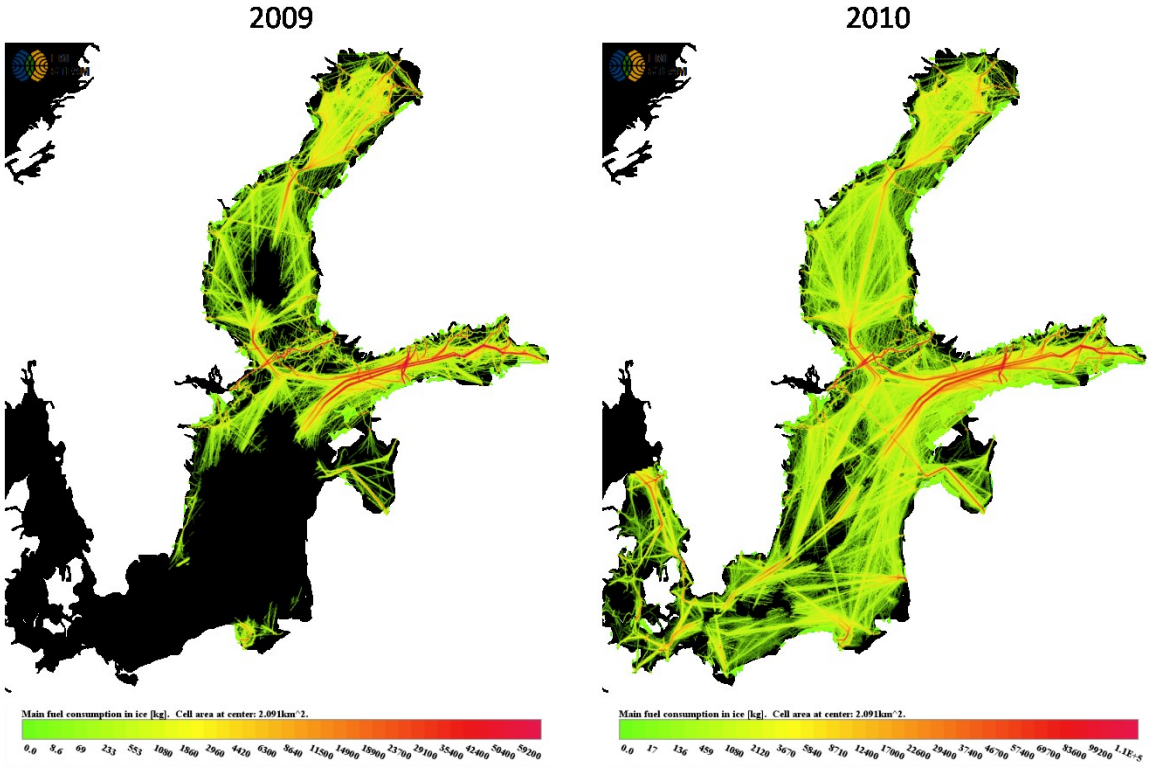

Figure 6 Main engine fuel consumption (kg) in ice conditions in the Baltic Sea 2009 and 2010.

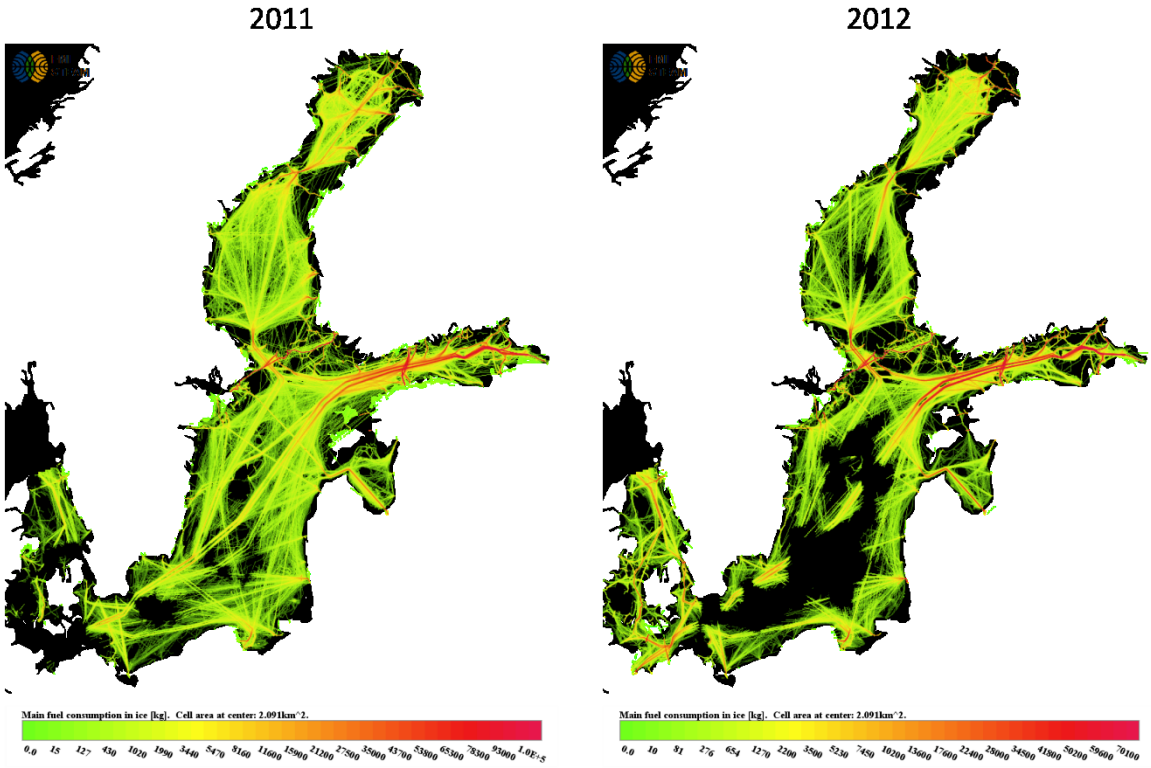

Figure 7 Main engine fuel consumption (kg) in ice conditions in the Baltic Sea 2011 and 2012.

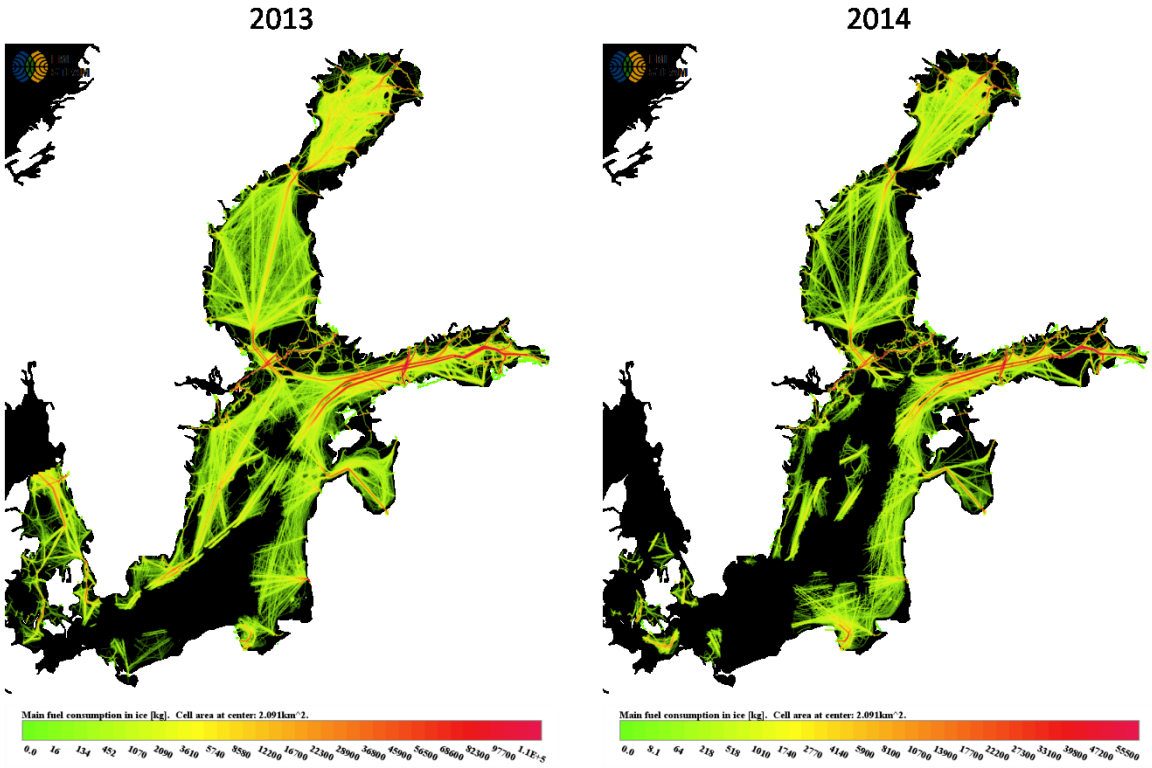

Figure 8 Main engine fuel consumption (kg) in ice conditions in the Baltic Sea 2013 and 2014.

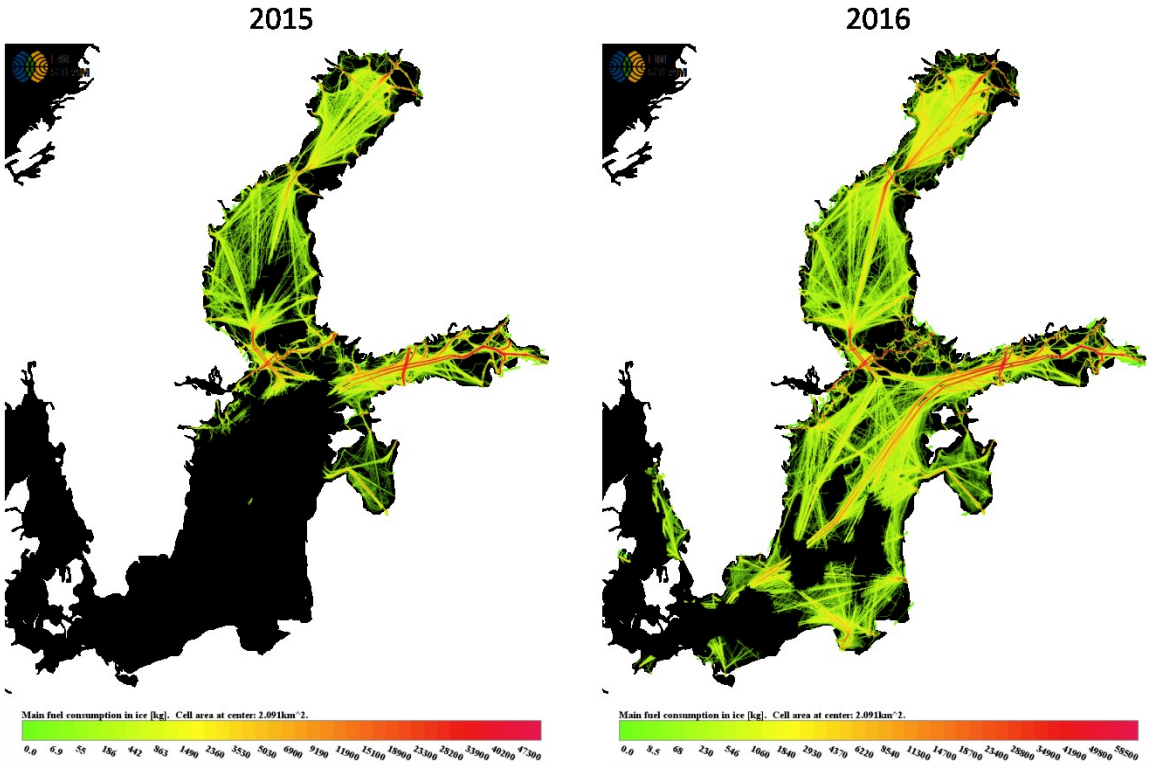

Figure 9 Main engine fuel consumption (kg) in ice conditions in the Baltic Sea 2015 and 2016.

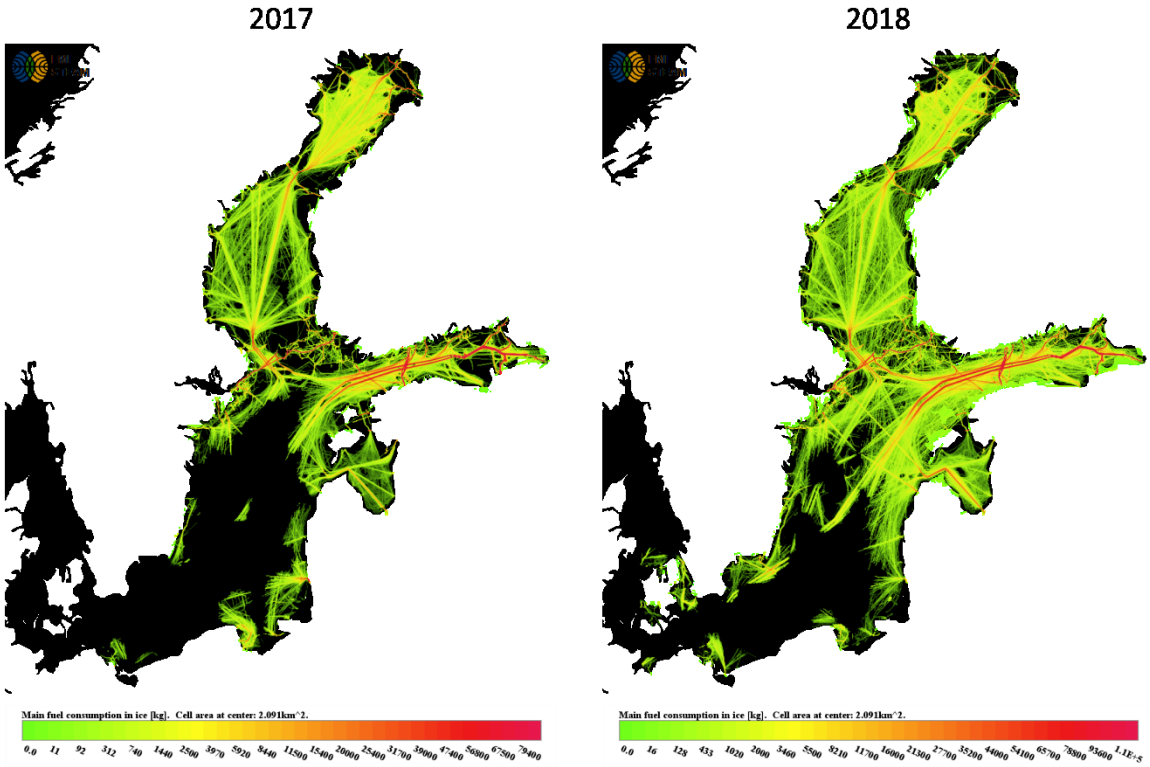

Figure 10 Main engine fuel consumption (kg) in ice conditions in the Baltic Sea 2017 and 2018.

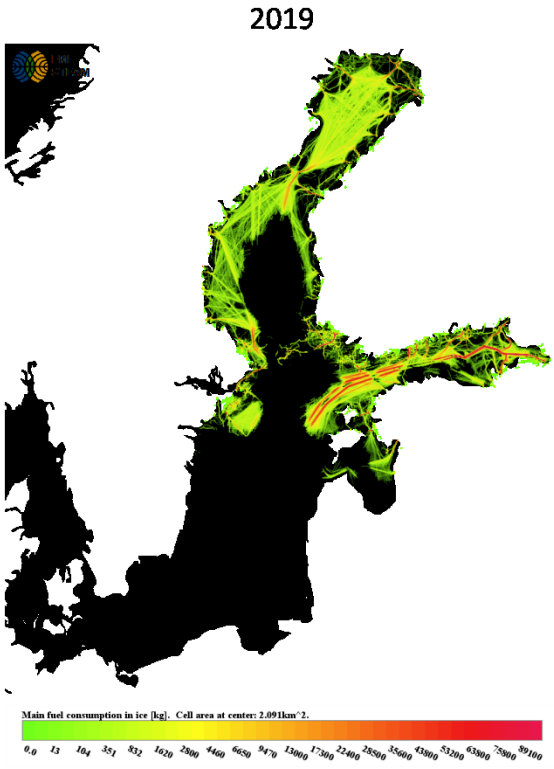

Figure 11 Main engine fuel consumption (kg) in ice conditions in the Baltic Sea 2019.

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Finnish Transport and Communications Agency Traficom

P.O.Box 320 FI-00059 TRAFICOM, Finland
Tel. +358 295 345 000

traficom.fi

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