Ship pollution: **From air to ocean**

The science on pollution scrubbers and why EPA should ban scrubber discharge

PACIFIC ENVIRONMENT

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Exhaust gas cleaning systems (EGCS), also known as exhaust gas scrubbers, remove pollutants from the exhaust gasses produced by combustion engines, particularly those found in ships. Scrubbers take harmful pollutants *out of the air* and dump them *into the water*.

Recent scientific studies show that scrubber discharge is extremely toxic to marine life at very low concentrations, and scrubber discharge may have a serious impact on the populations of key species of marine food webs. Pacific Environment has compiled 26 recent studies showing the breadth and depth of new and substantial data, making the case for why the U.S. Environmental Protection Agency must ban scrubber discharge.

The Biden administration and the U.S. Environmental Protection Agency should respond to these increasing environmental threats and lessen health risks by banning scrubber discharges in U.S. waters, as they finalize pending regulations under the Vessel Incidental Discharge Act (VIDA).

Scrubber rules stalled

VIDA requires the EPA to develop national standards of performance for incidental discharges. The EPA issued a Notice of Proposed Rulemaking in October 2020, but the rule has not yet been finalized.

EPA's October 2020 VIDA proposed rule regarding requirements for exhaust gas emission control systems, only incorporates the IMO's 2015 guidelines for exhaust gas cleaning systems; updated guidelines were adopted in 2021 and 2022, which are under review.

EPA wrote in the proposal that the agency considered several other options for regulating EGCS discharges, including "to require vessels to switch from scrubbers to low-sulfur fuels while in U.S. waters" and "to ban discharges from scrubbers outright."

In a summary of restrictions on discharges from Exhaust Gas Control Systems, dated August 11, 2020, EPA concluded that "insufficient data exist at this time to warrant prohibiting these discharges under the Clean Water Act. Technical committees at the IMO are currently revisiting the need to perform additional assessments of environmental impacts from EGCS discharges, and EPA will continue to monitor the availability of research findings compiled in connection with these discussions."

Substantial data has been published since EPA's 2020 consideration of regulating scrubbers, as shown in the summaries below, and this new information documenting harms justifies and compels action now. In addition, the IMO has essentially ceded the opportunity for near-term regulation of scrubbers to nations, regions and local authorities.

Scrubbers explained

The most popular type of scrubber, open loop, constantly discharges large amounts of wastewater that is acidic and contains polycyclic aromatic hydrocarbons (PAHs), particulate matter, nitrates, nitrites and heavy metals including nickel, lead, copper, and mercury. These pollutants are discharged into the marine environment where they can damage marine ecosystems, threaten marine wildlife, and worsen water quality. In addition to adverse effects on marine life, exposure to and consumption of these toxic pollutants have been documented to cause cancer, affect neurological development in children, and lead to a host of other debilitating impacts on human health.

Closed-loop scrubbers emit the same pollutants in lower volumes, but higher concentrations. Closed-loop systems are the most expensive and, unlike open-loop systems, continuously collect and store scrubber sludge that must be removed from the recirculating wastewater.

A dramatic increase in scrubber use has occurred because of a new regulation adopted by the International Maritime Organization (IMO) that took effect in 2020.

The IMO's new global fuel sulfur limit reduced the maximum sulfur content for marine fuels from 3.5% to 0.50%, except for ships that have an exhaust gas cleaning system. Rather than switch to the more expensive 0.50% low-sulfur fuel, many ship owners have installed scrubbers. The number of ships in the international shipping fleet fitted with scrubbers increased from 243 in 2015 to more than 4,600 in 2024.

A study from Canadian agency Environment and Climate Change Canada (ECCC) details the state of regulations on scrubbers and findings from 2020 commissioned research by ICCT. The data collected showed that the use of scrubbers prior to 2018 was relatively rare, but in the lead up to the regulation implementation date of 2020 the number of unique vessels operating in Canadian waters equipped with scrubbers increased four-fold from 2019 through 2022, from 5% to 18% of the total number of unique ships operating in Canadian waters.

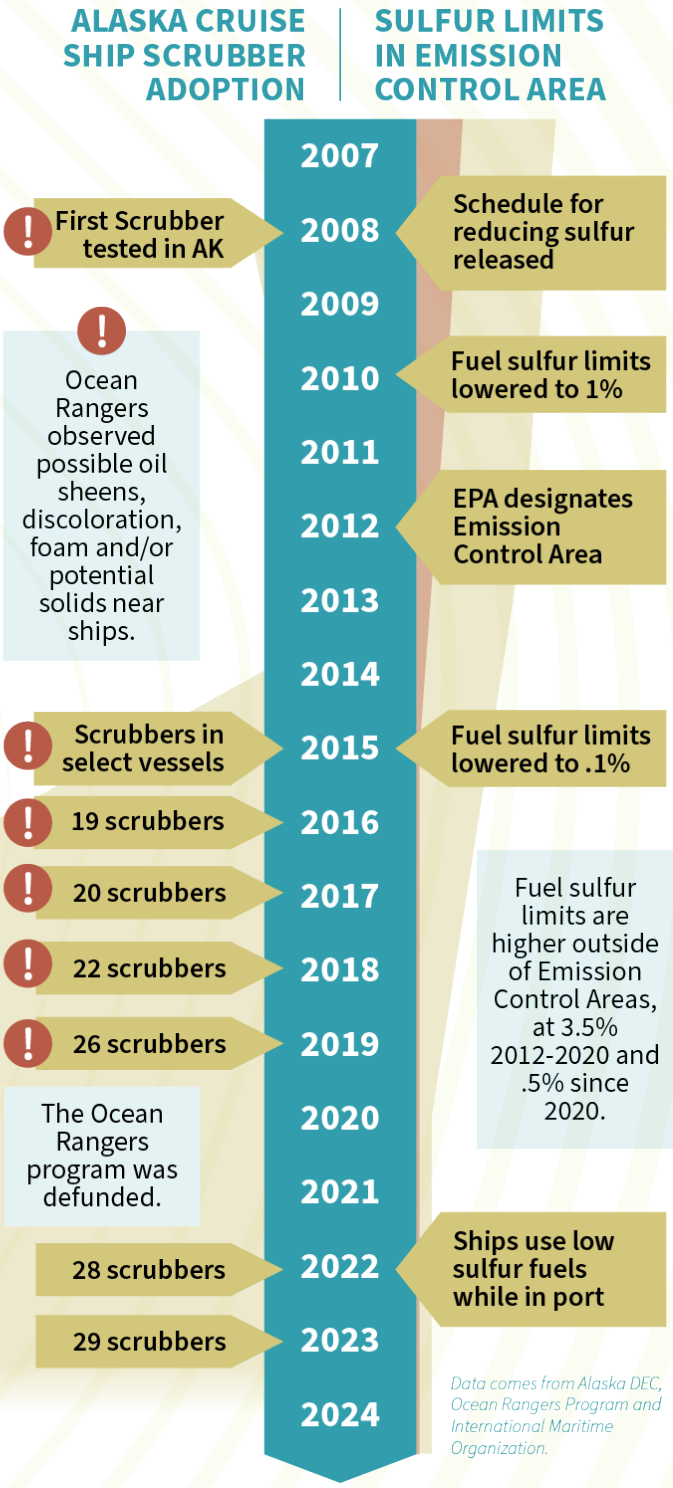


IMAGE 1. Courtesy of the Clean Arctic Alliance and Southeast Alaska Conservation Council

A growing body of scientific data indicates there is virtually no safe concentration of untreated scrubber effluent and that it negatively affects organisms throughout the marine food chain.The sources referenced found that concentrations of scrubber wastewater as low as 0.0001% have toxic effects on marine life. Scrubber discharges can increase seawater acidity, especially in places with high ship traffic, and discharges contain harmful and persistent substances like polycyclic aromatic hydrocarbons (PAHs), nitrates, nitrites, and heavy metals. For this reason, there have been 93 bans and restrictions on scrubbers across the globe, ranging from the port to national level and, most recently, in the countries of Denmark and Sweden.

A blog from Clean Arctic Alliance argues that scrubber usage violates multiple international agreements including the International Convention for the Prevention of Pollution from Ships (MARPOL) and the U.N. Convention on the Law of the Sea. These violations, the authors argue, suggest that scrubbers should be banned, considering that more than 90 bans and restrictions on scrubbers already have been adopted worldwide. In addressing concerns over sunk cost investments into scrubbers, the blog points to research that finds scrubbers pay for themselves quite quickly, with 95% of scrubbers' cost paid back within five years, meaning little financial damage to the maritime industry with a scrubber ban.

Scrubber environmental and wildlife harms

Harms from scrubbers have been documented to have significant impacts on the marine web of life and on the environment itself.

Significant impacts to the marine web of life

- Harmful impacts to multiple life stages of copepods and microplanktonic species that are the main food source for endangered species such as Resident Southern Killer Whales.
- Significantly elevated mortality rates and impaired molting of copepods in the lowest tested concentrations of open-loop effluent (1% dilution); this appeared more toxic than crude oil based on previous studies of oil toxicity in copepods.
- Unexplained high levels of mortality based on the concentrations of individual components of PAHs and heavy metals and multiple pollutants mixing together, leading to interactions between different compounds

being more toxic than the individual components indicating a “cocktail effect” from “witch’s cauldrons” where unknown toxic compounds form.

- Even very low concentrations of scrubber discharge have toxic effects on sea urchin egg fertilization (0.0001% concentration) and affect multiple species’ larvae development (0.001% concentration).
    - These harms begin much earlier than previously found and have a general effect across species.
- Scrubber discharge increased the mortality rate of copepod *Calanus helgolandicus* at the lowest concentration tested with controls for pH and alkalinity indicating that the physiological impacts were due to toxic effects of scrubber effluent and not pH.
    - In addition, further harms at even lower concentrations could not be ruled out.
- The reproduction of the marine copepod *Acartia tonsa* was found to be negatively affected by zinc, copper and nickel in concentrations of 0.64, 0.3 and 2.4 µg·L-1 which were exceeded for Zn by open loop scrubbers.
- There may also be limited efficacy in the testing protocol for pH, PAHs, and turbidity testing in isolation established by the IMO and adopted by many member states. Many studies found that combined effects of even trace amounts of metals and PAHs and other components of wash water can have debilitating effects on marine life, even when within the accepted levels set by the IMO.

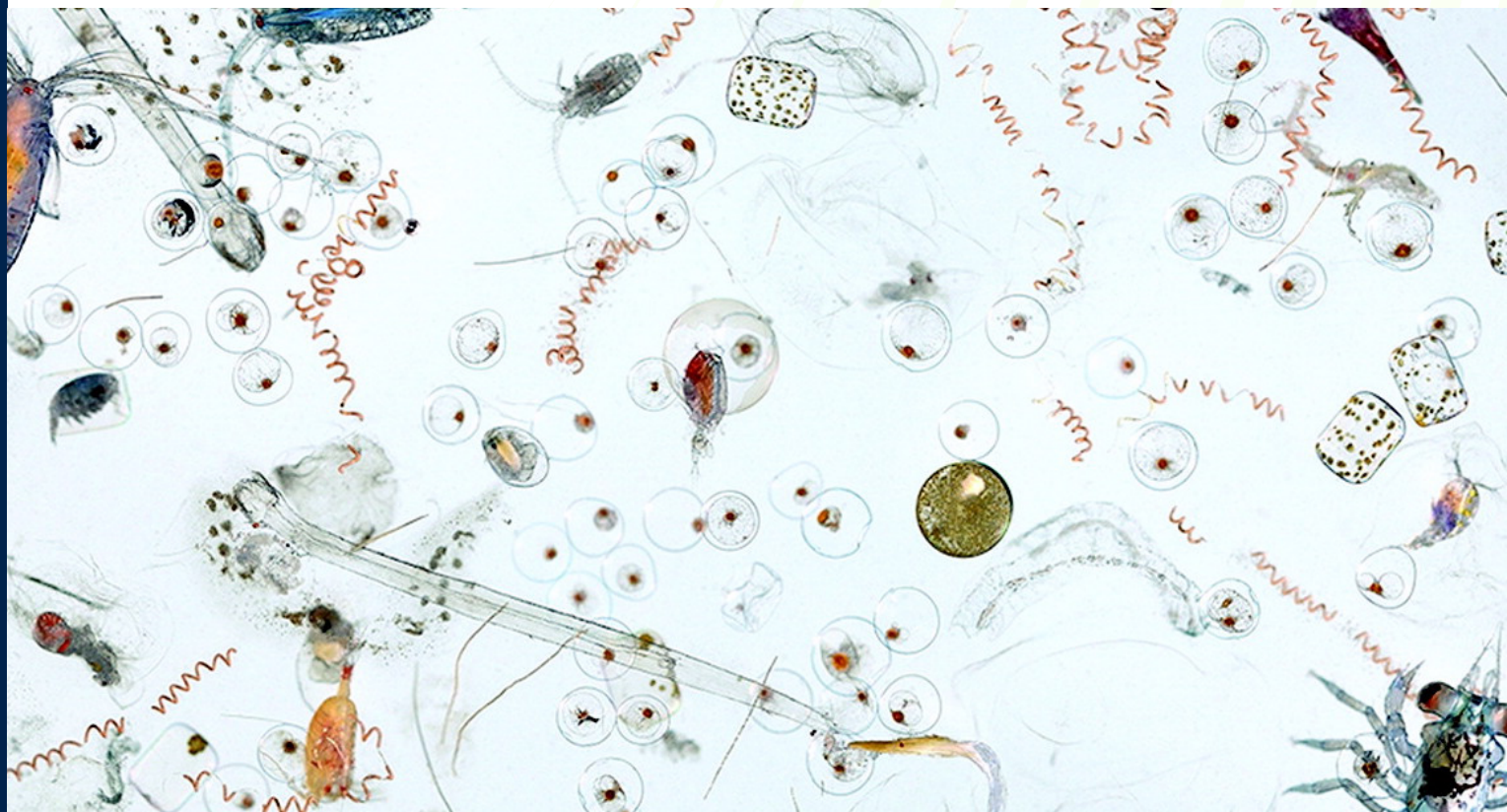
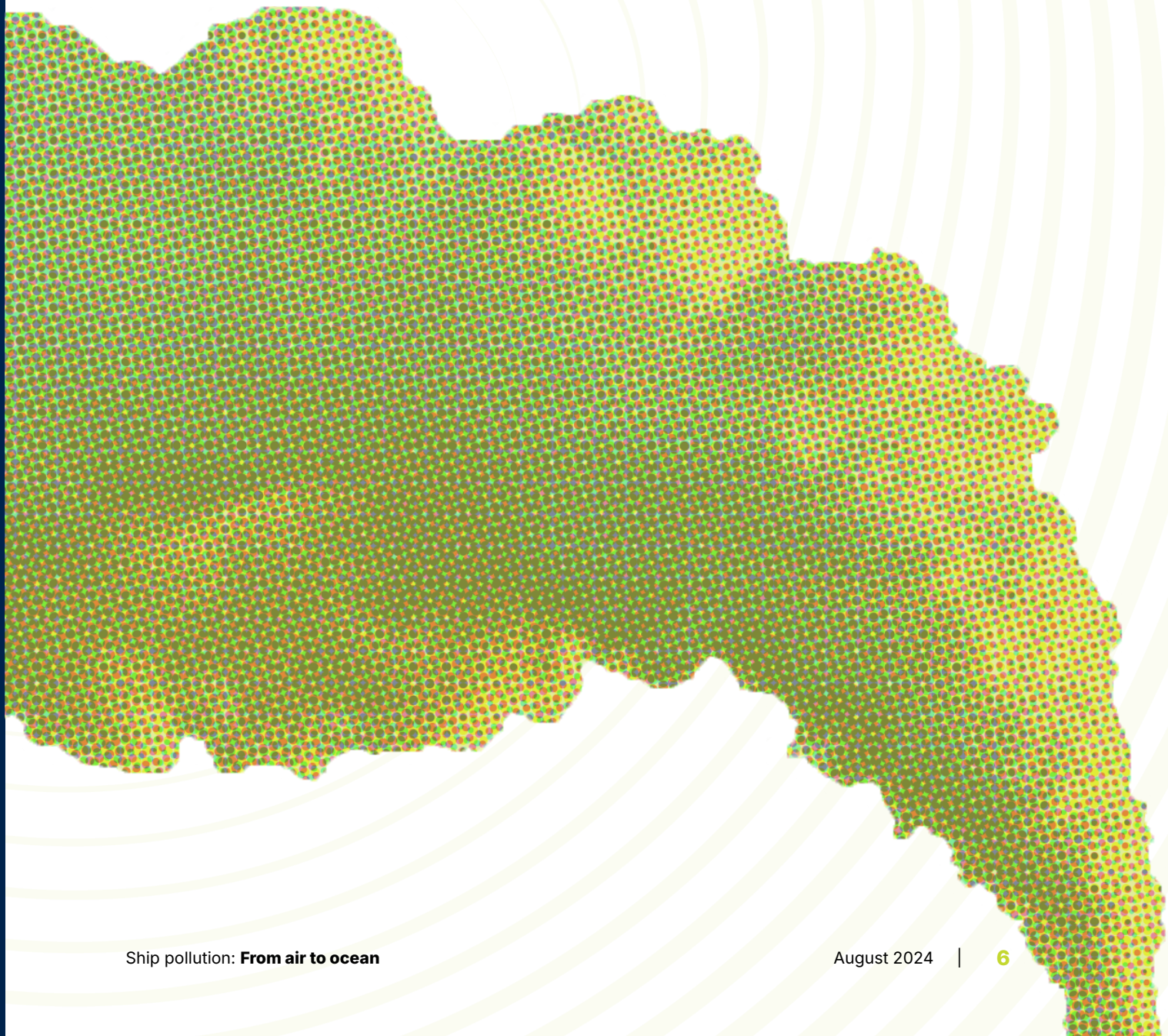


IMAGE: Marine microplankton (Wikimedia Commons)[1]

Significant impacts to the environment

- Use of scrubbers on ships burning heavy fuel oil (HFO) leads to even greater marine pollution and air emissions than use of HFO without scrubbers due to the additional energy demand and concentrated marine pollution.

- Additionally, scrubber discharge is still not well characterized and understood relative to marine and environmental impacts from PAHs derivatives and downstream compounds formed; thus the testing regime is even more limited as to not understanding the impacts of these compounds.



Published scientific studies and additional literature

Pacific Environment has summarized 26 scientific studies below that depict the harms from scrubbers utilized on ocean-going vessels.

Devastating air and water impacts from scrubbers

Johnson, K., College of Engineering-Center for Environmental Research and Technology University of California Riverside, Welch, B., Espinoza, C., Castelluccio, V., Asa-Awuku, A., & Miller, W. "Final Report Black Carbon and Other Gaseous Emissions from an Ocean-Going Vessel Auxiliary Engine Equipped with a Scrubber." Prepared for: California Air Resources Board, *California Air Resources Board Transportation and Toxics Division Emissions Assessment Branch*. (2013). https://ww2.arb.ca.gov/sites/default/files/2019-11/bc_scrubber_ADA_0.pdf

The California Air Resources Board (CARB) and the International Council on Clean Transportation commissioned this report to assess the effectiveness of exhaust gas after-treatment scrubbers at reducing SO_X, PM (including $PM_{2.5}$ and black carbon) and other pollutants at different engine loads. The results found that for black carbon removal, scrubbers' performance depended heavily on engine loads, with low loads removing only 10% of black carbon emissions and higher engine loads achieving up to 80% removal. This report builds on existing research demonstrating the lack of scrubber efficiency when applied in the real world, particularly the Parliament Transport Committee, Evidence from Maritime UK (SES 03b) which reported on several vessels whose scrubbers were unreliable and performed very short of the performance standards criteria. The evidence in this report helped support CARB's decision to prohibit the use of scrubbers to meet sulfur emission restrictions.

International Council on Clean Transportation. "Air emissions and water pollution discharges from ships with scrubbers." (2022, January 25). https://theicct.org/publication/air-emissions-and-water-pollution-discharges-from-ships-with-scrubbers/

The authors of this study use the methods from the fourth IMO Greenhouse Gas Study to estimate the air and water emission factors for ships using heavy fuel oil (HFO) with scrubbers compared to ships using marine gas oil (MGO). The results show that ships using HFO with scrubbers produce significantly more air pollution than ships using MGO. Ships using HFO with scrubbers had particulate matter emissions 70% higher, black carbon emissions up to 4.5 times higher and higher life cycle carbon dioxide emissions compared to ships running on MGO. In addition to greater air pollution, HFO ships with scrubbers also produce more water pollution with discharge water that is more acidic and turbid than surrounding water and that contains toxins like polycyclic aromatic hydrocarbons (PAHs), nitrates and heavy metals. This water pollution contributes to ocean acidification and cancer and reproductive disorders in threatened and endangered marine mammals. Given these effects, the authors recommend restricting or prohibiting scrubber discharge immediately and phasing out scrubber usage on an international level.

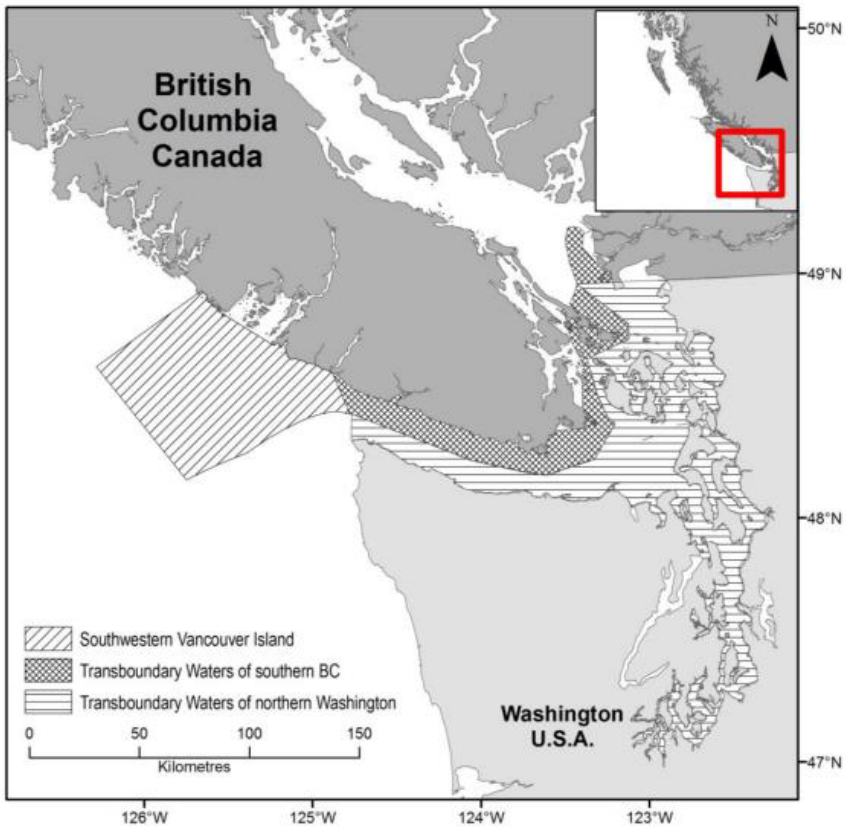
Government of Canada, Response to USMCA submission SEM-23-007 (*Vessel Pollution in Pacific Canada*) (12 April 2024), online at <http://www.cec.org/wp-content/uploads/wpallimport/files/23-7-rsp_en.pdf>.

This report from Canadian agency Environment and Climate Change Canada (ECCC) details the state of regulations on scrubbers and findings from 2020 commissioned research by ICCT. They found that discharge wastewater is low in pH, high in turbidity, and contains toxic substances including PAHs, nitrates, sulphuric acid and heavy metals. Canada submitted this report to the IMO PPR Subcommittee and states that it "plans to continue to evaluate the impacts of the growing use of scrubbers."

The data collected showed that the use of scrubbers prior to 2018 was relatively rare, but in the lead up to the regulation implementation date of

2020 the number of unique vessels operating in Canadian waters equipped with scrubbers increased four-fold from 2019 through 2022, from 5% to 18% of the total number of unique ships operating in Canadian waters. ECCC's Marine Emissions Inventory Tool calculates that **in 2022, ships equipped with scrubbers discharged more than 88 million tonnes of wastewater in Canada's Pacific Coast. In 2019, ships discharged 44 million tonnes — therefore the wastewater discharged nearly doubled from 2019 to 2022.** Scrubber wastewater contained 226 kg of PAHphe, and nearly 26,000 kg of metals in 2022.

ECCC estimates that more than 26 million tonnes of scrubber wastewater was discharged into southern resident killer whale (SRKW) critical habitat in 2022, including 69 kg of PAHphe and more than 8,000 kg of metals. Canada's Recovery Strategy for this species identifies environmental contaminants as a key threat to viability and recovery of SRKW populations while PAHs, copper, cadmium and lead are priority contaminants for SRKW primary prey Chinook salmon. **ECCC estimates that marine vessel scrubbers contribute between 40-98% of the loading of priority contaminants within 300 miles of SRKW critical habitat.** Further, ECCC calculated that scrubbers are estimated to be responsible for the largest proportion of vanadium within 300 miles of the SRKW critical habitat.



Hermansson, A. L., Hassellöv, I., Jalkanen, J., & Ytreberg, E. "Cumulative environmental risk assessment of metals and polycyclic aromatic hydrocarbons from ship activities in ports." *Marine Pollution Bulletin, 189*, 114805. (2023). https://doi.org/10.1016/j.marpolbul.2023.114805

This study uses a ship traffic model, coupled with the marine antifoulant model Marine Antifoulant Model to Predict Environmental Concentrations (MAMPEC) to calculate the predicted environmental concentrations of metals and polycyclic aromatic hydrocarbons (PAH) at four different ports. The study found unacceptable risk at three out of the four ports, with antifouling and scrubbers being the main sources of cumulative risk. Their assessment demonstrates that the MEPC's guidelines for environmental risk assessment would fail to adequately protect the marine environment, as these guidelines suggest only looking at the surrounding, not port, environment. Additionally, their assessment stresses the need to account for multiple contaminant sources when looking at how one contaminant might affect the marine environment.

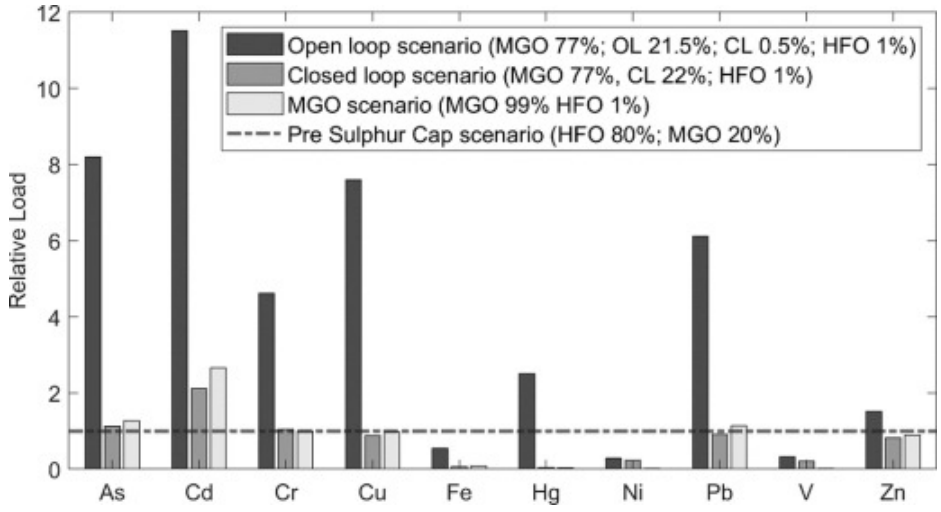
Hermansson, A. L., Hassellöv, I., Moldanová, J., & Ytreberg, E. "Comparing emissions of polyaromatic hydrocarbons and metals from marine fuels and scrubbers." *Transportation Research. Part D, Transport and Environment, 97,* 102912. (2021). https://doi.org/10.1016/j.trd.2021.102912

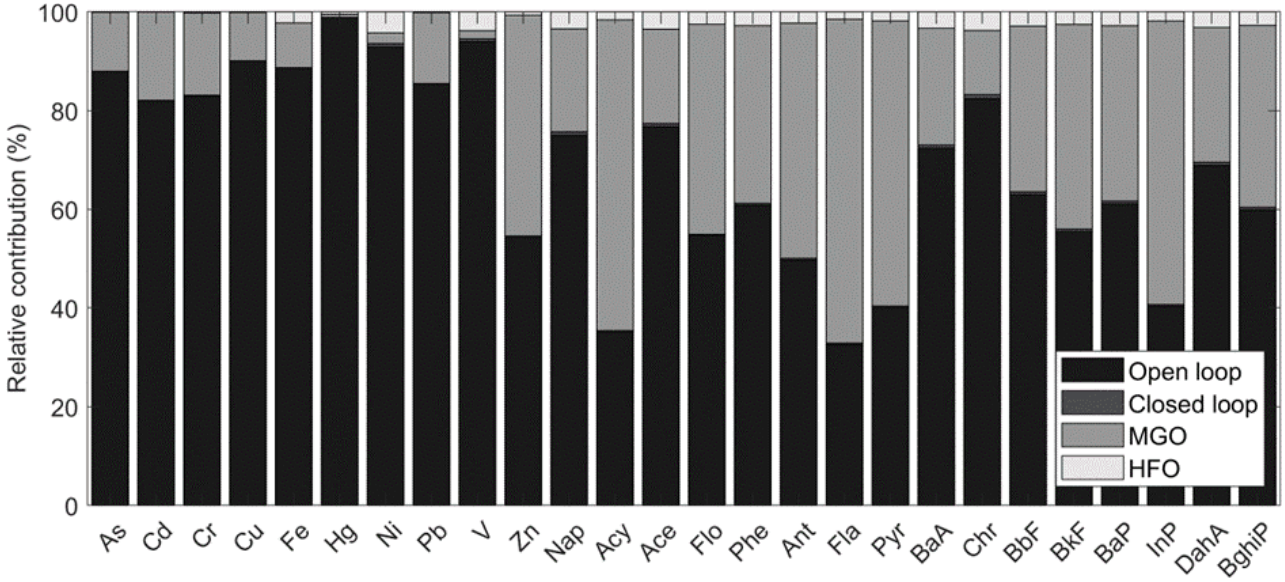
Hermansson et al. modeled four marine fuel demand scenarios under the IMO 2020 fuel sulfur regulation — a baseline pre-sulfur cap scenario consisting of 80% HFO use within the market and 20% MGO fuel use — along with three alternate scenarios to meet the regulation:

1. MGO scenario (99% MGO use, 1% HFO use)
2. A closed loop scenario (22% market using closed loop scrubbers
3. 77% using MGO, and 1% using HFO, and lastly,
4. An open loop scrubber scenario (21.5% market uses open loop scrubbers, 0.5% uses closed loop, 77% use MGO, and 1% uses HFO).

The environmental load (including air and water emissions) of metals and PAHs were compared in the four scenarios, with open loop scrubbers (at a 21.5% market share) leading to a significantly higher impact than any other scenario, including the baseline 80% HFO use scenario.

The authors found scrubbers likely play an additional polluting role to the marine environment even beyond a baseline HFO pre-sulfur cap scenario, given the increased Chromium emitted to the marine environment due to increased corrosion of scrubber pipes and use of seawater within the scrubbing system. The study concludes that the results suggest that allowing discharge of scrubber water to the marine environment is in direct conflict with the European Union Water Framework Directive's goals to achieve good environmental status in European waters.

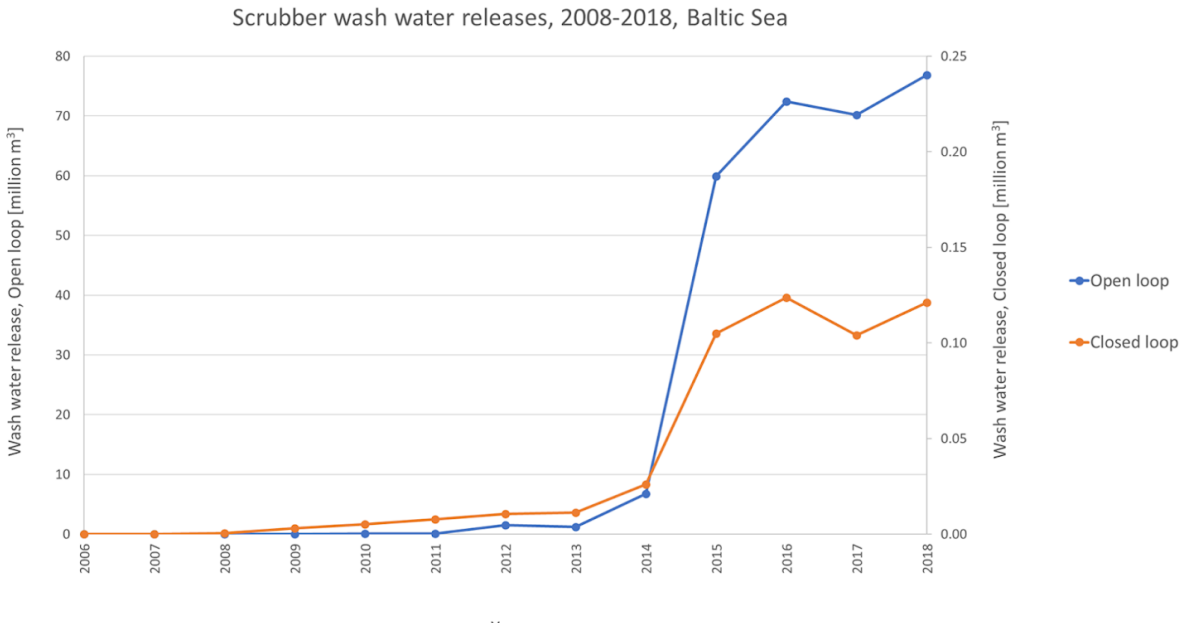




Jalkanen, J., Johansson, L., Wilewska-Bien, M., Granhag, L., Ytreberg, E., Eriksson, K. M., Yngsell, D., Hassellöv, I., Magnusson, K., Raudsepp, U., Maljutenko, I., Winnes, H., & Moldanova, J. Modelling of discharges from Baltic Sea shipping. *Ocean Science, 17*(3), 699–728. (2021). https://doi.org/10.5194/os-17-699-2021

This study models the discharge patterns for the year 2012 in the Baltic Sea to create an inventory for pollutant sources and identify major contributors to marine environmental pollution. Open loop scrubbers were found to be the second largest pollutant stream by volume. These discharge amounts increased significantly in recent years past what was identified in this study for 2012, and highlights the need for investigation of environmental impacts.

It should be noted that the scrubber discharge volumes have been increased by almost two orders of magnitude, which makes them currently the second-largest volumetric discharge from ships. In the Baltic Sea, these discharges increased from 150,000 cm3 in 2012 up to 7,710,000 cm3 in 2018, a more than 50-fold increase in volume.



García-Gómez, E., Gkotsis, G., Nika, M., Hassellöv, I., Salo, K., Hermansson, A. L., Ytreberg, E., Thomaidis, N., Gros, M., & Petrović, M. "Characterization of scrubber water discharges from ships using comprehensive suspect screening strategies based on GC-APCI-HRMS." ***Chemosphere, 343,*** **140296. (2023). https://doi.org/10.1016/j.chemosphere.2023.140296**

This scientific study utilized gas chromatography to identify specific polycyclic aromatic hydrocarbons (PAHs) present in scrubber wastewater as well as less characterized and discussed alkylated derivatives of parent PAHs. Many of these compounds remain uncharacterized despite the significant increase in their discharge to marine environments. PAHs are known to pose toxic threats to the environment and marine life, and their alkylated derivatives are expected to be present at even higher concentrations than their parent compounds.

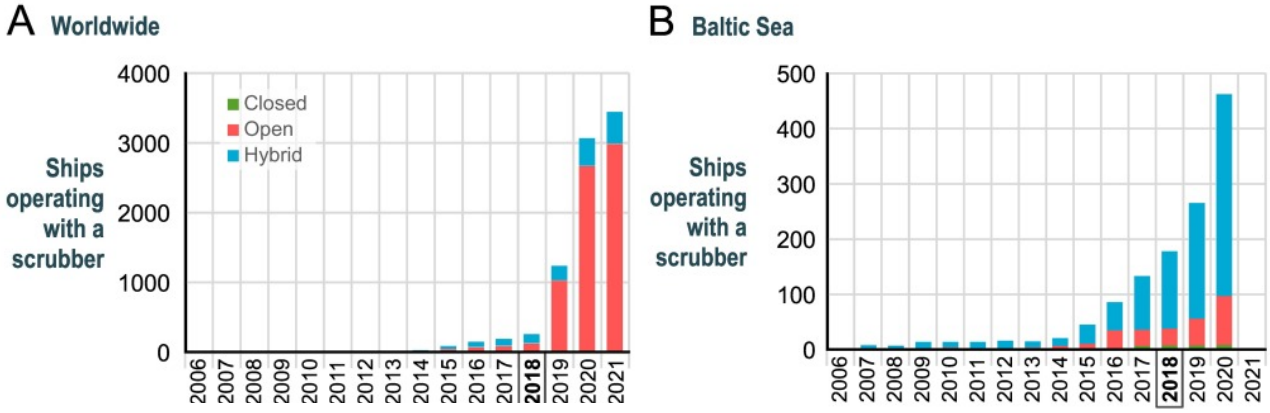
PAHs are known carcinogens and have mutagenic properties, and there is evidence that alkyl-PAHs can be even more toxic than parent PAHs, the primary hydrocarbon of study in discharge wastewater. This is especially the case for alkyl-PAHs with 3–5 rings, which have been identified as the main components of oil toxicity to aquatic organisms (Hodson et al., 2007).

The number of studies that evaluated the effects of scrubber water discharges to marine organisms are still limited and, in most cases, they only focused on the 16 priority PAHs as the major contributors to the toxicity, excluding the alkylated derivatives (Koski et al., 2017; Ytreberg et al., 2019). This study identified the most relevant non-polar organic contaminants that could be markers of scrubber water contamination in marine ecosystems and indication of discharge toxicity of scrubber effluents to marine ecosystems.

Ytreberg, E., Hansson, K., Hermansson, A. L., Parsmo, R., Lagerström, M., Jalkanen, J., & Hassellöv, I."Metal and PAH loads from ships and boats, relative other sources, in the Baltic Sea." ***Marine Pollution Bulletin, 182,*** **113904. (2022). https://doi.org/10.1016/j.marpolbul.2022.113904**

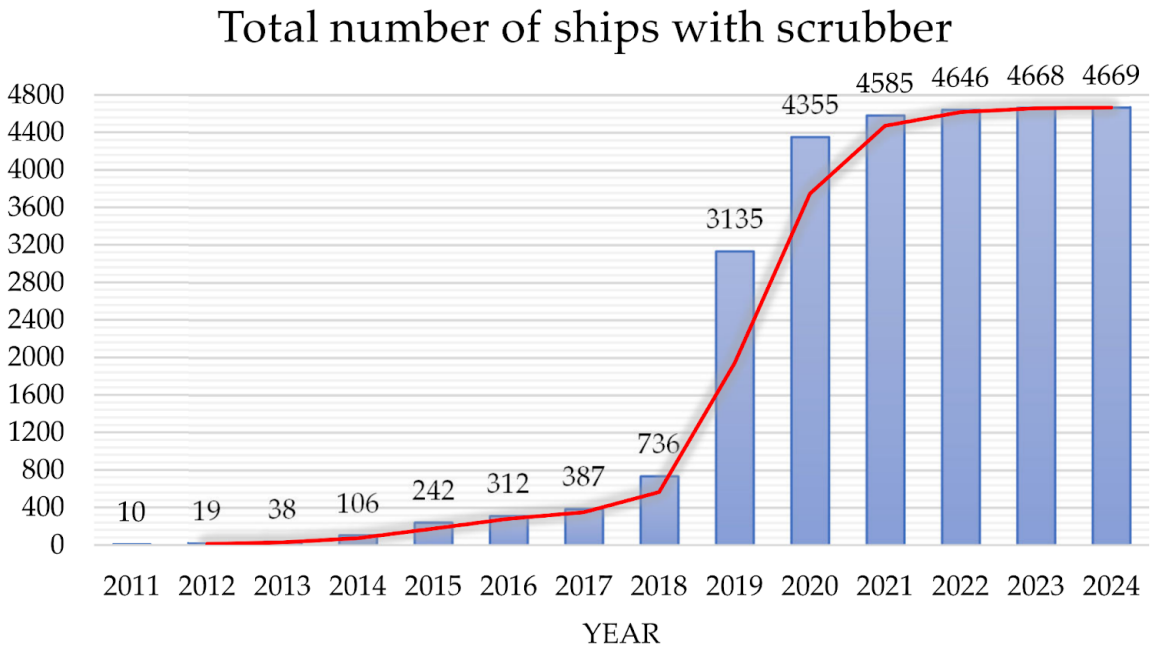
This study compiled the various sources of metals and PAHs to the Baltic Sea within the range of 2010-2018, focusing on 2018 for maritime shipping. In 2018, 178 vessels operated in the Baltic Sea with scrubbers and their discharge was estimated to 0.19 billion m3/year; by 2020, that had increased to 462 vessels. Globally statistics from IMO have shown a rapid increase from about 260 vessels in 2018 **to almost 3500** vessels in operation globally with a scrubber in 2020. Additionally, other studies have modeled the discharge rate of scrubbers using a flow rate of 45 m3/MWh based on 2008 data, and when a flow rate of 90 m3/MWh was applied instead, the total volume of discharge was found to be 3x higher than the estimate in this study, indicating higher levels than previously found based on outdated assumptions.

The results from this study suggest open loop scrubber wastewater to be a major source of PAHs to the marine environment, e.g. 8.5 % of the total load of anthracene in 2018 is caused by wastewater from scrubbers operated in open loop mode in the Baltic Sea, despite the relatively low number of ships being equipped with scrubbers. It must also be emphasized that emissions of PAHs and most metals to the atmosphere are significantly higher when a ship is operating with HSFO as compared to MGO, regardless if the vessel operating with HSFO is equipped with a closed loop scrubber system or not (Lunde Hermansson et al., 2021). Thus, to minimize the environmental load of PAHs and metals, the best practice would be not to use HSFO at all.



Karatuğ, Ç., Arslanoğlu, Y., & Soares, C. G. "Feasibility analysis of the effects of scrubber installation on ships." *Journal of Marine Science and Engineering, 10*(12), 1838. (2022) https://doi.org/10.3390/jmse10121838

This study conducted a feasibility analysis on a crude oil tanker to determine the changes in emissions with the use of a scrubber system along with a financial evaluation as to the cost of operation. As a result of the analysis performed, it is found that the power generation and fuel consumption for each diesel generator increases after scrubber installation and use. It has also been determined that scrubber implementation causes an increase in all pollutants' amounts except SO_X and therefore contradicts the zero-emission ship target and decarbonization strategy stated by IMO.



Comparison of releasing emissions before/after scrubber installation

Releasing emissions (tons)	CO_2	NO_X	SO_X	PM_{10}	$PM_{2.5}$
2 months before scrubber installation	9,413	178,798	30,091	4,719	4,335
2 months after scrubber installation	10,550	257,149	5,166	25,579	21,161
Change	**1,137**	**78,351**	**-24,92**	**20,860**	**16,826**

The findings of the study provide significant results and foresight to maritime companies, authorities, and stakeholders about the scrubber application on marine vessels. In line with the calculated results, although scrubber application is acceptable to comply with the sulfur regulation in the short term, other options, such as alternative fuels and more beneficial De-SO_X technologies, should be considered because of both environmental concerns and to meet environmental policies and strategies introduced by IMO.

Hermansson, A. L., Hassellöv, I., Grönholm, T., Jalkanen, J., Fridell, E., Parsmo, R., Hassellöv, J., & Ytreberg, E. "Strong economic incentives of ship scrubbers promoting pollution." ***Nature Sustainability*****. https://doi.org/10.1038/s41893-024-01347-1 (2024).**

In this peer-reviewed article in Nature Sustainability, the authors show that while private actors have strong economic incentives to use scrubbers, their use comes with significant costs in terms of marine ecotoxicity damage. Looking only at the marine ecosystem damage from metals and polycyclic aromatic hydrocarbons (PAHs) in scrubber water discharge in the Baltic Sea, the authors found damages totaling nearly €700 million from 2014-2022 in 2019 euros. Meanwhile, over 95% of ships recuperate scrubber costs in five years and by the end of 2022, the scrubber fleet had a surplus of €4.7 billion from scrubber usage. Due to the limited number of studies quantifying economic and social impacts from scrubbers, this study is not a full damage cost analysis.

In their discussion, the authors mention other impacts from scrubbers not assessed in the cost analysis of this study including the enablement of continued use of fossil fuels, increased fuel usage and associated increase in carbon dioxide emissions and the impact of acidic content of scrubber water discharge in high shipping areas affecting marine life and carbon dioxide dissolution in the ocean.

Policies on Scrubber Bans and Restrictions

International Council on Clean Transportation. "Global update on scrubber bans and restrictions." In *ICCT POLICY UPDATES* [Report]. (2023). https://theicct.org/wp-content/uploads/2023/06/Scrubbers_policy_update_final.pdf

This report, published in June 2023, reviews the 93 bans and restrictions on scrubbers across the globe, ranging from the port to national level. This growing number of restrictions and bans on scrubbers illustrates the mounting concern on the harmful effects of scrubber discharge among the emerging body of evidence revealing the damage scrubbers cause on marine ecosystems.

Clean Arctic Alliance. "Scrubbers: The Solution to Pollution is . . . Stop Using Dirty Fuel. Clean Arctic Alliance." (2024, April 12). https://cleanarctic.org/2024/04/04/scrubbers-the-solution-to-pollution-is-stop-using-dirty-fuel/

This blog summarizes key takeaways from recent publications evaluating the harmful effects of scrubber wastewater to illustrate how the use of scrubbers violates international agreements protecting the ocean. The sources referenced found that concentrations of scrubber wastewater as low as 0.0001% have toxic effects on marine life. Scrubber discharges can increase seawater acidity especially in places with high ship traffic, and discharges contain harmful and persistent substances like polycyclic aromatic hydrocarbons (PAHs), nitrates, nitrites and heavy metals. Using

this evidence, the blog argues that scrubber usage violates multiple international agreements like the International Convention for the Prevention of Pollution from Ships (MARPOL) and the U.N. Convention on the Law of the Sea. These violations, the authors argue, suggest that scrubbers should be banned, following the lead of the more than 90 and growing number of bans and restrictions on scrubbers worldwide. In addressing concerns over sunk cost investments into scrubbers, the blog points to research that finds scrubbers pay for themselves quite quickly, with 95% of scrubbers' cost paid back within five years, meaning little financial damage to the maritime industry with a scrubber ban.

MEPC 79-INF.4. "Inspections of exhaust gas cleaning systems - First experiences." (Netherlands)

Click: Sulphur Committee Meeting Summary - 25 Oct 2022

Click: Inspections of exhaust gas cleaning systems - First experiences Netherlands

This submission to the IMO from the Netherlands details European Union Member State (MS) experiences with scrubbers and real-world testing regimes as they compare to intended policies.The report noted the difficulty of manual inspections, including document retrieval and sample testing, based on the intensity of labor-hours and difficulty in standard, known protocol for main engine fuel sampling.

It was also noted that the low number of penalties levied for high sulfur fuel use could be linked to the fact that the check is done at berth, when the main engine is not used, hence it is not the fuel used in navigation that was sampled. Most of the sampling was taken from auxiliary engines in ports (0.10% berth requirement) and very few tank sampling or sampling next to main engine to verify the use of 0.50% fuels were carried out to check 'high seas' compliance.

The Director General of the Environment Council of the European Commission stressed more must be done on the global sulfur cap and in

view of new emission control areas (ECAs) including with use of smart monitoring technologies available in EMSA. However, monitoring by remote sensing and targeting will likely play a greater role in inspection protocols in the future and is felt to be more important than ever by certain Member States.

The results of 2021 campaigns in some MSs were presented. In SO_X ECA, the average of 438 measurements of fuel sulfur content (FSC) by the remote drone sensors from exhaust plumes was 0.11%. From these, 15% of the values had a FSC > 0.13%, resulting in an alert. In Non-sulfur ECAs, the average of 336 measurements was 0.43%, and from these 9% had a FSC much greater than 0.58%, resulting in an alert. **The use of remote sensing found 15% noncompliance within SECA boundaries through aerial sniffer technology and 9% noncompliance in non-SECA bounds; significant levels of ships not meeting global regulation requirements.**

Osipova, L., Rodrigues, P. F., Carvalho, F., Gore, K., & International Council on Clean Transportation. "From concept to impact: Evaluating the potential for emissions reduction in the proposed North Atlantic Emission Control Area under different compliance scenarios." In *ICCT WORKING PAPER* [Report]. (2024). https://theicct.org/wp-content/uploads/2024/06/ID-146-%E2%80%93-Atlantic-ECA_final-1.pdf

The International Council on Clean Transportation's (ICCT) study assesses the potential emissions reductions in sulfur oxides (SO_X), fine particulate matter ($PM_{2.5}$), and nitrogen oxides (NO_X) if the North Atlantic Ocean were designated as an Emission Control Area (ECA). The study results demonstrate that emissions reductions depend on the fuels and technologies used to comply with the ECA's regulations. Using heavy fuel oil with scrubbers was found to not be as effective as the use of distillate fuel, producing 17% more $PM_{2.5}$ and 32% more black carbon compared to distillates.

Jalkanen, J.-P., Grönholm, T., Hassellöv, I.-M., Finnish Meteorological Institute, & Chalmers University of Technology. "Modelling of discharges to the marine environment from open circuit flue gas scrubbers on ships in the OSPAR Maritime Area." (2023). https://oap-cloudfront.ospar.org/media/filer_public/fe/78/fe78b829-5ba5-47e3-805c-09315c16c29c/p00890_modelling_flue_gas_exhaust_scrubber_report_.pdf

The OSPAR report modeled discharges from open loop scrubbers within the North-East Atlantic Area, covering eastern Greenland waters down to the tip of Gibraltar and the Iberian coastline and European and Nordic waters up to the North Sea. Modeling was done using 2020 geographic vessel Automatic Identification System (AIS) data covering 5.2 billion positional reports synchronized with technical fleet characteristics such as size and engine parameters to model power consumption and scrubber discharge volumes. Weather considerations were not included.

Discharges from open loop systems are over 99.9% from the total EGCS discharge, which were estimated to be 622 million cubic meters in 2020 inside the OSPAR overall domain. Of this discharge, almost half occurs in the English Channel and the North Sea areas. The second largest contribution (25%) comes from ships operating along the main shipping lane from Gibraltar to the English Channel.

From the 622 million tonnes of EGCS effluent released to the sea in OSPAR Regions (I-V), about 84% is released closer than 200 nautical miles from the shoreline. Further, the effluent release inside the 12 nautical mile limit was estimated as 130 million tonnes, which is about 21% of the OSPAR total. Vanadium, known to be present in heavy fuel oil, constitutes the largest calculated load (106 tonnes) of individual metals in the OSPAR I-V region. Zinc (87 tonnes) and copper (22 tonnes) are hypothesized to primarily originate from marine growth protection systems and piping. Nickel (34 tonnes) may also originate from the fuel or from piping material in the scrubber system.

With respect to discrete sampling and chemical characterization of scrubber discharge water in lab, a recent study by Du et al. (2022) concludes that **reported data on EPA 16 PAHs, not including alkylated PAHs, may lead to significant underestimations (between 5-15 times lower) of PAH concentrations in scrubber discharge water.** An analogous relation has

previously been reported from analysis of crude oils, where the PAH content were (up to 30 times lower), when alkylated PAHs were omitted from the analysis (Yim et al. 2011).

Osipova, L., Georgeff, E., & Comer, B. "Global scrubber washwater discharges under IMO's 2020 fuel sulfur limit." (2021). https://theicct.org/wp-content/uploads/2021/06/scrubber-discharges-Apr2021.pdf

This study is the first of its kind to estimate the amount and location of wastewater discharges from ships with scrubbers globally. Because of heterogeneous shipping traffic patterns, scrubber discharges will be high in certain areas with greater impacts localized further based on ecological characteristics. The authors estimate ships to emit at least 10 gigatonnes (Gt) of scrubber wastewater in a year (based on pre-pandemic 2019 data). For context, the global shipping sector carries about 11 Gt of cargo each year.

Importantly, **about 80% of scrubber discharges occur within 200 nautical miles of shore, with hot spots occurring in heavily trafficked regions, including the Baltic Sea, North Sea, Mediterranean Sea, the Strait of Malacca and the Caribbean Sea.** Away from shore, scrubber discharges occur along major shipping routes.

The paper also summarizes recent findings of harm and impacts from scrubbers in the literature:

- A number of studies have shown that wastewater influx can damage marine ecosystems. High concentrations of PAHs and heavy metals in wastewater accumulate in sediments, especially in coastal areas, and also increase water toxicity in aquatic ecosystems (Koski, Stedmon, & Trapp, 2017; Teuchies et al., 2020; Winnes et al., 2016).

- Bioconcentration of PAHs and heavy metals has been linked with reproductive dysfunction and cancer in marine mammals (Georgeff et al., 2019; Martineau et al., 2002).

- PAHs and heavy metals also have a high likelihood of bioaccumulation in the marine food web, including in fish consumed by humans (Chouvelon et al., 2019; Valavanidis et al., 2008).

- Stips et al. (2016) found that seawater acidification from wastewater influx in the coastal areas of the North Sea could double the annual impact of greenhouse-gas induced acidification.

- A recent study by Dulière, Baetens, and Lacroix (2020) estimated that if 15% to 35% of the merchant fleet (by tonnage) operating in and near the English Channel were outfitted with open-loop or hybrid scrubbers, the rate of ocean acidification would double or quadruple in that area compared with how much it is expected to acidify due to climate change. Near Rotterdam, the annual acidification from these ships could be 50 times that expected from climate change.

- Comer et al. (2020) showed that all scrubbers (open, closed, and hybrid) discharge water that is more acidic and turbid than ambient seawater.

- Also, all scrubbers emit PAHs and heavy metals that have been linked to cancers and reproductive dysfunction in marine mammals, including threatened and endangered species like northern and southern resident killer whales and belugas.

Ports may be particularly affected by scrubber discharges. When the ambient water alkalinity is low, which is often the case in harbors situated in estuaries, less of the acidity of the wastewater is neutralized. Moreover, PAHs and heavy metals are discharged in shallow water, where they can be more concentrated and accumulate in sediments, which could lead to human health risks in addition to threats to marine life.

The prevalence of water pollution near coastal areas can be explained by the fact that scrubber-equipped ships spend approximately 40% to 50% of their time at anchor or at berth in or near ports. Given its prominence as a cruise vessel port, Port Everglades in Florida receives 1.1% of global in-port discharges (based on 2019 data) and is ranked in #10 globally for scrubber discharge levels.

The U.S. experiences the highest volume of scrubber discharge with 147 Mt in 2019 estimated.

The authors outline actions that could be taken at various levels of authority, from port/local level to national and global IMO actions. Outside of global scrubber bans, the most impactful action would be required use of zero-discharge mode scrubbers within national waters. The United States, the United Kingdom, and Italy all are expected to receive more than 300 Mt per year of wash water discharges and yet do not currently prohibit the use of scrubbers in their national waters.

Detrimental impacts on marine life

Georgeff, E. "A killer whale's tale: Protect critical habitats by addressing scrubber wastewater from ships - International Council on Clean Transportation." *International Council on Clean Transportation*. (2020, June 18) https://theicct.org/a-killer-whales-tale-protect-critical-habitats-by-addressing-scrubber-washwater-from-ships/

This blog from the International Council on Clean Transportation (ICCT) draws on existing scientific literature to show how scrubber wash water pollution harms endangered resident killer whales (RKW) in the Pacific Northwest. Drawing from publications in the National Library of Medicine, the author explains how toxins like polycyclic aromatic hydrocarbons (PAHs), heavy metals and nitrates accumulate in the fat of marine mammals like the RKW, leading to cancer. The author points out that this harm, inflicted by ships' expulsion of scrubber wash water known to contain these toxins, violates Fisheries and Oceans Canada's rule that makes it illegal to destroy habitats in designated 'critical areas' of recovery for RKWs.

International Council on Clean Transportation. "A whale of a problem? Heavy fuel oil, exhaust gas cleaning systems, and British Columbia's resident killer whales." (2021, November 24). https://theicct.org/publication/a-whale-of-a-problem-heavy-fuel-oil-exhaust-gas-cleaning-systems-and-british-columbias-resident-killer-whales/

This study estimates the location of heavy fuel oil (HFO) carriage, HFO use, and scrubber wastewater discharge from ships off the coast of British Columbia under three different scrubber use scenarios.These results were then compared to the location of resident killer whale (RKW) habitats to see how they would be impacted. The results found that scrubber water discharges disproportionately occurred in RKW habitats, a threat that is expected to grow with the increasing use of HFO and scrubbers. In addition to scrubber water discharges, the authors also note that scrubbers perpetuate the risk of an HFO spill.

Baker, R. "Endangered orca habitat sullied by Canadian cruise ship pollution." *Canada's National Observer.* (2024, May 15). https://www.nationalobserver.com/2024/05/15/news/endangered-orca-habitat-sullied-canadian-cruise-ship-pollution

This article reports on scrubber wastewater data along the West Coast recently published by the Canadian government's Environment and Climate Change Canada (ECCC). Key statistics reported by the ECCC include a 14 fold increase in ships' scrubber usage from 2018 to 2022, discharging 88 million tons of wastewater with 26,000 kilograms of toxic metals, including copper and lead. The toxic effects this scrubber water has on marine life, including the endangered resident killer whale, has prompted environmental groups like Stand.earth to urge the government to impose more stringent restrictions on scrubber pollution.

Ytreberg, E., Karlberg, M., Hassellöv, I., Hedblom, M., Nylund, A. T., Salo, K., Imberg, H., Turner, D., Tripp, L., Yong, J., & Wulff, A. "Effects of seawater scrubbing on a microplanktonic community during a summer-bloom in the Baltic Sea." *Environmental Pollution, 291,* 118251. (2021). https://doi.org/10.1016/j.envpol.2021.118251

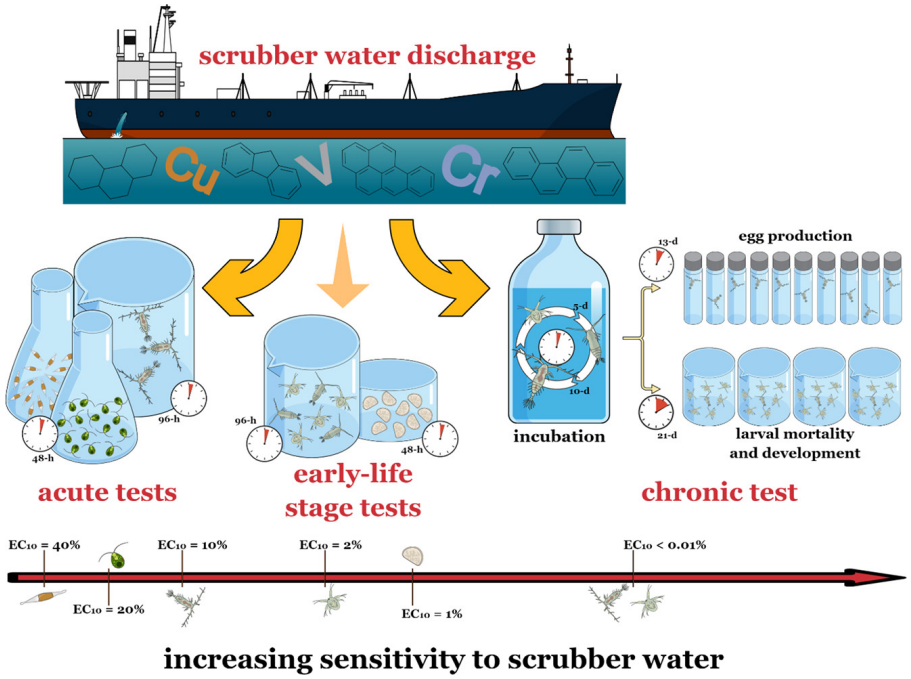
The aim of the study was to investigate how different treatments of scrubber discharge water (1, 3 and 10%) affect a natural Baltic Sea summer microplankton community. Impacts controlled for pH by adjusting natural sea water samples to match scrubber pH levels.

The study evaluated biological effects (including microplankton species composition, biovolume, and primary productivity) and chemical parameters (pH and alkalinity) over 14 days of exposure. The study found increased microplankton biovolume likely due to the increased levels of nitrates in scrubber discharge, a key limiting nutrient that when present in excess create phytoplankton blooms that impact other marine species and other nutrient levels. Group-specific impacts were recorded where diatoms, flagellates, chlorophytes and ciliates increased in biovolume with increasing concentrations of scrubber water while no effect was

recorded for cyanobacteria. In contrast, these effects were not observed in the "pH controls," a suggestion that other parameters/stressors in the scrubber water were responsible for the observed effects. Harmful blooms of phytoplankton can create anoxic environments and, depending on the species, produce toxins that harm other marine life.

Picone, M., Russo, M., Distefano, G. G., Baccichet, M., Marchetto, D., Ghirardini, A. V., Hermansson, A. L., Petrovic, M., Gros, M., Garcia, E., Giubilato, E., Calgaro, L., Magnusson, K., Granberg, M., & Marcomini, A. "Impacts of exhaust gas cleaning systems (EGCS) discharge waters on planktonic biological indicators." ***Marine Pollution Bulletin, 190,*** **114846. (2023). https://doi.org/10.1016/j.marpolbul.2023.114846**

The study tested the exposure of scrubber wastewater discharge on marine life, including larval development of mussels and copepods; acute effects on bacteria, algae and copopods; and effects on planktonic life. The authors found that exposure to scrubber discharge wastewater impaired several traits in planktonic life, had acute effects on multiple species of bacteria, algae, and copepods, as well as impaired the development of larvae by 50% at <5% treatment level. Larval development and reproductive success of copepod *Acartia tonsa* were severely affected at scrubber water concentrations ≤1.1 %, indicating the risk of severe impacts on copepod populations which in turn may result in impairment of the whole food web.



Thor, P., Granberg, M. E., Winnes, H., & Magnusson, K. "Severe Toxic Effects on Pelagic Copepods from Maritime Exhaust Gas Scrubber Effluents." *Environmental Science & Technology*, *55*(9), 5826–5835. https://doi.org/10.1021/acs.est.0c07805 (2021).

This study evaluated the effects of scrubber effluent on planktonic copepod *Calanus helgolandicus* and found high concentrations of heavy metals and polycyclic aromatic hydrocarbons (PAHs), including alkylated PAHs.

The study found severe toxic effects and significantly elevated mortality rates and impaired molting already in the lowest tested concentrations of each effluent: 0.04 and 0.1% closed-loop effluents and 1% open-loop effluent. These concentrations correspond to total hydrocarbon concentrations of 2.8, 2.0, and 3.8 µg/L, respectively, and compared to previous studies on oil toxicity in copepods, scrubber effluents appear more toxic than, for example, crude oil. None of the individual PAHs or heavy metals analyzed in the effluents occurred in concentrations which could explain the high toxicity. The effluents showed unexpected alkylated PAH profiles, and the authors hypothesized that scrubbers "act as witch's cauldrons where undesired toxic compounds form" that are understudied and pass by unknown based on current testing regimes.

Magnusson, K., Granberg, M., Marco Picone, Annamaria Volpi Ghirardini, Lina Zapata Restrepo, Malcolm Hudson, Ian Williams, Chiau Yu Chen, Ana Ré, Nelson Abrantes, Savvas Genitsaris, Polyxeni Kourkoutmani, Natassa Stefanidou, Maria Moustaka-Gouni, Anna Lunde Hermansson, Erik Ytreberg, & Ida-Maja Hassellöv. "Report on scrubber water whole effluent toxicity testing, at different geographical regions." (2022). https://www.ivl.se/download/18.5ae47fd818530c6f06024d0a/1676036161374/D2.3.%20%E2%80%9CReport%20on%20scrubber%20water%20whole%20effluent%20toxicity%20testing,%20at%20different%20geographical%20regions%E2%80%9D.pdf

The authors, working in partnership through the Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions (EMERGE) project, tested the effects of scrubber discharge on phytoplankton and planktonic invertebrates to evaluate the toxicity of scrubber wastewater on the marine ecosystem.

The results of this study find that the toxic effects of scrubber discharge start at considerably lower concentrations than previous reports noted. Concentrations of only 0.0001% of scrubber water affects sea urchin egg fertilization and concentrations of 0.001% affect larvae of species from different taxonomic classifications, suggesting scrubber wastewater has a general effect across species.

Their research highlights the need to conduct testing on a variety of species and at different life stages as the IMO's recommended standardized protocol would fail to capture the true impact of the discharge on marine life by only testing a select few species and life stages. The authors note that these weak testing protocols are "even more alarming when considering the explosion of scrubber usage following the agency's adoption of their sulfur regulation rules."

Magnusson, K., Thor, P., & Granberg, M. "Scrubbers: Closing the loop Activity 3: Task 2 Risk Assessment of marine exhaust gas scrubber water." *ResearchGate*. (2018). https://www.researchgate.net/publication/333973881_Scrubbers_Closing_the_loop_Activity_3_Task_2_Risk_Assessment_of_marine_exhaust_gas_scrubber_water

The main aim of the present study has been to investigate whether the discharged scrubber effluent (ESGE) from the three ships included in the study run the risk of having harmful effects on the marine ecosystems in the area where the ships operate. The risk assessment was done using two different approaches, one based on the results from the chemical analyses of the EGSE from the three ships and another based on data from the toxicity tests carried out on the whole EGSEs.The results show that **it is more relevant to base a risk assessment of a complex mixture such as EGSE on toxicity studies on the actual water itself rather than on chemical analyses of the water.**

The study finds:

- Mortality rate in juveniles (copepodite) stage CV of the copepod *Calanus helgolandicus* was found to be the most sensitive indicator of all measured endpoints in all toxicity tests of EGSE toxicity.
    - Toxic effects for copepodite stage CIII were observed at 1.0% dilution factor from the Stena Forerunner open loop scrubber.
    - Neither pH nor alkalinity (AT) was different from the control treatment at these EGSE concentrations, so we conclude that effects on copepod mortality (as well as all other measured physiological processes in the copepods) **were not caused by acidification but were primarily due to the toxic effects of EGSE.**
    - It should be noted that in both closed and open loop exposure the lowest tested concentration resulted in toxic effects on the copepodites. **Thus, it cannot be excluded that even lower concentrations would have been harmful to the tested zooplankton species.**
- Metal concentrations in the exposure water at the lowest toxic concentrations were also compared to data from the literature although data on relevant species were quite limited.

- The reproduction of the marine copepod *Acartia tonsa* was found to be negatively affected by Zinc, Copper and Nickel in concentrations of 0.64, 0.3 and 2.4 µg·L-1 (Bielmyer et al. 2006). These concentrations were exceeded for Zn in EGSE from Stena Forerunner (open loop).

- Medium term (1-2 weeks) chronic effects of EGSE from closed- and open-loop scrubber systems were investigated on the planktonic copepod. Exposure times were long and exposure concentrations were kept realistically low in order to detect chronic toxicity effects

  - The copepods reacted strongly to the exposure to both closed loop and open loop EGSE. While there was no mortality in any of the control treatments, all copepods died within one day when exposed to the 5% concentration of closed loop EGSE and within eight days when exposed to the 40% concentration of open loop EGSE.

  - The mortality rate from the different treatments was calculated and tested statistically among concentrations in order to find lowest effect concentration of EGSE. The lowest concentration where a significant effect on mortality rate was detected was 1% for open loop 2018. Significant effects actually occurring at lower concentrations than those tested for the open loop scrubber cannot be excluded.

- Cell viability was measured on cells from the haemolymph (blood) of the mussels. These cells are known to react quickly to pollution stress.

  - There is a clear trend in decreasing cell viability with increasing EGSE exposure (chart below).

  - Cell viability was only measured on mussels exposed to closed loop EGSE during the 2018 trial.

  - It is likely that the toxicity has mainly been caused by the hydrocarbons (including the PAHs). Although several metals, e.g. Zn, Cu, Ni and Cr, were found in the exposure water in the present study at concentrations close to concentrations found to be toxic, there was no consistency between the EGSE from the three ships.

  - **However, the lack of literature data on toxicity to zooplankton of several of the metals, mono aromatics and alkylated PAHs might have led to an underestimation of the toxicity of these groups of chemicals.**

- A lowest toxic concentration could not be established for any of the tested EGSE since toxic effects on zooplankton were found in the lowest EGSE test concentration in each experiment. It can therefore not be excluded that toxic effects may be detected at even lower concentrations.

- The most sensitive of the tested species was the copepod *Calanus helgolandicus*. This is a zooplankton species and therefore the group of marine animals that is likely to be most affected by the discharge of contaminated water from ships.

    - **Zooplankton is a crucial link between phytoplankton and higher trophic levels like fish and marine mammals. Toxic effects on zooplankton will therefore have serious consequences for the whole marine ecosystem.**

Results from the toxicity studies and ESGE discharge volumes indicate that there is a risk for harmful effects on zooplankton from the discharges from one single crossing. These effects were found to be higher for open loop scrubbers than for closed loop ("The predicted toxicity was higher for the EGSE from the open loop system PEC/PNEC = 6.3 than from the closed loop systems PEC/PNEC=1.9 and 3.8").

The results clearly show that it is more relevant to base a risk assessment of a complex mixture such as EGSE on toxicity studies on the actual water itself rather than on chemical analyses of the water.

- One important argument is that only compounds suspected to be present in the water will be selected for chemical analyses. Even a qualified assessment of what compounds would be relevant to analyze might overlook toxicologically important ones.

- Another equally important aspect is that the sum of toxic effects exerted by all compounds in the EGSE may be dramatically different from the effect predicted when focusing on the compounds one at the time. Compounds in a mixture may have both cumulative additive modes of action (toxic effects of two or more compounds add to each other) and synergistic (toxic effect of two or more compounds is stronger than just the sum of them).

- **Another likely explanation is that the toxicity of the EGSE is the result of what is known as the "cocktail effect," i.e., the joint effect of the mixture of all components in the discharged water is larger than the effect of the individual components.**

The results from the risk assessment based on actual toxicity testing of the EGSE give a very different picture than when the assessment is based on chemical analyses of the EGSE.

Koski, M., Stedmon, C., & Trapp, S. "Ecological effects of scrubber water discharge on coastal plankton: Potential synergistic effects of contaminants reduce survival and feeding of the copepod *Acartia tonsa*." *Marine Environmental Research*, 129, 374–385. (2017). https://doi.org/10.1016/j.marenvres.2017.06.006

The study investigated 1) the threshold concentrations of scrubber discharge water for survival, feeding and reproduction of the copepod *Acartia tonsa,* 2) whether the effects depend on the exposure route and 3) whether exposure to discharge water can be detected in field-collected organisms. It found a direct exposure to discharge water increased adult copepod mortality and reduced feeding at metal concentrations which were orders of magnitude lower than the lethal concentrations in previous single-metal studies, while reproduction was not influenced by dietary uptake of contaminants. Scrubber water constituents could also have synergistic effects on plankton productivity and bioaccumulation of metals, although the effects will depend on their dilution in the marine environment.

Klasios, N., Pozas, A., & Sha, J. (2020). "The Great Bear Sea – a toilet bowl for marine vessels: quantifying waste and the ecological, social, cultural, and economic risks of marine dumping." *Grand Challenges in Ocean Leadership*. https://open.library.ubc.ca/media/stream/pdf/42591/1.0396651/4

This paper collated resources on impacts of marine effluent, and specifically scrubber discharge, on marine habitat and life in the Great Bear Sea, which spans the waters from the Northern tip of Vancouver Island to the border of British Columbia and Alaska encompassing the archipelago of Haida Gwaii.

Assuming most vessels opt to install scrubbers rather than use MDO, the IMO predicted an increase of 35% of scrubber washwater discharges to an

estimated 47 million tonnes in 2020 coming from bulk ships, cruise ships, and other large vessels that will implement scrubber systems (Brown, 2019). Most of the discharge from open-loop systems originates overwhelmingly from cruise ships making up the main types of boats that discharge scrubber wastewater into the Great Bear Sea (GBS).

Given the predicted increase of 35% of wastewater in coming years, the concern about the consequences it will have on marine life also increases (Brown, 2019). The main contaminants of particular concern in scrubber wastewater are polycyclic aromatic hydrocarbons (PAH's) and heavy metals. PAH's are the product of incomplete combustion of heavy fuel oils used by boats, which results in small nonbiodegradable particulate matter entering the oceans. The smaller the particles, the more damaging to marine life as they can be ingested by zooplankton, and then consequently bioaccumulate in larger organisms higher up in the food chain, for instance in marine mammals, specifically whales (Endres et al., 2018; Marsili et al., 2001). Research has shown that PAH's are ingested by the whales when eating contaminated fish and are stored in their blubber layer (Formigaro et al., 2014). Consequently, when a whale accesses its blubber layer for energy reserves, the PAH's can enter its bloodstream altering its DNA leading to health issues and illnesses such as cancer. In the St. Lawrence River, belugas were found to have more incidents of digestive tract cancer correlated with higher PAH concentrations in the water (Martineau et al., 2002).

Georgeff et al. (2019) estimated PAH levels in the GBS based on data from 2017. They found that around 1,740 kg of PAH's were discharged in the study area of the GBS, including Vancouver Island and offshore waters. **Around 165 kg (~10%) of this discharge was within their defined critical habitat for SRKW's, an amount that was projected to increase by 36% by 2020 (Georgeff et al., 2019).**

Heavy metals in scrubber wastewater can also have detrimental effects on marine life as they can also be released into the bloodstream when accessing fat reserves, or during pregnancy and lactation (Kakuschke & Prange, 2007). Studies have also shown that exposure to high amounts of heavy metals, specifically lead, mercury, and copper, can lead to difficulties locating prey, poor metabolism, and reproductive dysfunction (Jakimska, Konieczka, Skóra, & Namieśnik, 2011). Given that the Resident Killer Whale populations are already critically endangered, discharge contaminants pose an additional threat to their populations and therefore the viability and intrinsic value of the GBS ecosystem.

[1] **Page 5 image:** Jay Nadeau, Chris Lindensmith, Jody W. Deming, Vicente I. Fernandez, and Roman Stocker. Image courtesy of David Liittschwager., CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons