Environmental Protection in Maritime Traffic – Scrubber Wash Water Survey

Final report

Umwelt
Bundesamt

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Abstract: Environmental Protection in Maritime Traffic – Scrubber Wash Water Survey

International regulations for reducing sulphur emissions in the maritime sector have introduced Exhaust Gas Cleaning Systems (EGCS), commonly referred to as "scrubbers", as a reduction technology to minimize atmospheric sulphur emissions. Numerous flag States, organizations and ship operators carry out research to address the concern that the use of EGCS might shift the pollution from the atmosphere to the marine water body by additional energy expenditure. Although this technique may improve the air quality, the consequences for the marine environment are still unclear and an environmental risk assessment of this technique is still not standardized.

The main aim of this study is to provide a basis for the evaluation of the increasing use of EGCS technology on seagoing ships, particularly with regard to water and marine environment protection. The focus was on gaining more knowledge on the wash water composition and to estimate expected wash water quantities to be released into the marine environment by seagoing ships. The study is based on the information gathered from five ships: three ships with a hybrid system, which were sampled under open and closed-loop conditions, and two ships with an open-loop system. The standard water parameters and the main pollutants such as heavy metals, PAHs, nitrate/nitrite, oil content and suspended particular matter, were analysed. The investigations show, among other things, pronounced pollutant profiles in the wash water samples, significantly increased pollutant concentrations in the closed-loop samples and significant variations between the on-board online unit and the parallel comparative measurements, which were carried out with a system quality-assured by the German Federal Maritime and Hydrographic Agency (BSH). Discrepancies between the data from both units were identified; especially concerning the turbidity and PAH_{PHE} measurements. Further research and calibration standardization work are needed for a clear definition and understanding of PAH_{PHE} as a threshold value.

A major part of the study was the dispersion modelling for developing a distribution simulation of wash water and potential concentration of pollutants based on AIS data for the Baltic Sea and North Sea Region. The results showed that the wash water accumulation in the Baltic Sea is higher than in the North Sea due to lower water exchange. Although wash water is only emitted in the surface layer, vertical distribution data suggest that substances emitted by EGCS can also reach deeper layers within one year.

The study concludes that EGCS may improve the air quality in harbor cities and at sea but will shift atmospheric pollution to the marine water body. Further research is needed for a better quantification and evaluation of the total impact on the marine environment of this relatively new and emerging abatement technology. This has to include an environmental risk assessment of this new technology, providing sound scientific data for future recommendations and for a revision of related regulations.

Kurzbeschreibung: Umweltschutz im Seeverkehr – Scrubber Waschwasser Studie

Internationale Vorschriften zur Verringerung der Schwefelemissionen im Seeverkehr lassen Abgasnachbehandlungssysteme (EGCS – Exhaust Gas Cleaning Systems), die sogenannten Scrubber, als eine Technologie zur Reduzierung dieser Emissionen zu. Zahlreiche Flaggenstaaten, Organisationen und Schiffsbetreiber forschen, um herauszufinden, ob und inwieweit die Verwendung von EGCS die Verschmutzung aus der Atmosphäre in das Meer verlagern könnte. Obwohl diese Technik die Luftqualität verbessern kann, sind die Folgen für die Meeresumwelt noch unklar, und eine umfassende Umweltrisikobewertung dieser Technik ist noch nicht vorhanden.

Hauptziel dieser Studie ist es, eine Grundlage für die Bewertung des zunehmenden Einsatzes der EGCS-Technologie auf Seeschiffen zu schaffen, insbesondere im Hinblick auf den Gewässer- und Meeresschutz. Der Schwerpunkt liegt auf der Gewinnung weiterer Erkenntnisse über die Waschwasserzusammensetzung und der Abschätzung der zu erwartenden Waschwassermengen, die von Seeschiffen in die Meeresumwelt abgegeben werden. Die Studie basiert auf den Informationen von fünf Schiffen: Drei Schiffe mit einem Hybridsystem, die unter offenen und geschlossenen Bedingungen getestet wurden, und zwei Schiffe mit einem offenen System. Die Untersuchungen zeigen u.a. ausgeprägte Schadstoffprofile, deutlich erhöhte Schadstoffkonzentrationen in den Closed-loop Proben und deutliche Abweichungen zwischen den On Board Online Units und den parallelen Vergleichsmessungen, die mit einer zweiten im Bundesamt für Seeschifffahrt und Hydrographie (BSH) qualitätsgesicherten Online Unit durchgeführt wurden. Insbesondere zeigten die Trübung und PAH_{PHE} deutliche Abweichungen. Darüber hinaus besteht weiterer Forschungs- und Kalibrierungsbedarf, um PAH_{PHE} als Schwellenwert klar zu definieren und zu verstehen.

Einen wesentlichen Bestandteil der Studie stellt die Modellierung für die Entwicklung einer Verbreitungssimulation von Waschwasser und potenzieller Schadstoffkonzentrationen auf Basis von AIS-Daten dar. Die Ergebnisse zeigen, dass die Waschwasseranreicherung im Ostseeraum im Vergleich zur Nordsee höher sind, was auf einen geringeren Wasseraustausch zurückzuführen ist. Obwohl Waschwasser nur in die Oberfläche abgegeben wird, deuten vertikale Verteilungsdaten darauf hin, dass die vom EGCS emittierten Stoffe innerhalb eines Jahres auch in die tiefere Schicht gelangen.

Die Studie kommt zu dem Schluss, dass EGCS zwar die Luftqualität in den Hafenstädten und auf See verbessern kann, aber die Verschmutzung in die Meeresgewässer verlagert wird. Weitere Forschungsarbeiten sind erforderlich, um die Gesamtauswirkungen auf die Meeresumwelt dieser relativ neuen Reinigungstechnik für Schiffsabgase besser zu quantifizieren und zu bewerten. Dazu gehört auch eine Umweltverträglichkeitsprüfung dieser neuen Technik, die fundierte wissenschaftliche Daten für künftige Empfehlungen und die Überarbeitung entsprechender Vorschriften liefert.

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List of Abbreviations

AAS	Atomic absorption spectroscopy
AA-EQS	Annual average - environmental quality standard
AEfS	Air Emissions from Ships
AIS	Automatic Identification System
AveWW	Average wash water emission rate
ASCII	American Standard Code for Information Interchange
BSH	*Bundesamt für Seeschifffahrt und Hydrographie* (Federal Maritime and Hydrographic Agency, Germany)
CDNI	Strasbourg Convention on the Collection, Deposit and Reception of Waste during Navigation on the Rhine and Inland Waterways of 9 September 1996
CL	Closed-loop scrubber system
CO_2	Carbon dioxide
CSS	Current State Scenario 2018
DF	Dissolved fraction (referred to metals)
DWD	*Deutscher Wetterdienst* (German Weather Service)
dwt	Dead weight tons
EAM	Emission Abatement Methods
ECA	Emission Control Area
EEZ	Exclusive Economic Zone
EGCS	Exhaust Gas Cleaning System (scrubber)
EMMA	*Emissions-Modell Marine Aktivitäten* (Emission Model Marine Activities)
EMSA	European Maritime Safety Agency
EPA	US Environmental Protection Agency
EQS	Environmental quality standard
FNU	Formazine Nephelometric Units
GISIS	Global Integrated Shipping Information System
HBM	Hiromb BOOS Modell
HFO	Heavy fuel oil
ICP-MS	Inductively coupled plasma mass spectrometry
HOI	Hydrocarbon oil index
IMO	International Maritime Organisation
MARPOL	International Convention for the Prevention of Pollution from Ships of the International Maritime Organization
LOD	Limit of detection
MAC-EQS	Maximum allowable concentration - environmental quality standard
MaxKonz	Maximum of measured substance concentration in wash water
MaxWW	Maximum wash water emission rate
MCR	Maximum continuous rating
MEPC	Marine Environment Protection Committee
MinKonz	Minimum of measured substance concentration in wash water
MinWW	Minimum wash water emission rate

MIS	Maximum Installation Scenario
m/m	Mass fraction (ratio of the mass of a particular substance to the total mass)
MSFD	Marine Strategy Framework Directive
MWh	Megawatt hour
NetCDF	Network Common Data Format
ng	nanogram
nm	Nautical miles
NO$_x$	Nitrogen oxides
NTU	Nephlometric turbidity units
OGewV	*Oberflächengewässerverordnung* (Surface Water Ordinance)
OL	Open-loop scrubber system
PAH	Polycyclic Aromatic Hydrocarbon
PAH$_{PHE}$	Polycyclic Aromatic Hydrocarbons as phenanthrene-equivalent
pg	picogram
pH	defined as the decimal logarithm of the reciprocal of the hydrogen ion activity
ppm	Parts per million
PPR	IMO Sub-Committee on Pollution Prevention and Response
(S)ECA	(Sulphur) Emission Control Area
SeeUmwVerhV	*Verordnung über das umweltgerechte Verhalten in der Seeschifffahrt* (Regulations on Environmentally Sustainable Behaviour in Maritime Shipping)
SO$_x$	Sulphur oxides
SPE	Solid-phase extraction
SPM	Suspended particulate matter
TXRF	Total X-ray fluorescence spectroscopy
UBA	*Umweltbundesamt* (German Environment Agency)
UNCLOS	United Nations Convention on the Law of the Sea
v	Volume
WFD	Water Framework Directive
WHG	*Wasserhaushaltsgesetz* (Federal Water Act)
ZHK-UQN	Zugelassene Höchstkonzentation - Umweltqualitätsnorm

Summary

International regulations (MARPOL Annex VI) for reducing sulphur emissions in the maritime sector have introduced EGCS as an alternative technology to low sulphur fuels to minimize atmospheric sulphur emissions from ships. Numerous flag States, organizations and ship operators carry out research to address the concern that the use of EGCS might shift the pollution from the atmosphere to the marine water body by additional energy expenditure. Although this technique may improve the air quality, the consequences for the marine environment are still unclear and an environmental risk assessment of this technique is still not standardized.

The main aim of the study is to provide a basis for the evaluation of the increasing use of EGCS technology on seagoing ships, particularly with regard to water and marine environment protection. The focus was on gaining more knowledge on the characterization of the wash water composition and to estimate expected wash water quantities to be discharged into the marine environment by seagoing ships. The study is based on the information gathered by a sampling campaign from five ships: three ships with a hybrid system, which were sampled under open and closed-loop conditions, and two ships with an open-loop system.

The starting point for the study was a market analysis for EGCS as well as a survey of current literature to gather publicly available information about the current spread and application of the technique in shipping industry. The data found in Global Integrated Shipping Information System (GISIS) served to evaluate the scrubber market. Because not all flag States participate by actively notifying in GISIS, the databank is not complete. For that reason, the results might differ from other market studies, but also because the latter include installations on-order and not only systems that have already been installed. Those market studies revealed that by 2020 around 5% of the global fleet will be EGCS-equipped, followed by a stop in the market growth after 2021. Furthermore, the data demonstrate that the market is dominated by open-loop systems. A prognosis for the scrubber market after the first years of implementation of the 2020 Global Sulphur Cap is very uncertain because there are many factors affecting the decision of the ship owners: fluctuating fuel prices, uncertain fuel demand and availability, modification of legal framework and development of new technologies.

Furthermore, a concept of a practicable sampling campaign was developed in the absence of established standards and ship operators were convinced to participate in this campaign. With the help of valuable networks and good cooperation with the ship-owners, it was possible to successfully carry out the elaborated sampling campaign and accompanying measurements on board as well as the subsequent laboratory analysis of the wash water samples and data obtained. During sampling, several limitations were faced, such as missing sampling points, unsuitable material and unsuitable size of the tubing at the sampling points. For better comparability in future investigations, better-designed sampling points are necessary to avoid any contamination during sampling from the tubing or other contamination sources.

Several parameters for the characterization of the samples were required, for instance pH value, the composition of dissolved components and suspended particulate matter. The wash water samples were analysed for certain pollutant contents (e.g. PAHs, metals). In addition to the wash water sampling and further chemical analysis, ship-specific data (e.g. engine performance data,

EGCS specifics) as well as general operational conditions during the campaign such as speed, engine load and fuel quality, were recorded and included in the evaluation of the test results.

The results of the chemical analyses demonstrated the presence of several substances scrubbed out from the ship exhaust fumes. In general, closed-loop wash water showed higher concentrations of the investigated compounds compared to open-loop wash water, due to the water recirculation process and the lower flowrate. In particular, PAHs, nickel and vanadium were enriched in both, open and closed-loop samples. Nitrate and nitrite did not show clearly enrichment in open-loop wash water, due to high variability of inlet and outlet concentrations, but elevated concentrations in the closed-loop system. The alkalinity was reduced to almost zero in both systems and pH was decreased in the discharged wash water.

Since the BSH conducts a general monitoring of the chemical status of both, the North Sea and the Baltic Sea, the data were used to discuss the measurement results from the EGCS campaign. The concentrations of measured PAHs and several metals, in particular vanadium and nickel, in the discharged wash water were in both EGCS modes significantly higher than current environmental concentrations.

The comparison between the data generated by the ship-monitoring on-board unit and parallel on-board measurements showed significant discrepancies, especially concerning turbidity and PAH$_{PHE}$. This demonstrates that the collection of reliable data by the online systems can only be guaranteed with better specifications (e.g. more frequent maintenance and calibration, training of the crew). Further research and calibration work for a clear definition and understanding of PAH$_{PHE}$ are important to set comparable and protective threshold values to prevent the discharge of PAHs or oil to the marine environment.

Based on the developed EGCS deployment scenarios (current state scenario (CSS): 81 ships with EGCS; maximum installation scenario (MIS): 5,885 ships with EGCS) and using real ship movement data, wash water dispersion simulations were calculated using a numerical transport model. The results were used as basis for the calculation of pollutant dispersion and enrichment in the North- and Baltic Sea due to EGCS operation. General assumptions were necessary for the model regarding the scrubber type used. In the model, all ships were treated as if they were equipped with hybrid systems and were using open-loop, where it is allowed. The results show a low pollutants contribution of closed-loop discharge water compared to the total estimated discharge (from both, closed- and open-loop) and demonstrate that, although concentrations are significantly lower in open-loop systems (due to the high dilution), a significant quantity of pollutants is emitted to the marine environment by the use of open-loop EGCS systems. However, closed-loop discharges are a highly contaminated point source (especially for PAHs).

The results from the model calculations demonstrate that in areas with low water exchange, like the Baltic Sea, wash water and thus pollutants enrichment is stronger than in areas with more frequent water exchange like the North Sea. In the area with the highest modelled wash water input, the sum of maximum modelled pollutant concentrations in the seawater and current environmental concentrations were still below environmental assessment criteria (maximum allowable concentrations, MAC-EQS) in both scenarios. However, depending on the scenario, the modelled additional concentrations of investigated PAHs due to EGCS operation can reach similar or even higher concentrations compared to current environmental concentrations. Hence, wash water emissions from EGCS may lead to a significant increase of the environmental

concentrations in areas with high ship traffic and low water exchange. Furthermore, the modelled three years period (MIS) indicates ongoing increasing wash water accumulation over the entire period, especially in the Baltic Sea. Therefore, the use and impact of EGCS in areas with low water exchange (e.g. Baltic Sea, lagoons or harbours) or other sensitive areas needs to be further investigated, in particular with regard to long-term effects.

Concluding, the increasing application of EGCS on ships may improve the air quality in harbour cities and coastal areas, but will shift atmospheric pollution to the marine water body. The presented EGCS study provides scientific data about the EGCS market, chemical wash water characterization and modelled emissions to the water column to improve the understanding about the potential impacts on the marine environment. Further research is needed to better quantify and evaluate the total impact on the marine environment of this relatively new and emerging abatement method. This has to include an environmental risk assessment of this new technology, to provide sound scientific data for future recommendations and revision of related regulations.

Zusammenfassung

Internationale Vorschriften (MARPOL Anhang VI) zur Verringerung der Schwefelemissionen im Seeverkehr lassen Abgasnachbehandlungssysteme als technische Alternative zu schwefelreduzierten Kraftstoffen zu. Zahlreiche Flaggenstaaten, Organisationen und Schiffsbetreiber forschen um herauszufinden, ob und inwieweit die Verwendung von EGCS die Verschmutzung unter erhöhtem Energieaufwand aus der Atmosphäre in das Meer verlagern könnte. Obwohl diese Technik die Luftqualität verbessern kann, sind die Folgen für die Meeresumwelt noch unklar, und eine Umweltrisikobewertung dieser Technik ist noch nicht standardisiert.

Hauptziel dieser Studie ist es, eine Grundlage für die Bewertung des zunehmenden Einsatzes der EGCS-Technologie auf Seeschiffen zu schaffen, insbesondere im Hinblick auf den Gewässer- und Meeresumweltschutz. Der Schwerpunkt lag auf der Gewinnung weiterer Erkenntnisse über die Charakterisierung der Waschwasserzusammensetzung und der Abschätzung der zu erwartenden Waschwassermengen, die von Seeschiffen in die Meeresumwelt abgegeben werden. Die Studie basiert auf den Informationen von einer Probenahmekampagne auf fünf Schiffen: Drei Schiffe mit einem Hybridsystem, die unter offenen und geschlossenen Bedingungen getestet wurden, und zwei Schiffe mit einem offenen System.

Ausgangspunkt für die Studie waren eine Marktanalyse für EGCS sowie eine Analyse der bis dato veröffentlichten Studien und öffentlich verfügbaren Informationen. Die im Global Integrated Shipping Information System (GISIS) gefundenen Daten dienten der Bewertung des Marktes. Da nicht alle Flaggenstaaten durch aktive Benachrichtigung in GISIS teilnehmen, ist die Datenbank nicht vollständig. Aus diesem Grund können sich die Ergebnisse von anderen Marktstudien unterscheiden, aber auch, weil letztere Anlagen im Auftrag und nicht nur bereits installierte Systeme beinhalten. Diese Studien ergaben, dass bis 2020 rund 5% der weltweiten Flotte mit EGCS ausgestattet sein werden, gefolgt von einem Stopp des Marktwachstums nach 2021. Darüber hinaus zeigen die Daten, dass der Markt von Open-Loop-Systemen dominiert wird. Eine Prognose für den EGCS-Markt nach den ersten Jahren der Einführung des Global Sulphur Cap ist sehr unsicher, da es viele Faktoren gibt, die die Entscheidung der Reeder beeinflussen: schwankende Kraftstoffpreise, ungewisse Kraftstoffnachfrage und -verfügbarkeit, Änderung der rechtlichen Rahmenbedingungen und Entwicklung neuer Technologien.

Es galt, eine praktikable Probenahmekampagne in Abwesenheit etablierter Standards zu planen und Schiffsbetreiber davon zu überzeugen, an dieser Kampagne mitzuwirken. Mithilfe wertvoller Netzwerke und guter Kooperation der Reederschaft gelang es, die ausgearbeitete Probenahme und begleitende Messungen an Bord sowie die anschließende Analyse der Waschwasserproben und erlangten Daten erfolgreich durchzuführen. Bei der Probenahme gab es mehrere Einschränkungen, wie z.B. das Fehlen geeigneter Probenahmestellen oder ungeeignete Materialien und Dimensionen der Leitungen an den Entnahmepunkten. Die Bedingungen für eine kontaminationsfreie Probenahme waren daher häufig unzureichend. Für eine bessere Vergleichbarkeit bei zukünftigen Untersuchungen sind besser ausgelegte Probenahmestellen erforderlich, um eine Kontamination während der Probenahme durch das Rohrmaterial oder anderen Kontaminationsquellen zu vermeiden.

Das erforderliche Minimum für die Charakterisierung der Proben waren z.B. pH-Wert, die Zusammensetzung von gelösten Komponenten und Schwebstoffe. Die Waschwasserproben wurden auf bestimmte Schadstoffgehalte (z.B. PAK, Metalle) analysiert. Neben der Waschwasserprobenahme und weiteren Messungen sollten auch schiffsspezifische Daten (z.B. Motorleistungsdaten, EGCS-Eigenschaften) sowie allgemeine Betriebsbedingungen während der Kampagne wie Schiffsgeschwindigkeit, Motorlast, Kraftstoffqualität, etc. erfasst und in die

Auswertung der Testergebnisse einbezogen werden. Diese Analysen zeigten, dass neben dem Schwefel auch weitere Schadstoffe aus den Schiffsabgasen ausgewaschen wurden. Im Allgemeinen zeigte das Waschwasser im Closed-Loop aufgrund der Wasserrezirkulation und des niedrigeren Durchflusses eine höhere Konzentration der untersuchten Verbindungen als das Waschwasser aus Open-Loop Systemen. Insbesondere PAKs, Nickel und Vanadium wurden sowohl in Closed- als auch Open-Loop Proben angereichert. Nitrat und Nitrit zeigten keine eindeutige Anreicherung im Open-Loop Waschwasser, da die Einlass- und Auslasskonzentrationen sehr variabel waren. Es wurden aber erhöhte Konzentrationen im Closed-Loop System gemessen. Die Alkalinität wurde im Waschwasser beider EGCS-Systeme auf nahezu Null reduziert und der pH-Wert im abgeleiteten Waschwasser deutlich gesenkt.

Das BSH betreibt regelmäßig ein chemisches Monitoring, das zur Zustandsbewertung von Nord- und Ostsee beiträgt. Chemische Umweltbelastungsdaten aus dieser Quelle wurden ebenfalls zur Validierung der Messergebnisse aus der EGCS-Kampagne herangezogen. Die Konzentrationen der gemessenen PAKs und mehrerer Metalle, insbesondere Vanadium und Nickel, im Waschwasser waren in beiden untersuchten EGCS-Modi signifikant höher als die aktuellen Umgebungskonzentrationen.

Der Vergleich zwischen den Daten, die von der schiffseigenen Online-Messeinrichtung und den parallelen Messungen vom BSH an Bord erzeugt wurden, ergab signifikante Unterschiede, insbesondere bei der Trübung und dem PAH_{PHE}. Dies zeigt, dass die Erfassung zuverlässiger Daten durch die Onlinesysteme nur mit besseren Vorgaben (z.B. häufigere Wartung und Kalibrierung, Schulung der Besatzung) gewährleistet werden können. Weitere Forschungs- und Kalibrierarbeiten für eine Definition und ein klares Verständnis von PAH_{PHE} sind notwendig, um vergleichbare und ambitionierte Grenzwerte festzulegen, um die Einleitung von PAKs oder Öl in die Meeresumwelt zu verhindern.

Basierend auf den entwickelten EGCS-Einsatzszenarien (Current State Scenario (CSS): 81 Schiffe mit EGCS; Maximum Installation Scenario (MIS): 5.885 Schiffe mit EGCS) und unter Verwendung realer Schiffsbewegungsdaten wurden Waschwasserausbreitungssimulationen mit einem numerischen Transportmodell berechnet. Diese bilden die Grundlage für die weitere Betrachtung der Schadstoffverteilung und -anreicherung in der Nord- und Ostsee durch den EGCS-Betrieb. Allgemeine Annahmen waren hinsichtlich des verwendeten Scrubbertypes erforderlich. Im Modell verwenden alle Schiffe Hybrid-Systeme. Es wurden angenommen, dass sie im Open-Loop Betriebszustand fahren, wo es erlaubt ist. Dies ergibt, im Vergleich zur abgeschätzten Gesamtemission aus allen EGCS-Systemen, einen geringen Beitrag aus Closed-Loop Systemen. Weiterhin konnte gezeigt werden, dass die Konzentrationen in Open-Loop Waschwasser zwar vergleichsweise deutlich niedriger sind (aufgrund der hohen Verdünnung), aber durch das beträchtliche Einleitungsvolumen eine erhebliche Menge an Schadstoffen in die Meeresumwelt abgeben wird. Emissionen aus Closed-Loop Scrubbern sind dagegen eine hochkontaminierte Punktquelle (insbesondere für PAKs).

Die Ergebnisse der Modellrechnungen zeigen, dass in Gebieten mit geringem Wasseraustausch, wie der Ostsee, die Anreicherung von Waschwasser und damit von Schadstoffen stärker ist als in Gebieten mit häufigerem Wasseraustausch, wie der Nordsee. In dem Gebiet mit dem höchsten modellierten Waschwassereintrag, lag die Summe der maximal modellierten Schadstoffkonzentrationen im Meerwasser und der aktuellen Umweltkonzentrationen in beiden Szenarien noch unter den Umweltqualitätsnormen (zugelassene Höchstkonzentration, ZHK-UQN). Je nach Szenario können die modellierten Konzentrationen der untersuchten Schadstoffe z.B. PAKs jedoch ähnliche oder sogar höhere Konzentrationen erreichen als die aktuellen Umgebungskonzentrationen. Daher könnten Waschwasseremissionen aus EGCS zu einem signifikanten Anstieg der Umgebungskonzentrationen in Gebieten mit hohem Schiffsverkehr

und geringem Wasseraustausch führen. Darüber hinaus wird im modellierten Dreijahreszeitraum (MIS) eine kontinuierlich steigende Waschwasserakkumulation ermittelt, insbesondere in der Ostsee. Daher sollte der Einsatz und die Auswirkungen von EGCS vor allem in Gebieten mit niedrigem Wasseraustausch (z.B. Ostsee, Buchten oder Häfen) oder anderen sensiblen Gebieten weiter untersucht werden, insbesondere im Hinblick auf langfristige Auswirkungen.

Zusammenfassend kann festgestellt werden, dass der zunehmende Einsatz von EGCS Systemen auf Schiffen zwar die Luftqualität in Hafenstädten und Küstengebieten verbessern kann, aber dabei die Schadstoffe nicht aus der Umwelt entfernt, sondern lediglich in den marinen Wasserkörper verlagert werden. Diese EGCS-Studie liefert wissenschaftliche Daten über den EGCS-Markt, die chemische Zusammensetzung des Waschwassers und eine Abschätzung des Eintrags in die Wassersäule, um das Verständnis über die möglichen Auswirkungen auf die Meeresumwelt zu verbessern. Weitere Forschungsarbeiten sind erforderlich, um die Gesamtauswirkungen dieser relativ neuen Abgasreinigungstechnologie auf die Meeresumwelt besser zu quantifizieren und zu bewerten. Dazu könnte eine umfassende Umweltrisikobewertung dieser Technik gehören, die fundierte wissenschaftliche Daten für die Entwicklung künftiger Empfehlungen und die Weiterentwicklung von Vorschriften und Regelungen bietet.

1 Introduction

1.1 Overview

Even though maritime transport has the highest relative energy efficiency pro carried cargo compared to other means of transportation (IMO, 2019), its contribution to global air pollution has to be considered significant. On most ships the main engines, especially the older designs of 2-stroke and 4-stroke engines, rely on the use of heavy fuel oil (HFO), which is a residue of crude oil distillation characterized by its high viscosity and high sulphur content. Sulphur oxides (SO_x), formed during fuel combustion, are air pollutants of great concern that have negative impacts on human health (e.g. on the respiratory system, especially due to fine sulphur particles) as well as on the environment (as precursor of acid rain, affecting aquatic species, forests and crops and contributing to acidification of the oceans). The continuous growth of marine traffic has raised concerns worldwide about the ecological impact of the shipping industry, leading to international environmental regulations to improve the air quality (IMO, 2019).

On 19 May 2005, Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL Convention) of the International Maritime Organization (IMO) entered into force in order to prevent air pollution from ships, regulating and specifying limit values for the main sources of air pollution, inter alia, SO_x, NO_x and CO_2. A revision was adopted during the 58th session of the Marine Environment Protection Committee (MEPC) and entered into force on 1 July 2010. This revision gradually strengthened the limit values considering the technology development and experience gained through its implementation. Regarding the SO_x emissions, the global progressive reduction on sulphur content in fuels are incorporated in Regulation 14.1, commonly referred to as the Global Sulphur Cap. Special areas have been designated (ECA-Emission Control Areas) where limit values (Regulation 14.4) were set even lower, as exhibited in Table 1. The Baltic Sea, North Sea, American Caribbean Sea and North America are currently defined as designated areas where the ECA Sulphur Cap applies (IMO, 2019).

Table 1: Limit values for the sulphur (m/m) content of fuels used on board according to Regulations 14.1 and 14.4 of the MARPOL Convention Annex VI (Resolution MEPC.176 (58))

Global requirements	(S)ECA requirements
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2015

Regulation 4.1 of MARPOL Annex VI (Resolution MEPC.176 (58)) allows for "any fitting, material, appliance or apparatus to be fitted in a ship or other procedures, alternative fuel oils, or compliance methods used as an alternative to that required by this Annex if such (…) are at least as effective in terms of emissions reductions as that required by this Annex, including any of the standards set forth in regulations 13 and 14". Regulation 4.4 of Annex VI states that those alternatives shall endeavour not to impair or damage the environment, human health, property, or resources. Exhaust Gas Cleaning Systems (EGCS), commonly referred to as "scrubbers", are recognized as an equivalent compliance method according to Regulation 4 of MARPOL Annex VI, capable of fulfilling the aforementioned standards of Regulation 14 while still allowing for the use of non-compliant fuel. Although this alternative was originally conceived as an exception and was intended to enable the medium-term operation of older propulsion technologies unsuitable

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for the use of low-sulphur fuels, it is now being installed in new ships. There are clear signs on the market that this technology is becoming increasingly widespread.

Regulation 14 of MARPOL Annex VI is basically a measure to control sulphur emissions by establishing fuel quality standards. By using compliant fuel, the formation of SO_x is prevented (to a certain extent), addressing the source of the problem. By use of scrubbers (allowed by Regulation 4), the formation of SO_x is not avoided. Instead, the formed SO_x are transferred from the exhaust gas to, typically, seawater after washing the exhaust gas. Depending on the type of scrubber system different waste streams are generated, which might contain pollutants of concern such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, particle matter and low pH (Lange et al., 2015). For ships using scrubber systems (and non-compliant fuel), Regulation 14 of MARPOL Annex VI cannot be monitored directly (by fuel composition analysis). Instead, SO_x emissions in exhaust gas have to be measured and, using the ratio SO_2 (ppm)/CO_2 (%v/v), can be indirectly compared to the limits set in Regulation 14 (see section 1.2.1). Additionally, due to the occurrence of scrubber wash water and other waste streams, additional regulations are required to control their discharge and disposal. In other words, both, emission streams to the air and to water bodies, are of concern and regulated in several laws and directives. Next section recapitulates briefly some international and national German regulations that apply to the control of scrubber wash water.

1.2 Legal Framework

1.2.1 International Regulations

Because of the increasing number of EGCS installations and the reasons mentioned above, MEPC 59 developed the guidelines for EGCS, which were last updated in 2015 (Resolution MEPC.259 (68), commonly known as "2015 EGCS Guidelines"), according to Regulation 4.3 of MARPOL Annex VI. Although these guidelines are not legally binding, administrations of the contracting Member States are effectively bound to consider them according to Regulation 4 of MARPOL Annex VI when approving the use of EGCS in accordance with Regulation 14 of MARPOL Annex VI.

Under paragraph 1.3 of the "2015 EGCS Guidelines", the ratio SO_2 (ppm)/CO_2 (%v/v) is proposed as a basis to demonstrate indirectly the compliance with Regulations 14.1 and 14.4. Such method is only applicable when using petroleum-based distillates or residual fuel oils. Under paragraph 10, several requirements for the scrubber wash water are described: discharge criteria (limit values for relevant parameters, summarised in Table 2), monitoring, data recording and residues (sludge) disposal (Resolution MEPC.259 (68)). Therefore, the management of scrubber wash water is predominantly regulated at international level by MARPOL Annex VI and its linked guidelines.

On European level, several regulations apply to scrubber wash water discharge. The EU Sulphur Directive (2016/802/EU) regulates the SO_x emissions from ships. It basically implements the MARPOL Annex VI (with regards to SO_x) and includes some additional requirements. The limit values for sulphur content in fuels are established in accordance with MARPOL Annex VI. In Article 8, the use of Emission Abatement Methods (e.g. scrubbers) as alternative methods for compliance is permitted. For their approval, Article 9 refers to the Guidelines developed by the IMO (EMSA, 2019).

Table 2:   **Wash water discharge criteria as described in section 10.1 of the "2015 EGCS Guidelines" (Resolution MEPC.259 (68))**

Parameter	Discharge criteria
pH	> 6.5 (measured in four meters distance from the point of discharge)
PAH	< 50 µg/L PAH$_{PHE}$ (normalized at 45 t$_{wash\ water}$/MWh) above the inlet water concentration and measured after any water treatment equipment but prior any wash water dilution or other reactant dosing unit.
Turbidity/Suspended Particle Matter	< 25 FNU (or 25 NTU) above the inlet water concentration and measured after any water treatment equipment but prior any wash water dilution or other reactant dosing unit.
Nitrates	< 60 mg/L (normalized at 45 t$_{wash\ water}$/MWh) at discharge or < associated with 12% removal of NO$_x$ from the exhaust, whichever is greater.
Wash water additives and other substances	Special assessment, and, if necessary, additional wash water discharge criteria should be established.

Another main instrument applicable to scrubber wastewater under European law is the EU Directive on port reception facilities for the delivery of waste from ships (2019/883), which includes discharge norms for new waste categories, in particular the residues from EGCS, consisting of both sludge and bleed-off water from scrubbers. Additionally, the EU Water Framework Directive (WFD) and the EU Marine Strategy Framework Directive (MSFD) contain general European environmental protection objectives that might be considered for the regulation of scrubber wash water discharge (Proelß and Schatz, 2019).

With regard to water protection (MSFD, WFD), a detailed evaluation of the use of EGCS on seagoing vessels appears to be urgently required. The knowledge about cumulative effects of pollutants is currently insufficient. In this respect, MEPC has also made its criteria for the discharge of wash water laid down in Regulation 10.1 of the resolution MEPC 259(68) subject to the proviso that these should be reviewed "at a later date when more data on the composition of the discharged water and its effects are available, taking into account all advice from the GESAMP expert group".

At the European level, the European Sustainable Shipping Forum (ESSF) was established to implement the Sulphur Directive; the ESSF Subgroup EAM (formerly AEfS) is discussing scrubbers.

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) contains in Part XII (Articles 192-237) the fundamental international provisions for protection and preservation of the marine environment. The General Provisions (Articles 192-196) shall be regarded for the acceptance of discharge of scrubber wash water (Proelß and Schatz, 2019). Of particular relevance is Article 195 specifying: "In taking measures to prevent, reduce and control pollution of the marine environment, States shall act so as not to transfer, directly or indirectly, damage or hazards from one area to another or transform one type of pollution into another".

1.2.2   National Regulations in Germany

In the German domestic law, the relevant provisions of MARPOL Annex VI and the EU Sulphur Directive are implemented in the *See-Umweltverhaltensverordnung* (SeeUmwVerhV) para. 13: "Compliance with the requirements for Low Sulphur Marine Fuel". In particular, paragraph 13.5 refers to the approval of equivalent compliance methods according to Regulation 4 of MARPOL Annex VI; and paragraph 13.7 prohibits the discharge of wash water from EGCS in sea-

waterways as well as in the Exclusive Economic Zone (EEZ) unless it has been demonstrated that the wash water discharge has no significant adverse effects on human health and the environment. Irrespective of this, the regulations include the presumption, that when using caustic soda for wash water treatment, it is deemed sufficient if the wash water complies with the criteria of the EGCS Guidelines adopted by IMO and its pH is not higher than 8.0, according to the EU Sulphur Directive 2016/802/EU.

For inland waterways the regulations of the Strasbourg Convention on the Collection, Deposit and Reception of Waste during Navigation on the Rhine and Inland Waterways of 9 September 1996 (CDNI) and the *Wasserhaushaltsgesetz* (WHG) are applicable. For the latter, the discharge of scrubber wash water constitutes a use of water within the scope of paragraph 9.1.4 WHG which must be subject to prior authorization according to paragraph 8.1. Nevertheless, scrubber wash water is also considered a type of "wastewater" within the scope of paragraph 54.1.1 WHG, therefore its discharge is generally prohibited by paragraph 57.1 WHG if not covered by an acquired permission. According to Article 3.1 of the CDNI, the discharge of ship-generated waste by all ships, including seagoing vessels, is prohibited. While scrubber wash water is not explicitly referred to within the CDNI, it can be classified as a form of "other waste generated from the operation of a vessel" under the CDNI, according to the German legal conception. Thus, the CDNI establishes an absolute prohibition for scrubber wash water discharges in German inland waterways (Proelß and Schatz, 2019).

1.3   EGCS Technology in the Maritime Sector

EGCS is an established technology in the land-based industry sector for air pollution abatement and for recovery of valuable products from a gas stream (US EPA, 2002). Depending on the medium used for removal of the target compounds, they can be classified as dry and wet scrubbers; the first one using packed bed granulated chemicals and the latter a liquid stream, typically water, as absorption medium.

In the maritime industry, wet scrubbers dominate the market, while for dry scrubbers just one manufacturer (EGCSA, 2012) and two installations (Den Boer E. and Hoen M., 2015) are reported. Marine wet scrubbers are divided in open and closed-loop scrubber depending on the mode of operation; if the installation is able to be operated in both modes, it is called hybrid. In open-loop EGCS, seawater is pumped into the tower and sprayed into the exhaust gas stream. Closed-loop systems use freshwater. In this case, sodium hydroxide is added to adjust the pH level. In the tower, SO_2 is transferred from the gas to the liquid phase and transformed to sulphate species. The SO_2 removal efficiency for every system depends on several factors (e.g. amount of water, system design, temperature, initial SO_2 concentration) that affect diffusivity and equilibrium solubility (US EPA, 2002). The efficiency has been reported above 98% (Fridell E. and Salo K., 2014; Lloyd's Register, 2012). See Figure 1 for a graphical description of open and closed-loop systems.

The open-loop system requires high amounts of seawater (average values of 45 m^3/MWh) and relies on its natural alkalinity for the scrubbing process (Lloyd's Register, 2012). The wash water is directly discharged back to the sea, in some cases with prior treatment or dilution with seawater.

In contrast, closed-loop system can use seawater or employ fresh water treated with an alkaline substance (e.g. NaOH) to adjust the pH level. After the washing process, the water is passed into a process tank. There, a small portion of the wash water is pumped out and discharged after being treated by either hydrocyclone or a separator often in combination with flocculants. The amount of water being discharged (bleed-off) is significantly lower (0.1 - 0.3 m^3/MWh) than the

water volume discharged from open-loop systems. Alternatively, bleed-off can be accumulated in a holding tank and properly discharged in port reception facilities. Residuals removed from the treatment are called sludge and have to be properly disposed onshore. From the process tank, most of the wash water is recirculated (20 m³/MWh) and after addition of an alkali for pH control, it is pumped back to the absorption tower (Den Boer, E. and Hoen, M., 2015; EGCSA, 2012).

The wash water discharged from wet scrubbers has low pH and elevated temperatures. It does not only contain removed sulphur but also pollutants, including PAHs, heavy metals and nitrate (Endres, S. et al., 2018). The specific composition of the wash water depends on several variables including system design and operation, fuel composition, water treatment and chemicals added. Because of the amounts and components of the wash water being discharged, there are concerns about the environmental impact of scrubber systems (Lange, B. et al, 2015). For this reason, the wash water is further studied in this project.

Figure 1:   Process flow for the two modes of operation of wet scrubbers: closed-loop (left) and open-loop (right)
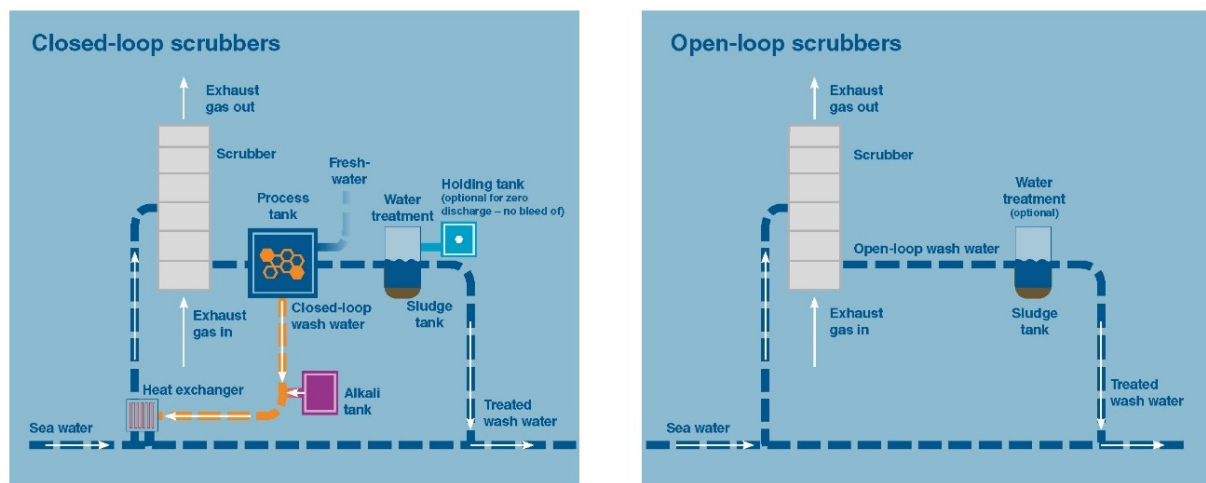
Source: BSH

1.4   Aim of this Study

This study is aimed to improve the basis on which decisions are taken on the use and further roll-out of EGCS technology in marine shipping, with particular regard to water and marine protection. Therefore information are provided on the current status of the implementation of this technology in maritime transport sector. Current installation numbers and their predicted development under actual economic conditions were estimated and information about construction and operating modes were gathered.

Since the seawater used to clean the exhaust gas is discharged into the marine water column either quantitatively or in extracts after treatment, an essential aspect for the evaluation if this technique is the estimation of the quantities of wash water released and its composition and properties. By combining the information about current and predicted installation with the expected wash water emissions and the knowledge of its composition, pollutant loads were estimated which are introduced into the water column by the operation of EGCS Systems.

These were qualified with current pollutant burden in the affected sea areas. For this purpose, measured concentration from the current pollutant monitoring in the North Sea and Baltic Sea were evaluated.

Using information on ship movements and water circulation in the North Sea and Baltic Sea and combining these with wash water and pollution load estimates, the numerical BSH circulation model was applied to calculate spatially and temporally structured wash water mixing ratios in the water column and the resulting pollutant burden.

As outcome of the project, the following general products were developed:

- Scenarios for the number of current installations of the EGCS technology and its maximum potential under precondition of its economic application.

- Development of a sampling and analysis concept, which is based on existing methods from water analysis and takes into account the requirements of the Scrubber Guidelines (MEPC 259(68)) as well as WFD and MSFD demands, especially with respect to substances and parameters.

- Summary statistics on wash water composition with pollutants, nutrients and other parameters.

- Estimates on the wash water and pollution load by EGCS installations on seagoing ships.

- Simulations of the spatial and temporal development of EGCS induced pollution of the North Sea and the Baltic Sea.

2 Market Analysis

2.1   Method

Several studies about the scrubber market for the maritime industry have been conducted by different stakeholders during the last years (EGSA Admin, 2018; Den Boer, E. and Hoen, M, 2015; DNV GL, 2019; DNV GL Maritime, 2018; MEPC 70/INF.9, 2016). Every study employs a different methodology for the data collection, with some including surveys by EGCS manufacturers and predictions based on economic analysis, leading to a particular degree of uncertainty of the results. Moreover, some studies are already outdated because the scrubber market has been very dynamic, due to the enter into force of the 2020 Global Sulphur Cap.

IMO has included in the Global Integrated Shipping Information System (GISIS) a section regarding the approval of equivalence compliance methods by ship (Regulation 4.2 of MARPOL Annex VI), and administrations are required to make entries into the database. GISIS is a public on-line platform developed by the IMO Secretariat in compliance with the decisions by IMO Members requesting public access to sets of data provided by the Maritime Administrations and collected by the IMO Secretariat (IMO, 2017). This public information served as a source to create a new database about the installed and approved scrubber systems worldwide. The data provided in the notifications until 11 February 2019, considering the type of equivalent compliance methods "Apparatus", "EGCS" and "Appliance", was collected including notifying party, IMO number, approval date and details of the EGCS (manufacturer, model, type and units installed). Since not all member States submit information to GISIS, the completeness of that database cannot be ensured. In this section the main results of the created database for this project are presented and compared with other scrubber market studies.

2.2   Future Development of the EGCS Market

The market analysis created for this study collected 205 notifications (i.e. vessels with approved EGCS) based on the information reported in GISIS (reviewed on 11 February 2019) (IMO, 2017).

Just 17 flag administrations (see Appendix 8.1), which represent around one third (33.5%) of the total global fleet (United Nations, 2018), have submitted notifications. Most of the entries are from the flag administrations of the Bahamas, Finland and Malta. Finland, representing just 0.28% of the global fleet, is the flag administration with the second highest number of notifications. Actually, its 26 notifications cover 10% of the total Finnish fleet. From Hong Kong, China, Greece and Japan (part of the ten biggest flag States) no notifications in GISIS were found when the data was collected. As aforementioned, IMO requires, but not enforces, flag administrations to submit information in GISIS, but not all of them participate. Nevertheless, an extrapolation of the data, assuming a similar quota of the non-notifying parties (representing two thirds of the global fleet), resulted in 612 vessels with approved EGCS. That number agrees with the information provided in the report of DNV GL Maritime (2018) updated in August 2018, which estimated 632 vessels with installed EGCS in 2018. A recent survey of the EGCS Association (EGCSA, 2018), where most of the scrubber manufacturers and suppliers are members, revealed 983 ships with scrubbers installed or on-order. A most updated database of DNV GL (2019) reports 765 vessels with installed EGCS at the end of 2018. Far away from those numbers is the prediction of the MEPC 70/INF. 9 (2016) which estimated 5,428 ships with EGCS by the end of 2018. The same document predicted 9,247 ships that will be fitted with scrubbers in time for the 1st January 2020 global 0.5% Sulphur Cap.

Certainly, none of the studies can offer the current actual number, but apparently, the predictions of the MEPC 70/INF. 9 (2016) overestimated the market development. Estimations

for the following years are even more uncertain; scrubber manufacturers claimed many orders pending for the next years. Moreover, fuel cost variation and modification of international and national regulations represent important decision factors for the selection of compliance method. Many ship owners see the scrubber technology as a medium term solution (Den Boer and Hoen, 2015). The database of DNV GL (2019) seems to present a more realistic scenario. Figure 2 exhibits the cumulative ships with scrubber system per year (2007-2018 already installed, 2019-2023 based on orders). It shows an S-shaped market growth (typical for development of new markets) with point of inflection in 2019 with 2,251 installations scheduled and reaching a steady state by 2023 with a cumulative total of 3,777 ships with EGCS. Regarding the present study (see Figure 3), 2019 started very active with 14 approvals during January, when compared to the 44 yearly average notifications between 2015 and 2018.

Figure 2:   Total number of ships with scrubbers (in operation and on-order)
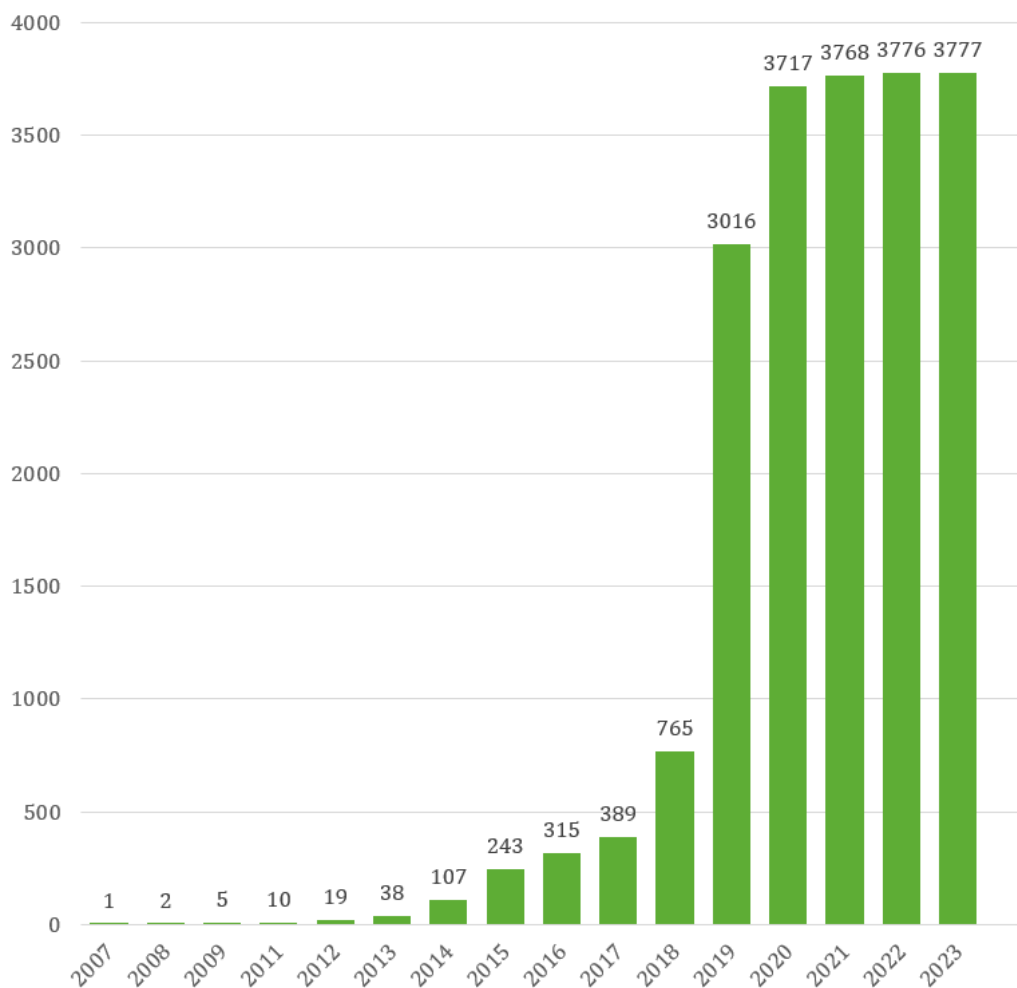
Source: Information as of 20 November 2019. Source: https://afi.dnvgl.com

Figure 3: **Accumulated number of notified vessels with an approved EGCS**
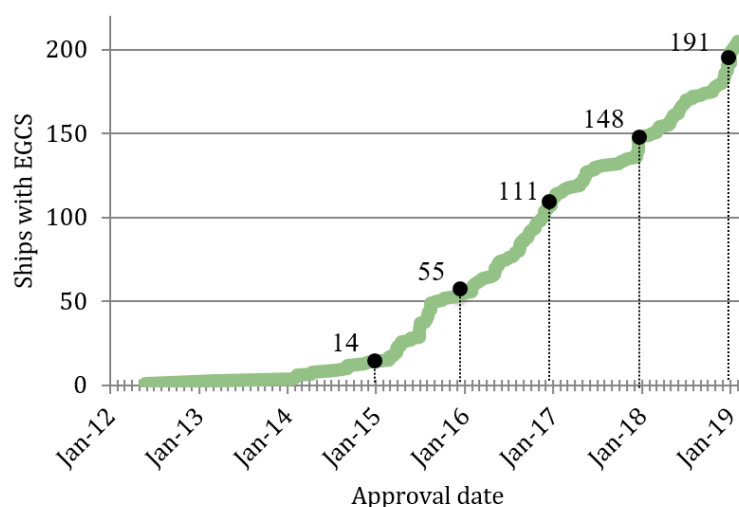
Stand on 11 February 2019: 205 ships. Source: Raw information obtained from GISIS (IMO, 2017).

Concerning the supplier market share, the biggest suppliers (Wärtsilä, Alfa Laval and EcoSpray) covered more than two thirds of the market (see Appendix 8.1.). This agrees with DNV GL Database (2019) that places the same companies as market leaders.

About the market share by type of system, wet scrubbers clearly dominate the market (Den Boer and Hoen, 2105). Unlike other reports that indicate open-loop system as most preferred type of system (EGCSA Admin, 2018; DNV GL, 2019; DNV GL Maritime, 2018), our study found out more approvals notifying hybrid EGCS with 40% share (see Figure 4, left). The low percentage of closed-loop systems (3%) coincides with other reports. Unfortunately, there is a significant amount of notifications (28%) not specifying the type of scrubber, neither in the notification form nor in the annexed documents in GISIS. Aggregated data from classification services, such as the alternative fuels insight by DNV GL, highlight a clear majority of open-loop systems (see Figure 4, right).

Figure 4: **EGCS market share by type of scrubber system from GISIS (left) and installed and on-order scrubbers by type from DNV GL (right)**
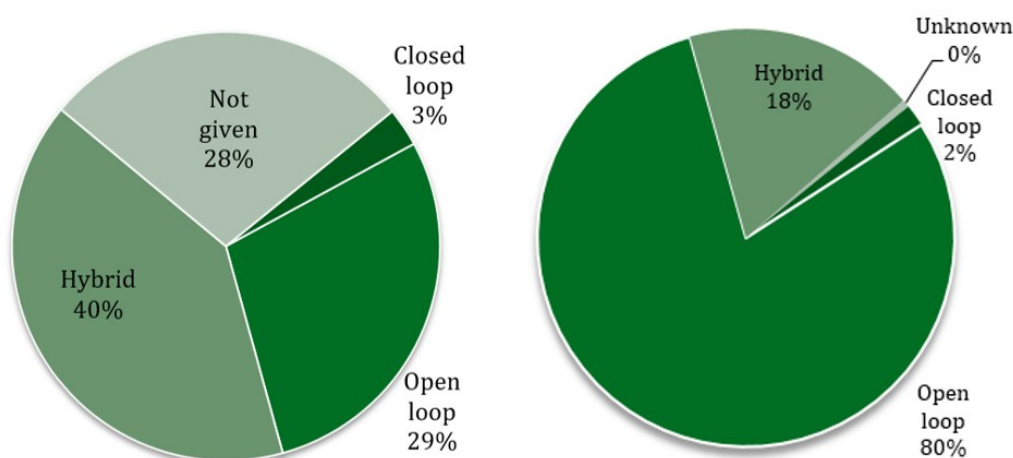
Left: Information as of 11 February 2019: 205 ships. Source: Raw information obtained from GISIS (IMO, 2017).
Right: Information as of 20 November 2019. Source: https://afi.dnvgl.com

Figure 5 shows the market share by ship type. Cruise ship is the ship type with the highest share (36.6%) despite being one of the smallest shares of the global fleet with only 520 vessels worldwide (MEPC 70, 2016). Actually, cruise ships together with RoPax and RoRo ships are mentioned as first adopters of scrubber technology in the maritime industry. These types of vessels operate mainly in (S)ECAs, so the implementation of the 0.1% Sulphur Cap as of 1 January 2015 was the main driver for the penetration of scrubbers (EGSA Admin, 2018; Den Boer and Hoen, 2015; MEPC-70, 2016). According to DNV GL's database (2019), North, Baltic and Caribbean Sea (S)ECAs are currently the regions with the highest traffic of vessels with installed EGCS. The smallest share, according to Figure 5, corresponds to the bulk carriers with only three vessels; an insignificant number compared to the 10,397 bulk carriers worldwide (MEPC-70, 2016). Annex 8.1provides more information on that regard. Other studies show a significant growth of scrubber installations and orders for bulk carriers taking the new role of top scrubber adopters, following container ships and tankers (EGCSA Admin, 2018; DNV GL, 2019).

Figure 5:   EGCS market share by ship type
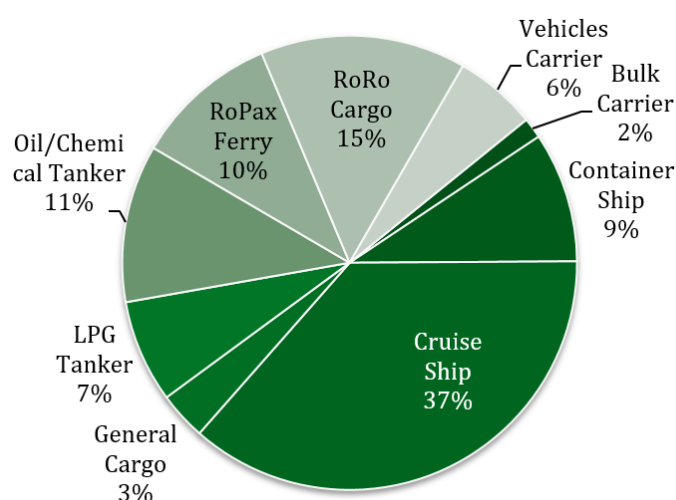
Stand on 11 February 2019: 205 ships. Source: Raw information obtained from GISIS (IMO, 2017).

Relevant changes and accelerated growth in the EGCS market can be illustrated by comparing the stand of the information here reported (GISIS, as of 11 February 2019) to a more recent review of the information in GISIS (as of 2 August 2019). From the latter, 352 notifications (vessels with installed and approved EGCS) were found; the market dominance of the open-loop systems and, the increase of the market share in container ships, bulk carriers and oil tankers are noticeable.

2.3   Conclusions – Market Analysis

The data of 205 notifications found in GISIS served to evaluate the scrubber market. Because not all flag States participate by actively notifying in GISIS, the databank is not complete. For that reason, the results might differ from other market studies, but also because the latter include installations on-order and not just systems already installed. The referred market studies revealed that by 2020 around 5% of the global fleet will be EGCS-equipped, followed by a stop in the market growth after 2021. Furthermore, the newest on-order and installed data demonstrate that the market is dominated by open-loop systems.

A prognosis for the scrubber market after the first years of implementation of the Global Sulphur Cap is very uncertain because there are many factors affecting the decision of the ship owners: fluctuating fuel prices, uncertain fuel demand and availability, modification of legal framework and development of new technologies.

3   Chemical Wash Water Characterization

3.1   Introduction

Wash water from EGCS was analysed for a wide range of different chemical parameters in the BSH laboratory. This includes alkalinity, polycyclic aromatic hydrocarbons (PAHs), dissolved metals (DF) and metals in suspended particulate matter (SPM), nitrate und nitrite, hydrocarbon oil index (HOI) and the mass of suspended particulate matter. The results are used in the next section in combination with the results of the dispersion modelling of the wash water to estimate the enrichment of the concerned substances in the modelled regions/areas.

The monitoring parameters pH, turbidity, and PAHs as phenanthrene-equivalent (PAH_{PHE}) were measured with a portable unit on-board by the BSH and compared to the ship monitoring data for these parameters. An overview of all analysed parameters is given in Table 5.

The selection of compounds to be analysed was based on their potential presence in EGCS wash waters as residues from fossil fuel combustion processes, current recommendations of international guidelines and their environmental relevance in the marine environment. For each parameter, specific sampling requirements and analytical methods were applied according to international standards.

Preliminary results of this study were submitted to the IMO Sub-Committee on Pollution Prevention and Response (PPR) (PPR6/INF.20, 2018). Those preliminary results did not include all data (e.g. results of all parallel samples or re-analyses data), as it was not available at that time, so some of the results and data were updated for this final report.

3.2   Materials and Methods

3.2.1   Ships Selection

The process for ship selection in this study followed certain requirements: EGCS types to be tested, the routes of the ships as well as their accessibility and availability.

In the early stages of this study, it was decided that the sampling campaign should cover various EGCS types being installed on ships from various operators, in order to get a perspective on differing systems and different approaches with regard to EGCS management and operation. Apart from that, wash water samples should be collected during sea voyage, with the EGCS actively treating main engine exhaust gas from HFO combustion. EGCS on seagoing vessels are mainly constructed for the use during the cruise. In this operating mode, the main engine runs relatively constant at high load (~80%). In port operation, the reduced ships energy requirements at berth are most times met just by the operation of auxiliary diesel engines. Commonly these are operated with high-quality low sulphur fuels in the harbour. Therefore, sampling was not performed in the harbour but during operation at sea by two members of the project team.

Wash water samples from EGCS are a mixture of components in different concentrations washed out from the ship exhaust gas. In order to ensure any chemical analysis of such samples to be representative and to minimize transformation processes, the transport times between sampling and laboratory analysis needed to be as short as possible. The transport of the samples to the laboratory after collection on-board was considered time sensitive. Therefore, it was important to disembark the ship in a port close to Hamburg/Germany, where the BSH laboratory is located. The task was to find ships equipped with an EGCS and calling a port close

to Hamburg for embarking and disembarking the ship in order to keep the logistics manageable and the time delay between sampling an analysis as short as possible.

Additionally, the ship operator had to be contacted for the permission of sampling on the different ships. The support of the European Sustainable Shipping Forums' subgroup on EGCS in identifying and contacting possible participants for this study was highly appreciated.

With the background on these restrictions, it was possible to arrange sampling on five ships which met the requirements: three ships with a hybrid system, which were sampled under open and closed-loop conditions and two ships with an open-loop system (see Table 3). The selected ships and corresponding companies are anonymous as requested by the ship owners.

Table 3:   **Information about the sampled ships (system, ship type)**

Name	Type	EGCS	Sampling points	Sampling period
Ship 1	Car Carrier	Hybrid	5	May 2017
Ship 2	Cruise Ship	Hybrid	5	June 2017
Ship 3	Cruise Ship	Open-loop	4	July 2017
Ship 4	Cruise Ship	Hybrid	5	September 2017
Ship 5	RoRo Vessel	Open-loop	4	November 2017

3.2.2   Sample Preparation for EGCS on Ships

In order to obtain an extensive overview of the wash water use in the various EGCS, sampling points at different operating modules of the system were considered, e.g. the seawater inlet before the scrubber, after the scrubber and before wash water treatment, after treatment and finally at wash water discharge overboard (Figure 6).

Figure 6:   **Sampling points: I-O: seawater inlet, O-O: open-loop wash water outlet, C-AT: closed-loop after treatment, C-BT: closed-loop before treatment, BD: before dilution**
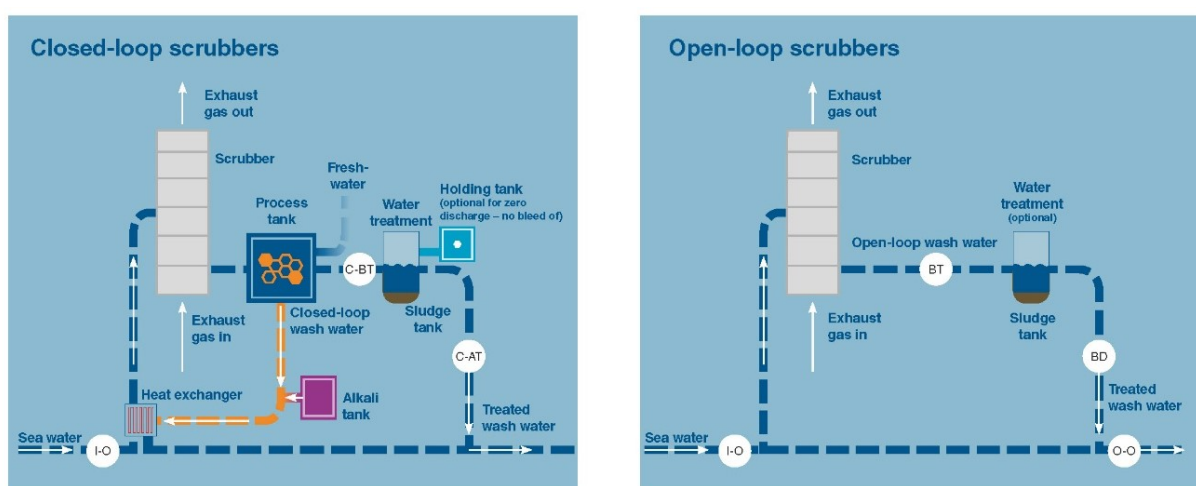
Source: BSH

Currently, there is no requirement for operators and manufacturers to equip the system with designated sampling points. In Appendix 3 of the "2015 EGCS Guidelines" (Resolution MEPC.259(68)), it is described the wash water should be sampled at the inlet (for background),

after the scrubber (but before any treatment system) and at the discharge. However, the Guidelines do not precisely require designated sampling points or how the sampling should be performed apart from requiring EPA and ISO test procedures.

A handout for the ship operator was developed (see Annex 8.3), which includes the requirements for sampling and analyses, to ensure that the operator was informed about what kind of action was planned to be carried out on board and to have a basis for future sampling campaigns with the same methodology.

To raise the awareness and to find a solution for the problem of missing sampling points as well as missing detailed instructions for analyses, a document was prepared within the project team and the ESSF EGCS-Subgroup. It was submitted to the PPR in October 2017 to facilitate and improve the wash water sampling and data collection (PPR 5/11).

3.2.3 Sampling on Board

In collaboration with the respective ships' crew, adequate sampling points were identified for each participating ship individually. Sampling points available on board under real conditions differ significantly from optimally equipped sampling points that meet all favored requirements. In reality, the sampling points are often difficult to access. Sometimes sampling points are completely missing at the stipulated process stage, or the available valves and tube diameters do not meet requirements for ideal sampling. The conditions for low-contamination sampling are also mostly not given. For example, copper pipes can lead to copper contamination of the samples, or antifouling systems in the sea chest can lead to contamination of the seawater inlet samples. Thus, sampling was performed under realistic conditions, with the sampling team aiming at keeping the framework and set conditions as stable as possible. All sampling points were sampled twice for most of each parameter group. The ship performance parameters regarding wash water volume, engine load, flowrate and the sulphur content of each ship during sampling are given in Table 4.

Table 4: Wash water volume (m³/h) at the discharge point (incl. dilution water), engine load (%MCR), flowrate (m³/MWh) during the sampling and sulphur content (%) of used fuel (na = data not available)

Samples System	Wash water* [m³/h]	Engine load [%MCR]	Flowrate [m³/MWh]	Fuel sulphur content [% m/m]
Ship 1 OL	1203*	84	92	3.2
Ship 1 CL	Na	na	na	3.2
Ship 2 OL	757	58	140	2.5
Ship 2 CL	1	58	0.2	2.5
Ship 3 OL	918*	74	102	2.7
Ship 4 OL	548	78	75	0.7
Ship 4 CL	na	40	na	0.7
Ship 5 1OL	1000	53	86	2.0
Ship 5 2OL	568	60	na	2.0

*Wash water [m3/h] indicates the volume flow at the discharge (after dilution, if existing). Use of dilution water prior to the discharge was identified for Ship 1 OL and Ship 3 OL. For details see table 10.

3.2.4   Preparation, Storage and Analyses

Sample preparation and storage requirements can be found in the "Handout for the ship operator" in Annex 8.3. Storage and preservation requirements were according to ISO 5667-3. Samples for nitrate and nitrite analyses were transported and stored frozen (- 18°C), PAH and metal samples were transported and stored cooled (4°C). After transporting the samples to the laboratory, metal and nitrate/nitrite samples were filtrated immediately. Metal samples filtrates were acidified with 4 mL of nitric acid (65 %).

The samples for the laboratory analyses were codified as in the following example:

1 – 1 I-Oa

Where the first digit (1-5) refers to the ship number; second digit (1 or 2) indicates if the ship has two independent EGCS; capital letters (I-O: inlet open-loop; O-O: outlet open-loop; C-AT: closed-loop after treatment) refers to the sampling point, and lower case letter (a or b) for parallel samples. On-board monitoring samples were also taken before dilution (BD), or after dilution (AD).

After transport to the laboratory, samples were analysed according to standard methods applied in the BSH laboratory. An overview about the analysed parameters and the corresponding methods is given in Table 5.

Table 5:   Parameters, abbreviations and corresponding methods

Parameter	Method
Alkalinity	Potentiometric Titration according to Gran
PAH (bold **PAH$_{EPA16}$**): **naphthalene (NAPH)**, 2-methyl-naphthalene (2M-NAP), 1-methyl-naphthalene (1M-NAP), **acenaphthylene (ACY), acenaphthene (ACN), fluorene (FLU)**, dibenzothiophene (DBT), **phenanthrene (PHE), anthracene (ANT), fluoranthene (FLA), pyrene (PYR), benzo[a]anthracene (BAA), chrysene (CHR)**, benzo[b]fluoranthene, **benzo[b]fluoranthene (presented as benzo[b+k]fluoranthene)(BbkF)**, benzo[e]pyrene (BeP), **benzo[a]pyrene (BaP)**, perylene (PER), **indeno[1,2,3-cd]pyrene (IND), dibenz[a,h]anthrancene (DBAA), benzo[ghi]perylen (BghiP)**	According to EN 16691 (SPE)
Metals – dissolved fraction: Vanadium (V), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Lead (Pb)	According to ISO 17294 (ICP-MS)
Metals – suspended particulate matter fraction: Vanadium (V), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Lead (Pb)	TXRF and AAS (in-house method)
Nitrate and nitrite	IC (in house method)
Hydrocarbon Oil Index (HOI)	According to ISO 9377-2
Suspended Particulate Matter (SPM)	According to EN 872

3.2.5   BSH On-board Measurements (pH, turbidity, PAH$_{PHE}$)

It is obligatory according to "2015 EGCS Guidelines" to monitor the parameters pH, PAHs (as PAH$_{PHE}$) and turbidity on board at all times when the EGCS is in operation (MEPC.259(68)). To verify these values of the on board in-situ systems, the project team conducted parallel

measurements with a portable system manufactured by TriOS (TriOS Mess- und Datentechnik GmBH, Rastede, Germany) at each sampling point. Any additional measurement in the wash water stream was not possible, so water samples were filled into glass baker for the comparison exercises.

The portable system was equipped with a control system (TriBox3, TriOS), a UV-fluorescence sensor (enviroFlu, TriOS) for PAHs, an oxidation and reduction potential sensor (eCHEM pH digital differential sensor, TriOS) for pH and an optical turbidity sensor (NEPH Turbidity Clean Water, TriOS) working with the 90° scattered light method. The portable unit and sensors are similar to those installed systems on ships as TriOS is a market leader in this sector. There are known interferences of the PAH_{PHE} measurement with the turbidity of the sample, therefore PAH_{PHE} values were corrected by a turbidity factor as recommended by the manufacturer.

3.3   Results and Discussion – Chemical Analyses

3.3.1   BSH Laboratory Analyses

3.3.1.1   Alkalinity

Seawater inlet (I-O) alkalinity was between 1.6 and 2.5 mmol/L. Alkalinity dropped to zero in all closed-loop outlet (C-AT) samples. Open-loop outlet (O-O) alkalinity was lower than inlet with values between 0 and 1.4 mmol/L. There were no significant differences between the parallel samples (A and B). All results are summarised in Figure 7.

Figure 7:   **Alkalinity of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT)**
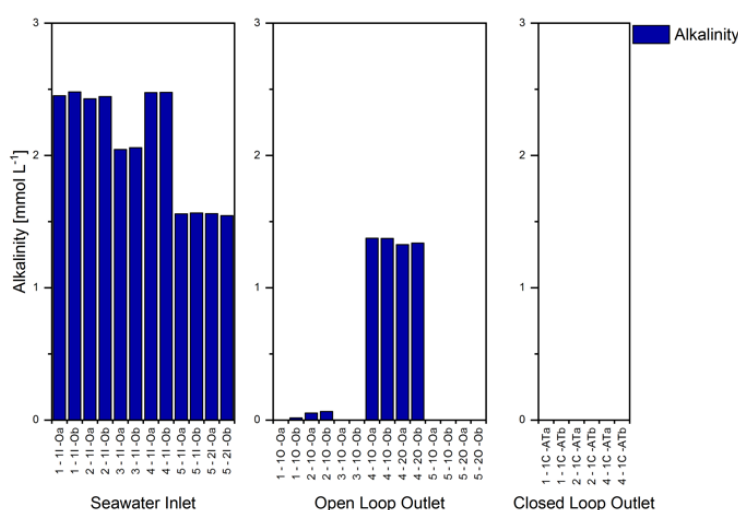
Alkalinity is an important factor for the exhaust gas scrubbing process and the amount of wash water needed for a sufficient SOx extraction depends on the alkalinity of the seawater. In fresh water closed-loop systems sodium hydroxide is added to increase the puffer capacity. The significant drop of alkalinity during the scrubbing process, which was detected in the scrubber-outlet, demonstrates that the buffer capacity of the wash water is consumed completely in most of the systems – independently if it is an open or closed-loop system. Only the discharged wash water of ship 4 shows an alkalinity of above 1 mmol/L. One reason might be that ship 4 was using a higher wash water flow as needed.

In general the discharge of wash water with a very low or no alkalinity combined with a lower pH (see section 3.3.2) might influence the buffer capacity and pH of the seawater in areas with

high ship traffic and already lower buffer capacity. This effect is expected to increase in areas with low water exchange and may contribute to ocean acidification in some regions.

3.3.1.2   Nitrate and Nitrite

Nitrate concentrations in the seawater inlet (I-O) were low with values between <0.08 and 1.5 mg/L. Nitrite was below detection limit (<0.06 mg/L) in the seawater inlet. Nitrate and nitrite concentrations in the open-loop outlet (O-O) water were close to inlet concentrations ranging between 0.1 – 1.7 mg/L and <0.06 – 1.3 mg/L, respectively. Closed-loop outlet (C-AT) water concentrations were increased with values between 6.3 – 351 mg/L for nitrite and 44 – 290 mg/L for nitrate, exceeding inlet concentrations considerably. Results are shown in Figure 8.

Figure 8:   **Nitrate and nitrite concentrations of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT). Please note the different concentration scale of the C-AT results**
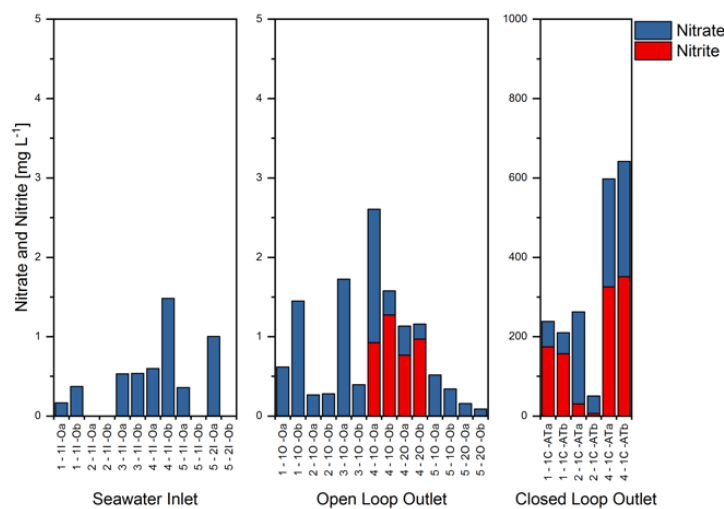
3.3.1.3   Suspended Particulate Matter

Suspended particulate matter (SPM) concentrations in the seawater inlet (I-O) were between 0.6 and 5.6 mg/L, similar to those in the open-loop outlet (O-O) water (0.8 – 3.2 mg/L). Closed-loop outlet (C-AT) water concentrations were increased in most of the samples with values between 3.5 – 125 mg/L. All results are summarised in Figure 9.

SPM in the open-loop system does not give a clear picture and an increase in the open-loop outlet (O-O) was not observed. SPM is naturally present in the seawater (e.g. algae or sediment particles), which explains the higher concentrations in the open-loop inlet samples compared to the outlet samples. However, this is only the mass of SPM, not a characterization of the particles itself. It should be noted, that SPM in the seawater outlet might contain soot and other combustion residues. Furthermore, if algae were present in the inlet, these will probably be dead in the outlet due to antifouling, high temperatures and pH changes.

Two of the three analysed closed-loop systems show significant elevated SPM concentrations. In this case, we assume that this is due to combustion residues. Soot particles were visible in these samples. The difference between the closed-loop system of Ship1 (lower SPM in the outlet water) to Ship 2 and Ship 4 (both higher SPM concentration) was the treatment unit. Ship 1 was equipped with a hydrocyclone for removing particles. Ship 2 and 4 were using flocculants. In this case the hydrocyclone seems to be a more suitable technique for removing particles. However, due to the small number of sampled EGCS and the manifold factors that are influencing the

amount of SPM in the samples, it is not possible to evaluate the different treatment systems, which could be addressed in future research.

Figure 9: **Suspended particulate matter concentrations of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT). Please note the different concentration scale of the C-AT results**
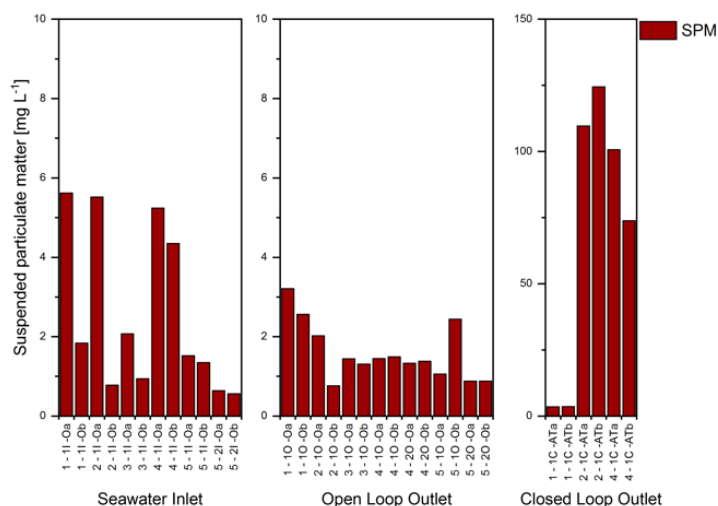
3.3.1.4 Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbon concentrations in seawater inlet (I-O) were in most of the samples below the detection limits with a total range of <LOD – 0.4 µg/L (PAH$_{EPA16}$: <LOD – 0.3 µg/L). The open-loop outlet (O-O) concentrations were above the inlet values with total PAH concentrations of 3.9 – 33.2 µg/L (PAH$_{EPA16}$: 1.6 – 14.0 µg/L)[*]. Closed-loop samples (C-AT) concentrations were between 13.7 – 71.8 µg/L (PAH$_{EPA16}$: 11.8 – 54.4 µg/L). Samples of closed-loop system 2 and 4 show differences between the A and the B samples. These differences might be explained by differing matrix of the samples and sampling, due to high oil content and the different SPM content in the samples.

Figure 10: **PAH concentrations of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT). Left: all PAHs analysed in this study. Right: only PAH$_{EPA16}$**

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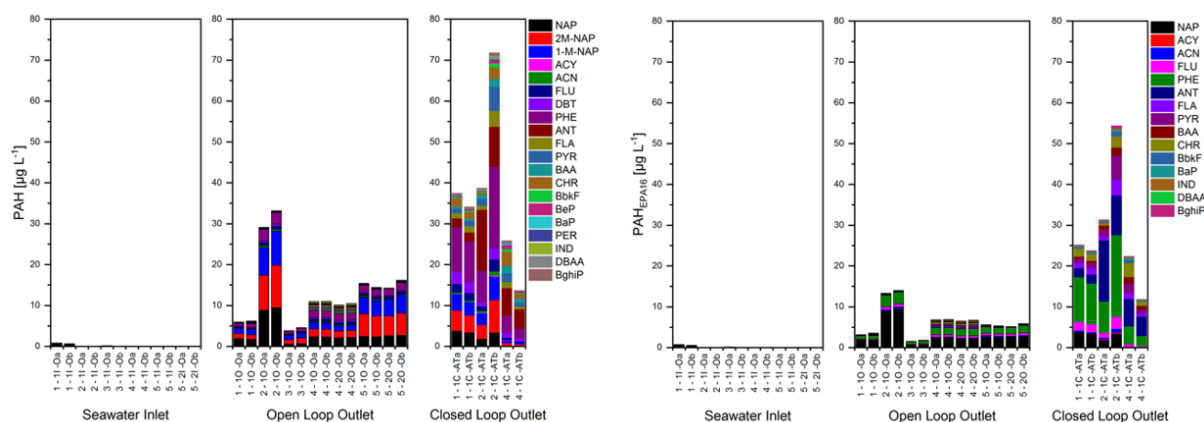
[*] The preliminary data (PPR6/INF.20, 2018) included a significant elevated anthracene value of one outlet sample. Analyses of the parallel sample and sample re-analyses did not confirm this high value.

PAHs in EGCS discharged wash waters may originate from different sources. They might originate directly from the HFO, as certain PAHs occur in fuels depending on the specific type of fuel and used oils and lubricants of the engine may contain PAHs. In addition, PAHs are generated during the incomplete combustion of fossil fuels, thus are present in the particulate and gaseous fraction of exhaust fumes of ships (Cooper, 2003, Sippula et al. 2014), and in consequence will be washed out by the EGCS.

PAH concentrations of inlet seawater of most of the ships were below detection limits, which correspond to the low concentrations of PAHs in water which were measured in the North Sea during the annual BSH environmental monitoring campaign. According to these monitoring results PAH_{EPA16} concentrations in the open North Sea are between 0.7 – 1.8 ng/L (station ENTE3, 2016 - 2018). The measured PAH concentrations in the outlet were about three order of magnitudes higher than the environmental concentrations. Therefore the influence of seawater inlet concentrations on the discharged wash water concentrations can be neglected as current environmental concentrations of North Sea seawater and analyses of the inlet concentrations were very low.

Total PAH_{EPA16} concentrations in open-loop wash water was 1.6 – 14.0 µg/L. Closed-loop total PAH_{EPA16} concentrations were 11.8 – 54.4 µg/L. These concentrations are significantly higher than environmental concentrations in the North Sea as shown above. This demonstrated that PAH concentrations in the discharged wash water originate directly from the "scrubbing" process and not from the seawater used for scrubbing.

Elevated concentrations of two methylated PAHs, methylated naphthalenes (1-methyl naphthalene (1.1 - 8.3 µg/L) and 2-methyl-naphthalene (1.1 – 10.4 µg/L)) were detected in the open-loop samples, which might be considered to be included in future investigations as these substances are not part of the PAH_{EPA16}. These PAHs were also detected in high concentrations in ships exhaust fumes (Cooper, 2003). Lower concentrations in the closed-loop wash water might be due to the treatment process or volatilization from the water during the recycling process of the wash water. This may also explain the different relative PAH concentrations, with high contribution of naphthalene and phenanthrene and low contribution of 4-6 ring PAHs in open-loop samples, while in closed-loop samples an increase of 4-6 ring PAHs was observed.

Although the number of sampled ships of the present study is low (5), PAH concentrations from open-loop systems reported in this study are in a similar range as reported from recent studies (see Table 6) with a significant higher number of sampled ships by Carnival Corp. (n = 53, Carnival Corp. & PLC 2019) and CESA (n = 20, MEPC 73/INF.5, 2018). In comparison, data from closed-loop systems are rare (n =2, IVL, Magnusson et. al. 2018; CESA: n = 4, MEPC 73/INF.5, 2018).

Table 6:   **Comparison of naphthalene (NAPH), phenanthrene (PHEN) and PAH_{EPA16} from different studies**

PAH (µg/L)	Open-Loop			Closed-Loop		
	BSH (5)	Carnival (53)*	CESA (20)	BSH (3)	IVL (1-2)	CESA (4)
NAPH	0.6 - 9.5	3.3	0.02 - 14	0.1 - 3.9	4.4 – 4.8	0.06 - 5.7
PHEN	0.7 - 2.9	2.0	0.1 - 6.1	2.4 - 20.1	10.0	0.5 - 4.5
PAH_{EPA16}	1.6 - 14	8.9**	0.5 - 24	12 - 54	22	0.8 - 13

(n): number of sampled ships; *average values (Post-EGCS-Tower); **sum of average values of single PAHs

BSH: this study. Carnival: Carnival Corp. & PCL 2019; CESA: MEPC 73/INF.5, 2018; IVL: Magnusson et al. 2018

The results of this study and the mentioned recent studies showed a wide PAH concentrations range in the discharged EGCS wash water. The reasons might be the variety of different factors, which are influencing PAHs in the wash water: fuel type, combustion conditions, engine performance, EGCS performance and amount of wash water.

3.3.1.5 Hydrocarbon Oil Index

The hydrocarbon oil index (HOI) was applied as an indicator of the oil content in the wash water. It is not a mandatory parameter for EGCS assessment. According to the EGCS Guidelines (Resolution MEPC.259(68); para 10.2.1), the PAH concentration shall be a benchmark for the oil content in the wash water. In the seawater inlet only traces of oil were detected in two samples with concentrations <0.03 mg/L. All analysed open-loop wash water samples contained oil with concentrations between 0.05 – 0.27 mg/L. Closed-loop samples showed an enrichment of oil with concentrations between 5.3 and 11.4 mg/L. Although wash water of closed-loop systems is treated, the oil content is higher compared to the open-loop systems, but still below the oil content threshold, which is set for bilge water discharges (15 ppm) according to MARPOL Annex I. Due to insufficient sample volume for HOI analysis, not all samples were analysed (marked as "na" in Figure 11).

Figure 11:   **Hydrocarbon oil index (HOI) of EGCS wash water at selected sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT). Please note the different concentration scale of the C-AT results. na: not analysed**
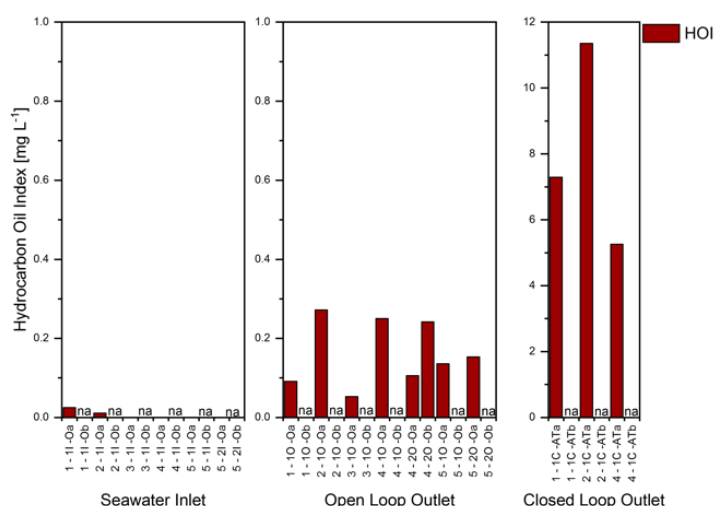

3.3.1.6 Metals

Nine metals were analysed in the dissolved (DF) and in the suspended particulate matter fraction (SPM). Here vanadium, nickel, copper, zinc, cadmium, lead, manganese, arsenic and iron concentrations are depicted. In general, most of the metals are also naturally present in the inlet seawater (see Figure 12 – Figure 14).

Total metal concentration (DF + SPM) in the seawater inlet were between 0.5 – 6 µg/L (vanadium), 0.4 – 142 µg/L (nickel), 1.1 – 140 µg/L (copper), 1.4 – 58 µg/L (zinc), 0.01 – 0.06 µg/L (cadmium), 0.06 – 0.2 µg/L (lead), 3 – 9 µg/L (manganese), 1 – 14 µg/L (arsenic), and 4 – 129 µg/L (iron).

Open-loop outlet (O-O) concentrations of the different metals were between 12 – 313 µg/L (vanadium), 6 – 73 µg/L (nickel), 2 – 16 µg/L (copper), 2 – 133 µg/L (zinc), 0.01 – 0.07 µg/L (cadmium), 0.09 – 2.2 µg/L (lead), 2 – 6 µg/L (manganese), 1 – 7 µg/L (arsenic), and 24 – 221

µg/L (iron). Closed-loop outlet (C-AT) concentrations of the different metals were between 3542 – 10,637 µg/L (vanadium), 478 – 6,289 µg/L (nickel), 10 – 58 µg/L (copper), 76 – 240 µg/L (zinc), 0.05 – 0.4 µg/L (cadmium), 1 – 3 µg/L (lead), 23 – 51 µg/L (manganese), 9 –25 µg/L (arsenic), and 314 – 709 µg/L (iron).

Figure 12: **Vanadium (V) and nickel (Ni) concentrations in the dissolved (DF) and particulate matter (SPM) fraction of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT). Please note the different concentration scale of the C-AT results**
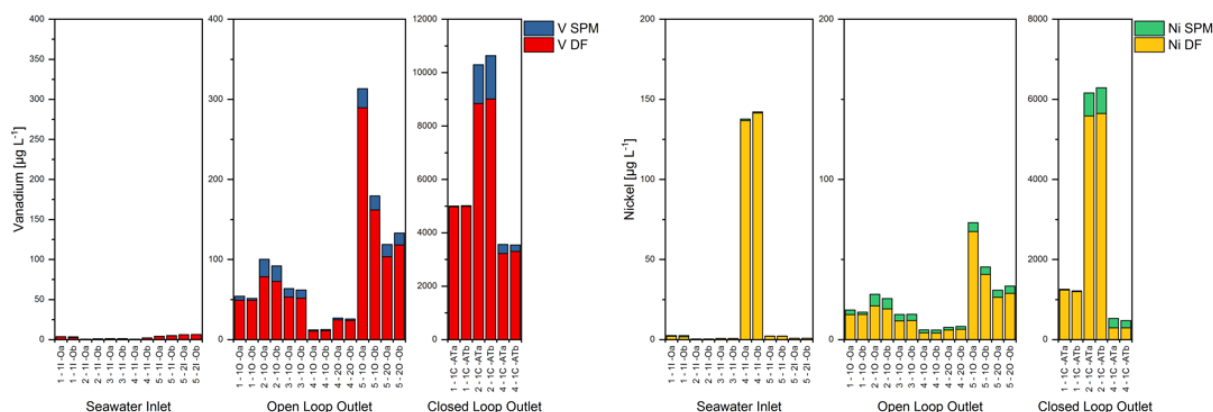
**Figure 13:** **Copper (Cu) and Zinc (Zn) concentrations in the dissolved (DF) and particulate matter (SPM) fraction of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT). Please note the different concentration scale of the C-AT results**
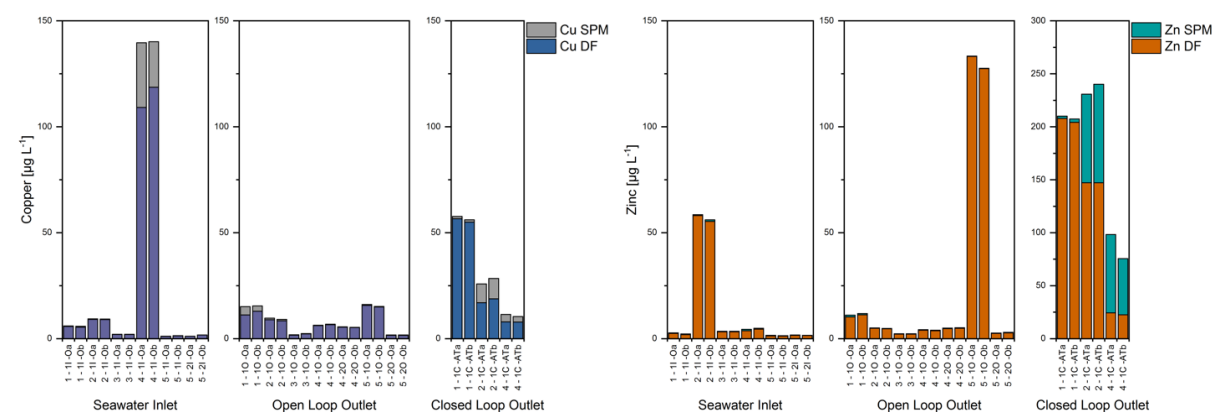
Figure 14:   **Cadmium (Cd), arsenic (As), iron (Fe), lead (Pb), manganese (Mn) concentrations in the dissolved (DF) and particulate matter (SPM) fraction of EGCS wash water at the different sampling points: seawater inlet (I-O), open-loop outlet (O-O) and closed-loop outlet (C-AT)**
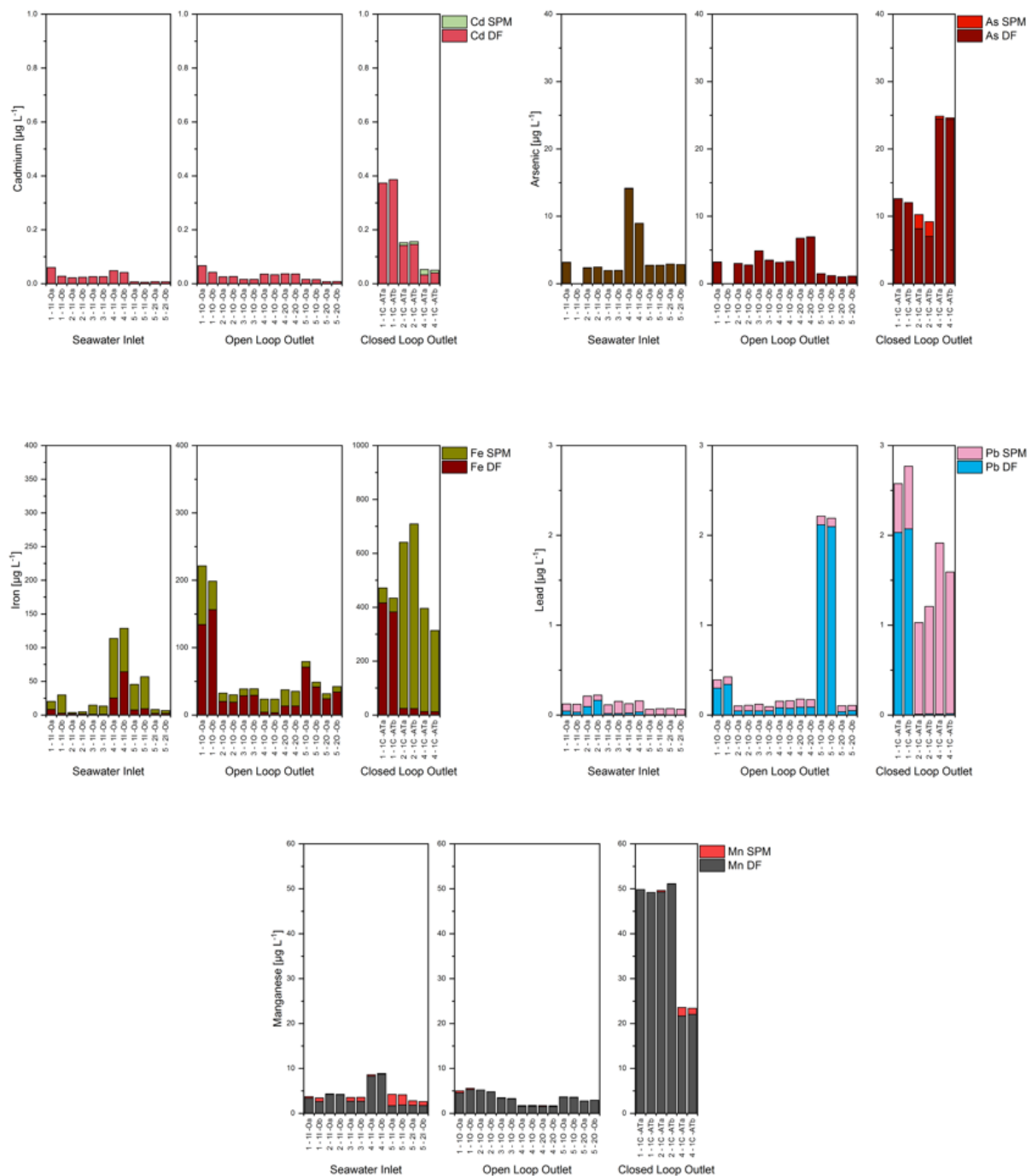
Particularly, vanadium and nickel demonstrated a significant enrichment in the wash water compared to the seawater inlet and seawater concentrations obtained from the BSH environmental monitoring program in the North Sea.

Vanadium is the major metal present in the discharged wash water. The concentrations reach the mg/L concentration range in the closed-loop and high μg/L values in open-loop systems. Inlet concentrations in this study and environmental seawater concentrations of vanadium are low with e.g. concentrations of 1.4 - 1.5 μg/L in the open North Sea (DF, Station ENTE3, BSH

monitoring data, 2014). Vanadium is known to be present in HFO as it is difficult to be removed during the refinery process. Due to the occurrence of vanadium in HFO related exhaust fumes, it is often used as tracer for maritime transport emissions (e.g. Viana et al. 2014). Vanadium in HFO can reach mg/kg concentrations and in consequence, concentrations in open and closed-loop wash water show corresponding high concentrations. Furthermore, results present in this study correspond to the previously mentioned EGCS wash water studies, that detected high concentrations of vanadium in EGCS wash water. Currently vanadium is not listed as substance of concern in the marine environment (OSPAR 2020). Due to new emission sources of vanadium (e.g. steel production) to the environment, Watt et al. (2018) proposed an improvement of the hazard and environmental risk assessment of vanadium.

Similar to vanadium, nickel is also present in HFO and in consequence, in high concentration in both, open and closed-loop discharge waters. Similar to vanadium, nickel reached mg/L concentrations in the closed-loop systems. Marine nickel concentrations from the BSH environmental monitoring program were 0.19 – 0.22 µg/L (DF) (Station ENTE3, BSH 2014).

The sampling point or tubing system can also influence nickel concentrations, which may explain the high inlet concentration at one sampling point. This demonstrated the importance of metal free sampling points to avoid any contamination during the sampling. However, although nickel concentrations were influenced at one inlet sampling point, data suggest that nickel concentrations in the discharge water mainly originate from the EGCS process and not from other contamination sources. Elevated nickel concentrations were also reported from other studies (see Table 7).

Copper and zinc do not show a significant increase in open-loop discharge water, in contrast to other wash water studies (see Table 7). Two inlet samples (Cu, Zn) and one outlet sample (Zn) show elevated concentrations, but this might be explained due to the tubing at the sampling point, from anti-fouling systems (copper) or from corrosion protection systems (e.g. zinc based galvanic anodes), thus measured zinc and copper concentration might also originate from these sources and not only from the EGCS.

Table 7:   **Comparison of vanadium (V), nickel (Ni), zinc (Zn) and copper (Cu) concentrations (dissolved fraction) from BSH samples with other studies**

	Open-Loop			Closed-Loop		
Metal (µg/L)	BSH (5)	Carnival (53)*	CESA (20)	BSH (3)	IVL (1-2)	CESA (4)
V	11 - 290	117	20 - 860	3,222 – 9,014	9,800	2,800 – 25,000
Ni	4 - 67	94	20 - 240	295 – 5,646	830 – 4,400	220 – 6,600
Zn	2 - 133	122	20 – 2,000	23 - 208	<70	40 – 2,400
Cu	2 - 16	298	6 - 140	8 - 57	150	<10 - 200

(n): number of sampled ships; *average values (Post-EGCS-Tower); BSH: this study. Carnival: Carnival Corp. & PCL 2019; CESA: MEPC 73/INF.5, 2018; IVL: Magnusson et. al. 2018

3.3.2 BSH On-board Measurements (pH, turbidity, PAH$_{PHE}$)

3.3.2.1 Comparison of on-board Data

The results from the on-board measurements by BSH and the data from the ship monitoring systems of three different parameters are reported in Table 8. In contrast to pH, turbidity and PAH$_{PHE}$ have to be monitored prior to any dilution according to the "2015 EGCS Guidelines". If wash water was diluted (Ship 1 and 3), before dilution (BD) values were reported.

Table 8: **Ship-monitoring data and BSH on-board measurement data of pH, turbidity and PAH$_{PHE}$***

Sample	pH		Turbidity (NTU)		PAH$_{PHE}$ (µg/L)	
	Ship	BSH	Ship	BSH	Ship	BSH
1 1I-O	8.1	7.9	0.2	12.8	112.5	17.9
1 1O-O	6.0	3.1	-	17.3	-	35.0
1 1O-BD	-	2.5	1.0	39.4	48.8	103.0
1 1C-AT	8.4	6.3	18.0	39.4	48.0	92.7
2 1I-O	8.8	7.9	0.2	16.7	26.9	3.9
2 1O-O	5.7	5.2	0.1	4.5	12.8	126.4
2 1C-AT	8.2	4.9	2.9	4.6	50.9	51.3
3 1I-O	-	7.6	0	3.7	1.0	8.8
3 1O-O	5.3	4.4	-	4.7	-	66.6
3 1O-BD	-	2.7	8.0	6.0	17	119.0
4 1I-O	8.7	7.7	-5.4	4.1	-11.1	4.0
4 1O-O	5.9	5.5	0.1	4.7	0.1	110.5
4 2O-O	5.9	5.4	0.2	4.8	0.0	95.4
4 1C-AT	-	7.1	3.6	16.6	3.8	143.4
5 1I-O	-	5.8	2.5	7.8	7.3	13.9
5 1O-O	4.2	2.8	3.6	6.6	19.5	90.6
5 2I-O	-	6.4	4.6	2.5	7.3	18.0
5 2O-O	5.4	3.6	3.9	5.9	40.1	78.1

First digit (1-5) ship number; second digit (1 or 2) if the ship had two independent EGCS; capital letters (I-O: inlet open-loop; O-O: outlet open-loop; O-BD: open-loop before dilution; C-AT: closed-loop after treatment) sampling point. - = no data available. *The preliminary BSH PAH$_{PHE}$ data (PPR6/INF.20, 2018) were not turbidity corrected.

For **pH**, the deviation between BSH on-board data and ship-monitoring data for most of the samples is below 25 %, except for three outlet samples with a deviation between 30 - 50 % (Figure 15C). However, although the deviation between the two measurements is lower

compared to turbidity and PAH_{PHE}, it has to be noted that little differences of pH values mean significant changes as pH is based on a logarithmic scale. The sampling procedure might induce a bias, such as filling the water in bottles for the BSH measurement of pH, turbidity and PAH_{PHE}, compared to the measurements in a flow chamber of the ship-monitoring system. Additionally, sampling points for BSH measurements were not always in close vicinity of the ship-monitoring measurements and thus, it is not always clear, if the compared wash water data correspond to the same waterbody.

Figure 15:   Comparison between ship-monitoring data and BSH in situ data. A: NTU_{out-in} (outlet - inlet turbidity) for open-loop and closed-loop. B: PAH_{PHE} out-in (outlet - inlet PAH_{PHE}). C: pH values of seawater outlet of open-loop systems (O-O) and closed-loop systems (C-AT)
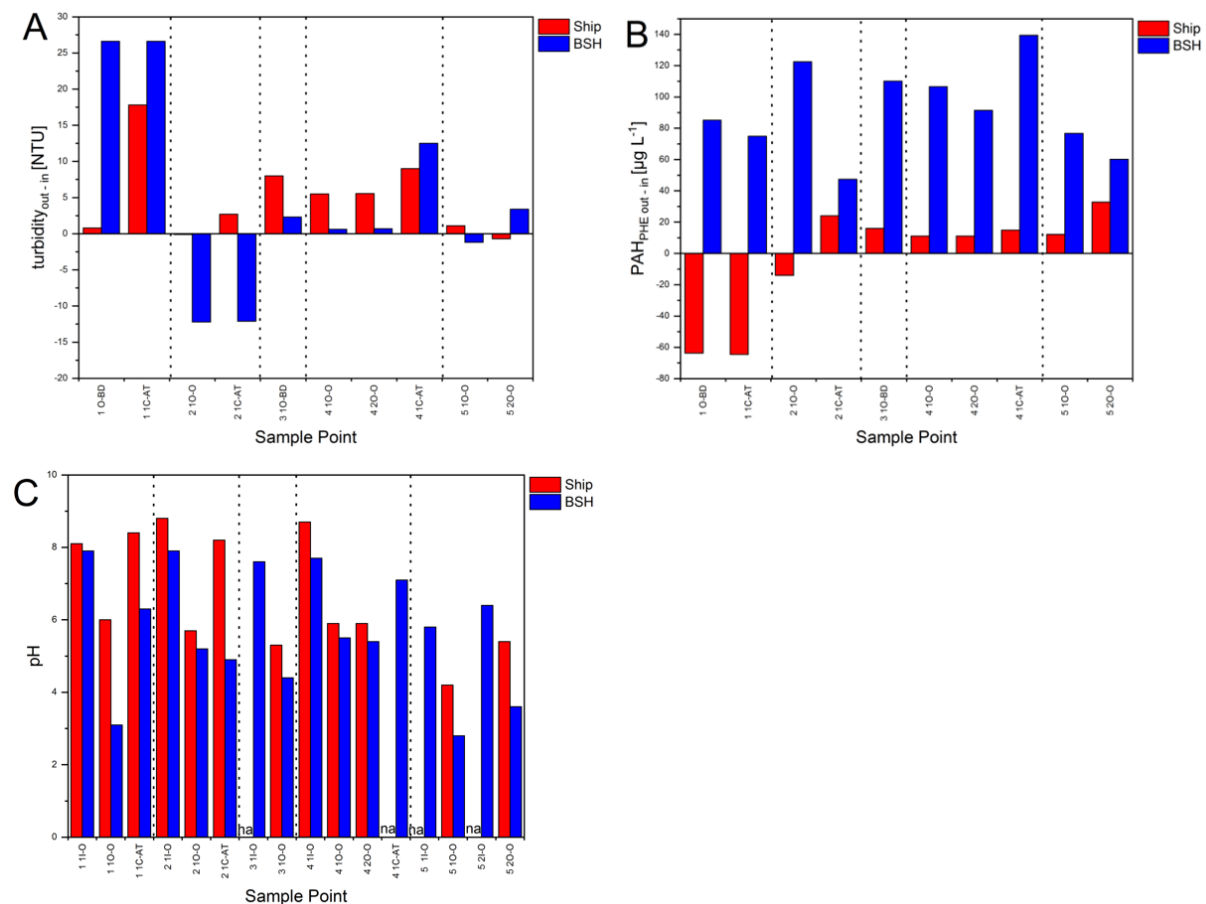
Concerning **turbidity** measurements, there are differences between ship-monitoring data and BSH on-board data, with higher NTU values in most of the BSH data. The limitations of the sampling procedure as discussed above, might be one reason for these differences.

The threshold values of MEPC.259(68) are related to the turbidity increase between inlet and outlet (prior to the dilution) that should not be exceeded by more than 25 NTU (NTU_{out-in} = outlet - inlet values, shown in Figure 15A). Nearly all the results were within this range, except ship 1, where BSH data show increase of 26.6 NTU. Negative NTU_{out-in} values may originate from organic matter content or algae already present in seawater inlet. It is possible that these differences between the two measurement approaches are a calibration issue (e.g. the negative NTU value of the ship-monitoring data) or other technical problems.

Ship-monitoring data and BSH on-board data for **PAH$_{PHE}$** differ widely for each ship. The ship-monitoring data are generally lower compared to BSH on-board data. Reasons for the differences of the PAH values might be, that the unit "PAH$_{PHE}$" is not clearly defined. The instrument supplier of the present study applies a factor of 6.2 to the measured signal, so that PAH$_{PHE}$ represents the PAH$_{EPA16}$ concentration. However, it is not clear if all installed systems are using this factor. Also the correction factor for turbidity might not always be applied. In addition, there is no correlation between ship PAH$_{PHE}$ and BSH PAH$_{PHE}$ on-board data, which exclude the problem of an offset between the data.

Similar to the turbidity, threshold values are related to the PAH$_{PHE}$ increase between inlet and outlet prior to any dilution (PAH$_{PHE\ out-in}$ = outlet - inlet values, shown in Figure 15B). High negative PAH$_{PHE\ out-in}$ values of the ship-monitoring data (meaning high PAH concentrations in the seawater inlet) suggest a malfunction, incorrect installed or poorly calibrated PAH probe or other sources of contamination/error. Laboratory analyses of PAHs in inlet seawater and known environmental PAH concentrations in the seawater do not correspond to these high values.

These results indicate a discrepancy between the data generated by the ship-monitoring on-board unit and parallel on-board measurements, especially concerning turbidity and PAH$_{PHE}$. This might need further investigation by additional comparison studies with on-board measurements and laboratory analyses (a first comparison see next section).

Although the total number of analysed samples is small, the results indicate that more effort is necessary for on-board ship-monitoring of EGCS wash water discharges. In particular, the results of the on-board system (e.g. negative values, high seawater inlet values) suggest that a higher calibration and maintenance frequency of the systems is necessary. Furthermore, the ship crew should be trained to check the plausibility of the data (e.g. high concentrations of PAHs seawater inlet) to react immediately if the system is not working properly. In addition, for the "2015 EGCS Guidelines" the term PAH$_{PHE}$ has to be clearly defined (e.g. as an equivalent for PAH$_{EPA16}$).

3.3.2.2   Comparison PAH$_{PHE}$ On-Board Values with Laboratory Values

PAH$_{PHE}$ has to be monitored on-board as an indirect measurement of the oil content in the discharged wash water to prevent emission of oil to the marine environment.

In order to assess the quality of the PAH$_{PHE}$ online measurement and their relation to detailed laboratory analysis, Table 9 summarises results of both. Values produced by the ships on-board unit and related BSH on-board measurements are presented in the first column. The additional laboratory results are added in the middle and right column. Displayed are the PAH$_{EPA16}$ contents and the oil index (HOI) measurements in related wash water samples.

Inlet on-board values are expected to be close to zero. All BSH laboratory values of the seawater inlet are below 1 µg/L, while the marine environmental concentrations are in the ng/L range.

Possible reasons for the elevated concentrations of both BSH and Ships' on-board measurements are the already mentioned sampling conditions for the PAH$_{PHE}$ or calibration issues, especially for the negative/zero values. The BSH on-board data show concentrations between 4 – 18 µg/L for the seawater inlet. This suggests that this optical method, which is used usually for on-board measurements, might be affected by several factors, such as naturally occurring aromatic compounds in the seawater, contamination of the inlet-system and other matrix effects.

Table 9:   **Comparison of PAH$_{PHE}$ on-board values with BSH laboratory analyses of PAH$_{EPA16}$ and Hydrocarbon Oil Index (HOI)**

	on -board PAH$_{PHE}$ (µg/L)		laboratory PAH$_{EPA16}$ (µg/L)		Hydrocarbon Oil Index (µg/L)
	Ship	**BSH**	**A**	**B**	
1 1I-O	112.5	17.9	0.3	0.2	25
1 1O-BD	48.8	103.0	8.2	8.1	370
1 1C-AT	48.0	92.7	25.1	23.8	7293
2 1I-O	26.9	3.9	0.0	0.0	11
2 1O-O	12.8	126.4	13.3	14.0	272
2 1C-AT	50.9	51.3	31.3	54.4	11356
3 1I-O	1.0	8.8	0.1	0.0	0
3 1O-BD	17.0	119.0	4.4	4.2	187
4 1I-O	-11.1	4.0	0.0	0.0	0
4 1O-O	0.1	110.5	6.8	6.9	250
4 2O-O	0.0	95.4	6.5	6.7	242
4 1C-AT	3.8	143.4	22.3	11.8	5260
5 1I-O	7.3	13.9	0.0	0.0	0
5 1O-O	19.5	90.6	5.6	5.3	136
5 2I-O	7.3	18.0	0.0	0.0	0
5 2O-O	40.1	78.1	5.1	5.9	153

First digit (1-5) ship number; second digit (1 or 2) if the ship had two independent ESGC; capital letters (I-O: inlet open-loop; O-O: outlet open-loop; O-BD: open-loop before dilution; C-AT: closed-loop after treatment) sampling point.

The open-loop ship-monitoring data of PAH$_{PHE}$ do not show any correlation between the BSH laboratory values of PAH$_{EPA16}$ and the HOI. In contrast, PAH$_{PHE}$ open-loop values of the BSH on-board data show a certain relation with the open-loop PAH$_{EPA16}$ laboratory data (samples a: $r^2 = 0.90$; samples b: $r^2 = 0.89$) and with the open-loop HOI ($r^2 = 0.91$). The dataset suggests that with a well-calibrated on-board system, the PAH$_{PHE}$ may represent PAH$_{EPA16}$ and HOI, if a factor is applied. However, the dataset is insufficient to conduct any robust statistical analyses and further investigations are necessary. If a large comparison study demonstrates a strong correlation between these three parameters (PAH$_{PHE}$, PAH$_{EPA16}$, HOI), different factors could be calculated to estimate the PAH$_{EPA16}$ and the oil content from the PAH$_{PHE}$ online value. A clear definition and understanding of PAH$_{PHE}$ is important to set protective threshold values to prevent the discharge of PAHs or oil to the marine environment.

3.4 Conclusions - Chemical Wash Water Characterization

The wash water from five different ships with open and closed-loop EGCS was sampled. Several limitations were faced during sampling, such as missing sampling points or unsuitable material or the size of the tubing at the sampling points for sampling under "clean" conditions. For better comparability of future investigations, better-designed sampling points are necessary to avoid any contamination during sampling from the tubing or other contamination sources.

The chemical characterization of the discharged wash water from open and closed-loop systems demonstrated the presence of several substances scrubbed out from the ship exhaust fumes in addition to sulphur. In general, closed-loop wash water showed higher concentrations of the investigated compounds compared to open-loop wash water, due to the water recycling process and the lower flowrate.

In particular, PAHs, nickel and vanadium were enriched in both, open and closed-loop samples. PAHs can originate from the HFO as HFO can contain certain PAHs and they are also generated during the combustion of HFO. In addition, HFO contains high concentrations of vanadium and nickel, which explain the high concentrations of these metals in the wash water. Nitrate and nitrite did not show clearly enrichment in open-loop wash water, due to high variability of inlet and outlet concentrations, but elevated concentrations in the closed-loop system. The alkalinity was reduced to almost zero in both systems and pH was decreased in the discharged wash water. Thus, emissions may have implication for eutrophication or ocean acidification in some areas. The discharges may influence the current environmental concentrations of some of the investigated substances in the marine environment. For instance, the concentrations of measured PAHs and several metals, in particular vanadium and nickel, in the discharged wash water were in both EGCS modes significantly higher than current environmental concentrations in the North Sea. Dispersion modelling in the next section will discuss in more detail the impact on environmental concentrations in the marine environment.

The comparison of on-board BSH measurements with the on-board monitoring data of the ship and laboratory analyses demonstrated that more effort is needed to provide reliable data (e.g. more frequent maintenance and calibration, training of the crew). Further research and calibration work for a clear definition and understanding of PAH_{PHE} is important to set comparable and protective threshold values to prevent the discharge of PAHs or oil to the marine environment.

4 Dispersion Modelling

4.1   Introduction

The aim of this task was to investigate the potential distribution of pollutants and to identify regions of high accumulation and local concentration maxima. The results from the previous section were used to investigate the accumulation of pollutants in various regions. Here, wash water refers to wash water that is discharged over board. The modelled concentration of pollutants in the seawater derives from the modelled amount of discharged and distributed wash water. The following list shows the main steps of the working process applied:

1. Implementation of an emission source concept (point, line, area) into a numerical circulation model described in section 4.2. The discharged wash water is distributed by the Eulerian dispersion coupler module of that model.
2. Two different emission scenarios were defined (Current State Scenario, CSS; Maximum Installation Scenario, MIS) according to a varying number of ships using EGCS. For both scenarios, three different wash water "sub-scenarios" were defined depending on different amounts of wash water per MWh (minimum, average, maximum).
3. For the two different scenarios mentioned above, ship tracks were selected from the AIS database and used with an emission model, which is described in section 4.2.4, to calculate ship performance dependent emissions per track.
4. The emissions were rasterized onto the model grid for the utilization in the Eulerian dispersion module of the circulation model with the two emission scenarios for 1 to 3 years of simulation.
5. Finally, the concentration of various substances in the seawater were calculated. A discussion of maximum concentrations reached and temporal evolution at several points in the North and Baltic Sea followed.

This study is intended to provide a basis for the evaluation of the effects of increasing use of EGCS technology in maritime shipping on the marine environment. Here, the spatial effect is estimated by simulating the distribution of wash water and its pollutants in the North Sea and the Baltic Sea over a temporal scale of 1 (CSS) and 3 years (MIS). Dilution and spread were calculated conservatively as passive tracers by means of a mesoscale Eulerian propagation model. In the model, the pollutants are not deposited and neither decomposed by biological or chemical processes. The Eulerian dispersion model is coupled with the HIROMB-BOOS-Modell BSH version 4 (BSH-HBMv4) (Brüning et al., 2014; Berg and Poulsen, 2012), which runs at BSH. See section 4.2.

The coupled HBM-Eulerian dispersion module computes the concentration of the wash water relative to the volume of the model grid cell and updates the emission within a fixed time interval of one minute. The concentration is calculated as liter wash water per cubic meter seawater. The emitted wash water is mixed instantaneously with the surrounding seawater in one model grid cell. This mixture is distributed to the surrounding grid cells via model-intern advection and diffusion. The mass balance is not altered within the model because concentrations are considered, i.e. during emission a part of the seawater is pumped on-board and passed back as wash water. The concentration of various substances is retrieved from the modelled wash water concentration under consideration of the measured substance pollution in wash water (see Section 3).

4.2   Model and Method

4.2.1   The HIROMB-BOOS Model

The HBM (Berg and Poulsen, 2012) is a three-dimensional hydrostatic circulation model. It uses spherical horizontal and generalized vertical coordinates (Kleine, 2003). The model domain extends from 4°W to 30.5°E and from 48.5°N to 60.5°N in the North Sea and to 66°N in the Baltic Sea. It has two different horizontal grid resolutions. Mainly it runs on the coarse grid with a spacing of 3 nautical miles (nm) (see Figure 16). The grey shaded area in Figure 16 marks the nested fine grid, which has a horizontal grid spacing of 900 m (see Figure 17). While the coarse grid consists of 35 vertical layers and extends down to a maximum depth of 695 m, the vertical extension of the fine grid is smaller and extends down to 80 m with 25 layers. Since HBM uses generalized coordinates, the thicknesses of the layers are changing over time. The layer thickness is about 2 m at the surface and about 3 m down to 50 m. Below that, it increases up to 100 m (coarse-grid), while the bottom layer thickness always measures about 4 m. Therefore, the size of a grid cell varies depending on the depth.

HBM consists of a northern open boundary in the North See and a western open boundary at the entrance of the English Channel. The boundaries are enclosed with a sponge layer. Within this layer, temperature and salinity are restored towards monthly mean climatological values (Janssen et al, 1999).

Figure 16:   **Bathymetry of the coarse gridded area with a resolution of 3 nm. The grey shaded area indicates the area of the nested fine grid (see Figure 17)**
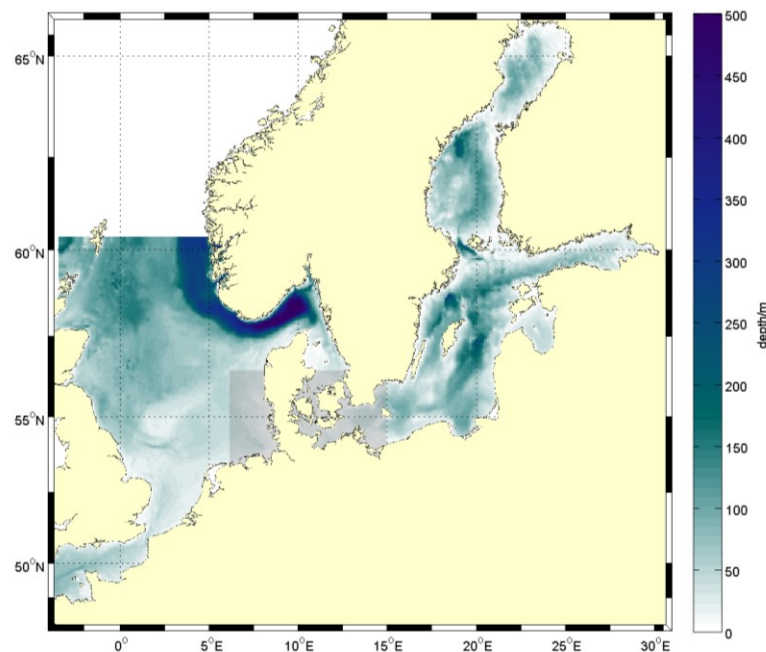
Figure 17: **Bathymetry of the fine gridded area with a resolution of 900 m**
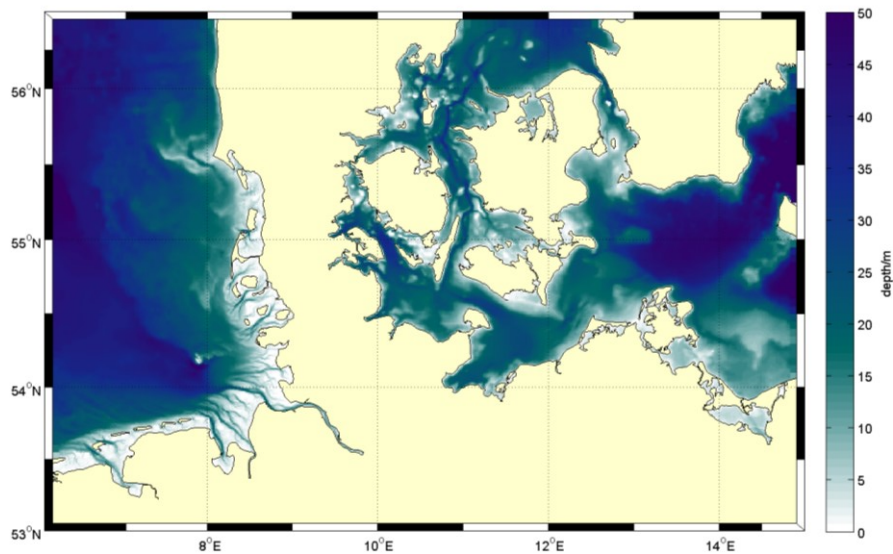
At the open boundaries tidal forcing is prescribed from 14 tidal constituents. External surges are computed by the BSH's 2-dimensional surge model for the North East Atlantic and are added to the tidal elevation at the open boundaries. HBM also integrates wetting and drying of tidal flats. River runoff is included as fresh water fluxes at grid cells in the regions of the main rivers.

The atmospheric forcing at the surface (wind, pressure, etc.) derive from operational meteorological forecasts provided by the German Weather Service (DWD).

Advection in HBM is realized by a flux-corrected transport scheme and diffusion is driven by horizontal eddy viscosity parametrized by Smagorinsky (1963) and vertical eddy diffusivity calculated by a k-ω turbulence model (Berg, 2012).

Within this project the Eulerian coupler was enhanced with the ability to input from different sources. The sources can have different spatial shapes (line, point, area) and different temporal patterns of input (instantaneous, regular, or continuous):

- Point sources input at given geographical coordinates in a specific cell-depth.

- Vertical line sources input at given geographical coordinates spreading over a specific cell-depth range. If the lower depth is larger than the local wet cell depth, then the source covers the whole range from the upper wet cell depth to the bottom.

- Horizontal line sources input between two given geographical coordinates in a specific cell depth. If the depth is larger than the local wet cell depth, then the line source follows the bathymetry.

- Horizontally dynamic sources move at a given speed over ground between given geographic coordinates in a specific cell depth. This case cannot be combined with the vertical source extension. Different scenarios can be computed, depending on the time step resolution, object velocity, and cell size.

  o For relatively low velocities, a cell might be affected for several time steps until the object proceeds into the next cell.

      o   For relatively high velocities, more than one cell might be affected for each time step. In this case, the concentration input would be averaged for each cell according to the number of affected cells.

      o   In any case, the current implementation checks if the number of time steps per cell(s) should be altered regularly to account for round-off errors that would otherwise decrease the velocity-resolution (e.g. 6.5 time-steps should be spend per cell, will result in alternating between 6 and 7 time steps).

- Horizontal source distribution map at a specific cell depth is necessary for complex source shapes. This input type was used in the context of this project. The input is stored either in an ASCII or a NetCDF file. The source resolution has to match the horizontal grid resolution of HBM. Temporal concentration variations are possible by defining different source shapes in the source file(s).

The following temporal setups are possible:

1. Source(s) emitting once, at a specific date and time.

2. Source(s) emitting continuously, starting and ending at specific dates and times. The emitted concentration per source can vary over time.

4.2.2   Model Application

The HBM model computes the distribution of wash water concentrations based on the wash water emission data gained from the EMMA model (Emission Model Marine Activities), described in section 4.2.4.1. Separate model runs are required for the closed-loop and open-loop wash water emissions. Each scenario is computed several times with different wash water emissions: one time with emission from closed-loop EGCS and another time with emission from open-loop EGCS. The concentration of wash water is used afterwards, during the post-processing step, for the derivation of the concentrations of various pollutants measured in the discharge of open-loop and closed-loop systems. Closed-loop wash water input based on an average assumption for wash water flowrate ($0.2 \, m^3$/MWh), while for the open-loop three different flow rates (minimum, maximum and average), based on on-board measurements during the sampling campaigns, were distinguished and computed separately. This results in four simulations for each scenario, i.e. three open-loop and one closed-loop.

HBM runs in time-steps of 30 seconds in the coarse gridded area and with time-steps of 15 seconds in the fine gridded area. However, the Eulerian coupler module runs with a time step of one minute in both areas. HBM uses wash water emission data as the source of input. The emission data are rasterized on model grid and provided as daily sums for the period Jan, 1st – Dec, 31st. During pre-processing, the data is transferred to volume per minute. The simulated wash water distribution is stored as daily means. For the three-year simulation, the ship emission data from 2015 is used as well in the years 2016 and 2017.

4.2.3   Scenarios and General Assumption

Two different scenarios have been developed for simulating the distribution of wash water and potential concentration of pollutants. These scenarios differ in the number of ships using EGCS.

These are the current state scenario 2018 (CSS) and the maximum installation scenario (MIS). In addition, general assumptions were necessary due to model limitations and data availability, and in order to reduce the complexity.

4.2.3.1   General Assumption Regarding the EGCS Type Used

For most of the seagoing vessels, it is unknown where, when, and how they discharge wash water from closed-loop EGCS and – if they have a hybrid system – where they switch from open-loop to closed-loop mode and vice versa. Furthermore, information about installed scrubber systems is limited. Therefore, the following conservative assumptions were made for the model:

1. All ships have a hybrid system and behave the same way.

2. Open-loop EGCS are used outside of Federal waterways and outside of German ports by all ships; within the mentioned areas only closed-loop EGCS are used. Again, this applies to all ships.

3. Wash water from closed-loop EGCS is accumulated within the above mentioned areas. The accumulated wash water is discharged into the sea after the ships have left the Federal waterways.

4.2.3.2   Current State Scenario 2018 (CSS)

The CCS is based on the number of ships that were equipped with EGCS by March, 20th 2018. A number of 157 ships were listed in the GISIS database. About 81 of them proceeded through German waters. These 81 ships were used for modelling the CSS over the modelled time period of one year (Jan, 1st 2015 until Dec, 31st 2015). Although this scenario refers to 2018, the input data (weather and sea conditions for the modelling of the wash water dilution; and ship traffic for the modelling/calculation of the wash water discharges) is from 2015. The emissions of wash water along the shipping routes are visible in Figure 18.

Figure 18:   **Example of wash water emission computed for the CSS for one day. The left picture shows the open-loop mode and the right picture shows the closed-loop mode of the EGCS. Red shapes indicate the Federal waterways. Please note the different scales of both figures**
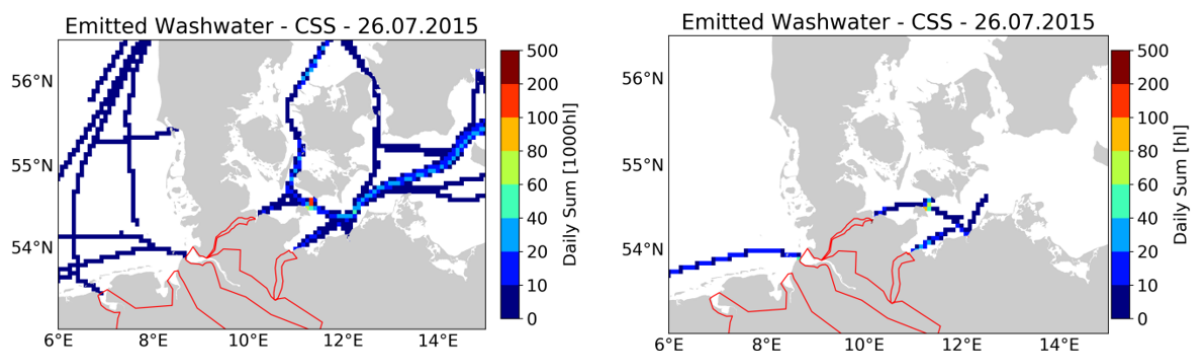
4.2.3.3   Maximum Installation Scenario (MIS)

The MIS based on the assumption that all ships for which an installation of an EGCS is economically profitable (e.g. due to its size and distance covered in the ECA) have installed an EGCS and use it.

In 2015 in the modelled area, AIS-signals were received from a total number of 27,067 ships of which 17,466 were identified by their IMO-number. Their detailed technical ship-data was found in the data portal Seaweb-Ships of the IHS maritime portal. The other signals that were received (9,601 ships) did not have an IMO-number and were not considered in the simulations (with the assumption that an EGCS will only be equipped on seagoing ships with an IMO number). Regarding the 17,466 ships with an IMO-number, 13,482 ships could be accounted as freight and passenger ships – hence, ship types for a potential EGCS installation. The other ships were workboats, inland vessels, or objects similar to a ship such as platforms.

Economically feasible criteria from table 3-18 in MEPC70/INF.9 (2016) were applied to the remaining 13,482 that are transport vessels for passengers and goods. The other vessel types are either not listed or the installation of an EGCS is not economically feasible due to its size and distance covered in the ECA. Based on these criteria, we assume that the installation of an EGCS is economically profitable for only 5,885 of these 13,482 vessels. This number is not comparable with the amount of ships calculated in MEPC70/INF.9, because only specific ships with an AIS signal in the modelled area in 2015 were considered. In the end, 5,885 ships remain with respect to the MIS.

The ship density from the 2015-AIS-data is applied for the modelled time period of 3 years (Jan, 1st 2015 until Dec, 31st 2017). The calculation was limited to three years, due to complexity of the model and limited computing resources. An example of wash water emissions is given for MIS in Figure 19.

Figure 19:   **Wash water emission computed for the MIS for one day. Left picture shows open-loop and right side closed-loop EGCS. Red shapes indicate the Federal waterways. Please note: The order of magnitude of the closed-loop emissions are 1000 times lower**
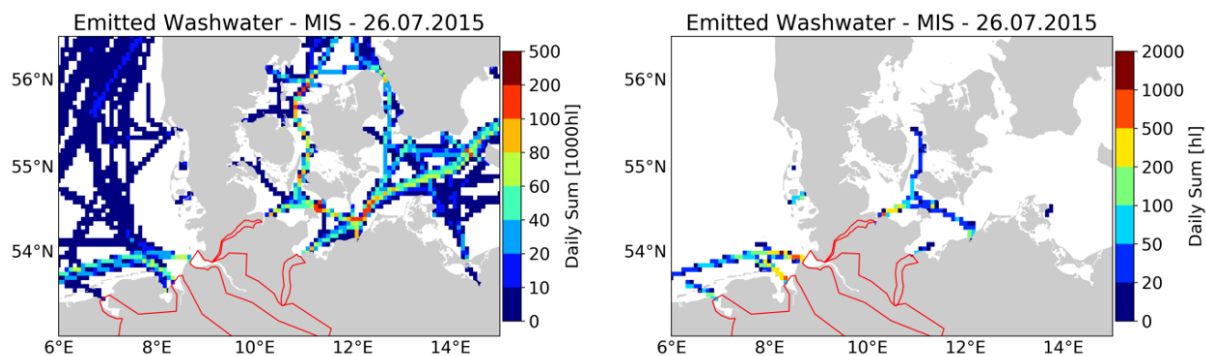
4.2.4   Data Input

This section describes the data input for the coupled HBM-Euler model. The location of the emission of wash water is modelled with EMMA on the base of AIS ship positions in the year 2015. The actual simulated number of ships with an EGCS depends on the selected scenario (CSS or MIS). After retrieval of the wash water emissions, the data are rasterized or summarised to emitted volume in liter per model grid-cells.

4.2.4.1   EMMA Model

The wash water emission is calculated with the EMMA Model. EMMA was developed at the BSH for emission reporting. The model estimates the quantity of emissions (SOx, NOx, etc.) that is emitted by ships in German Waters based on the amount of fuel used. It takes the AIS database from EMSA (2015), which lists the AIS position data from 2015. Ship information data about

engine-performance, -consumption, and -size are received from the IHS maritime portal. The ships are subdivided into categories in accordance to the IMO-number. Ships without an IMO-number were not considered further in this study because they could not be linked to data from the IHS portal. In case of insufficient information on engine properties, the common value of the corresponding category was taken as a basis. Outputs of the model are dynamic data files (position, emission) and static data files (e.g. category of the ship). Wash water emissions correlate to the performance of the engine and increase with velocity. Assumed emission factors of wash water derived from engine performance data and the wash water emissions measured in this project (see Table 10).

The outputs of EMMA are shape files of ship tracks with minimum, mean and maximum emitted wash water from open-loop EGCS and emitted wash water from closed-loop EGCS. EMMA simulates starting point and ending point of each sub-track section with a time-interval of 15 minutes.

Table 10:   **Ship data and wash water emissions (in open-loop mode) measured during sampling campaigns**

	Ship data measured during sampling campaigns				Computed Open-loop wash water emission from the measured ship data	
Ship	Wash water emission [m³/h]	Dilution water [m³/h]	Engine performance [MW]	Derived fuel consumption [t/MWh]	Emission without dilution [m³/MWh]	Emission with dilution [m³/MWh]
Ship 1	802	401	13.1	0.21	61.22	91.83
Ship 2	757	0	5.5	0.24	137.64	137.64
Ship 3	531	387	9.0	0.24	59.00	102.00
Ship 4	548	0	7.3	0.22	75.07	75.07
Ship 5	1000	0	11.8	0.23	84.75	84.75

Data in Table 10 provides the basis for simulating the emissions of wash water by open-loop EGCS. Because of the wide range of possible wash water emissions and the uncertainty due to the small number of measurements, three "sub-scenarios" of wash water emission were defined: minimum (60 m^3/MWh), average (100 m^3/MWh), and maximum (140 m^3/MWh). These emission factors correspond to the abbreviations MinWW, AveWW, and MaxWW, respectively, that are used in Table 11. This enables emission simulation of wash water between two AIS positions for open-loop EGCS. Wash water is emitted continuously outside of the Federal waterways. It was assumed that no emissions would occur within the Federal waterways.

Wash water from closed-loop EGCSs is emitted differently. We assumed a wash water production of 0.2 m^3/MWh, but no information is available, where and when this water is disposed. It can be emitted directly into the sea or accumulated and disposed randomly into the sea or on land. For this study, a disposal at the border to the Federal waterways was assumed, whenever a ship had left these areas. Closed-loop EGCS are primary applied in Federal waterways where the use of open-loop systems is prohibited (DBWK1000, 2016). These waterways include rivers, estuaries, the Kiel Canal, and the port of Hamburg and they are masked out in EMMA for the open-loop scrubbers. It is assumed that the switch at a hybrid system from open-loop EGCS to the closed-loop EGCS done at the border to the Federal waterways. Thus, ships with closed-loop EGCS collect the wash water travelling on Federal

waterways. If a ship exits such a region into the open sea, it is assumed that the switch happens directly after the border to the Federal waterways. The borders are shown in Figure 19.

We assumed that the open-loop EGCS are started also directly at the border and wash water from closed-loop EGCS is released into the sea at the same time. The volume of emitted wash water is derived from the time that the ship had spent in the proscription region. In EMMA, the time is summed up. The volume of accumulated closed-loop wash water is released in the first AIS track section after leaving the proscription region and addressed to the corresponding grid cells.

4.2.4.2   Rasterization

Although it is possible to simulate the emission of moving ships with the HBM model directly, performance issues made it necessary to raster the ship track emissions from EMMA onto HBM grid in a processing step, which we call rasterization. For the spatial rasterization onto the HBM model grid the calculated emissions of the ship tracks from EMMA are introduced into a conversion tool. This tool written in R (programming language), intersects the ship tracks with the grid cell and computes for each grid cell the total emissions for one day of all ships crossing the cell. The output is the volume of emitted wash water (liter) during one day for each grid cell. The emission is determined for the coarse model grid only. For calculation of the nested grid area, the rasterized emission data are interpolated on the fine grid. The annual amount of wash water after rasterization for CSS and MIS is depicted in Figure 20.

Figure 20:   **Total annual amount of emitted wash water from the EMMA model for the current state scenario (CSS), left, and the maximum installation scenario (MIS), right, after rasterization. Red shapes indicate the Federal waterways**
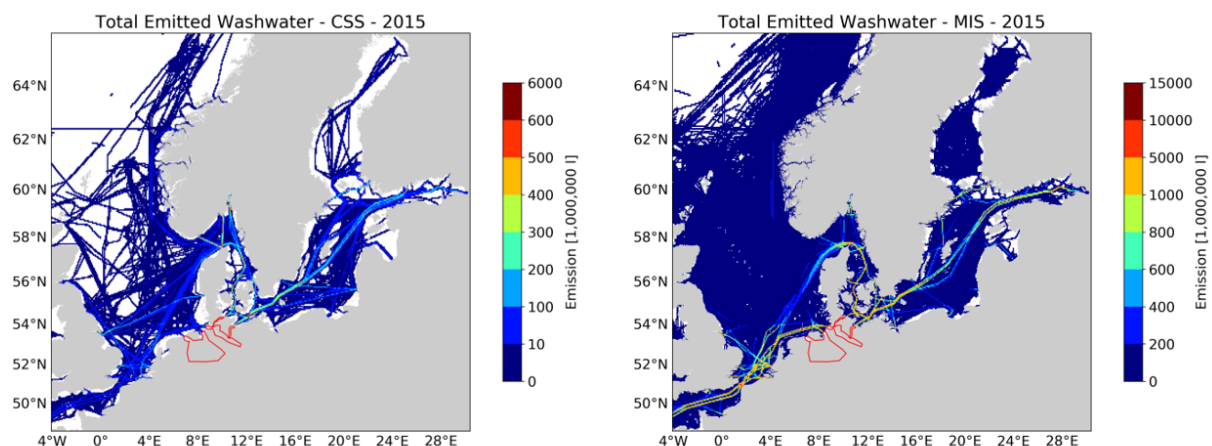
4.2.5   Post-processing of the Model Results

4.2.5.1   Distribution of Wash Water

The HBM-Euler model simulates distribution and concentration of wash water in the North- and Baltic Sea. Concentration of pollutants is derived during post-processing. Wash water concentration is computed as liter per cubic meter seawater within a grid-cell or in other words as the proportion of seawater that has been used by EGCS. Within a grid-box wash water is instantaneously mixed with seawater and transported to other grid cells by advection and diffusion. Wash water accumulates with time and spreads over the model domain. As mentioned above, wash water distribution is simulated for each scenario with four different emissions: closed-loop emission rate, open-loop minimum, maximum, and average emission rates. Closed-

loop EGCS emit much less wash water than open-loop EGCS but the wash water from closed-loop EGCS are contaminated with much higher concentrations of pollutants.

4.2.5.2   Derivation of the Pollutant Concentration

During the post-processing, the concentration of each pollutant is derived from modelled wash water concentration and the measured substance concentration during the sampling campaigns (see section 3, Table 19 Appendix). The maximum and minimum measured concentrations in the wash water samples are used for the derivation of contamination in seawater. To get the total concentration of pollutants ($conc_{total}$), the measured concentrations from open-loop ($conc_{ol}$) and closed-loop ($conc_{cl}$) EGCS is multiplied with the concentration of modelled wash water from open-loop (ww_{ol}) and closed-loop (ww_{cl}) EGCS, respectively:

$$conc_{total}\left[\frac{\mu g}{l}\right] = \frac{ww_{ol} * conc_{ol} + ww_{cl} * conc_{cl}}{1000}$$

The total concentrations are scaled down to nanogram per liter (ng/L) or picogram per liter (pg/L) depending on the magnitude of the contamination and gives the concentration of pollutants in a grid cell. There are three different distributions of wash water from open-loop EGCS, which results from different emission rates, and one distribution from closed-loop EGCS. Adding open-loop and closed-loop emissions finally gives three distributions of wash water, one for each emission rate. Together with the minimum and maximum values of measured pollutant concentrations in the wash water (see Annex 8.2) this retrieval leads to six different modelled concentrations for each pollutant in each scenario. Table 11 gives the explanation for the titles that are used in the graphics in the following section.

Table 11: **List of abbreviations of the six different contamination emissions: These are retrieved from three wash water emission rates (MinWW, AveWW, MaxWW) and from two measured concentrations during the sampling campaigns (Min_Konz and Max_Konz)**

Abbreviation	Pollutant concentration	Wash water emission rate
MinKonz_MinWW	Minimum concentration	Minimum emission
MinKonz_AveWW	Minimum concentration	Average emission
MinKonz_MaxWW	Minimum concentration	Maximum emission
MaxKonz_MinWW	Maximum concentration	Minimum emission
MaxKonz_AveWW	Maximum concentration	Average emission
MaxKonz_MaxWW	Maximum concentration	Maximum emission

The total concentrations are retrieved for a series of substances that were measured during the sampling campaigns. These substances include nitrate, nitrite, polycyclic aromatic hydrocarbons, the dissolved and SPM fraction of heavy metals. For substances that are listed in Directive 2013/39/EU on priority substances respective the German Ordinance on the Protection of Surface Waters (Oberflächengewässerverordnung, OGewV) (2016) the focus is set on the compliance with the Environmental Quality Standards (EQS; see table 2 in OGewV, 2016).

4.3   Results and Discussion – Dispersion Modelling

The following chapter describes results of the numerical simulation of the EGCS induced wash water dispersion in the North Sea and Baltic Sea. It is divided into three parts: maximum concentration, spatial distribution and temporal variation. Generally, the presented results show just the modelled substance enrichment due to wash water emissions. Current environmental concentration is not added to the calculated concentration levels. Here, the modelled concentration increase will be simply called modelled concentration to make the term short.

4.3.1   General Wash Water Distribution and Total Wash Water Emissions

The following numbers, maximum, average and standard deviation of wash water concentrations are computed over the whole fine grid model domain in 2015. In average, the ratio between closed-loop and open-loop is less than 1% (see Table 12). However, the ratio reaches up to 6% in CSS and 1.45% in MIS, which is reached at the borders of the Federal waterways. The quantity of wash water from open-loop is large in comparison to wash water from closed-loop EGCSs. The difference is in order of three magnitudes.

Table 12:   **Statistics of distributed wash water from different types of EGCS: open-loop with maximum emission (open-loop max), closed-loop, combination of open-loop with maximum emission and closed-loop (both types) and ratio between closed-loop and open-loop concentration (CL/OL ratio). Listed are: maximum, average, and standard deviation (SD) of wash water concentration in l/m³ for the scenarios CSS and MIS**

Wash water	CSS – maximum	CSS - average	CSS - SD	MIS - maximum	MIS - average	MIS - SD
open-loop max	0.7995	0.0410	0.0485	2.3084	0.6850	0.4448
closed-loop	0.0017	0.0000	0.0000	0.0103	0.0007	0.0007
both types	0.7998	0.0411	0.0485	2.3097	0.6857	0.4450
CL/OL ratio	0.0611	0.0003	0.0005	0.0145	0.0013	0.0014

The concentration of wash water is higher in MIS than in CSS. In average, the concentration is with 0.69 l/m³ to 0.04 l/m³ about 17 times higher in MIS than in CSS. Maximum concentrations differ less. It is about three times larger in MIS than in CSS. Within the modelled framework the maximum concentration of wash water in CSS is reached in the highly frequented region between Puttgarden (Germany) and Rødby (Denmark), where four ferries are equipped with EGCS (later it turned out that the ferries in question operate exclusively in closed-loop mode and that the produced wash water is disposed on land; "zero discharge mode", Scandlines, 2019). Due to the already high traffic of these ferries in the CSS the difference between CSS and MIS maximum values is lower than in other regions like north of Rostock. In CSS the concentration of wash water in the North Sea is more than 10 times lower than around Fehmarn. This is shown in Figure 23, where the maximum concentration of wash water simulated with the emission factors MaxWW, MinWW and AveWW, are shown for both scenarios.

Figure 21:   **Maximum concentration of wash water for CSS (left, one year) and MIS (right, three years). Wash water is modelled with the minimum wash water emission rate. (Consider different concentration scales)**
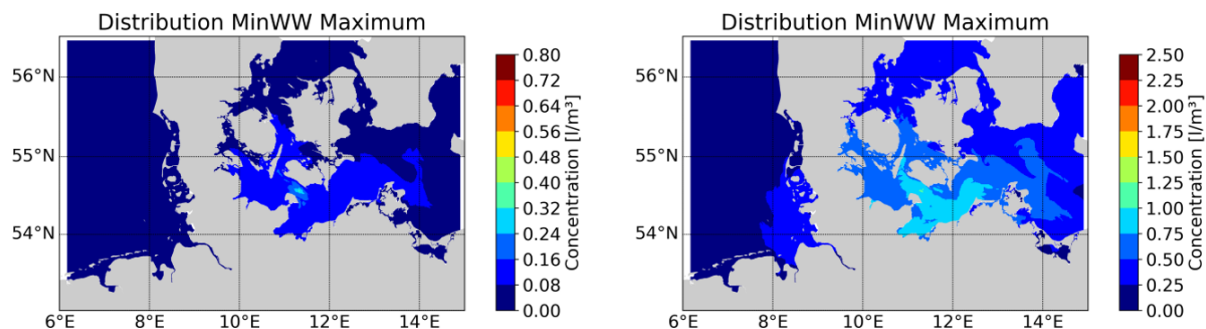
Figure 22:   **Maximum concentration of wash water for CSS (left, one year) and MIS (right, three years). Wash water is modelled with the average wash water emission rate. (Consider different concentration scales)**
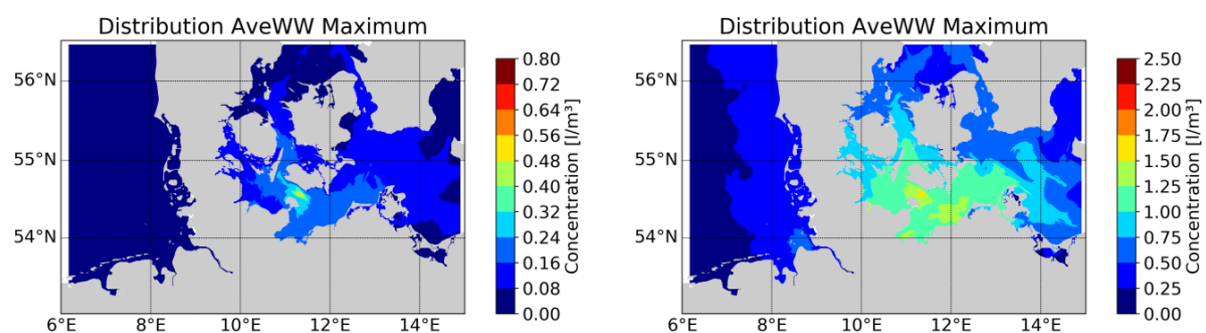
Figure 23:   **Maximum concentration of wash water for CSS (left, one year) and MIS (right, three years). Wash water is modelled with the maximum wash water emission rate. (Consider different concentration scales)**
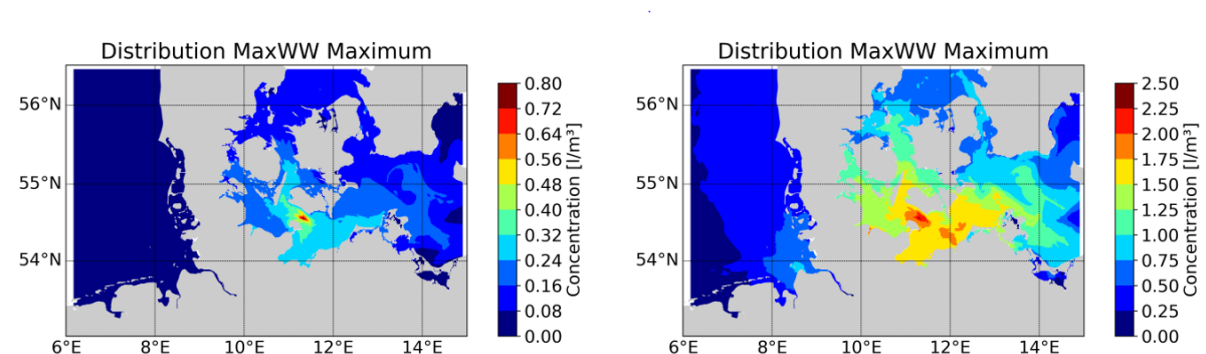
The total amount of annual wash water emissions into the entire investigated area is summarised in Table 13 for the MinWW, AveWW and MaxWW (sum of open and closed-loop emissions). Total annual discharges of the different substances were estimated for the entire modelled area (coarse gridded, Figure 16) based on total wash water emissions.

Table 13: **Total annual wash water emissions (sum of open and closed-loop) and corresponding emissions (MinKonz_MinWW - MaxKonz_MaxWW) of the different analysed substances in the coarse gridded area (compare Figure 16)**

Estimated Annual Wash Water Emissions (l)		
	CSS	**MIS**
MinWW	2.07×10^{11}	1.92×10^{12}
AveWW	3.44×10^{11}	3.20×10^{12}
MaxWW	4.82×10^{11}	4.48×10^{12}
Estimated Annual Chemical Emissions (t)*		
	CSS MinKonz_MinWW - MaxKonz_MaxWW	**MIS** MinKonz_MinWW - MaxKonz_MaxWW
Nitrite + Nitrate	$20 - 1,275$	$201 - 12,069$
Naphthalene	$0.1 - 5$	$1 - 43$
Phenanthrene	$0.1 - 1$	$1 - 13$
Benzo[a]anthracene	$<0.0001 - 0.02$	$<0.001 - 0.2$
Benzo[a]pyrene	$<0.0001 - 0.05$	$<0.001 - 0.5$
PAH$_{EPA16}$	$0.3 - 7$	$3 - 63$
Oil	$11 - 131$	$105 - 1,226$
V$_{total}$	$3 - 151$	$26 - 1,411$
Ni$_{total}$	$1 - 35$	$12 - 331$
Cu$_{total}$	$0.4 - 8$	$3 - 72$
Zn$_{total}$	$0.5 - 64$	$5 - 598$
As$_{total}$	$0.2 - 3$	$2 - 31$
Cd$_{total}$	$0.002 - 0.03$	$0.02 - 0.3$
Pb$_{total}$	$0.02 - 1$	$0.2 - 10$

*The preliminary data (PPR6/INF.20, 2018) included only the average wash water emissions (AveWW).

These estimated emissions were compared to other emission sources into the marine environment to qualify their order of magnitude. Here is to mention, that comparison data do not cover the same area, as data are not always available. Comparison data correspond to smaller areas (e.g. only North Sea or only riverine input to the North Sea).

Estimated nitrate + nitrite emissions from EGCS are 20 – 12,069 t and thus significant lower compared to the reported direct discharges and riverine inputs of nitrate into the main North Sea body with 1,580,150 -1,675,622 t (based on 357,500 to 379,100 t NO_3-N in 2017 (OSPAR 2019)). For the main North Sea body, copper input was 653 – 678 t, zinc 1,099 – 1,190 t, and lead 139 – 150 t (OSPAR 2019) compared to 0.4 – 72 t , 0.5 – 598 t and 0.02 – 10 t estimated emissions from EGCS to the entire investigated area (coarse grid), respectively.

Emissions of about 4,000 t oil from process waters from the Oil and Gas Industry were reported in 2016 for the entire OSPAR region (OSPAR 2016) compared to 11 – 1,226 t derived from the HOI in the coarse gridded area of this study.

Comparison data for PAHs are rare, e.g. German riverine PAH-inputs to the North Sea for the years 2015/2016 are estimated to around 10 t and to the Baltic Sea to around 0.85 t (UBA, 2019) and are in the same order of magnitude as the estimated emissions in CSS. Annual wet atmospheric deposition of phenanthrene to the North and Baltic Sea was estimated by Mai (2012) with about 12 t and is comparable to maximum concentrations in the MIS, where 13 t are reached.

Although estimated emission data suggest that total annual discharges are lower compared to most of the inputs from other sources, and therefore regarded as neglectable or of minor importance, the results from the dispersion modelling in the next section provides a more differentiated insight. It could be shown that emissions from EGCS to the marine environment lead in specific regions to additional pollutant burdens of the same order of magnitude as already existing environmental pollutant concentrations.

4.3.2   Maximum Concentrations

This section discusses the maximum concentration of all modelled substances, which are emitted by EGCS systems and are add to the existing environmental concentration in the surface layer (about 2 – 3 m) of the investigated area. Maximum reached values in the CSS scenario are listed in Table 14 (one year) and those in MIS in Table 15 (three years). The maximum concentrations were calculated for the three different wash water emission rates (MinWW, AveWW, and MaxWW) and the measured minimum (MinKonz) and maximum (MaxKonz) concentration of each substance in the wash water. The concentration range from MinWW + MinKonz (first column) to MaxWW + MaxKonz depicts the uncertainty of the modelled concentrations related to the estimated amount of wash water and the measured concentrations in the wash water.

The maximum modelled concentrations (Table 14 and 15) in the seawater of most substances in the CSS and MIS are in the ng/L range. Nitrate and nitrite reach values up to µg/L. Anthracene Benzo[a]pyrene, Benz[a]anthracene, cadmium (DF), and lead (SPM) are lower with pg/L. Cadmium (SPM) only reaches fg/L.

However, some of these substances could be decomposed in the marine environment, which was not considered in the model. Wash water was modelled as a passive tracer. This means that no biological, mechanical, or chemical decomposition is occurring. The modelled distribution of the compounds is driven by the spread of the wash water.

The resulting maximum concentration of each substance is highly dependent on the range of estimated wash water emission rates and measured wash water component concentrations. The relative difference is visible in the results. The uncertainty due to the range of measured concentrations is large in comparison to the modelled concentrations. As an example, in the CSS

the concentration of Sum PAH in the surface layer ranges between 1.3 ng/L for
MinKonz_MinWW and 30.2 ng/L for MaxKonz_MaxWW (Table 14).

Table 14: **Maximum reached concentration for each substance for CSS over the total model
period of one year in the surface layer. DF: Dissolved metals; SPM: metals in
suspended particulate matter. Note the different units**

Substance	Unit	MinKonz			MaxKonz		
		MinWW	AveWW	MaxWW	MinWW	AveWW	MaxWW
Nitrite	[µg/L]	0.01	0.01	0.01	0.64	0.85	1.14
Nitrate	[µg/L]	0.08	0.08	0.09	0.69	1.09	1.48
Vanadium (DF)	[ng/L]	5.8	7.2	9.7	102.5	168.6	234.7
Nickel (DF)	[ng/L]	1.5	2.5	3.4	25.1	40.6	56.0
Copper (DF)	[ng/L]	0.6	0.9	1.3	5.4	9.0	12.6
Zinc (DF)	[ng/L]	0.7	1.2	1.7	45.7	76.2	106.6
Cadmium (DF)	[pg/L]	2.8	4.6	6.4	23.1	38.4	53.7
Lead (DF)	[ng/L]	0.01	0.02	0.03	0.7	1.2	1.7
Vanadium (SPM)	[ng/L]	0.5	0.9	1.3	8.7	14.2	19.6
Nickel (SPM)	[ng/L]	0.5	0.89	1.1	2.7	4.4	6.0
Copper (SPM)	[ng/L]	0.03	0.05	0.08	1.4	2.3	3.2
Zinc (SPM)	[ng/L]	0.05	0.08	0.1	0.3	0.5	0.7
Cadmium (SPM)	[fg/L]	0.0	0.0	0.0	33.2	33.2	33.2
Lead (SPM)	[pg/L]	15.7	26.5	37.0	34.0	56.1	78.2
Napthalene	[ng/L]	0.2	0.2	0.5	3.3	5.4	7.6
Phenanthrene	[ng/L]	0.2	0.4	0.5	1.0	1.7	2.3
Anthracene	[pg/L]	3.8	4.8	6.4	57.8	92.8	127.7
Benzo[a]anthracene	[pg/L]	0.8	0.8	0.8	15.8	25.8	35.9
Benzo[a]pyrene	[pg/L]	0.1	0.1	0.1	33.7	56.1	78.5
PAH$_{EPA16}$	[ng/L]	0.4	0.9	1.3	6.4	10.6	14.9
Sum PAH	[ng/L]	1.3	2.2	3.1	13.0	22.0	30.2
Oil Index	[ng/L]	20.1	32.2	44.3	96.1	158.2	220.3

Table 15: **Maximum concentration for each substance for the MIS over the total model period of three years in the surface layer. DF: Dissolved metals; SPM: metals in suspended particulate matter. Note the different units**

Substance	Unit	MinKonz			MaxKonz		
		MinWW	AveWW	MaxWW	MinWW	AveWW	MaxWW
Nitrite	[µg/L]	0.06	0.06	0.06	4.7	5.4	6.1
Nitrate	[µg/L]	0.5	0.6	0.6	4.5	5.4	6.3
Vanadium (DF)	[ng/L]	42.6	48.2	53.6	348.5	499.8	680.0
Nickel (DF)	[ng/L]	6.7	8.8	10.9	117.8	152.8	187.2
Copper (DF)	[ng/L]	1.7	2.7	3.1	16.6	26.6	36.6
Zinc (DF)	[ng/L]	2.3	3.7	5.0	140.7	224.9	307.8
Cadmium (DF)	[pg/L]	8.5	13.5	18.5	71.4	113.5	155.2
Lead (DF)	[ng/L]	0.04	0.06	0.08	2.2	3.6	4.9
Vanadium (SPM)	[ng/L]	1.7	2.7	3.6	37.7	50.1	62.3
Nickel (SPM)	[ng/L]	1.5	2.3	3.2	13.1	16.8	20.6
Copper (SPM)	[ng/L]	0.1	0.2	0.2	4.2	6.8	9.2
Zinc (SPM)	[ng/L]	0.2	0.2	0.3	1.7	2.1	2.6
Cadmium (SPM)	[fg/L]	0.0	0.0	0.0	206.3	206.3	206.3
Lead (SPM)	[pg/L]	49.2	78.3	106.9	105.3	166.0	226.4
Napthalene	[ng/L]	0.6	1.0	1.3	10.0	17.0	21.9
Phenanthrene	[ng/L]	0.7	1.1	1.5	3.1	4.9	6.7
Anthracene	[pg/L]	28.4	32.1	35.7	289.8	369.2	447.4
Benzo[a]anthracene	[pg/L]	5.2	5.2	5.2	59.1	81.9	104.4
Benzo[a]pyrene	[pg/L]	0.7	0.7	0.7	103.8	165.7	226.7
PAH$_{EPA16}$	[ng/L]	1.7	2.7	3.6	14.8	23.7	32.4
Sum PAH	[ng/L]	4.1	6.5	8.9	35.1	56.6	76.7
Oil Index	[ng/L]	101.0	128.6	155.6	322.3	468.9	638.2

The environmental concentrations in the Fehmarn Belt (2017, monitoring data) were compared to the modelled concentrations of phenanthrene, anthracene and benzo[a]pyrene. The seawater concentrations of these three PAHs were 1.6 ng/L, 30 pg/L and 76 pg/L, respectively. The modelled enrichment of phenanthrene, anthracene and benzo[a]pyrene already reach these values in the CSS (Max_Konz) scenario. In summary, it should be highlighted that, depending on the scenario modelled, the calculated pollutant burden after one to three years is in a similar range or even higher as the already existing current environmental pollutant concentrations. Thus, wash water emissions from EGCS may lead to a significant increase of the environmental concentrations in that area.

For some of the investigated compounds, environmental quality standards (EQS) are set in the Directive 2013/39/EU, they are specified as AA-EQS (annual average concentration) and MAC-EQS (maximum allowable concentration).

For selected substances the AA-EQS and MAC-EQS are as followed: anthracene 100 ng/L (AA-EQS and MAC-EQS), benzo[a]pyrene 0.17 ng/L (AA-EQS) and 27 ng/L (MAC-EQS), naphthalene 2 µg/L (AA-EQS) and 130 µg/L (AA-EQS), cadmium 200 ng/L (AA-EQS) and 450 ng/L (MAC-EQS), nickel 8.6 µg/L (AA-EQS) 34 µg/L (MAC-EQS), lead with 1.3 µg/L (AA-EQS) and 14 µg/L (MAC-EQS).

These EQS are compared with the maximal modelled concentrations (MIS_Max_Konz MaxWW). The concentrations are as followed: anthracene 0.5 ng/L, benzo[a]pyrene 0.2 ng/L, naphthalene 0.02 µg/L, cadmium 0.15 ng/L, nickel 0.2 µg/L and lead 0.005 µg/L.

Comparing the MAC-EQS and AA-EQS with the modelled seawater maximum concentrations, demonstrates that MAC-EQS values are not reached for any of these compounds in the MIS_Max_Konz MaxWW scenario. In addition, maximal modelled concentrations of all substances, except benzo[a]pyrene, are well below the AA-EQS. Benzo[a]pyrene MIS_Max_Konz MaxWW concentration is in the same order of magnitude as AA-EQS value, but it should be noted that modelled values represents the maximum value during the modelled period and not an annual average. Furthermore modelled benzo[a]pyrene concentrations in MIS are between 0.0007 ng/L (MinKonz MaxWW) to 0.22 ng/L (MaxKonz Max WW), which demonstrates the high uncertainty for this value, due to the concentration range in the wash water. Therefore the meaningfulness of a direct comparison of the modelled maximum values with AA-EQS seems to be restricted.

It is important to note that the applied model only calculates the pollutant enrichment and distribution due to EGCS emissions. The current pollutant load present in the sea, on the other hand, is not taken into account. It must be summed up with the model results when comparing with environmental quality standards. However, the sum of current environmental seawater concentrations in the Fehmarn Belt region and the modelled concentrations of the three PAHs does not exceed MAC-EQS values. In the model simulation, the Fehmarn Belt region shows the highest accumulation of pollutants in the entire model area. These modeled values in the Fehmarn area are strongly influenced by the ferries. These concentrations correspond to a scenario where these ferries are assumed to use open-loop outside the port (due to the general model assumptions described in section 4.2). These ferries are actually using a closed-loop system with land disposal ("zero discharge mode", Scandlines, 2019). This means that the model may overestimate the emissions and in consequence the modelled pollution enrichment in this area. Nevertheless, EGCS wash water emissions over longer periods in areas with already elevated environmental concentrations and areas with low water exchange should be studied and future modelling studies should include current environmental concentrations and accumulative effects.

4.3.3   Spatial and Vertical Distribution

4.3.3.1   Spatial Distribution

Since the calculated spread of pollutant concentration is derived from the modelled wash water dispersion and the measured EGCS outlet concentrations, the modelled distribution pattern is the same for all substances. Furthermore, no transformation and sink processes were taken into account in the model simulation and thus the calculated spatial structures of individual pollutants only differ due to their different input quantities. Hence, all spatial pollutant

enrichment structures can be discussed and illustrated by one of them; here, is the Sum PAH taken as example. Thus, distribution maps are similar for most of the modelled compounds and give information about areas which are mostly affected by EGCS emissions in both scenarios. In this section, the maximum annual concentrations distribution of Sum PAH in the surface layer of the modelled area are presented and discussed.

Figure 24:   Maximum modelled concentration of Sum PAH in the CSS over one year in the surface layer. The pictures show different combinations of input data MinKonz and MaxKonz with MinWW, AveWW and MaxWW
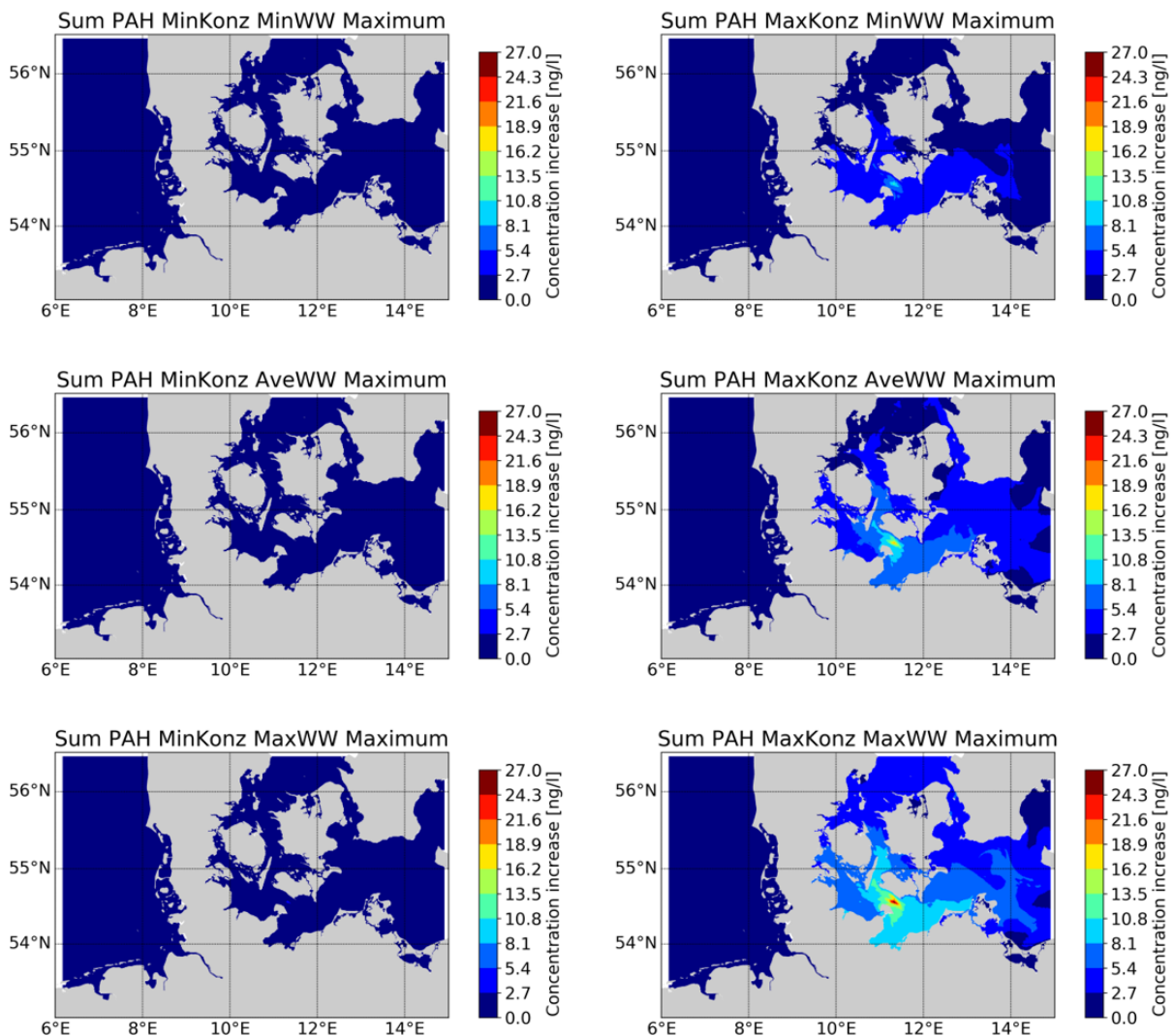
In the Baltic Sea, the modelled concentrations reach much higher values than in the North Sea, which might be due to the lower water exchange compared to the North Sea. In the North Sea the concentration of Sum PAH never exceeds 3.3 ng/L, while in the Baltic Sea, it reaches up to 29.0 ng/L (MaxKonz_MaxWW; see Figure 24). This maximum is visible in the Fehmarn Belt between Puttgarden (Germany) and Rødby (Denmark) due to the high frequent ferries lines (as discussed already before).

Figure 25:   **Concentration increase of Sum PAH for CSS (MaxKonz_MaxWW) on the coarse gridded area**
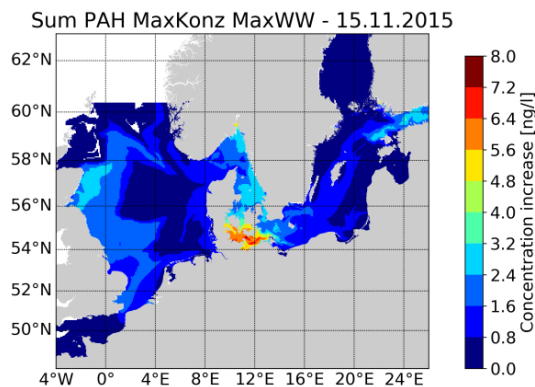
Figure 26:   **Maximum concentration of Sum PAH in the MIS over three years. The pictures show different combinations of input data MinKonz and MaxKonz with MinWW, AveWW and MaxWW**
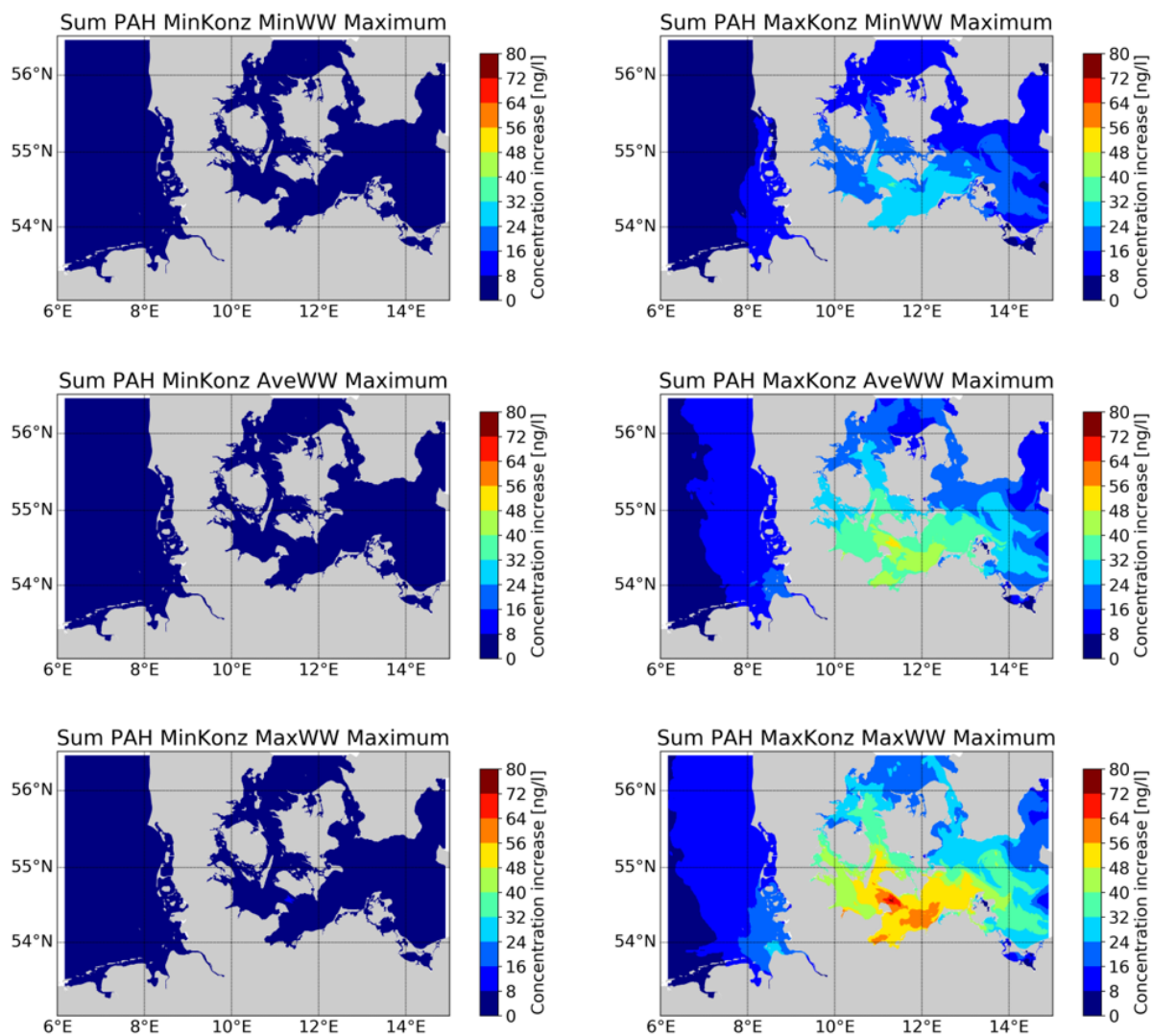
Figure 25 shows the concentration distribution for almost the entire SECA area. On this larger scale, the main shipping routes are visible in the CSS. The spatial distribution of the maximum concentrations in the MIS scenario is computed over the simulation period of three years (2015 – 2017). The difference of maximum reached concentrations between the Baltic Sea and the North Sea after three years is smaller than in the in the one year modelled in CSS.

In the North Sea, the modelled concentration peaks north of Cuxhaven are around 30 ng/L (MaxKonz_MaxWW). In the Baltic Sea, the highest values are again reached between Puttgarden and Rødby with more than 80 ng/L (MaxKonz_MaxWW). In that region, two more peaks emerge north of Warnemünde and in the area nearby Travemünde with concentrations of more than 63 ng/L (see Figure 26).

In both scenarios, the highest concentrations were reached in the Baltic Sea, in particular in the Fehmarn Belt and surrounding areas. These are areas with high ship traffic. Especially the ferries crossing the Fehmarn Belt are present in both scenarios. These are four ships, which are going back and forth 24-hours a day. As already mentioned in the previous section, the values in both scenarios might be overestimated for this particular area and correspond to a situation where these ferries would use open-loop outside the port and not closed-loop with land disposal. However, the spatial distribution in the North- and Baltic Sea clearly demonstrates that areas with a low water exchange, like the Baltic Sea, are more affected by EGCS emissions, than those with high water exchange.

4.3.3.2   Vertical Distribution

The vertical distribution of the modelled concentration of Sum PAH in the CSS and in the MIS (MaxKonz_MaxWW) for the surface and for every second model layer down to the bottom are shown in Figure 27 and Figure 28, respectively. All layers have a thickness of about 2 to 3 meters so that the concentrations are represented in various water depths up to about 30 to 35 meters.

The North Sea is well mixed and the modelled concentration are all in the range between 0 – 2.7 ng/L (CSS) or 0 – 16 ng/L (MIS) in all depths. While the North Sea is well mixed for large parts of the year, the Baltic Sea is heavily stratified throughout the whole year. Less dense water (low salt content) overlay the higher salt content water body at the bottom. An exchange between these layers is almost non-existent, which means that pollutants accumulated in bottom water of the Baltic Sea will remain there for a long time. In addition, there is a strong salinity gradient from west to east. The modelled EGCS pollutant enrichment in the Baltic Sea generally decrease with depth. In contrast to most of the regions, a downward positive gradient is visible northeast of Rügen in the Arkona basin in the MIS scenario. This might be due to the strong salinity gradient from west to east. Baltic inflow events (Mohrholz, 2018) ensure that the more saline water is transported eastwards and settles in deeper layers there due to its higher density. This leads to the fact that even in regions with low emissions and low pollutant concentrations at the surface, there may be higher pollutant concentrations near the bottom, like the Arkona Basin, where pollutants can accumulate.

The results demonstrate that emitted pollutants from EGCS can reach deeper layers of the North- and in particular the Baltic Sea within one to three years. This imply that persistent pollutants, like certain metals and PAHs, can reach the bottom layer and be stored in the surface sediments. In consequence, an increase use of EGCS will also affect sediment concentrations in the marine environment, which might have implication for sediment quality and benthos organisms.

Figure 27:   **Maximum concentration of Sum PAH in the CSS over one year for eight different model layers (MaxKonz_MaxWW)**
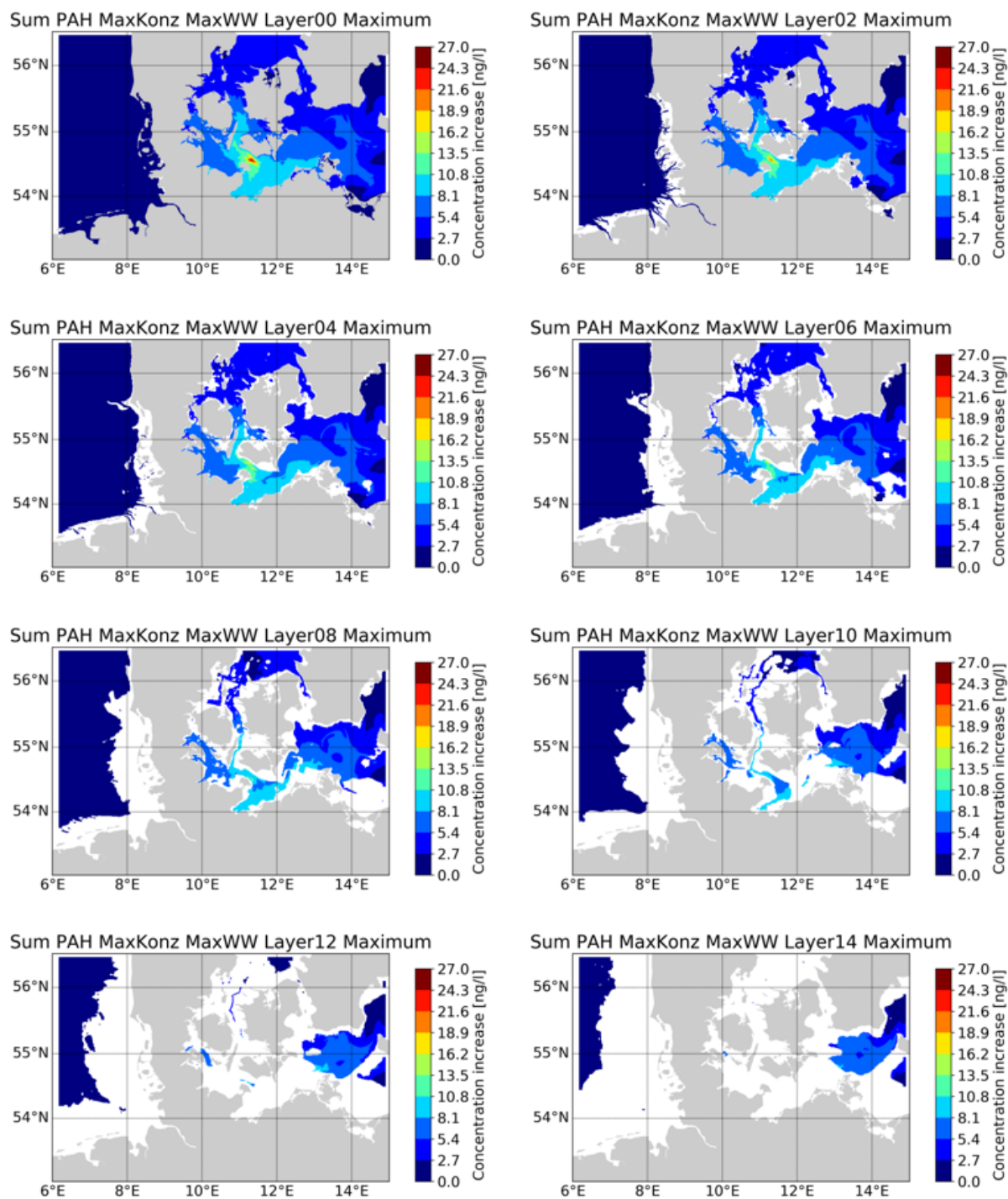
Figure 28:   **Maximum concentration of Sum PAH in the MIS over three years for eight different model layers (MaxKonz_MaxWW)**
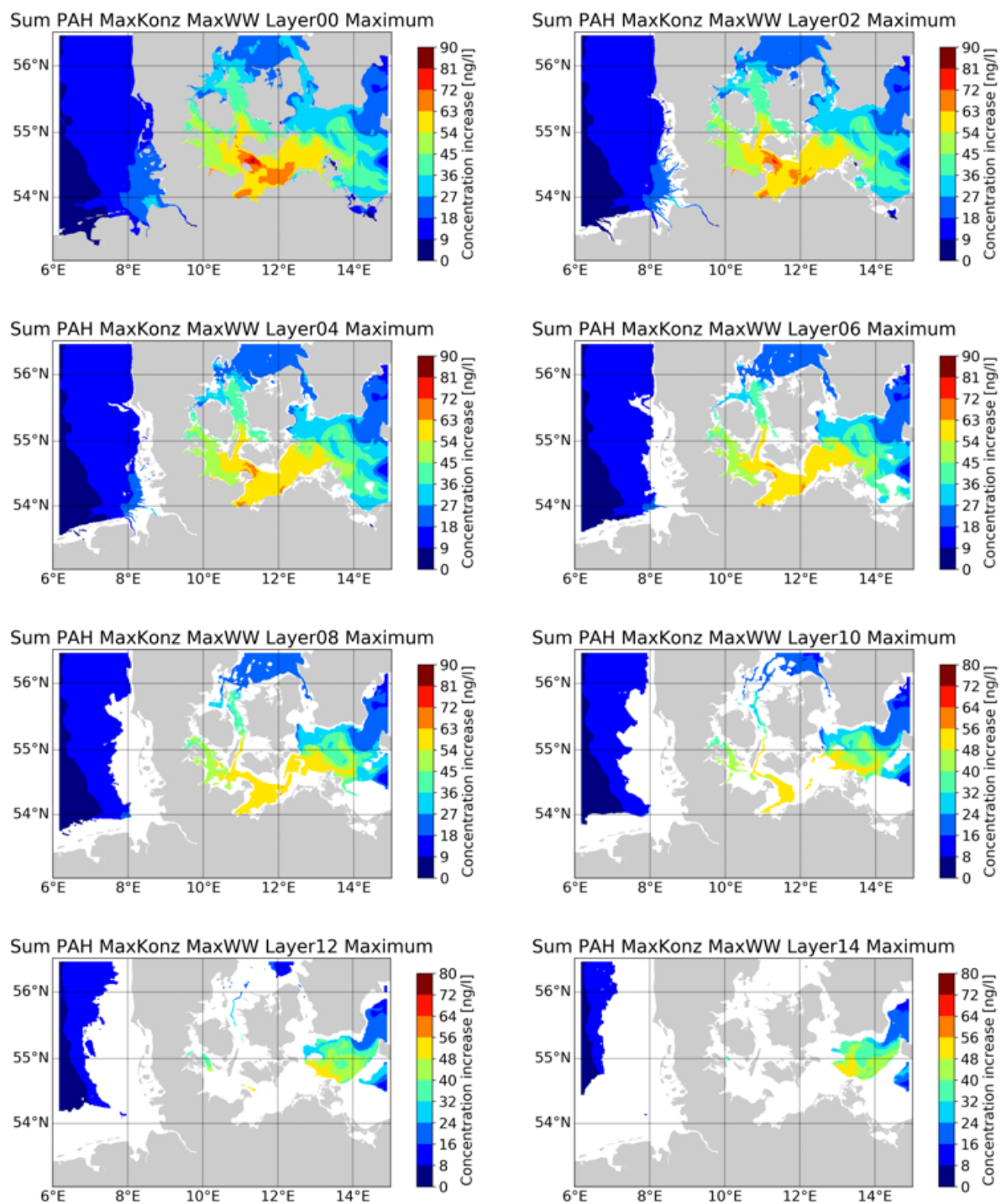
4.3.4 Temporal Variation of Pollutant Concentrations

The temporal variation of the modelled concentration of Sum PAH was investigated in the surface layer at 10 different locations, 5 in the North Sea (P0 – P4) and 5 (P5 – P9) in the Baltic Sea (see Figure 29).

Figure 29:   **Locations of the points for the time-series (black stars). The background is the concentration of wash water in the MIS relative to the highest value obtained in this scenario**
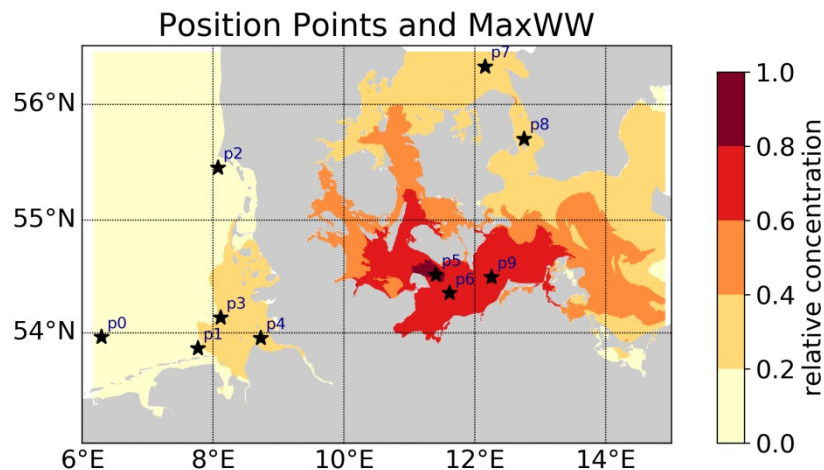
The investigated points were selected to evaluate the temporal variation of pollutants concentration in areas of special interest (e.g. close to shipping routes or environmental protected areas):

1. P0 (06,29°E 53,96°N): point located in the nature conservation area Borkum-Riffgrund

2. P1 (07,77°E 53,86°N): topographic junction of Weser and Jade north of Spiekeroog

3. P2 (08,08°E 55,45°N): point west of Esbjerg

4. P3 (08,12°E 54,14°N): point close to Helgoland

5. P4 (08,73°E 53,95°N): point north of Cuxhaven in the area of the natural reserve Wadden Sea

6. P5 (11,41°E 54,52°N): point located in nature conservation area Fehmarn-Belt

7. P6 (11,62°E 54,35°N): increasing contamination with depth, especially pronounced in the basin between Wismar and Fehmarn

8. P7 (12,16°E 56,32°N): point located at the northern edge of the fine gridded domain

9. P8 (12,76°E 55,70°N): point between Malmö and Copenhagen

10. P9 (12,26°E 54,50°N): point located in the nature conservation area Kadet Trench

The following figures depict the modelled concentration with MaxKonz for Sum PAH in the CSS. Figure 30 shows the annual variation at five points in the North Sea. The time series were smoothed with a 5-day running mean of MaxKonz_MaxWW. In the German Bight, the highest value is reached west of Esbjerg (P2) during August. Esbjerg locates a large port and, during that time, wash water was not transported away from this region due to only little residual currents that varies in direction during that time of the year ("Nordseezustand Aktuell" (BSH, 2019)). In such periods, the dispersion/dilution of the wash water is less. Since the North Sea is well mixed, the concentration progresses similar in all depths. Afterwards the concentration decreases. During summer the second highest concentration is at P4, north of Cuxhaven. In spring the concentration of P4 is even higher than at the other points during that time. This point is located close to the border of the Federal waterways (Elbe estuary). At this position, wash water from open-loop EGCS mixes with wash water from closed-loop EGCS.

The concentration shows an increasing trend at all points in the North Sea (Figure 30). Concentration of Sum PAH increases strongly at P0 (Borkum Riff), P1, and P3 (Helgoland) during December. At this time seawater with a higher concentration of wash water, emitted in the western North Sea, flows with a long-lasting, stable cyclonic circulation eastwards (BSH, 2019). In this situation, the wash water is transported to Borkum Riff (P0) from the West and continuous to the East. Therefore, Sum PAH increases first at P0, then at P1 and later at P3 and P4 - a procedure, which can be seen in December 2015.

Figure 30: **Concentration increase of Sum PAH at five different locations in the North Sea (CSS_MaxKonz_MaxWW)**
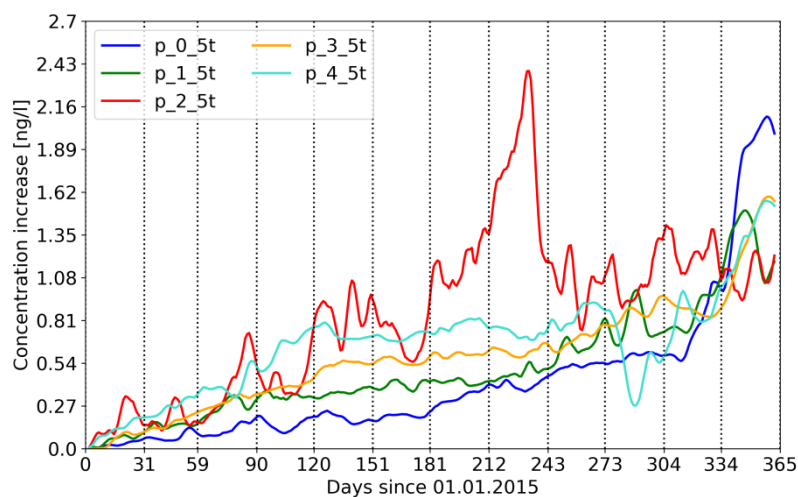
In Figure 31, the temporal progress of modelled concentration is shown for five points in the Baltic Sea. The time series of MaxKonz_MaxWW were again smoothed with a 5-day running mean. The highest values are reached at P5 (Fehmarn). It shows a fluctuation throughout the year evolving with a periodicity of about three weeks and noticeable higher values in summer. The second highest concentration is at P6 (between Fehmarn and Wismar) and the third highest at P9 (Kadet Trench). P5, P6 and P9 are located close to each other (within a distance of 50 km). Therefore, their temporal variation during the year is similar. The fluctuation is visible for all of them and has a periodicity of about two weeks. This may be related to circulation processes. In

periods of weak currents, more wash water accumulates; in periods of stronger currents, a widespread horizontal mixing occurs. In the points P7 (north of the Zeeland island, Denmark) and P8 (between Copenhagen and Malmö) the concentrations are significantly lower than at the other points, which can be (partly) explained by the large seawater exchange between North and Baltic Sea at these points.

Figure 31: **Concentration increase of Sum PAH at five different locations in the Baltic Sea (CSS_MaxKonz_MaxWW)**
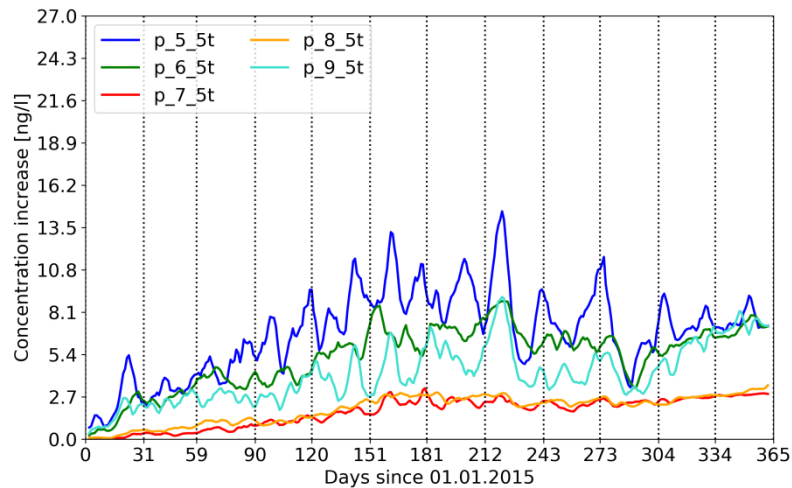
In the MIS the temporal variation of the modelled concentration of Sum PAH was investigated for a three years period. The following figures show the monthly mean of MaxKonz_AveWW, the monthly maximum of MaxKonz_MaxWW, and the monthly minimum of MaxKonz_MinWW in the North- and Baltic Sea. This visualizes the uncertainty of the modelled concentration due to the range of measured wash water emissions.

Figure 32: **Concentration increase of Sum PAH in the North Sea during the period 2015-2017 with three wash water emission rates (MIS): AveWW (solid), MaxWW (dotted), MinWW (dotted)**
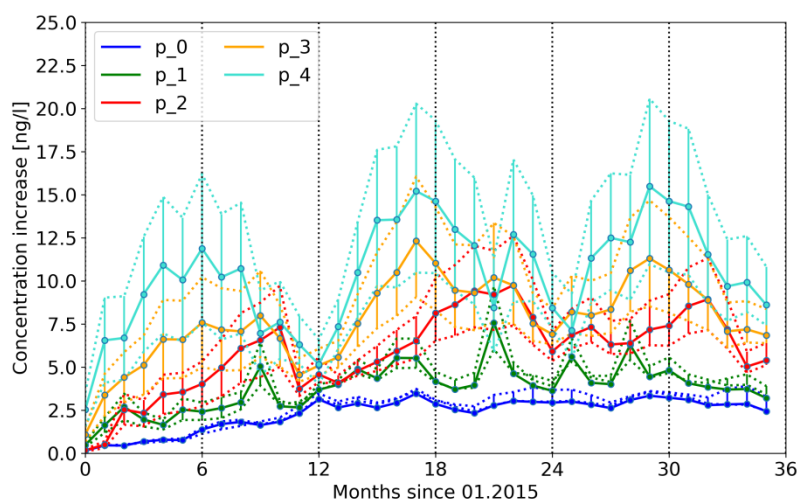
The MIS aims to investigate effects on longer time scales of a widespread use of EGCS over three years. In the North Sea the maximum concentration is reached around Cuxhaven and Helgoland (Figure 32). In comparison to the one year CSS, the concentration of Sum PAH is smaller in Esbjerg than in Cuxhaven (compare P2 with P4). Wash water emission peaks in CSS and MIS are

distributed differently due to varying numbers and geographical distributions of seagoing vessels. The difference of wash water emission between MIS and CSS is much larger around Cuxhaven than around Esbjerg. A seasonal cycle is visible at P3, P4 and P2 with a maximum in summer-autumn and a minimum in winter. In the North Sea a small increase of Sum PAH is visible. The minimum PAH accumulation in winter (November-January) could be attributed to increased wind/storm activity during this season, which leads to effective mixing of the water column and increased water exchange in the German Bight. In addition, seasonal fluctuations of the wash water discharge can occur, e.g. in certain regions the activity of cruise ships is lower in winter than during summer.

Figure 33: **Concentration increase of Sum PAH in the Baltic Sea during the period 2015-2017 with three wash water emission rates (MIS): AveWW (solid), MaxWW (dotted), MinWW (dotted)**
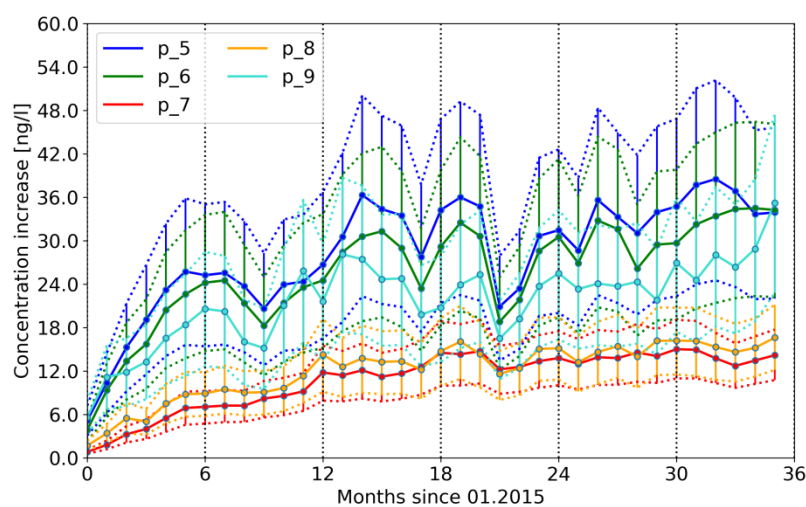
In the Baltic Sea the amount of wash water at the surface increases over the whole three years, whereas the gradient is largest in the first year (see Figure 33). The highest concentration of Sum PAH is reached around Fehmarn (P5). At the points nearby (P6, P9) the concentration is slightly smaller. The concentration is influenced by two major events in May 2016 (17th months) and September 2016 (21th month). There, the monthly mean concentration drops clearly at P5, P6, and P9. Phases with predominating easterly winds can explain these drops. Wind measurements from Darsser Schwelle (Copernicus, 2018) show several phases of continuous winds from the East during the year 2016. Between May, 25th and June, 7th wind mostly came from Northeast to East. Between September, 12th and 21st wind mostly came from East and between October 3rd and 16th it came from Northeast (first) and Southeast (later). Winds transfer their impulse to the surface and influence the surface currents of the sea. During these stable weather conditions with easterly winds, surface water with lower Sum PAH concentration from further East might be pushed further West resulting in a concentration drop at P5 and P6.

Summarising, the annual cycle is clearly visible in the North Sea, with lower concentrations in the winter season. North Sea surface concentrations do not show a clear increasing trend over the entire modelled three years period. This might be due to the strong influence of the tide and the high water exchange to other regions like the North Atlantic.

The Baltic Sea modelled data do not show this clear annual trend. Surface water concentrations in the Baltic Sea show an increasing trend over the three years period, so no equilibration is

reached within this three-year period between emission input and e.g. transportation to sinks (like sediments or deeper layer) or water exchange to the North Sea.

Nevertheless, the modelled time period is too short to determine if the North Sea can reach an equilibrium or if the concentrations would continue increasing over time. The data of the Baltic Sea suggest a further increase, but this has to be verified by longer modelling periods.

4.4   Conclusions - Dispersion Modelling

The HIROMB-BOOS model in combination with the modelled emission data from the EMMA model was successfully applied. Real ship movement data are used to estimate the wash water emissions from EGCS into the North and Baltic Sea. A general assumption for the type of scrubber used was made: EGCS on-board are hybrid and are operated in open-loop mode, where it is allowed. Although substances were modelled as passive tracers, this study gives a first insight of a potential distribution of these substances in the investigated area.

In general, Baltic Sea concentrations are always higher than North Sea concentrations due to lower water exchange. Depending on the scenario, modelled concentrations of some PAHs reached similar or even higher concentrations than current environmental concentrations, for example, in the Fehmarn Belt area. In this specific area the wash water input might be overestimated, because the modelled concentrations are corresponding to a situation where the high frequent ferries would use open-loop outside the port. As aforementioned, these ferries are actually using a "zero-discharge" closed-loop system with land disposal (Scandlines, 2019). However, environmental quality standards (maximum allowable concentrations, MAC-EQS) are not exceeded within the modelled time of three years in the maximum installation scenario, bearing in mind that not for all substances detected in the wash water EQS are available.

From the three years period modelled in MIS, data suggest seasonal concentration cycles in the North Sea, and only just a small enrichment is visible. The modelled data for the Baltic Sea show a clear increase and thus an accumulation of pollutants. Although wash water is only emitted in the surface layer, vertical distribution data suggest, that substances emitted by EGCS will also reach deeper layers within one year.

As a conclusion, EGCS emissions in areas with low water exchange and high ship traffic may increase pollutant concentrations in the marine environment. Areas with already elevated environmental concentrations and areas with low water exchange should be further studied. This study only covers a three years period, future modelling studies should consider longer periods to better identify long-term effects of scrubber usage and should include current environmental pollutant concentrations and accumulative effects for better comparison with EQS values. For a further understanding of the fate of the substances in the marine environment, dispersion modelling in combination with an ecosystem and/or chemical transport module is necessary. This would certainly provide more accurate information about the fate and distribution of the compounds in the marine environment.

5 Conclusions and Outlook

The international regulation of the IMO for the reduction of atmospheric sulphur emissions from sea-going vessels included EGCS as an alternative technology for reaching the sulphur limits in MARPOL Annex VI. Even though MEPC.259(68), the "2015 EGCS Guidelines", regulates the discharge of wash water, the possible negative impact to the marine environment are of concern. Several organizations and institutes as well as ship operators carry out research to address the concern that the use of EGCS might just shift the pollution from the atmosphere to the marine water body.

The EGCS technology improves the air quality, but it is not clear yet what the impacts of the discharge of wash water, which contains pollutants, for the marine environment are. The assessment of the impact is an important basis for possible future considerations about regulating the use of EGSC technology at least in in sensitive marine areas. This study wants to contribute to the assessment of impacts with scientific results of the wash water survey and the modelling scenarios for the concentration and distribution of pollutants in the North and Baltic Sea.

The market analyses demonstrated that around 5% of the global fleet will be equipped with EGCS by 2020. Further estimations are unclear as the development of the fuel market is uncertain and thus, affecting the future of this technology. Despite being initially discussed as a short-term retrofit solution for older ships, in practice, EGCS are also installed in new ships. The data demonstrated that mainly open-loop or hybrid systems have been installed so far. Due to the expected increased application of the EGCS in the future, a better understanding of its impact on the marine environment is necessary.

In this study, chemical analyses of wash water samples for a wide range of substances were performed to increase the knowledge about the potential pollutant emissions of EGCS to the marine water body. The conditions for reproducible and quality-assured sampling were not always met on board. During the sampling campaigns, it became apparent that suitable sampling points could be difficult to access, material or dimension did not meet the requirements, or were not available at all. In order to improve the quality and comparability of wash water sampling and measurements on board, suitable technical standards for the design and arrangement of sampling points should be developed. Additionally, detailed descriptions about all necessary steps from sample collection to the laboratory analyses, including sampling preparation, storage and transportation, are necessary for a sufficient quality assurance. Therefore, the project team developed a handout for ship operator "Concept for sampling and analysis of wash water from Exhaust gas cleaning systems" (see Annex 8.3) and together with the ESSF EGCS-subgroup submitted to PPR detailed instructions for wash water sampling, data collection and analysis (PPR 5/11).

The chemical analyses demonstrated the occurrence of a wide concentration range of metals, suspended particulate matter, nitrate, oil and PAHs in the discharged wash water. Bleed-off water from closed-loop systems was higher contaminated than open-loop wash water. The concentration of all measured substances varied between ships and EGCS-types. This might be explained by different EGCS design features, scrubbing efficiency, wash water quantity, fuel type and consumption, combustion conditions, and engine performance.

The concentration of most of the investigated parameters in both EGCS operation modes were increased in the discharged wash water compared to inlet and current environmental seawater concentrations in the North and Baltic Sea, which may lead to pollutant accumulation or, with regard to nitrate, to eutrophication. The strongest enrichment in the wash water was observed

for vanadium, nickel and some PAHs. Furthermore, the reduced pH and alkalinity of the wash water may have implication for the discussion about ocean acidification. In this study, only target analyses were performed, therefore future investigation should also include non-target methods to identify the full range of substances in the wash water.

This study also revealed that more effort is needed for the quality assured operation of on-board monitoring units to provide reliable indicators of wash water quality. The comparison of the PAH_{PHE} measurements of the automated on-board unit with the results of the detailed PAH measurements in the laboratory showed a mixed picture. As a result, the relationship between online measurements and PAH concentration in wash water samples are still bearing open questions. Further research and calibration standards are necessary in order to elaborate comparable thresholds for both methods, online measurements and laboratory analysis, to enable the reliable evaluation of wash water emissions with regard to their PAH and oil contamination. Then, the currently applied threshold values should be carefully evaluated about their protecting potential for the marine environment.

Wash water emissions to the North and Baltic Sea were successfully modelled based on real ship movement data. However, general assumptions were necessary regarding the scrubber type used. In the model, all ships are using hybrid systems. Ships were using open-loop, where it is allowed. This results in the low contribution of closed-loop discharge water compared to the total estimated discharge (from both, closed- and open-loop) and demonstrates that, although concentrations are significantly lower in open-loop systems (due to the high dilution), a significant quantity of pollutants will be emitted to the marine environment by the use of open-loop EGCS systems. Closed-loop discharges are a highly contaminated point source (especially for PAHs).

The results from the model calculations demonstrate that in areas with low water exchange, like the Baltic Sea, wash water and thus pollutants enrichment is stronger than in areas with more frequent water exchange like the North Sea. In the area with the highest modelled wash water input, the sum of maximum-modelled pollutant concentrations in the seawater and environmental concentrations of selected substances were still below environmental assessment criteria (maximum allowable concentrations, MAC-EQS) in both scenarios (Current State Scenario – CSS; Maximum Installation Scenario – MIS). However, depending on the scenario, the modelled additional concentrations of investigated PAHs due to EGCS operation can reach similar or even higher concentrations compared to current environmental concentrations. Hence, wash water emissions from EGCS may lead to a significant increase of the environmental concentrations in areas with high ship traffic and low water exchange. Furthermore, the modelled three years period (MIS) indicate ongoing increasing wash water accumulation over the entire period, especially in the Baltic Sea. Therefore, the use and impact of EGCS in areas with low water exchange (e.g. Baltic Sea, lagoons or harbours) or other sensitive areas needs to be further investigated, in particular with regard to long-term effects.

For future studies, chemical and biochemical processes should be included in the model, as far as possible, to add transformation processes to the transport calculations. In addition, current environmental concentrations have to be included. This could provide a significant step to improve pollutant level calculations. In addition, sedimentation processes should be included for a better understanding of the pollutant transfer from the water column to the marine sediment.

For an environmental risk assessment, more ecotoxicity test data of EGCS wash water is necessary. First studies already investigated the toxicity of EGCS and reported toxic effects (Magnusson et al. 2018). In contrast to pollutant based chemical analyses, toxicity tests offer information of the combination effects of the pollutants in the wash water. In a next step, the

toxicity data has to be combined with modelled concentration values and compared with environmental assessment criteria. This might help to identify areas, which are sensitive to EGCS emissions and where measures might be necessary to reduce or restrict EGCS emissions, such as "zero emission-zones". Furthermore, the impact of the wash water on the seawater pH or nutrients and thus acidification and eutrophication, respectively, should be also included in future investigations. Further research will support a reliable database for considering a revision and extension of the criteria in MEPC.259(68) to ensure a better protection of the marine environment.

Concluding, the increasing application of EGCS on ships may improve the air quality in harbour cities and coastal areas, but will shift atmospheric pollution to the marine water body. This EGCS study provides scientific data about the EGCS market, chemical wash water characteristics and modelled emissions to the water column to improve the understanding about the potential impacts on the marine environment. Further research is needed for a better quantification and evaluation of the total impact on the marine environment of this relatively new and emerging abatement method. This has to include an environmental risk assessment of this new technology, providing sound scientific data for future recommendations and for a revision of related regulations.

6   Acknowledgements

7   References

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8 Appendix

8.1   EGCS Market Study – Detailed Results

Table A- 1:   **Amount of vessels with approved EGCS (as equivalent method) as notified by flag States in GISIS and the respective total fleet of those notifying parties**

Flag State	Notifications of vessels with approved EGCS in GISIS [i]		Total fleet [ii]	
	Amount of vessels	Share (%)	Amount of vessels	Share of global fleet (%)
Bahamas	38	18.5%	1,418	1.5%
Belgium	3	1.5%	192	0.2%
Cyprus	7	3.4%	1,020	1.1%
Denmark	14	6.8%	452	0.5%
Finland	26	12.7%	259	0.3%
Germany	8	3.9%	629	0.7%
Italy	16	7.8%	1,405	1.5%
Liberia	5	2.4%	3,321	3.5%
Lithuania	5	2.4%	61	0.1%
Malta	25	12.2%	2,205	2.3%
Marshall Islands	8	3.9%	3,419	3.6%
Norway	17	8.3%	519	0.6%
Panama	18	8.8%	7,914	8.4%
Singapore	3	1.5%	3,526	3.7%
Sweden	3	1.5%	359	0.4%
United Kingdom	5	2.4%	1,157	1.2%
United States	4	2.0%	3,692	3.9%
Total amount	**205**	**100%**	**31,548**	**33.5%**
Non-notifying Parties	(estimated) 407	-	62,621	66,5%

Source:

[i] IMO, 2017 (reviewed on 11 February 2019)

[ii] United Nations, 2018

Table A- 2:   Supplier market share of EGCS in the maritime industry

Manufacturer	Amount of ships equipped	Market share
AEC Maritime	4	2.0%
Alfa Laval	51	24.9%
Clean Marine	8	3.9%
CR Ocean	12	5.9%
EcoSpray	38	18.5%
Green Tech	1	0.5%
Hellmich	2	1.0%
Langh Tech	7	3.4%
Marine Exhaust	1	0.5%
ME Production	4	2.0%
Mitsubishi Kakoki	1	0.5%
Pacific Green	1	0.5%
Valmet	3	1.5%
Wärtsilä	57	27.8%
Yara	14	6.8%
Unknown	1	0.5%
Total amount	**205**	**100%**

Source: IMO, 2017 (reviewed on 11 February 2019)

Table A- 3: **Amount of vessels with approved EGCS (as equivalent method) by ship type and the respective total fleet of every ship type**

Ship type	Amount of vessels with EGCS [i]	Market share (%)	Global fleet [ii]	Share of global fleet with EGCS installed (%)
Bulk Carrier	3	1.5%	10,397	0.03%
Container Ship	19	9.3%	5,132	0.37%
Cruise Ship	75	36.6%	520	14.42%
General Cargo	7	3.4%	16,486	0.04%
LPG Tanker	15	7.3%	1,612	0.93%
Oil/Chemical Tanker	23	11.2%	12,330	0.19%
RoPax Ferry	21	10.2%	6,019	0.35%
RoRo Cargo	30	14.6%	1,745	1.72%
Vehicles Carrier	12	5.9%	837	1.43%
Total amount	**205**	**100%**	**56,317 [a]**	**0.36% [b]**

[a] Total amount of vessels includes categories "Other liquids" (149) and "Refrigerated bulk" (1090), therefore it does not correspond to the summation of the amounts in the column "Global fleet" (55,078).

[b] Result of 205 / 56,317.

Source:

[i] IMO, 2017 (reviewed on 11 February 2019)

[ii] MEPC-70, 2016

8.2   Chemical Analyses

Table A- 4:   Overview of analytical results for seawater inlet (I-O), open-loop discharges (O-O) and closed-loop discharges (C-AT)

	Seawater Inlet (I-O)			Open-loop Discharges (O-O)			Closed-loop Discharges (C-AT)		
	min	max	average	min	max	average	min	max	average
Nitrite, Nitrate and Sulphate [mg/L]									
Nitrite	< 0.06	< 0.06	< 0.06	< 0.06	1.3	0.3	6.3	351	174
Nitrate	< 0.08	1.5	0.4	0.1	1.7	0.6	44.1	290	159
Sulphate	426	2716	1,054	490	2,462	1,136	24,719	65,041	41,521
PAH [µg/L]									
Naphthalene	<0.003	0.03	0.005	0.57	9.47	3.02	0.12	3.84	2.16
2-methyl-Naphthalene	<0.003	0.03	0.005	1.09	10.39	3.70	0.46	7.87	3.57
1-methyl-Naphthalene	<0.002	0.01	0.002	1.05	8.32	3.00	0.40	5.83	2.83
Acenaphthylene	<0.002	<0.002	<0.002	<0.002	0.14	0.03	<0.002	0.19	0.08
Acenaphthene	<0.005	<0.005	<0.005	0.05	0.45	0.21	<0.005	1.04	0.37
Fluorene	<0.003	0.02	0.002	0.19	0.78	0.49	0.33	2.89	1.48
Dibenzothiophene	<0.002	0.03	0.006	0.16	0.45	0.31	0.62	2.91	1.82
Phenanthrene	<0.001	0.14	0.024	0.67	2.89	1.61	2.43	20.05	9.25
Anthracene	<0.004	<0.004	<0.004	0.01	0.15	0.04	2.16	14.99	6.76
Fluoranthene	<0.002	0.02	0.004	0.02	0.36	0.14	0.66	3.88	1.64
Pyrene	<0.002	0.03	0.001	0.01	0.50	0.20	0.94	5.90	2.18
Benzo[a]anthracene	<0.006	0.01	0.002	<0.006	0.04	0.02	0.51	1.96	1.13
Chrysene	<0.004	0.04	0.007	<0.004	0.49	0.18	0.55	3.41	1.92
Benzo[b+k]fluoranthene	<0.008	0.01	0.002	<0.008	0.13	0.05	0.19	1.11	0.50
Benzo[e]pyrene	<0.003	0.01	0.002	0.01	0.22	0.07	0.21	1.01	0.54
Benzo[a]pyrene	<0.012	<0.012	<0.012	<0.012	0.10	0.04	0.06	0.38	0.19
Perylene	<0.01	<0.01	<0.01	<0.01	0.06	0.02	0.01	0.17	0.07
Indeno[1,2,3-cd]pyrene	<0.02	<0.02	<0.02	<0.02	0.38	0.11	0.03	0.31	0.12
Dibenzo[a,h]anthrancene	<0.012	<0.012	<0.012	<0.012	0.05	0.02	0.04	0.14	0.09
Benzo[ghi]perylene	<0.007	<0.007	<0.007	<0.007	0.04	0.02	0.07	0.65	0.25

	Seawater Inlet (I-O)			Open-loop Discharges (O-O)			Closed-loop Discharges (C-AT)		
Sum PAH	<LOD	0.40	0.07	3.86	33.19	13.27	13.68	71.78	36.94
PAH$_{EPA16}$	<LOD	0.32	0.06	1.56	14.01	6.16	11.82	54.37	28.12
Hydrocarbon Oil Index [mg/L]									
HOI	<0.01	0.03	0.01	0.05	0.27	0.17	5.26	11.36	7.97
Metals (DF) [µg/L]									
V	0.3	6.4	2.8	10.6	290	78.4	3222	9014	5726
Ni	0.4	142	24.2	4.1	67.4	20.0	295	5646	2376
Cu	1.1	119	22.2	1.6	15.7	7.3	7.9	56.6	27.2
Zn	1.2	58.1	11.5	2.1	133	22.8	22.5	208	125
As	2.0	14.1	4.2	1.0	6.9	3.3	7.0	24.5	14.8
Cd	<0.01	0.06	0.03	<0.01	0.07	0.03	0.03	0.4	0.2
Pb	<0.06	0.16	0.04	<0.06	2.1	0.4	<0.06	2.1	0.7
Mn	1.7	8.7	3.7	1.5	5.3	3.3	21.7	51.0	40.5
Fe	1.1	64.2	10.6	3.3	156	42.3	11.9	416	145
Metals (SPM) [µg/L]									
V	<0.02	0.8	0.2	1.6	23.8	10.6	25.5	1622	617
Ni	0.03	1.0	0.3	1.4	7.3	3.8	15.2	644	278
Cu	<0.05	30.6	5.4	0.1	4.0	0.7	1.1	9.6	4.4
Zn	0.1	0.8	0.3	0.1	0.8	0.3	2.2	92.9	51.5
As	<0.01	0.07	0.03	<0.01	0.04	0.06	<0.01	2.2	1.0
Cd	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.02	0.01
Pb	0.06	0.1	0.09	0.05	0.1	0.08	0.5	1.9	1.2
Mn	0.08	2.5	0.9	<0.03	0.4	0.1	<0.03	1.9	0.9
Fe	2.0	88.4	26.5	7.2	87.2	20.7	51.9	685	349
Alkalinity [mmol/L]									
Alkalinity	1.6	2.5	2.1	0.0	1.4	0.4	0.0	0.0	0.0
SPM [mg/L]									
SPM	0.6	5.6	2.5	0.8	3.2	1.6	3.5	125	69

8.3   Handout for Ship Operator as Submitted to PPR

PROPOSED AMENDMENTS TO APPENDIX 3 OF THE 2015 GUIDELINES FOR EXHAUST GAS CLEANING SYSTEMS (RESOLUTION MEPC.259(68)) DISCHARGE WATER DATA COLLECTION

1   Introduction

1.1 The discharge water quality criteria are intended to act as initial guidance for implementing EGCS designs. The criteria should be revised in the future as more data become available on the contents of the discharge and its effects, taking into account any advice given by GESAMP.

1.2 Administrations should therefore invite the collection of relevant data. To this end, shipowners in conjunction with the EGCS manufacturer are invited to sample and analyse samples of EGC Systems.

1.3 The sampling may be conducted during approval testing or shortly after commissioning and at about twelve-monthly intervals.

1.4 In the future the extent of sampling may be adapted or enhanced in the light of developing knowledge.

1.5 It is recommended that a ship that has provided information according to this appendix and to the satisfaction of the Administration should be granted a waiver as regards compliance of the existing installation(s) with possible future stricter discharge water standards whilst acknowledging the relevance of UNCLOS article 195 and the fact that restrictions may be in place in certain areas in order to ensure that environmental quality standards under regional or national water quality legislation are met. The Administration should forward information submitted on this issue to the Organization for dissemination by the appropriate mechanisms.

2   Sampling

In order to evaluate the contents of the discharge water and its effects, samples should be analysed for the parameters listed under paragraph 2.5 of this appendix. Sampling water should be taken from the following sampling points:

Open-loop: Inlet, Outlet and after the treatment but before dilution.

Closed-loop: Inlet, before treatment, after treatment and dilution. Temporarily stored discharge water, from any tank designed for that effect, from the bottom of the storage tank.

2.1   Preparation

This section describes preparations required prior to any sampling.

2.1.1 The EGCS needs to be equipped with sampling points for sampling of the following water streams:

- inlet water (for background);

- water after the EGC unit (before or after treatment but before any kind of dilution); and

- discharge water after treatment and dilution.

The sampling points should meet the requirements listed under 10.6 of the Guideline.

2.1.2   Preparation for sampling, handling and transport

2.1.2.1 Sampling equipment

The sampling equipment in accordance with paragraph 2.5 needs to be on board prior to sampling. The equipment can be ordered from the laboratory performing the analysis. The equipment should be ordered well before the sampling takes place, taking into consideration the itinerary of the ship.

Labelling of the sampling bottles should be completed before sampling, as the bottles might get wet during filling. The labelling should contain information that can identify which bottle contain which water (OL/CL, inlet/outlet etc.) and at which hour the sample was drawn. In this manner, continuous recorded EGCS control parameters can be retrieved at a later stage. A list with the required information is sown under paragraph 3.2.7.

The table below lists the recommended physical properties of the sampling bottles needed. It takes ISO 5667-3 and the appropriate analytical standard into account. The table furthermore informs how the samples should be stored when drawn and when they latest need to reach the laboratory for analysis (be aware that laboratories do not perform work during weekends).

Parameter	Bottle material	Volume	Method specifying sampling bottle requirements	Storage temperature	Maximum time until analysis
NO_2^-/NO_3^-	PE	250 mL	ISO 10304-1	Frozen (≤ -18°C)	8 days
Metals	PE	0,5 L	ISO 17294-2	Cooled (4°C) / dark	1 month
PAHs	Amber-glass with PTFEseal	2 L (OL), 1 L (CL)	DIN EN 16691 or EPA 8270	Cooled (4°C) / dark	7 days
Oil detailed GC-MS analysis	tba	tba	ISO 9377-2	tba	tba

2.1.2.2 Preparation for storage and holding of samples

In order to ensure proper storage and holding, the onboard space for samples and ice packs as required needs to be prepared. E.g. the cold garbage room or a provision room may serve as onboard storage space for samples. If the samples have to be stored in a food-handling area, they must be leakage proof, away from food items, and secured against the ship's movement, preferably in an enclosed container.

2.1.2.3 Preparation for transport

In order to ensure proper transport of samples, ice packs as required under 2.4.1 of this appendix, should be deep-frozen at least 48 h prior to sampling.

Shipping of the samples should be arranged in advance with the port agent of the destination port.

2.1.2.4 Preparation of personnel conducting the sampling

In order to ensure the safety of the ship and the health and safety of the personnel taking the samples, the following should be ensured:

> 2.1.2.4.1 Personnel conducting the sampling are aware of the hazardous nature of the sampled water and the risk from consuming it or from contact with soft tissues like the eyes.

> 2.1.2.4.2 Personal protection equipment should be used in accordance with ship/company requirements. Protective eyeglasses/goggles, ear protection, gloves, protective clothing and safety shoes are recommended.

2.1.2.5 Personnel qualifications and responsibilities.

It is important that the personnel taking the samples are well trained. They need to be aware of:

- • how the system is working and where the sampling points are located; and

- • how to dispose of the flushing water collected during flushing.

2.1.2.6 Information prior to sampling

Prior to sampling the template under 3.1 should be completed.

2.2   Collection

Sampling should be conducted at the sampling points described in paragraph 2.2.1, below.

2.2.1   Sample Time Schedule

A Sampling Time Plan should be produced in advance and agreement reached with the ship's master/captain as to how Engine and EGCS are operated during sampling. Sampling should be executed at least at two different Engine loads (50% and 85% MCR), having consideration for the relevant operational constraints as decided by the ship's master/captain.

Should auxiliary engines be fitted with EGCSs, samples may be taken while the vessel is at sea or at berth, and auxiliary engines should be operated at the highest practicable load. The sampling should be carried out after the system has been running under stable conditions (stable engine load, same fuel oil and stable washwater flow) for a sufficient time:

2.2.1.1 Open-loop operation: The system should have been running under stable conditions for 15 minutes before sampling.

2.2.1.2 Closed-loop operation: The objective for sampling and analysis of EGCS in Closed-loop operation should be the evaluation of the Water Treatment efficiency and to obtain

information on the typical pollutant contents in a holding/storage tank. Sampling should be executed during bleed-off.

2.2.2   Sampling schedule in relation to stage of journey

Samples should be taken no more than 24 hours before berthing. (see 2.3 of this appendix, regarding the maximum allowable sample preservation time).

2.2.3   Filling of the sampling bottle

In order to prevent any contamination of the sampling bottles, the correct filling of the sampling bottle is critical. Therefore it should be ensured that:

- Only sampling bottles prepared by the laboratory are used. For each parameter listed under paragraph 2.5.1 at least one bottle in accordance with 2.1.2.1. needs to be filled.

- Safety requirements as described under 2.1.2.4 are applied.

- The water flow is steady before and during sampling.

- The valve should be flushed with a minimum of 10 litres of sampling water before taking out samples and is not closed or touched after flushing and before the sampling is done.

- If more than one bottle is filled, the valve should not be closed in between.

- The use of any hydrocarbon-based cleaning agents at the sampling point must be avoided.

- Because of the risk of sample contamination, in-situ hoses must not be used for filling sample bottles. In general the use of hoses, funnels and secondary containers should be avoided.

2.2.4   Information while sampling

While sampling the template 3.2 should be completed.

2.3   Transportation

During transportation it is important to meet the requirements listed under 2.1.2.1 above.

2.3.1   Transportation container

For transportation an insulated and leak proof container should be used. The transportation container should be provided by the laboratory. It should be able to receive a sufficient quantity of ice packs.

2.3.2   Shipping to the laboratory

Shipping of the samples to the laboratory should take place as fast as possible. Labelling of the transportation container should be in accordance with local requirements for shipping and handling of water samples.

Immediately before handing over the samples to the port agent, the ice packs should be put into the box.

2.3.3   Chain of custody

Usually it is not necessary to include a customs declaration as these are water samples of zero commercial value.

2.3.4   Information from the laboratory

Take into consideration information, if any, provided by laboratory.

2.4   Sample preparation and analysis

Analysis should be undertaken by ISO 17025 accredited laboratories using EPA, ISO or equivalent test procedures. Methods used in the laboratories need to be within the scope of ISO 17025 accreditation of the laboratory.

2.4.1   To ensure comparability of laboratory results, the following methods are recommended:

Parameter	Recommended method for sample analysis	Recommended method for sample preparation
Polycyclic Aromatic Hydrocarbons (PAH): 16 EPA PAHs: Acenaphthene Acenaphthylene Anthracene Benzo-a-anthracene Benzo-a-pyrene Benzo-b-fluoranthene Benzo-g,h,i-perylene Benzo-k-fluoranthene Chrysene Dibenzo-a,h-anthracene Fluoranthene Fluorene Indeno-1,2,3-pyrene Naphthalene Phenanthrene Pyrene	To be determined DIN EN 16691 (recognising DIN EN 16691 as ISO is currently under consideration) (alternatively: EPA 8270)	To be determined DIN EN 16691 (alternatively: EPA XXXX)
Oil detailed GC-MS analysis	ISO 9377-2	ISO 9377-2
Nitrate and nitrite (NO_3^-/NO_2^-)	ISO 10304-1	No preparation required

| Metals:
▪   Cd
▪   Cu
▪   Ni
▪   Pb
▪   Zn
▪   As
▪   Cr
▪   V | Dissolved and total metal concentrations:

ISO 17294-2 | Total metal concentrations:
ISO 17294-2

Unsolved metals:
ISO 15587-2 |
| Discharge water pH should be determined by instant on-board measurements | tba | tba |

2.5   *Disposal*

Disposal should be in compliance with the local and laboratory requirements. If any special additives or reactants are present in or added to the samples, these should be indicated on the sampling bottles.

3   *Template for required sampling data*

When submitting sampling data to the Administration, the data should include information according to paragraphs 1 and 2 as well as the results from the analyses as described under paragraph 5.

3.1 Data Template Part 1 Information prior to sampling		
Parameter	Value	Unit
3.1.1 Ship information		
Ship's name		
IMO number		
Ship build date		dd.mm.yyyy
3.1.2 Combustion unit(s) details Engine questions should be answered for every fuel-burning facility connected to the EGCS		
Number of combustion units connected to EGCS		
Combustion units manufacturers		
Type of combustion unit(s) (ME, AE, 2/4-stroke, boiler)		
EGCS capacity in MW		
3.1.3 EGCS general		
Name of manufacturer		
Name of system		
Number of streams	single / multiple	
System operation mode	open / closed / hybrid	
Type of washwater treatment		

EGCS retrofit or new building		
Installation date		
ETM scheme A or B approval		
Additional notes:		

3.2 Data Template Part 2 Information for each sampling point while sampling		
Parameter	Value	Unit
3.2.1 Ship information during sampling		
Min. cruise speed		knots
Max. cruise speed		knots
Start of sampling date and time		UTC
Stop of sampling date and time		UTC
Ship's position start of sampling		GPS
Ship's position end of sampling		GPS
Weather conditions (during sampling)		calm / rough
3.2.2 EGCS operation during sampling		
Number of exhaust gas streams	single / multiple	
System operation mode	open / closed / hybrid	
Type of wash water treatment		
Added chemicals for treatment		Name
Dosage rate of added chemicals for treatment during sampling		[l/m³]
Average washwater flow rate to EGCS during sampling period		[m³/h]
Average dilution water flow rate during sampling period		[m³/h]
3.2.3 Combustion unit(s) operation during sampling		
Average combustion unit(s) load to EGCS		MW
Fuel consumption		t/h
Fuel sulphur content (according to fuel analysis)		
Fuel sulphur content (according BDN)		
Fuel viscosity if available		
Additional notes:		

3.2.4 Online monitoring readings during sampling, for each sampling point			
Monitoring unit	pH	PAH [µg/L / ppb]	Turbidity [FNU / NTU]

Inlet (if available), average during sampling period			
Discharge point, average during sampling period (Outlet)		NA	NA
Before dilution, average during sampling period	NA		

3.2.6 Results to be reported by the laboratory			
Question	Answer		Comments
Temperature requirements fulfilled during transportation	Yes / No		
Sampling bottles and transportation container prepared by laboratory	Yes / No		
Methods within the scope of ISO 17025 accreditation of the laboratory	Yes / No		
Date and time samples arrived at laboratory			
Date and time of analyses			
Parameter	Bottle ID	Preparartion method	Analytical method	Result + [unit]

Parameter	Bottle ID	Preparartion method	Analytical method	Result + [unit]
Polycyclic Aromatic Hydrocarbons (PAH): 16 EPA PAHs:				
Acenaphthene Acenaphthylene Anthracene Benzo-a-anthracene Benzo-a-pyrene Benzo-b-fluoranthene Benzo-g,h,i-perylene Benzo-k-fluoranthene Chrysene Dibenzo-a,h-anthracene Fluoranthene Fluorene Indeno-1,2,3-pyrene Naphthalene Phenanthrene Pyrene				
Oil detailed GC-MS analysis				
Nitrate and nitrite (NO_3^-/NO_2^-)				

Metals:				
▪ Cd ▪ Cu ▪ Ni ▪ Pb ▪ Zn ▪ As ▪ Cr ▪ V		97		

3.2.7 List of Bottle IDs

Sampling point	Parameter PAH	Parameter Metals	Parameter X
Inlet/discharge point etc.	Bottle #1 + time stamp	Bottle #2 + time stamp	Etc.
discharge point	Bottle # + time stamp	Bottle # + time stamp	Etc.
Etc.	Etc.	Etc.	Etc.

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