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Supplement of

Lightning declines over shipping lanes following regulation of fuel sulfur emissions

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Supplemental Information

S1. Ship traffic

As noted in the main manuscript, fuel sales statistics from the Port of Singapore are a reasonable proxy for the amount of large ship activity in the two shipping lanes considered here. While not accounting for vessels that might fuel elsewhere prior to transiting one of the shipping lanes, it is likely that if a ship transits the Indian Ocean shipping lane to Singapore it will fuel there for a subsequent journey through the South China Sea (or a return to the Indian Ocean) and vise versa for a ship first transiting the South China Sea. Thus, that gross fuel sales for large vessels at the Port of Singapore has remained largely constant or even increased since 2020 (see Figure S1) suggests fairly minimal changes in ship traffic through these two shipping lanes. There is nothing like a 50% drop in shipping that might explain the change in lightning.

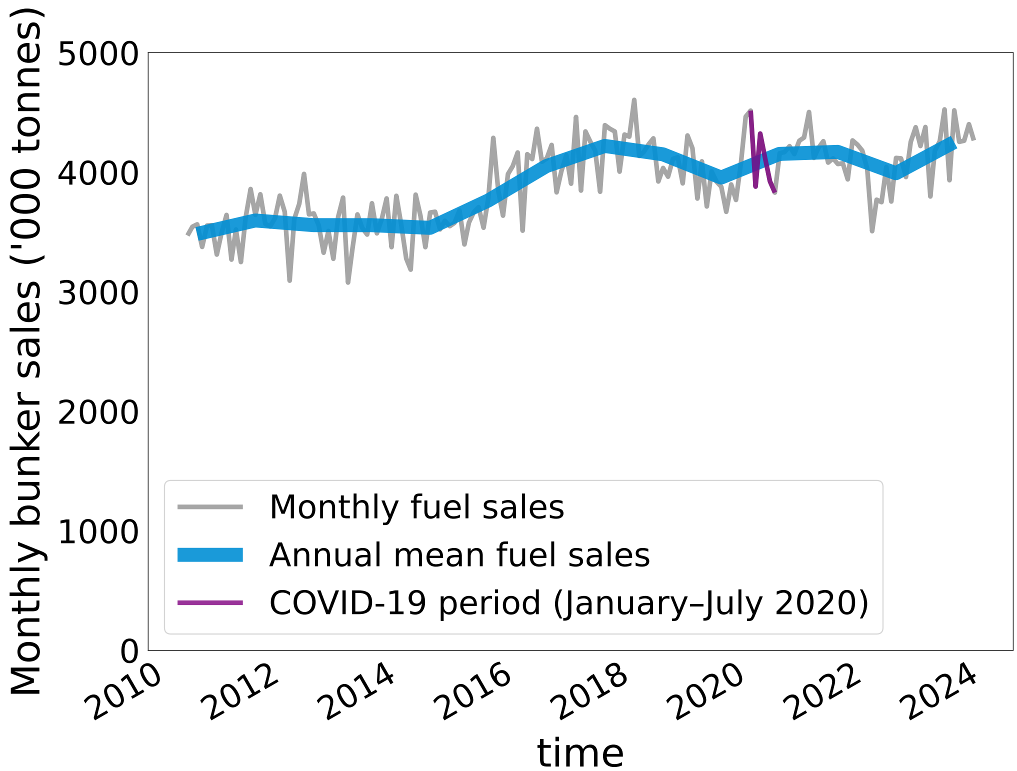

Fig. S1. Total fuel sales at the Port of Singapore have been generally increasing

Our approach to lightning stroke density analysis differs slightly from that of Thornton et al., (2017), in that only the Southern Indian Ocean reference region is used for CAPE–Precip analysis due to its similarity to the Indian Ocean shipping lane in frequency of convection and precipitation during the high-lightning season (November to April). Conducting the same analysis with the Northern Indian Ocean reference region does not alter the conclusions of this analysis. Blue boxes in Figure S2 show regions used for compositing lightning and N_d as a function of distance from the shipping lane.

Over both shipping lane regions, seasonal to subseasonal variability is dominated by the migration of the ITCZ, also called the monsoon, as well as the Madden-Julian Oscillation (MJO). The high lightning season in each region occurs when the ITCZ migrates over the shipping lane before reaching a stable location a few hundred kilometers away. This passage of the ITCZ, on top of periodic MJO-related convection, cause considerable variability in the background within a single high lightning season and across years. For this reason, we analyze the data first on

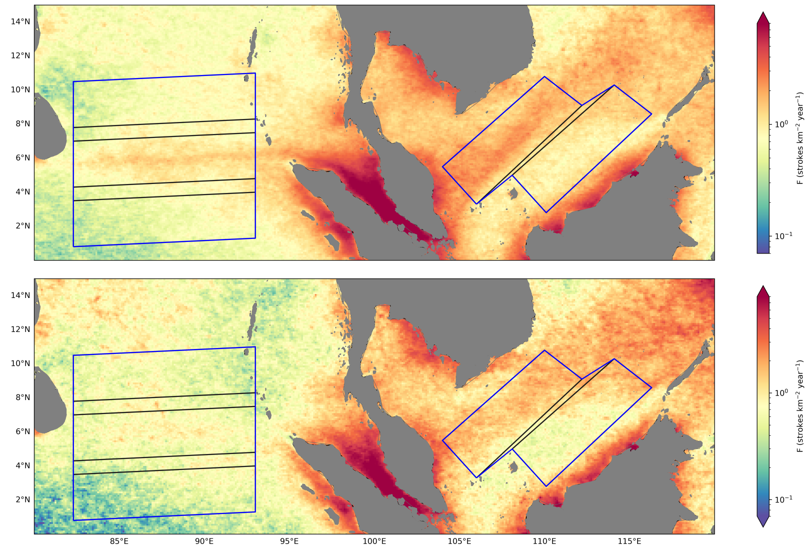

Fig. S2. Climatology (top) as in Figure 1, but with the boxes indicated in black that are used for calculating the shipping lane lightning enhancements as a function of CAPE and Precipitation presented in Figure 3. Stroke density since the regulation (bottom) used to make the difference plot in Figure 2.

an annual basis, taking an entire high lightning (monsoon) season (Figure 2 in the main manuscript), to complement the more rigorous high resolution (3-hourly) analysis shown in Figure 3 in the main manuscript.

For calculating the anomalous lightning enhancement over the shipping lanes shown in Figure 2B of the main manuscript, we regress out of the lightning stroke density the interannual variations in CAPE, Precipitation, and large scale climate variability represented by the ENSO ONI index. The predicted lightning stroke density using these variables outside of the shipping lane is shown in Figure S3 below.

In both Figure 2B and Figure 3 in the main manuscript, we remove the effects of CAPE and precipitation, which are considered reliable measures of MJO and monsoon activity and intensity (Zhang et al., 2022). To illustrate the predictive value of CAPE and precipitation in the region, we provide an example of a non-normalized CAPE–Precip diagram for the Indian Ocean pre–IMO S4. These analyses also control for interannual variability of ITCZ strength as well as variations in MJO phase. Moreover, the intraseasonal variability associated with the MJO, shown in S5, has no clear trend since 2020 and thus its specific role in the changes in the lightning enhancement is negligible.

SST-driven fluxes on heat and moisture may also be important for setting the stage for convection to occur and for driving instability; however, the connection between SSTs and lightning is less obvious than that for the more direct measures of instability (CAPE and precipitation) used here. For a more in-depth analysis of the SST-pattern drivers of convection and ITCZ migration in this region, we refer the reader to Zhang et al. (2022).

S2. Reflectivity

Thornton et al (2017) showed that DCC over the shipping lane exhibited anomalously higher radar reflectivity in the mixed phase region prior to 2015, but we find statistically robust tests of changes in DCC reflectivity since the IMO regulation are not yet possible. We use the GPM precipitation feature database from Chuntao Liu's group to probe the shipping lane enhancement of cold, strong reflectivity echoes (Liu et al., 2008). Note that this approach to examining reflectively is slightly different from that done in Thornton et al. (2017), but follows that in Blossey et al. (2018). Due to infrequent sampling and small swath width, the reflectivity signal shown here requires very long records to show the effect of the shipping lane (previous studies, such as Blossey et al. (2018), use the full TRMM record, which is well over a decade). Splitting

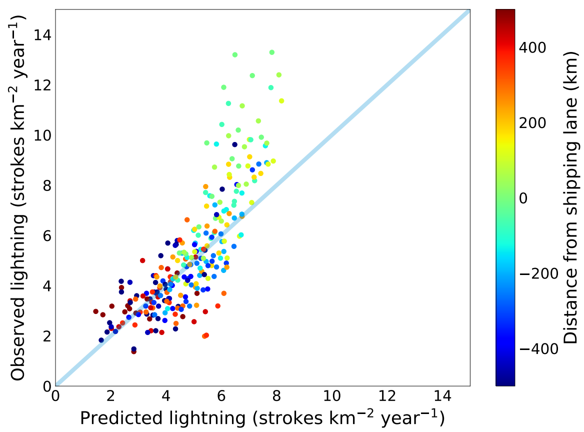

Fig. S3. Observed vs predicted lightning stroke density in the vicinity of the shipping lanes. Annual mean predictions are from linear regression of lightning stroke density against CAPE, precipitation, ONI, latitude (lat), longitude (lon), lat*lon, lat^2, and lon^2. Colors show the distance from the shipping lane. R^2 is 0.65.

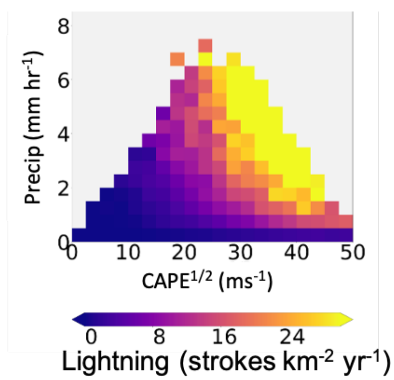

Fig. S4. Mean stroke density near the Indian Ocean shipping lane, binned by CAPE and precipitation, as in Figure 3 of the main text.

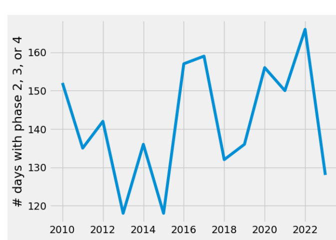

Fig. S5. Number of days with MJO phase 2, 3, or 4 from Realtime Multivariate MJO Index (RMM). This indicator of intraseasonal variability shows no clear trend since 2020

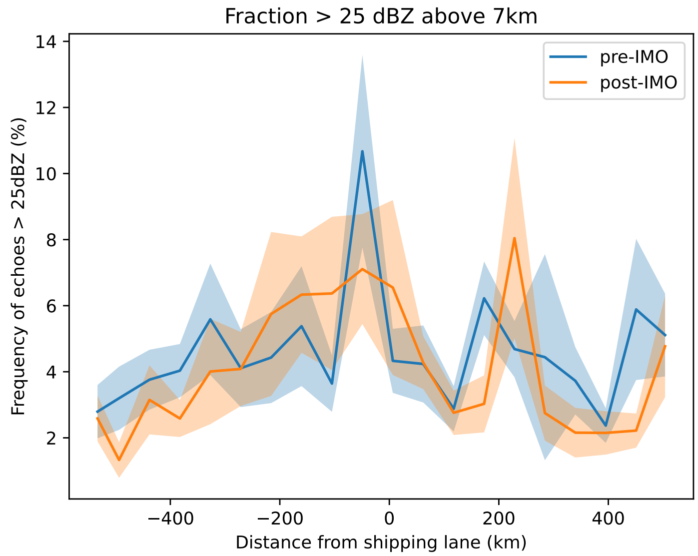

Fig. S6. Frequency of cold echoes (25dBZ or greater, above 8km) from GPM, discussed in Blossey et al (2018) and citations therein as a proxy for lightning. The peak in reflectivity has diminished since the regulation, but weak sampling power does not allow us to confirm this change (the pre-IMO record is restricted GPM's record, i.e. years since 2016).

the relatively short (8 year) GPM record of reflectivity into a pre- and post-IMO period therefore greatly reduces the statistical power of the retrievals. Indeed, the peak in reflectivity established over the shipping lane between 2016 and 2019 has diminished (Figure S5). However, the difference between the two periods is not statistically significant (p less than 0.05), and we therefore refrain from concluding that there has or has not been a change to reflectivity above the shipping lanes.

S3. Why not use AOD?

As noted in the main manuscript, we expect that perturbations to CCN in the shipping lane regions is best represented by MODIS N_d retrievals, rather than by AOD because 1) clear sky conditions are rare in this region leading to limited AOD retrievals and consequently limited statistical power and 2) AOD being proportional to aerosol cross sectional area columns does not directly correspond to CCN number at cloud base, the subject of this paper. For example, as shown in Figure S6, AOD estimates from MERRA-2 reanalysis, nudged by both their aerosol model and the limited AOD observations by MODIS, exhibit no observable enhancement over the shipping lanes prior to or after the 2020 IMO regulation. This lack of AOD enhancement is expected given that ship emissions of aerosol particles are concentrated in smaller, less radiatively active particle sizes [see, e.g., Hobbs et al. (2000) and Seppälä et al. (2021)], statistical sampling is limited by infrequent cloud-free scenes, and that particle scavenging and dilution rates in these regions are relatively high due frequent convection.

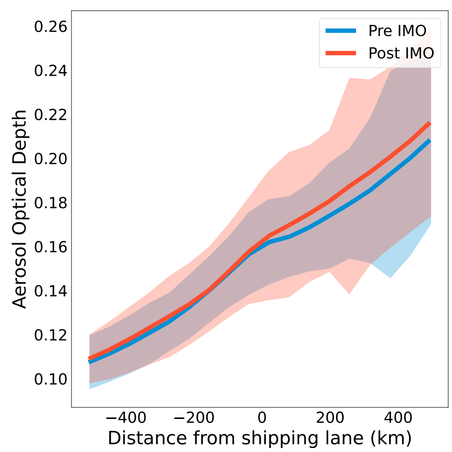

Fig. S7. Mean Aerosol Optical Depth from MERRA-2 as a function of distance from the shipping lane. Shading indicates 95% confidence.

S4. Bibliography

Blossey, P. N., Bretherton, C. S., Thornton, J. A., and Virts, K. S.: Locally Enhanced Aerosols Over a Shipping Lane Produce Convective Invigoration but Weak Overall Indirect Effects in Cloud-Resolving Simulations, Geophysical Research Letters, 45, 9305–9313, doi:10.1029/2018GL078682, URL https://onlinelibrary.wiley.com/doi/abs/10.1029/2018GL078682, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018GL078682, 2018.

Hobbs, P. V., Garrett, T. J., Ferek, R. J., Strader, S. R., Hegg, D. A., Frick, G. M., Hoppel, W. A., Gasparovic, R. F., Russell, L. M., Johnson, D. W., O'Dowd, C., Durkee, P. A., Nielsen, K. E., and Innis, G.: Emissions from Ships with respect to Their Effects on Clouds, URL https://journals.ametsoc.org/view/journals/atsc/57/16/1520-0469_2000_057_2570_efswrt_2.0.co_2.xml, section: Journal of the Atmospheric Sciences, 2000.

Liu, C., Zipser, E. J., Cecil, D. J., Nesbitt, S. W., and Sherwood, S.: A Cloud and Precipitation Feature Database from Nine Years of TRMM Observations, doi:10.1175/2008JAMC1890.1, URL https://journals.ametsoc.org/view/journals/apme/47/10/2008jamc1890.1.xml, section: Journal of Applied Meteorology and Climatology, 2008.

Seppälä, S. D., Kuula, J., Hyvärinen, A.-P., Saarikoski, S., Rönkkö, T., Keskinen, J., Jalkanen, J.-P., and Timonen, H.: Effects of marine fuel sulfur restrictions on particle number concentrations and size distributions in ship plumes in the Baltic Sea, Atmospheric Chemistry and Physics, 21, 3215–3234, doi:10.5194/acp-21-3215-2021, URL https://acp.copernicus.org/articles/21/3215/2021/, publisher: Copernicus GmbH, 2021.

Thornton, J. A., Virts, K. S., Holzworth, R. H., and Mitchell, T. P.: Lightning enhancement over major oceanic shipping lanes, Geophysical Research Letters, 44, 9102–9111, doi:10.1002/2017GL074982, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/2017GL074982, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2017GL074982, 2017.

Zhang, H., Seager, R., and Xie, S.-P.: How Does Sea Surface Temperature Drive the Intertropical Convergence Zone in the Southern Indian Ocean?, Journal of Climate, 35, 5415–5432, doi:10.1175/JCLI-D-21-0870.1, URL https://journals.ametsoc.org/view/journals/clim/35/16/JCLI-D-21-0870.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2022.