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Has Reducing Ship Emissions Brought Forward Global Warming?

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Abstract Ships brighten low marine clouds from emissions of sulfur and aerosols, resulting in visible "ship tracks". In 2020, new shipping regulations mandated an ~80% reduction in the allowed fuel sulfur content. Recent observations indicate that visible ship tracks have decreased. Model simulations indicate that since 2020 shipping regulations have induced a net radiative forcing of +0.12 Wm^{-2}. Analysis of recent temperature anomalies indicates Northern Hemisphere surface temperature anomalies in 2022–2023 are correlated with observed cloud radiative forcing and the cloud radiative forcing is spatially correlated with the simulated radiative forcing from the 2020 shipping emission changes. Shipping emissions changes could be accelerating global warming. To better constrain these estimates, better access to ship position data and understanding of ship aerosol emissions are needed. Understanding the risks and benefits of emissions reductions and the difficulty in robust attribution highlights the large uncertainty in attributing proposed deliberate climate intervention.

Plain Language Summary Ships have a unique climate effect due to brightening of low marine clouds, resulting in visible "ship tracks". These ship tracks are due to clouds interacting with ship emissions, particularly sulfur. Recently, regulations have drastically reduced allowable ship sulfur emissions. This has resulted in a decrease in observable ship tracks. Modeling and observations indicate that the reduction in ship sulfur emissions could have slightly warmed the planet starting in 2020. These changes are remarkably co-incident with observed patterns of cloud changes and may have accelerated global warming.

Key Points:

- Recent regulations on ship sulfur emissions have decreased ship tracks and resulted in +0.12 Wm^{-2} of radiative forcing
- Observed cloud anomalies are correlated with observed ocean temperature anomalies and shipping radiative forcing
- Reduced ship emissions may have accelerated global warming contributing to recent warm Northern Hemisphere surface temperatures

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

In 2020 the International Maritime Organization (IMO) instituted new regulations reducing the maximum allowed sulfur emission per kg of fuel in ships by 80% (IMO, 2019). Upon combustion, sulfur in fuel is released mostly as sulfur dioxide (SO_2), while a small fraction (a few percent) is emitted as primary sulfate aerosol. The gaseous SO_2 is oxidized in the atmosphere to sulfuric acid (H_2SO_4) and sulfate aerosol (SO_4^{2-}). The oxidation to aerosol (increasing aerosol mass) is rapid (<1 hr) in the presence of clouds, but slower in clear sky conditions, with lifetimes for SO_2 in plumes of up to 20 days (Kroll et al., 2015). The result is increased sulfur-containing aerosol number over time (Yu et al., 2020). Sulfur-containing aerosol particles are effective Cloud Condensation Nuclei (CCN), and clouds in the presence of more CCN tend to have higher cloud drop number and higher albedo, resulting in radiative cooling by scattering more sunlight back to space. When ships sail into a region susceptible for shallow marine cloud formation, bright linear clouds or "ship tracks" are often seen (Conover, 1966).

Studies estimate the global average change in radiative forcing due to all shipping in the range of −0.06 to −0.6 Wm^{-2} (Yuan et al., 2022), or 10%–40% of the total aerosol cooling effect (Lauer et al., 2007). The stronger (negative) estimates above, however, used simulations with stronger effects of aerosols on clouds than more recent assessments (Bellouin et al., 2020) and are thus unlikely.

Recent studies (Watson-Parris et al., 2022; Yuan et al., 2022) indicate that the reduction in ship emitted sulfur due to the IMO2020 regulations has dramatically reduced visible ship tracks, similar to earlier regulations in specific emissions zones near populated coasts (Gryspeerdt, Smith, et al., 2019). The reduction in ship tracks seems to be less than 80%. The IMO2020 regulations should also have reduced the general loading of sulfur and aerosols in the marine environment, contributing to further diffuse changes in radiative forcing even when the direct impacts

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of shipping are not visible in the form of ship tracks (Diamond, 2023; Diamond et al., 2020; Manshausen et al., 2022, 2023).

2023 was the warmest year on record, with temperatures 1.18°C above the 20th century average (NOAA National Centers for Environmental Information, Monthly Global Climate Report for Annual 2023, published online January 2024, retrieved on 25 January 2024 from https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202313). How much have the sudden reduction in shipping emissions and in ship tracks contributed to recent temperature increases?

In this work, we assess the latest information on the changes due to the IMO2020 regulations from several published studies, bringing together a variety of lines of evidence, and present new modeling results and recent observations that indicate a possibly significant regional role for shipping emissions reductions in recent warm temperature anomalies. Section 2 discusses the data and methods to be used, Section 3 provides a review of recent studies of the shipping emission changes. New results from models and observations are presented in Section 4, a synthesis and conclusions are in Section 5.

2. Methods

In addition to the review of previous work below (methods described in those references), we analyze further observations and provide some new modeling results for shipping emissions changes. Surface temperatures are from the NOAAGlobalTemp data set (Huang et al., 2020, 2023; Zhang et al., 2024). We have also performed the analysis with ECMWF ERA5 reanalysis temperatures, and results are similar. Top of Atmosphere Cloud Radiative Effect (CRE) data are from the Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition-4.2 data set (Loeb et al., 2018).

We use several new model simulations in this work. We performed simulations with the Community Earth System Model version 2 (CESM2, Danabasoglu et al. (2020)). CESM2 features a two-moment cloud microphysics parameterization (Gettelman & Morrison, 2015) and a modal aerosol model (Liu et al., 2016) coupled through droplet activation (Abdul-Razzak & Ghan, 2000) and ice nucleation (Liu et al., 2012) schemes. It represents the effect of increases in cloud drop number due to aerosol perturbations and subsequent cloud adjustments. These simulations are atmosphere-land simulations described in Christensen et al. (2022), and similar in design to those performed to estimate the impact of COVID19 perturbations by Gettelman et al. (2021). Simulations were nudged to 1 year (2017) of meteorology and sea surface temperature (SST) and repeated 12 times (the model is run for 12 years with annually repeating nudged meteorology). This eliminates differences in synoptic meteorology (weather noise), but the clouds are not identical each year (preserving some random uncertainty in cloud evolution around this state). Two simulations are performed. One with default shipping emissions (Figure S1 in Supporting Information S1), and one with only sulfur emissions from shipping reduced by 80% from the default simulations. In order to assess the impact of a particular meteorological year, the pair of 2 simulations (with full and reduced sulfur) was repeated with nudging to 2019 meteorology. The two different years were chosen to have different states of the El Niño Southern Oscillation (ENSO: 2017 was a moderate cold year, and 2019 a moderate warm year), and to not encompass the emission reduction period of 2020–2023. The simulated Net CRE difference between these years is -2.5 Wm^{-2}, and the observed CERES difference in CRE is -0.7 Wm^{-2}. These are about the largest differences in the CERES record, and illustrate that the simulated IMO2020 CRE effect is indepenent of particular pattern of CRE in any year. Similar perturbations are performed with two similar Earth System Models to check the regional and global estimates, nudging meteorology with and without IMO2020 sulfur reduction. ECHAM-HAM model (Tegen et al., 2019) simulations are run for 1 year and simulations with UKCA (Gordon et al., 2018) were performed for 3 years. All simulations include changes from all clouds.

Finally, we perform simulations with the FAIR energy balance model (Smith et al., 2018) to understand possible temperature effects of the assessed shipping radiative forcing. We use version 2.1.0 described by Leach et al. (2021) with calibration on CMIP6 model output.

3. Review of Recent Work

Table 1 provides a summary of recent work on the IMO2020 (and earlier) emissions changes. Gryspeerdt, Smith, et al. (2019) examined the impact of earlier sulfur reductions in the California Emission Control Area (ECA) in

Table 1
Estimates of Radiative Forcing From the IMO2020 Regulations

Source	Region	% Reduction (%)	ΔRF (Wm^{-2})	Variable assessed
Observations				
Gryspeerdt, Smith, et al. (2019)	California ECA	73		Visible Tracks
Diamond (2023)	S. E. Atlantic	35–70	O(+0.1)	Albedo
Yuan et al. (2022)	60°S–60°N	46		Visible Area
Watson-Parris et al. (2022)	Global	25		Visible Area
Manshausen et al. (2023)	Atlantic & E. Pacific	17		Vis + Invis Albedo
Simulations				
SILAM (Sofiev)	Global	80	+0.07	
CESM (Gettelman)	Global	100 ± 25	+0.11	
ECHAM (Watson-Parris)	Global	80	+0.15	
UKCA (Yoshioka)	Global		+0.14	
GEOS (Yuan)	Global		+0.12	

2010 and 2015. Watson-Parris et al. (2022) and Yuan et al. (2022) use automated methods to identify visible ship tracks globally. Diamond (2023) analyzed cloud microphysical changes within a major shipping lane and extrapolated the regional values globally. Manshausen et al. (2023) examined changes in cloud property responses in the North Atlantic, and the estimate in Table 1 is for the Atlantic and E. Pacific using the same method. These methods indicate significant reductions in visible ship tracks, which vary by region. Near global values are 25%–50% reductions, with higher reductions in specific emissions control areas. The overall effect on albedo in the N. Atlantic (which would include “invisible” ship tracks) was smaller (in percent terms). Only Diamond (2023) provided a radiative forcing estimate, extrapolating from results in the South East Atlantic off the coast of Africa. Thus multiple methods indicate significant regional and global reductions in ship tracks. Note that most of these studies (with the exceptions of Diamond (2023) and Manshausen et al. (2023)) concern themselves with just the visually detectable tracks, and that the radiative effect of reducing sulfur will change the brightness of the tracks as well as their presence or absence.

We also examine modeling studies. Sofiev et al. (2018) used a chemical transport model (SILAM) and empirical forcing relationships. The other simulations are conducted with Earth System Models (ESMs) with comprehensive aerosol and cloud microphysics schemes that have been previously used to look at Aerosol-Cloud Interactions (ACI) from a variety of different anthropogenic and natural sources. All the simulations are perturbation studies where sulfur emissions from shipping were reduced by 80%, and two different simulations performed. The difference is reported as the radiative forcing. Note that models do not produce individual ship tracks, but rather emit sulfur into the lower atmosphere in shipping lanes, with subsequent effects on marine low clouds. Possner et al. (2016) indicate that this method might overestimate the effect of shipping emissions by 50%. The simulations show a remarkable consensus on the global radiative effect of the IMO2020 80% sulfur reduction of about +0.12 Wm^{-2}, with an uncertainty based on inter-annual variability from multi-year model simulations from CESM of ±0.03 Wm^{-2} (which is also the intermodel mean standard deviation).

4. Results

Given these observed and simulated changes in shipping from the IMO2020 regulations, we now explore recent observed changes to temperatures and clouds, focusing on the period 2022–2023. We then compare these changes to simulated changes from CESM.

4.1. Recent Warming and Cloud Changes

Figure 1a illustrates surface temperature anomalies from 2022 to 2023 (Dec 2021–Nov 2023) relative to 2000–2019 as the baseline period from the NOAAGlobalTemp data set. The base period is chosen to isolate the period just before 2020, and the anomalies for the most recent 2 years. Results are similar if only 2023 is used so they are

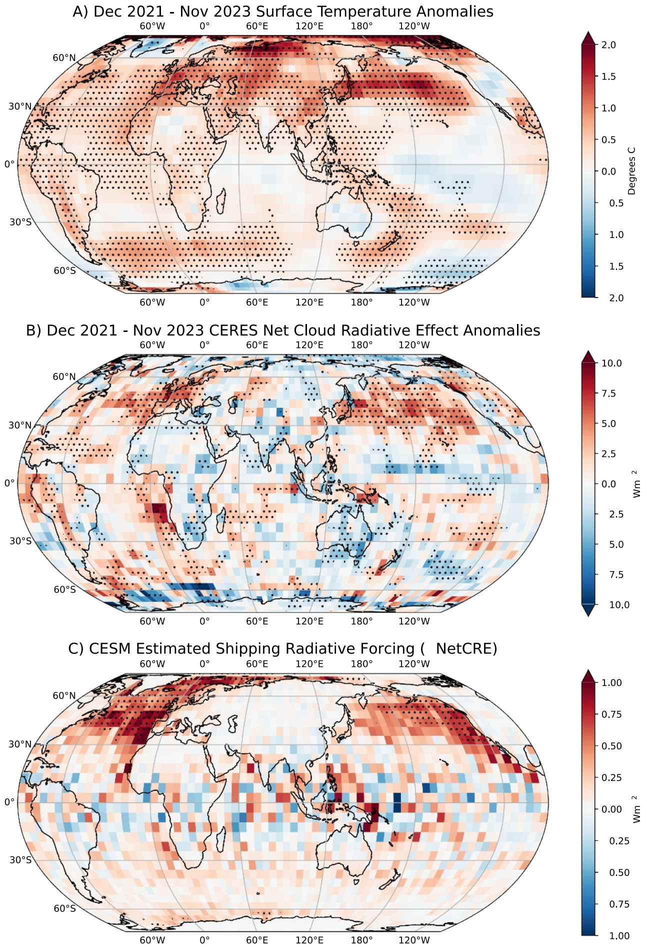

Figure 1. (a) Surface temperature anomalies from NOAAGlobalTemp data set for Dec 2022–Nov 2023. Anomalies are relative to 2000–2019 from the same data set. (b) Dec 2022–Nov 2023 anomalies in net (SW + LW) top of atmosphere Cloud Radiative Effect from the CERES-EBAF4.2 data. Anomalies are from the 2004–2019 mean. (c) Simulated change in net Cloud Radiative Effect due to 80% reduction in shipping emissions from CESM, averaging simulations using 2017 and 2019 meteorology. Stippled regions are significant based on a 90% threshold using the False Discovery Rate (FDR) approach (see text).

not dependent on specific periods after 2020. Stippling indicates anomalies significant at the 90% level using the False Discovery Rate (FDR) method (Wilks, 2006). The observed temperature anomalies in 2022–2023 illustrate significant warming throughout the Northern Hemisphere over land and ocean. Peak anomalies over the ocean are in the N. Pacific storm track, and the sub-tropical Eastern Atlantic. There are also significant anomalies over Europe and Central Asia, and some warm anomalies in the Southern Ocean.

Figure 1b illustrates that the observed recent anomalies in the net (shortwave (SW) + longwave (LW)) CERES CRE has a similar pattern to the temperature anomalies, particularly over the Northern Hemisphere extra-tropical oceans. Stippling again indicates significant anomalies. The Pearson pattern correlation coefficient between CERES CRE anomalies and surface temperature from 20 to 70°N over the ocean is 0.51. The tropics are not included in the correlation since these correlations may be due to other effects like the ENSO. The pattern correlation clearly indicates a relationship between clouds and the surface temperature. Given that this is only 2 years, we also explore the implications for other years. Figure S2 in Supporting Information S1 illustrates the correlation each year since 2001. From 2001 to 2020, the mean annual pattern correlation is 0.33 and the standard deviation is 0.13. The period 2021–2023 is anomalous with annual correlations >0.4. The hemispheric contrast is also consistent with cloud effects mostly in the Northern Hemisphere, though the temperature anomalies are also significant in the Southern Ocean, indicating that the correlation is not high everywhere.

The positive pattern correlation does not prove causation that observed cloud anomalies drive SST changes. It is possible that cloud responses to increased surface temperatures might create positive CRE anomalies, consistent with low cloud feedbacks (Sherwood et al., 2020). The positive average annual correlation between surface temperature and CRE implies this. However, the magnitude of the changes are larger than expected from cloud feedbacks. Over the mid-latitude ocean, net cloud feedbacks in CESM for example, are on the order of 1–2 $\mathrm{Wm^{-2}K^{-1}}$ (Gettelman et al., 2019; Figure 2), similar to other models (e.g., Sherwood et al., 2020; Zelinka et al., 2020). The 2023 temperature anomalies were ~0.5 K in this region, not sufficient to produce the CRE anomalies observed in Figure 1b of 5–10 $\mathrm{Wm^{-2}}$. Thus during the 2021–2023 period, surface temperature anomalies are more likely driven by cloud anomalies rather than the other way around.

4.2. Simulated Impact of IMO2020 Regulations

Figure 1c illustrates the CESM simulated change in net CRE due to the emissions changes associated with the IMO2020 shipping regulations. All of the significant forcing is in the SW, the LW forcing from ships is not significant. As with the other panels, stippling indicates significant differences (90% level) using the FDR methodology (Wilks, 2006). The pattern of forcing is consistent with ECHAM and UKCA as illustrated in a zonal mean forcing plot in Figure S3 in Supporting Information S1, but the shorter simulations have more noise. CESM is different at high latitudes, likely due to differences in ice and mixed phase processes in the models. This change is a hypothetical 80% reduction in ship sulfur emissions. Note that the scale is a factor of 10 smaller than the CERES radiative anomalies in Figure 1b. The observed anomalies (Figure 1b) are a factor of 3–5 times larger than what is expected from changes in shipping alone (Figure 1c). Possible cloud feedback changes have not been removed. A rough estimate would be 2 $\mathrm{Wm^{-2}K^{-1}} \times 1.5\ \mathrm{K} = 3\ \mathrm{Wm^{-2}}$ for a feedback. Thus 30%–50% of the cloud anomalies could be attributed to feedbacks. Shipping effects still have a smaller magnitude. However, the patterns are remarkably similar: anomalies are found in the European Arctic, the N. Pacific, and the North and Subtropical Atlantic. The anomalies are consistent with the regions of largest shipping emissions (Figure S1 in Supporting Information S1). The largest CESM simulated forcing is located in the 2015 emissions control areas around Europe and N. America (particularly California). These regions are largely absent in the observed CRE

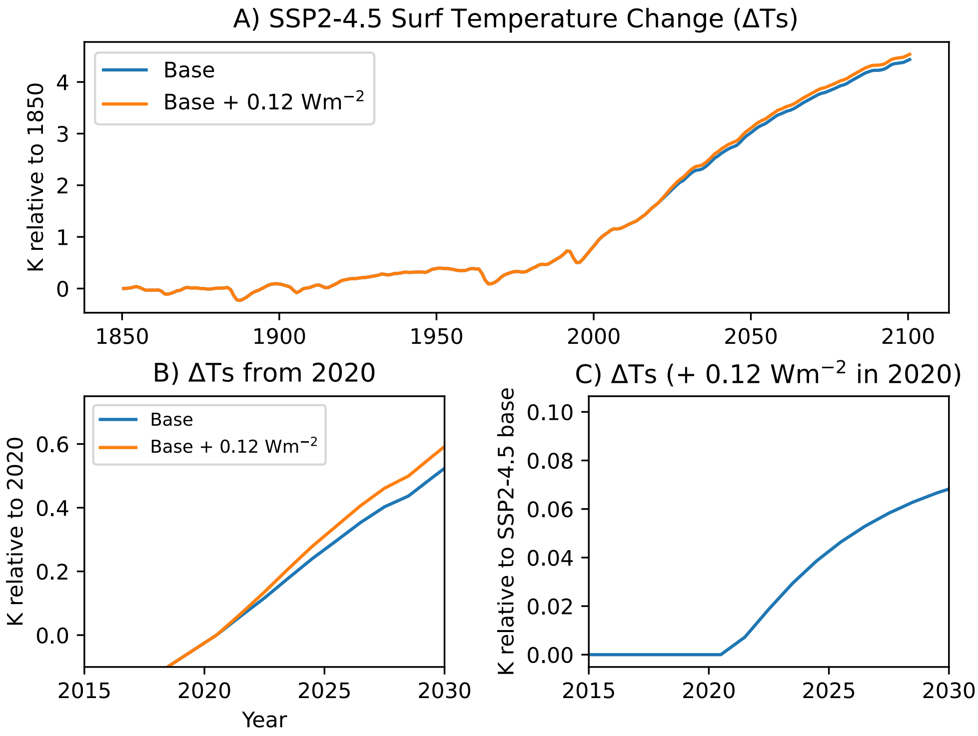

Figure 2. FAIR model simulation results. (a) Surface Temperature relative to 1850 from the base simulation (blue) and base simulation +0.15 Wm^{-2} additional radiative forcing (orange). (b) Temperatures for the two simulations over 2016–2030 as anomalies from 2020 (c) Temperature difference (perturbed—base) from 2016 to 2030.

anomalies, which would make sense as in reality these regions were cleaned up in 2015 but in "model world" not until 2020. Given that the model is run with fixed climatological SSTs that do not contain ENSO, we do not expect to see anomalies match in the tropics. The Pearson pattern correlation over 20°N–70°N oceans between CERES anomalies (Figure 1b) and CESM differences averaged using both 2017 and 2019 meteorology (Figure 1c) in CRE is significant at 0.26 for 2021–2023. We have explored the correlation between the CESM ΔCRE and CERES CRE anomalies from 2003 to 2023 each year (Figure S2 in Supporting Information S1), and the mean annual pattern correlation is 0.02, with a standard deviation of 0.11.

The sudden reduction in aerosol cooling in 2020 simulated in CESM and the other models in Table 1 corresponds to a sudden and sustained net anthropogenic radiative warming. To estimate the effect of such a forcing on surface temperatures, we use the FAIR energy balance model version 2.1.0. Simulations are performed with a radiative forcing scenario using historical data, and then projecting forward with a moderate warming scenario (SSP2-4.5). Two simulations are performed, one with default settings, and one with the radiative forcing of climate instantaneously and continuously increased by +0.12 Wm^{-2} in 2020. The results are not dependent on the warming scenario used. Figure 2 shows the temperature evolution for each scenario (A), with a zoom in on the temperature temperature increase relative to the 2020 annual mean from 2016 to 2030 (B) and difference between the simulations (C) over the period 2016–2030. By 2023, the realized global warming due to IMO2020 changes is about +0.04 K, which is about 50% of the long term response to IMO2020 of about +0.07 K. This warming is 17% of the total anthropogenic warming from 2020 expected by 2023, and 13% of the total simulated anthropogenic global warming by 2030 (Figure 2b). Note that the forcing is heavily concentrated over the Northern Hemisphere mid-latitude oceans which are a small fraction of the planet (20%). The actual observed anomalies over the 2000–2019 period are about 0.55 K in this region (Figure 1a). While it is not possible to directly scale the global energy balance estimates (due to advection of heat for example), it is likely that the portion of regional warming due to shipping emissions is much larger than the global average estimated contribution from shipping to warming of nearly 20%. This indicates a potentially substantial role for shipping emissions changes in regional temperature change, and continued increased trends through about 2030.

5. Synthesis and Conclusions

New methods are making rapid progress in identifying ship tracks with machine learning, and using trajectory methods and satellite imagery to understand the evolution of cloud properties over time for both visible and invisible tracks. These methods indicate significant reductions in visible ship tracks since the IMO2020 shipping regulations changes reduced sulfur emissions from ships. Global estimates are 25%–50% reduction in the number of visible tracks. This work should help us better constrain at the process level the impact of visible and "invisible" ship emissions on marine clouds and extend that globally.

Simulations with hybrid approaches and global models indicate a radiative forcing change of $+0.12 \pm 0.03$ Wm^{-2} could result from the reductions in sulfur emissions. This result is based on simulations from several models. However, further refinement of models is still desired. For example, simulations reduce shipping sulfur mass emissions, but the IMO2020 sulfur regulation has had a drastic effect on the size distribution and number of primary aerosols from shipping (Yu et al., 2020), affecting aerosol number and possibly radiative forcing.

There has been speculation that the record warm temperatures in 2023 are at least partially attributable to the reduction of cooling as a result of the IMO2020 regulations. The analysis of recent temperatures shows that the anomalies in temperature in 2022 and 2023 were correlated (in space) with changes in clouds. Since 2020 the correlation between temperature and clouds has been above 0.4, higher than over any 3 year period in the CERES record back to 2002. The magnitude of the observed cloud changes is too large to only be a cloud feedback response to temperature changes, implying that other factors have been modifying clouds. Further simulations analyzing cloud anomalies with and without surface temperature anomalies could be used to try to quantify the feedback contribution. Furthermore, there are significant (but weak) pattern correlations with simulations of cloud changes due to shipping emissions. The magnitude of the observed CRE anomalies is about 3X larger than would be expected from shipping emissions alone. On a global or Northern Hemisphere average, the CERES observed CRE is not anomalous over the 2020–2023 record, so no large scale shift in clouds is evident due to meteorology.

This analysis indicates it is plausible that the IMO2020 shipping regulations changes through sulfur emission reduction have significantly contributed to recent Northern Hemisphere temperature anomalies. Shipping cannot account for all of the observed warming. The analysis is done using 2 years of data data under the new shipping emissions, and only one set of model simulations is used for pattern correlations. However, the results are not that sensitive to the exact surface temperature data or dates used for the correlations, and the forcing is similar across models, and not dependent on the specific nudging period. Pattern correlations are significant but weak, and more detailed process analysis is needed.

Attribution with an energy balance model indicates that the global average contribution of shipping changes could be nearly 20% of expected warming by 2023. Energy balance modeling also indicates that perhaps half the total global warming of ~0.07 K from the shipping emissions effects of $+0.12$ $\mathrm{W\,m}^{-2}$ has been realized after four years (2020–2024), and continued warming is expected. The forcing is however highly localized. Based on the patterns of warming, a substantial part of 2023 warming over the N. Hemisphere mid-latitude oceans could be attributed to shipping emissions reductions. To constrain the attribution, further simulations with constrained coupled model simulations with an interactive ocean would likely be needed. However, this will not be trivial: the global shipping perturbation of $+0.1$ Wm^{-2} and about 0.07 K of temperature rise would have to be discerned from coupled simulations with climate noise. As an example, the interannual standard deviation of 101 years (years 1100–1200) of the CESM2 pre-industrial control simulation (Danabasoglu et al., 2020) is 0.47 Wm^{-2} for net TOA flux and 0.09 K for SST. Thus large ensembles, long runs and/or careful constraints would be required.

The IMO2020 regulations are a critical "natural laboratory" to determine whether continued declines in general air pollution due to regulations around the world will continue to increase and possibly accelerate global warming over the next decades (Hansen et al., 2023). This is critical for reducing the large uncertainty in climate forcing due to aerosols (Bellouin et al., 2020), and for evaluating the potential of intentional modification of marine clouds to offset global warming (Diamond et al., 2022).

To better constrain these results further at the process level, we need better access to ship position and type information from the Automatic Identification System (AIS), which broadcasts ship position and identification information. Almost all the AIS data (especially satellite derived open ocean data), even historical, is only available at a prohibitive cost. Releasing such data for research would allow detailed identification of specific ships with tracks, enabling extension of work by Gryspeerdt, Goren, et al. (2019) and Manshausen et al. (2022, 2023) to be conducted statistically and globally. This would enable us to directly link emissions to cloud perturbations and better constrain how much the IMO2020 regulations, and air pollution control in general, will contribute to global warming over the next decade.

The IMO2020 regulations can be seen as an inadvertent experiment in solar geo-engineering, but in reverse (warming). Ship sulfur reductions may have contributed a significant amount to the 2023 extreme temperatures in the Northern Hemisphere, but the estimated magnitude appears to be too small to be the only cause. The significant ENSO warm event in late 2023 would have played a role as well. Understanding and attributing the changes is not just relevant for ships and the current decade, but for several decades to come as the world rapidly decarbonizes and reduces all anthropogenic emissions of sulfur and other particulates. To what extent are we accelerating climate change by cleaning up air quality faster than limiting greenhouse gas emissions? Our inability to provide a robust attribution of global radiative forcing and resulting temperature changes even 3 years after such a large experiment speaks to the huge challenges in managing any deliberate intervention (Diamond et al., 2022) due to natural variability.

Data Availability Statement

NOAAGlobalTemp data is available from https://www.ncei.noaa.gov/products/land-based-station/noaa-global-temp (Huang et al., 2023). CERES EBAF CRE data is available at: https://ceres.larc.nasa.gov/data/. Analysis scripts and model output are available at Gettelman (2024).

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