Evaluating simulations of ship tracks in a km-scale model

Author Response

Anna Tippett, Paul R. Field, and Edward Gryspeerdt

We thank both reviewers, and the editors, for their helpful comments on this manuscript. We hope that this revised manuscript sufficiently alleviates any concerns about our methodology, and the interpretability of our results.

Referee #1

	Comment	**Response**
1	Figure 5: The diurnal variation in the ERA5 precipitation is profound and needs to be noted/discussed. Unfortunately, it opens a question as to how important is the diurnal variation of these MABL clouds on the simulations and analysis? For example, is the 15-hour ship track analysis period during the day, when the cloud is naturally thinning and precipitation can stop? And why don't we see a similarly strong diurnal variation in the UM-CASIM precipitation?	Thank you to the reviewer for this comment. The 12-hourly time slices in Fig. 5 were selected to give a broad overview of the agreements/disagreements between the UM-CASIM precipitation and ERA5/GPM without making the figure too big. Somewhat unfortunately, the 07-12 00Z slice we included gives the indication that the UM-CASIM simulation is not representing the same diurnal variation that is seen in ERA5. However, if we look across all time steps at the domain-wide mean surface precipitation, we see that UM-CASIM is reproducing the diurnal cycle. It is simply the colour scale and individual slices selected which give the indication that it isn't. To address this and avoid any confusion, we have updated Fig. 5 to include a panel which depicts the diurnal cycle (new Fig. 5 attached further down in the response). **Changes made** • Fig 5 modified to demonstrate the diurnal variation in precipitation in the model (see bottom of response)

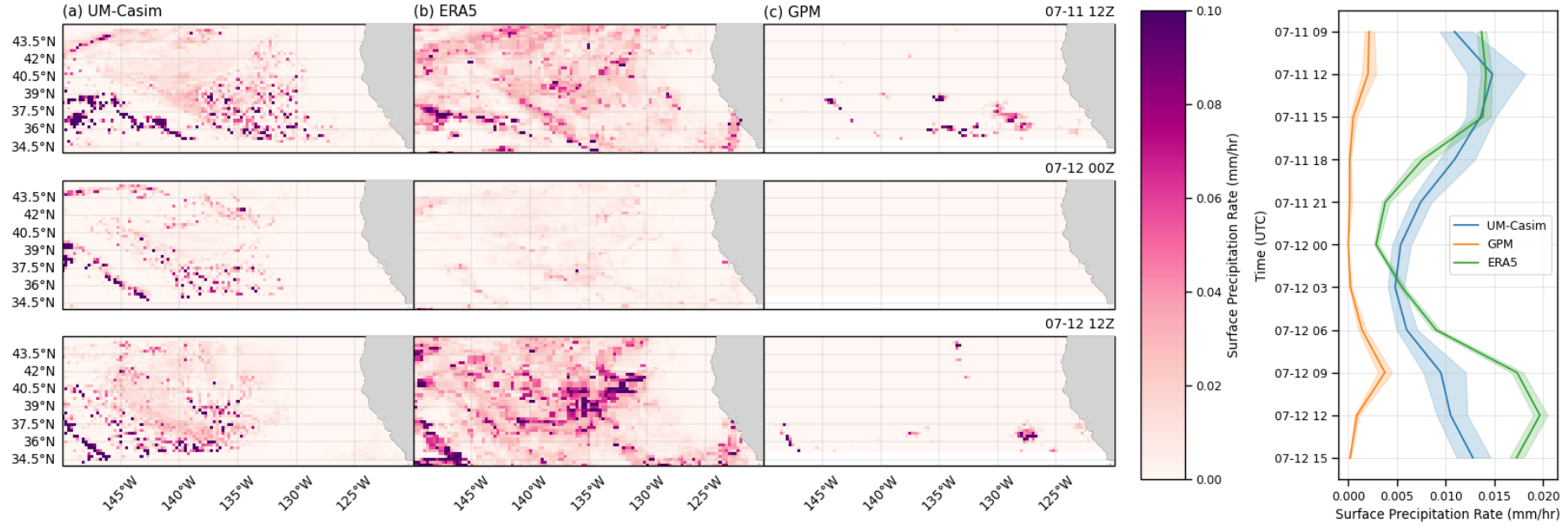
	Comment	Response
2	I recommend restructuring the model evaluation section so that the evaluation against physical observations (Figures 5, 6 and 7) occur before the 'evaluation' of control vs ships-control (Figure 4). While I am clearly biased in placing a greater importance on evaluation against physical observations, I also see this improving the flow of the paper with Figure 4 leading into section 3.3.1 (In track values).	We thank the reviewer for this suggestion and see their point about how Figure 4 could be useful if it appeared after Figures 5,6,7 since the right-hand column (ships-control) leads nicely on to Section 3.3.1. However, the left-hand column (control) is discussed more in the earlier sections, when evaluating the control against observations. We do agree that it would be nice to group all evaluation against observations together and present this first, the way in which we have structured our manuscript is more along the lines of evaluating the control (before the ships are put in) and then evaluating the ship tracks. If we were to move Fig. 4 later, we feel that the presentation of the control in the left-hand column would be out of place after current Fig.7, since current Fig. 7 contains the ships in it already. We believe that there is a certain element of subjectivity in a reader's preference for the flow of the manuscript, since the reviewer would prefer: 1. All observational evaluation of the model, including ship simulations 2. Results pertaining to the ship simulations Whereas we believe that the following structure reads better: 1. All evaluation of the model background state (is our model suitable for putting in the perturbations?) 2. Adding the ships and evaluation of these ship tracks against observations (how realistic are the ship tracks?) As such, we would prefer to keep the structure and ordering of sections as it is, however, we do appreciate the suggestion.

		Changes made
		N/A
	Comment	**Response**
3	As an optional suggestion, section 3.1 could/should be moved to an appendix. While this correction to the ARG scheme is clearly important, it is quite distinct from the key findings creating a digression in my eyes.	Thank you for this suggestion. We agree that whilst the findings with regards to the ARG scheme are important, they are distinct from the remainder of the findings of the paper. However, we worry that in an appendix they may be overlooked. These findings have been noted elsewhere, but not specifically in the context of modelling ship tracks – especially the impact in that tracks appear split. Therefore, we choose to keep section 3.1 in the main text, despite it being a slight digression.
		Changes made
		N/A
	Comment	**Response**
4	Table 1: If the model resolution is ~1.5 km, it's unnecessary to specify location to the nearest hundred meters.	Thank you for this comment, we have reduced the resolution of the quoted ship locations to the nearest 0.01º such that it is more appropriate for the resolution of the model.
		Changes made
		• Table 1: reduce precision of values to 2d.p.
	Comment	**Response**
5	Line 230: Please revise this sentence as the smoothing method has nothing to do with the precision of the estimation.	We have revised the sentence as detailed below such that it is correct.
		Changes made
		Line 259: • "To mitigate stochastic noise between model runs, we apply Gaussian smoothing to the model fields (smoothing with a Gaussian kernel with standard deviation of 0.75 km) before calculating the percentage difference to obtain enhancements in Nd and LWP (ϵN and ϵL). This approach allows for an ~~precise~~ estimation of aerosol-induced changes while minimising the influence of small-scale variability in between model runs."

	Comment	Response
6	Line 261: typo	Thank you for identifying this typo. **Changes made** Line 288: “we obtain aerosol number concentrations within the ship track of roughly 20,000 cm-3”
	Comment	**Response**
7	Line 264: typo – shiptrack	Thank you for spotting this typo. **Changes made** Line 292: “unphysical split-ship track”
	Comment	**Response**
8	Line 300: Since there is no product for ‘12-hourly instantaneous rain rate’, I assume this is actually the average rain rate over 12 hours. Please rephrase.	Our apologies for the confusion. This is in fact the large-scale rain rate (mean in the grid box) at the given time (we show at 12 hourly intervals in this case). The sentence has been rephrased to make this clearer. **Changes made** Line 328: • Remove: “~~12-hourly instantaneous surface rain rates are shown for UM-CASIM control simulation (regridded to the same 0.25º resolution as ERA5), and compared against ERA5 and GPM-IMERG surface rain rates~~” • Add: “Surface rain rates are shown for UM-CASIM control simulation (regridded to the same 0.25º resolution as ERA5) at 12 hourly intervals, and compared against ERA5 and GPM-IMERG large scale surface rain rates at the same time.
	Comment	**Response**
9	Line 320: While I accept this speculation for the Eastern Pacific blob, I am unconvinced for the Central Pacific blob. The satellite imagery (NASA	Thank you for this comment. We modify the text as detailed below to address this slight difference between the two regions, and indicate that there are greater discrepances in the Central Pacific region. **Changes made**

worldview) suggests differences in the cloud structure/field from the UM-CASIM simulation.	Line 348: • "This is largely in line with that seen in satellite observations (Fig. 7a,c), with there been better agreement in the Eastern Pacific, and more noticeable differences in cloud structure in the Central Pacific. ~~however~~ We note that two large sources of cloud droplets are missing from our model simulation. This is likely due to our initialisation from a constant aerosol field, and therefore we are missing these sources of aerosol in our simulation. Future work in initialising from a more realistic aerosol field would be beneficial."

New Fig 5 with diurnal cycle:



Referee #2

We thank the reviewer for these comments.

An important clarification should be made with regards to the simplified aerosol configuration – it is only our initialised field which is solely accumulation mode aerosol. Emissions (both natural and anthropogenic) are still enabled and therefore there will still be some aerosol in other modes. Therefore, our aerosol scheme still contains the all the same microphysical processes, however the concentrations will be dominated by the accumulation mode. We clarify this further in the manuscript. This is evidently not a perfect representation of reality, by any means, however the focus of this study is primarily to investigate the cloud adjustments following a cloud droplet number concentration perturbation. Specifically, since we are not altering the concentrations of these other modes when adding our ship emissions, then when we calculate our deltas between *ships* and *control* simulations, any inclusion of other modes will cancel out (assuming there is not significant transport between modes). We argue that by achieving a "realistic" cloud droplet number perturbation we can investigate the model representation of the processes involved in the subsequent cloud adjustments, since these will be mainly a function of the cloud droplet number concentration.

We acknowledge that ignoring much of the contribution from other chemical components to other aerosol size modes remains a significant assumption, and in our previous response we attempted to address potential impacts of this. In this revised manuscript we attempt to address it even further. Specifically, we discuss how the neglection of different components might impact our representation of the background cloud droplet field.

Overall, we frame our evaluation of the aerosol in the context of the background Nd concentration - this is for two reasons. Firstly, this background Nd concentration is important for the determination of the enhancement in the cloud properties inside the ship tracks. How the cloud came to obtain that cloud droplet number concentration (i.e. from which aerosol species) is not a focus of this work. Secondly, and more logistically, we cannot obtain output for these simulations other than the sulphate mass mixing ratio or the accumulation mode number concentration, therefore a more in-depth evaluation of model AOD or CCN is not possible.

Detailed responses to each individual comment can be found below, with some comments combined where they have been addressed in the same response.

	Comment	Response
1	"Sufficient information has been provided about CASIM, however details on GLOMAP and the aerosol configuration are still very thin. The revised manuscript states that 'Non-ship aerosol sources are described in Mann et al. (2010)...'. While referring to Mann et al. (2010) would tell you which types of aerosol sources the original version of GLOMAP is using, it conveys no information about what emissions inventories are used in the current study. For a study of aerosol interactions, basic information about the aerosol inventories is more than a trivial detail and should be included. There is no information on how secondary aerosol formation is handled."	Thank you for these comments, and we apologise for the omission of key information about the non-ship aerosols included within the simulation. We have updated the manuscript as detailed below to further expand which emissions inventories are used within the model, and how secondary aerosol formation is handled. **Changes made** Line 175: • Delete: "~~Non-ship aerosol sources are described in Mann et al. (2010), with emissions from marine phytoplankton, SO2 from volcanoes, fires, and industrial sources. These sources can exist across different aerosol modes (not just the accumulation mode).~~" • Add: "Whilst we only consider our initial aerosol field to be in the accumulation mode, there are still background emissions into other modes. The different types of non-ship aerosol sources are described in Mann et al. (2010), with emissions from marine phytoplankton, SO2 from volcanoes, fires, and industrial sources. In the simulations of our study, we use anthropogenic emissions from the Coupled Model Intercomparison Project (CMIP6) inventory (Feng et al., 2020). The emissions are at a low resolution of ≈135 km (Gordon et al., 2023). Natural emissions of sea salt, primary marine organic aerosol, and dust are parameterized as described in Mulcahy et al. (2020) and Gordon et al. (2020). The emissions of sea spray, sulphate and carbonaceous aerosols are allocated to modes according to their size distribution (Mulcahy et al., 2020), whereas biofuel, fossil fuel, and biomass burning emissions are emitted into the Aitken insoluble mode and then undergo "ageing" (Mann et al., 2010) into the Aitken mode in certain conditions. Secondary organic aerosol (SOA) are produced

		from the oxidation of monoterpenes (Mulcahy et al., 2020). Further details on other trace gas and aerosol emissions within this regional model set up are described in Gordon et al. (2023). These emissions can enter different aerosol size modes, not just the accumulation mode that the simulation is initialised from, however it is the accumulation mode aerosol concentrations that will dominate."
	Comment	**Response**
2	"There is no information on how [...] aerosol microphysics [is handled] in the modified aerosol configuration There is no information on the direct effect calculation (if any) that is used, and in particular how it has been modified in light of the modified aerosol configuration."	As requested, we provide further details on the handling of aerosol microphysics within GLOMAP-mode within our Section 2.2 ("Model Configuration"), including how radiation is treated. Whilst we describe how the direct effect is calculated; in the context of this study, it is not of great significance since we are considering cloudy skies and are not concerned with the direct effect of aerosols. The aims of this study are not to calculate the radiative impact of aerosols, but instead to investigate the cloud adjustments following a cloud droplet number concentration perturbation. In light of this, we provide details on how the aerosol microphysics relates to cloud droplet formation in this simplified configuration, and discuss the implications of our assumptions in the paper discussion. **Changes made** • Line 149: "We couple CASIM to the double moment modal Global Model of Aerosol Processes aerosol microphysics scheme (GLOMAP-mode; Mann et al., 2010), within United Kingdom Chemistry and Aerosols (UKCA) sub-model, where aerosols are represented by five log-normal modes. These are the nucleation, Aitken, accumulation, coarse, and "Aitken insoluble" modes. Both the number and mass of each of the four chemical components (sulphate, sea salt, black carbon, and organic carbon) are prognosed in this double moment

scheme. Black carbon cannot enter the nucleation mode, and sea salt cannot enter either the nucleation or Aitken modes. Dust is represented separately within the CLASSIC binned sectional scheme (Woodward, 2001). GLOMAP-mode simulates aerosol microphysical processes such as the nucleation of new particles, coagulation of particles, condensation, and cloud processing (Mann et al., 2010). Particles can grow through condensational growth or coagulation between particles, and is represented by an increase in particle diameter, which can move particles into a greater size mode. Particles in soluble modes can also absorb atmospheric water and undergo hygroscopic growth (Yoshioka et al., 2025)."

- Line 159: "Coupling between GLOMAP-mode and CASIM allows for aerosol mass and number concentrations of the Aitken, accumulation, and coarse aerosol modes to be passed into the CASIM activation scheme for the production cloud droplets (Gordon et al., 2020), which is parametrised by Abdul-Razzak and Ghan (ARG; 2000). Autoconversion and accretion rates from CASIM are summed and passed back into GLOMAP-mode to calculate the removal of aerosol (that are inside droplets) by rain. Rain rates also determine the removal of aerosol through impaction scavenging. GLOMAP-mode also uses the liquid water content from CASIM to calculate the rate of conversion of sulphur dioxide into sulphate inside cloud droplets (Gordon et al., 2020). Our simulations are coupled to the standard radiative transfer scheme in the UM (using the RADAER module; Bellouin et al., 2013) in order to calculate the aerosol radiative effects, however the direct radiative effect of aerosols from shipping is not the main focus of this study."

- Line 190: add “This assumption is evidently a significant simplification to our aerosol configuration, as the accumulation mode will dominate the aerosol concentrations, with the concentrations of other modes only impacted by the natural and anthropogenic emissions described above. We discuss the potential consequences of this in Section 4.1.2.”

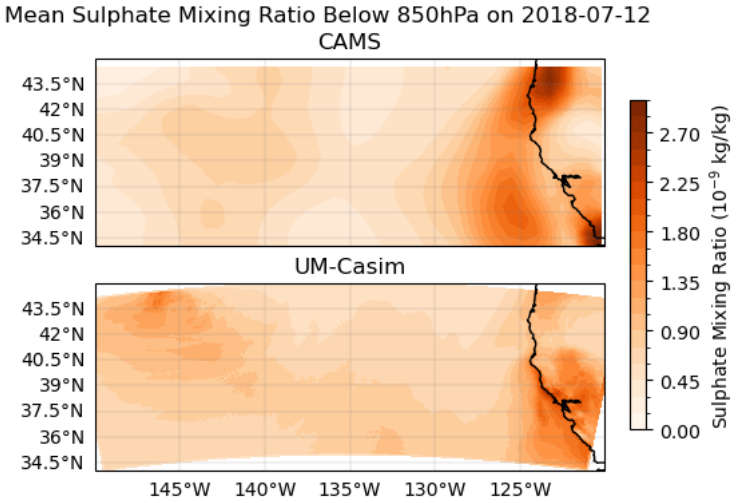
- Line 486:
    - Remove “In this work, we only consider aerosols in the accumulation mode, and neglect other aerosol size modes such as sea salt and organic matter. These other modes have different hydroscopicities, which can affect cloud droplet formation and the initiation of precipitation. For example, sea salt can modulate the activation of sulphate nuclei into cloud droplets (Fossum et al., 2020), therefore inclusion of even small concentrations of sea salt aerosol may reduce Nd concentrations. McCoy et al. (2018) also found that increasing sea salt concentrations limits Nd due to reduction in supersaturation by the larger sea salt CCN. This effect occurs because of the different hydroscopicity of sea salt, but also its larger size, making it an effective CCN. The neglecting of other aerosol modes with different hydroscopicities should not significantly impact cloud droplet number concentrations or initiation of precipitation, however the neglecting of aerosols with different sizes may impact our analysis, since the size of the aerosol mode remains the more important factor for cloud nucleating ability of aerosol particles (Dusek et al., 2006). Future work with a more comprehensive aerosol configuration would be beneficial in order to investigate the impact of

different aerosol size modes on cloud droplet activation in ship tracks."

- Add "In this work, our simulations are initialised from a simplified aerosol field of solely accumulation mode aerosol. This produces realistic accumulation mode aerosol, but underestimates aerosol concentrations in the Aitken or coarse modes (since these will only be contributed to by the background emissions detailed in Section 2.2). An evaluation of the sulphate mass mixing ratio is provided in the Supplement (Fig. S3), and is found to only have small spatial differences to CAMS reanalysis. However, neglecting other aerosol components might impact the formation of cloud droplets and the initiation of precipitation in this work (although we find that the precipitation representation is reasonable; Fig. 5). These other aerosol components, such as organic matter and sea salt, which are likely to be present in this case (Fig. S4), will have both different hydroscopicities and different sizes, which can affect cloud droplet formation and the initiation of precipitation. For example, sea salt can modulate the activation of sulphate nuclei into cloud droplets (Fossum et al., 2020), therefore inclusion of even small concentrations of sea salt aerosol may reduce Nd concentrations. McCoy et al. (2018) also found that increasing sea salt concentrations limits Nd due to reduction in supersaturation by the larger sea salt CCN. This effect occurs because of the different hydroscopicity of sea salt, but also its larger size, making it an effective CCN. This neglecting of other aerosol components with different hydroscopicities should not significantly impact cloud droplet number concentrations or initiation of precipitation, however the neglecting of aerosols with different sizes may impact our analysis, since the size of

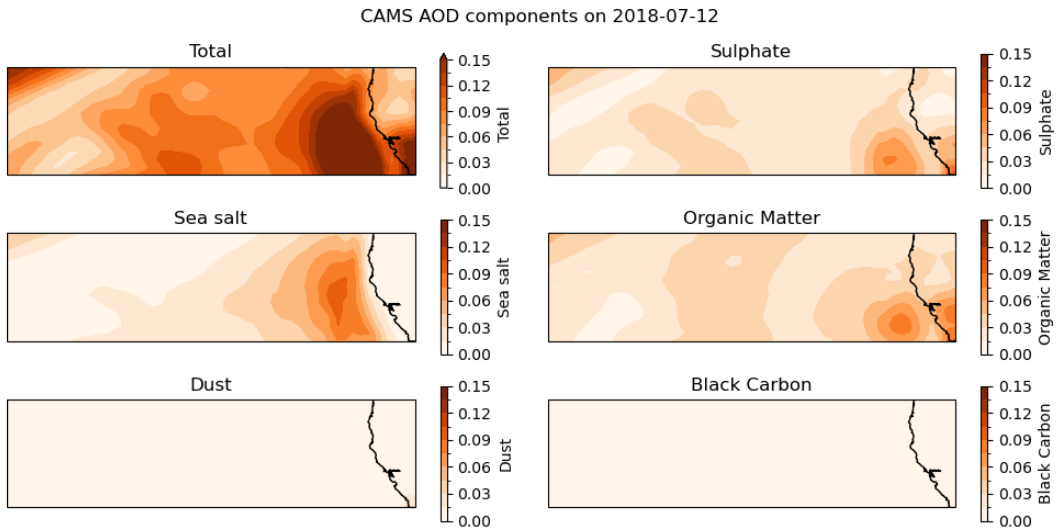
		the aerosol mode remains the more important factor for cloud nucleating ability of aerosol particles (Dusek et al., 2006). Despite this, we find that our background cloud droplet number concentrations in our simulation are within 15 cm−3 between UM-CASIM and MODIS observations, with our model only slightly underestimating background droplet number concentrations. For the purposes of this study, the main requirement of our simplified aerosol configuration is to produce a realistic background cloud droplet field which can then be perturbed by extreme ship aerosol emissions, so the model representation of the subsequent adjustments can be investigated. Whilst there may be some slight inaccuracy in our initial background Nd field from neglecting other aerosol components with other size modes, this is unlikely to be the cause of the large discrepancies in the lifetime of the LWP response in the ship tracks between observations and model. Future work with a more comprehensive aerosol configuration would be beneficial in order to reduce any uncertainty in the interactions between different aerosol size modes and their impacts on cloud droplet activation in ship tracks."
	Comment	**Response**
3	There is no aerosol evaluation. The standard GLOMAP configuration has been extensively evaluated for aerosol number, mass, and AOD, but those evaluations are not relevant here. In introducing an entirely new aerosol configuration,	We argue that if our background cloud droplet number concentrations are accurate, then our simplified aerosol configuration is sufficient for the purposes of this study. Nevertheless, we present some evaluation of the pertinent aerosols and the potential impacts on our results.

I would expect to see at least an evaluation of CCN and AOD in the environment where the model is being used.



Investigating how the daily mean sulphate mixing ratio below 850hPa compares between our model simulation and CAMS, we see a good match in magnitude with some slight spatial discrepancies. The sulphate mass mixing ratio is too great in the Central Pacific region of the domain, and perhaps not great enough near the coast. In general, however, the initialisation from a constant field of sulphate aerosol manages to match well with the reanalysis product after 24 hours of initialisation.

The main concern of the reviewer, however, is with neglecting other aerosol components. We investigate the CAMS reanalysis AOD contributions from different components to determine how valid this neglection is.



Whilst the sulphate is a major contributor to the AOD, other components such as sea salt and organic matter provide equally important contributions to the AOD, specifically near the coast. Ignoring these components will impact the background cloud droplet formation, and a more in-depth exploration of the potential consequences (and the impact on our results) of this has been added to the discussion.

These two Figures have been added to the supplementary information in a section titled “Aerosol Evaluation”.

Ultimately, for the results and conclusions of this study, we focus on the cloud processes which occur within the ship tracks after a significant Nd perturbation. The main requirements of our simplified aerosol configuration used in this study are to ensure the initial background cloud droplet number concentration is accurate, and therefore the cloud is realistically susceptible to the ship perturbation. Therefore, the more important evaluation is the

evaluation of the background Nd that is discussed towards the end of Section 3.2 and throughout the Results.

Changes made

- New Figures S3 and S4 in new Section 3 ("Aerosol Evaluation") in the Supplement.
- Further discussion in discussion Section 4.1.2:
  - Line 492: "In this work, our simulations are initialised from a simplified aerosol field of solely accumulation mode aerosol. This produces realistic accumulation mode aerosol, but underestimates aerosol concentrations in the Aitken or coarse modes (since these will only be contributed to by the background emissions detailed in Section 2.2). An evaluation of the sulphate mass mixing ratio is provided in the Supplement (Fig. S3), and is found to only have small spatial differences to CAMS reanalysis. However, neglecting other aerosol components might impact the formation of cloud droplets and the initiation of precipitation in this work (although we find that the precipitation representation is reasonable; Fig. 5). These other aerosol components, such as organic matter and sea salt, which are likely to be present in this case (Fig. S4), will have both different hydroscopicities and different sizes, which can affect cloud droplet formation and the initiation of precipitation."
- Line 360: "Due to the missing high Nd region in the Central Pacific part of the domain, ship tracks are only considered up to 15 hours along their length, since times longer than this are within this missing high Nd region and therefore accurate comparison between model and observations is not possible due to differences in the background. Before 15 hours, the modelled background Nd is within 15cm−3 of the

		MODIS background, indicating that the simplified aerosol configuration reproduces the background Nd to sufficient accuracy for this work."
	Comment	**Response**
4	The new Section 4.1.2 contains the line 'neglect other aerosol size modes such as sea salt and organic matter'. This statement shows a fundamental non-understanding of GLOMAP and possibly aerosol in general. Sea salt and organic matter do not represent size modes, but are instead components.	Amended. **Changes made** • Paragraph beginning Line 486: "In this work, our simulations are initialised from a simplified aerosol field of solely accumulation mode aerosol. This produces realistic accumulation mode aerosol, but underestimates aerosol concentrations in the Aitken or coarse modes (since these will only be contributed to by the background emissions detailed in Section 2.2)..."
	Comment	**Response**
5	My opinion is that the reader has not been presented with sufficient information to understand and evaluate the methodology, raising questions about the suitability of the approach. Without confidence in the methodology, the reader cannot have confidence in the results nor conclusions. I cannot recommend publication of this manuscript, as my concerns over the suitability of the aerosol configuration have not been dispelled. Additionally, the authors seem to have an insufficient understanding of the aerosol scheme, a key component of the study they present.	We hope that within this response we have been able to alleviate your concerns about the suitability of our methodology to investigate the cloud response after a perturbation to the cloud droplet number concentration. We acknowledge the severe limitation of this approach in accurately representing the partitioning of aerosol species across size modes, however with the aims of this study being to investigate the model representation of the cloud adjustments (which are a function of the droplet number concentration), as long as our initial cloud droplet number concentrations are realistic, then our results and conclusions remain valid. We comprehensively address the uncertainties introduced by the assumptions made within the methodology, and the impact these may have on our results. Ultimately, within this study we reveal that there are major issues with the representation of LWP adjustments due to severe precipitation suppression

	and wet scavenging feedback which are unlikely to be a result of the simplified aerosol initial field.
	Changes made
	N/A