Shipping regulations lead to large reduction in cloud perturbations
Duncan Watson-Parris1*, Matthew W. Christensena,b, Angus Lauresonc, Daniel Clewleyc, Edward Gryspeerdt, and Philip Stiera

Global shipping accounts for 13% of global emissions of SO2, which, once oxidized to sulfate aerosol, acts to cool the planet both directly by scattering sunlight and indirectly by increasing the albedo of clouds. This cooling due to sulfate aerosol offsets some of the warming effect of greenhouse gases and is the largest uncertainty in determining the change in the Earth’s radiative balance by human activity. Ship tracks—the visible manifestation of the indirect effect of ship emissions on clouds as quasi-linear features—have long provided an opportunity to quantify these effects. However, they have been arduous to catalog and typically studied only in particular regions for short periods of time. Using a machine-learning algorithm to automate their detection we catalog more than 1 million ship tracks to provide a global climatology. We use this to investigate the effect of stringent fuel regulations introduced by the International Maritime Organization in 2020 on their global prevalence since then, while accounting for the disruption in global commerce caused by COVID-19. We find a marked, but clearly nonlinear, decline in ship tracks globally: An 80% reduction in SO2 emissions causes only a 25% reduction in the number of tracks detected.

Significance
Ship tracks have long been studied as a clear manifestation of broader anthropogenic aerosol effects, but typically only in specific regions or for relatively short periods of time. Now, with the help of a machine-learning algorithm we have detected all of the tracks across the world’s oceans over two decades—more than 1 million in total. This allows us to determine where tracks are more likely to form and the sensitivity of clouds to such perturbations. Crucially, we see a sharp reduction in tracks due to the more stringent ship emission regulations since 2020. This constitutes clear evidence of a global cloud response to environmental regulations despite no such change being observed in other cloud properties.

Ship Track Climatology

While the total radiative effect of detectable ship tracks is small, and the adjustments to the initial perturbation in droplet number are still contested (5), they nevertheless provide unique opportunities for experiments to quantify the effects of aerosol on clouds in general. While studies to date have focused on particular regions or cloud regimes and, at most, tens of thousands of examples, we use a machine-learning model trained on such hand-labeled datasets (Materials and Methods) to create a global database of more than 1 million ship tracks over a 20-y period, as shown in Fig. 1A.

This long-term, global view of ship track occurrence confirms the findings of previous studies that they are most prevalent in low and shallow marine stratocumulus (Sc) clouds found above the cold upwelling waters to the east of the major ocean basins. While the ship tracks are evenly dispersed over the Californian Sc deck, the prevailing meteorology in the Southeast Atlantic constrains these tracks very closely to the main shipping corridors (6). We also find significant numbers of tracks in other, more unexpected locations. There is a discernible increase in density along the shipping corridor along the South Indian Ocean and a high density along the Great Australian Bight. Not all of the detected tracks can be attributed to shipping, however. Local hotspots around Indonesia (shown in SI Appendix, Fig. S4) suggest these could be caused by the large number of volcanic sources in this region. Such tracks might provide valuable insights into these emissions when cloud cover would otherwise prevent remote-sensing estimates.

This dataset provides a unique opportunity to explore the spatial and temporal distribution of these features in different environmental conditions in response to a broad range of emissions. Indeed, the introduction by the International Maritime Organization (IMO) of stringent emissions limits in the emission control areas (ECAs) around the coast of North America and the North Sea, reducing the limit on sulfur (S) in fuel oil to 1% S (by mass) in 2010 and to 0.1% in 2015, and a global reduction on the limit from
Fig. 1. (A) The average monthly frequency of occurrence of ship tracks detected in Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua imagery between 2002 and 2021 with a single contour level of average shipping emissions at 0.4 ng m$^{-2}$ s$^{-1}$ SO$_x$ overlaid in white. (B) The absolute difference between the frequency of occurrence between 2002 to 2014 and 2015 to 2019 (inclusive), highlighting changes due to near-shore sulphur emission control area (SECA) emissions regulations. (C) The absolute difference between the frequency of occurrence between 2015 to 2019 and 2020 to 2021 (inclusive), highlighting changes due to IMO global shipping emissions regulations.

3.5 to 0.5% after 1 January 2020 provide an opportunity to assess these sensitivities. Unfortunately, at about the same time as the global emissions regulations came into force, the global COVID-19 pandemic took hold and disrupted global shipping (7), making a direct comparison with previous years challenging. By 2021, however, most shipping had returned to its prepandemic level (7) and a clearer picture of the impact of the regulatory changes is revealed.

The spatial distribution of these changes is shown in Fig. 1 B and C, which shows the changes in ship track occurrence between 2002 to 2014 and 2015 to 2019 and between 2015 to 2019 and 2020 to 2021, highlighting the effect of regional and global regulatory changes, respectively. The changes seen in Fig. 1 B clearly show the large reduction in ship tracks that occurred off the coast of California with the introduction of the 0.1% limit within the ECA around the North American coast, but no discernible change in the North Sea ECA, as has already been noted (11). A small reduction is seen in the Northwest Atlantic off the coast of Nova Scotia, but as few ship tracks are ever found here, the absolute change is negligible. There is a marked increase in ship tracks just outside the ECA in the North Pacific as shipping routes were changed to avoid the regulatory area between 2016 and 2019 (Fig. 3). There appears to be a small increase inside the ECA again in 2021 as the price differential between ECA and non-ECA routes is reduced. The changes due to IMO regulations are stark and much more uniform: There is a large reduction in ship track incidence everywhere they typically occur (see regional changes in SI Appendix, Fig. S3). This uniform reduction clearly shows the impact of, and general adherence to, the IMO regulations introduced in 2020.

Fig. 2. The total number of ship tracks by ocean region between 2003 and 2021 (inclusive), overlaid by the global mean shipping emissions of SO$_x$ where available. Ocean region boundaries are shown in SI Appendix, Fig. S7.

Sensitivity of Clouds to Ship Emissions

These clear reductions in ship track occurrence are in contrast to the broader changes in marine cloud droplet number that do not show any particular effect of the changes in regulations outside of the longer-term decline since around 2007 (SI Appendix, Fig. S5). Such large-scale changes have been attributed to total anthropogenic emissions changes over the period and also show a sublinear response (12). Even regionally though, the only discernible...
change occurs in the South Atlantic where the influence of continental aerosol sources may be less than in the South Pacific.

By regressing the changes in ship track occurrence against the associated (large) changes in shipping emissions of SO\textsubscript{x}, we can determine the global sensitivity of clouds to these perturbations, as shown in Fig. 4. As expected, this sensitivity is positive everywhere and generally higher where ship tracks tend to be found since shipping covers a large portion of the ocean over multiyear timescales and the emissions reductions were uniform. Increased sensitivity can be seen in the extratropical shallow clouds, with the North Pacific and high cloud-fraction Sc particularly sensitive. Cloud fraction has been shown to play a leading role in determining the occurrence of ship tracks (11) and we find a similarly strong dependence, although there is also a (weaker) dependence on the background droplet number concentration: Cleaner clouds are more likely to produce ship tracks in response to ship emissions, as seen in Fig. 5.

While locally the relative sensitivity of ship track formation to emissions changes can be as large as 1.0, there is large spatial variability and the global change in the number of tracks is clearly sublinear: An 80% reduction in SO\textsubscript{x} emissions causes only a 25% reduction in the number of tracks detected. Since the change in droplet number is known to respond logarithmically with increased condensation nuclei (13), this demonstrates how far from their preindustrial conditions the shipping corridors are, even after such a large reduction in emissions. It also highlights the difficulty faced by proposed marine cloud brightening efforts due to the diminishing returns on injected aerosol.

Discussion

Ship tracks can generally be discerned (either manually or automatically) only in homogenous cloud fields but, although hard to detect, cloud perturbations in inhomogeneous clouds such as broken cumulus can exist (14) and have recently been shown to have distinct and important liquid water path responses (15). Future work will combine these approaches to better determine the radiative forcing induced by shipping and the degree to which cloud perturbations are saturated by present anthropogenic emissions. Such an approach would also allow a determination of the sensitivity of this, and other ship track detection studies, to the brightness and linearity of the tracks.

By detecting and analyzing more than 1 million ship tracks over two decades we have been able to unambiguously demonstrate the response of anthropogenic changes in clouds to changing emissions, despite a negligible response in other background cloud properties over the period. This unique dataset highlights the impact of the successful implementation of the global aerosol emissions control regulations on the climate system and the limited effect of the COVID-19 pandemic. Combining the vast amount of Earth observing data now available with modern machine-learning techniques provides additional ways to assess global emission perturbations and will allow governments and international regulatory bodies to monitor the compliance to, and climate effects of, much needed emissions reductions schemes.
Materials and Methods

Training Data. The model input comprises MODIS ‘day microphysics’ composites, inspired by ref. 16 and constructed (using SatPy) from channels 1, 20, and 32 (corresponding to wavelengths of 645 nm, 3.75 μm, and 12.5 μm, respectively). This composite was designed to provide information in the visible (toward the middle of the solar spectrum), the near infrared (which provides information about the cloud droplet size), and the infrared (which allows discrimination of cloud liquid and ice). Histogram equalization was applied to scale each channel about the cloud droplet size), and the infrared (which allows discrimination of cloud liquid and ice). Histogram equalization was applied to scale each channel prior to training and inference. The original 1,350 × 2,030-pixel (px) images were bilinearly interpolated to 1,344 × 2,240 px and then split into 15,448 × 448 px images to be as large as possible while enabling a batch size of 8 during training and maintaining the full 1-km resolution. The training data were provided in the form of 4,500 hand-logged tracks marking the head and each turning point along the track (4, 11, 17, 18). These points were connected by straight lines of width 10 px, approximating the average ship track width of 9 km (19), and converted into 4,320,448 × 448-px bitmaps for use in training the model (20). An example image and the corresponding hand-logged data are shown in SI Appendix, Fig. S1.

Ship Track Detection Model. The ship track detection model (21) is a standard neural-network-based segmentation model with a UNet architecture (22), a resnet-152 backbone (23) pretrained on the 2012 ImageNet Large Scale Visual Recognition Challenge ImageNet dataset (24), and sigmoid activation on the final layer. We train using Adam optimization (25) with a learning rate of 0.01 and a batch size of 16 over 100 epochs on two NVIDIA Tesla V100 GPUs (200,000 CUDA cores), 400 CPU cores, and 2.5 TB of RAM. Ship track polygons were determined from contours of 50 and 80% confidence in each inferred mask and the resulting geolocated objects saved in a geographic information system database (29). While the model was found to generalize well to unseen regions of the globe, a marked increase in false positives was found in cold frontal clouds near each pole and over very bright desert surfaces. The average 12.5-μm brightness temperature was determined for each track and those found to be less than 273 K or over land were filtered out of the analysis set. While the full unfiltered dataset is available, all results and figures quoted in the text refer to the filtered dataset. Ocean regions are determined using the centroid of each ship track and the Natural Earth ocean basin polygons shown in SI Appendix, Fig. S7. The maps of ship track density presented in Fig. 1 were determined by counting the number of shiptrack polygons that intersect the centroid of each 0.1° gridbox each month.

Ship-borne SOx emissions data are obtained from the monthly CAMS-GLOB-SHIP v3.1 product at a 0.1° resolution (30). The sensitivity of ship track occurrence to SOx emissions is calculated using these data after taking the mean over 40 × 40 grid cells to upscale the resolution to 4°. To determine the sensitivity of ship track formation to emissions as a function of environmental controls (Fig. 5) we use the mean single-layer retrieved liquid cloud fraction from the monthly MODIS level 3 product (MYDDB_13). The background droplet number concentration is calculated using the condensation rate temperature corrected adiabatic approximation (31, 32).

Data, Materials, and Software Availability. Machine learning training data, inference output and all analysis data have been made available as follows:

- The raw machine learning output, including segmentation masks: 10.5285/0d88dc06df514 e819c6d53f00a7be0 (28)
- The derived data: 10.5281/zenodo.7038703 (29)
- Machine learning training data: 10.5281/zenodo.7038715 (20)

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