Response to Reviewer 1
Legend: Reviewer comments - black, author responses - blue, manuscript text changes - green

Lucas et al. present an interesting study in which they use Langevin particle modeling applied to realistic LES outputs to investigate the importance of the emission spreading rate of sprayers (ships) for Twomey forcing. They further examine the influence of variability in aerosol properties, including the number of sprayers and their motion type, aerosol decay timescales and age, concentration bins, and background aerosol concentrations, as well as meteorological conditions. Their results show that the velocity and type of sprayer motion have little influence on Twomey forcing. Assuming that cloud adjustments are relatively small, they further demonstrate that the effect of the spreading rate on Twomey forcing is limited, with the forcing being strongly controlled by aerosol lifetime. Their findings suggest that the common assumption in GCMs of an infinitely fast spreading rate could result in a 10–200% overestimation of Twomey forcing. Overall, I found the manuscript to be well written, and the methodology to be sound. I have only a few minor comments that can be addressed easily by the authors.

We would like to thank the reviewer for their time, positive feedback, and comments that will help improve the clarity of our final draft.

Minor comments:
1. Line 43: Goren et al. (2025) also attributed the co-variability to two factors: (1) large-scale meteorological conditions, which influence cloud properties such as cloud liquid water path (LWP) and cloud droplet number concentration (Nd), causing these variables to covary simultaneously and inversely; and (2) microphysical processes associated with cloud development, during which an increase in LWP is generally accompanied by a decrease in Nd. Goren et al. (2025): Co-variability drives the inverted-V sensitivity between liquid water path and droplet concentrations, Atmos. Chem. Phys., 25, 3413–3423. https://doi.org/10.5194/acp-25-3413-2025

We have added a citation to the Goren et al. (2025) study in the following sentence:

"When trying to constrain cloud adjustments from observations, separating the confounding influence of meteorological variability from the cloud responses to aerosols represents a major challenge (Goren et al., 2025; Gryspeerdt et al., 2016; Stevens and Feingold, 2009)."

2. Line 45: By constraining cloud morphology using MODIS observations, Goren et al. (2026) reported contrasting results, finding that LWP adjustments nearly offset the Twomey forcing. Goren et al (2026): Beyond discrete stratocumulus regimes: a ternary continuum of morphology reveals within-regime variability in cloud susceptibilities, Atmos. Chem. Phys., 26, 7193–7206. https://doi.org/10.5194/acp-26-7193-2026

We have edited the following excerpt to account for the Goren et al. (2026) results which incorporate cloud morphology as an additional variable:

"After attempting to control for meteorological variability, several studies find that radiative forcing changes associated with cloud adjustments are relatively weak compared to the Twomey forcing (Tippett et al., 2024; Diamond et al., 2020; Christensen et al., 2026). In contrast, Goren et al. (2026) found that after accounting for cloud morphology, Twomey forcing and cloud adjustments can offset one another, highlighting the potential importance of targeting MCB to focus on the most susceptible cloud regimes."

3. Line 75–76: Are there any references demonstrating that these 17 LES simulations are in close agreement with the observations. Or the term "observations" is used loosely here to represent general shallow marine clouds. Please clarify.

The term "observations" in this statement refers mainly to the SW CRE measurements from CERES, which are discussed later on in Section 2.2. But more broadly speaking, you are correct that the term is used somewhat loosely to encapsulate the general evolution of the clouds along the northeast Pacific trajectories, which aligns well with both CSET observations (Mohrmann et al., 2019; Bretherton et al., 2019) and previous satellite analyses of diurnal stratocumulus behavior (Wood et al., 2002; Wood and Hartmann, 2006; Burleyson and Yuter, 2015).

To clarify this, we have altered the following sentence:
"The following analysis is restricted to a subset of the full LES library (54 simulations), focusing on the cloudy LES cases (17 simulations with median cloud fraction >50%) that most closely match satellite observations of reflected shortwave energy and represent likely candidate environments for MCB."

4. Line 76: The abbreviation LPM appears for the first time here without being defined.

Thank you for catching that. We have added the abbreviation to the following sentence:

"The horizontal spreading of aerosols injected from a point source into the marine boundary layer can be reasonably modeled by Langevin particle models (LPMs) (Stohl et al., 2005; McMichael et al., 2024),…"

5. Line 118: Could the authors also describe how Nd is derived from the CERES measurements? In addition, how is Na computed from the MERRA-2 data? A brief description or an appropriate reference would be sufficient.

CERES Nd is calculated based on Eq. (7) in Painemal and Zuidema (2011) from cloud optical depth and effective radius. MERRA-2 Na is calculated from the mass mixing ratio of aerosol species, assuming appropriate particle size distributions, following the methodology described in Appendix A of Erfani et al. (2022).

Reference: Painemal, D., and P. Zuidema, 2011: Assessment of MODIS cloud effective radius and optical thickness retrievals over the Southeast Pacific with VOCALS-REx in situ measurements. *J. Geophys. Res.*, **116**, D24206, https://doi.org/10.1029/2011JD016155.

We have added the following sentence to point to the relevant papers describing the methodology:

"Details on how CERES Nd is calculated based on measurements of cloud optical depth and effective radius are given in Painemal and Zuidema (2011). MERRA-2 Na is calculated from the mass mixing ratios of aerosol species, following the methodology described in Appendix A of Erfani et al. (2022)."

6. Line 263: This assumption is inconsistent with Equation (2), where only 80% of aerosol particles, rather than 100%, are assumed to activate as cloud droplets.

You are correct to point out that the two values are different, but they serve slightly different purposes. The 80% activation percentage in the CERES-corrected Na estimate is informed by observations, with the primary purpose being to accurately initialize the aerosol conditions in the LES. In contrast, the 100% activation rate in the particle model is used to provide an upper bound on the potential impact of plume spreading. Adding in differences in activation efficiency complicates the causal link between spreading rates and Twomey forcing, but it is certainly a relevant question that we are investigating with ongoing work.

We mention the rationale for 100% activation on line 477:

"Assuming 100% aerosol activation simplifies the analysis and provides an upper bound on potential spreading rate-driven Twomey forcing differences."

7. Line 272: Please define NAc

Thank you for finding this. We have added the following:

"…and accumulation mode aerosol (NAc)"

8. Figure 3: Please define what the top panel in each panel group represents in the figure caption.

We added a short description of what the top panel represents:

"The top panels show each individual LES simulation, while the bottom panels show the ensemble median (black line) and IQR (green shaded region)."

9. Line 391 and Figure 10 (also in other instances): Is the twomey forcing calculated for these simulations "global"?

That is correct for Figures 7, 9, 10, and 12. However, Figures 13 and 14 show the domain-mean Twomey forcing to quantify the grid box-level errors in a GCM, but these figures have been moved to the Supplement in an effort to shorten the manuscript (as suggested by Reviewer 2).

10. Section 4: Could the authors also comment on the role of cloud morphology and cell size on the spreading rate and Twomey forcing relationship?

The interplay between cloud fraction/morphology, cell size, spreading rates, and Twomey forcing is certainly worth discussing, as it is related to one of the main results of the paper. Day 2 conditions trend toward more broken clouds on average, along with deeper, more decoupled boundary layers with larger mesoscale cell sizes. The decoupling/cell size (more organized, stable boundary layer generally results in smaller dissipation rates) and velocity variance increases act together to increase the relaxation timescale (T_L) by nearly a factor of 2. The increase in the relaxation timescale will increase the spreading rate, given a constant background TKE, but this increase in the spreading rate is not shown to impact the Twomey forcing when we fix the cloud fraction (susceptibility analysis in Figure 8). Using Day 2 turbulence with Day 1 cloud morphology, background aerosol, and boundary layer depth does not change the Twomey forcing even though the underlying aerosol concentration distribution changes, meaning that the spreading rate differences, while substantial, don't translate to major differences in Twomey forcing. An important wrinkle to this relationship is that we have only focused on horizontal spreading rates in the current study. The deeper, more decoupled boundary layers may have a more difficult time effectively transporting aerosol to the cloud layer, violating our well-mixed assumption, but this is something we are in the process of exploring.

We want to more clearly state the result that Day 1 and Day 2 spreading rates are quite different, but when we fix the remaining variables (cloud morphology, boundary layer depth, background aerosol), the spreading rate differences do not translate to differences in Twomey forcing, despite shifting of the underlying aerosol concentration distributions.

"Day 1 and Day 2 spreading rate regimes differ by over 2 km hr^{-1} at times, with Day 2 relaxation timescales (T_L) that are nearly a factor of 2 larger than those on Day 1. These longer relaxation timescales are associated with dissipation rate decreases related to larger mesoscale cells, more decoupled boundary layers, and modest increases in velocity variances. To isolate the effect of turbulence-driven spreading differences on Twomey forcing, we repeated the Day 1 LPM simulations using the Day 2 turbulence characteristics while maintaining the Day 1 cloud morphology, boundary-layer depth, mean wind, and background aerosol concentration conditions. Despite the substantially faster spreading associated with the Day 2 turbulence, the resulting Twomey forcing changes are smaller than 1\%. Therefore, in these simulations, the differences in turbulence-driven plume spreading alone do not produce appreciable changes in

Twomey forcing, even though the underlying aerosol concentration distributions are impacted by the spreading rate differences.”