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Lightning Declines Over Shipping Lanes Following Regulation of Fuel Sulfur

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Abstract

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Aerosol interactions with clouds represent a significant uncertainty to our understanding of the Earth system. Deep convective clouds, in particular, can have complex responses to aerosol that have proven difficult to elucidate. Here, we leverage the two busiest shipping lanes in the world, which carve a narrow path of pollution through a pristine marine boundary layer, to make headway on the influence of aerosol on deep convective clouds. We use the recent change in allowable fuel sulfur by the International Maritime Organization to test the sensitivity of the lightning to shifting aerosol size distributions. We find that, across a range of thermodynamic conditions, the enhancement of lightning over the shipping lanes has fallen by over 30%. Retrievals of cloud droplet number show a similar decline. The enhancement is therefore at least partially aerosol-mediated, a conclusion that is supported by observations of droplet number at cloud base. These results have fundamental implications for our understanding of aerosol-cloud interactions, suggesting that deep clouds show sensitivity to the shifts in aerosol number distribution in the remote marine environment.

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Chapter 1

INTRODUCTION

Aerosols influence clouds and, in turn, the Earth's energy balance. Aerosol interactions with clouds represent a significant uncertainty to our understanding of the Earth's climate. [20]. Fuel combustion by maritime shipping vessels underway in the open ocean leads to the emission of aerosol particles and aerosol particle precursors, such as SO₂, into relatively clean marine air. These emissions have been shown to perturb low-level marine stratus cloud droplet number distributions by increasing the concentrations of cloud condensation nuclei (CCN).[34, 142, 38, 95]. Deep convective cloud (DCC) systems, commonly known as cumulonimbus or thunderstorms if they produce lightning, occur throughout the tropics, and are essential to the Earth's water and energy cycles. However, there is no strong consensus on the mechanism or magnitudes of aerosol particle impacts on DCCs [119, 105, 55, 129].

Thornton et al [124] showed that lightning, a feature of DCCs, is enhanced over two the world's busiest maritime shipping routes in the Indian Ocean and South China Sea (Fig. 3.1). Cloud electrification, and thus lightning, requires sufficient updraft velocity, vertical ice fluxes, and super-cooled liquid water in the mixed-phase region of a DCC [117, 32]. The enhancement of lightning over the polluted shipping corridors could thus be related to the suppression of warm rain initiation by additional aerosol particles enhancing cloud droplet nucleation, compared to non-polluted regions, which then leads to either 1) a perturbation to the super-cooled liquid water and ice hydrometeor distributions in the mixed-phase region of DCC [83, 19, 114]; or 2) an increase in the frequency or intensity of deep convection needed to support charge separation due to aerosol particle driven changes in the vertical distribution of humidity or heating [2, 40, 101]. Some combination of 1 or 2 is also possible. The first step in either of these mechanisms is similar to the Twomey effect in shallow-clouds [127], where the proportion and number of small droplets increases with additional CCN.

In January 2020, the International Maritime Organization (IMO) reduced the amount

of allowable sulfur in fuel by a factor of seven, from 3.5% to 0.5% to curb air pollution effects [58]. After similar reductions in fuel sulfur content, studies of maritime ship plumes in the Baltic Sea documented a shift in the aerosol size distribution to smaller sizes [106]. Analyses of shallow stratocumulus marine clouds over shipping lanes find changes to cloud brightness, droplet number, and droplet size, amounting to a globally averaged radiative forcing perturbation of $O(0.1 \text{ Wm}^{-2})$ associated with the IMO regulation [133, 142, 33]. To date, no study has quantified the impact of the IMO regulation on DCCs.

DCCs may exhibit a very different response from shallow clouds, even in the warm phase, given the high supersaturations achieved and the potential for activation of Aitken-mode aerosol. Moreover, lightning may be sensitive to the number of ice nucleating particles, the response of which to the IMO regulation implementations is not known. Thus, examining whether and how the enhancement of lightning over the two shipping lanes has changed since the IMO regulation may shed light on which mechanisms of DCCs-lightning-aerosol particle interactions are operative and deserving of more study.

We investigate how recent changes in ships' fuel sulfur content impact lightning over the shipping lanes in the tropical Indian Ocean and South China Sea [63]. We show that the shipping lane lightning enhancement decreases significantly with the onset of the IMO regulation and that this decrease in lightning is persistent in time across a range of atmospheric conditions. We further show that the mean cloud droplet number concentration (Nd) of shallow warm clouds over the Indian Ocean shipping lane was enhanced before the IMO regulation and also exhibits a decrease since the IMO regulation. We discuss the implications of these results for the mechanisms of shipping lane lightning enhancement and for aerosol-particle-DCCs interactions generally.

Chapter 2

MATERIALS AND METHODS**2.1 WWLLN Network**

Lightning stroke density observations come from the Worldwide Lightning Location Network (WWLLN), a ground-based lightning detection network with continuous global coverage of lightning at a resolution of 10km [36]. WWLLN uses very low frequency radio impulses (3-30 kHz) that, upon emission from a lightning stroke, propagates between the Earth-ionosphere waveguide and disperses into a wave train. The phase and frequency of that wave train determine the time of group arrival (TOGA) at three or more measurement stations, which can be used to back out the location of the stroke. While the detection efficiency for individual events is lower than satellite-based methods, continuous observations for more than a decade offer much more statistical power over our region of interest.

We use IMERG precipitation rates and ERA5 CAPE to compare the enhancement across various thermodynamic conditions.

2.2 IMERG Precipitation

IMERG precipitation combines microwave and radar retrievals from TRMM and the GPM constellation. While additional coverage and information is available from IR cloud retrievals, here we elect to use only high quality microwave retrievals, which does little to diminish spatial coverage. IMERG has been shown to overestimate precipitation over the tropical oceans, particularly light precipitation [134, 94].

2.3 ERA5 CAPE

In ERA5, a value for CAPE is calculated for every level between the surface and 350hPa as follows:

$$CAPE = \int_{z_{dep}}^{z_{top}} g \left(\frac{\theta_{ep} - \bar{\theta}_{esat}}{\bar{\theta}_{esat}} \right) dz$$

Where z_{dep} is the departing level, z_{top} is the level of neutral buoyancy, θ_{ep} is the virtual potential temperature of the parcel, and $\bar{\theta}_{esat}$ is the saturation virtual potential temperature of the environment. Once CAPE has been calculated for all levels, the most unstable layer is selected. We use $CAPE^{1/2}$, which is directly proportional to w_{max} , the theoretical maximum vertical velocity achievable at a location given the stability of the atmosphere. This follows from the proportionality between kinetic energy and the square of velocity. Further discussion of CAPE as it relates to lightning can be found in [25] and [100].

2.4 Establishing a counterfactual and accounting for background meteorology

Lightning in Figure 3.1 is shown on $0.1^\circ \times 0.1^\circ$ grid, calculated from 3-hourly lightning stroke densities. For subsequent calculations of the enhancement (Figures 3.2-3.4) all data (CAPE, precipitation, and lightning) is 3-hourly and mapped to a $0.5^\circ N \times 0.625^\circ E$ grid to minimize collocation errors and noise, and for comparison with MERRA-2 aerosol fields. Smoothly varying data (CAPE) is remapped bilinearly, while non-smoothly varying data (precipitation and lightning) are remapped conservatively. To provide some basic control for thermodynamic and meteorological variability, we only consider precipitating clouds (precipitation greater than 0.1mm/hr). We use data from 2010 onward, as WWLLN detection efficiency was still increasing rapidly prior to 2010. The shipping lanes are defined as regions where the Emissions Database for Global Atmospheric Research (EDGAR) $PM_{2.5}$ shipping emissions are greater than $5 \times 10^{-12} \text{ kg m}^{-2} \text{ s}^{-1}$ [63]. To remove influence from katabatic flows and sea-breeze driven convergence, we only consider the larger blue regions outlined in Figure S1. This notably removes the straight of Malacca, a region with both very high shipping emissions and active convection. There, surface convergence from land-based precipitation outflows on Sumatra and Malaysia and the adjacent landmasses make it challenging to establish a counterfactual, given the well-known land-ocean contrast in lightning rates.

2.5 Retrievals of MODIS Cloud Droplet Number (N_d)

) We utilized the "brightest 10%" method (Zhu et al., 2018) to obtain reliable N_d (cloud droplet number concentration) retrievals across our target domain from 2010 to 2023. This

method involves selecting the brightest 10% of clouds within each scene to calculate N_d values for every $0.5^\circ \times 0.5^\circ$ grid box. The validity of this retrieval method has been corroborated through comparisons with ship-based observations (Efraim et al., 2020; Wang et al., 2021). N_d is computed using the cloud effective radius (r_e) and cloud optical depth (τ), as described by the equation:

$$N_d = \frac{\sqrt{5}}{2\pi k} \left(\frac{f_{ad} C_w \tau}{Q_{ext} \rho_w r_e^5} \right)^{\frac{1}{2}}$$

where k represents the volume radius ratio of cloud droplets (r_v) to r_e ($k = (r_v/r_e)^3 = 0.8$). The term f_{ad} denotes the adiabatic fraction, for which we assumed a constant value of 1 in our study, due to the absence of more refined alternatives (Bennartz and Rausch, 2017; Grosvenor et al., 2018). C_w signifies the adiabatic cloud water condensation rate within an ascending cloud parcel, expressed in grams per cubic meter per meter ($\text{g m}^3 \text{ m}^{-1}$). The extinction efficiency factor, Q_{ext} , is assumed to be 2, and ρ_w is the density of water. To enhance the accuracy of our N_d estimations for each $0.5^\circ \times 0.5^\circ$ grid box, we excluded pixels where the solar zenith angle exceeded 65 degrees (Grosvenor and Wood, 2014). We also excluded of scenes containing mixed-phase, ice, or multilayer clouds. Consequently, after applying these filtering criteria, the remaining dataset comprised less than 1% of multilayer cloud pixels in any given grid.

Chapter 3

RESPONSE OF LIGHTNING TO THE REGULATION OF FUEL SULFUR

At first glance, the change in lightning over both the Indian Ocean and South China Sea shipping lanes (hereafter "the shipping lanes") has been dramatic since the onset of the 2020 IMO regulation of sulfur emissions (Fig. 3.1). In Figure 3.1, we illustrate the intensity of the shipping lane traffic in both shipping lanes using the number of Automatic Identification Systems (AIS) transponder calls, used by maritime vessels for collision avoidance, from the IMF World Seaborne Trade dataset (top panel). The two shipping lanes have nearly an order of magnitude higher traffic than other shipping lanes in the region (and around the world). Associated with these shipping lane is an enhancement in mean lightning stroke density, consistent with previous work of Thornton et al, but updated for the time period of 2010 to 2019 in Figure 3.1 (middle panel). Since 2020, lightning over the shipping lanes has declined by about 1 stroke per km^2 per year as indicated by the difference in lightning stroke density between the mean of years 2020-2023 and that of 2010-2019 shown in Figure 3.1 (bottom panel). While some of the largest absolute declines in lightning since 2020 occur over the shipping lanes, lightning has increased or decreased in other parts of this region and time period, suggesting that changes in the dynamic and thermodynamic context for convection over these shipping lanes should be taken into account.

The constant emissions of the ship traffic, paired with continuous observations of lightning from the World Wide Lightning Detection Network (WWLLN), provide large samples to generate robust statistics. By constructing two different counterfactuals that match the thermodynamic setting of the shipping lane in a given 3-hourly period, we control for potential meteorological changes dictated by sources of interannual variability.

To ensure that we primarily capture changes in the enhancement, we implement two basic controls on the meteorology: 1) we only consider samples of precipitating clouds, using

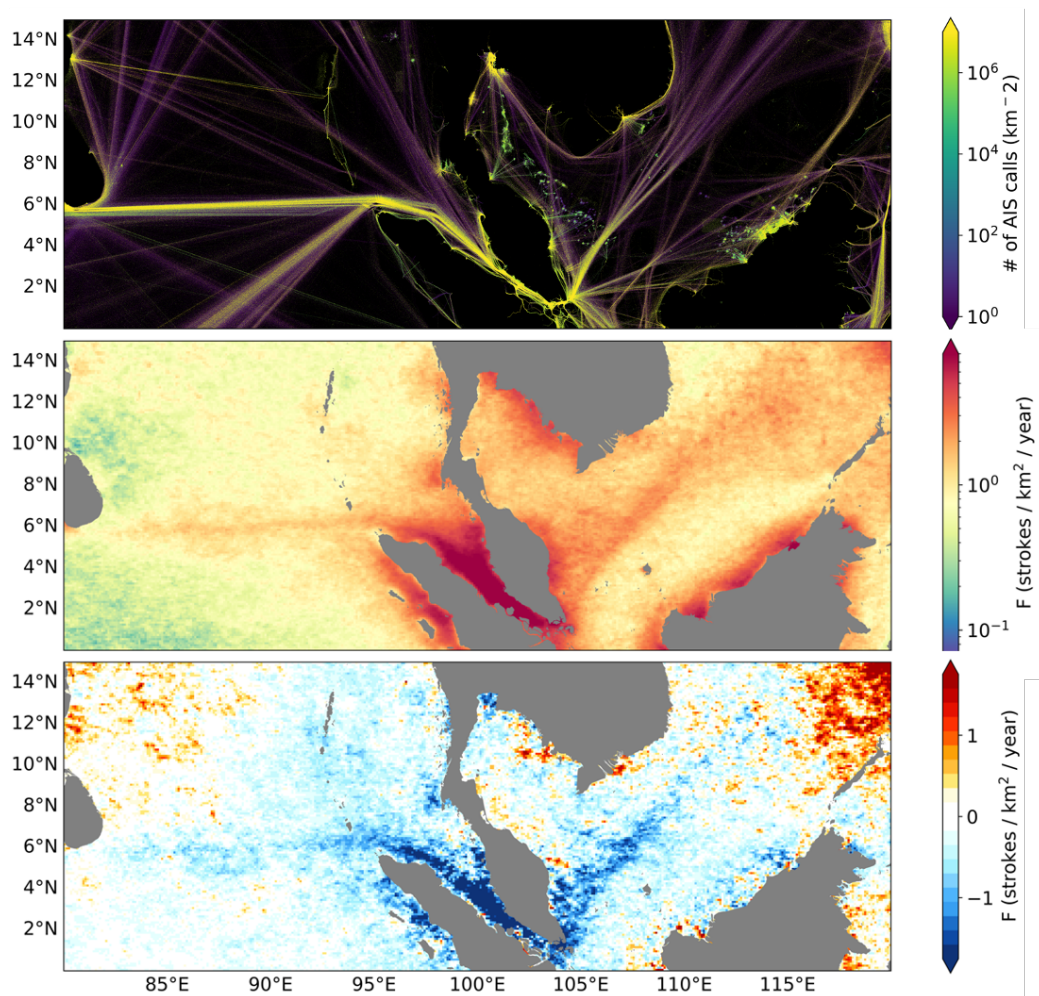


Figure 3.1: (top) AIS ship transponder events from 2015-2021 (Data from [23]). (middle) Climatology mean lightning stroke density near the Port of Singapore (2010-2019). (bottom) Absolute anomaly since the regulation (2020-2023)

radar and microwave precipitation measurements from IMERG [94, 134]. That is, for a given observation within a 3-hourly window, we use only lightning strokes which correspond to a precipitation event measured by microwave satellite sensors. 2) we restrict analyses to seasons for which the conditions for lighting are favorable in each region (November to April in the Indian Ocean; June to November in the South China Sea). Given these controls, we then composite the observations from both shipping lanes as a function of distance to the shipping lanes, defined by the peak in emissions (see Methods). Mean lightning as a function of distance from the shipping lanes before and after the regulation shows that the clear enhancement, extending from approximately 150km south to 150km north of the shipping lane, has decayed in the years since the regulation (Figure 3.2b). Where the enhancement was previously very pronounced over the shipping lanes, the effect of the aerosol seems to have dulled. Still, lightning region-wide seems to have fallen, particularly to the south of the shipping lanes.

To account for natural variability in the frequency and intensity of convection in the region, we construct an estimate of the natural (unperturbed) yearly baseline lightning stroke density by identifying inflection points in the profile on either side of the shipping lanes where the enhancement becomes apparent, about 165km in either direction. We linearly interpolate between these points to create a baseline, i.e., the expected lightning stroke density in the absence of the shipping lanes as a function of distance from the shipping lane. This baseline fluctuates year to year, presumably due to natural variability in the drivers of convection and lightning in the region. We subtract the yearly baselines from the mean lightning stroke density maxima located over the shipping lane and then calculate a relative enhancement in lightning stroke density associated with the shipping lanes for each year, the time series of which is shown in Figure 3.2. Also shown in the right panel of Figure 3.2 is the percent of fuel sales at the Port of Singapore that are "high sulfur". Prior to the IMO regulation, essentially 100% of fuel sold at the port was the high sulfur type. During this period, the enhancement of lightning over the shipping lanes varied about 70% (+/- 25%). Early adoption of the new fuel type began in 2019 and became widespread in 2020, such that less than 30% of fuel sold at the Port of Singapore is now the high sulfur type. Since the adoption of lower-sulfur fuels in late 2019, the shipping lane lightning enhancements have

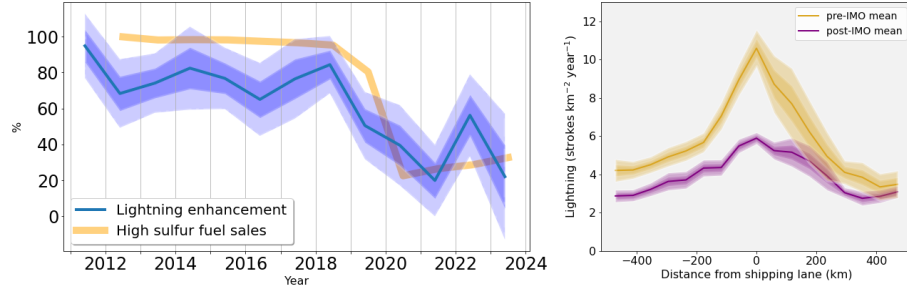


Figure 3.2: (a) Time series of high sulfur fuel sales in the port of Singapore (orange) and the associated lightning enhancement over nearby shipping lanes (blue). The enhancement is measured as the peak lightning within 150km of the shipping lane, divided by the background lightning, which has been interpolated across the shipping lane. (b) Lightning stroke density as a function of distance to the shipping lanes before and after the IMO regulation. Negative distances are south of the shipping lane, positive distances are north.

all been lower than any of those determined for years prior, and the lowest enhancements on record occurred in 2021 and 2023. The shipping lane lightning enhancements since 2019 vary about an average 30% (+/- 25%), a decline in the magnitude of the enhancement of approximately 40% from the pre-regulation average.

The preceding analysis relies on an assumption that the baseline estimate accounts for year-to-year variations in the regional drivers of convection and lightning. To further control for such variations in the large-scale thermodynamic conditions, we examine the lightning enhancement in a 2-dimensional Convective Available Potential Energy (CAPE) and precipitation space. (Fig. 3.4). [100] showed that CAPE*precipitation is a reasonable proxy for lightning frequency, and Cheng et al showed that, after adjusting for a CAPE threshold, CAPE*precipitation is a reasonable proxy for tropical oceanic lightning frequency [25]. CAPE provides an estimate of the potential for deep convection and the associated updraft strength while precipitation rate is similar to a delta function for a storm occurring (or not) and an indicator of storm size. By partitioning 3-hourly lightning observations from either the shipping lanes or adjacent reference regions into CAPE and precipitation

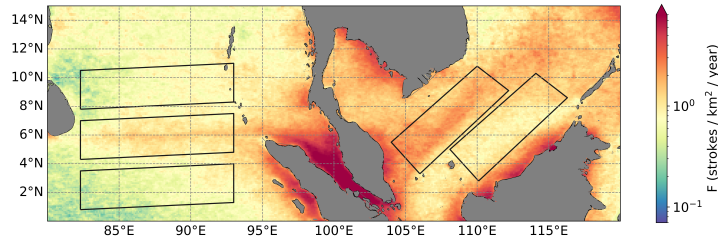


Figure 3.3: As in Figure 3.1, but with shipping lanes and reference regions shown.

bins, we control for regional and temporal variations in the environmental conditions which influence lightning to better isolate the impact of the shipping lane on stroke density.

We construct the CAPE-Precip lightning stroke density histograms using data from a latitude-longitude box centered over shipping lanes and from reference boxes adjacent to the shipping lanes, similar to those in [124] 3.3. We then compute a relative enhancement in lightning over the shipping lanes before and after the IMO regulation onset by taking the difference between corresponding CAPE-Precip bins in the shipping lane and reference box histograms. These shipping lane lightning enhancement histograms in the CAPE-Precip space are shown in Figure 3.4. Before the IMO regulation (Pre-IMO), a strong shipping lane lightning enhancement existed in nearly every thermodynamic setting (e.g., in each CAPE-Precip bin, Figure 3.4a,d) for both shipping lanes. In the South China Sea, the enhancement seems to be largest when \sqrt{CAPE} is less than 25, which corresponds to the lower threshold of the parameterization found by [25], suggesting that perhaps the aerosol enhancement is greatest when environmental conditions are marginal.

For the period after the IMO regulation (Post-IMO), both shipping lanes exhibit significantly weaker lightning enhancements across most CAPE-Precip regimes (Figure 3.4b,e). The bin-by-bin differences between the Pre and Post-IMO lightning enhancement histograms for each shipping lane are shown in Figure 3.4 (c and f). For the vast majority of CAPE-Precip bins with a statistically significant sample size, the lightning enhancement Post-IMO

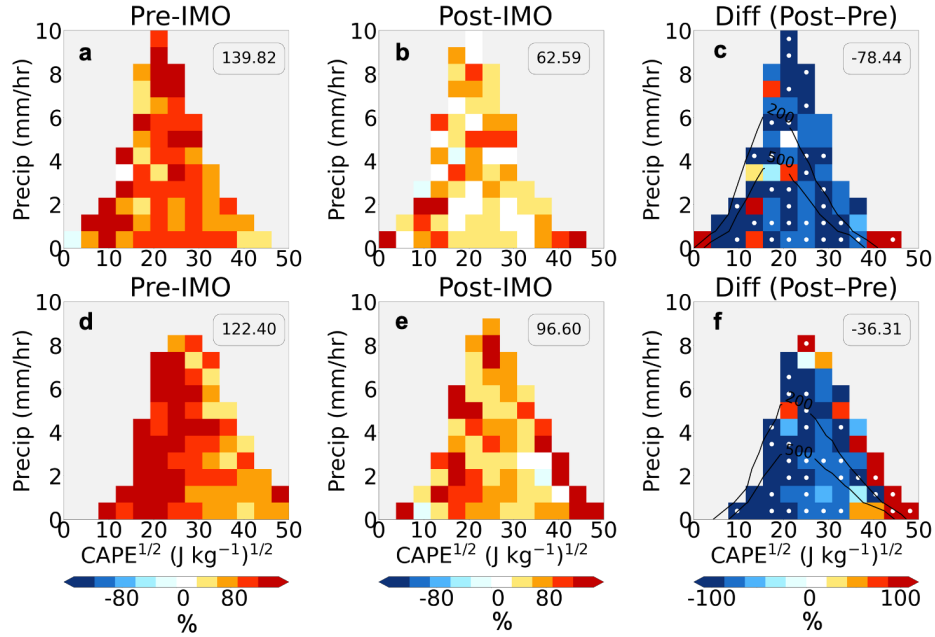


Figure 3.4: Mean enhancement in lightning binned by CAPE and precipitation for the Indian Ocean (a)–(c) and South China Sea (d)–(f) shipping lanes. Enhancements since the regulation (b, e) are lower than before the regulation (a, d). The difference between pre- and post-IMO periods is represented in (c, f), where stipples represent significance.

has been smaller than that Pre-IMO. On average across all CAPE-Precip conditions, the lightning enhancement has decreased by 78% and by 36% for the Indian Ocean and South China Sea shipping lanes, respectively.(Figure 3.4c,f).

As the total fuel sales at the Port of Singapore have been either stable or increasing between the Pre and Post-IMO periods 3.5, the results suggest that the changes in the lightning enhancement are consistent with changes to ship emissions associated with the IMO regulation. To test whether cloud microphysics in the region have changed, and thus whether the effect may be CCN-mediated, we use satellite observations of cloud droplet number (N_d) in warm (shallow) clouds over the region. The retrievals of N_d follow the method outlined in [145], such that we sample only the brightest, most active warm clouds to ensure that assumptions of adiabatic ascent are as realistic as possible. Due to the optical

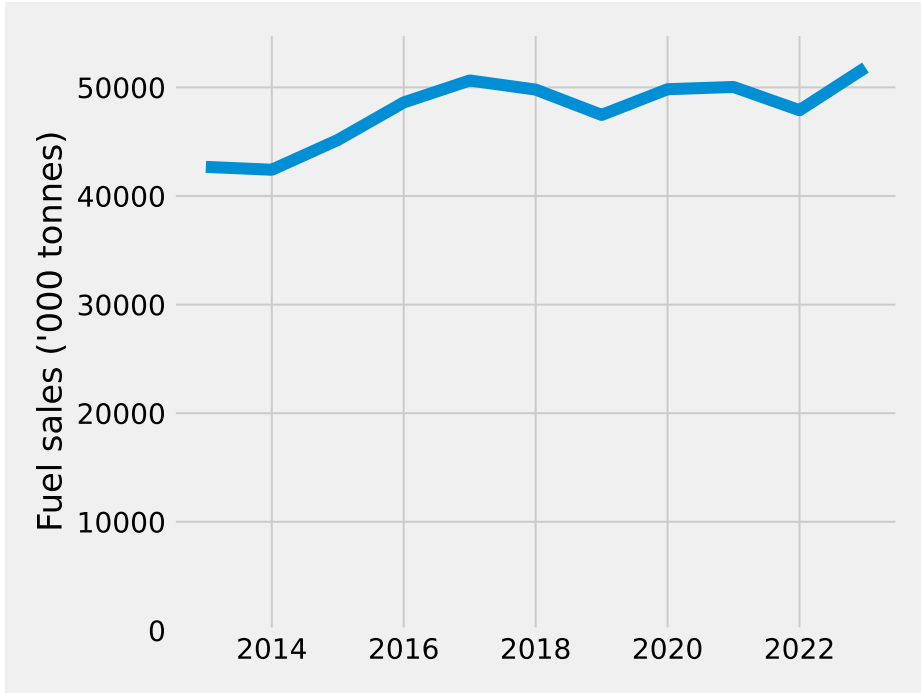


Figure 3.5: Fuel sales at the Port of Singapore, as reported by the port.

thickness of deep clouds, these retrievals can only be done for shallow warm clouds, and therefore this analysis samples a different set of conditions than the lightning observations. We assume that the behavior of N_d in shallow clouds from the same region is related to, though not necessarily a direct proxy for, N_d at cloud base in deeper clouds.

As shown in figure 3.6, we see that prior to the IMO regulation, N_d generally increases from the south of the shipping lane to the north, with a clear enhancement over the shipping lane. This N_d perturbation is roughly 5-10% above the background, which is similar in magnitude to the perturbation detected by [34] for low stratocumulus clouds in the Southeast Atlantic. Since the IMO regulation, N_d has declined region-wide, and the enhancement in N_d over the shipping lane has become undetectable. This corresponding decline in N_d over the shipping lane establishes additional support for the declining lightning enhancement being related the shift in aerosol particle and therefore CCN distributions induced by the IMO regulation.

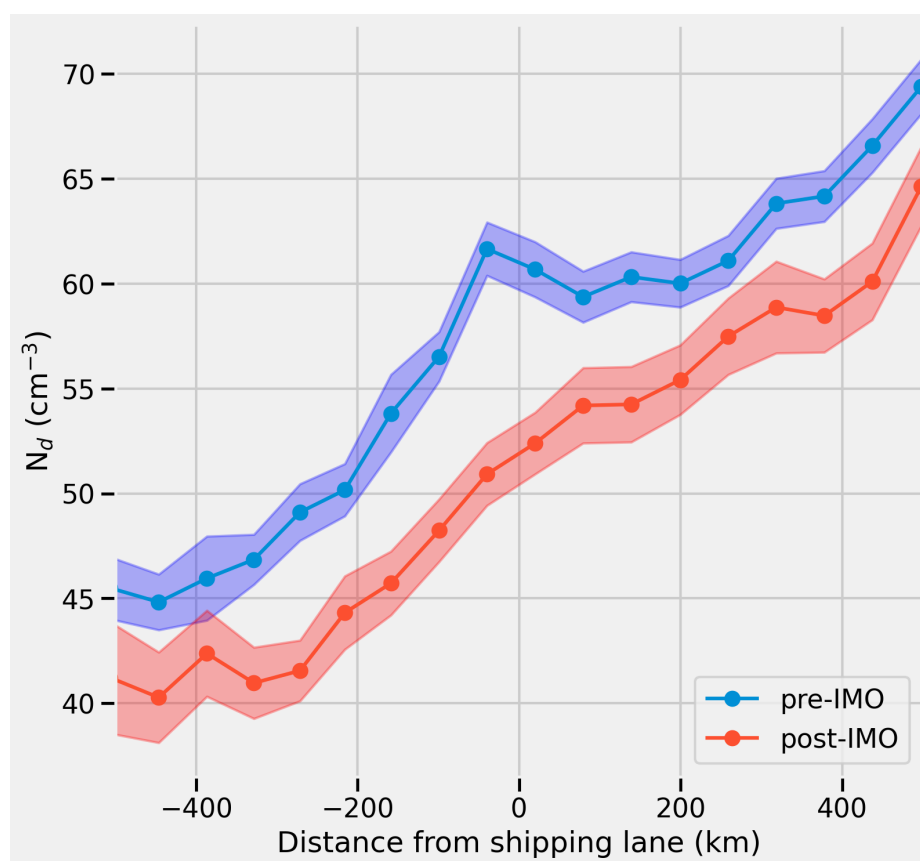


Figure 3.6: Warm cloud-base droplet number concentrations over the Indian Ocean, derived from MODIS observations of optical depth and effective radius following the procedure from [145]. The pre-regulation period is 2010-2019. Note the increasing trend toward land (positive distances), and the broad enhancement over the shipping lane prior to the regulation.

Chapter 4

IMPLICATIONS

We find that the enhancement in lightning over the two major shipping routes near the Port of Singapore has declined by over 30% since 2020. Using backgrounds informed by nearby lightning, we see this decline has taken place across a range of thermodynamic conditions. The strong response of lightning to the regulation provides some insight on the mechanism for the lightning enhancement. First, the mechanism for the enhancement is aerosol-mediated to a significant degree. While the ships themselves do likely act as attractors of lightning due to their prominence over the flat ocean [93], the aerosol enhancement is clearly present, as evidenced by its sensitivity to the regulation. Second, the shipping lane aerosol produces a perturbation to cloud droplet number, which shows a dramatic decline following the regulation. This correlated behavior between cloud droplet number and lightning lends credence to the hypotheses proposed for dynamic and microphysically driven invigoration of lightning. Indeed, the droplet number perturbation seems to disappear completely. Both the initial and final perturbations to droplet number are smaller than the enhancement in lightning, which may be attributable to the different peak supersaturations reached in these shallow warm clouds, or additional interactions between deep clouds and aerosol as ice nucleating particles (INP).

Precisely how these elevated droplet number concentrations invigorate lightning remains somewhat unclear. However, our findings suggest that the enhancement is likely not entirely attributable to updraft invigoration by activation of ultrafine aerosol [41]. [106] find that, in the case a factor of 10 reduction in sulfur in ship fuel, in-plume aerosol size distributions generally shift toward lower sizes. Concentrations of ultrafine aerosol decrease very little, or even increase as a result of the regulation. We therefore expect that an ultrafine invigoration mechanism would be largely insensitive to the regulation. Rather, the enhancement is more likely caused by perturbations to 1) cloud microphysics, such as elevated supercooled liquid

water concentrations or rime splintering [83] or 2) invigoration of updrafts by increased detrainment of water vapor [2].

This experiment links changes in aerosol chemistry to properties of deep clouds and sheds light on fundamental cloud processes necessary to understand our Earth system. We use the regulation of ship fuel to illuminate a connection between smaller, sootier aerosol, cloud microphysics, and lightning. Further work is needed to clarify this connection and to quantify the relative roles of dynamic and microphysical invigoration. Given the weak signal to noise ratio of reflectivity from the intermittent observations of GPM Ku-band radar, we do not consider changes to microphysics within the DCC-core. However, as time passes, statistical strength for the comparison between the two periods will increase.

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