Muted aerosol response in polluted deep convection: a Lagrangian approach in a TRACER case study

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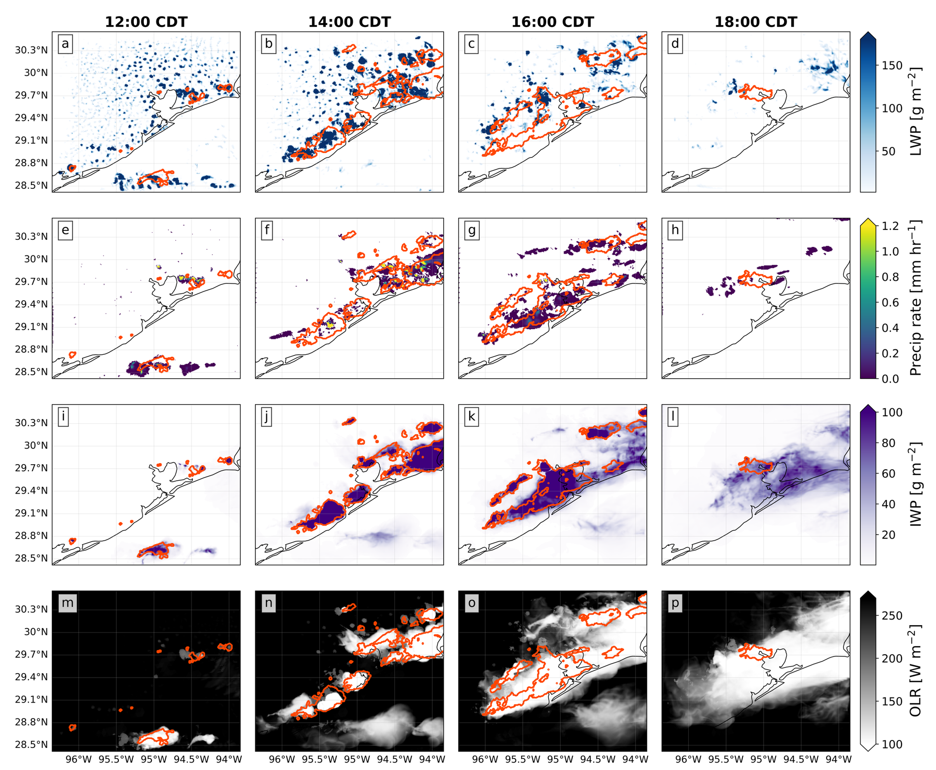
Motivation

Aerosol-cloud interactions are highly uncertain, affecting weather and climate prediction. While aerosols as CCN influence warm clouds, their impact on deep convective clouds (DCCs) is less understood. DCCs are crucial for redistributing heat, moisture, and momentum, impacting regional and global weather with an uncertain radiative effect. Studies have examined aerosol effects across clean-to-polluted cases, but high baseline aerosol regimes are underexplored.

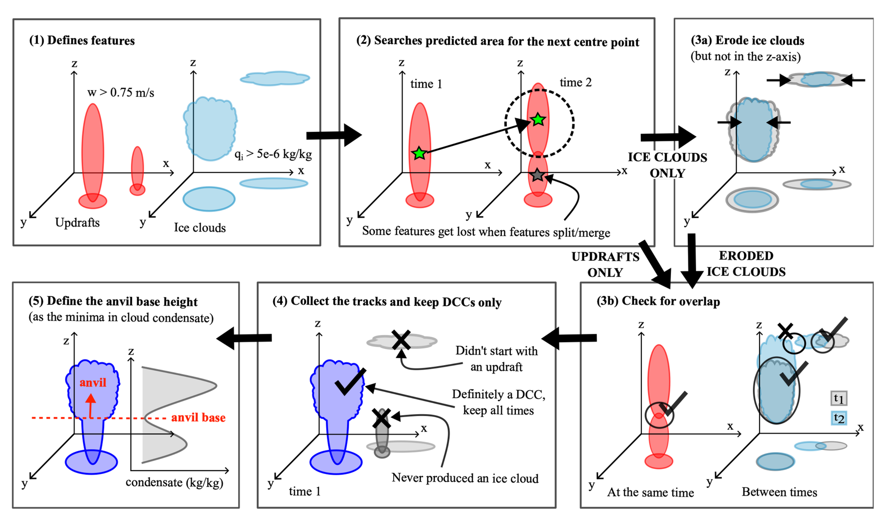
→ **In a polluted regime, how deep into the convective microphysical chain do aerosol perturbations propagate?**

Methods

- A sea-breeze driven deep convective event over **Houston**, Texas (17.06.22) using **ICON-HAM-lite** [1], with **~0.6 km** grid spacing. Three simulations follow the **TRACER-MIP** protocol [2]: a reference run (using **CAMS**) and two perturbation runs scaled by factors of **0.3 and 3**.

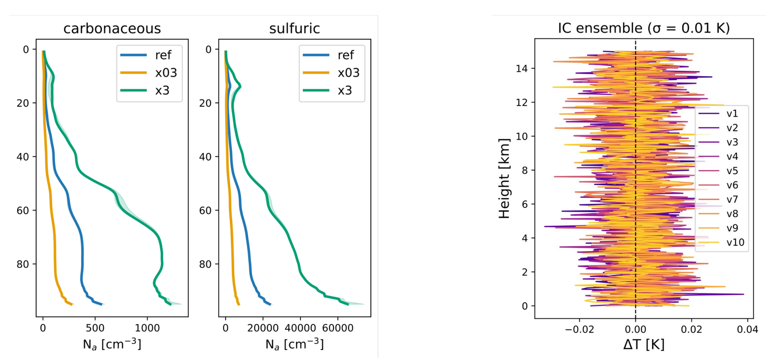


- Lagrangian tracking using 3D+time **tobac** [3,4]. Thresholds of **1 m s⁻¹** vertical velocity and **0.5 g kg⁻¹** total frozen condensate (~marking the onset of freezing).



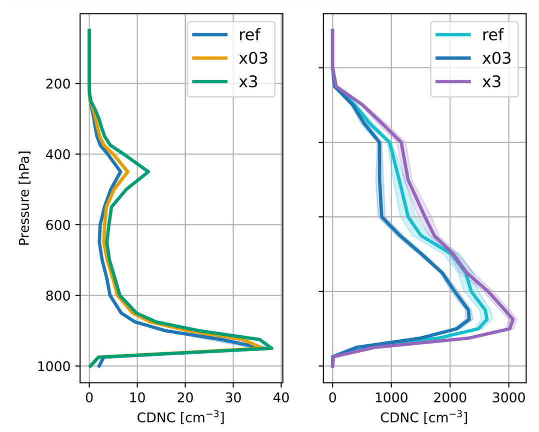
Ritman et al., 2026 [4]

- Each case is run with **10 ensemble members**, generated by adding temperature perturbations drawn from a Gaussian distribution (**σ = 0.01 K**).

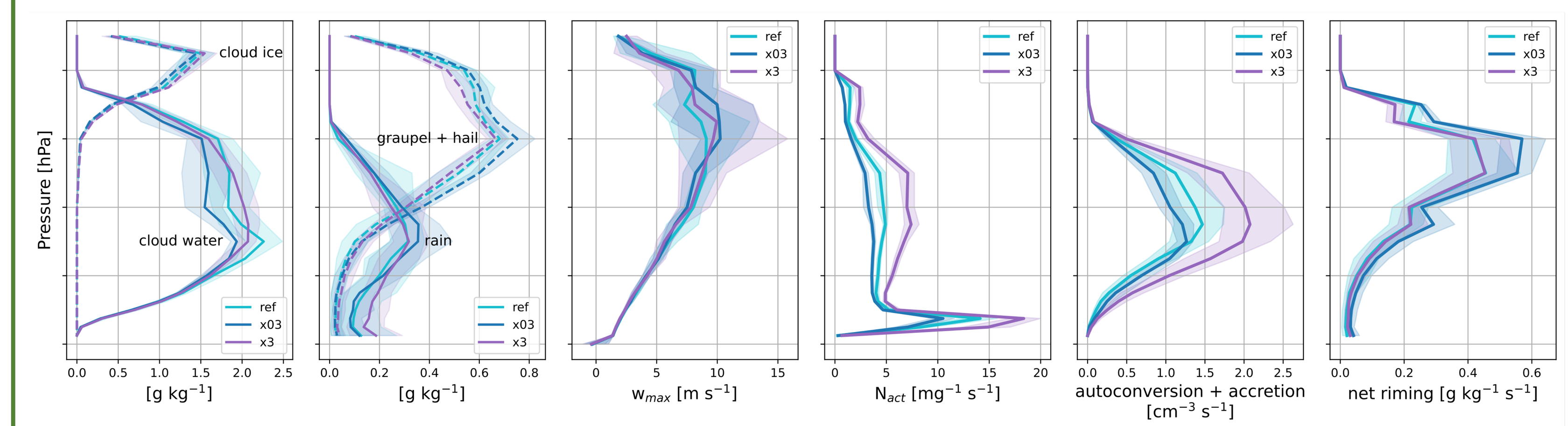


Results

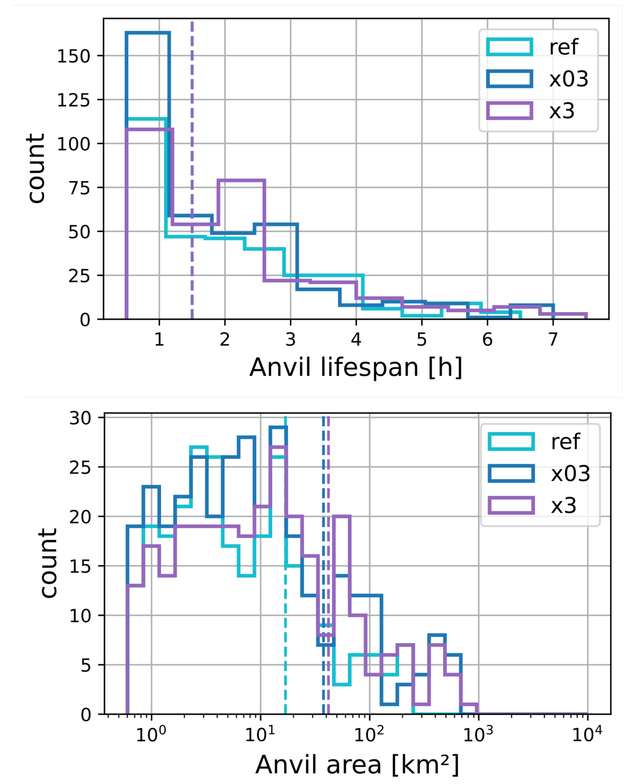
- A 9-fold aerosol perturbation yields only a 1.5-fold difference in CDNC within tracked convective systems, with no signal in the domain mean.



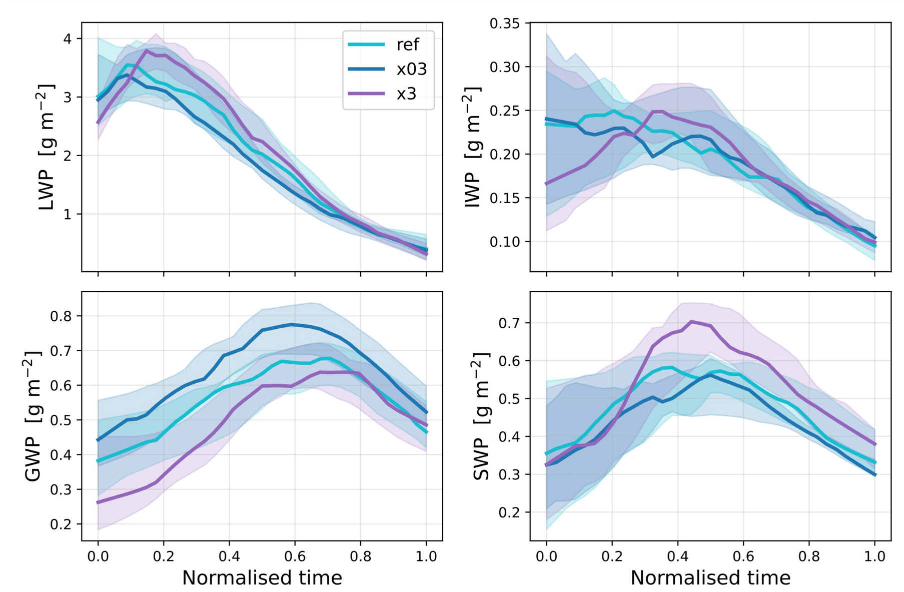
- Bulk cloud properties are indistinguishable across cases within ensemble noise.
- The aerosol fingerprint is confined to early microphysical processes: droplet activation and autoconversion (scale with CDNC), and riming (inverse to CDNC).
- Whether the similar ratio of activation to autoconversion across cases implies similar conversion efficiency remains an open question.



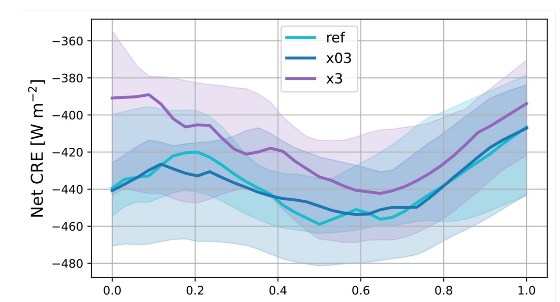
- Anvil morphology is broadly similar across cases, though the most polluted case shows a suggestive shift toward fewer, larger, longer-lived anvils (consistent with riming suppression reducing efficient precipitation and allowing more condensate to spread laterally).



- Normalised lifecycle composites show a robust graupel difference, consistent with the riming signal. Liquid, ice, and snow water paths are within noise, though a possible delay in their peak is suggested for the most polluted case, which may co-occur with the observed differences in net radiative cooling. The mechanism linking these remains unclear.



- The non-monotonic relationship between aerosol loading and net cooling suggests that the aerosol perturbation does not propagate coherently to anvil-scale radiative effects. By the time the signal traverses the microphysical chain, it is sufficiently attenuated that anvil geometry and internal variability become the dominant controls on CRE.



ref	x0.3	x3
5.19 W m⁻²	7.51 W m⁻²	6.99 W m⁻²

Summary

Within a highly polluted regime, aerosol perturbations are strongly attenuated at every step:

- Aerosol 9-fold ⟶ CDNC 1.5-fold ⟶ no impact on cloud profiles
- However, signals confined to **activation**, **autoconversion**, and **riming**.
- most polluted case: **longer anvil lifespans** and **delay in anvil development** (near ensemble noise!)

Conclusions and outlook

The aerosol perturbation is largely absorbed within early microphysical processes and does not propagate into convective dynamics, consistent with a buffered, regime-dependent sensitivity.

This method is essential to recover these signals and provides a transferable framework for aerosol-cloud interaction studies in non-idealised, polluted environments.

Acknowledgments

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References

1. Weiss, P., Herbert, R., and Stier, P.: ICON-HAM-lite 1.0: simulating the Earth system with interactive aerosols at kilometer scales, Geosci. Model Dev., 18, 3877–3894, https://doi.org/10.5194/gmd-18-3877-2025, 2025.
2. Jensen M. P., J. H. Flynn III, P. Kollias, C. Kuang, G. McFarquhar, H. Powers, S. Brooks, E., et al. 2023. Tracking Aerosol Convection Interactions Experiment (TRACER) Field Campaign Report. Ed. by Robert Stafford, ARM user facility. DOE/SC ARM-23-038. https://doi.org/10.2172/2202672.
3. Heikenfeld, M., Marinescu, P. J., Christensen, M., Watson-Parris, D., Senf, F., van den Heever, S. C., and Stier, P.: Tobac 1.2: Towards a Flexible Framework for Tracking and Analysis of Clouds in Diverse Datasets, Geoscientific Model Development, 12, 4551–4570, https://doi.org/10.5194/gmd-12-4551-2019, 2019a.
4. Ritman, M., Jones, W., and Stier, P.: Convective controls on anvil cloud evolution in the ICON km-scale global climate model, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-580, 2026.