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Integration of air quality and climate change policies in shipping: The case of Sulphur Emissions Regulation

Christos A. Kontovas
Liverpool Logistics, Offshore and Marine Research Institute (LOOM)
and Dept. of Maritime and Mechanical Engineering
Liverpool John Moores University, Liverpool, L3 3AF, United Kingdom email: c.kontovas <at> ljmu.ac.uk

Abstract
Ship air pollution has attracted much attention from the shipping community. Besides Greenhouse Gases (such as carbon dioxide) that contribute to Climate Change, shipping emits many other gases including sulphur and nitrous oxides. There is much scientific evidence that measures to reduce these pollutants do improve air quality but, at the same time, contribute to the acceleration of global warming, because they result in removing the cooling effect of these gases. Until now climate change and air quality regulations have been discussed independently. This work tries to assess the effect of policies to improve air quality on climate change, and vice versa. This paper discusses an approach to assess the impact of SOx reduction measures on global warming by presenting a way to place both emissions on a common scale to allow a comparison between them and to estimate their aggregate effect. Such integration can lead to better decisions by policymakers.
Keywords: Climate Change; Air quality; Sulphur regulations; Climate Metrics.

1. Introduction

Ship air emissions have been for quite some time now at the center stage of discussion by the shipping community and regulatory bodies, such as the International Maritime Organization (IMO). Gases emitted from ships can be classified into mainly two categories: (a) Green House Gases (GHGs) such as carbon dioxide (CO2) and methane (CH4), which are responsible for Climate Change, and non-GHGs, which include sulphur oxides (SOx) and nitrogen oxides (NOx) that are responsible for poor air quality. According to the latest IMO study (IMO, 2014), also referred to as the 3rd IMO GHG study, shipping accounted for approximately 3.1% of annual global anthropogenic carbon dioxide (CO_2) emissions, that is 1,016 million tonnes CO_2. The same study estimates average annual totals for the period 2017-2012 of 20.9 million tonnes NOx emissions and 11.3 million tonnes SO_x emissions from shipping, representing about 15% and 13% respectively of global NO_x and SO_x emissions (IMO, 2014).

IMO is the responsible UN body to tackle ship air emissions. In 2008, the Marine Environment Protection Committee (MEPC) of the IMO introduced the so-called Emission Control Areas (ECAs) to deal with SOx and NOx emissions. To control SOx emissions, measures such as exhaust gas cleaning systems (scrubbers) and alternative fuels have been proposed. However, the first level of control had been to set a cap on the actual sulphur content of the fuel oil within the ECA areas and outside (referred to as the global cap). Under the revised IMO regulations, the so-called IMO 2020 rule, effective from January 2020, the global sulphur cap will be reduced from current 3.50% to 0.50%, and inside the established ECAs the cap will be 0.10%.
On the GHG front, progress has been rather slow. In a historic move, in 2018, IMO adopted the so-called 'Initial IMO Strategy', which sets out a vision to drastically reduce GHG emissions from shipping, setting an ambitious target to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 (IMO, 2018).
The nature of the contribution of ship air emissions to climate change is rather complex. For instance, GHG emissions, such as CO_2, cause long-term climate warming but sulphur oxide (SO_x) emissions cause cooling through effects on atmospheric particles and clouds, while nitrogen oxides (NO_x)

increase the levels of ozone (O_3) and reduce methane (CH_4), which leads to warming and cooling, respectively. The only way to compare and weight emissions of different gases, that have different atmospheric lifetimes and effects on the Climate, is by using the so-called climate change metrics; see Section 2 for more. This is in line with the latest report of the UN Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5); see IPPC (2014).

Various studies by climate scientists have reported on the effect of shipping. The total effect of the different ship emissions is a strongly negative net global mean radiative forcing (RF) (Fuglestvedt and Berntsen, 2009; Eyring et al., 2010; Lauer et al., 2007). These studies expressed concerns that regulations to reduce SOx emissions would reduce the cooling effect and therefore the total effect of ship air emissions would be net warming, meaning that shipping would further contribute to global warming and, therefore, climate change. Indeed, recent studies, see for example Sofiev et al. (2018), argue that while cleaner fuels will reduce ship-related premature mortality and morbidity, policymakers face trade-offs whereby achieving health benefits there might be climate change consequences.

Undoubtfully, the regulations presented above will result in drastic emission reductions. The main issue though is that in maritime transportation, and this is also the case for other transport sectors as well, policymakers have discussed climate change and air quality regulations independently. One explanation might be that the science behind estimating the co-benefits of sulphur and carbon reductions is not clear. Besides the uncertainties, it is might also be very difficult and complicated to be understood by policymakers at IMO level. The need for a holistic approach in the shipping industry is rather urgent, especially given the upcoming IMO regulation that will reduce SOx emissions, remove their cooling effect and, thus, accelerate the effects of Climate Change. A recent report published by the United Nations Environment Programme (UNEP, 2019) urges governments to address their environmental problems using holistic approaches as Climate Change and Air quality "are not independent problems: they are inexorably linked, and so too are their solutions". Gilbert (2014) also noted that given the link between the various emissions, the maritime sector runs the risk of "taking a very short-sighted approach" if it chooses to tackle SOx emissions without looking at the carbon repercussions.

However, excluding the studies published by climate scientists, very few studies have actually looked at the various gases from shipping holistically, i.e trying to integrate the effects on climate and air quality. For example, Lindstad et al. (2015) investigate the climate impact of various emissions expressed in CO2- equivalents, as a function of power load using region-specific GWP factors. They argue that it might be desirable to "allow burning very dirty fuels at high seas, due to the cost advantages, the climate cooling benefits, and the limited ecosystem impacts". Lindstad and Eskeland (2016) argue that global NOx and SOx regulations raise global warming impacts. CONCAWE (2018) presents the impact of emissions from international shipping on air quality. The warming effect of SOx emissions is discussed and it is demonstrated that it is generally not cost-effective to reduce emissions from shipping outside of coastal zones.

To that extent, this paper discusses a simple way for a holistic approach to assessing the impact of SOx reduction measures on global warming. We present a way to place the different emissions on a common scale to allow for a comparison between them and the estimation of their aggregate effect. This approach of comparing and weighting different gases by using a climate change metric is supported by the Intergovernmental Panel on Climate Change (IPCC); see the latest Assessment Report (AR5) (Myhre and Shindell, 2013; IPCC, 2014). Thus, we hope that this paper will stimulate further research and, especially, discussion at the IMO.

The organization of the rest of this paper is as follows. Section 2 describes the way to estimate the quantity of CO_2 and SOx emissions produced when burning fuel oil and the methodology to convert the SO_2 emissions to an equivalent amount of CO_2 emissions by using climate metrics. Section 3 presents a rough estimation of the impact of the upcoming IMO 2020 rule. Finally, the paper concludes with a short discussion and conclusions.

2. The effect of SOx Emissions

2.1 Estimating the quantity of CO_2 and SOx emissions

There are various methods to calculate emissions. The easiest way to estimate emissions from transportation is to multiply the energy or fuel used by an appropriate 'emissions factor', which is the ratio of emissions produced per unit energy or unit fuel consumed (Kontovas and Psaraftis, 2016). For CO_2, the factors are empirical and differ among studies.

Carbon Dioxide Emissions
One way to estimate CO_2 emissions is to multiply the fuel consumption by an appropriate emissions factor. These factors are empirical. In some recent regulation that is used to measure the energy efficiency of new ships (the EEDI regulation) and in the 3rd IMO GHG study, the values of 3.114 tonnes CO_2 per tonne of fuel for heavy fuel oil (HFO) and 3.206 tonnes CO_2 per tonne of gas/diesel oil (MGO/MDO) fuel are used.

Sulfur Oxide (SOx) Emissions
Sulfur Dioxide (SO_2) emissions -that is 98% of SOx emissions- depends on the type of fuel used and in particular on the amount of sulfur present in the fuel. One has to multiply total bunker consumption (in tonnes) by the percentage of sulphur present in the fuel (for instance, 3.5%, 1.5%, 0.5%, or other) and subsequently by the exact factor of 0.02 to compute SO_2 emissions (in tonnes). The factor of 0.02 is exact in the sense that it is derived from the chemical reaction of sulphur with oxygen. For instance, to estimate emissions when burning marine fuel that contains 2.5% sulfur, the appropriate emissions factor is equal to 50 kgr SO_2 per tonne of fuel.

2.2 Estimating CO2 equivalency of SOx emissions

Ship air emissions have a wide range in their atmospheric lifetimes and differ in their abilities to affect climate – some cause cooling others cause warming, some do both. However, there is often a requirement to place them on a common scale in order to allow a comparison between them and estimate the aggregate effect. The word 'metric' refers to the methods that allow such a comparison by providing the equivalence between CO_2 emissions and emissions of other gases or aerosols. Although these metrics are being widely used by climate scientists (see IPCC, 2007;2014) they are also, highly controversial.

2.2.1 Climate Metrics

We present a simple, yet effective, way to integrate air quality and climate change policies. In particular, we focus on approaches to convert SOx emissions to CO_2 equivalent emissions based on various metrics. The same approach can be used for NOx emissions (and others).

There is much work on metrics during the last decade, also supported and researched by the UN IPPC and used in the Kyoto Protocol and its successors. The interested reader is referred to Shine (2007), Fuglestvedt et al. (2010) and Myhre and Shindell (2013) for a detailed analysis of the various metrics. Among the metrics that have been proposed in the literature, the most commonly used ones are the following (Azar and Johansson, 2012):

- Global Warming Potential (GWP) metric: "a measure of the integrated radiative forcing from the emission of 1 kg of a gas compared to the integrated radiative forcing of 1 kg of CO2".
- Global Temperature change Potential (GTP): "a measure of the temperature response at time H from a kg of gas emitted at present, divided by the temperature response at time H from 1 kg of CO2 at present".

Some reports (such as the 3rd IMO GHG study) have used the Radiative forcing (RF) metric, which is short for 'radiative forcing of climate change', to compare the effects of the various emissions. The Kyoto Protocol uses the global warming potential (GWP) with a 100 year time horizon. The Global Warming Potential (GWP) is based on the time-integrated RF due to a pulse emission. Being integrated over time, one of the most important parameters is the choice is actually the time horizon. The adequacy of the GWP, which has been used in most of the transportation-related literature (see Lindstad et al. (2015; 2016), Lindstad and Eskeland (2016) and CONCAWE (2018)) has also been much debated (Fuglestvedt et al., 2010; Allen et al., 2018).

Shine et al. (2007) proposed a new metric, the Global Temperature change Potential (GTP), which is consistent with long-term climate targets that set a constraint to the global mean surface temperature increases, such as for example the Kyoto Protocol target to keep the mean temperature below 2ºC above pre-industrial levels. The GTP metric uses a global mean temperature change at the end of a given time horizon, rather than an integration over time, which is the case of the GWP metric. Allen et al. (2018) propose the use of an updated metric, the so-called GWP*, to be used to implement mitigation strategies for meeting the global goals of the Paris Agreement.

We feel that the presentation of more details on these metrics is out of the scope of this work. Again, the interested reader is referred to Fuglestvedt et al. (2010), Shine (2007), Myhre and Shindell (2013) and Allen et al. (2018) for a detailed analysis.

2.2.2 Methodology of calculating the CO_2-equivalent emissions

To transfer different non-GHG emissions (e.g. SOx, NOx) to a common scale, i.e. CO_2 equivalents, using one of the above metrics (GWP or GTP), the following equation can be used:

$$CO_2eq\,(H) = E_i \times M_i\,(H) \qquad \text{(Eq.1)}$$

where Ei represents the emissions of gas i measured by mass, M is the metric used (see Table 1 for some values) and H the time horizon in years.

Table 1: Values for different metrics: GWP values from a one-year pulse emissions of SO_2 emissions from shipping for a 20, 100 year time horizons and GTP values for 20, 50 and 100 years. Source: Fuglestvedt et al. (2010).

Study	Specific forcing ($Wm^{-2}\,kg^{-1}$)	GWP		GTP		
		H = 20	H = 100	H = 20	H = 50	H = 100
Endresen et al.	−2.70E-10	−120	−34	−35	−5.7	−4.8
Eyring et al.	−1.66E-10	−73	−21	−21	−3.5	−2.9
Lauer et al.	−8.75E-11	−37	−11	−11	−1.8	−1.5
Fuglestvedt et al.	−3.43E-10	−150	−43	−44	−7.3	−6.1
Indirect						
Lauer et al. A	−3.54E-09	−1600	−440	−450	−75	−63
Lauer et al. B	−1.72E-09	−760	−220	−220	−37	−31
Lauer et al. C	−3.30E-09	−1500	−410	−420	−70	−58

Note: All sulphur values are on SO_2 basis. The GTP values are specific to a given value of climate sensitivity. The three values presented for Lauer et al. (2007) are for different emission inventories.

Table 1 is taken from Fuglestvedt et al. (2010) and presents the GWP and GTP metric values specifically for the shipping sector based on various studies (Eyring et al., 2005; Lauer et al., 2007; Fuglestvedt et al., 2009). Note that gases that are emitted into the atmosphere may cause radiative forcing (RF) of climate directly due to their own radiative properties, but also indirectly by "changing the concentrations of other climate gases through chemical processes in the atmosphere" (Fuglestvedt et al., 2010). By adding both the direct and indirect effects one can estimate the net total effect.

Based on these values we produce Table 2, which presents the average values for GWP and GTP as well as the minimum ones, which corresponds to the minimum cooling effect (minimum net total warming) in order to be conservative. Only one study (Lauer et al., 2007) has so far reported detailed calculations of the indirect forcing for shipping; and the uncertainty is particularly large.

Note that in the limited transport-related literature, see for example Lindstad and Eskeland (2016) , the indirect effect is ignored, probably as being very uncertain. In addition, the values used are generic ones and not related to shipping. We thus feel that our study presents better estimates.

Table 2: Average and minimum GWP and GTP values for various time horizons. Source: Authors - Data based on Fuglestvedt et al. (2010).

	GWP		GTP		
	H = 20	H = 100	H = 20	H = 50	H = 100
Direct average	-95	-27.3	-27.8	-4.6	-3.8
Direct minimum	-37	-11	-11	-1.8	-1.5
Indirect average	-1287	-357	-363	-61	-51
Indirect minimum	-760	-220	-220	-37	-31
TOTAL average	-1382	-384	-391	-65	-54
min	-797	-231	-231	-38.8	-32.5

3. The effect of Sulphur Regulations on Climate Change: A rough estimation

As noted above, emissions of different gases with different lifetimes and different effects on the climate can only be compared and weighted by using a climate change metric. This is the standard approach, also supported by the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) (Myhre and Shindell,2013; IPCC,2014).

We present here a rough estimation of the impact of the upcoming sulphur IMO regulation on the Climate. From January 2020, stricter limits will come into effect. As per the updated MARPOL Annex VI, referred to as the IMO 2020 rule, the sulphur content of fuel used in vessels outside sulphur Emission Control Areas (ECAs) must not exceed 0.50% m/m. Our analysis reveals that while the upcoming IMO regulation will reduce SO_x emissions, and their adverse effect on human health and the environment, on the other hand, this leads to more warming and, thus, accelerates the effects of Climate Change.

Our estimations are based on the following: We assume that the fuel currently used by vessels (heavy fuel oil with a current global maximum content of 3.50% mass/mass) will be mostly replaced by LSFO (low sulphur oil with a content of 0.5%). We further assume that HFO currently used has an average sulphur content of 2.60%, which corresponds to the average of the tested fuels in 2018, as reported to the IMO MEPC per the 'Guidelines for monitoring the worldwide average sulphur content of fuel oils supplied for use on board ships'.

The annual fuel consumption figures for 2019 and 2020 (in million barrels per day) are provided by the International Energy Agency (IEA). IEA (2018) predicts that the use of MGO will increase in 2020 as a result of the stricter cap and at the same time the use of HFO will decrease. HFO will be used by vessels that will be fitted with scrubbers and also due to non-compliance. The exact predictions for 2019 and 2020 are shown in the first two columns of Table 3.

Table 3: Equivalent CO2 emissions based on GWP values 100 years.
Source: Authors - Data based on IEA (2018) and Fuglestvedt et al. (2010).

Fuel type	Fuel Consumption (mb/day)		CO_2 emissions (mil. tonnes)		SO_2 emissions (mil. tonnes)		CO_2 equivalent of SO_2 emissions	
	2019	2020	2019	2020	2019	2020	2019	2020
MGO (0.07%)	0.767	1.736	120.31	272.31	0.05	0.12	-2.26	-5.11
VLSO (0.5%)	-	0.969	-	166.75	-	0.52	-	-22.37
HFO (2.6%)	3.231	1.292	498.29	199.25	8.32	3.33	-357.79	-143.07
TOTAL	3.998	3.997	618.60	638.32	8.37	3.97	-360.05	-170.55

By using an emission factor of of 3.114 tonnes CO_2 per tonne of fuel for heavy fuel oil (HFO) and 3.206 tonnes CO_2 per tonne of gas/diesel oil (MGO/MDO) fuel we estimate CO_2 emissions for 2019 and 2020.

As you can see in Table 3, the total CO_2 emissions are 618.60 million tonnes for 2019 and 638.32 mil. tonnes for 2020. The SO_2 emissions for the same years are 8.37 million tonnes for 2019 and just 3.97 million tonnes for 2020 due to the lower sulphur cap. Note that these values are a bit lower compared to the ones calculated in the 3rd IMO GHG due to the difference in the approaches used; IEA uses marine fuel sales data while the IMO study uses modeling; see more on the so-called 'bottom-up' vs 'top-down' approaches in IMO (2014, p.26). Our example, therefore, presents a rough estimation. The actual purpose of our example is to present the general trend, i.e. that strict sulphur limits reduce the cooling effect produced by SOx emissions and accelerate global warming. This can support our argument on integrating the IMO policies.

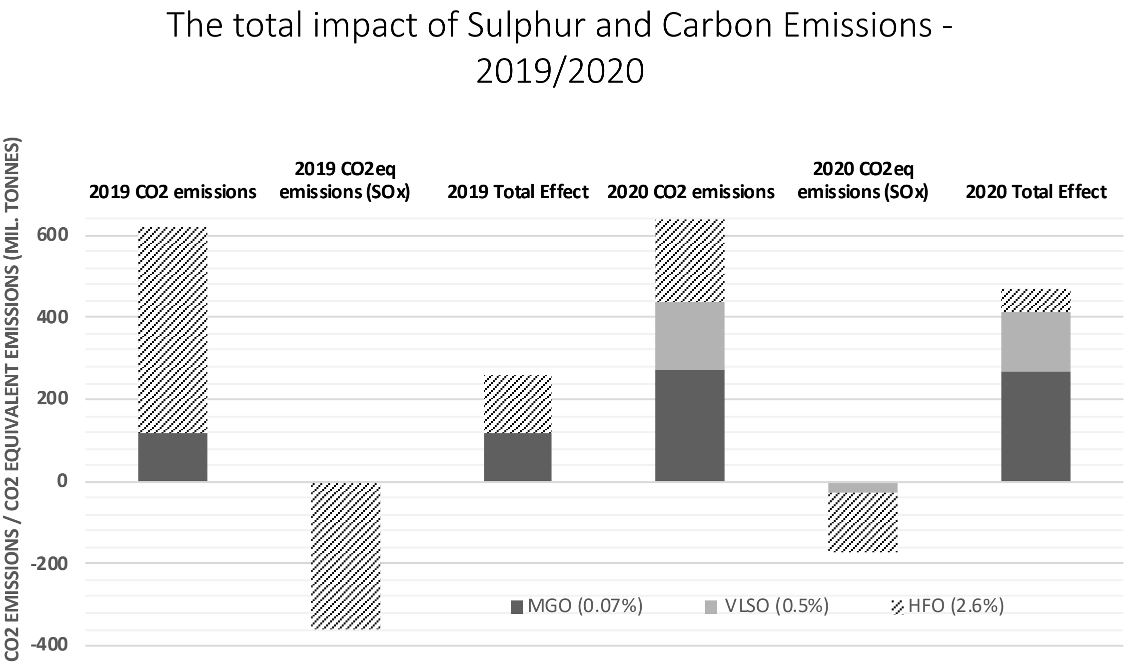

Figure 1: Total Impact of CO2 and SOx emissions for 2019 and 2020

We estimate the CO_2 equivalent emissions for the SO_2 emissions based on the GWP value for 100 years, which is -43, as per Fuglestvedt et al. (2010). This value is also used in the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) (Myhre and Shindell, 2013; IPCC, 2014) and is by far the most conservative estimate as no indirect effects are included.

Thus, our estimates are extremely conservative. Even so, the effect of the upcoming regulations is tremendous. As you can see in Figure 1, although CO_2 emissions for 2019 and 2020 are very close, including the effect of SOx emissions, the total CO2 equivalent emissions are way higher for 2020.

The CO_2 equivalent impact of SO_2 emissions (based on the GWP value for 100 years) is -360.05 million tonnes for 2019 and -170.55 million tonnes for 2020, respectively. The negative sign denotes the cooling effect of SO_2 emissions. The upcoming stricter limits in 2020 will lead, and this is the conservative estimate, to a net warming impact of -170.55-(-360.05) = 189.50 million tonnes of equivalent CO_2 emissions.

Similar results could be obtained by using the GTP metric, and/or different time horizons. Therefore, if we were to focus only on the effect on Climate, the upcoming regulations have an equivalent warming effect almost equivalent to emitting 189.50/618.60=30.63% MORE CO_2 emissions. It is clear that the cooling effect of the SO_2 shipping emissions will by grossly reduced after the introduction of the stricter sulphur limits. Policymakers should therefore urgently consider the acceleration of Climate Change effects due to the upcoming 2020 regulation.

4. Discussion and Conclusions

International shipping has been a fast-growing sector of the global economy (IMO, 2014), having direct and indirect effects on climate, air quality, and human health. However, the nature of the contribution of the various gases emitted from ships to climate change is complex as discussed in the Introduction. Global climate models are the central tools for assessing climate change as they simulate the physics, chemistry and biology of the atmosphere, land, and oceans in detail. Such models allow projections of future climate based on different emission scenarios. Many studies have focused on modeling climate effects of emissions from the global transport systems including maritime transportation (e.g., Lauer et al., 2007, Fuglestvedt et al., 2009; Righi et al., 2015). These models are indeed more accurate at estimating the total effect of transportation on the Climate. The metrics presented in Section 2 are indeed used in these complex models. We thus present in isolation a part of these complex models that can clearly illustrate to policymakers the effect of air pollution measures on climate change.

To that extent, Section 3 presents a rough estimation of the effect of the IMO2020 sulphur regulation. Regardless of the metric used, the reduction of the sulphur content of marine bunkers leads to a net warming effect; which implies that the effect on climate is similar to emitting more CO_2 emissions. The upcoming regulation (also referred to as the 2020 rule) that reduces the sulphur cap from 3.5% (average world sulphur content of 2.60%) to 0.5%, has an equivalent global warming effect of emitting about 30% more CO_2 emissions.

We promote the integration of Climate change and air pollution strategies in shipping as "it seems that simultaneous increase in welfare and mitigation of the effects on climate are possible when decision-makers integrate both sets of policies" (Bollen et al., 2009). Modeling the total impacts of various ship air emissions requires a framework using climate metrics that calculate the net effect on Climate, such as the two metrics that we present in Section 2. We acknowledge that designing policies to reduce different types of emissions is complicated due to the many uncertainties associated with evaluating the complex interactions of the different emissions. It is expected that in the future many of the uncertainties on climate metrics will be resolved. Note that the Fifth Assessment Report (AR5), that was finalized in 2014, includes a section based on the findings of the UN Framework Convention on Climate Change Ad Hoc Working Group that has been working on the technical assessment of climate metrics such as the two presented in this work. Thus, the rationale of using climate metrics is well established.

Despite all the relevant uncertainties (many of which will be resolved in the future), our work supports the idea of using a holistic approach to assess the impact of SOx reduction measures to global warming. Policymakers need to address the issue of ship air emissions based on an integrated approach in order to guarantee the best possible results at the lower cost and to avoid adverse effects. **Our research supports the findings in, amongst others, Lindstad et al. (2015), Lindstad and Eskeland (2016), CONCAWE (2018) and Sofiev et al.(2018), that the cooling effect of current SO_2 emissions will be largely eliminated with the introduction of the lower global sulphur limit in 2020. Given the acceleration of Climate Change due to removing the cooling effect of the SOx emissions, more ambitious carbon emissions reduction targets might be needed. We hope that this work can stimulate further research on this area and discussion in the relevant IMO fora.**

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