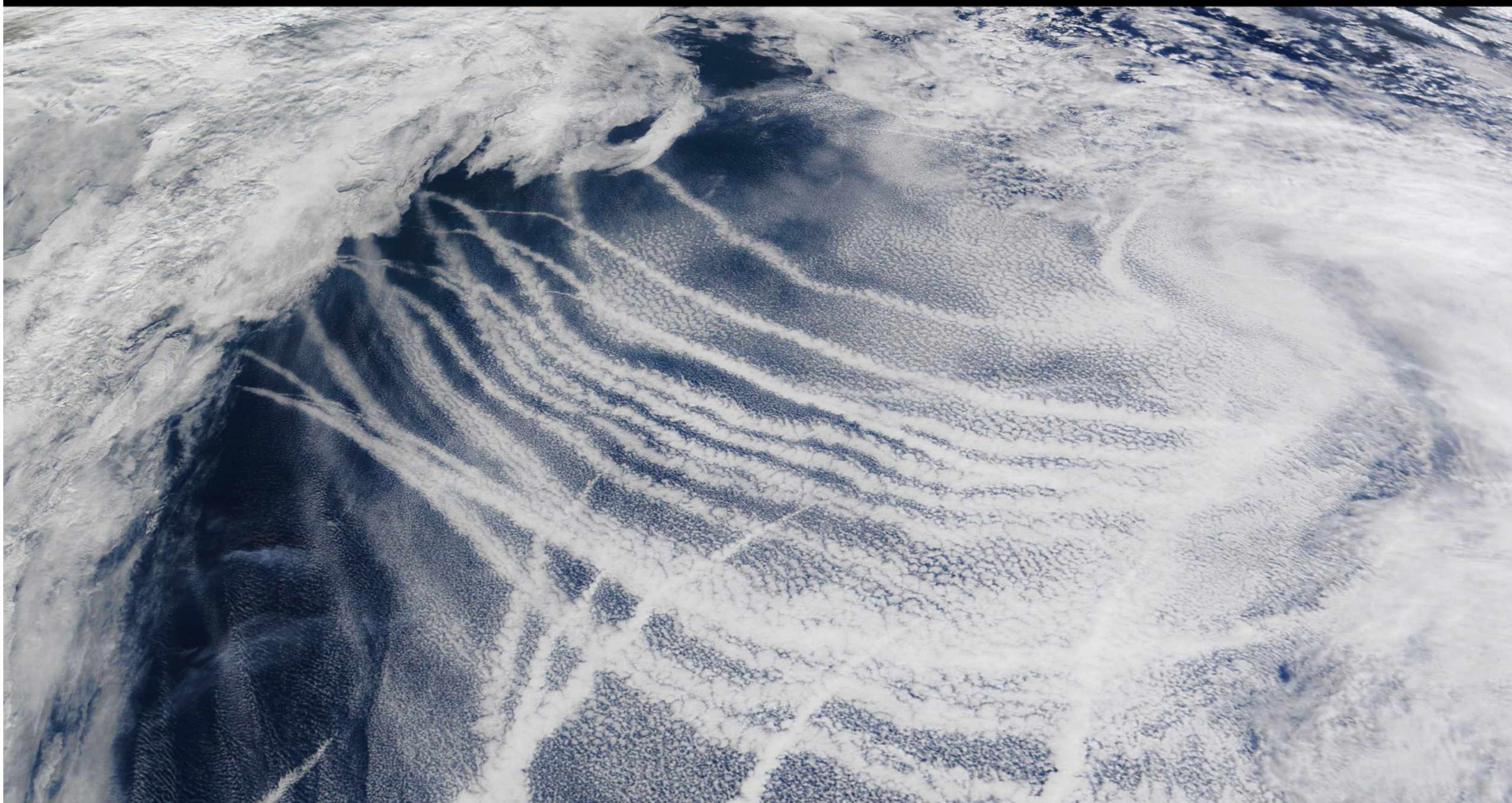
Open Letter
to the International Maritime Organization

Sulfur Reduction Regulations in Shipping Fuels Have Accelerated Global Warming



In 2020, International Maritime Organization regulations became effective that sharply limited the sulfur content of shipping fuel to protect human health from dangerous sulfur oxide emissions. However, multiple research studies suggest that these restrictions have also significantly increased global warming by reducing these global-cooling sulfur oxide emissions at a time when warming is accelerating and threatening the 1.5 C warming target significantly ahead of projections. This open letter asks the International Maritime Organization to urgently sponsor research and pilot testing and emergency regulations to reduce this harmful and unexpected global warming impact by, (a) relaxing sulfur restrictions over the "high seas" where the sulfur oxide emissions have less effect on humans, and (b) requiring that shipping fuels that do not contain sulfur include alternative substances that generate global-cooling emissions that are not harmful to humans or nature.

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Sulfur oxide emissions create global cooling ship tracks, NASA imagery, North Pacific, 2009

An Open Letter to the IMO Supporting the Utilization of Ship Fuels that Cool the Atmosphere While Preserving Air Quality Benefits

Authors: R. Baiman,[1] R. Bishop,[2] C. Elsworth,[3],B. Melton,[4] O. Peterson,[5] Y. Tao[6]

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We are in a global warming emergency that is being exacerbated by a rapid decline in anthropogenically caused atmospheric aerosol loading (Hansen et al, 2023).

Recently implemented (2015 and 2020) International Maritime Organization (IMO) regulations on bunker-fuel sulfur oxide (SO_x) are an important contributor to these reduced aerosol loadings and high sea surface temperatures (Hansen, 2023b; Hansen et al., 2023; WMO, 2014, 2023).

Numerous studies have suggested that these reduced aerosol loadings have and will significantly increase global warming (Hansen et al., 2023; Diamond, 2023; Voosen, 2023; Hausfather & Forester, 2023; Yuan et al. 2023, 2022; Bilsback et al., 2020; Jin et al., 2018; Sofiev et al., 2018; Partanen et al., 2013; Fuglestvedt et al., 2009; Lauer et al., 2007). Higher sea surface temperatures have been implicated in the intensification of extreme flooding worldwide and in the dying of an estimated 19 percent of coral reefs globally since 2009 (Aumann & Wang, 2018; UNEP, 2021).

This suggests the need to reconsider refinement of the regulations.

Following Partenan et al (2013), it may be possible to offset the global warming harm of these regulations by temporarily relaxing them for “high seas” sulfur emissions (i.e., far from ports and population centers) while largely preserving air quality benefits in ports and coastal areas like current IMO “Emission Control Areas”.[7] It may also be possible to increase the cooling effect of shipping emissions while preserving or enhancing air quality by including benign tropospheric aerosol precursors in existing and future non-GHG, or net-zero GHG emitting, maritime fuels (Baiman et al., 2023).

We therefore ask that the International Maritime Organization and other international and national health and environmental organizations urgently support and sponsor research, pilot testing and emergency regulations, that would:

[1] Corresponding Author: rbaiman@ben.edu , Benedictine University and Healthy Planet Action Coalition, USA
[2] Healthy Planet Action Coalition, Australia
[3] Climate Arks Ltd., UK
[4] Climate Change Now Initiative and Healthy Planet Action Coalition, USA
[5] Atmospheric Methane Removal AG, Switzerland
[6] MIrrors for Earth’s Energy Rebalancing, USA
[7] For “Emissions Control Areas” delineations see IMO (2020).

1) Partially relax the IMO's maritime bunker fuel sulfur emissions regulation for "high seas" maritime transport outside of Emissions Control Areas in ways that - as much as possible-- would increase the global cooling benefits of sulfur or similar aerosols without causing harm to humans or natural systems, and

2) Require that benign tropospheric aerosol precursors such as sea water (referred to as the "marine cloud brightening method") or other possible tropospheric aerosols (referred to as the "climate catalysts method") that would create the global cooling benefits of sulfur aerosols without - as much as possible - causing harm to humans or natural systems be included in existing fuel, and in future non-GHG and net-zero GHG emitting fuel (Baiman et al., 2023).

Signed by:

John MacDonald, Climate Foundation, Australia

Stephen Salter Ph.D., University of Edinburgh, UK

Rob de Laet, Future of the Amazon Foundation, Netherlands

Alan Gadian Ph.D., University of Leeds and National Center for Atmospheric Science, UK

Brian von Herzen, Ph.D., Climate Foundation, USA

Robert Tulip, rebrighten.org, Australia

Veli Albert Kallio, Sea Research Society, USA

Franz Dietrich Oeste, gM-Ingenieurbüro, Germany

Colin Forrest, Scotland, UK

Herb Simmens, Healthy Planet Action Coalition, USA

Jonathan Cole, Reflective Energy Engineer, USA

Clif Alferness, Engineer, Paradigm Climate, USA

Gregory Slater, U.S. citizen, USA

Daniel Kieve MSc., Healthy Planet Action Coalition, UK

Barbara J. Sneath Ph.D., Mirrors for Earth's Energy Rebalancing and Healthy Planet Action Coalition, USA

Peter Dynes, Mirrors for Earth's Energy Rebalancing, Ireland

John Nissen, Planetary Restoration Action Group, UK

Jerry Rivers, North American Climate, Conservation and Environment, USA

Anton Keskinen, Operaatio Arktis, Finland

Viktor Jaakkola, Operaatio Arktis, Finland

David Schwartz, LAD Fund, USA

William Barclay Ph.D., Chicago Political Economy Group, USA

Paul Buhle Ph.D., Brown University, USA

Technical Addendum

We are in a global warming emergency that is being exacerbated by a rapid decline in anthropogenically caused atmospheric aerosol loading (Hansen et al., 2023). Recently Implemented International Maritime Organization (IMO) regulations on bunker-fuel sulfur content are an important contributor to these reduced aerosol loadings (Hansen, 2023b).. Reduced sulfur content in bunker fuels thus appears to be resulting in significant warming of the upper ocean (WMO, 2023). For example, while the cause of the recent unprecedented high sea surface temperatures was initially thought to be the current El-Nino, the latest observations suggest that this has been a quite weak influence (Hansen, 2023b). The primary cause now appears to be a reduction in cloud albedo due to a reduced atmospheric sulfate aerosol loading, much of this reduction resulting from reduced SO_2 emissions from international shipping (Hansen, 2023b). The new regulations have resulted in the higher sea surface temperatures that have been implicated in the intensification of extreme flooding worldwide and in the dying of an estimated 19 percent of coral reefs globally since 2009 (Aumann & Wang, 2018; UNEP, 2021). This suggests the need to reconsider refinement of the regulations.

On January 1, 2020, International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC) regulations lowering the permissible sulfur oxide (SO_x) and particulate matter content of marine fuels from 3.5% to 0.5% outside of Emission Control Areas (ECA) by mass became fully effective (IMO, 2020).[8] Earlier regulations that came into effect in January 2015 limited sulfur oxide and particulate matter content in ECAs to 0.10% from the limit of 1.00% that had been in effect through 2014 (IMO, 2020; 2014).[9] The objective of the regulations was to reduce harmful public health impacts from sulfate and particulate matter pollution that often reached high levels in populated ports where large numbers of ships were in port or waiting to dock, constantly running their engines (Diamond, 2023; IMO, 2019; Partanen et al., 2013; Sofiev et al., 2018; Zhang et al., 2022).

IMO MEPC data indicate that before 2020 the average sulfur mass content of marine fuel oils was ~2.5%, and ~80% of the global fuel oil supply exceeded 0.5 %. Since 2020, the data indicate that the average sulfur mass content has declined to ~1%, and only ~20% of fuel has exceeded 0.5%, a reduction of ~ 60% in average fuel sulfur content (Diamond 2023; IMO MEPC 2020 - 2023). Moreover, as a “carriage ban” forbids ships from carrying noncompliant fuel oil unless they have scrubbers installed, this is likely an understatement of effective compliance (IMO, 2018). Thus, the regulations have likely significantly reduced shipping-caused sulfur emissions and thus sulfate loadings in highly populated port-regions around the world, resulting in reduced impacts on long-term health in these regions.

However, because these regulations have also reduced the global loading of sulfate aerosols that provide a cooling offset to global overheating from the increasing concentrations of carbon dioxide and other greenhouse gasses (GHGs), these regulations are adding to net global warming and its many associated health and environmental impacts.

[8] For ECA delineations see IMO (2020). An allowable alternative approach would require ships to install costly scrubbers to achieve an equivalent reduction in sulfur oxide (SOx) emissions.

[9] For a Table with a history of IMO sulfur oxide and particulate matter regulations inside and outside of ECA from 2010 to 2020, see IMO (2020).

The mechanism for the climatic effects is quite clear. Shipping effects on clouds, which were identified in the mid-1960s when satellite imagery captured images of “ship tracks,” have been found to increase the number and concentration of cloud droplets and decrease their average size. These changes tend to brighten clouds and make them more reflective (Conover, 1966; Twomey et al., 1968; Twomey, 1974, 1977). In addition, cloud macrophysical adjustments (referred to as the Twomey effect) have been observed within ship tracks to enhance their brightening effect by suppressing precipitation, which in turn can lead to longer cloud lifetimes (Albrecht, 1989; Goren and Rosenfeld, 2012) or, alternatively, depending on the situation, to reduce their brightening effect by enhancing cloud break up or entrainment (Chen et al., 2012; Coakley and Walsh, 2002; Toll et al., 2019).

Hansen et al. (2023) estimates the increased global forcing impact of the 2015 and 2020 IMO bunker fuel sulfur content regulations to be about 1.05 W/m^2.

Diamond (2023) estimates the effect of the 2020 regulations to be on the order of 0.1 W/m^2. Diamond’s paper built on earlier studies that had found that, using artificial intelligence-based satellite image recognition, clouds induced by ships (i.e. ship tracks) had been 10 times more numerous before 2020 than previously estimated based on manual identification techniques, and that ship tracks had declined by more than 50% in the main shipping corridors after the 2020 IMO regulations came into effect (Voosen, 2023; Yuan et al., 2022). Another recent study, currently under review, by Yuan and co-authors, using this data reportedly estimates a similar 0.1 W/m^2 radiative forcing increase due to loss of maritime sulfur aerosol after 2020 (Voosen, 2023).

Estimates from earlier studies have shown a range of influences for different (2015 or 2020) regulatory regimes and sulfate, or sulfate and other, marine fuel induced aerosols. Hausfather & Forester (2023) found 0.079 W/m^2; Yuan et al. (2023) estimate 0.12 W/m^2, Yuan et al. (2022) give a range of 0.02-0.27 W/m^2; Bilsback et al. (2020) estimate 0.027-0.041 W/m^2; Jin et al. (2018) estimate 0.153 W/m^2; Sofiev et al. (2018) 0.071 W/m^2; Partanen et al. (2013) 0.39 W/m^2; Fuglestvedt et al. (2009) 0.097 W/m^2; and Lauer et al. (2007) 0.11-0.36 W/m^2.

Considering that recent (i.e., January 2020 - June 2023) CERES data on the total Earth Energy Imbalance, or total excess energy from the sun absorbed by the earth, averages 1.36 W/m^2, all of these estimates suggest that a significant global heating impact has resulted from the regulations, as there are no other indications of such a large positive forcing (Hansen et al., 2023; Hansen, 2023a, 2023b).

Partenan et al. (2013) also compared the global cooling and health effects of the pre-2020 shipping emissions scenario (ship-fuel sulfur content of 2.7%) with two alternatives: (a) scenario 1 in which ship-fuel sulfur content was 0.1% in coastal waters and 5.4% elsewhere, and (b) scenario 2 in which global ship-fuel sulfur content was 0.1% in coastal waters and 0.5% elsewhere (roughly corresponding to the current post-2020 sulfur content regime). They found that scenario 2 had more beneficial health impacts than the pre-2020 emission regulation scenario, reducing deaths by 96% of the 2013 total (48,200 deaths avoided per year), but much less cooling impact ($-0.06\ W\ m^{-2}$ *vs.* $-0.39\ W\ m^{-2}$), and that *scenario 1 had a slightly stronger cooling effect from shipping than the pre-2020 shipping emissions* *scenario ($-0.43\ W\ m^{-2}$ vs. $-0.39\ W\ m^{-2}$) while still greatly reducing premature mortality from shipping, by 69% globally (34,900 deaths avoided per year).*[10,11]

Following Partenan et al (2013), it may be possible to offset the global warming harm of these regulations by temporarily relaxing them for "high seas" sulfur emissions (i.e., far from ports and population centers) while largely preserving air quality benefits in ports and coastal areas like IMO Emission Control Areas (ECA). It may also be possible to increase the cooling effect of shipping emissions while preserving or enhancing air quality by including benign tropospheric aerosol precursors in existing and future non-GHG, or net-zero GHG emitting, maritime fuels (Baiman et al., 2023).

We therefore ask that the International Maritime Organization and other international and national health and environmental organizations *urgently support and sponsor research, pilot testing and emergency regulations, that would:*

1) *Partially relax the IMO's maritime bunker fuel sulfur emissions regulation for "high seas" non-ECA maritime transport* in ways that - as much as possible-- would increase the global cooling benefits of sulfur or similar aerosols without causing harm to humans or natural systems, and
2) *Require that benign tropospheric aerosol precursors* such as sea water (referred to as the "marine cloud brightening method") or other possible tropospheric aerosols (referred to as the "climate catalysts method") that would create the global cooling benefits of sulfur aerosols without - as much as possible - causing harm to humans or natural systems *be included in existing fuel, and in future non-GHG and net-zero GHG emitting fuel* (Baiman et al., 2023) .

[10] In comparison, a recent paper estimates existing and future deaths from global warming to be orders of magnitude greater: "Several studies are consistent with the "1000-ton rule," according to which a future person is killed every time 1000 tons of fossil carbon are burned (order-of-magnitude estimate). If warming reaches or exceeds 2 °C this century, anthropogenic global warming caused by mainly richer humans will be responsible for the earlier deaths of roughly 1 billion mainly poorer humans by the end of the century; such an action could be viewed as comparable to "involuntary or negligent manslaughter." (Pearce & Parncutt, 2023, Abstract).

[11] Similarly, the cost of achieving $-0.39\ W\ m^{-2}$ cooling through greenhouse gas drawdown (though necessary in the long run) will likely be many orders of magnitude greater than the cost of proposals 1) and 2). For example, Hansen et al. (2023) estimate the cost of achieving $-0.03\ W\ m^{-2}$ cooling in 2022 by capturing carbon directly from the air and permanently storing it to be $3.4 -7.0 trillion.

References:

Albrecht B.A. (1989). Aerosols, Cloud Microphysics, and Fractional Cloudiness, *Science* 245 1227–1230: https://doi.org/10.1126/science.245.4923.1227

Aumann H. H.& Wang A. B .Y. (2018). Increased Frequency of Extreme Tropical Deep Convection: AIRS Observations and Climate Model Predictions. *Geophysical Research Letters* 45(24): https://doi.org/10.1029/2018GL079423

Baiman R., Clarke S., Elsworth E., Field L., Hoffman A., MacCracken M, et al.(2023). Understanding the Urgent Need for Direct Climate Cooling. *ESS Open Archive.* October 17: DOI: 10.22541/essoar.169755546.65919302/v1

Bilsback K., Kerry D., Croft B., Ford B., Jathar S. H., Ellison C., et al. (2020). *Environmental Research Letters:* https://iopscience.iop.org/article/10.1088/1748-9326/abc718/pdf

Jin Q., Grandey B. S., Rothenberg D., Avramov A. & Wang C. (2018). Impacts on cloud radiative effects induced by coexisting aerosols converted from international shipping and maritime DMS emissions. *Atmospheric Chemistry and Physics* 18(22): https://doi.org/10.5194/acp-18-16793-2018

ChenY. C., Christensen M. W., Xue L., Sorooshian A., Stephens G. L., Rasmussen R. M., et al. (2012). *Atmos. Chem. Phys.*, 12, 8223–823: https://doi.org/10.5194/acp-12-8223-2012 .

Coakley J. & Walsh C. D. (2002) Limits to the aerosol indirect radiative effect derived from observations of ship tracks. Journal of the Atmospheric Sciences 59(3): https://doi.org/10.1175/1520-0469(2002)059<0668:LTTAIR>2.0.CO;2

Conover J.H. (1966). Anomalous Cloud Lines. *J. Atmos. Sci.* 23 778–785: 10.1175/1520-0469(1966)023<0778:ACL>2.0.CO;2

Diamond M.(2023). Detection of large-scale microphysical changes within a major shipping corridor after implementation of the International Maritime Organization 2020 fuel sulfur regulations. *Atmos. Chem. Phys.* 23 8259-8269: https://doi.org/10.5194/acp-23-8259-2023

Fuglestvedt J., Berntsen T., Eyring V., Isaksen I., Lee L. S. & Sausen R. (2009). How should shipping emissions' ability to cool or warm the climate be addressed? *Environ. Sci. Technol* 43(24) 9057–9062: https://doi.org/10.1021/es901944r

Goren T. & Rosenfeld D. (2012). Satellite observations of ship emission induced transitions from broken to closed cell marine stratocumulus over large areas. *JGR Atmospheres* 117(D17): https://doi.org/10.1029/2012JD017981

Hansen J.,Simons L., Nazarenko L. S., Sangha I., Kharecha P., Zachos J. et al. (2023). Global warming in the pipeline. *Oxford Open Climate Change* 3(1): https://doi.org/10.1093/oxfclm/kgad008

Hansen J. (2023a). "Global Warming is Accelerating. Why? Will We Fly Blind?". Newsletter Sep. 14: https://www.columbia.edu/~jeh1/mailings/2023/FlyingBlind.14September2023.pdf

Hansen J. (2023b). “El Nino Fizzles. Planet Earth Sizzles. Why?”. Newsletter Oct. 13: https://www.columbia.edu/~jeh1/mailings/2023/ElNinoFizzles.13October2023.pdf

Hansen J., Sato M., Ruedy R. (2023. Uh-Oh now what? Are we acquiring the data to understand the situation. Aug. 14: https://www.columbia.edu/~jeh1/mailings/2023/UhOh.14August2023.pdf

Hausfather Z. & Forster P. (2023). Analysis: How low-sulphur shipping rules are affecting global warming. *Carbon Brief* July 3: https://www.carbonbrief.org/analysis-how-low-sulphur-shipping-rules-are-affecting-global-warming/

IMO. (2014). Ships face 0.10% sulphur fuel requirements in emission control areas. December 23: https://www.imo.org/en/MediaCentre/PressBriefings/Pages/44-ECA-sulphur.aspx

IMO. (2018) RESOLUTION MEPC.305(73) (adopted on 26 October 2018) AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1997 TO AMEND THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973, AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO. London, UK: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.305(73).pdf

IMO. (2019). RESOLUTION MEPC.320(74) 2019 GUIDELINES FOR CONSISTENT IMPLEMENTATION OF THE 0.50% SULPHUR LIMIT UNDER MARPOL ANNEX V, London, UK: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/ResolutionMEPC.320(74).pdf

IMO MEPC. (2020). 75/5/9 Sulphur monitoring for 2019. London, UK: https://docs.imo.org/Category.aspx?cid=47&session=75

IMO. (2020). Sulphur oxides (SOx) and Particulate Matter (PM) – Regulation 1. London, UK: https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx

IMO MEPC. (2021). 76/5/2 Relevant information reported to IMO related to the entry into force of the global 0.50% sulphur limit (IMO 2020) and outcomes of the sulphur monitoring programme for 2020. London, UK: https://docs.imo.org/Category.aspx?cid=47&session=76

IMO MEPC. (2022). 78/INF.4 Relevant information reported to IMO related to the implementation of the global 0.50% sulphur limit (IMO2020) and outcomes of the sulphur monitoring for 2021. London, UK: https://docs.imo.org/Category.aspx?cid=47&session=78

IMO MEPC. (2023). 80/INF.4 Relevant information reported to IMO related to the entry into force of the global 0.50% sulphur limit (IMO 2020) and outcomes of the sulphur monitoring for 2022. London, UK: https://docs.imo.org/Shared/Download.aspx?did=142046

Jin Q., Grandey B. S., Rothenberg D., Avramov A. & Wang C. (2018). Impacts on cloud radiative effects induced by coexisting aerosols converted from international shipping and maritime DMS emissions. *Atmospheric Chemistry and Physics* 18(22): https://doi.org/10.5194/acp-18-16793-2018

Lauer A., Eyring V., Hendricks J., Jockel P. & Lohmann U. (2007). *Atmos. Chem. Phys*., 7, 5061–5079: https://acp.copernicus.org/articles/7/5061/2007/acp-7-5061-2007.pdf

Partanen A.I., Laakso A., Schmidt A., Kokkol, H., Kuokkanen T., Pietikäine J.P., et al. (2013). Climate and air quality trade-offs in altering ship fuel sulfur content. *Atmos. Chem. Phys.* 13 12059–12071: https://doi.org/10.5194/acp-13-12059-2013

Pearce J. M. & Parncutt R. (2023). Quantifying global greenhouse gas emissions in human deaths to guide energy policy. *Energies* 16(16): https://www.mdpi.com/1996-1073/16/16/6074

Sofiev M., Winebrake J. J., Johansson L., Carr E.W., Prank M., Soares J., et al. (2018). Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nat. Commun.* 9(406): https://doi.org/10.1038/s41467-017-02774-9

Toll V., Christensen M., Quaas J. & Bellouin N. (2019). Weak average liquid-cloud-water response to anthropogenic aerosols. *Nature* 572 51-55: https://doi.org/10.1038/s41586-019-1423-9

Twomey S., Howell H.B. & Wojciechowski T.A. (1968). Comments on "anomalous cloud lines". *J. Atmos. Sci.* 25 333–334: https://doi.org/10.1175/1520-0469(1968)025<0333:COCL>2.0.CO;2

Twomey S. (1974). Pollution and the planetary albedo. *Atmos. Environ.* 8 1251–1256: https://doi.org/10.1016/0004-6981(74)90004-3

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds, *J. Atmos. Sci.* 34 1149–1152: https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2

UNEP. (2020). Status of coral reefs of the world 2020. *United Nations Environmental Program* Oct. 5: https://www.unep.org/resources/status-coral-reefs-world-2020

Voosen P. (2023). Ship fuel rules have altered clouds and warmed waters. *Science* 381(6657):467-468: https://doi.org/10.1126/science.adk0831

WMO. (2023). Earth had hottest three-month period on record, with unprecedented sea surface temperatures and much extreme weather. *World Meteorological Organization* Sep. 6: https://public.wmo.int/en/media/press-release/earth-had-hottest-three-month-period-record-unprecedented-sea-surface

Yuan T., Song H., Oreopoulos L., Wood R., Bian H, Breen K. et al. (2023). Substantial Radiative Warming by an Inadvertent Geoengineering Experiment from 2020 Fuel Regulations. *Physical Sciences* Oct. 30 Preprint Version 1: https://www.researchsquare.com/article/rs-3490826/v1

Yuan T., Song H., Wood R., Wang C., Oreopoulos L, Platnick S. E. et al. (2022). *Atmospheric Science* 8(29): DOI: 10.1126/sciadv.abn7988

Zhang Y., Eastham S.D., Lau A. K.H., Fung J. C.H. & Selin N.E. (2021). Global air quality and health impacts of domestic and international shipping. Environ. *Res. Lett.* 16(084055): https://doi.org/10.1088/1748-9326/ac146b