Supplementary material

Airborne Measurements Reveal the Underestimated Impact of Black Carbon Emissions from Ships

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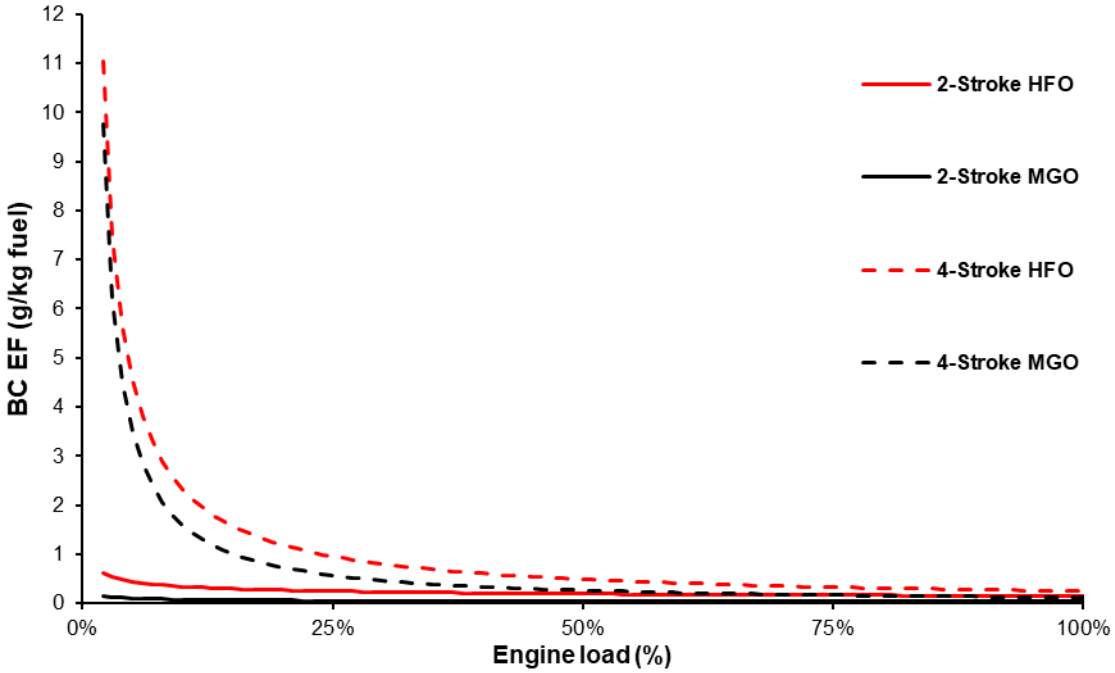
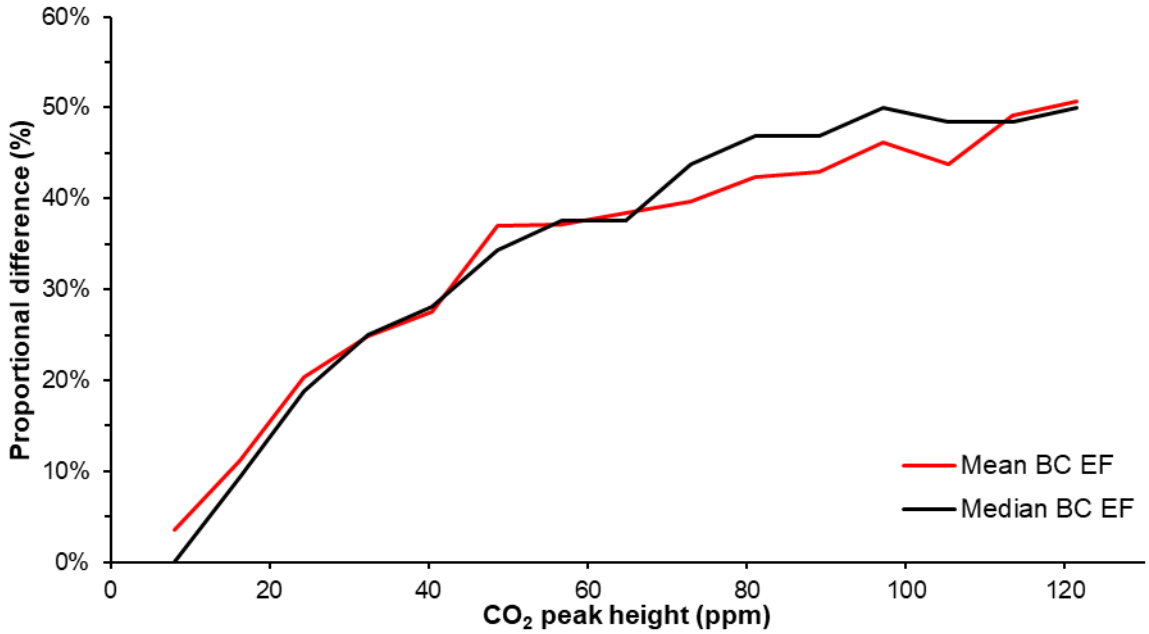
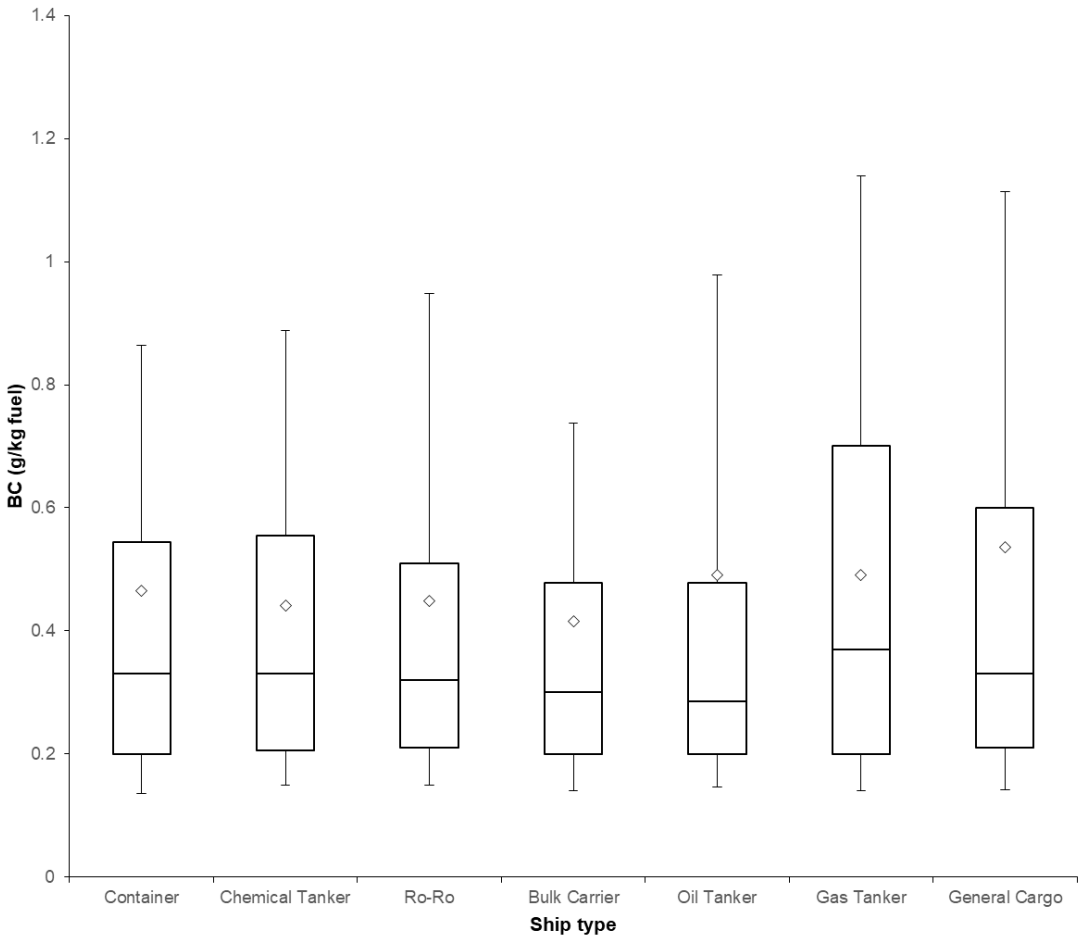


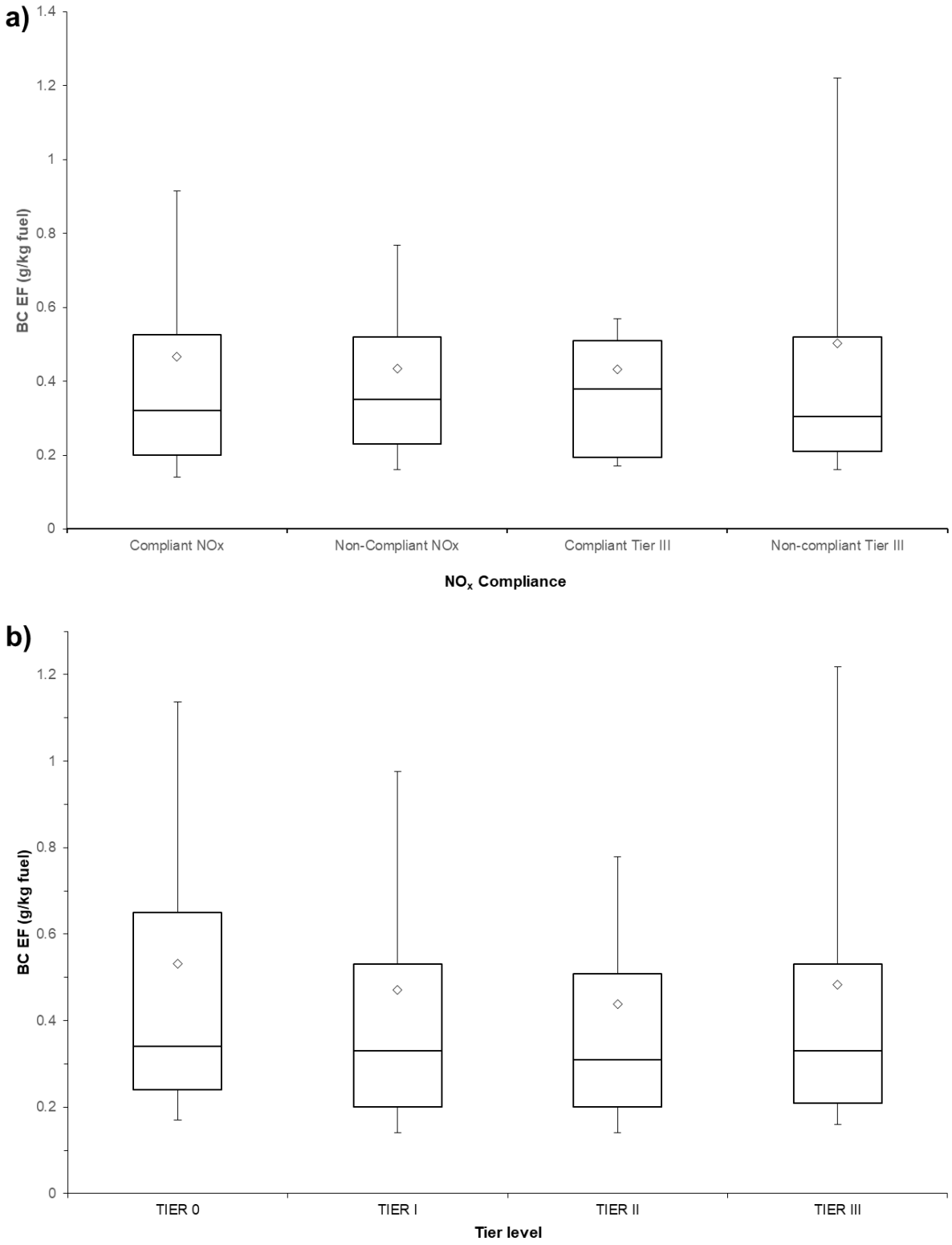
Supplementary figure 1. BC EFs in function of engine load based on a power function (derived from IMO) [32].



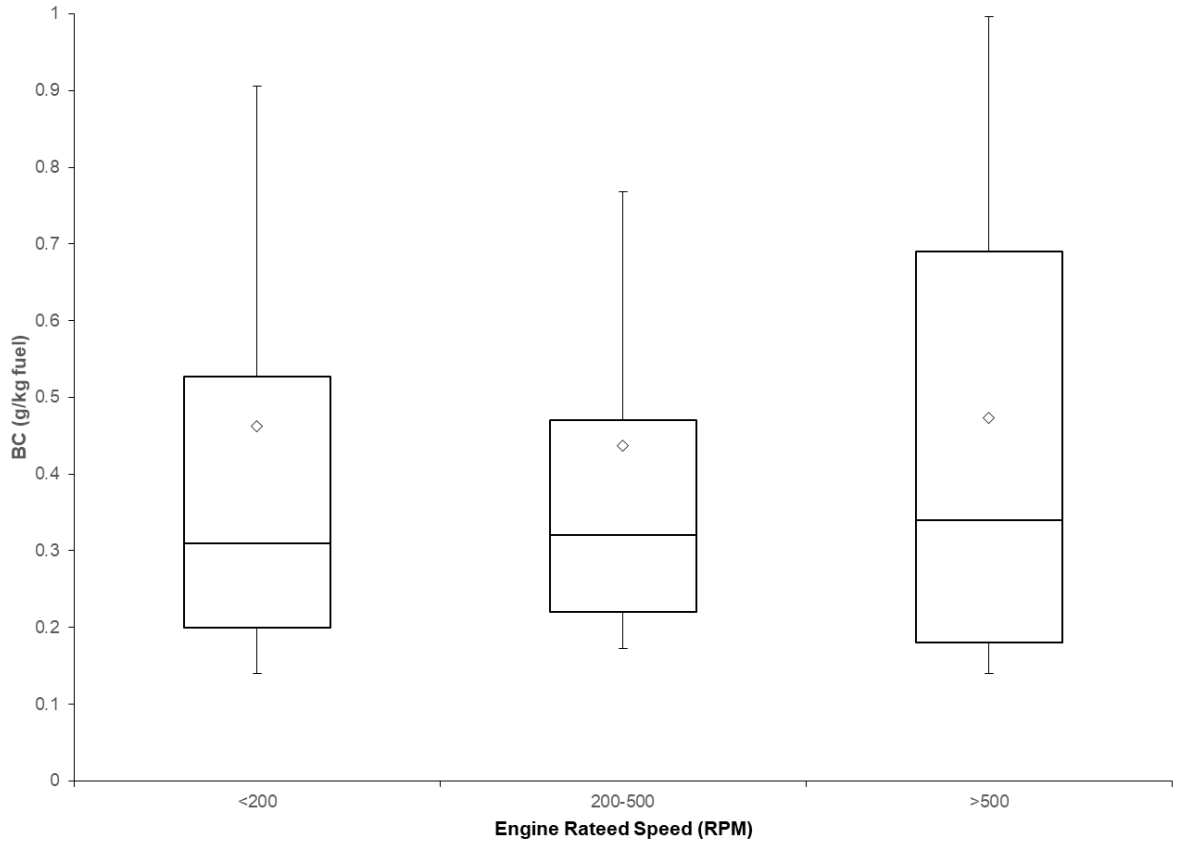
Supplementary figure 2. Impact of the peak height of CO_2 on the observed mean and median BC EFs.



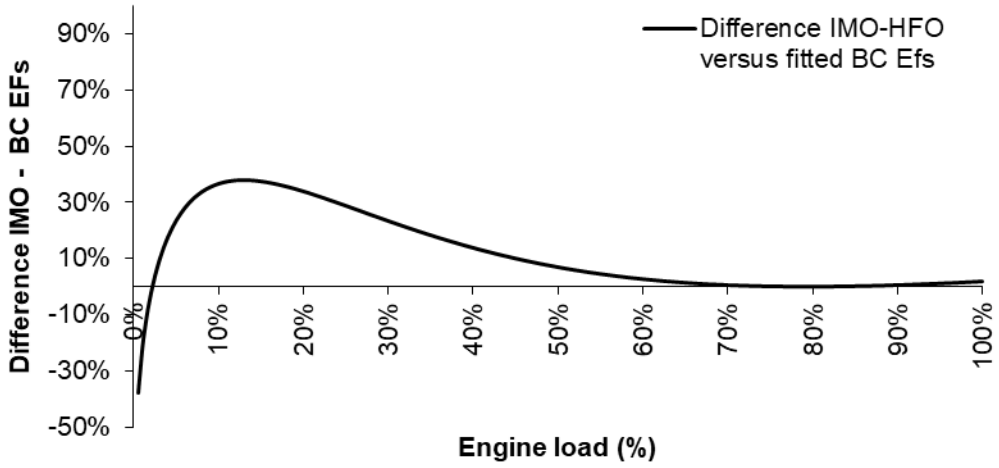
Supplementary figure 3. Box plot of median, 10, 25, 75 and 90% percentiles and mean (◊) BC EFs according to ship type.



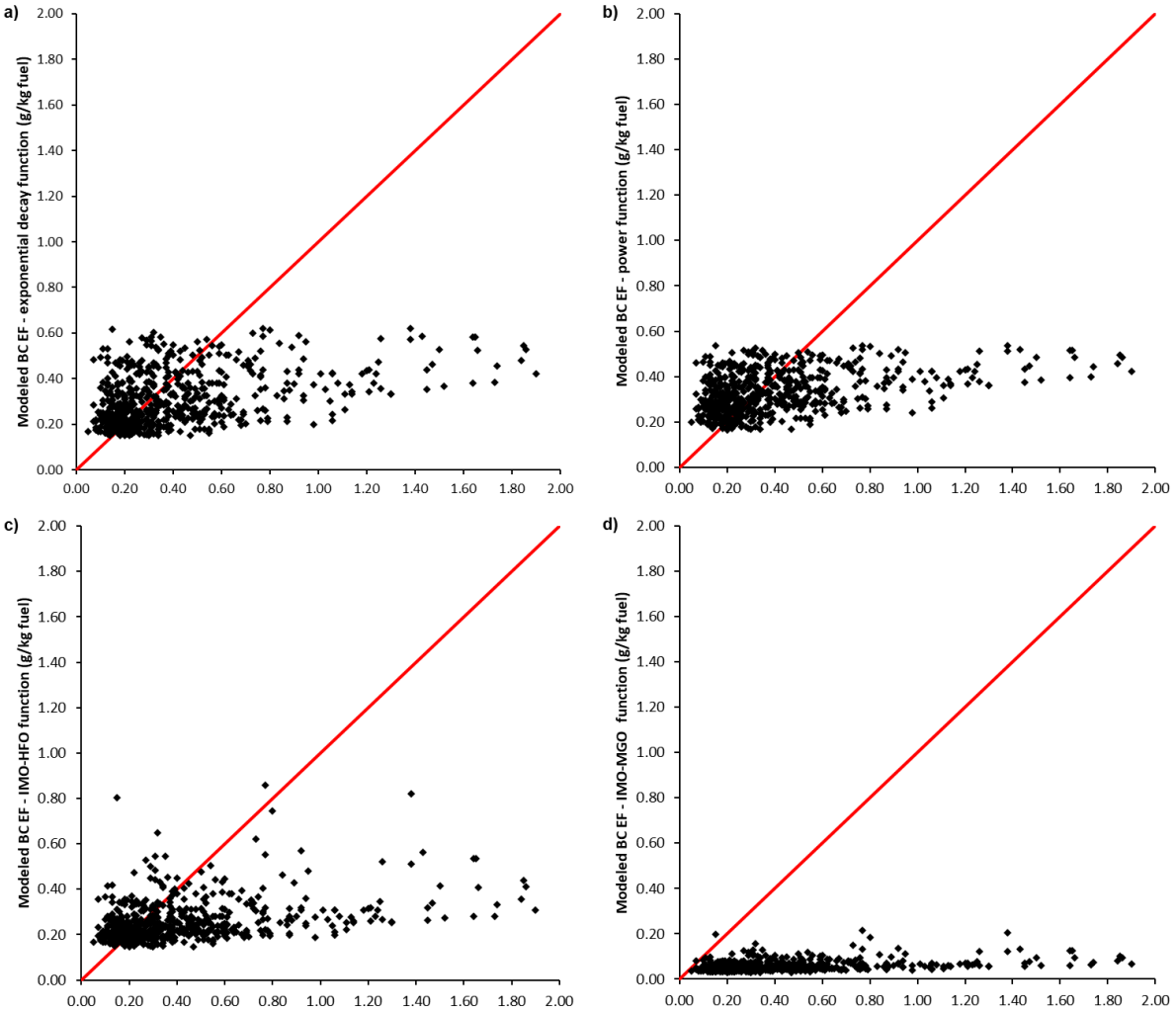
Supplementary figure 4. Box plot of median, 10, 25, 75 and 90% percentiles and mean (◊) BC EFs according to the NO_x compliance level (a) and the NO_x tier level (b).



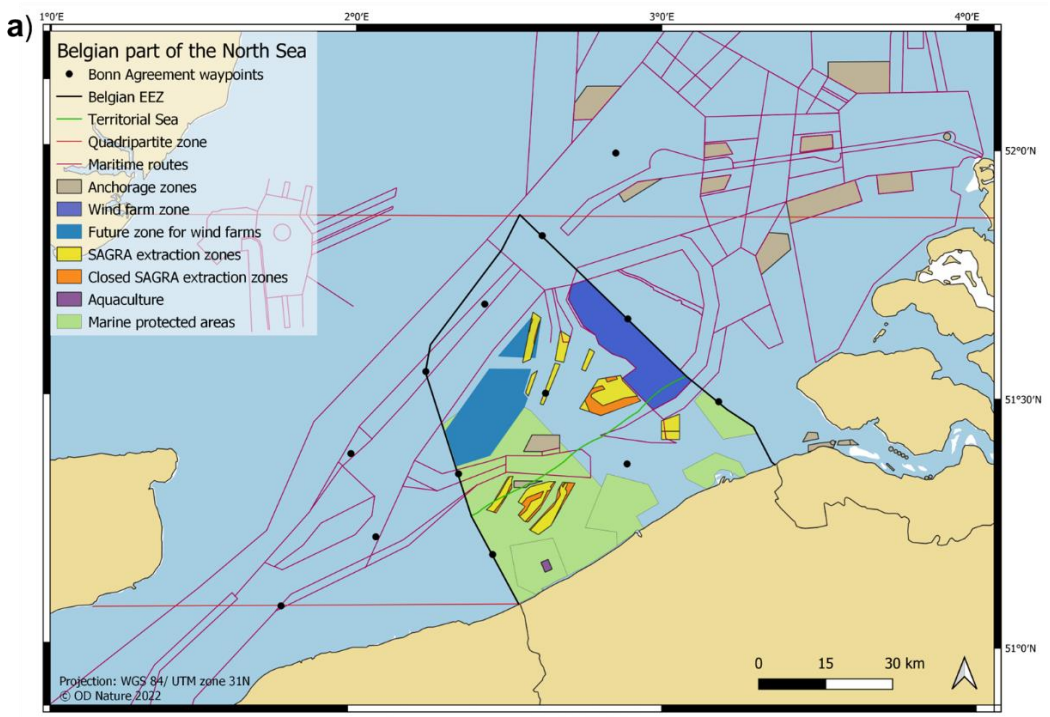
Supplementary figure 5. Box plot of median, 10, 25, 75 and 90% percentiles and mean (◊) BC EFs according to the engine rated speed (RPM).

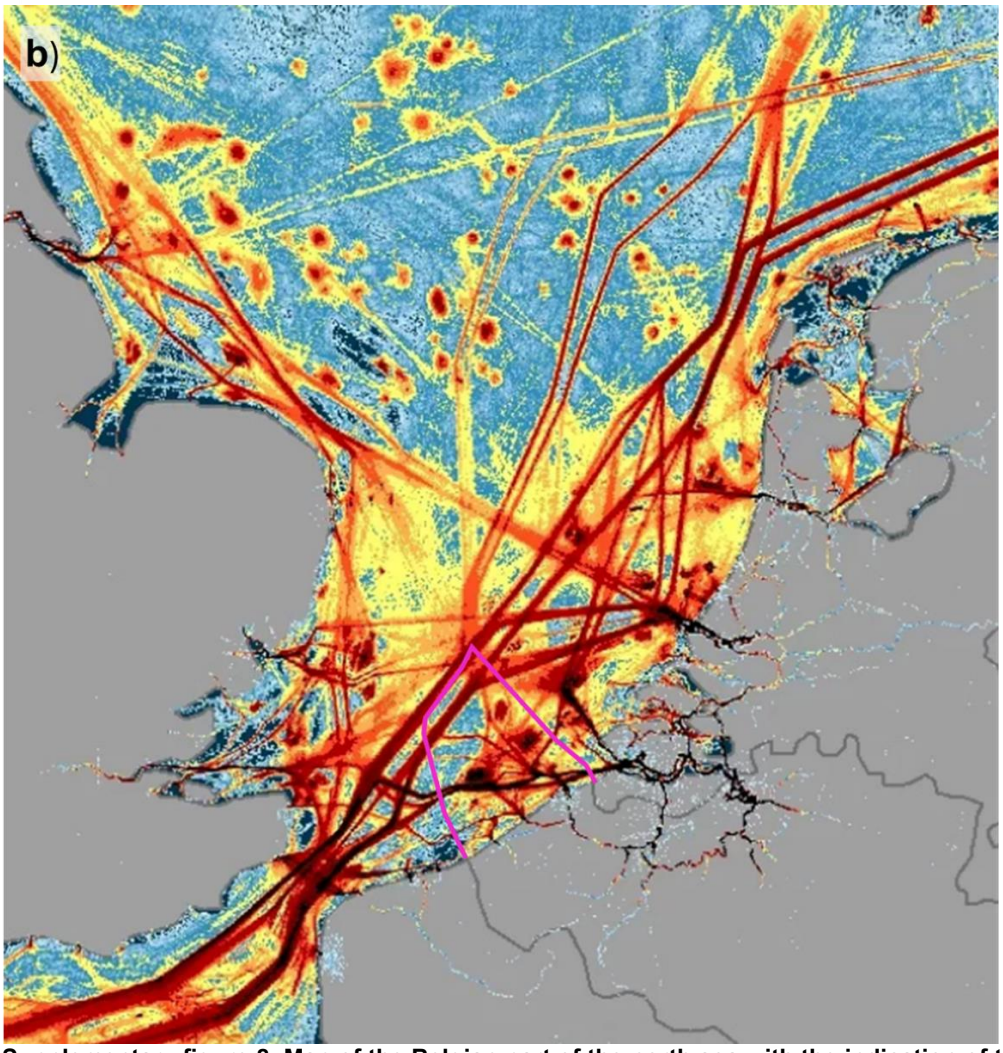


Supplementary figure 6. Difference between IMO power function and the modeled BC EFs based on an exponential decay distribution.

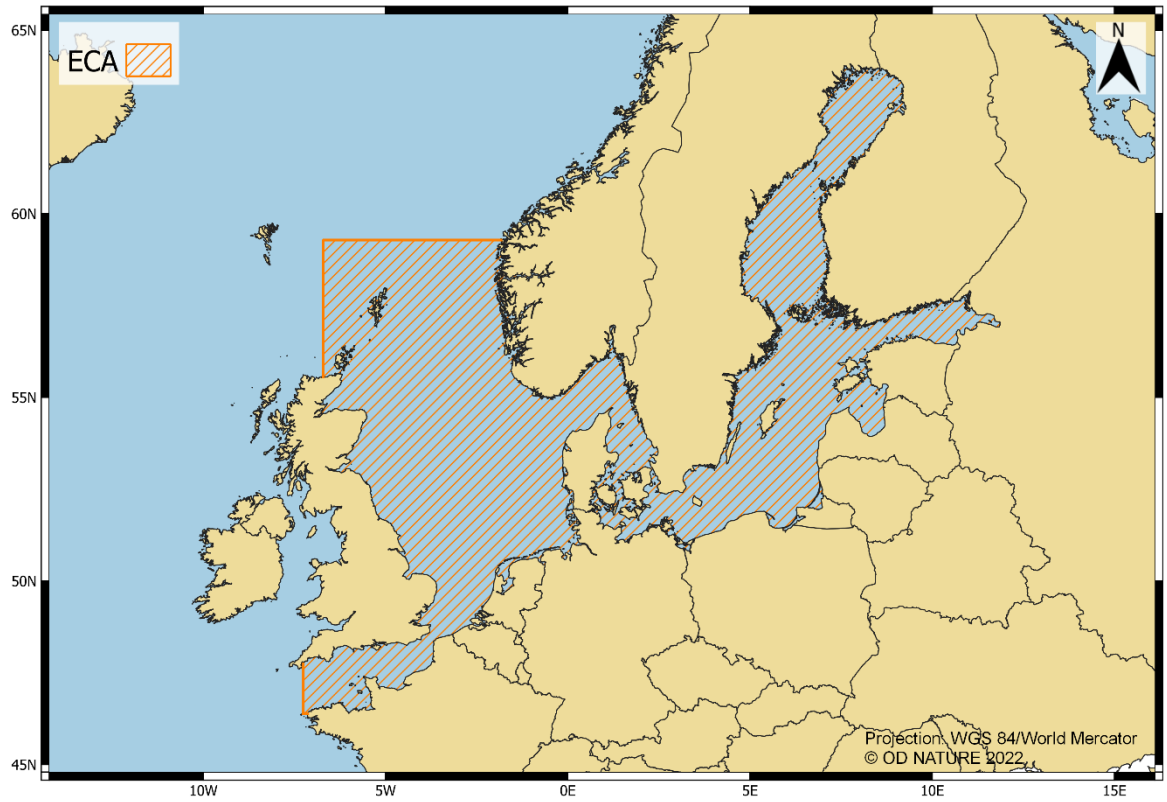


Supplementary figure 7. Comparison of observed BC EFs versus modelled BC EFs based on the engine load for exponential decay function (a), modified power function (b), IMO HFO function (c) and IMO-MGO function (d).

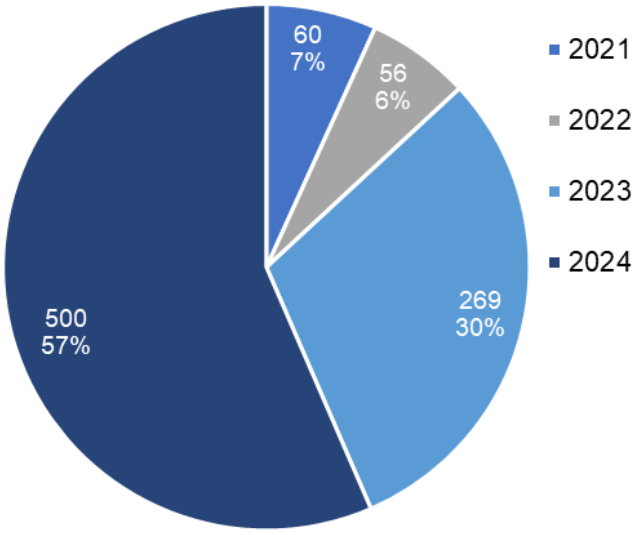




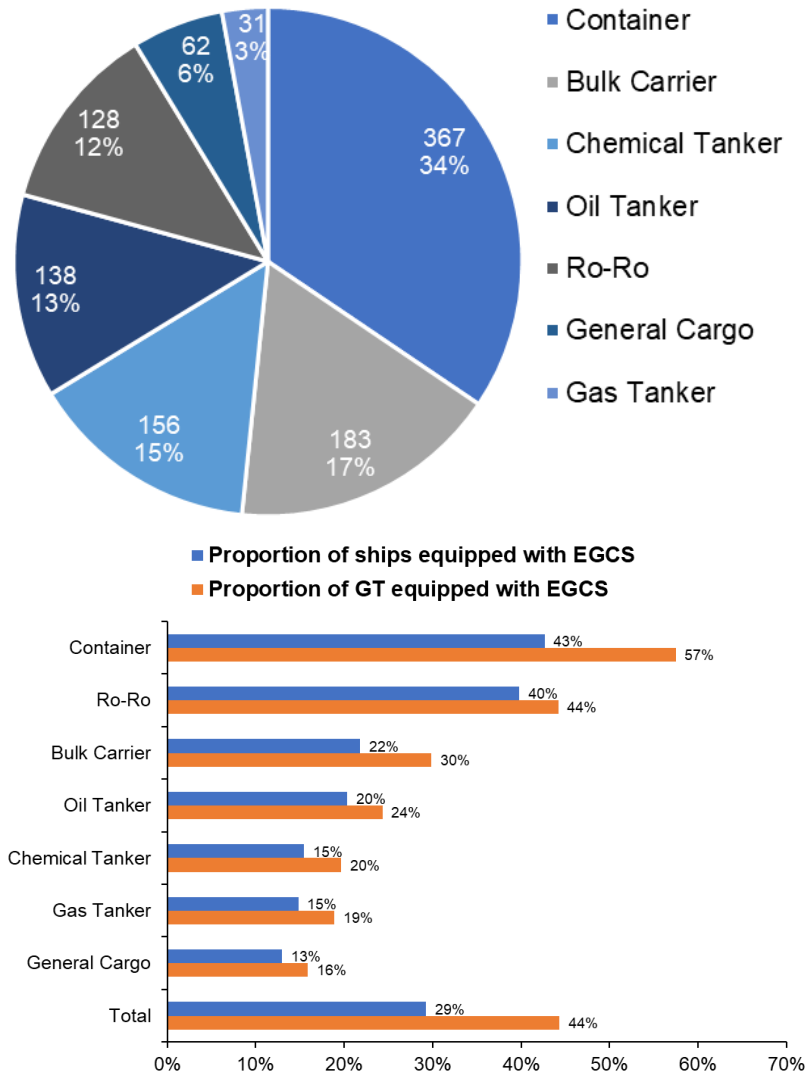
Supplementary figure 8. Map of the Belgian part of the north sea with the indication of the shipping lanes and dedicated spatial areas (a) and map of the north sea with the shipping density based on AIS traffic with delimitation of the Belgian part of the North sea (magenta) (b) [72].



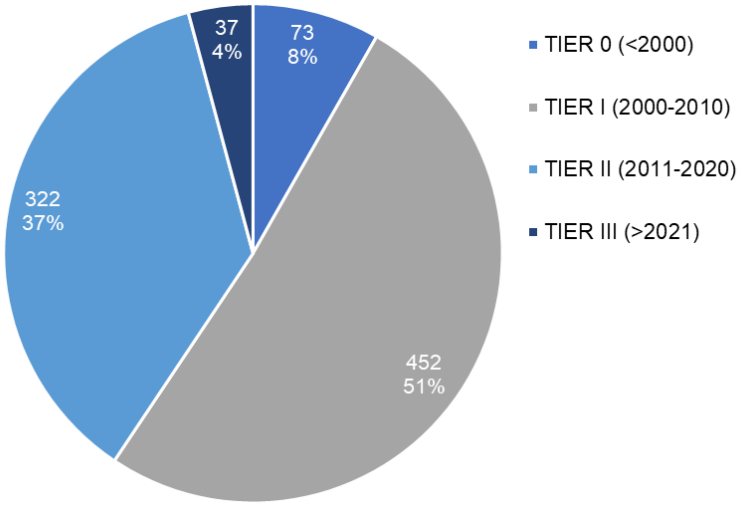
Supplementary figure 9. North Sea and Baltic Sea ECAs for both NO_x (NECA) and SO_x (SECA)



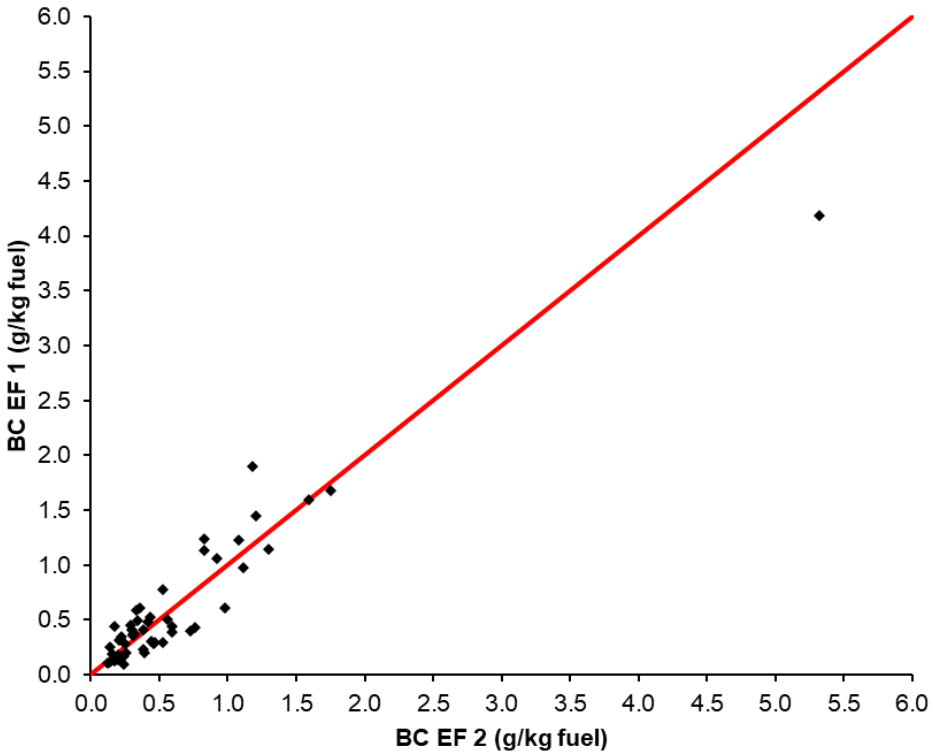
Supplementary figure 10. Distribution of the observed ships per year.



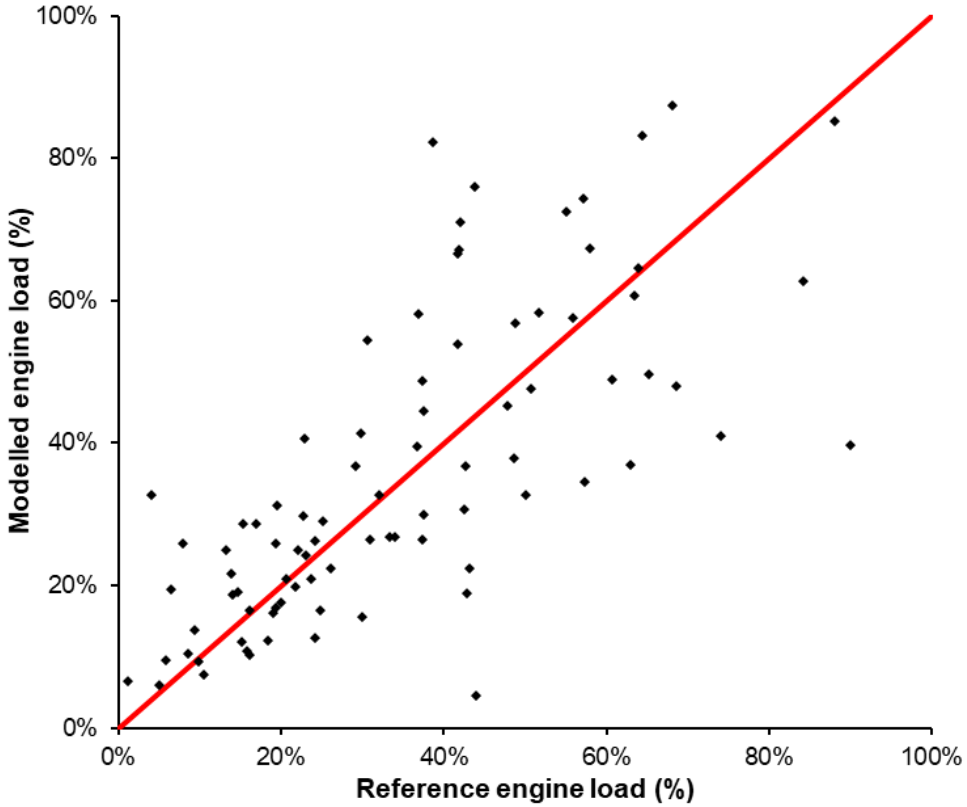
Supplementary figure 11. Distribution of the observed ship types, and the proportion equipped with an EGCS.



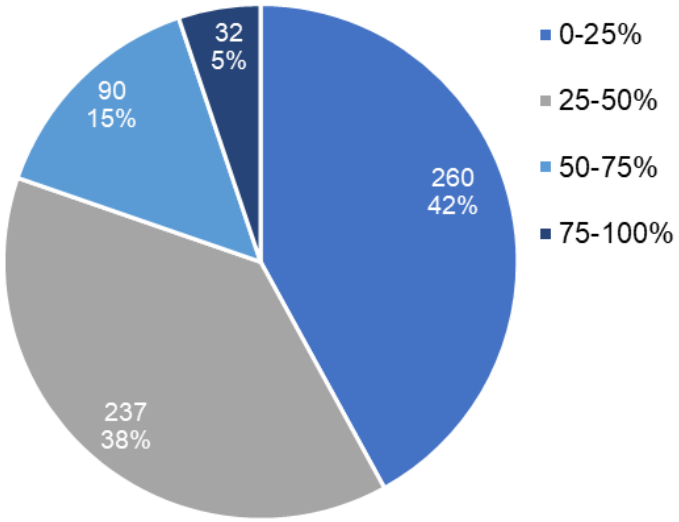
Supplementary figure 12. Distribution of the observed ships according to their Tier level.



Supplementary figure 13. Regression between repeated measurements showing a good correlation (R^2 = 0.93), with the red line y = x as reference.



Supplementary figure 14. Correlation between the modelled engine load and the reference engine load. For the modelled engine load the propellor law was used, for the reference engine loads, radio communication with the ship was established to obtain the present power use of the main engine.



Supplementary figure 15. Distribution of the engine loads used by the observed ships.

Supplementary tables

Supplementary table 1. BC EFs from literature [3,4,26–29,47,73–77]

Study	Year	BC EF (g/kg fuel)
Bond et al.	2013	0.17-0.85
Petzhold et al.	2008	0.179
Sinha et al.	2003	0.16-0.2
Lack et al.	2008	0.38-0.97
Eyring et al.	2010	0.53
Dentener et al.	2006	0.69
Corbet et al.	2010	0.37
Peters et al.	2011	0.35
Winther et al.	2014	0.35
Comer et al.	2017	0.30-0.56
Fuglestvedt	2010	1.08

Supplementary table 2.Statistical tests comparing BC EFs between groups of engine loads.

Tested variables (Engine load)	Mann-Whitney	Kolmogorov-Smirnov	Kruskal-Wallis	*n* group 1	*n* group 2
Between all groups (n = 609)	-	-	0.000		
0-25% vs 25-50%	0.000000	$p < 0.001$		253	234
25-50% vs 50-75%	0.000866	$p < 0.005$		234	90
50-75% vs 75-10%	0.426926	$p > 0.1$		90	32

Supplementary table 3. Statistical tests comparing BC EFs between compliance and EGCS.

Tested variables (FSC Compliance / EGCS)	Mann-Whitney	Kolmogorov-Smirnov	Kruskal-Wallis	*n* group 1	*n* group 2
Compliance/EGCS all groups			0.0000		
Compliance levels all groups			0.0013		
Compliant vs non compliant	0.000306	$p < 0.001$		814	72
Green vs orange	0.009193	$p < 0.1$		814	46
Orange vs red	0.549902	$p > 0.1$		46	26
EGCS vs Non-EGCS	0.000078	$p < 0.001$		627	259
Compliant non EGCS vs compliant EGCS	0.000052	$p < 0.001$		591	223
Compliant non-EGCS vs Non-compliant non-EGCS	0.000172	$p < 0.001$		591	36
Compliant non-EGCS vs Non-compliant EGCS	0.019414	$p > 0.1$		591	36
Compliant EGCS vs Non-compliant non-EGCS	0.052641	$p > 0.1$		223	36
Compliant EGCS vs Non-compliant EGCS	0.510425	$p > 0.1$		223	36
Non-compliant non-EGCS vs Non-compliant EGCS	0.376537	$p > 0.1$		36	36

Supplementary table 4. Statistical tests comparing BC EFs between between ship types.

Tested variables (Ship type)	Mann- Whitney	Kolmogorov-Smirnov	Kruskal-Wallis	*n* group 1	*n* group 2
Between all groups (*n* =886)			0.4356	886	
Container vs oil tanker	0.404918	$p > 0.1$		307	118
Container vs RO-RO	0.816666	$p > 0.1$		307	109
Container vs Chemical tanker	0.633366	$p > 0.1$		307	123
Container vs General cargo	0.663689	$p > 0.1$		307	54
Container vs Bulk Carrier	0.305751	$p > 0.1$		307	142
Container vs Gas Tanker	0.661682	$p > 0.1$		307	27
Oil tanker vs RO-RO	0.504422	$p > 0.1$		118	109
Oil tanker vs Chemical Tanker	0.273043	$p > 0.1$		118	123
Oil tanker vs General Cargo	0.436187	$p > 0.1$		118	54
Oil tanker vs Bulk Carrier	0.490339	$p > 0.1$		118	142
Oil tanker vs Gas Tanker	0.404918	$p > 0.1$		118	27
RO-RO vs Chemical Tanker	0.577112	$p > 0.1$		109	123
RO-RO vs General Cargo	0.689025	$p > 0.1$		109	54
RO-RO vs Bulk Carrier	0.497819	$p > 0.1$		109	142
RO-RO vs Gas Tanker	0.666479	$p > 0.1$		109	27
Chemical tanker vs General Cargo	0.891036	$p > 0.1$		123	54
Chemical tanker vs Bulk Carrier	0.197146	$p > 0.1$		123	142
Chemical tanker vs Gas Tanker	0.885258	$p > 0.1$		123	27
General Cargo vs Bulk Carrier	0.330863	$p > 0.1$		54	142
General Cargo vs Gas Tanker	0.972028	$p > 0.1$		54	27
Bulk Carrier vs Gas Tanker	0.400348	$p > 0.1$		142	27

Supplementary table 5. Statistical tests comparing BC EFs between NOx Tiers and NOx compliance

Tested variables (NO_x Tier and NO_x Compliance)	Mann-Whitney	Kolmogorov-Smirnov	Kruskal-Wallis	*n* group 1	*n* group 2
NOx tiers (*n* = 886)			0.4339		
Tier 0 vs Tier I	0.463667	p > 0.1		74	453
Tier 0 vs Tier II	0.137839	p > 0.1		74	322
Tier 0 vs Tier III	0.721417	p > 0.1		74	37
Tier I vs Tier II	0.240092	p > 0.1		453	322
Tier I vs Tier III	0.810566	p > 0.1		453	37
Tier II vs Tier III	0.482354	p > 0.1		322	37
NOx compliant vs NOx non-compliant	0.323138	p > 0.1		803	83
Compliant Tier III vs non-compliant Tier III	0.854987	p > 0.1		11	26

Supplementary table 6. Statistical tests comparing BC EFs between engine types based on engine rated speed.

Tested variables (ERS)	Mann-Whitney	Kolmogorov-Smirnov	Kruskal-Wallis	*n* group 1	*n* group 2
ERS groups (n = 569)			0.6178		
<200 RPM vs 200-500 RPM	0.503229	$p > 0.1$		458	73
<200 RPM vs >2000 RPM	0.437284	$p > 0.1$		458	38
200-500 RPM vs >2000 RPM	0.765390	$p > 0.1$		73	38

Supplementary table 7. Factors for power and exponential decay function of the real world BC EFs of all observed ships

Function	Factor	25%	Median	Mean	75%	90%

Power	a	-0.26	-0.37	-0.45	-0.46	-0.65
	c	0.14	0.18	0.20	0.23	0.24
	R^2	0.64	0.83	0.88	0.81	0.89
Exponential decay	a	0.22	0.40	0.66	0.88	1.71
	b	3.99	3.39	4.87	5.39	7.58
	c	0.15	0.14	0.15	0.21	0.24
	d	0.70	0.54	0.45	0.49	0.40
	R^2	0.68	0.90	0.94	0.93	0.92

Supplementary table 8. Factors for power and exponential decay function BC EFS of high concentration plumes

Function	Factor	Mean
Power	a	-0.45
	c	0.16
	R^2	0.65
Exponential decay	a	0.52
	b	4.84
	c	0.10
	d	0.39
	R^2	0.83

Supplementary table 9. Supplementary uncertainty factors and the combined supplementary standard uncertainty.

Supplementary uncertainty factor	Uncertainty (%)
CO_2 span gas drift (6 months)	0.92%
CO_2 span gas concentration*	2.00%
Measurement accuracy BC sensor	5.00%
Measurement accuracy CO_2 sensor	0.5%
Uncertainty molar mass O	1.88E-05
Uncertainty molar mass C	0.01%
Uncertainty C content in marine fuel	0.83%
Combined supplementary standard uncertainty	5.55%

** According to gas certificate*

Supplementary table 10. Correction factors used to model engine load with the propellor law

Ship type	CF	*n*
Bulk Carrier	1.1	12
Chemical Tanker	0.7	6
Container	1.0	51
Gas Tanker	1.0	3
Oil Tanker	0.6	7
Passenger Vessel	1.4	1
Ro-Ro	1.0	5