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Supplement of

Weak liquid water path response in ship tracks

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S1 Null experiment with uncorrelated winds and satellite data

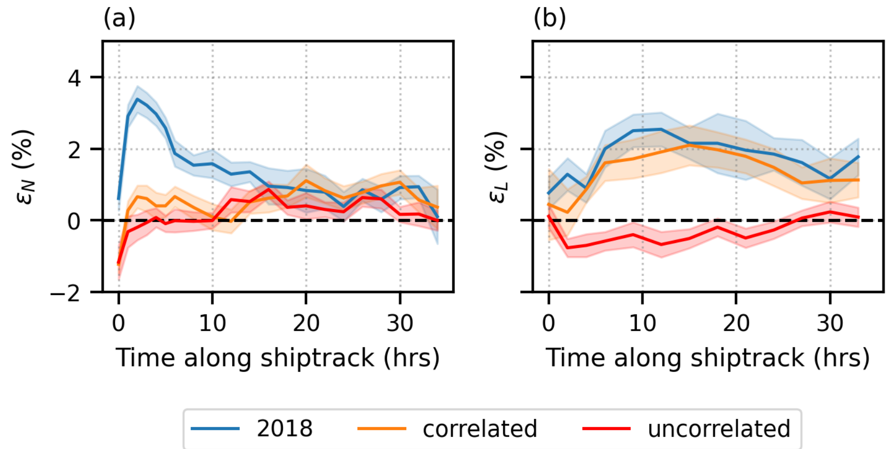

Figure S1. The 3 cases investigated in this study: the 2018 ship tracks case, the first null experiment (with both winds and MODIS data from 2019), and the second null experiment (with winds from 2018 and MODIS data from 2019). The uncorrelated null experiment has significantly different response to the correlated null experiment, recovering more of a null response.

We consider an analogy to the null experiment of Manshausen et al. (2023), as seen in Tab. 1, where the ship locations and ERA5 winds are from the year before the satellite overpass. These winds that are used to predict the ship track locations will be essentially uncorrelated to the cloud properties retrieved, and therefore the assumption that each ship track is randomly oriented with respect to the background gradient is perhaps more valid.

In Fig. S1, we find that the N_d and LWP responses in the “uncorrelated null experiment" (red line) are much closer to zero compared to the “correlated null experiment” (orange line). The only difference between these two cases is the year from which the winds that are used to predict the ship track locations are taken, highlighting the importance of the correlation between the winds and the cloud properties in the null experiment. The LWP response in this uncorrelated null experiment is still weakly negative, but is consistent with the LWP response in the null experiment of Manshausen et al. (2023). This may be due to there still being some correlation between winds of different years, or shipping routes being similar from year to year.

In Fig. S2a, we show the regional "enhancements" in LWP from our analogy to the null experiement of Manshausen et al. (2023). Fig. S2b shows the correlation between means of the LWP second derivatives and the windspeed. This essentially demonstrates that it is the correlation between winds and cloud properties in weather systems that is important for this bias, rather than than climatological gradients.

S2 Filters on response in entire Atlantic region

If we do not subset our tracks into those in the Namibian stratocumulus deck, we obtain the N_d and LWP responses in Fig. S3. The LWP response, when compositing this large region with multiple cloud regimes, is found to be close to zero for all times, and insensitive to the background environment of the ship tracks. The stark difference between these responses and those found in the Namibian stratocumulus deck suggests that the cloud regime is an important control on the LWP response to aerosol perturbations, and that the marine stratocumulus deck is much more sensitive to aerosol loading than shallow cumulus clouds.

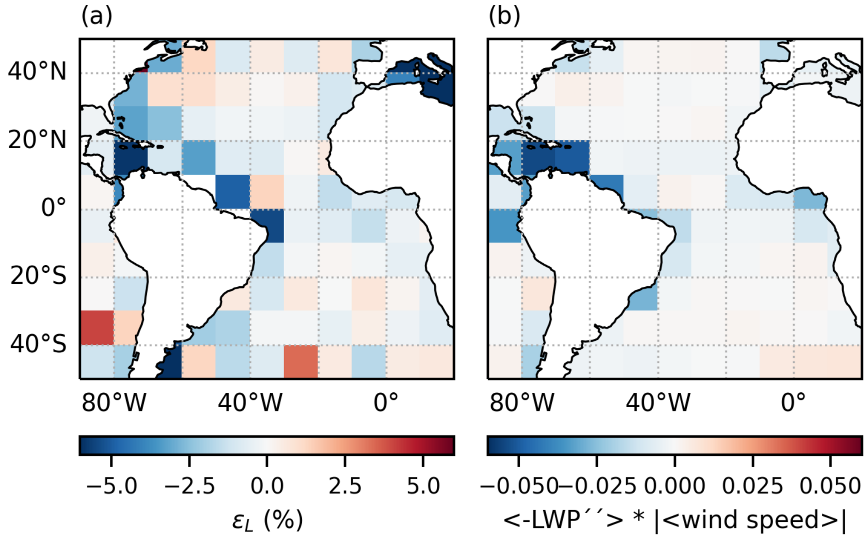

Figure S2. (a) Regional "enhancements" in the uncorrelated null experiment ship tracks (where winds and cloud data are from different years), averaged over the 36 hour length of track and central track location binned to 10º. **(b)** Correlation between the **mean** second derivative in LWP (local maxima) and **mean** windspeed (from ERA5). False enhancements are much closer to zero, and we do not see much correlation in yearly means of LWP and windspeed.

EIS bounds (K)	β_{L-N}	$\pm$ (95% conf. interval)
$<$ -13.8	NaN	NaN
-13.8 to 2.1	0.091	0.077
2.1 to 3.9	0.730	0.020
3.9 to 6.9	-0.026	0.011
$>$ 6.9	0.030	0.023

Table S1. EIS bins and LWP sensitivities

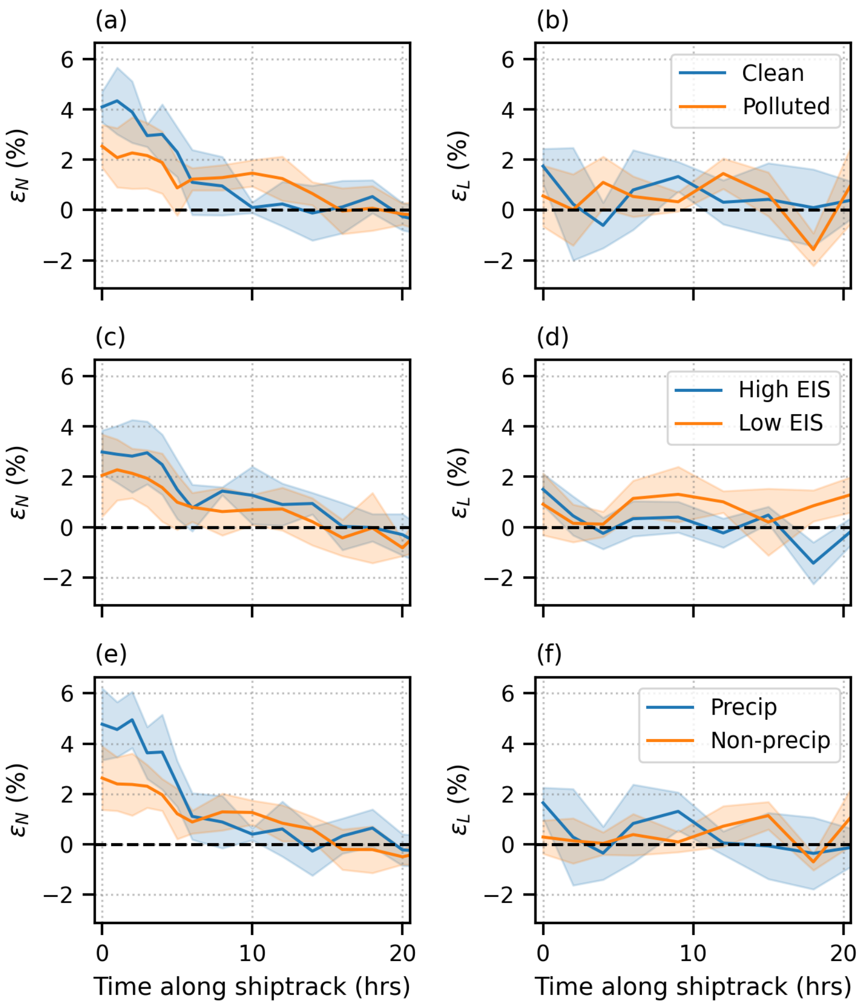

Figure S3. Time evolution of N_d and LWP responses in (**a,b**) polluted and clean, (**c,d**) stable (high EIS) and unstable (low EIS), and (**e,f**) precipitating and non-precipitating background environments, for the Atlantic region of this study. A weak LWP response is seen in all cases and there is much more noise in the response.

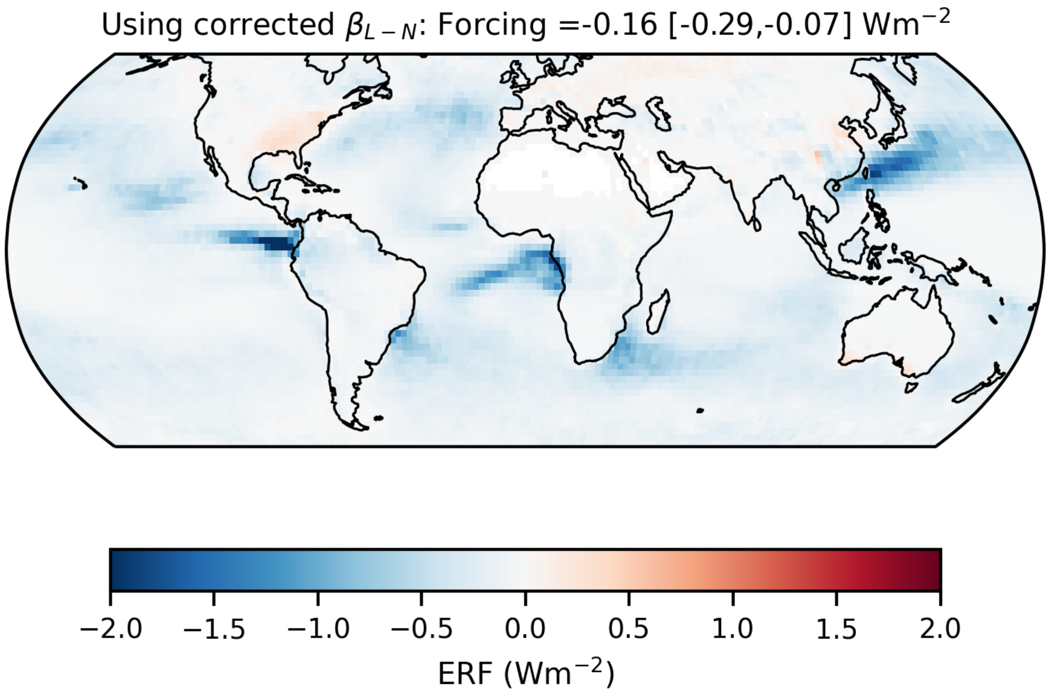

Figure S4. Radiative forcing from LWP adjustments to N_d perturbations

S3 LWP sensitivities and radiative forcing

Following the method of Manshausen et al. (2022), we calculate the sensitivity to LWP adjustments for different EIS bins (β_{L-N}).

$$\beta_{L-N} = \frac{\mathrm{d}\ln \mathrm{LWP}}{\mathrm{d}\ln N_d} = \frac{\ln \epsilon_L}{\ln \epsilon_N} \tag{1}$$

where ϵ_L and ϵ_N are the corrected enhancements in LWP and N_d. We calculate the LWP enhancement after 5 hours, and the N_d enhancement before 5 hours (following Manshausen et al., 2022), to provide an estimate on the sensitivity to changes in N_d.

This is done for four different EIS bins, and the values of β_{L-N} for each EIS bin can be found in Tab. S1. We extrapolate this globally to estimate the radiative forcing due to LWP adjustments, and the global distribution of the forcing can be seen in Fig. S4.

It is worth noting that we do not see a strong control of EIS on the LWP response, and therefore this method to calculate the forcing may not be entirely appropriate, however we use it for the sake of consistency between studies and purely to obtain an estimate of the forcing.

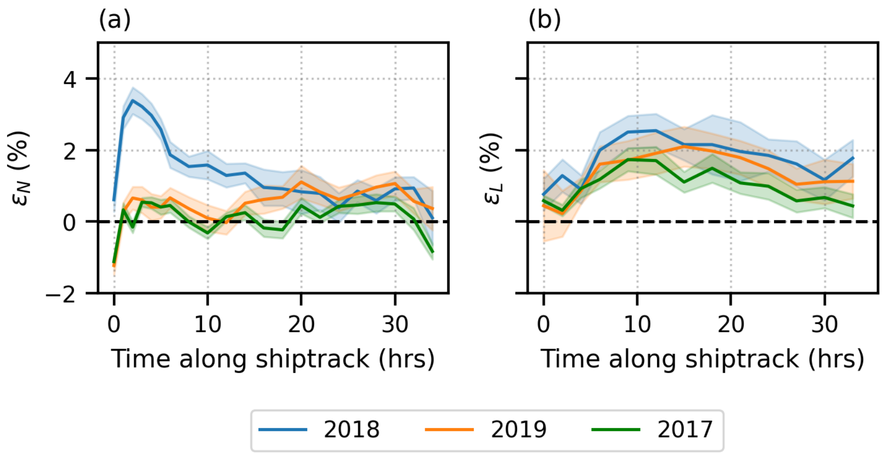

Figure S5. N_d and LWP responses for 2017 and 2019 null experiments, compared to the 2018 ship track data.

S4 Impact of year used for null experiment

In order to investigate the impact of the year used for the null experiment, we repeat our analyis using 2017 ERA5 and MODIS data. The resultant N_d and LWP responses are shown in Fig. S5. We see that the enhancement profiles are largely the same for the 2017 and 2019 null experiments. The mean absolute difference when averaged over the 36 hours is 0.5% for N_d and 0.3% for LWP. This suggests that the choice of year for the null experiment does not have a significant impact on the results of this study, yet will contribute to some uncertainty in the magnitude of the response, which will propagate through to the radiative forcing estimates.

Repeating our radiative forcing calculations, but instead using the 2017 null experiment to correct for the ship track bias, we obtain an estimate of the radiative forcing of -0.08 [-0.12,-0.07] Wm^{-2}. This does not exceed the uncertainty range of our quoted radiative forcing of -0.16 [-0.29,-0.07] Wm^{-2}, suggesting it is not the significantly important.

Whilst there are decisions to be made when choosing how to best represent the background meteorology in the null experiment, we find that the choice of year will not majorly impact the results of this study. Therefore, we choose to use the 2019 null experiment for the rest of results of this study.

S5 Reason for correlation between LWP and windspeed

We propose that the reason for these non-linear background gradients is due to correlations between LWP maxima and windspeeds. Ship track locations are a strong function of winds, and therefore are a strong function of weather systems and the location of fronts. We typically find that within ship track locations we can see an imprint of the winds, as demonstrated in Fig. S6a). Since ship track locations are often aligned with these weather systems (Fig. S6b), which themselves will consist of local maxima in LWP (Fig. S6c), when we consider the perpendicular-to-track gradient, we end up with our convex gradients. In Fig. S6b and c we demonstrate this for the ship tracks that occur on the 11th July 2018 in the South Atlantic.

Evidently, this is only one specific case study, but it demonstrates how ship track locations are not randomly oriented, and are often correlated to the winds of weather systems. Bands of high liquid water path in fronts, for example, can therefore be responsible for the non-linear background gradients that we see in our composite ship tracks.

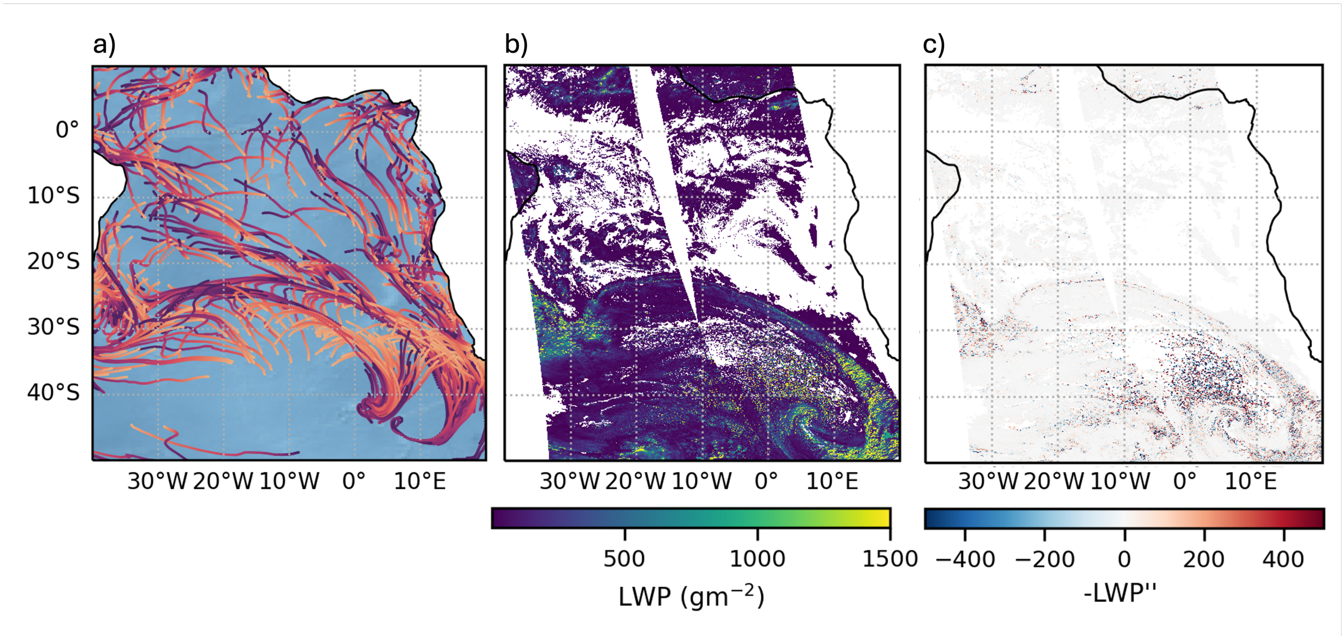

Figure S6. a) Ship track locations on 11th July 2018. Ship tracks can be seen to be very strongly aligned with weather systems. b) LWP and c) LWP maxima on 11th July 2018. Ship tracks are aligned with these maxima, and hence tend to have non linear background gradients.

References

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