MSc Program
Environmental Technology & International Affairs

The Disappearance of Ship Tracks – On the Impact of Sulfur Reduction in Marine Fuel on the Climate

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 10.06.2024

Affidavit

I, **NIKOLA MIRČETIĆ, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE DISAPPEARANCE OF SHIP TRACKS – ON THE IMPACT OF SULFUR REDUCTION IN MARINE FUEL ON THE CLIMATE", 68 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

In response to concerns regarding human health and environmental protection, the International Maritime Organization (IMO) adopted the IMO 2020 regulation, which reduced the sulfur content in marine fuel from 3.5% to 0.5%. This regulation, effective since 2020, has significantly reduced sulfur dioxide (SO_2) emissions from ships by more than 80%. However, this reduction has led to the unintended consequence of diminishing the atmospheric cooling effects provided by sulfate aerosols, which previously contributed to the formation of clouds known as ship tracks, cloud brightening, and the scattering of solar radiation. This loss has potentially exacerbated global warming.

This thesis investigates the climatic impact of the IMO 2020 regulation through a comparative literature review, analyzing divergent views within the scientific community. Key discrepancies are highlighted between the Intergovernmental Panel on Climate Change (IPCC) and climate scientist James E. Hansen and his colleagues. The IPCC's 6th Assessment Report downplays the cooling effect of pre-2020 shipping emissions, whereas other studies indicate a significant cooling influence for the same period. In particular, recent publications co-authored by Hansen demonstrate that the IMO 2020 regulation has considerably reduced the formation of ship tracks and contributed to recent warming.

There is now compelling evidence that the IMO 2020 regulation has led to an increase in absorbed solar radiation, resulting in an acceleration of global warming rates. This indicates that sulfur reductions are contributing to the occurrence of more extreme weather events. The thesis concludes that while sulfur reductions are intended to improve human health and reduce premature deaths attributable to ship emissions, the climatic repercussions necessitate reevaluation. The findings call for an improved understanding of aerosol impacts to enhance climate models and propose deliberate geoengineering measures, such as marine cloud brightening via aerosol injection, to mitigate the unintended warming effects of sulfur emission reductions.

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List of Abbreviations

AQG	Air Quality Guideline
AQS	Air Quality Standards
ASR	absorbed solar radiation
BC	black carbon
CCN	cloud condensation nuclei
ECA	Emission Control Area
ECS	equilibrium climate sensitivity
ERF	effective radiative forcing
GHG	greenhouse gas
ICCT	International Council on Clean Transport
IPCC	Intergovernmental Panel on Climate Change
IPCC AR6	Sixth Assessment Report of the IPCC
IMO	International Maritime Organization
LNG	liquified natural gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
NAO	North Atlantic Ocean
NPO	North Pacific Ocean
NMVOC	non-methane volatile organic compound
ODS	ozone-depleting substance
OECD	Organisation for Economic Co-Operation and Development
PM	particulate matter
PM2.5	particulate matter up to 2.5 µm
PM10	particulate matter up to 10 µm
RF	radiative forcing
SLCF	short-lived climate forcer
TCR	transient climate response
WHO	World Health Organization
UNFCCC	United Nations Framework Convention on Climate Change

Acknowledgments

I would like to take this opportunity to express my heartfelt gratitude, first and foremost, to my family, especially my mother and my aunt Ivanka, who made it possible for me to pursue this degree. I am profoundly thankful for their immense support, their patience, and their unwavering belief in me. I would also like to extend my sincere thanks to my professor and supervisor, Dr. Hans Puxbaum, who was always there to guide me whenever I had concerns or questions. I greatly appreciated his insightful guidance and the stimulating discussions we shared, which allowed me to delve into the fascinating fields of atmospheric chemistry and climatology.

Uh-oh, we also fxcked up on aerosol climate forcing!

—James E. Hansen, *Global Warming Acceleration: Hope vs Hopium*

1 Introduction

1.1 A World Made by the Sea

The world as we know it would not be the same without seafaring. The horizons were no longer inaccessible but became something to be explored and conquered. For millennia, ships have been carrying people and goods across the oceans. Cultures like the Phoenicians, Greeks, Egyptians, and Romans would not have become what history tells us they were. The world was connected and shaped by seafaring. Distances became shorter, and wealth greater. Innovations that improved the steam engine during the Industrial Revolution unleashed a new form of seaborne trade, leading to the introduction of the first cargo ships. Innovative hull designs made it possible to transport much larger quantities of goods. As a result, trade began to favor sea routes over land routes. In the 1950s, container ships were developed to replace the inefficient method of break bulk shipping. Containerization ultimately changed the global economy. Trade flourished, and global demand soared. In response to the escalating needs of the expanding global economy, even larger ships were constructed. Nowadays more than 80% of goods are transported by the sea (IMO 2019a). In the last three decades alone, the volume of goods transported has doubled (Statista 2024). Not only has maritime trade grown rapidly, but the cruise ship industry has also become a booming market.

Most ships are powered by internal combustion engines and burn large amounts of marine fossil fuel. The resulting emissions of carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) are harmful to the environment and human health and impact the climate. CO_2 is a potent greenhouse gas (GHG) and the main contributor to global warming. The others are known to be harmful to human health. To reduce the impact of ship emissions and protect human health, the International Maritime Organization (IMO) decided already in 2008 to act and reduce gradually the sulfur content of marine fuels. The latest sulfur reduction, known as IMO 2020 and discussed in more detail in chapter 2.4, became effective in 2020 and was so significant that sulfur dioxide (SO_2) emissions were reduced by approximately 80% (Hausfather and Forster 2023). This change can be considered a triumph of international regulations on environmental protection. Unfortunately, there is a downside to this success story.

The release of SO_2 into the air causes the formation of tiny particles called sulfate aerosols. These aerosol particles brighten existing clouds and create ship tracks, i.e., long, linear clouds in the wake of ships moving through the ocean. Bright clouds and increased cloud cover prevent sunlight from reaching the Earth's surface, which has a cooling effect. Reducing the sulfur content of marine fuels has caused these ship tracks to disappear (Gryspeerdt et al. 2019, 2157). As a result, more solar radiation reaches the surface, causing additional global warming (Hansen, Sato, and Kharecha 2024, 2). The magnitude of the warming is a matter of great uncertainty and is currently being debated within the scientific community. It will be a task of this thesis to bring some clarity to this matter. But first, the above issue will be placed in a larger context and against the background of climate change.

1.2 A Planet out of Balance

The history of our planet throughout the eons can be described as turbulent. Tectonic plate movements, impact events such as the one that caused the Cretaceous-Paleogene extinction, the Milankovitch cycles, changes in atmospheric composition, biological evolution, etc., make the Earth a place of great revolutions. However, for the last 12.000 years, our planet has been in a state of relatively stable temperatures. The conditions of this geological period called the Holocene, as illustrated in figure 1, seemed to be a sweet spot for humanity to thrive. Except for a few natural variations, such as volcanism, solar activity, axial tilt, and albedo changes due to land use, the Earth's energy budget appeared to be in equilibrium, allowing for a smooth temperature profile.

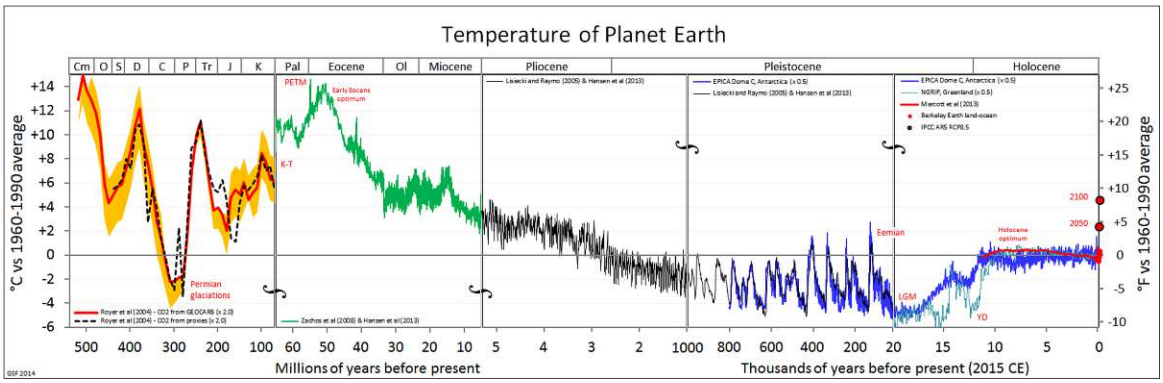

Figure 1. Overview of the global average temperature of the last 540 Ma. *Source*: Glen Fergus. "All paleotemps." Accessed 4 April 2024. https://commons.wikimedia.org/wiki/File:All_palaeotemps.png.

The state of equilibrium did not last long, as another revolution, this time anthropogenic, was about to change it. After the onset of the Industrial Revolution in the late eighteenth century, increased human activity and the burning of fossil fuels began to alter the composition of the atmosphere by injecting additional GHGs and aerosol particles into the atmosphere. GHGs, primarily water vapor, CO_2, and methane (CH_4), trap outgoing infrared radiation and lead to global warming. Aerosol particles, especially sulfate aerosols, on the other hand, have a strong net negative radiative forcing, i.e., a cooling effect, by reducing the amount of incoming solar radiation, thereby masking a significant portion of the GHG-induced warming. However, it was not until the end of the nineteenth century that someone realized that human activity could change the climate. Svante Arrhenius (1896), in his paper *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground*, proposed that increased levels of CO_2 and water vapor would lead to global warming and introduced the concept of climate sensitivity, arguing that a doubling of CO_2 in the atmosphere would lead to a 5–6°C increase in temperature. As shown in figure 2, significant warming could have been observed after the post-World War II economic boom in the 1970s.

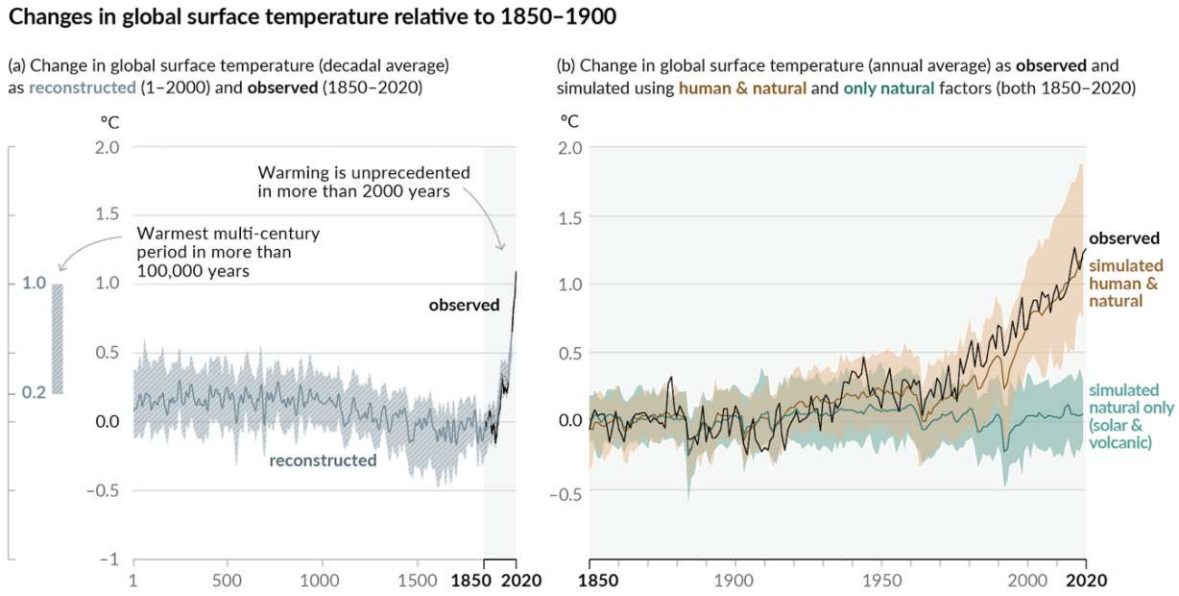

Figure 2. Reconstructed temperatures of the last 2000 years and observed records and simulations between 1850–1900. *Source*: IPCC. 2021. "Figure SPM.1 | History of global temperature change and causes of recent warming." In *Summary for Policymakers* in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 6. Cambridge: Cambridge University Press (2023). https://doi.org/10.1017/9781009157896.001.

Fossil fuel combustion closely mirrored exponential growth and consumption patterns. Although the scientific community's confidence that human activity was the primary cause of this unprecedented warming grew rapidly beginning in the 1960s, the international community did little until the end of the twentieth century. However, as the world realized the need to prevent further damage to the environment and to humanity itself, international conventions were drafted and adopted to address the imminent threat of global warming and pollution. One of these conventions is the International Convention for the Prevention of Pollution from Ships, in short MARPOL. A particular amendment to MARPOL, i.e., Annex VI, aims to combat air pollution caused by ships and is discussed in chapter 2.4.

1.3 The Faustian Payment

The Marine Environment Protection Committee (MEPC), a specialized committee within the IMO, decided in 2008 to phase in the reduction of sulfur content in marine fuels (IMO 2008, 19). The resolution called for the largest sulfur reduction, i.e. from 3.5% to 0.5%, to take place on January 1, 2020, hereafter referred to as IMO 2020. The goal was simple: reduce emissions of SO_2, a precursor of sulfate aerosols, to reduce the impact of ship emissions on human health. Although it seemed a sensible decision at the time, and the motive was undeniably good, the IMO or, respectively, the scientists involved, either overlooked or did not grasp the downside of this action in its magnitude, which is understandable since there were significant uncertainties and challenges in fully understanding and quantifying the effects of aerosol particles on the climate. As James E. Hansen recently pointed out in a webinar on November 2, 2023, "*Humanity has made a Faustian bargain by offsetting a substantial but uncertain fraction of greenhouse gas warming with aerosol cooling. Now as we want to reduce all the chronic health effects of aerosols, our first Faustian payment is due*." Sulfate aerosols are the antagonists of GHGs, so to speak. The crux of this Faustian bargain is that reducing ship SO_2 emissions without reducing GHG emissions will result in increased global warming. While the scientific community agrees on this, there is considerable disagreement on the magnitude of the cooling effect of sulfate aerosols from ships on the climate, and thus on the magnitude of the additional warming. This disagreement extends to the question of climate sensitivity, which

is indirectly linked to the effect of aerosol particles through their role in radiative forcing. Climate sensitivity is critical to climate change projections. If aerosol forcing is assumed to be strong, then the resulting net positive forcing by greenhouse gases is rather small, which would imply high climate sensitivity, and vice versa. These uncertainties arise from the still limited understanding of aerosol-cloud interactions and the wide range of values used in climate modeling and projections; issues which will be discussed in chapter 3.1, 3.2, and 3.3.

1.4 Motivation and Research Question

Although global SO_2 emissions began to decline in the 1970s, shipping was still responsible for about 15% of global emissions before 2020, as discussed in chapter 2.2.4. With growing awareness concerning environmental issues and international efforts to protect human health and the environment from air pollution, the IMO has progressively implemented regulations to contribute to these goals. The IMO 2020 regulation successfully reduced SO_2 emissions by more than 80% (Hausfather and Forster 2023). However, an unanticipated consequence was the significant climate impact of reducing sulfur in marine fuels. Sulfate aerosols, which have a cooling effect on the climate, were significantly reduced, sparking controversy about the magnitude of this cooling.

Initially, the IPCC (Szopa et al. 2021) suggested a negligible climate impact, but previous modeling studies (e.g., Partanen et al. 2013) and observations of the global radiation budget (Hansen et al. 2023a) indicate a significant impact on the radiation budget, resulting in warming due to reduced SO_2 emissions and their direct and indirect effects such as the formation of ship tracks. At present, an increasing number of scientific reports and papers suggest that the climate impact of SO_2 emissions from ships, in addition to global reductions in land-based SO_2 emissions, may be contributing to the current rise in global temperatures (Hansen et al. 2023b).

The aim of this thesis is to conduct a comparative literature review to investigate the positive and negative impacts of the IMO 2020 regulation and to assess the extent to which reducing SO_2 emissions from ships accelerates warming and the resulting implications. In this context, several questions arise: whether the IMO 2020 regulation should be reassessed in light of new findings, especially if the negative climate effects outweigh the health benefits

of SO_2 emission reductions, whether the negative results of sulfur reduction can contribute to a new perspective on the geoengineering approach of sulfur injection, and whether there are new or unconventional methods for comparing health with climate impacts.

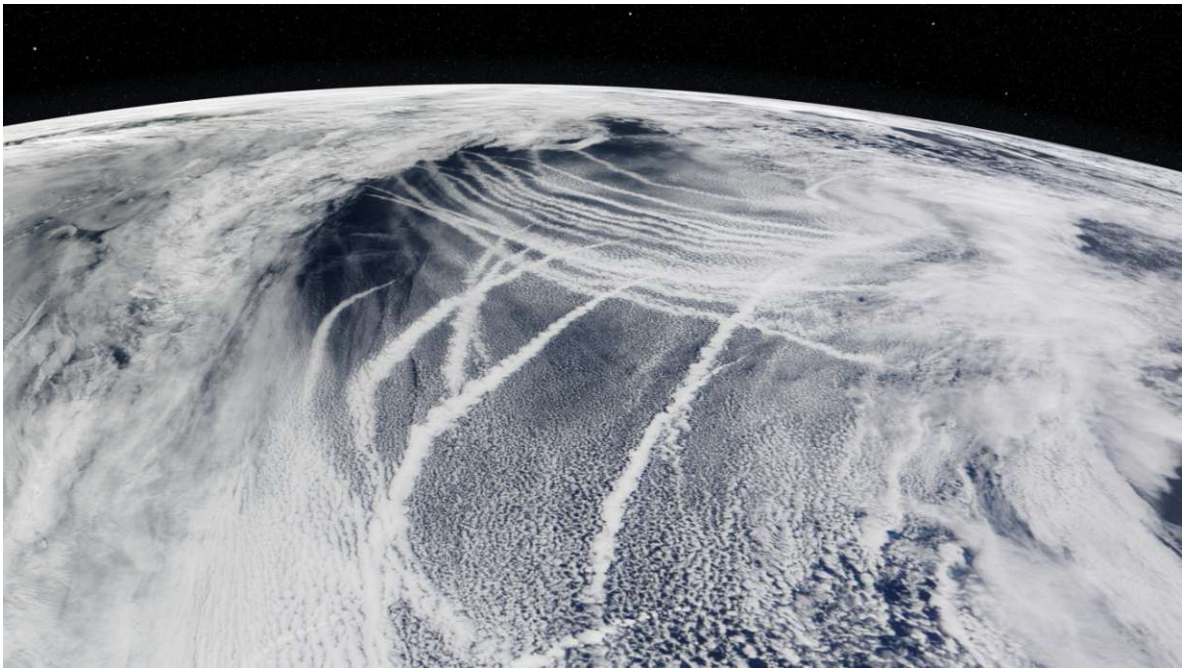

Figure 3. Ship tracks revealed by the NASA MODIS satellite instrument. *Source*: "Visible ship tracks on Northern Pacific on March 4th, 2009." NASA/Goddard Space Flight Center Scientific Visualization Studio, Helen-Nicole Kostis (Lead Animator). https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3667.

2 Air Pollution

2.1 The Rise of Fossil Fuels

To approach the research question, it is first necessary to discuss the issue of air pollution and the role of ships in it. The global increase in air pollution is directly linked to the history of fossil fuel use, which became significant during the Industrial Revolution. At that time, the United Kingdom, the cradle of the Industrial Revolution, was rich not in oil but in coal. Due to its abundance, easy accessibility through mining, and technologies such as the steam engine, powered factories, and railroads, coal was by far the dominant energy source until the mid-twentieth century. Oil was also used but began to rise to prominence after World War II. In the mid-twentieth century, the world experienced a significant

paradigm shift in energy consumption, as shown in figure 4, due to the rapid growth of the global economy.

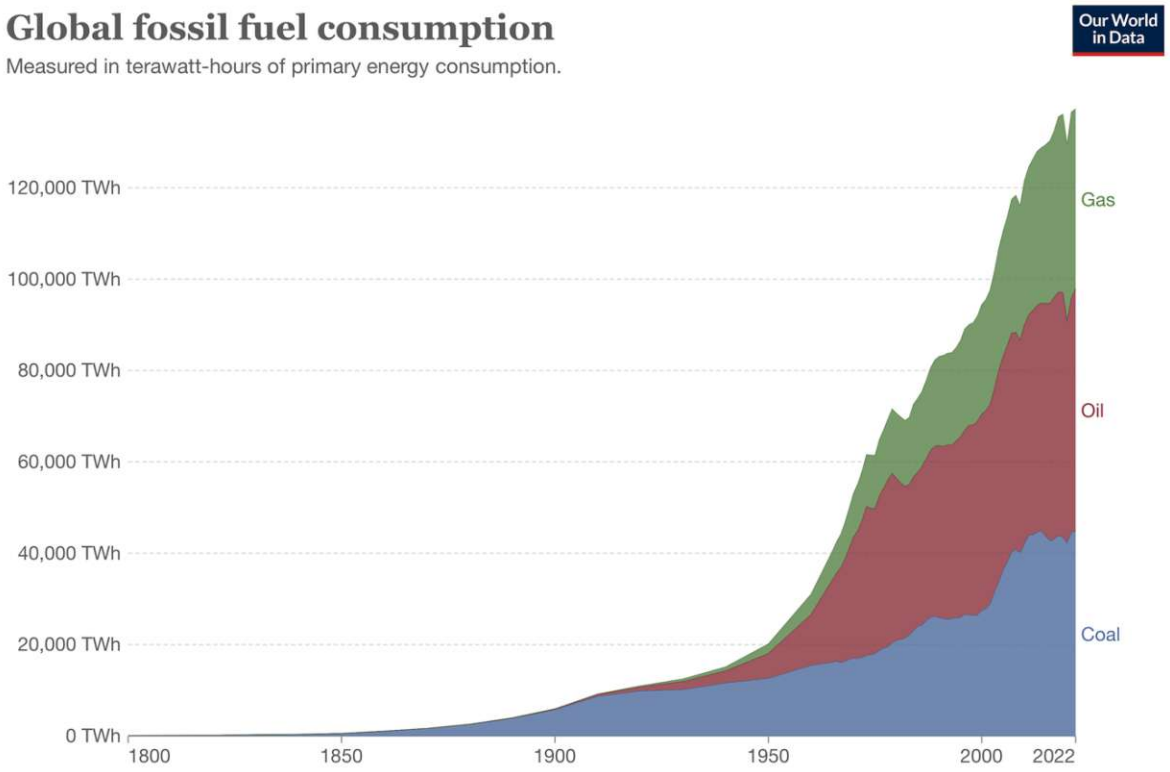

Figure 4. The development of fossil fuel consumption since the Industrial Revolution. *Source*: Our World in Data. "Fossil fuels." Based on data sources: Energy Institute. 2023. "Statistical Review of World Energy." And Smil, Vaclav. 2017. "Energy Transitions: Global and National Perspectives." 2nd ed. Appendix A. Accessed April 7, 2024. https://ourworldindata.org/fossil-fuels.

According to historians Odinn Melsted and Irene Pallua (2018, 395), the causes of the transition from coal to hydrocarbons, i.e., oil and natural gas, between the 1940s and the 1970s are rather complex and can be assessed through an integrative perspective on energy supply and demand. On the supply side, oil became the dominant fuel mainly because of its physical properties, i.e., its significantly higher energy density compared to coal and its easier transportability, and because its extraction required much less labor compared to mining (Melsted and Pallua 2018, 401–402). These factors, along with the argument of efficiency and cost-effectiveness in terms of transportation, ushered in the era of supertankers, i.e., giant oil tankers. On the consumption side, energy demand increased not only at the industrial level but also at the household level, for example in terms of residential heating and fossil-fueled vehicles (Melsted and Pallua, 2018, 407). Coal alone could not meet the skyrocketing

demand for energy, and it was no longer suitable for certain technologies. However, its use did not disappear. New means of transportation, such as airplanes, ran exclusively on oil-based fuels. Eventually, the diesel engine replaced the steam engine in ships due to the advantages of making sea transportation faster, allowing them to "*travel farther at higher speeds without refuelling*" during a voyage (Melsted and Pallua 2018, 410). Since ships are generally equipped with diesel engines, they can run on different types of fuel. There are two main categories of marine fuels, distillate (marine gas oil) and residual (heavy fuel oil), which can be blended into marine diesel oil (lower heavy fuel oil content) and intermediate fuel oil (higher heavy fuel oil content) (Uhler et al. 2016). A third, liquefied natural gas (LNG), i.e., basically CH_4, is emerging. The sulfur content of distillate and residual fuel oils varies widely, and IMO regulations set new limits that came into effect on January 1, 2020. Under the IMO 2020 regulation, marine fuels can be defined according to their sulfur (S) limits, i.e., high sulfur heavy fuel (>0.50% S), very low sulfur fuel oil (max 0.50% S), and ultra-low sulfur fuel oil (max 0.10% S) (IMO 2019b). The proportion of different fuel types used by ships is shown in figure 5.

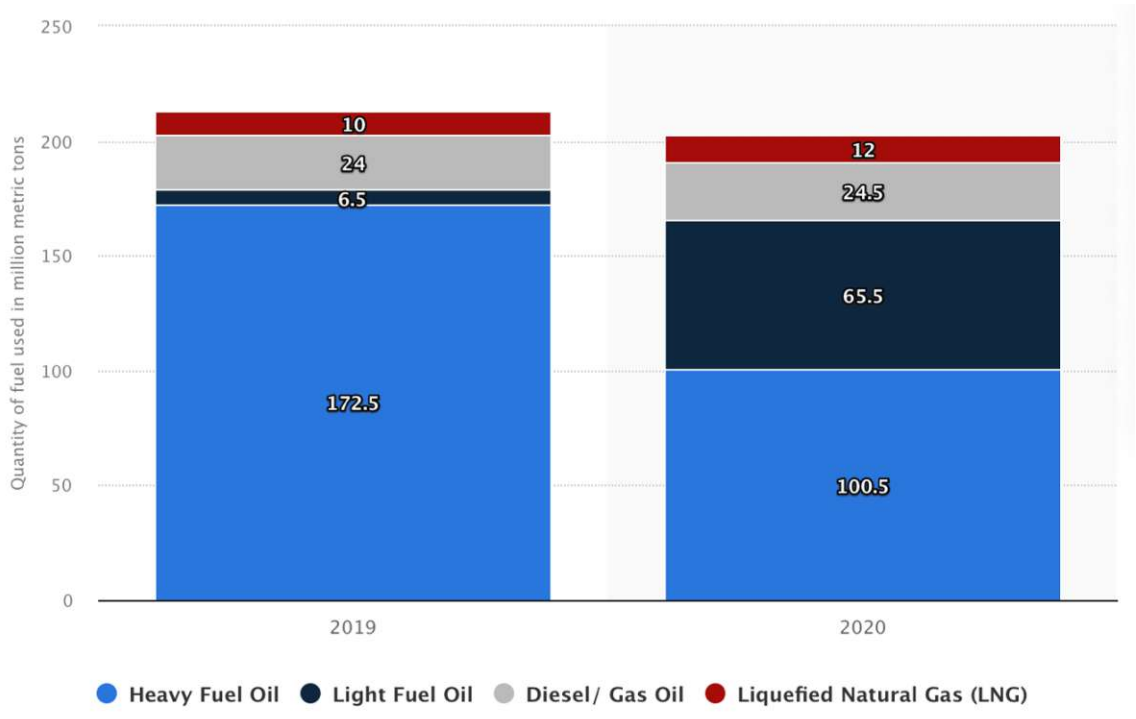

Figure 5. The impact on the use of different types of fuel due to the IMO 2020 regulation. *Source*: Statista. "Annual fuel consumption by ships worldwide from 2019 to 2020, by fuel type." Accessed April 9, 2024. https://www.statista.com/statistics/1266963/amount-of-fuel-consumed-by-ships-worldwide-by-fuel-type/.

The IMO 2020 regulation has significantly reduced the use of heavy fuel oil and replaced it with light fuel oil, which has a much lower sulfur content. The reason why 100.5 million tons of heavy fuel oil were still used in 2020 is that the IMO allows ships to install scrubbers that clean the exhaust gas and reduce SO_2 emissions.

2.2 Ship Emissions

> If there was no dust in the air there would be no fogs, no clouds, no mists, and probably no rain.
>
> —John Aitken, *On Dust, Fogs, and Clouds*

As mentioned in the introduction, the combustion of fossil fuels emits certain substances that affect the climate and the environment and can be harmful to human health, even causing premature death. These emissions include CO_2, SO_2, NO_x, carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), black carbon (BC), and particulate matter (PM2.5, PM10) (Eyring et al. 2010, 4735). While CO_2 is considered one of the most potent greenhouse gases, SO_2, NO_x, and PM are the main pollutants that adversely affect air quality and therefore human health, especially in ports and coastal regions. Regarding the growing trend of LNG in shipping, it should be mentioned that although LNG has its advantages, such as significantly lower CO_2 emissions and almost no pollutants, the danger of CH_4 leaks must also be pointed out. CH_4 has a global warming potential of about 80 over 20 years and about 30 over 100 years.

2.2.1 PM – Particulate Matter

In the series of ship emissions, aerosol particles, or, respectively, PM, should be placed and discussed first, as they are partly end products of all other emissions, have direct and indirect effects on the environment and climate, and represent the actual adverse impact on human health. Exactly how they are produced depends on the source substance, the production method, and the atmospheric conditions. Aerosol particles and PM are used

interchangeably here since the PM of interest originates from ship emissions and is dispersed in the air.

PM comprises micrometric solid, liquid, and mixed particles. They can be categorized into primary and secondary aerosols. Primary aerosols (organic or inorganic) are emitted directly from the source, whereas secondary aerosols are the product of precursor gases such as SO_2 and NO_x or a precursor material such as sea salt. They are either chemically transformed in the atmosphere or mechanically produced, for example, by abrasion or grinding. The size and the physical and chemical properties of PM are critical to its residence time in the atmosphere (Saxena et al. 2017, 31), its impact on human health, and its impact on the environment and climate, e.g. certain aerosol particles in the 0.1–1 µm diameter range have the largest impact on light scattering (Finlayson-Pitts and Pitts 2020, 370). Its size is typically expressed in terms of the aerodynamic diameter and measured in microns, i.e., micrometers, or even nanometers. The PM concentrations are usually reported in terms of mass concentrations (µg/m^3) or terms of number concentrations (#/cm^3). The two main size categories are PM2.5 and PM10. Figure 6 illustrates the size relationships between the different particles.

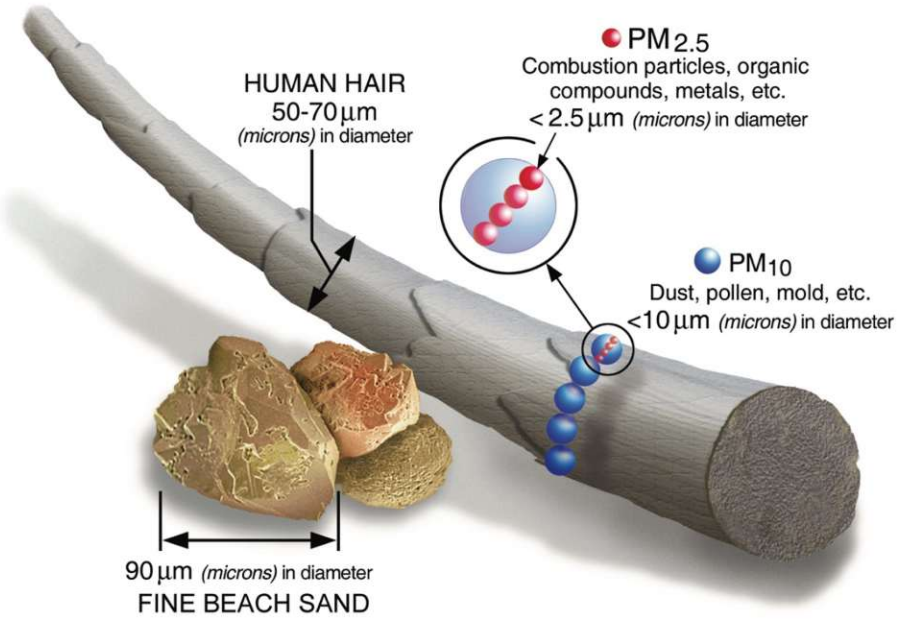

Figure 6. PM2.5 and PM10 compared to human hair and fine beach sand. *Source*: United States Environmental Protection Agency. "Particulate Matter (PM) Basics." Accessed April 15, 2024. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.

PM2.5 includes all matter up to 2.5 µm and is considered the fine particle group, while PM10 includes all matter below 10 µm, including PM2.5. Particles between 2.5 µm and 10 µm are considered coarse particles ("PMC"). In ambient air monitoring, the specific size ranges of PM2.5 and PM10 were chosen because both have an impact on human health, i.e., PM2.5 can penetrate deep into the lungs, while PM10 can irritate the upper respiratory tract (US EPA 2024). In addition, their size is a key property that determines how long they can remain in the atmosphere before being washed out by precipitation or deposited. According to Saxena et al. (2017, 32), particles with a diameter of 2.5–10 µm remain in the atmosphere for minutes to hours, while particles with a diameter of ≤2.5 µm remain in the atmosphere for days to weeks. Other parameters that determine the residence time are altitude and the physicochemical properties of the particles. Particles are grouped into four modes according to their size. Those smaller than 0.01 µm belong to the nucleation mode, those between 0.01–0.05 µm to the Aitken mode, those between 0.05–1 µm to the accumulation mode, and those larger than 1 µm to the coarse mode, as shown in figure 7.

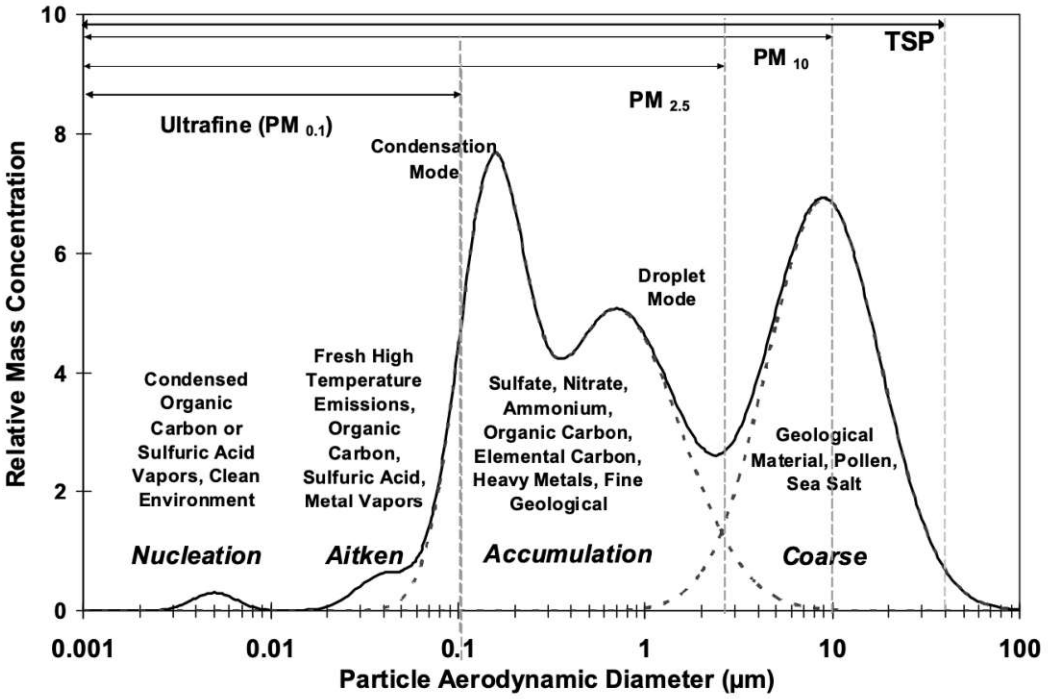

Figure 7. The particle size distribution and the respective modes wherein certain particle sizes are grouped. *Source*: Watson et al. 2010. "Measurement system evaluation for fugitive dust emissions detection and quantification." Accessed April 16, 2024. https://www.researchgate.net/publication/235341860_Measurement_system_evaluation_for_fugitive_dust_emissions_detection_and_quantification.

As mentioned above, PM can be emitted directly from the source or can be formed through various transformation pathways in the atmosphere. However, the focus of this thesis is on sulfate aerosols. Therefore, it is necessary to discuss the formation of secondary aerosols since sulfate aerosols are not emitted directly but are formed in the atmosphere. Secondary aerosols are formed by either heterogeneous or homogeneous nucleation, i.e., gas-to-particle conversion. The Air Quality Expert Group to the Department for Environment, Food and Rural Affairs of the United Kingdom (AQEP 2005, 17) describes these processes as follows: Heterogeneous nucleation is the attachment of emitted gaseous compounds to the surface of foreign particles already present in the air. Once these molecules or clusters of molecules are deposited on foreign particles, they condense on them, thereby initiating particle growth. Heterogeneous nucleation is also a major process in cloud formation, where pre-existing particles act as cloud condensation nuclei (CCN) by providing a surface for water vapor to condense on and thereby forming droplets (Winkler and Wagner 2022, 1). Homogeneous nucleation, on the other hand, is the coalescence of emitted gaseous compounds and their condensation without a foreign surface. Wallace and Hobbes (2006, 212) point out that the definition of heterogeneous and homogeneous nucleation in cloud physics differs from that in chemistry. In chemistry, a heterogeneous system involves the reaction between compounds that have different aggregate phases (gaseous, liquid, solid), whereas a homogeneous system involves matter of the same phase.

Once nucleation mode particles (0.001–0.01 µm) are formed by either homogeneous or heterogeneous nucleation they grow into Aitken mode particles (0.01–0.5 µm). These particles, however, can also be formed under high-temperature conditions (AQEP 2005, 19) as indicated in figure 7. The underlying process in both modes is gas-to-particle conversion via condensation. In order to grow larger, the nucleation and Aitken mode particles further condensate or coagulate, i.e., they collide and accumulate, into accumulation mode particles (0.5–1 µm) (AQEP 2005, 19). However, these particles do not always follow the described path of formation but can be emitted directly, e.g. from combustion processes, and undergo chemical processes in the atmosphere (Watson et al. 2010, 2). Accumulation mode particles, however, do not grow into coarse mode particles and have the longest residence time in the atmosphere, i.e., they influence the persistence of clouds. Sulfate, nitrate, and black carbon

aerosols belong to this mode. Coarse mode particles such as sea spray and dust are typically formed by mechanical processes such as abrasion and grinding.

2.2.2 BC – Black Carbon

BC, the main component of soot, results from incomplete combustion or pyrolysis, which typically occurs when there is insufficient oxygen during the combustion of carbonaceous materials such as fossil fuels, wood, and agricultural waste. BC is the term used when determined by light absorption methods and is called elemental carbon (EC) when determined by optical-thermal methods (Jansen 2012, vii). Due to its variable size, which is in the range of less than PM2.5 up to PM10, and its insolubility, BC can penetrate deep into the lungs. Although it is not toxic, it can be a carrier of other toxic substances emitted with BC during combustion processes (Jansen 2012, viii).

BC has a deep black appearance which makes it a strong light absorber and therefore an environmental and climate issue. It is considered a potent short-lived climate forcer (SLCF) due to two main effects: Since BC is insoluble and very light, it can remain in the atmosphere for several days to weeks, darkening clouds and reducing their albedo to the point where the clouds absorb solar radiation instead of reflecting it, resulting in a significant positive radiative forcing, i.e., warming. Furthermore, BC can stay in the air long enough and thus can be carried far by wind and deposited on distant surfaces. If the surface happens to be ice, its albedo is reduced, and it may melt more quickly. This may occur in the Arctic since it is affected by black carbon emissions from ships (IMO 2021).

Overall, BC emissions are decreasing due to better practices, i.e., less open burning of carbonaceous materials and improved filtration technologies in power plants and vehicles. However, according to the International Council on Clean Transport (ICCT 2017), BC emissions are increasing in the shipping sector due to an increase in the number of ocean-going vessels. The ICCT finds that BC accounts for 7% of CO_2 equivalent emissions from shipping over 100 years and 21% of CO_2 equivalent emissions from shipping over 20 years. Cleaner distillate fuels and the installation of particulate filters on ships could significantly reduce BC emissions. The IMO has recognized the need to address BC emissions. The MEPC adopted Resolution MEPC.342(77), which "*encourages Member States and ship operators*

to voluntarily use distillate fuels or other cleaner alternative fuels or propulsion methods that are safe for ships and could contribute to the reduction of BC emissions from ships operating in or near the Arctic" (IMO 2021).

2.2.3 NO_x – Nitrogen Oxides

NO_x comprise nitric oxide (NO) and NO_2. Although NO_2 is known to cause cardiovascular and respiratory disease, both compounds must be considered because NO is rapidly oxidized to NO_2 in the atmosphere. NO_2 has a low solubility in water and therefore penetrates deeper into the lungs than SO_2 (Hurst and Martin 2017, 614). NO_x also play a role in the formation of ground-level (tropospheric) ozone via the photolysis of NO_2, which contributes to cases of respiratory disease (Nguyen et al. 2022, 2). The photolysis of NO_2 and volatile organic compounds (VOCs) are responsible for the formation of photochemical smog which is also known as Los Angeles smog. In addition to adverse health effects, NO_x play an important role in the formation of secondary aerosols in the PM2.5 and PM10 range and lead to eutrophication and acidification. Furthermore, NO_x play an important role in climate chemistry and are considered SLCFs due to their influence on ozone concentrations, methane concentrations (Isaksen et al. 2014, 519), and particle formation, e.g. nitrate aerosols.

There are two main categories of NO_x, i.e., fuel NO_x and thermal NO_x. Fuel NO_x are formed by the reaction of nitrogen (N) in the fuel with oxygen (O_2) in the air. Therefore, fuel NO_x can be reduced by using fuels with a low N content. Thermal NO_x, on the other hand, are formed due to the air-fuel ratio and high temperatures in the combustion air that cause atmospheric N_2 to react with atmospheric O_2. These high temperatures are easily reached in internal combustion engines of on-road vehicles (automobiles), off-road vehicles (ships), and power plants.

Combustion conditions, excess air control, selective catalytic reduction, and the implementation of advanced combustion technologies can help to reduce thermal NO_x emissions, but only to a certain extent. As shown in figure 8, NO_x emissions have decreased significantly on land, while they are estimated and projected to remain more or less stable at sea (EEA 2013, 6).

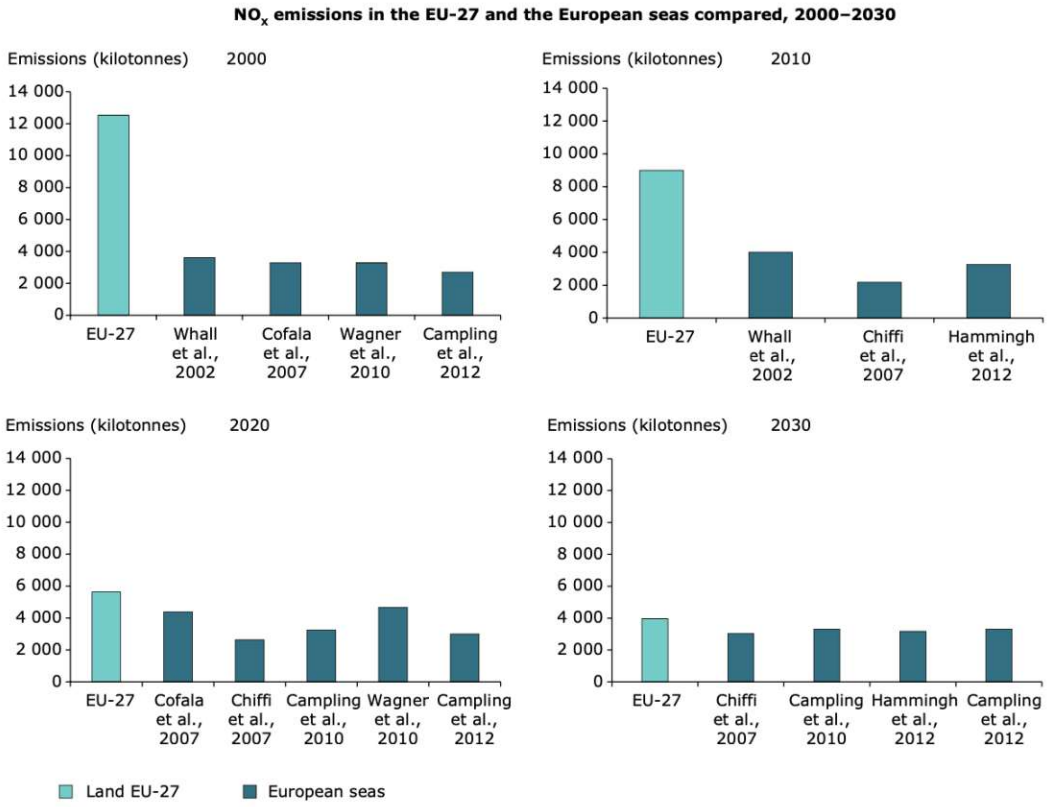

Figure 8. Comparison of estimated (2000 and 2010) and projected (2020 and 2030) NO_x emissions in the EU-27 and the European seas based on six different studies and land-based emission data. *Source*: European Environment Agency. "The impact of international shipping on European air quality and climate forcing." *EEA Technical Report* no. 4 (2013). https://www.eea.europa.eu/publications/the-impact-of-international-shipping.

The IMO has addressed the issue through Regulation 13 of Annex VI to MARPOL, which deals with NO_x control measures and applies to any "*marine diesel engine of over 130 kW output power other than those used solely for emergency purposes irrespective of the tonnage of the ship onto which such engines are installed*" (IMO 2019c). Three levels of NO_x control, i.e., Tier I, II, and III, limit emissions to a certain value and are based on the ship's construction date and determined by the engine's operating speed (IMO 2019c). In Emission Control Areas (ECAs), ships are required to comply with Tier III standards, i.e., not to exceed the NO_x limits of 3.4 g/kWh at an engine's rated speed of less than 130 revolutions per minute (rpm) and 2 g/kWh at ≥ 2000 rpm (IMO 2019c). In addition, marine diesel engines must undergo testing and certification procedures outlined in the 2008 Technical Code in order to receive an Engine International Air Pollution Prevention Certificate.

It should be noted that nitrate aerosol concentrations in the atmosphere will increase despite measures to reduce NO_x emissions from ships. According to Wen et al. (2023, 1) and Bauer et al. (2007, 5044), there is a correlation between the reduction of SO_2, i.e., the reduction of sulfate aerosols such as sulfuric acid and ammonium sulfate, and the increase in the formation of nitrate aerosol, i.e., NH_4NO_3. A common form of sulfate aerosol is ammonium sulfate [$(NH_4)_2SO_4$]. The formula shows that one mole of sulfate binds two moles of ammonium (Bauer et al. 2007, 5044). A decrease in sulfate concentrations would result in an abundance of ammonia, which would then react with nitrate to form ammonium nitrate, increasing the nitrate aerosol concentration (Bauer et al. 2007, 5045).

2.2.4 SO_2 – Sulfur Dioxide

Along with NO_x and PM, SO_2 is one of the most important pollutants. The main anthropogenic source of SO_2 is the combustion of fossil fuels containing sulfur, such as coal and fuel oil. SO_2 is an acidic, colorless gas that is readily soluble in water. It is a major precursor of secondary inorganic aerosols, i.e., sulfate aerosols, mainly in the PM2.5 range, and poses a threat to human health. Like nitrate aerosols, sulfate aerosols penetrate deep into the respiratory tract, potentially causing pulmonary and cardiovascular diseases and thereby increasing morbidity and premature mortality (Eyring et al. 2010, 4765). Until the significant sulfur reduction in marine fuels in 2020, harbors and coastal regions with heavy maritime traffic were significantly exposed to high levels of SO_2. In addition to adverse health effects, SO_2 can cause serious environmental damage in the form of acid rain, i.e., precipitation with a pH below 5.6. This definition is derived from the natural acidity of rainwater from an unpolluted atmosphere, which has a pH of 5.6 (Hill and McCreary 2015, 414–15). One of the main components of acid rain is sulfuric acid (H_2SO_4). Once formed in the atmosphere, due to its solubility in water, it can be easily scavenged by precipitation, making the rain highly acidic. Acid rain leads to the acidification of soils and waters, which has multiple effects on the environment and ecosystems. Acidification causes the leaching of essential nutrients and toxic metals such as aluminum (US EPA 2023). The lack of nutrients causes vegetation starvation, and the uptake of aluminum prevents the uptake of other essential nutrients. In addition, the leached aluminum can enter waterbodies such as lakes via interflow

and cause additional stress to the fauna (US EPA 2023). The lowered pH of the water is harmful to some aquatic life, such as fish, but especially to snails and clams, because the acidity dissolves their shells, which are composed mainly of calcium carbonate. Acid rain in the form of acid fog and droplets can directly affect leaves and defoliate trees (US EPA 2023). Since limestone, sandstone, and marble are common materials in architecture and art, buildings and sculptures are susceptible to deterioration once exposed to acid rain. Furthermore, H_2SO_4 is a major component of sulfate aerosols and has several pathways of formation. Although sulfate aerosols are at the core of this thesis, they will be discussed in more detail in the chapter on their impact on climate.

As shown in figure 9, based on Community Data Emissions Systems (CDES 2021) data, global SO_2 emissions peaked at 133.53 million t in 1979 and declined to 71.66 million t in 2019, due to international regulations to control air pollution.

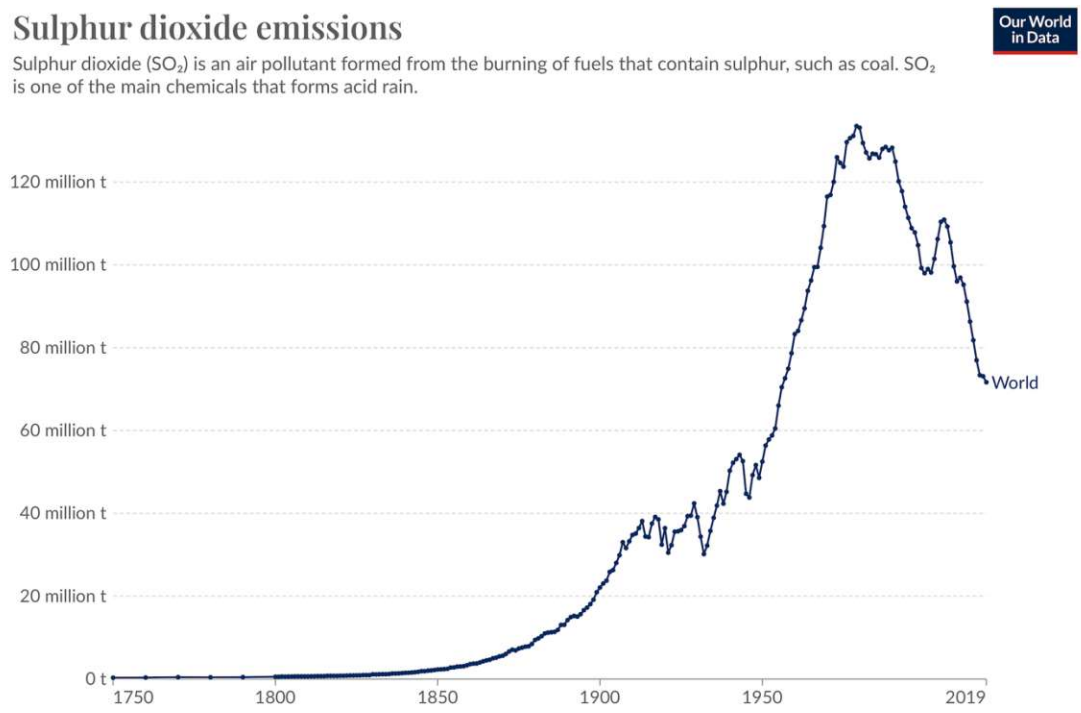

Figure 9. The development of SO_2 emissions over the past 250 years. *Source*: Our World in Data. "Sulphur dioxide (SO_2)." Based on data source: Community Emissions Data System (CEDS). 2021. https://ourworldindata.org/explorers/air-pollution?facet=none&country=~OWID_WRL&pickerSort=asc&Pollutant=Sulphur+dioxide+%28SO₂%29&Fuel=From+all+fuels+%28Total%29&Per+capita=false.

According to Jin et al. (2018), prior to the IMO 2020 regulation, sulfur emissions from ships accounted for 5.4 Tg S yr^{-1} (1 teragram is equal to 1 megaton or 1 million tons), of global anthropogenic sulfur emissions. This is equivalent to about 10.8 Tg SO_2 yr^{-1}. Compared to the data in figure 9, this suggests that SO_2 emissions from international shipping accounted for about 15% just before 2020 and changed significantly thereafter. The main change in SO_2 emissions was the reduction in the sulfur content of marine fuels from 3.5% to 0.5% outside ECAs, representing an 86% reduction. However, fuels with a higher than 0.5% sulfur content were still allowed, provided scrubbers were operating to clean the exhaust gas emissions. The 0.1% sulfur limits within ECAs have not been changed by the IMO 2020 regulation. "*Since SO_2 emissions are directly proportional to the sulfur content of fuels*" (Wang and Corbett 2007, 578), an 86% reduction in sulfur would be equivalent to a reduction of about 9.3 Tg SO_2 yr^{-1}, resulting in annual SO_2 emissions of 1.5 Tg from international shipping which represents 2% of global SO_2 emissions and a 13% reduction of the global SO_2 emissions. However, other sources suggest that this may be an idealized figure. Hausfather and Forster (2023) argue that not all ships comply with the new regulations, suggesting projections of 2.5 Tg SO_2 in 2020, as shown in Figure 10.

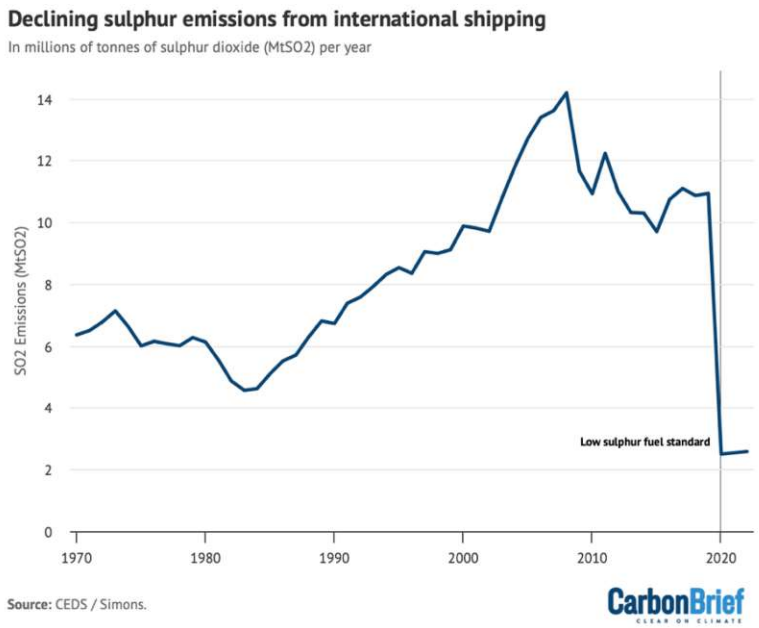

Figure 10. Impact of IMO 2020 on SO_2. *Source*: Zeke Hausfather for Carbon Brief. 2023. "Analysis: How low-sulphur shipping rules are affecting global warming." Based on data: CEDS / Leon Simons. https://www.carbonbrief.org/analysis-how-low-sulphur-shipping-rules-are-affecting-global-warming/.

Regarding the distribution of global SO_2 emissions from shipping, figure 11 shows their clear dominance in the Northern Hemisphere, as about 7 out of 8 billion people live in these latitudes. The vast majority of SO_2 is emitted in the North Atlantic Ocean (NAO) and North Pacific Ocean (NPO) (Jin et al. 2018), while the contribution to sulfur from marine dimethyl sulfide (DMS) from natural sources is by far greater.

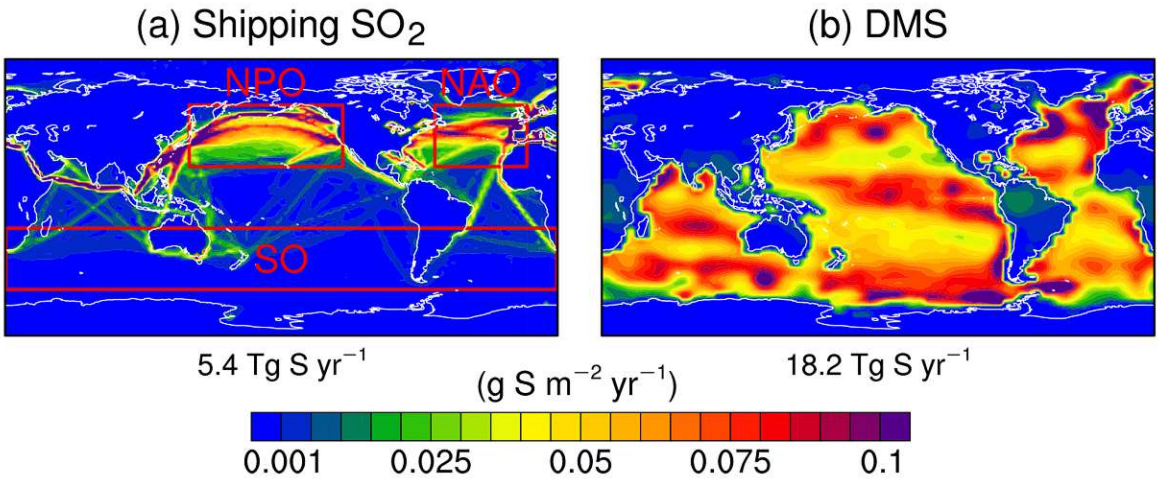

Figure 11. Simulated distribution of annual sulfur emissions (a) from ships and (b) maritime dimethyl sulfide (DMS). *Source*: Jin et al. 2018. "Impacts on Cloud Radiative Effects Induced by Coexisting Aerosols Converted from International Shipping and Maritime DMS Emissions." *Atmospheric Chemistry and Physics* 18, no. 22 (November): 16793–808. https://doi.org/10.5194/acp-18-16793-2018.

2.2.5 CO_2 – Carbon Dioxide

International shipping is directly linked to the global economy as the main instrument of transportation. The huge size of container and bulk ships allows for cheap transportation of cargo, making a huge amount of foreign goods available and affordable. However, according to various sources, the global fleet will emit between 858 million tons of CO_2 (OECD 2023) and 710 million tons of CO_2 (Statista 2023) in 2022. Using figures from Earth System Science Data, global fossil emissions in the same year were 36.4 ± 1.8 Gt CO_2 yr^{-1} (1 gigaton is equal to 1 billion tons) and 40.7 Gt CO_2 yr^{-1} total emissions, i.e., including land use (Friedlingstein et al. 2023, 5304). This means that emissions from international shipping are in the range of 2–3%. However, Friedlingstein et al. (2023, 5322) estimate a total share of 2.8% for shipping and aviation combined, each contributing roughly the same amount of emissions. While acknowledging the environmental burden of seaborne trade, it could be

argued that it has far less environmental impact than other long-distance modes of transportation relative to the volume of cargo. About 80% of trade in goods is seaborn (IMO 2019a), according to the Organisation for Economic Co-operation and Development even 90% (OECD 2022), at a cost of 2–3% of global CO_2 emissions. Container ships and bulk carriers account for about 50% of total shipping emissions, while cruise ships account for about 3% (OECD 2023). Figure 12 shows the share of CO_2 emissions caused by the different modes of transportation. The comparison between road and sea transport confirms the previous statement about the relationship between transport volume and environmental impact.

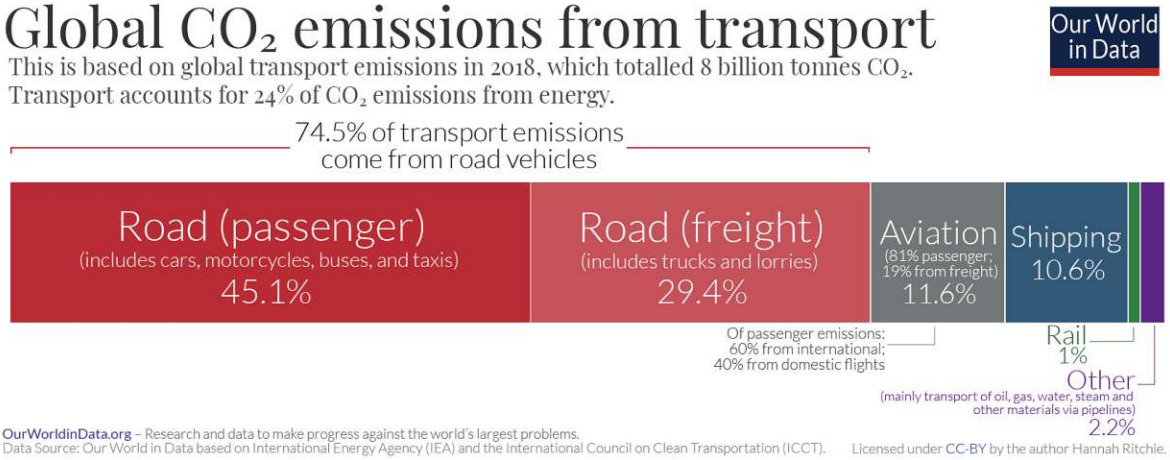

Figure 12. The emission shares of different transportation modes. *Source*: Hannah Ritchie for Our World in Data. 2020. "Cars, planes, trains: where do CO_2 emissions from transport come from?" https://ourworldindata.org/co2-emissions-from-transport.

2.3 WHO Air Quality Guidelines and EU Air Quality Standards

The previous chapters provided an overview of the main pollutants and GHG emitted by ships. It has been pointed out that PM, especially the smaller fraction of PM2.5, can cause adverse health effects, mainly on the respiratory and cardiovascular systems. Since the IMO has adopted regulations to combat air pollution from international shipping, it seems necessary to review the guidelines of the World Health Organization (WHO) recommendations as well as to allocate the share of air pollution contributed by ships.

According to the WHO, 99% of the world's population is exposed to air pollution concentrations that exceed the organization's limits (WHO n.d.). Thus, it has developed Air

Quality Guidelines (AQGs) which shall help to mitigate health risks. These AQGs are not legally binding regulations but serve as guidelines for member states, supranational organizations such as the EU, and policymakers. They consist of average concentration limits, expressed in µg/m^3 and mg/m^3, that must not be exceeded for a specified number of times within a specified period of time. Table 1 gives an overview of past threshold levels and present ones.

Table 1. Recommended Air Quality Guidelines of 2005 and 2021. *Source*: WHO. 2021. *WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. 136. Geneva: WHO (2021). Accessed April 24, 2024. https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf.

Pollutant	Averaging time	2005 air quality guideline	2021 AQG level
$PM_{2.5}$, µg/m^3	Annual	10	5
	24-hour[a]	25	15
PM_{10}, µg/m^3	Annual	20	15
	24-hour[a]	50	45
O_3, µg/m^3	Peak season[b]	–	60
	8-hour[a]	100	100
NO_2, µg/m^3	Annual	40	10
	24-hour[a]	–	25
SO_2, µg/m^3	24-hour[a]	20	40
CO, mg/m^3	24-hour[a]	–	4

[a] 99th percentile (i.e. 3–4 exceedance days per year).
[b] Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration.

Unlike the WHO AQGs, the EU air quality standards (AQSs) are mandatory for member states. Failure to comply with the standards may result in legal consequences for EU member states. The AQSs are based on the Ambient Air Quality Directives, i.e., Directive 2004/107/EC and Directive 2008/50/EC, and "*take into account relevant World Health*

Organisation standards, guidelines and programmes" (ECa n.d.). Since the focus of this thesis is on SO_2 emissions and the resulting sulfate aerosols, which are located in the PM2.5 range, it is worth noting that the EU AQSs currently state that SO_2 concentrations shall not exceed 350 µg/m3 averaged over one hour more than 24 times per year and 125 µg/m3 averaged over 24 hours more than 3 times per year (ECb n.d.). For PM2.5 concentration limits, which were introduced by Directive 2008/50/EC, there were successive target and limit values: 25 µg/m3 averaged over one year, 20 µg/m3 based on a 3-year rolling annual mean, and 18 µg/m3 by 2020 (ECb n.d.).

More recently, in April 2024, new concentration limits were adopted that will take effect in 2030. Table 2 shows a comparison of the current and future (revised) levels of pollutant concentrations. The SO_2 limit of 20 µg/m^3 will be even more stringent than the current WHO limit of 40 µg/m^3, while the PM2.5 concentration limit of 25 µg/m^3 will be tightened to 10 µg/m^3.

Table 2. Current and revised pollutant concentrations. *Source*: Vivienne Halleux for the EU Parliament. "Revision of EU air quality legislation: Setting a zero pollution objective for air." Briefing, April 19, 2024. Accessed April 24, 2024. https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747087/EPRS_BRI(2023)747087_EN.pdf.

Pollutant	Averaging period	Legal nature	Revised standard	Permitted exceedances	Current standard
$PM_{2.5}$	Annual	Limit value	10 µg/m^3		25 µg/m^3
$PM_{2.5}$	24-hour	Limit value	25 µg/m^3	18 times/year	
PM_{10}	Annual	Limit value	20 µg/m^3		40 µg/m^3
PM_{10}	24-hour	Limit value	45 µg/m^3	18 times/year	50 µg/m^3
O_3	Max daily 8-hour mean	Target value	120 µg/m^3	18 days/year averaged over 3 years	120 µg/m^3
O_3	Max daily 8-hour mean	Long-term objective	100 µg/m^3	3 exceedance days/year	120 µg/m^3
NO_2	Annual	Limit value	20 µg/m^3		40 µg/m^3
NO_2	24-hour	Limit value	50 µg/m^3	18 times/year	
SO_2	Annual	Limit value	20 µg/m^3		
SO_2	24-hour	Limit value	50 µg/m^3	18 times/year	125 µg/m^3
CO	24-hour	Limit value	4 mg/m^3	18 times/year	
CO	Max daily 8-hour mean	Limit value	10 mg/m^3		10 mg/m^3

Regarding the contribution of ships to air pollution in terms of sulfate aerosols, i.e., PM2.5: Jonson et al. (2020, 11399) state that in coastal regions, ship emissions contribute about 10% of "*controllable PM2.5 concentrations*", that this figure applies in most cases to

both regional and global levels, and that PM2.5 concentrations are expected to decrease significantly as a result of the IMO 2020 regulation. According to Barregård et al. (2019), emissions from Baltic shipping accounted for an average exposure of 0.22 µg/m^3 PM2.5 per capita in ten countries, with a peak in Denmark of 0.57 µg/m^3, which is well below the EU concentration limits.

Research papers provide a rather wide range of estimates regarding the premature deaths associated with shipping emissions. Apart from a few studies, most papers allocate their best estimates in the range of 50.000–60.000 premature deaths per year. Table 3 presents a comparison of figures from research papers on premature mortality due to ship emissions (mainly PM2.5).

Table 3. Comparison of premature deaths from shipping-related emissions based on various research papers. Global estimates per year.

Source	*Mortality Range*	*Best Estimate*	*Comments*
Corbett et al. 2007	19.000–64.000	60.000	PM2.5 emissions in 2002
Eyring et al. 2010	20.000–104.000	60.000	PM emissions in 2000
Partanen et al. 2013		50.200	0.1% S near coast and 5.4% S elsewhere: 34.900 avoided deaths 0.1% S near coast and 0.5% elsewhere: 48.200 avoided deaths
Lin et al. 2016	8700–25.000	17.100	PM2.5 emissions
	14.500–37.500		PM2.5 + O_3 emissions
IMO MEPC 70/INF.34 aka	57.900–257.000	158.200	2020: Delayed IMO 2020, PM emissions
"Finland Study on Health Benefits" 2016	18.400–82.300	50.400	2020: On-time IMO 2020, 108.000 avoided deaths, PM emissions
	64.700–286.600	176.500	2025: Absent IMO 2020, PM emissions
	20.200–87.700	55.600	2025: IMO 2020; ~570.000 avoided deaths over a 5-year period, PM emissions
Sofiev et al. 2018	403.300		BAU 2020, PM2.5 emissions
	266.300		IMO 2020, 137.000 avoided deaths, PM2.5 emissions
Scott 2023	19.000–91.000		sulfur emissions

2.4. The IMO's Combat against Air Pollution[1]

2.4.1 MARPOL Annex VI in the Context of International Conventions

Against the background of the Convention on the 1979 Long-Range Transboundary Air Pollution and the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, the IMO saw the need to implement measures regarding emissions and therefore adopted Resolution A.719(17) on November 6, 1991. It recognized "*the urgent necessity of establishment of a policy on prevention of air pollution from ships, and development of reduction objectives and measures to achieve the objectives for control of emissions of all the elements of air pollution* […]" and thus considered a new annex to the Convention (IMO 1991, 1). The MEPC was mandated to collect data on exhaust and cargo emissions to establish a baseline emission inventory and to assess technologies that could be effective in reducing air pollution in order to draft the new annex.

In the context of the emerging awareness of human impact on the environment in the 1990s, it is important to outline the development and interrelationship of international environmental law that ultimately led to the introduction of Annex VI. The objective of the United Nations Framework Convention on Climate Change (UNFCCC), adopted on May 9, 1992, was a "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*" (UNFCCC 1992, Article 2). Furthermore, Article 3(3) stated that "*the Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects*." The Convention was then opened for signature at the United Nations Conference on Environment and Development, held in Rio de Janeiro from June 3–14, 1992. The document adopted at this conference—the Rio Declaration on Environment and Development—contained 29 principles. Like Article 3(3) of the UNFCCC, Principle 15 stated that "*to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities*" (Rio Declaration 1992). In 1997, the Conference of

[1] Chapter 2.4 was included in the seminar paper "*MARPOL – An Analysis of the International Convention for the Prevention of Pollution from Ships*" and submitted at the Diplomatische Akademie Wien as part of the master's thesis for the seminar "Environment and Security" in 2023.

the Parties to MARPOL 73/78 convened on the matter of air pollution and adopted a Protocol that aimed to "*prevent and control air pollution*" (IMO 1997) by reducing SO_x and NO_x, and by prohibiting "*any deliberate emissions of ozone depleting substances*" (IMO 1997). Recalling Principle 15 of the Rio Declaration, namely the precautionary approach, the Conference considered that the best way to achieve this objective was to amend MARPOL 73/78 and establish a strong set of instruments. It added another annex to the MARPOL Convention—Annex VI, entitled Regulations for the Prevention of Air Pollution from Ships. Regulation 14 of the Protocol also introduced SO_x ECAs, i.e., "*area*[s] *where the adoption of special mandatory measures for SO_x emissions from ships is required to prevent, reduce and control air pollution from SO_x and its attendant adverse impacts on land and sea areas*" (IMO 1997). Furthermore, Regulation 13 established the NO_x Technical Code for ships with an engine power of 130 kW, or more, which sets out mandatory survey and certification procedures of marine diesel engines. The 1997 Protocol, and thereby Annex VI, entered into force in May 2005. At its 56th session in 2007, the MEPC decided to refer to the Convention and its six Annexes as MARPOL, since MARPOL 73/78 didn't include Annex VI and had already undergone numerous amendments. It is worth noting that there appear to have been some links between the 1997 Protocol and the Kyoto Protocol. The adoption and entry into force of Annex VI occurred almost simultaneously with the adoption of the Kyoto Protocol in December 1997, and its entry into force in February 2005. Although these two instruments contained different mechanisms, they shared the same objective of reducing GHG emissions. In addition, Article 2(2) of the Kyoto Protocol established an indirect link to Annex VI by stating that "[t]*he Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels through the International Civil Aviation Organization and the International Maritime Organization, respectively*" (Kyoto Protocol 1998).

2.4.2 Annex VI – Prevention of Air Pollution from Ships

As aforementioned, Annex VI aims to prevent air pollution by reducing emissions resulting from combustion, i.e., ozone-depleting substances (ODSs), NO_x, SO_x, and VOCs. The Annex was adopted with the 1997 Protocol on October 28, 1997, and entered into force

on May 19, 2005**.** Resolutions MEPC.176(58) and MEPC.177(58) were adopted on October 10, 2008, and amended Annex VI and the NO_x Technical Code by expanding the ECAs, implementing new standards for diesel engines, and introducing progressive reductions for SO_x, NO_x, and PM emissions. The amended Annex VI and the NO_x Technical Code 2008 entered into force on July 1, 2010. Initially, the maximum sulfur content of fuel was set at 4.5%. However, due to continuous revisions and the latest sulfur limits introduced by the IMO 2020, the sulfur content has been reduced to 0.50%, and within ECAs even to 0.10%.

Regulation 12 deals with ODSs and prohibits deliberate emissions of these substances which may also occur during the maintenance and disposal of equipment. Regulation 13 concerns NO_x emissions and applies to vessels with a 130 kW marine diesel engine. However, it does not apply to marine diesel engines which are used for emergency purposes only, and to ships that do not engage in international voyages but stay "*within the waters to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly* […]" (IMO 1997). This regulation also introduces standards for marine diesel engines, i.e., Tier I, Tier II, and Tier III. The operation of a marine diesel engine is prohibited unless the date of the ship's construction falls within a certain timeframe and the NO_x emissions stay within certain limits, e.g., Tier III applies to ships built on or after January 1, 2011, and allows the lowest amount of NO_x emissions. The procedures to analyze these emissions are entailed in the revised NO_x Technical Code 2008. Regulation 14 prescribes the limits for sulfur content in fuel oil. Regulation 15 provides that tankers have a VOC management plan which entails procedures to minimize the emission of VOCs which can cause several health risks. VOCs are compounds of crude oil that evaporate while the cargo is being loaded or transported. Regulation 16 comprises a further measure to decrease harmful emissions, i.e., by prohibiting certain substances from being incinerated onboard. Even the quality of fuel oil was made a subject and is dealt with in Regulation 18.

3 The Impact of Sulfur Reduction on the Climate

The previous chapters have reviewed the performance of SO_2 and sulfate aerosols as PM in terms of their performance as air pollutants, and the reason for sulfur reduction in marine fuels, i.e., to reduce health risks. This chapter highlights another property of sulfate

aerosols, i.e., their role in radiative forcing (RF) and thus climate impact. This is also the core question of this thesis. However, before discussing the important role of sulfate aerosols as climate forcers in more detail, some principles of atmospheric science need to be outlined.

3.1 Earth's Energy Budget, Radiative Forcing, and Climate Sensitivity

Climate forcers include anthropogenic and natural factors such as GHGs, aerosol particles, changes in solar radiation, and changes in albedo, i.e., the measure of the reflectivity of surfaces, e.g. via changes in land use or cloud cover. Their influence alters the Earth's energy balance, which is basically the absorbed solar (shortwave) radiation minus the outgoing longwave radiation. In other words, some of the sunlight hits the surface, the energy is converted into heat and emitted as longwave radiation from the Earth's surface towards space. The energy balance is maintained when the total amount of energy entering the system, in the form of radiation, is equal to the total amount of energy leaving the system. The incoming and outgoing flow of radiation, referred to as radiative flux, is expressed in watts per square meter (W m^{-2}), with the watts being the unit of power, representing energy per unit of time (joules per second, J s^{-1}). The amount of solar radiation reaching the top of Earth's atmosphere varies with the angle of incidence of sunlight, resulting in the highest energy reception at the equator, with a decrease observed at higher latitudes.

According to a figure from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) (Forster et al. 2021), about 340 W m^{-2}, averaged over the globe, reach the top of the atmosphere. Approximately 100 W m^{-2} are reflected by clouds, another 25 W m^{-2} are reflected by surfaces with high albedo such as ice and snow fields, sand dunes, salt flats, etc., and about 80 W m^{-2} are absorbed by the atmosphere, resulting in about 160 W m^{-2} being absorbed by the oceans and landmass surfaces. In total, about 240 W m^{-2}, i.e., the sum of the energy in the atmosphere and the energy reaching the surface, are absorbed by Earth's system. The absorbed energy increases the temperature of the surface, which then emits energy in the form of longwave radiation, i.e., about 390 W m^{-2}. This longwave radiation is selectively absorbed in the atmosphere by GHGs and subsequently re-emitted in all directions. About 342 W m^{-2} are re-emitted back to the surface. As illustrated

in the upper panel of figure 13, about 239 W m^{-2} leave the system, representing a net difference of about 1 W m^{-2} that remains within the system.

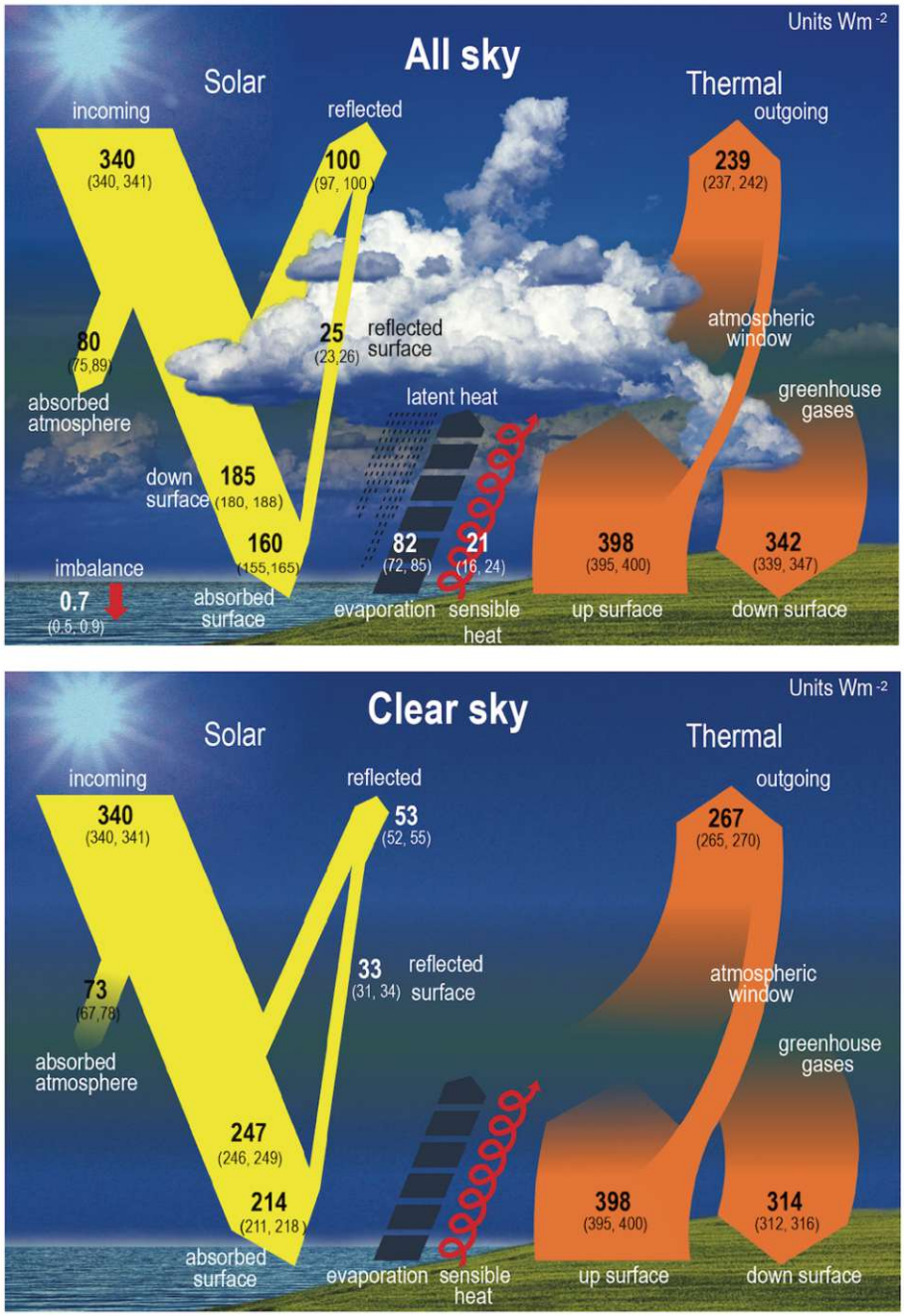

Figure 13. The radiative fluxes within Earth's energy budget and how they interact with various components of the system. *Source*: IPCC. 2021. "Figure 7.2 | Schematic representation of the global mean energy budget of the Earth (upper panel), and its equivalent without considerations of cloud effects (lower panel)." *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 934. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf.

The 1 W m^{-2} that remains in the system creates an imbalance in the Earth's energy balance and leads to additional global warming because the planet needs to increase its temperature in order to emit more energy as longwave radiation until a new equilibrium is reached. The bottom panel of figure 13, illustrates a scenario without cloud cover and indicates that the imbalance of the system would be much greater, i.e., about 20 W m^{-2}, and global mean temperatures would increase much more.

The Earth's energy budget is in equilibrium when the energy input equals the energy output. As a result, the global mean temperature remains balanced, except for some natural perturbations. Forcings affect this process either by reflecting sunlight back into space, which has a cooling effect, i.e., negative radiative forcing, or by trapping the outgoing longwave radiation and re-emitting a substantial fraction of it back to the surface, i.e., positive radiative forcing. Increased concentrations of GHGs from anthropogenic activities, such as the burning of fossil fuels, trap additional outgoing longwave radiation, thereby creating an energy imbalance. In effect, less energy is leaving the Earth's system than is entering it. Apart from GHGs, other agents also exhibit either negative or positive radiative forcing. Regarding the definition of RF, it should be noted that there is a broader term and some more specific ones.

In the Fifth Assessment Report of the IPCC, Myhre et al. (2013, 664) define RF as "*the net change in the energy balance of the Earth system due to some imposed perturbation. It is usually expressed in watts per square meter averaged over a particular period of time and quantifies the energy imbalance that occurs when the imposed change takes place.*" A more recent definition of RF found in the latest IPCC report includes three subcategories of RF, i.e., stratospherically adjusted, instantaneous, and effective RF:

> "*The change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide (CO_2), the concentration of volcanic aerosols or the output of the Sun. The stratospherically adjusted radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once both stratospheric and tropospheric adjustments are accounted for is termed the effective radiative forcing.*" (IPCC 2021a, 2245)

According to Andrews et al. (2021, 1), effective radiative forcing (ERF) is the "*most commonly used*" and it "*measures the energy imbalance after allowing for atmospheric temperatures, water vapor, and clouds to adjust to the forcing agent, while keeping surface conditions (specifically temperature) unchanged*." Figure 14 provides an overview of how anthropogenic emissions have changed EFR between 1750 and 2019 (a), how this has changed the global surface temperature (b), and the newly assessed contribution of aerosol particles to EFR.

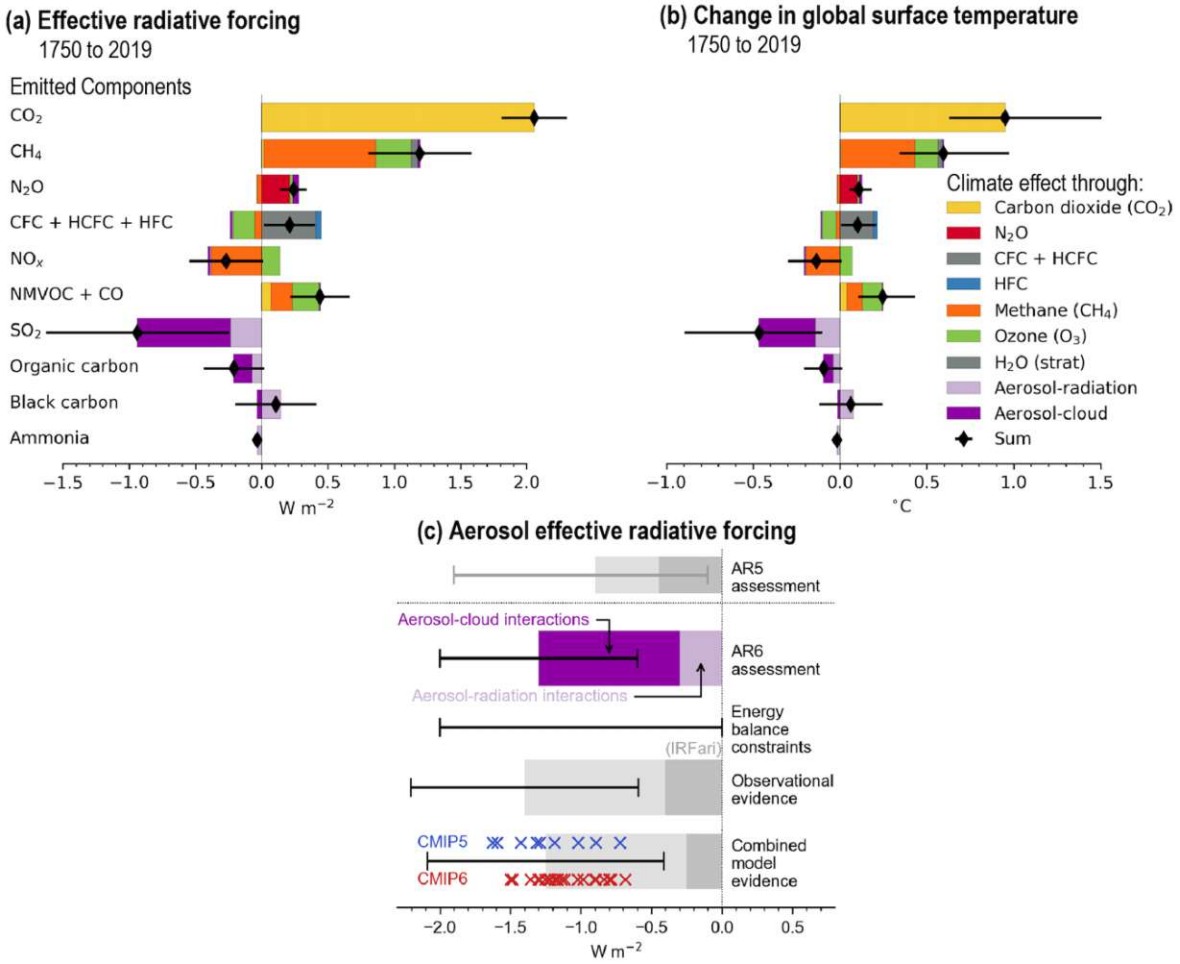

Figure 14. The ERF of different climate forcers, their contribution to global warming and cooling, and the newly assessed role of aerosols in ERF. Source: IPCC. 2021. "Figure TS.15 | Contribution to (a) effective radiative forcing (ERF) and (b) global surface temperature change from component emissions for 1750–2019based on Coupled Model Intercomparison Project Phase 6 (CMIP6) models and (c) net aerosol ERF for 1750–2014 from different lines of evidence." *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 92. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf.

It is important to point out that the question of how much positive or negative EFR translates into warming or cooling is the question of climate sensitivity. A sensitive climate would yield more change in temperature than a robust one. In other words, if a small amount of GHGs added to the atmosphere would cause a large increase in global mean temperature, this would indicate a high climate sensitivity of the Earth system. Two main types of climate sensitivity are considered, the transient climate response (TCR) and the equilibrium climate sensitivity (ECS). Both concepts are based on a doubling of CO_2 concentration and the resulting temperature change. For thousands of years before the Industrial Revolution, the CO_2 concentrations were around 280 ppm. In recent years, they have reached 420 ppm (Stein 2022), which corresponds to a 1.1°C increase in global mean temperature since 1850 (Arias 2021, 89). The TCR represents the temperature change when the CO_2 concentration reaches 560 ppm, equivalent to a doubling of pre-industrial levels. In contrast, the ECS indicates the temperature change after a long-term integration of all feedbacks resulting from the doubling of CO_2, representing a new equilibrium state. Thus, the ECS can only manifest itself after several decades, provided that the emission of GHGs stays constant. In other words, as long as GHG concentrations in the atmosphere continue to change, the climate system will not reach a new equilibrium state. According to the IPCC AR6, there is a "*broad agreement across* […] *multiple lines of evidence, supporting a best estimate of equilibrium climate sensitivity of 3°C, with a very likely range of 2°C to 5°C*" (Arias 2021, 93). A doubling of CO_2 results in a radiative forcing of 3.7 W m^{-2} (Rahmstorf 2008, 38). Consequently, an ECS of 3°C yields a temperature increase of 0.81°C per W m^{-2}. However, due to the sheer complexity of the Earth system, there are many uncertainties associated with the ECS concept. The IPCC itself has altered its estimates in the past, and there are also models and calculations from various other scientific institutions and individual researchers. Hansen et al. (2023a, 20) "*compare recent glacial and interglacial climates to infer ECS with a precision not possible with climate models alone*" and conclude that the "*ECS implied by the LGM* [Last Glacial Maximum] *is thus 1.22 ± 0.29°C (2σ) per W/m², which, at this final step,* [they] *round to 1.2 ± 0.3°C per W/m².*" Compared to the IPCC's best estimate, Hansen et al.'s ECS is about a third higher.

The aforementioned aspects, i.e., climate forcers, radiative forcing, and climate sensitivity, are coupled in such a way that, for example, a GHG affects the radiative flux

(expressed in W m^{-2}) to a certain extent and thus has an effect on temperature, with the magnitude of this effect depending on the physical properties of the forcing agent, its concentration in the atmosphere and the sensitivity of the climate itself. It is also crucial to point out that the effects of radiative forcing can manifest at the regional or global scale. Reducing the uncertainty in the ECS would also greatly assist mitigation and adaptation efforts in the face of climate change.

The detour via the Earth's energy budget and balance, radiative forcing, and climate sensitivity was important, as these are fundamental principles that provide a framework within which to locate the research question of this thesis, i.e., the effect of sulfate aerosols on the climate.

3.2 Sulfate Aerosols as Climate Forcers

In contrast to GHGs, aerosol particles have a net negative radiative forcing, i.e., a cooling effect that offsets to an uncertain extent the GHG-driven warming. Among the most prominent types of aerosol particles are sulfate aerosols. The uncertainty or disagreement within the scientific community about the magnitude of the negative radiative forcing of these particles is at the core of this thesis. However, before the findings on this matter from scientific literature can be compared, some explanations concerning sulfate aerosols as climate forcers are in order.

Following the combustion of sulfur-containing fossil fuels, such as those used in international shipping, SO_2 is emitted into the atmosphere and undergoes various oxidation reactions, ultimately forming sulfate aerosols. One of the most significant reactions in the gas phase is the oxidation of SO_2 by "*OH* [hydroxyl] *radicals or Criegee intermediates*" (Berndt et al. 2023, 1). However, in clouds, i.e., primarily within the aqueous phase, the main oxidation pathways are via hydrogen peroxide (H_2O_2), transition metal ion catalysis, and to a lesser extent ozone (O_3) (Harris et al. 2013, 727). The main oxidation products of SO_2, i.e., sulfate aerosols, are H_2SO_4, sulfate ions (SO_4^{2-}), and $(NH_4)_2SO_4$.

These sulfate aerosols exhibit certain properties that categorize them as climate forcers. They "*effectively scatter incoming solar radiation and affect the formation of cloud condensation nuclei (CCN). CCN in turn may have significant influences on the*

microphysical and radiative properties and lifetime of clouds" (Berndt et al. 2023, 1). This refers to the direct and indirect effects of sulfate aerosols on RF. The direct effect, also referred to as aerosol–radiation interaction, is the phenomenon whereby these aerosol particles scatter incoming solar radiation, resulting in a slight negative RF. The indirect effects are the formation of new clouds and the aerosol–cloud interaction in pre-existing clouds. Once aerosol particles have penetrated a cloud or been chemically formed within it, they act as CCN. CCN serve to enhance the surface area available for water vapor to condense upon, thereby distributing the present water vapor over a greater area. This results in a higher number of smaller droplets, which in turn increases the optical thickness of clouds and therefore the cloud albedo effect. This phenomenon is referred to as the Twomey effect. Another indirect consequence of this process is that the smaller droplets are not sufficiently heavy to precipitate, thereby prolonging the lifetime of clouds. In other words, clouds that are polluted with sulfate aerosols have a higher negative radiative forcing. The contribution to ERF from aerosol–radiation and aerosol–cloud interactions is shown in figure 14.

The performance of clouds in RF is highly complex and depends on cloud type, altitude, optical thickness, and "*diurnal and seasonal cycles of cloudiness*" (Boucher et al. 2013, 582). However, the following pattern can be derived and used as a rule of thumb. According to Boucher et al. (2013, 580–82), high-altitude clouds, which are predominant over landmasses in the equatorial region, tend to trap more longwave radiation than reflect shortwave radiation and are responsible for most of the 26 W m^{-2} of positive RF ascribed to clouds per year. Low-altitude clouds, such as marine stratocumulus clouds, form mainly above the oceans and cover about 30% of the ocean surface (Jin et al. 2018). In contrast to high-altitude clouds, they do not trap longwave radiation well but strongly reflect shortwave radiation and are therefore responsible for about –47 W m^{-2} negative RF, which yields a global net radiative negative RF of about –21 W m^{-2} (Boucher et al. 2013, 580). The IPCC acknowledged in its Fifth Assessment Report, that "*clouds have the potential to cause significant climate feedback*" and that "[t]*he sign of this feedback on climate change cannot be determined from the sign of CRE* [cloud radiative effect] *in the current climate, but depends instead on how climate-sensitive the properties are that govern the LWCRE* [longwave cloud radiative effect] *and SWCRE* [short-wave cloud radiative effect]" (Boucher et al. 2013, 582). Jin et al. (2018, 16793) state that "*even a few percent change in marine*

stratocumulus cloud cover can double or offset the anthropogenic global warming due to greenhouse gases." Figure 15 illustrates that low clouds are predominantly distributed above the oceans. Given that most shipping routes traverse the North Atlantic and North Pacific, it can be concluded that the aerosol–cloud interaction is especially pronounced in these regions.

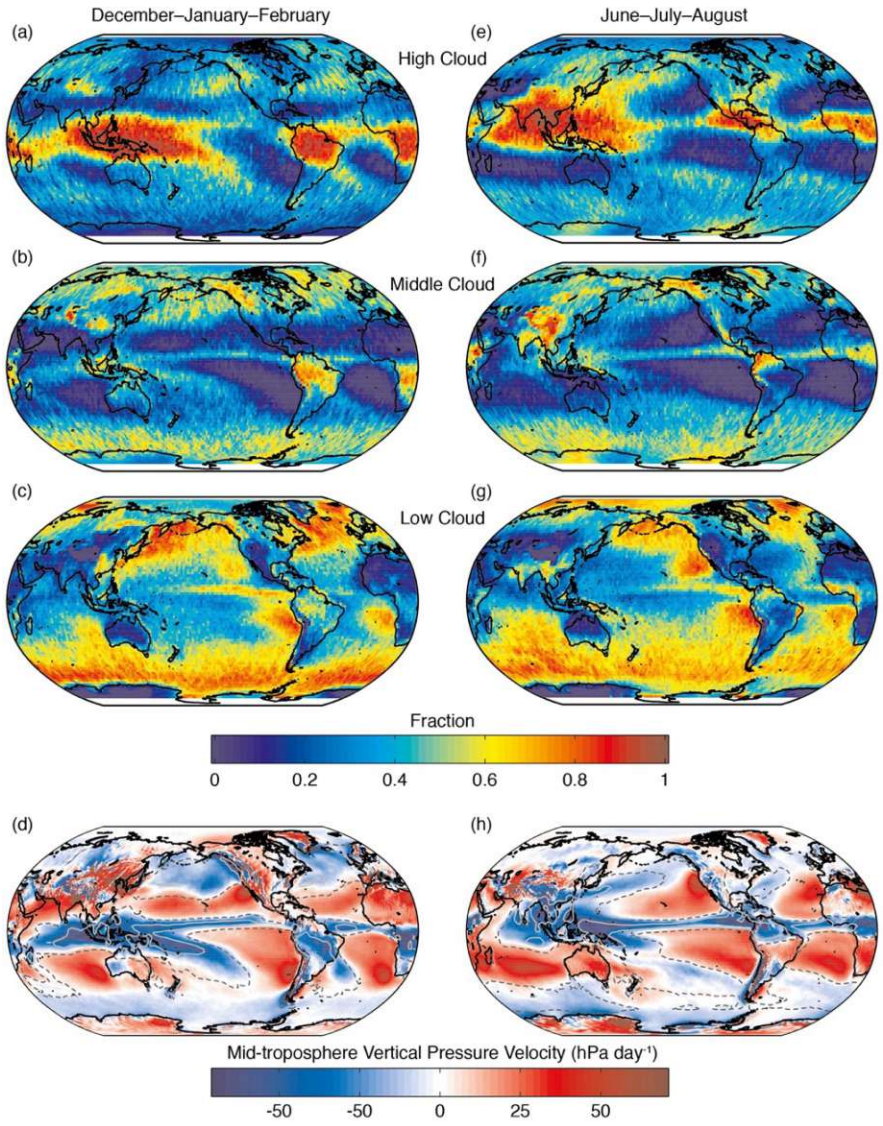

Figure 15. The distribution of cloud cover according to type. Source: IPCC. 2013. "Figure 7.6." Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 581. Accessed May 6, 2024. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter07_FINAL-1.pdf.

This is of significant importance since the reduction of sulfur content in marine fuel by the IMO 2020 regulation deprives these regions of the aerosol–cloud interaction, i.e., the

additional cooling effect of sulfate aerosols. Figure 16 shows the distribution of the longwave and shortwave cloud radiative effect and supports the hypothesis.

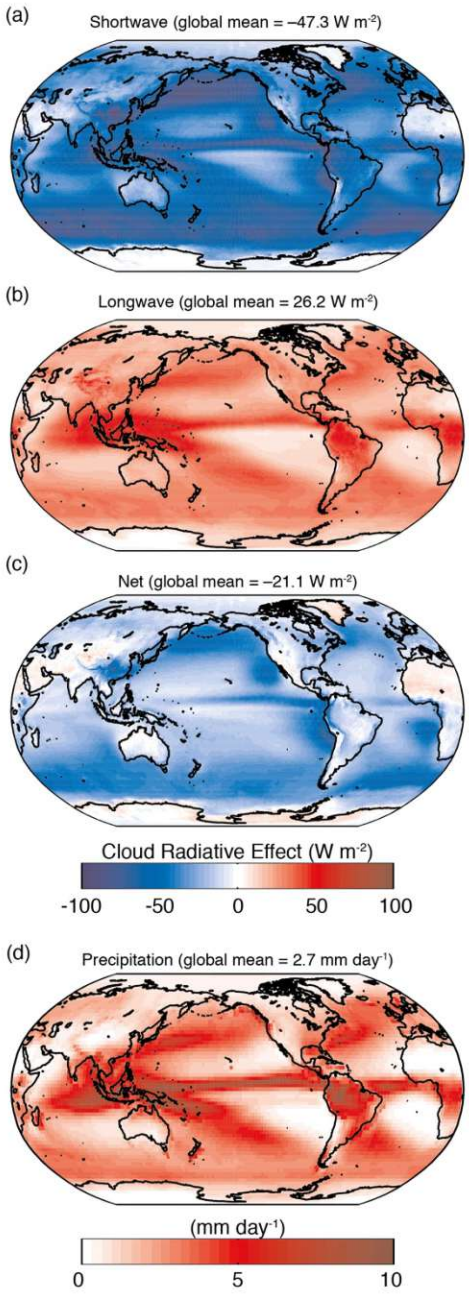

Figure 16. The distribution of the longwave and shortwave cloud radiative effect. Source: IPCC. 2013. "Figure 7.7." Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 582. Accessed May 6, 2024. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter07_FINAL-1.pdf.

Although land-based measures to reduce SO_2 emissions date back to 1970, when the U.S. Congress passed the Clean Air Act, and began to decline globally in 1979, as previously shown in figure 9, China experienced an abrupt drop in SO_2 emissions in 2016 after a steady decline (Wang, Zhuo, and Zhao 2023). Wang et al. (2024) argue that this decline in air pollution led to "*atmospheric circulation anomalies beyond its source region, driving a substantial mean surface warming in the NEP* [Northeast Pacific], *which provides a favorable condition for extreme ocean warming events*." The suspicion is growing that the climate is more sensitive and that aerosols play a greater role than assumed.

With the intention of reducing the harmful influence of SO_2 and sulfate aerosols, which are part of PM2.5, the IMO 2020 regulation simultaneously deprived the atmosphere of three effects: light scattering, cloud formation, and cloud brightening. However, the extent of the consequences of this deprivation is a point of disagreement and uncertainty in the scientific community. The following chapter will shed some light on this matter.

3.3 Expected Warming vs Observed Warming

As aforementioned, a positive energy imbalance of the Earth's system, i.e., more energy entering the system than leaving it, leads to an increase in global mean temperature. The rate of this increase depends on the change in the amount of energy retained in the system and the sensitivity of the system itself, i.e., by how many °C per W m^{-2} the system responds. Thus, an increase in the amount of energy retained means accelerated warming. Again, the increase in the Earth's energy budget is due to a rise in the concentration of GHGs in the atmosphere and a decrease in aerosol particles and hence clouds. In order to estimate the magnitude of the negative RF of aerosol particles, it is necessary to compare two figures, i.e., the expected temperature anomaly induced by GHGs based on an assumed ECS and the observed warming. The subtraction of the observed warming from the expected warming yields the magnitude of aerosol cooling. Before delving into this matter, it is necessary to provide a brief overview of ECS estimates.

Jule G. Charney, chairman of the Ad Hoc Study Group on Carbon Dioxide and the Climate of the U.S. National Academy of Sciences, and fellow scientists estimated "*the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of* ±

1.5°C" (National Research Council 1979, 2). This doubling of CO_2 relates to a 4 W m^{-2} RF (National Research Council 1979, 7), which yields 0.75°C ECS per W m^{-2} based on a 3°C warming. The IPCC (2021b, 11) assumes an ECS that is likely between 2.5–4.0°C and very likely between 2.0–5.0°C, with a best estimate, as with Charney, of 3°C. In contrast, to the estimates of the IPCC and Charney, Hansen et al. (2023a, 18) provided an alternative figure, namely 1.2 ± 0.3°C per W m^{-2} based on an ECS of 4.8°C ± 1.2°C, which indicates a significantly more sensitive climate. Furthermore, they noted that high-sensitivity scenarios are based on the assumption of substantial cloud feedbacks (Hansen et al. 2023a, 20), which are in turn influenced by the concentration of aerosol particles present in the atmosphere.

Figures 17 (IPCC AR6) and 17 (Hansen et al. 2023a) show the relationship between expected and observed warming. Thus, they allow an estimate of the aerosol cooling.

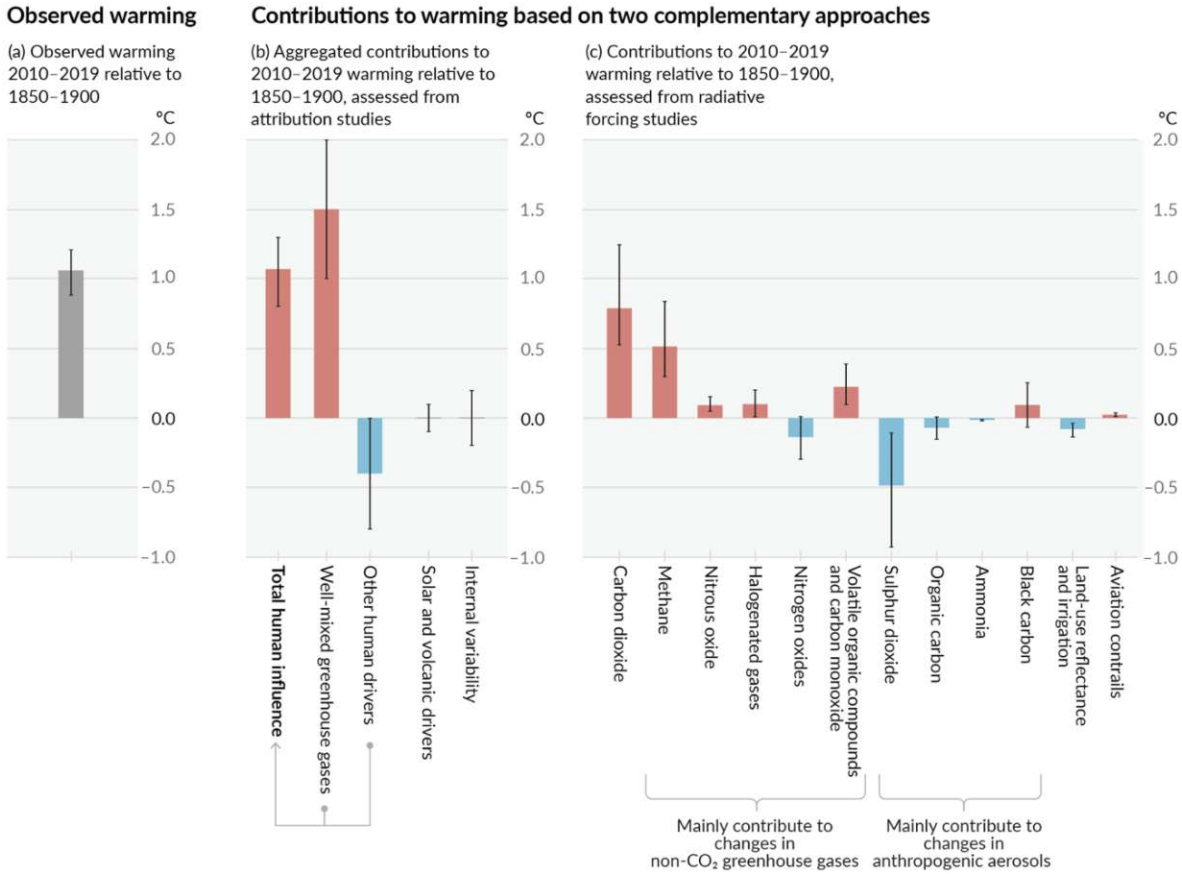

Figure 17. An overview of climate forcers and their contribution to temperature change. *Source*: IPCC. 2021. "Figure SPM.2 | Assessed contributions to observed warming in 2010–2019 relative to 1850–1900." In *Summary for Policymakers* in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 6. Cambridge: Cambridge University Press (2023). https://doi.org/10.1017/9781009157896.001.

In figure 17, the expected warming due to GHGs is 1.5°C while the observed warming is 1.1°C, resulting in a cooling of 0.4°C. Although the cooling effect of SO_2 or sulfate aerosols is estimated to be 0.5°C in this figure, it is in sum slightly damped by the positive forcing of BC. Since Hansen et al. (2023a) assume an ECS of 1.2°C per W m^{-2}, the expected warming is about 2.6°C around 2022, as illustrated in figure 18. The observed warming correlates with the IPCC AR6 figure. However, according to their figure, the aerosol cooling effect is approximately 1.5°C, i.e., almost three times stronger than the IPCC value.

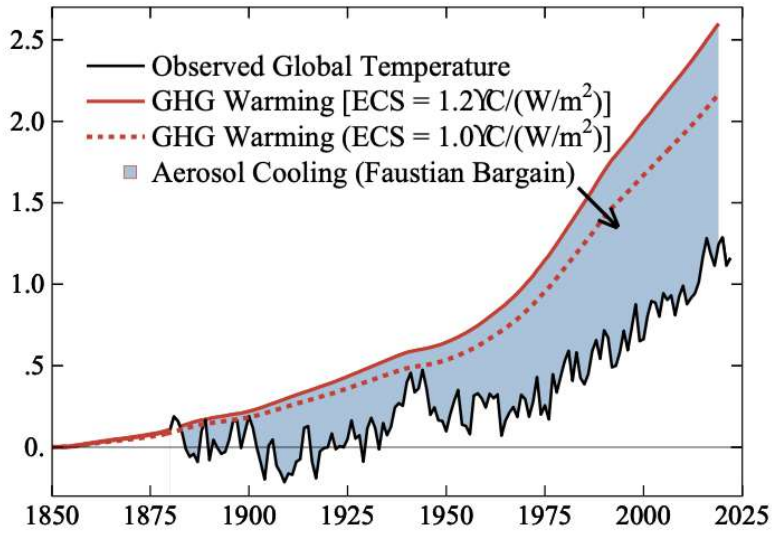

Figure 18. Relationship between expected and observed warming and thus aerosol cooling. *Source*: Hansen et al. 2023a. "Figure 13." In *Global Warming in the Pipeline*. 15. https://doi.org/10.1093/oxfclm/kgad008.

A comparison of the above-cited values is provided in table 4 for a more comprehensive overview.

Table 4. Comparison of the ECS, estimated and observed warming, and the resulting aerosol cooling in IPCC AR6 and Hansen et al. 2023a.

	IPCC AR6	*Hansen et al. 2023a*
ECS (2 x CO_2)	2.0–5.0°C very likely 2.5–4.0°C likely	3.6–6.0°C
ECS (2 x CO_2) – best estimate	3°C	4.8°C
ECS (°C per W m^{-2}; on best estimate basis)	0.75°C	1.2°C
Estimated Warming (2022) *	1.5°C	2.5°C
Observed Warming (2022)	1.1°C	1.1°C
Aerosol Cooling	0.4°C	1.5°C

* without aerosol cooling

3.4. The Disappearance of Ship Tracks and Accelerated Warming

In general, singular weather anomalies such as temperature peaks are not evidence that the Earth's climate changes. However, a few events that repeat at certain intervals suggest change and allow averages to be drawn that indicate a tendency or direction of where the system is heading.

Since 1970, the climate has warmed steadily by an average of 0.18°C per decade. This almost linear increase has changed since 2010. Hansen et al. (2023a, 21) provide a compelling explanation for the observed increase in the rate of warming that occurred in that year. In the paper *Global Warming in the Pipeline*, they argue that a combination of events led to a decrease in aerosol particle formation. China has been steadily reducing SO_2 emissions, although the big drop occurred in 2016. Furthermore, global SO_2 emissions from ships began to decline in 2010 due to newly imposed regulations. Hansen et al. presumably refer to the MARPOL Annex VI amendment that entered into force in 2010. The amendment to the new annex, which is dedicated to the reduction and prevention of air pollution from ships, expanded the ECAs and tightened the NO_x Technical Code. However, it is worth noting that Annex VI entered already into force in 2005, although it did not have the desired impact. The implementation of the regulation and China's pollution control measures led to an increased warming rate between 2010 and 2023 of 0.27°C per decade (Hansen et al. 2023a, 21) or 0.30°C per decade (Hansen, Sato, and Kharecha 2024, 2). This acceleration intensified even further in 2020. Hansen, Sato, and Kharecha (2024, 2) argue that the recent acceleration cannot be attributed to GHGs, solar irradiance, or volcanic eruptions. Instead, they argue that it can be explained by a reduction in cloud albedo. The disappearance of ship tracks and the "darkening" of clouds has been attributed to the decrease of CCN resulting from the IMO 2020 regulation, which has significantly reduced the formation of sulfate aerosols. As this was the intended outcome of the regulation, it can be considered one of the most successful environmental regulations to date. Consequently, a reduction in cloud cover leads to an increase in the amount of solar radiation reaching the surface, with minimal obstruction. This is evidenced by the increase in zonal mean absorbed solar radiation (ASR), especially at latitudes 30°–60°N, the region where most international shipping occurs. The increased ASR also coincides geographically and temporally with zonal mean sea surface temperature (SST)

and zonal-mean surface temperature (Hansen, Sato, and Kharecha 2024, 2–3), as illustrated in figure 19.

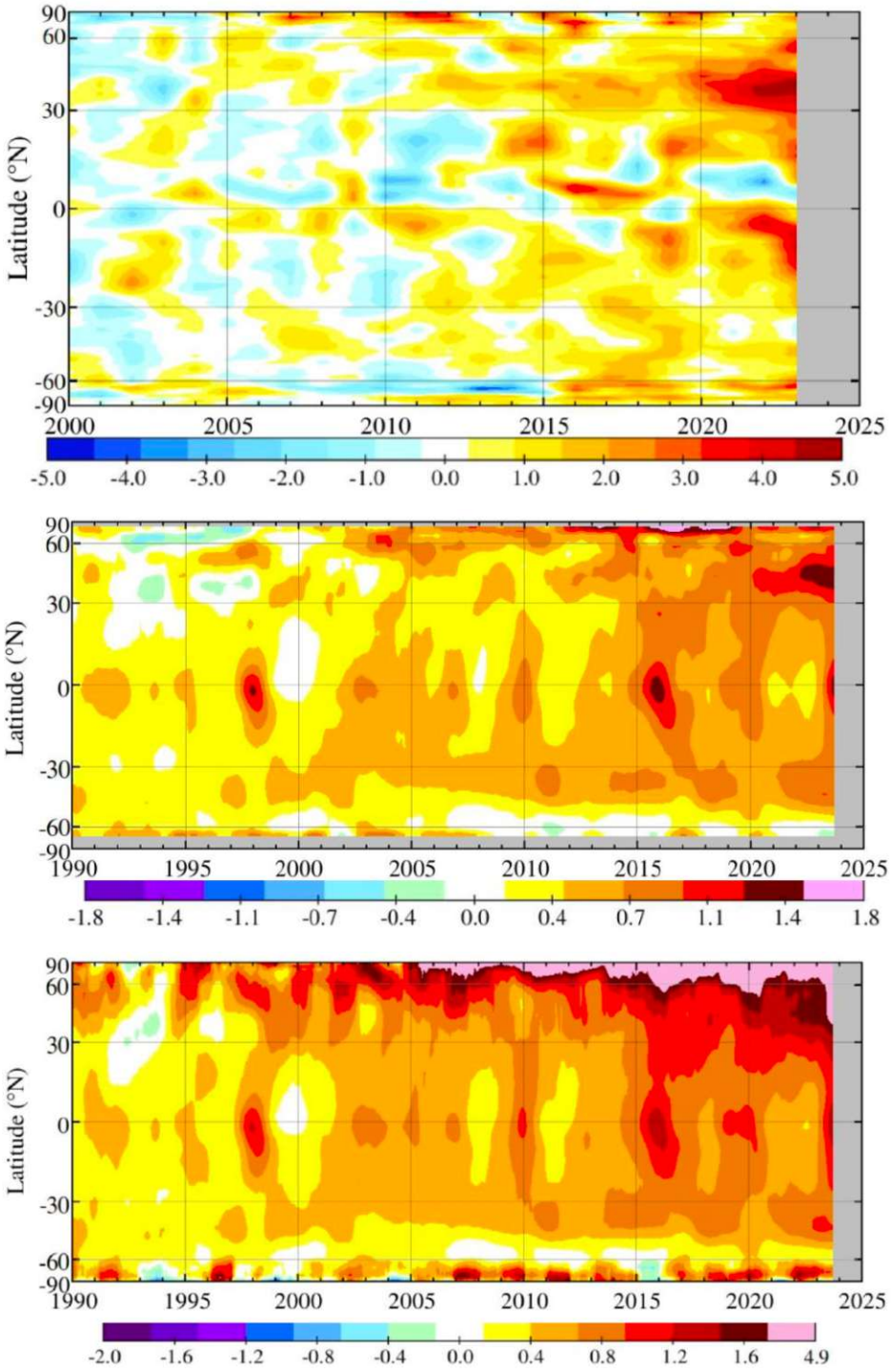

Figure 19. Top to bottom: The geographical and temporal distribution of zonal-mean ASR (W m^{-2}), SST, and land surface temperature (°C) relative to 1951–1980. *Source*: Hansen, Sato, and Kharecha. 2024. "Figure 4, 5, and 6." https://www.columbia.edu/~jeh1/mailings/2024/Hopium.MarchEmail.2024.03.29.pdf.

The rise in ASR ultimately increased Earth's energy imbalance. The left graph in figure 20 shows a jump in ASR of 0.44 W m^{-2} between the Jan 2015 – Dec 2019 and Jan 2020 – Dec 2023 means. This corresponds to an increase in Earth's energy imbalance (right graph) of 0.25 W m^{-2} between the same periods. The figure also shows that the Earth's energy imbalance has more than doubled compared to the Jan 2001 – Dec 2014 mean.

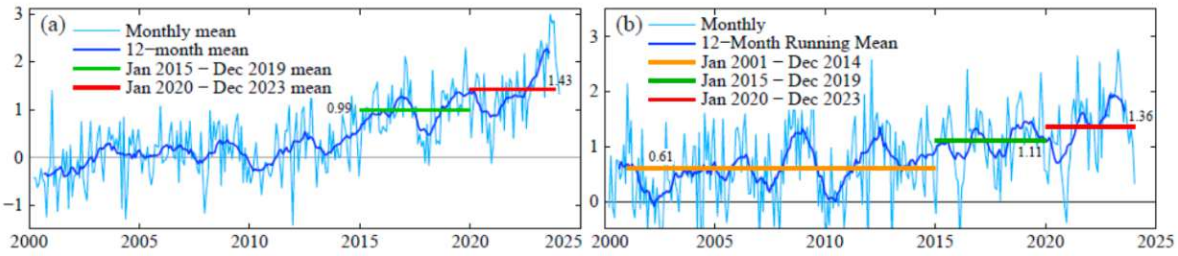

Figure 20. Comparison of global ASR and Earth's energy imbalance. Source: Hansen, Sato, and Kharecha 2024. "Figure 7." https://www.columbia.edu/~jeh1/mailings/2024/Hopium.MarchEmail.2024.03.29.pdf.

Despite recent acknowledgments by the IPCC and the broader scientific community that warming is accelerating, they have not identified the cause. According to Hansen, Sato, and Kharecha (2024, 3–4), scientists attribute the recent El Niño as the primary driver of the observed warming, overlooking the fact that three consecutive years of La Niña masked the acceleration which was already underway since 2020. As shown in figure 21, the same masking happened in 2010 at the beginning of the acceleration, which could still be observed.

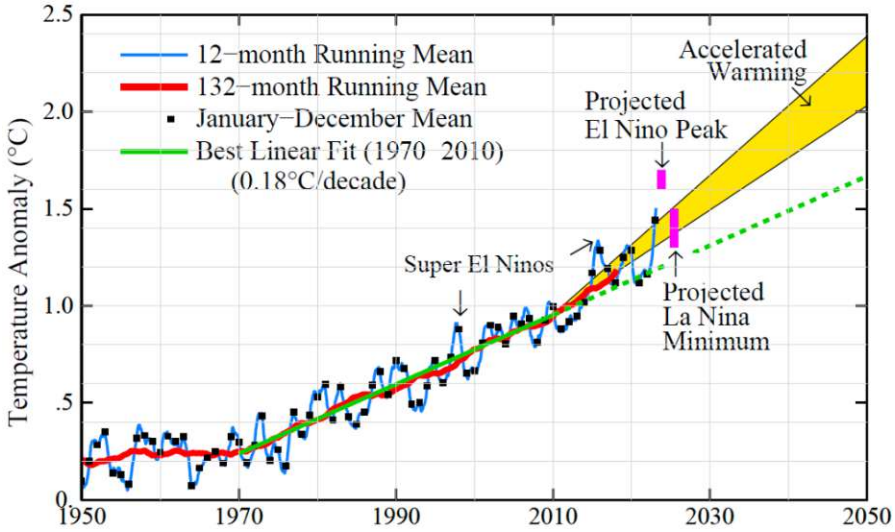

Figure 21. Global temperature development compared to 1880–1920. *Source*: Hansen, Sato, and Kharecha 2024. "Figure 10." https://www.columbia.edu/~jeh1/mailings/2024/Hopium.MarchEmail.2024.03.29.pdf.

3.5. Radiative Forcing from Ships and Implications

The global anthropogenic aerosol RF appears to be underestimated by the majority of the scientific community to be at the lower end of the range as discussed in the following lines. The IPCC AR6 provides a best estimate for the RF of global anthropogenic SO_2 emissions of –0.94 W m^{-2} with a range of –1.63 to –0.25 W m^{-2} (Szopa et al. 2021, 854), whereas Hansen et al. (2023b) assume a *"(negative) human-made aerosol forcing of 1-2 W/m²*." The difference in the attribution to the cooling effect of ships is even greater. The IPCC states that "*a year's worth of present-day global shipping emissions (i.e., without the implementation of the 2020 clean fuel standards) cause a net global cooling (–0.0024 ± 0.0025°C) on 10–20 year time horizons (high confidence) but its magnitude is of low confidence*" (Szopa et al 2021, 867). According to these figures, the large reductions in SO_2 resulting from the 2015 and 2020 IMO regulations would have hardly any effect on the climate and would leave the question of the cause of the accelerated warming unanswered. The IPCC merely mentions some previous estimates of RF attributed to shipping in "*the range* [of] *–47 to –8 mW m^{-2} (direct radiative effect) and –600 to –38 mW m^{-2} (indirect radiative effects)*" (Szopa et al 2021, 867). Although some of these values would indicate a significant impact on the climate, the IPCC AR6 does not provide a clear and unequivocal stance on the matter.

Sofiev et al. (2018, 6) estimated and compared a BAU scenario of international shipping with the impact of the IMO 2020 and concluded that the regulation would reduce the aerosol RF from –0.093 W m^{-2} to –0.022 W m^{-2}.

In contrast, Partanen et al. (2013, 12059) attributed a much higher ERF to shipping (–0.39 W m^{-2}) and compared the status quo with different sulfur content scenarios. In their first scenario, they basically proposed an intriguing geoengineering approach: A 0.1% S fuel would be used in proximity to the coast, and a very high 5.4% S fuel would be used elsewhere. They computed that this scenario would result in an increased aerosol ERF of –0.43 W m^{-2} and prevent 34.900 premature deaths annually. This scenario is compelling for two reasons, it reduces the ASR and the number of premature deaths by 69%. With respect to increasing the aerosol ERF, Yuan et al. (2024, 5) are also in support of a geoengineering approach, since their "*results suggest that MCB* [marine cloud brightening]*, through adding*

more aerosols instead, may be a viable option in temporarily cooling the global mean temperature." However, Partanen et al.'s second scenario is essentially in line with the IMO 2020 regulation, i.e. 0.1% in ECAs and 0.5% elsewhere, and results in a significantly reduced ERF of –0.06 W m^{-2} and a reduction of 48.200 premature deaths, i.e., 96% of the total. In essence, Partanen et al. (2013, 12059) argue that a strong negative aerosol RF can be maintained while air quality in coastal regions can be improved.

Similar to Partanen et al. (2013) although with different figures, Jin et al. (2018, 16793) argue that stringent regulations, such as the IMO 2020, would result in a significant decrease in the aerosol RF from –0.153 ± 0.004 W m^{-2} to an insignificant –0.001 ± 0.007 W m^{-2}. According to Yuan et al. (2023, 6), the IMO 2020 regulation has resulted in an average of 0.12 W m^{-2} of aerosol RF (0.19 W m^{-2} in the Northern Hemisphere, 0.07 W m^{-2} in the Southern Hemisphere), which is almost the half of the planetary heat uptake of 0.25 W m^{-2} since 2020. The 0.12 W m^{-2} correspond to an additional global warming of 0.15°C per decade if the heat uptake by the oceans is neglected (Yuan et al. 2023, 5). They argue that "[t]*he forcing is estimated to effectively double the warming rate of global mean temperature in this decade with strong spatiotemporal heterogeneity*" (Yuan et al. 2023, 1). Although, Yuan et al. (2024, 6) describe the IMO 2020 as a "*strong temporary shock to the net planetary heat uptake*", they are reluctant to attribute the extremes of the temperature anomalies of 2023 to the regulation. To counteract the warming increase, and in recognition of the strong cooling effect of aerosols, they promote marine cloud brightening by pumping aerosols into marine low clouds, as previously mentioned. The IMO regulations to reduce SO_2 emissions are referred to by Hansen et al. (2023a, 18) as a "*great inadvertent aerosol experiment*." According to them, the recent sulfur reductions in marine fuel have resulted in a substantial forcing of 0.5–0.7 W m^{-2} (Hansen, Sato, and Kharecha 2024, 5). However, they emphasize the regional impact of aerosol depletion. Along the most frequented shipping routes, particularly at certain locations in the North Atlantic and the North Pacific, the ASR has increased by 3 W m^{-2} after the regulation entered into force (Hansen et al. 2023b, 5). As aforementioned, energy of this magnitude was measurable in changes in SST and land surface temperature. The reason for the large differences in the figures presented, such as between Sofiev et al. (2018) and Partanen et al. (2013), lies in the variety of global climate models that use different values for parameters such as climate sensitivity, cloud and aerosol-cloud

modeling, and fast albedo feedbacks. However, a review of recent events and an assessment of the available data indicate a strong tendency for the hypothesis proposed by Hansen and his colleagues to be proven correct. According to their paper *Global Warming Acceleration: Hope vs Hopium*, new cloud modeling techniques already yield a higher ECS (Hansen, Sato, and Kharecha 2024, 6). *Global Warming in the Pipeline* undoubtedly attracted significant attention from the scientific community and likely raised greater awareness of observational methods rather than a narrow focus on climate modeling. The papers by Eyring et al. (2010), Partanen et al. (2013), Hansen et al. (2023a; 2023b), Hansen, Sato, and Kharecha (2024), and Yuan et al. (2023) emphasized the important role aerosol particles play in cloud formation and brightening and their substantial impact on reducing global warming. It seems probable, that the next few years will provide further data to substantiate their assumptions. Table 5 provides an overview of a few estimates regarding aerosol RF from shipping.

Table 5. Comparison of the RF attributed to international shipping in scenarios with no IMO 2020 regulation and with its implementation, and the resulting loss of negative RF leading to warming.

Radiative Forcing from ships (W m^{-2})	**RF No IMO 2020**	**RF IMO 2020**	**RF Difference**	**Comments**
IPCC AR6 (Szopa et al. 2021)	10–20-year horizon: –0.0024 ± 0.0025°C 100-year horizon: +0.00033°C ≤ 0.00015°C			The IPCC itself does not provide figures in W m^{-2} for ship emissions; the °C suggest hardly any effect by ships on the climate
Eyring et al. 2010	–0.408 –0.026 to –0.824			RF; based on a review of seven studies and their RF ranges
Partanen et al. 2013	–0.39	–0.06	0.33	ERF
Sofiev et al. 2018	–0.093	–0.022	0.071	ERF
Yuan et al. 2023			0.12	RF
Hansen, Sato, and Kharecha 2024			0.5–0.7	RF

4 Summary and Conclusion

In order to protect human health and the environment, the International Maritime Organization (IMO) adopted a regulation in 2008 that entered into force in 2020. This regulation, known as IMO 2020, aimed to reduce the sulfur content of marine fuel from 3.5% to 0.5% outside of Emission Control Areas (ECAs). In ECAs, a 0.1% sulfur limit became mandatory as early as 2015. The regulation has been highly successful in terms of international environmental law, as it has reduced SO_2 emissions from ships by more than 80% (Hausfather and Forster 2023).

However, this reduction has invoked an unintended effect that the IMO was unaware of. The reduction in sulfate aerosols in the atmosphere has resulted in a loss of certain cooling effects on the climate. These include the formation of clouds known as ship tracks, the brightening of existing shallow marine clouds, and the direct scattering of incoming solar radiation.

From this situation, a number of highly critical questions emerged, particularly regarding whether the extent to which the sulfur reduction has affected the climate. The scientific community is divided on this issue, especially between the two main protagonists, the Intergovernmental Panel on Climate Change (IPCC) and James E. Hansen.

Strangely, the role of ship emissions as climate forcers in the IPCC's 6th Assessment Report (Szopa et al. 2021) was apparently misinterpreted. The report indicates that prior to the implementation of the IMO 2020 regulations, shipping emissions exhibited a cooling effect of only –0.0024 ± 0.0025°C (Szopa et al. 2021, 867), thus neglecting the relevant data from a range of publications.

Nevertheless, specific investigations of the cooling effect of shipping emissions between 2010 and 2018 have already indicated a notable global influence of -0.09 to -0.39 W m^{-2} for the pre–IMO 2020 situation (details are provided in table 5).

Hansen, Sato, and Kharecha (2024, 5) estimate that the reduction in cooling due to the IMO 2020 regulation is even in the range of 0.5-0.7 W m^{-2} of radiative forcing. This implies a higher climate sensitivity, with a best estimate of 4.8°C for a doubling of CO_2 (Hansen et al. 2023a, 18), whereas the IPCC assumes a much lower value with a best estimate of 3°C (IPCC 2021b, 11). The higher equilibrium climate sensitivity (ECS) is attributed to

cloud feedbacks, which are influenced by aerosol particles (Hansen et al. 2023a, 20). The disappearance of ship tracks and the “darkening” of marine clouds, therefore, have a noticeable effect on climate.

Undisputed is an increase in absorbed solar radiation (ASR), which leads to a greater imbalance in the Earth's energy budget and consequently to an acceleration of global warming. The rate of warming, which was 0.18°C per decade from 1970–2010, has increased at least to 0.27°C (Hansen et al. 2023a, 21) or 0.30°C per decade from 2010–2023 (Hansen, Sato, and Kharecha 2024, 2). The acceleration observed from 2010 onward was further amplified in 2020 (Hansen, Sato, and Kharecha 2024, 9). This effect is confirmed by Yuan et al. (2023, 5) and in principle also by Hausfather (2023).

After investigating other potential contributing factors, Hansen, Sato, and Kharecha (2024, 9) argue that the explanation for this recent acceleration is the significant sulfur reduction resulting from the IMO 2020 regulation.

As previously stated, sulfur reductions have been implemented with the objective of protecting human health. The estimated range of premature deaths attributed to ship emissions is listed in table 4 and centers around 60.000, which is approximately 0.1% of global deaths. However, it should be noted that this figure is subject to a considerable degree of uncertainty. It is assumed that the IMO 2020 regulation reduces annual mortality.

New findings on the climate impacts of aerosol particle reduction continue to emerge. In the near future, further evidence is anticipated regarding the role of aerosol direct and indirect forcing from ship emissions and other anthropogenic pollution reduction effects. Should the magnitude of the aerosol effect be confirmed, and the trend already suggests a correlation, that the reduction of sulfur in marine fuel and the associated atmospheric alterations are responsible for additional warming, then the increased frequency and intensity of storms, droughts, floods, heatwaves, and other extreme weather events may be partly attributed to the sulfur reduction. The full impact on human health, the way of life of billions of people, and the environment cannot yet be quantified, but it is likely that the negative effects will outweigh the positive aspects of the IMO 2020 regulation.

A key takeaway from this study is the need to improve the understanding of anthropogenic aerosols as cooling agents, as opposed to warming agents such as greenhouse gases, in the general climate modeling community. Future large-scale reductions of aerosols

must take into account their respective climatic consequences (Persad, Samset, and Wilcox 2022).

Hansen et al. (2023a) and Yuan et al. (2023) consider the changes in the global anthropogenic sulfur emissions in connection with the warming situation of the climate-active gases to be “a great inadvertent aerosol experiment” and “inadvertent geoengineering experiment”.

One quick countermeasure would be to reverse the sulfur reduction for shipping in open waters: Deliberate geoengineering, as proposed by Partanen et al. (2013) in their first scenario, would involve a sharp reduction in sulfur emissions near coastal areas, but allow a higher sulfur content of 5.4% for ships operating far from the coast on the high seas. This strategy aims to improve air quality in coastal regions while at the same time brightening marine clouds, creating ship tracks, i.e. increasing cloud albedo, and thereby allowing aerosol cooling of the climate. The geoengineering approach, known as marine cloud brightening, has also been promoted by Yuan et al. (2023, 6). This proposal, although controversial, deserves consideration and focused research in light of the complex and urgent situation that humanity is facing in regard to climate change.

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