Response to reviews of "Inferring processes governing cloud transition during mid-latitude marine cold-air outbreaks from satellite" by J. Zhang et al.

We would like to thank the editor and the three reviewers for their insightful feedback and constructive comments and suggestions on our manuscript, which have helped us to improve the original manuscript. First, we want to highlight key updates to the revised manuscript, as suggested by the reviewers' comments:

1. **Section 2.1 have been substantially expanded** to discuss satellite retrieval uncertainties and limitations, clarify retrieval algorithms and the validity of underlying assumptions, and—most importantly—emphasize how the retrievals are interpreted and used in this study.
2. **Discussions of liquid and mixed-phase process fingerprints have been refined** to improve clarity and consistency.
3. **A new Fig. 2 has been added** to demonstrate the relative steadiness of key large-scale meteorological conditions, providing physical grounding for the proposed *space–time exchange* approach.
4. **Discussions of large-scale meteorological conditions along trajectories now appear earlier in the manuscript**, and additional meteorological factors, particularly 700 hPa subsidence, have been incorporated (**new Fig. 4**).
5. **The 2DS imagery has been replaced with a new analysis (new Fig. 7)** quantifying the duration of ice-liquid coexistence using in-situ cloud probe measurements, providing independent observational support for the inferred process fingerprints.
6. **Terminology related to cloud processes and transitions has been streamlined** for consistency throughout the manuscript.
7. **Section organization has been re-structured as follows: 1. Introduction; 2. Data and Methods; 3. Results and Discussions; and 4. Conclusions,** in order to improve manuscript structure and narrative flow. Section 3 now includes: 3.1 Met overview; 3.2 LWP-Nd; 3.3 LWP-IWP; 3.4 Cloud Org (LvL); 3.5 Diurnal variations, and we now show results followed by discussions, implications, and limitations in each subsection.

We have also made unsolicited updates and changes to the manuscript for clarification and readability.

Specific point-by-point responses to each comment are contained below, with the reviewers' comments provided in **blue** and our responses in **black**. Changes to the manuscript made in response to the reviewer are provided in ***red italics***.

Reviewer#1 (Florian Tornow)

For five marine cold-air outbreaks (MCAOs) that occurred during the ACTIVATE campaign, the authors generate Lagrangian trajectories and extract geostationary satellite retrievals along them, in particular liquid and ice water paths (LWP and IWP) and cloud droplet number concentration (Nd). Using stereotypical process signatures, the authors infer process occurrence during overcast-to-broken cloud transitions. Lastly, the authors examine cloud organizational metrics.

While the approach is highly innovative and the paper is well written, it rests on a series of assumptions. In my opinion, the authors should verify these assumptions. Given the scope of the proposed revisions, I recommend returning the manuscript for major revisions.

We thank the reviewer for the encouraging words and constructive comments.

Major concerns

1. Satellite retrievals and derived products: The authors should explain SatCORPS retrievals performance under MCAO conditions where publications exist or else express the lack of such performance analysis. In addition, the authors should explain in more detail the pixel-based liquid-ice phase categorization. The latter issue is particularly relevant where condensate becomes increasingly mixed and retrievals may confuse condensate mass (e.g., in updrafts that are typically both high in LWP and IWP) and how it would affect the shown analysis. Furthermore, the authors should at least briefly demonstrate the veracity of subadiabaticity assumptions needed for Nd retrievals (e.g., via ACTIVATE dropsonde data), especially where clouds are increasingly convective natured. Lastly, the authors should clarify whether LWP includes cloud and rain condensate.

We thank the reviewer for raising these points. To our knowledge, there has been no dedicated, systematic evaluation of SatCORPS cloud property retrieval performance specifically under MCAO conditions. That being said, SatCORPS retrievals have been validated against active sensors (Yost et al. 2021) and in-situ measurements (Painemal et al. 2021, Kang et al., 2021) under broad cloud regimes, which include polar/high-latitude clouds.

The pixel-based thermodynamic phase classification, which identifies the radiatively dominant cloud phase, is determined by iteratively matching model-calculated radiances with observed radiances following the CERES-VISST algorithm (Minnis et al., 2008, 2011, 2021). The retrieval assigns a single phase (liquid or ice) that best explains the observed top-of-atmosphere radiances, with the decision further constrained by cloud-top temperature through a series of logical tests (Minnis et al. 2021). This thermodynamic phase selection should be interpreted as '*the radiatively dominant cloud phase that best explains the observed radiances at the top of the atmosphere*'.
At the pixel level, this phase classification does not report mixed-phase (in a column sense) as a distinct class. To overcome this limitation, we leverage the fact that the satellite phase classification indicates the *radiatively dominant* phase of the entire cloudy atmospheric column and characterize 'mixed-phase' in a spatial sense, that is the *fraction of liquid (or ice) dominated* pixels within a given area (1x1 degree in our case). Importantly, because our goal is to qualitatively characterize cloud evolution along the MCAO trajectories, rather than quantitatively capture the column mixing states of the cloud field as they evolve, our analysis does not rely on exact phase classification or absolute partitioning between liquid and ice mass. We now explicitly streamline these points in the revised manuscript to clarify how 'mixed-phase' should be interpreted in this study.
L114-130"A limitation in SatCORPS pixel-based thermodynamic phase classification is that mixed-phase clouds are not reported as a distinct class. The classification identifies a single, radiatively dominant cloud phase (liquid or ice) that best explains the observed top-of-atmosphere radiances, using iterative model-observation matching which is further constrained by retrieved cloud-top temperature through a series of logical tests \citep{Minnis08,Minnis11,Minnis21}. Therefore, the GOES-16 cloud phase classification used in this work should be interpreted as `\textit{the radiatively dominant cloud phase that best explains the observed multispectral radiances at the top of the atmosphere}'. Although to the best of our knowledge no validation work has specifically targeted MCAO clouds, this retrieval algorithm has been validated against active sensors \citep[e.g.,][]{Yost21} and in-situ measurements \citep[e.g.][]{Painemal21,Kang21} under broad cloud regimes. The cloudy scene type investigated in this study, i.e., non-polar, snow-/ice-free scenes, exhibit the highest hit rate (0.971) and the highest Hanssen-Kuipers' skill score (HKSS; 0.941) across all scene types when compared to phase classifications based on an active sensor \citep{Yost21}. To overcome this limitation, we leverage the rich spatial information contained in satellite snapshots to characterize the ``mixing'' state of hydrometeors in a spatial sense. Specifically, we characterize and infer mixed-phase process fingerprints in a GV space describing cloud evolution in domain-mean (1$^\text{o}$ by 1$^\text{o}$) cloud liquid water path (LWP) and ice water path (IWP). This approach

alleviates the reliance on exact phase classification and on absolute liquid-ice partitioning within the column when inferring mixed-phase processes."

The subadiabaticity assumption is indeed challenged when the cloud field become more broken and more convective natured. For visible & infrared imager remote sensing of cloud properties, an adiabatic cloud model framework is used, in which cloud liquid water content is assumed to increase linearly with height above cloud base, modified by a subadiabatic factor to account for entrainment and mixing. To assess the robustness of our results to the subadiabatic assumption, we performed sensitivity tests using different subadiabatic fractions. **Figure R1** shows that varying cloud subadiabaticity, representing different degrees of entrainment mixing, quantitatively affects the cloud evolution in LWP-Nd space, as expected; however, the qualitative characteristics of these evolutions, which reflect underlying cloud and boundary-layer processes, remain robust. Of interest is that as adiabaticity decreases, N_d decreases and the r_e at which the transition to drizzle increases.

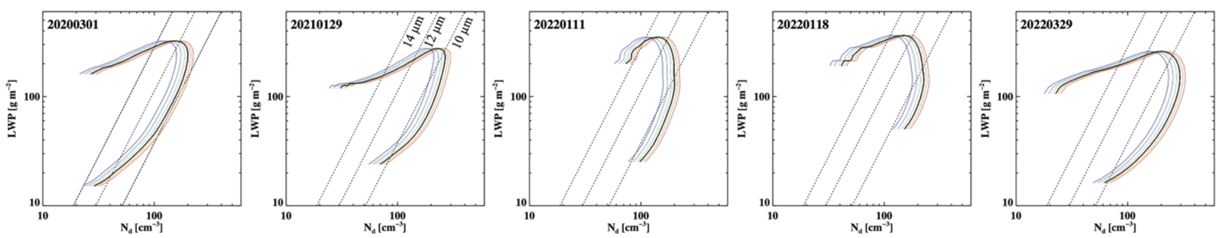


Figure R1. As in new Fig. 5b, but using a range of (sub)adiabatic fractions, spanning from 1 (warmest color) to 0.5 (coolest color), with 0.8 highlighted in black, which is used in the main body of this work. Three effective radius lines are shown for reference.

In addition, in-situ profiling of liquid water content (LWC) could serve as potential validation of the (sub)adiabatic assumption. Chellappan et al. (2024) have documented these profiles for 2020 and 2021 campaign years, which include MCAO cases 20200301 and 20210129. Here we show one additional case on 20220111 in **Figure R2**. In general, these in-situ profiles support the use of a (sub)adiabatic framework for remote sensing of cloud properties. We caution that ACTIVATE Falcon ascent legs sometimes sampled different parts of the cloud field given the airspeed and time required to ascend. Consequently, these in-situ LWC profiles do not always represent the LWC profile in a true column sense.

In summary, sensitivity tests and prior literature (e.g., Grosvenor et al. 2018) indicate that variations in the subadiabatic assumption primarily affect the absolute value of retrieved N_d, while preserving spatial and temporal patterns that are focus of this study, from which we infer process characteristics (or "fingerprints"). We have added a discussion to address this concern in the revised manuscript:

L103-115"The (sub)adiabaticity assumption used in N_d retrievals has been widely applied to global marine single-level clouds \cite[e.g.,][]{Quaas06,Gryspeerdt19} and has been shown to perform well for stratiform clouds, though less so for more convective and broken cloud fields \citep{Gryspeerdt22AMT,Grosvenor18,Painemal21}. Importantly, this retrieval method has been extended to MCAO clouds, particularly in the polar regions \citep[e.g.,][]{Murray-Watson23} and mid-latitude regions including the North Atlantic \citep[e.g.,][]{Chellappan24}. An adiabatic cloud model assumes that cloud liquid water content (LWC) increases linearly with height above cloud base, modified by an adiabatic fraction factor (i.e., f_ad) to account for entrainment-mixing. In-situ LWC and r_e profiles measured during the ACTIVATE campaign \citep[e.g., in][]{Chellappan24} generally support the validity of this assumption. To assess the robustness of our results to the subadiabatic assumption, we conducted sensitivity tests using different f_ad values in N_d calculations. Figure S1 shows that *varying cloud subadiabaticity, representing different degrees of entrainment-mixing, quantitatively affects the cloud evolution in LWP-N_d space, as expected. However, the qualitative characteristics of these evolutions, which reflect underlying cloud and boundary-layer processes, remain robust. Thus, variations in the adiabatic assumption primarily influence the absolute magnitude of retrieved N_d, while preserving the spatial and temporal patterns that are the focus of this study."*

In the revised manuscript, we have clarified that SatCORPS retrieved LWP is cloud liquid water path.

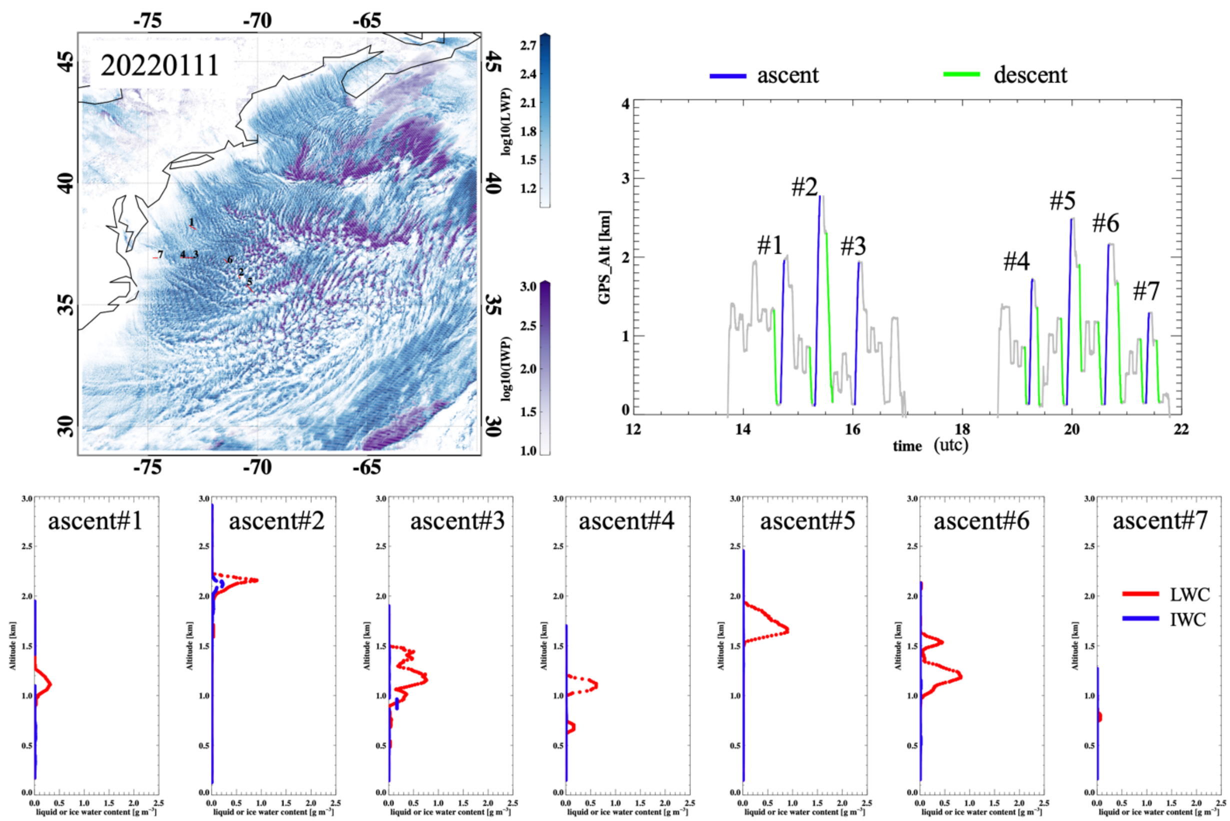


Figure R2. GOES-16 retrieved map of LWP and IWP on 20220111 (upper left), with ascent legs labeled, Falcon flight track with ascent legs highlighted in blue (upper right), and profiles of LWC (red) and IWC (blue) from FCDP for each ascent leg (bottom).

2. Process signatures: The authors show anticipated LWP-Nd process signatures in Fig. 3a. While the authors cite previous work, they should in more detail explain which synoptic conditions were previously targeted (e.g., is the cited work investigating subtropical Sc?) and weather any differences are expected under MCAO conditions. For example, currently entrainment is shown to have either no impacts on Nd when homogeneous or subtle impacts when heterogeneous; previous work (e.g., Tornow et al., 2022) has demonstrated strong cloud condensation nucleus (CCN) dilution effects as cleaner free-tropospheric (FT) air is entrained into the marine boundary layer. Furthermore, given the non-negligible role of secondary ice production in these cases – what type of process signature is expected?

The reviewer has raised an important point on the role of synoptic regime in affecting the interpretation of process signatures. Indeed, a distinct synoptic condition under MCAO is the more rapid deepening of the boundary layer as the MCAO clouds evolve compared to the deepening during subtropical Sc evolution. This rapid BL deepening can lead to entrainment dilution reducing both LWP and N_d. In addition, as the reviewer demonstrated in Tornow et al. (2022), the mixing of BL and clean FT air via entrainment can dilute CCN concentration in the MBL, limiting the source for cloud droplets. In the revised manuscript, we have added discussions of these effects driven by large-scale evolution of the MBL in addition to the microphysical process signatures.

L242-247"We note that these directionalities (arrows) are intended to conceptually illustrate the characteristic effects of a given process; other processes may also contribute to or amplify the observed behavior. For example, during MCAO events, rapid expansion of the MBL can lead to dilution of liquid condensate through entrainment of drier air, reducing both LWP and N_d. In addition, mixing between the MBL and free-tropospheric air masses can further dilute cloud condensation nuclei concentrations within the MBL, thereby limiting cloud droplet formation \citep[e.g.,][]{Tornow22}."

Regarding the role of secondary ice production (SIP), its signature would be a marked increase in N_i, however, such retrievals from satellite remote sensing can be highly uncertain and thus unreliable. Therefore, we chose not to show evolutions of N_i during these MCAO cases. Since the SIP process primarily modifies the ice number rather than directly affecting the total mass of ice, "fingerprints" of SIP will not manifest in the LWP-IWP phase space that we show. In the revised manuscript, we acknowledge this limitation in inferring SIP process that can be quite active in these MCAO clouds (e.g., Abel et al. 2017, Chellappan et al. 2024). Added discussion reads:

L320-323"Previous studies have demonstrated that secondary ice production can play a non-negligible role in shaping the evolution of MCAO clouds \citep[e.g.,][]{Abel17,Chellappan24}. However, because space-retrieved ice particle number concentrations are highly uncertain, we do not attempt to infer this process here. Importantly, the occurrence of secondary ice production does not affect the trace evolution in the mass-centric LWP-IWP GV space (Fig. 6)."

3. Steady conditions: The authors show that horizontal winds remain approximately steady during daytime hours. Given the important role of large-scale vertical winds in shaping MCAO cloud evolution (e.g., Tornow et al., 2023), were vertical wind speeds along the trajectory truly steady? The authors should at least briefly explore this question for a single layer close to cloud tops (e.g., 700 hPa).

We thank the reviewer for raising this point. Steady horizontal winds is a unique condition of MCAO that allows us to perform this "space-time exchange" static trajectory analysis. Although generating these static trajectories does not rely on steady vertical winds, spatial gradients in large-scale subsidence (and associated FT humidity gradients) are important for shaping MCAO clouds, as the reviewer demonstrated in Tornow et al. (2023). The central idea of our analysis relies on the *temporal* steadiness of the spatial gradient in large-scale conditions, that is the gradient along trajectories should remain relatively invariant throughout the day. **Figure R3** shows the veracity of this condition for large-scale subsidence (ω700); it demonstrates that, in general, spatial patterns in large-scale subsidence field remain relatively invariant throughout the day (maps) and gradients along trajectories exhibit *temporal* steadiness (right column), with the 20220329 case showing the most drift in along-trajectory gradient.

In the revised manuscript, we have included a new Fig. 2, demonstrating the steadiness of large-scale meteorological conditions during these MCAO events, including additional Met variables (as reviewer #2 suggested). Adjusted wording now reads:

L175-181"To further demonstrate the validity of the `space-time exchange', we examine gradients in additional large-scale meteorological conditions beyond surface winds, including SST, LHF, SHF, buoyancy flux, the M-index, and subsidence and RH at 700 hPa, along instantaneous trajectories for each MCAO event (Fig. 2). Diurnal variations (between 14-20 UTC; denoted by colors in Fig. 2) are minimal for most meteorological conditions, with subsidence and RH at 700 hPa exhibiting the strongest diurnal variability. The steady gradients in surface buoyancy flux and temperature support the applicability of the `space-time *exchange', while diurnal variations in the dynamical environment are used to interpret the observed diurnal variations in process fingerprints discussed in Section 3.6."*

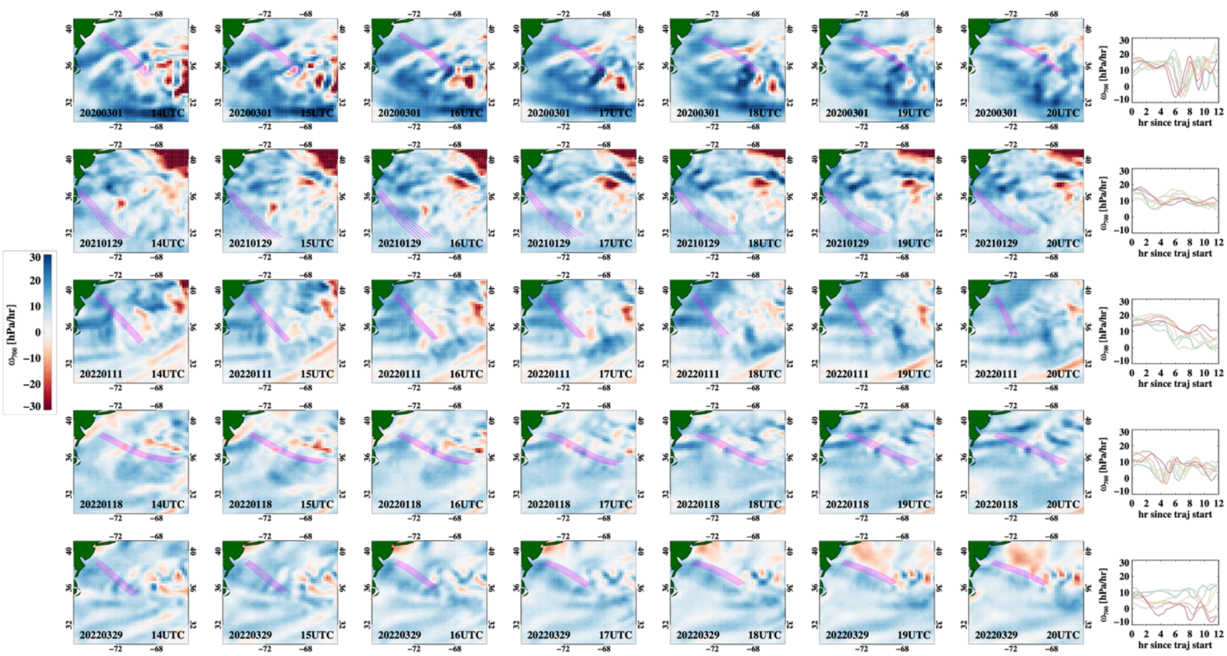


Figure R3. ERA5 large-scale subsidence (ω) at 700 hPa for 14-20 UTC (9-15LT), overlaid with static trajectories generated with the 1000 hPa wind fields at each hour. Right column shows ω700 along static trajectories at each hour during daytime (color-coded for14-20 UTC).

4. Test on Lagrangian simulations: In their discussion (l. 358-360) the authors suggest applying this framework to Lagrangian simulations. LES and SCM simulations now exist for four out of the five cases (https://github.com/NASA-GISS/LES-SCM). While LES simulations could serve as an additional proxy for field data. (e.g., to assess subadiabaticity assumptions), it also offers microphysical source terms that can directly connect to the process signatures. Lastly, observational constraints from MAC-LWP (Elsaesser et al., 2017, located at https://github.com/NASA-GISS/LES-SCM/tree/main/data_files) may help to further corroborate SatCORPS LWP retrievals.

This is an excellent suggestion; as the reviewer noted, LES is a powerful tool for process understanding and benchmarking process signatures. We are definitely interested in analyzing LES output with this approach and compare the process signatures with those derived from satellite observations. We believe this kind of analysis is worthy of a dedicated, follow-up study, and we will be in touch soon to coordinate such a collaborative study. The goal of the current study is to illustrate the concept of this approach and demonstrate how process understanding can be inferred from satellite observations alone using combinations of geophysical variable spaces. We have added *L435-437"A follow-on study is planned to apply this framework to Lagrangian large-eddy simulations of the five selected MCAO events that are particularly well suited for Lagrangian modeling \citep{Tornow25,Tornow25b}."*

Microwave imagery retrieved total LWP (cloud + rain) is indeed a strong quantitative constraint on retrievals using shortwave imagery, under non-precipitating and overcast conditions. Smalley & Lebsock (2023) have performed such a comparison for GOES-16 and found a systematic differences but for a much wider viewing geometry range than that observed for ACTIVATE. Since we rely on tendencies of cloud properties instead of their absolute values to infer process signature, systematic biases have minimal impact on the interpretation of cloud evolution characteristics. We have added discussions in the revised manuscript to address this concern:

L96-102"For LWP, microwave imagery retrievals \citep[e.g.,][]{Elsaesser17} provide an independent constraint on visible imagery retrievals, which are known to be biased under high SZA \citep{Maddux10,Grosvenor14,Grosvenor18}. By excluding pixels with SZA > 65$^\text{o}$ and restricting our analysis to 09-15 local time, we largely remove the nonlinear biases associated with high SZA. The remaining biases at lower SZA appear to be systematic when evaluated against independent microwave imagery retrievals \citep{Smalley23}. Because the primary quantities of interest for process inference in this study are the spatiotemporal gradients and tendencies of cloud properties, rather than their absolute magnitudes, the impact of the remaining systematic biases in LWP on identifying process fingerprints is minimal."

Minor concerns

l. 164 It would be good to show the range of meteorological conditions across trajectories for each case as shading behind lines. It would also be good to show large-scale subsidence (see above major concerns).

Thanks for the suggestion. We have included the range of meteorological conditions (new Fig. 2) and large-scale subsidence (ω_{700}) in the revised manuscript.

Regarding showing the range of meteorological conditions across trajectories for each case as shading behind lines, we attempted to do so but the resulting figure appears too busy and difficult to interpret due to overlapping among the five cases. In addition, there is no easy way to show uncertainty ranges for two variables concurrently as shading. For these reasons, we chose to just show the mean evolution.

ll. 173-174 Precipitation appears to set in at re << 15 um; please modify or else explain.

Thanks for catching this. In the revised the manuscript we denote this transitional regime with a range, instead a single value, from 11 to 15 um, supported by existing literature cited.

L235-236"In particular, the 11 and 15 \textmu m r_e isolines approximately delineate the transition from non-precipitating to precipitating regimes governed by collision-coalescence processes \citep{Gerber96,vanZanten05}."

ll. 182-184 Nd appears to decrease once LWP ~ 100 g m^-2 is reached; could this be explained by early collision-coalescence or alternatively by FT CCN dilution (see above major concerns)?

We note that 3 of the cases are still gaining Nd once LWP~100g/m^2 is reached, with the other two maintain a steady N_d, but with increasing r_{eff}. We thereby interpret this feature as an indication of condensational growth whereby water droplets continue to grow larger through condensation. Then, N_d starts to decrease–approximately as LWP approaches 200 g/m^2—indicating the collision-coalescence process. Once N_d starts to decrease, we cannot completely rule out the contribution from the entrainment-driven dilution. We modified the discussion to clarify this.

L245-247"In addition, mixing between the MBL and free-tropospheric air masses can further dilute cloud condensation nuclei concentrations within the MBL, thereby limiting cloud droplet formation \citep[e.g.,][]{Tornow22}."

ll. 192-193 Is this corroborated by ACTIVATE measurements?

According to Tornow et al. (2025) Fig. 5, both 20220329 and 20200301 exhibit elevated N_d, marked by the 95th percentile of FCDP measured N_d values. We note that in-situ N_d measurements can be biased due to 1) instrument uncertainty (e.g., CDP N_d values are systematically lower than FCDP and N_d values), 2) spatial and temporal sampling biases.

ll. 193-195 Is a reduced LWP consistent with the existing literature?

We realized our wording here is indeed a bit confusing. The revised version now reads *L257-263"The event on 29 March 2022 is marked by the highest peak-N_d and the lowest peak-LWP among the 5 cases (Fig. 5b and c). The suppressed cloud thickening is in line with cloud-top entrainment feedbacks, whereby smaller cloud droplets promote entrainment-mixing by evaporating more rapidly and remaining longer within the entrainment interface layer due to reduced gravitational sedimentation, ultimately leading to reduced LWP \citep{Wang03,Xue06,Bretherton07}. Meanwhile, a clear delay in cloud breakup is evident on this day (Fig. 5b, star markers), suggesting a shift from precipitation-driven to entrainment-driven cloud breakup mechanisms \citep[e.g.,][]{Yamaguchi17,Goren19,Christensen20}."*

ll. 201-205 Since most IWP retrievals are notoriously uncertain, it is important to explain any strengths and weakness of the SatCORPS retrieval (see above major concerns). Can we even trust the order of magnitude here?

We agree and acknowledge that satellite-based IWP retrievals are inherently challenging due to assumptions regarding ice particle shape and their associated radiative properties. However, rather than relying on absolute IWP magnitudes, we circumvent this limitation by extracting physical information on process signatures through the "rate" of change, using the 'space-time exchange' approach that leverages the broad spatial coverage of geostationary satellites at a given instance. These discussions are added to the revised manuscript.

L270-273"Satellite-based IWP retrievals are inherently challenging due to assumptions regarding ice particle shape and their associated radiative properties. We therefore circumvent the reliance on absolute IWP magnitudes by extracting physical information on process signatures through the ``rate'' of change, using the `space-time exchange' approach that leverages the broad spatial coverage of geostationary satellites at a given instance."

Fig. 4 Along with the above concern, please add error bars to data points.

Figure R4 shows the same new Fig. 6 with error bars indicating the range of the ensemble (5 members) trajectories each separated by 0.1 degrees in longitude and latitude. Given the already busy plot, with information denoted by different markers, marker colors, marker sizes, and fill-vs-open, we prefer not to show the error bars to make the figure more interpretable. We have included Figure R4 as a supplementary figure in the revised manuscript (Fig. S3).

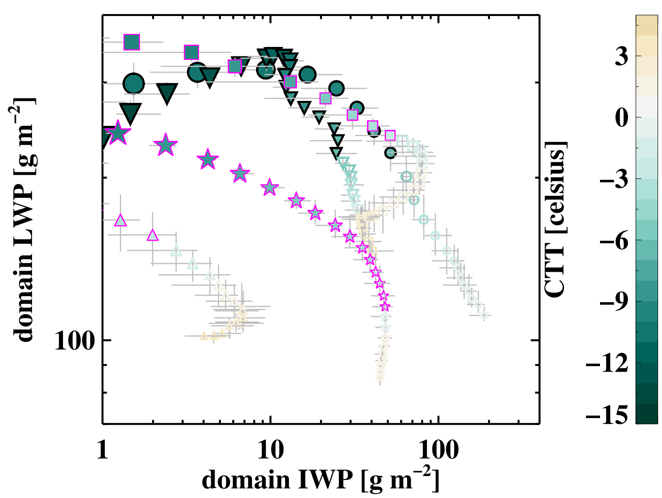


Figure 4. As in new Fig. 6, but with gray error bars indicating ranges across the instantaneous trajectory ensemble.

ll. 207-209 How many pixels are there in a 1x1 degree domain and is one ice pixel is sufficient to render the domain "mixed"?

Given that GOES-16 pixel-footprint is 2-3 km (slightly varying spatially due to viewing geometry), there are roughly 1,600 pixels within a 1x1 degree domain in the study area. We start showing traces in LWP-IWP phase space once domain-IWP is greater than 1 g m^{-2}. The exact classification and rendering of a "mixed" domain is not a subject of investigation here and thereby won't affect the results shown.

ll. 214-216 Could rain also cause liquid depletion?

Yes, precipitation, as well as dynamical feedbacks, could also deplete liquid water. We have re-written the interpretation of cloud evolution in the LWP-IWP phase space in the revised manuscript.

L286-298"A key distinction between the two groups is the ratio between changes in LWP and IWP (i.e., $\frac{d(\mathrm{LWP})}{d(\mathrm{IWP})}$) as domain IWP increases. While ice emergence begins at different LWP values, which reflects variations in large-scale meteorological conditions (Fig. \ref{f6}), the inferred $\frac{d(\mathrm{LWP})}{d(\mathrm{IWP})}$ is nonetheless similar across the magenta group. Here, the less negative $\frac{d(\mathrm{LWP})}{d(\mathrm{IWP})}$ suggests the prevalence of a diffusional process where water vapor migrates from droplets to ice through evaporation and deposition, known as the Wegener-Bergeron-Findeisen (WBF) process \citep{Wegener12,Bergeron35,Findeisen38}. In contrast, the black group is characterized by rapid liquid depletion (i.e., a more negative $\frac{d(\mathrm{LWP})}{d(\mathrm{IWP})}$) preceded by the co-growth of ice and liquid, a signature of riming where existing ice particles collect droplets through collisional freezing \citep{Pruppacher10,Tornow21}. In this regime, liquid loss is further accelerated by precipitation fallout associated with the fast sedimentation of rimed ice, as well as by dynamical feedbacks whereby latent heat release from freezing promotes cloud-top entrainment-mixing. While riming- and precipitation-driven liquid depletion likely occur in both cases of the black group, as evident by the large effective radius (Fig. 5b), dynamical feedbacks further amplify liquid loss during the 11 January 2021 event (the most negative $\frac{d(\mathrm{LWP})}{d(\mathrm{IWP})}$; downward triangles) as a result of the dry free troposphere (Fig. 4c)."

ll. 207-220 To what degree can this LWP-IWP evolution be affected by the binary condensate classes? I wonder if retrieval samples (e.g., spatially resolved IWP and LWP values in progressive domains) could be informative.

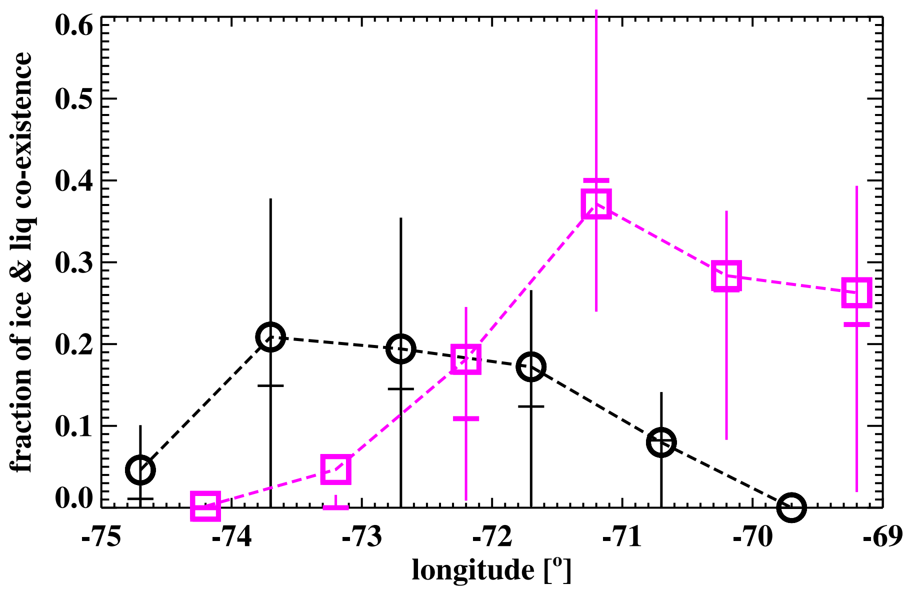
As mentioned in the response to major concern #1, because of the limitation of the binary classification, we purposely design this LWP-IWP phase space with domain-mean ice and liquid content, leveraging the rich spatial information contained in a satellite snapshot, while circumventing the need to resolve the vertical dimension. Our goal is not to quantitatively represent cloud column mixing state with spatially aggregated binary classifications. Thus, the interpretation of the LWP-IWP evolution is discussed strictly in a qualitative, characteristic manner. We further clarified this point in the revised manuscript:

L277-281"Because GOES-16 retrievals provide only a single radiatively dominant cloud phase for each pixel, we use the combination of domain-mean LWP and IWP to characterize the `mixing state' in a spatial, rather than a column, sense. This approach exploits the rich spatial information contained in a satellite snapshot while circumventing the need for a vertically resolved mixing state. Thus, cloud evolution in domain-mean LWP-IWP GV space is interpreted in a qualitative manner, focusing on characteristic behaviors."

ll. 225-228 It is unclear how representative these 2DS samples are. Perhaps other metrics may be more informative (e.g., how many flight seconds of co-existing liquid and frozen particles from in-situ probes) or there is a way to quickly determine sample representation?

Thanks for the great suggestion! We have replaced the 2DS images with a figure showing the duration of liquid-ice co-existence based on FCDP and 2DS probes as a function of fetch (approximated by longitude). As fetch increases, the magenta group begins to exhibit clear evidence of longer duration of liquid and frozen particles, whereas the black group exhibits less co-existence time, indicating fast processes likely associated with riming and rapid precipitation fallout. The discussion associated with this part now reads:

L303-311"To validate the process fingerprints inferred from satellite snapshots, we seek in-situ evidence for distinct microphysical signatures between the black and magenta groups. A useful metric for distinguishing rapid collisional growth from slower diffusional growth of ice particles is the duration of ice-liquid coexistence, quantified as the fraction of in-cloud sampling time during which both LWC and IWC exceed 0.01 g m^{-3} \citep{Kirschler23}. Falcon in-cloud sampling includes above-cloud-base (ACB), ascent, below-cloud-top (BCT), and descent legs, and the data are binned by longitude as a proxy for the stage of cloud evolution during MCAO events. Figure 7 shows that as MCAO clouds evolve farther downstream from the coast, the magenta group exhibits systematically longer ice-liquid coexistence durations than the black group, consistent with slower diffusional growth. In contrast, the shorter coexistence times in the black group suggest cloud evolution dominated by riming and rapid precipitation fallout of rimed ice."



New Fig. 7 in the revised manuscript.

l. 232 Specific thresholds from the retrieval would be quite important here (see above major concerns).

Thanks! The threshold is specified in the revised manuscript.

ll. 232-234 CTTs from ACTIVATE's HSRL seem to disagree here, showing 2022-01-29 at -10 degC (Fig. 5 in Tornow et al., 2025). Could this stem from surface contamination in optically thinner or broken clouds within GOES pixels?

On 20210129, as clouds evolve, CTT did reach ~-9 degC (Fig. 4), in agreement with ACTIVATE remote sensing (Tornow et al. 2025). If we compare the coldest CTT reached during the evolution among the five cases, 20210129 was indeed the warmest, but only by about 1 degree. We have modified the discussion to clarify this:

L313-317"This behavior can be partly explained by the minimum cloud-top temperature (CTT) reached as clouds deepen along their trajectories, such that the coldest minimum-CTT (~-15°C; 11 January 2022; Fig. 4) is associated with the earliest ice emergence, occurring while liquid mass is still growing, whereas the warmest minimum-CTT (~-9°C; 29 January 2021) corresponds to the latest onset of ice formation, when liquid condensate has already begun to deplete through warm precipitation and entrainment."

ll. 247-256 A lot of the earlier findings (that were initially "intended to conceptually indicate the dominant characteristics of a given processes") are relied on here without any uncertainty. This very much reads like a discussion, and I suggest moving it there.

Agreed. The manuscript is re-organized such that Section 3 now includes results and discussions (which contain interpretations, implications, and limitations of the results shown).

ll. 252-253 Please check this sentence.

Thanks. Sentence is reworded.

ll. 254-255 (and also l. 11 and l. 348) It is unclear what exactly the "spread" is. Is it a large range in albedo at any given cloud fraction?

Yes. We have reworded the sentences at these instances in the revised manuscript.

ll. 257-266 Given the general importance of meteorological boundary conditions, I wonder if this paragraph should be moved to the beginning of Section 3?

Thanks for the suggestion. We have moved the discussion of large-scale meteorological conditions that setup these MCAO events, including their spatial gradients along the trajectories and the steadiness of these large-scale conditions, to the beginning of Section 3.

L191-193"Further contextual large-scale meteorological conditions during these MCAO events are described Section 3.1, as well as in Table 2 of \citet{Sorooshian23} and in \citet{Tornow25}."

ll. 271-275 Could the diurnal evolution of MBL aerosol upwind of cloud formation (e.g., Tornow et al., 2025b) explain some of this behavior?

Thanks for pointing this new work to us! Its findings are indeed well aligned with the GOES-16 derived diurnal variations in cloud evolution. We added this point to the revised manuscript.

L392-394"Alternatively, this pattern may reflect a diurnally evolving aerosol size distribution in the MBL prior to cloud formation so that prescribing the observed afternoon size distribution in simulations leads to delayed precipitation \citep{Tornow25b}."

ll. 289-290 I suggest also looking into changing subsidence patterns here (see earlier comment).

Thanks. Large-scale subsidence at 700 hPa is now examined and discussed throughout the revised manuscript (new Fig. 2 and new Fig. 4). In terms of diurnal variations, large-scale subsidence exhibits the most variation, especially for the 20220329 case. Discussion on large-scale subsidence diurnal variations is added to the revised manuscript.

ll. 337-340 I would soften "evident" here, assuming that a combination of other processes (e.g., entrainment plus collision-coalescence) could also lead to a precipitation signature.

Thanks for the suggestion. We decided to remove this sentence in the bullet point summary, as it doesn't convey a new finding of this study (e.g., previous work by Chellappan et al. and Tornow et al. have documented it in a much-detailed manner).

ll. 358-360 Output from observationally constrained Lagrangian simulations of four of these cases is now available (see major concerns). Application of the authors' approach to simulations would make the paper (and the "line of evidence" for model evaluation) stronger by (1) bypassing potential satellite retrieval issues and (2) applying it to coherent output with known process rates in it. Please contact me (email: ft2544@columbia.edu) if needed.

We really appreciate this suggestion and are encouraged that modeling efforts have already been devoted to these MCAO cases. We fully agree that applying this framework to LES outputs will yield valuable process-level insights.

That said, we believe the novelty of the present study warrants a standalone publication. Specifically, this work introduces a new framework that can be applied to: (1) extract process signatures from satellite observations alone, providing an additional and independent "line of evidence" alongside modeling efforts; and (2) diagnose the impacts of different microphysical schemes or parameterizations on process signatures in LES and single-column models (SCMs). In addition, this study demonstrates how geophysical variables can be grouped to reveal process fingerprints. For these reasons, we prefer to present this work as a standalone contribution, followed by a dedicated study that integrates multiple lines of evidence by applying this framework synergistically across modeling and observational tools.

In response to Major Concern #1, we have also addressed how potential quantitative biases in satellite retrievals may affect the inferred process fingerprints and have clarified how this framework is explicitly designed to circumvent these retrieval uncertainties.

L435-437"A follow-on study is planned to apply this framework to Lagrangian large-eddy simulations of the five selected MCAO events that are particularly well suited for Lagrangian modeling \citep{Tornow25,Tornow25b}."

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Reviewer 2

This study applies a 'space–time exchange' method to analyze satellite snapshots along the instantaneous trajectories of five marine cold-air outbreak (MCAO) events over the northwest Atlantic. The authors examine the evolution of geophysical variables (Nd, LWP, IWP, albedo) to infer cloud processes in stratiform and transition regimes. I found the approach effective for diagnosing dominant processes. However, as noted by another reviewer, assumptions and retrieval uncertainties deserve more careful treatment given the complexity of MCAO cloud–boundary layer interactions.

We thank the reviewer for the encouraging words and constructive comments.

Major Comments

1. The manuscript uses a range of terms to describe cloud regimes and their transitions (e.g., cloud street, closed-cell, stratiform, overcast, convective, open-cell, closed-to-open transition). These are sometimes interchangeable but can imply different meanings. Please clarify definitions and adopt consistent terminology throughout.

Thanks for the comment, and we agree these terms can sometimes lead to confusion without explicit definitions. In the revised manuscript, we have streamlined these discussions and adopt consistent terminology throughout. For example, a major part of the second paragraph in the Introduction has been re-written to avoid ambiguity (also a concern from reviewer#3).

2. Equation (1) is used for Nd estimation across both liquid and mixed-phase clouds. Is the expression valid for mixed-phase conditions without adjustment to constants like k or ρw? Please justify its application and discuss whether the apparent Nd decrease in mixed-phase regimes (Fig. 3b) reflects physical processes or retrieval artifacts. Similarly, retrieval uncertainties in LWP and especially IWP should be discussed.

We appreciate this comment, which is also raised by reviewer #1. We have substantially expanded Section 2.1 to address these concerns, discuss satellite retrieval uncertainties and limitations, clarify retrieval algorithms and validity of assumptions, and, importantly, emphasize how retrievals are interpreted in this study. Please see responses to reviewer #1's major comment #1 and the revised Section 2.1 for details.

3. Cloud-top temperature appears to increase after cloud breakup, is it unexpected? You state that only cloudy pixels are used for domain-mean values. Please confirm that clear-sky pixels were excluded from averaging. Mixing in SST could bias cloud-top temperatures higher in broken cloud regimes.

We confirm only cloudy pixels are used for calculating domain-mean CTT. CTT increasing after cloud breakup, accompanied by decreasing CTH, is indeed an expected feature with MCAO. It is associated with cloud thinning due to precipitation fallout and cloud-top entrainment mixing. We further clarified this point in the revised manuscript.

L218-221"As the transition progresses toward a broken cloud field, cloud tops subsequently become shallower and warmer. This shallowing and warming of cloud tops results from a combination of factors, including weakened buoyancy fluxes (Figs. 2 and 4) and cloud thinning induced by entrainment-mixing and precipitation."

4. Could retrieval uncertainty and satellite viewing geometry (e.g., solar zenith and azimuth angles) contribute to the observed diurnal differences in Fig. 8? A brief discussion would strengthen this section.

Thanks for the comment. A viewing geometry dependent retrieval bias can definitely contribute to the observed diurnal differences. But, by excluding pixels with SZA > 65 and restricting to 9-15 local time, we try to minimize this effect as much as we can. According to Figs. 5b and 7e in Smalley et al. (2023) JTECH, after applying these filtering criteria, the remaining biases in LWP retrieval appear systematic when compared to microwave imagery retrievals, suggesting minimal influence on our process inference, which is based on spatiotemporal gradients, rather than absolute magnitudes. We now include discussion of this point in both Section 2.1 and Section 3.6.

L96-102"For LWP, microwave imagery retrievals \citep[e.g.,][]{Elsaesser17} provide an independent constraint on visible imagery retrievals, which are known to be biased under high SZA \citep{Maddux10,Grosvenor14,Grosvenor18}. By excluding pixels with SZA > 65$^\text{o}$ and restricting our analysis to 09-15 local time, we largely remove the nonlinear biases associated with high SZA. The remaining biases at lower SZA appear to be systematic when evaluated against independent microwave imagery retrievals \citep{Smalley23}. Because the primary quantities of interest for process inference in this study are the spatiotemporal gradients and tendencies of cloud properties, rather than their absolute magnitudes, the impact of the remaining systematic biases in LWP on identifying process fingerprints is minimal."

L395-399"As discussed in Section 2.1, SZA-dependent biases can potentially contribute to the observed diurnal variations in cloud evolution. By restricting our analysis to 09-15 local time (LT), we largely constrain SZA-dependent biases in LWP \citep{Smalley23}, with the aim of attributing the observed variations to physical processes rather than retrieval artifacts. That said, we acknowledge that differences between traces in the early morning (9 LT) or later afternoon (15 LT) and those near midday may still be affected by residual SZA-related artifacts."

Minor Comments

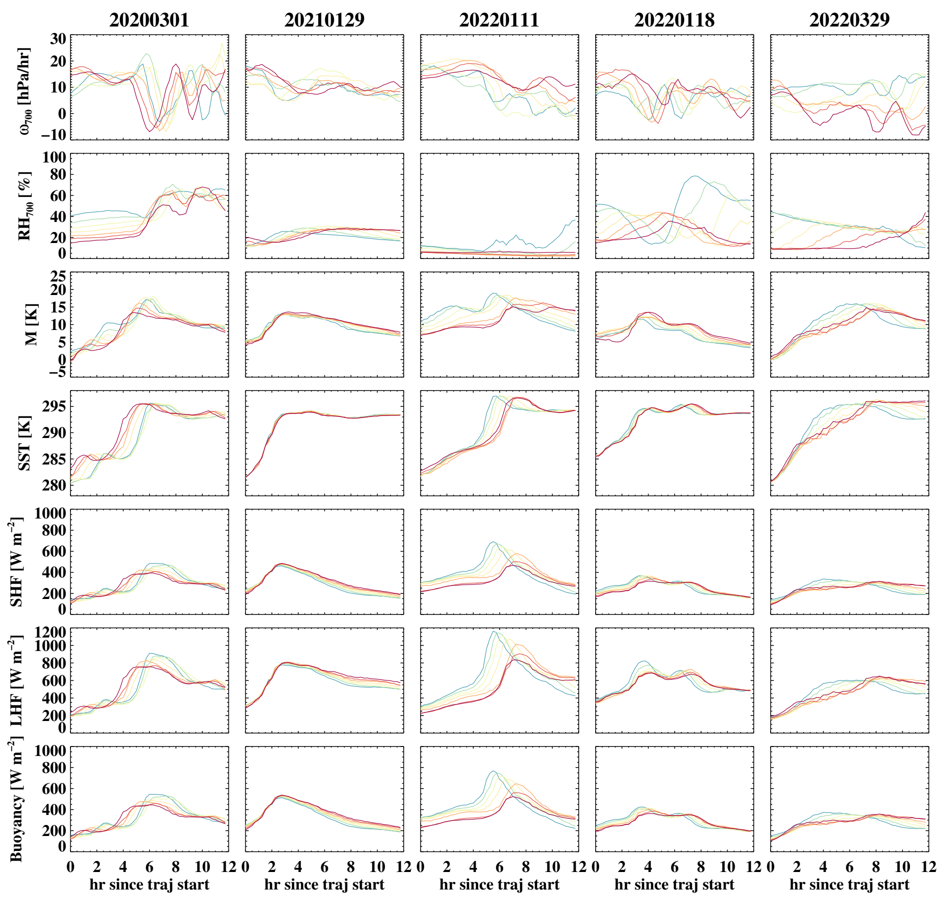
Line 90: Please clarify what is meant by "relatively liberal thresholds."

We clarified this in the revised manuscript with more details. *L93-95"We tested a stricter filtering of r_e > 4 um and tau > 4 \citep[e.g.,][]{Murray-Watson23}, which does not alter the resulting evolutionary characteristics in the LWP-N_d space. Therefore, to better capture the optically thin roll clouds at the western edge of the deck during cloud emergence, we adopt the relatively liberal thresholds for r_e and tau in N_d calculations."*

Section 2.4: In comparing Lagrangian and instantaneous trajectories, beyond wind, how invariant are other meteorological drivers of MCAO evolution (e.g., LHF, SHF, buoyancy, temperature)?

The invariance of meteorological gradient along trajectories is actually demonstrated in Fig. 8 (new Fig. 10), where SST, temperature difference between 800 mb and surface, as well as buoyancy fluxes exhibit minimal diurnal variations. However, we realized this was only shown and discussed at the very end, without being mentioned in Section 2.4 where this steadiness of large-scale condition is invoked to support the "space-time exchange" concept.

Therefore, in the revised manuscript Section 2.4, we refer to a **new Fig. 2** that demonstrates the invariant nature of large-scale meteorological gradients along MCAO trajectories. Added discussion reads: *L175-181"To further demonstrate the validity of the `space-time exchange', we examine gradients in additional large-scale meteorological conditions beyond surface winds, including SST, LHF, SHF, buoyancy flux, the M-index, and subsidence and RH at 700 hPa, along instantaneous trajectories for each MCAO event (Fig. 2). Diurnal variations (between 14-20 UTC; denoted by colors in Fig. 2) are minimal for most meteorological conditions, with subsidence and RH at 700 hPa exhibiting the strongest diurnal variability. The steady gradients in surface buoyancy flux and temperature support the applicability of the `space-time exchange', while diurnal variations in the dynamical environment are used to interpret the observed diurnal variations in process fingerprints discussed in Section 3.6."*



New Figure 2 in the revised manuscript, demonstrating the steadiness of large-scale meteorological conditions along instantaneous trajectories.

Lines 188–190: Could the decreased albedo also reflect the emergence of ice-phase clouds later in the trajectory?

For scene albedo, yes. However, here in Fig. 5c, we show 'liquid cloud albedo' (different from Fig. 8 where scene albedo is shown), therefore, we attribute the decrease in 'liquid cloud albedo' for a given LWP mostly to changes in droplet size (i.e., available surface area for reflection). We added *"liquid"* before "cloud albedo" to clarify this in the revised manuscript.

Line 190: How is the location of cloud breakup (transition from filled to open symbols in Fig. 3) determined? Is a specific cloud fraction threshold applied?

Yes. We used a domain cloud fraction (including both liquid and ice pixels) of 0.99 to indicate cloud breakup. We now include this information in the revised manuscript.

Figure 6: Consider adding evolution direction arrows as in Fig. 4. Also, the use of filled/open symbols for trajectory stages might be confused with the closed/open-cell regimes in Figs. 3–4.

Thanks for the suggestion! We added an evolution direction arrow to the new Fig. 8 and modified the marker convention to be consistent with the closed/open-cell regimes in Figs. 4–6.

Line 247: Based on Fig. 6 and your description, should this be "black group showing a steeper scaling"?

Yes! Thanks for catching this!

Reviewer 3

The authors have compiled a set of space-time-exchange 'trajectories', which are instantaneous snapshots of cold air outbreaks taken along a trajectory driven by 1000hPa winds observed at a single time step. This approach eliminates diurnal sampling problems due to daytime-only microphysical retrievals, allowing for a more complete picture of the time evolution of the cloud systems in CAOs. Results show that ice processes are major contributors to the scene albedo, and that these trajectories show evidence of vapor deposition and riming processes. There is also evidence that increased cloud drop concentration prolongs cloud lifetime while reducing peak LWP and possibly albedo.

This novel approach is noteworthy for its effectiveness and simplicity, and is appropriately applied in the CAO outbreak regime, where downstream evolution remains consistent for days, and cloud processes are less strongly influenced by the solar cycle. The work is well constructed and clearly written and presented. I only have a few minor points to raise, so I recommend only minor revisions.

We thank the reviewer for the encouraging words and constructive comments.

Main points:

In the abstract, you mention that Elevated Nd suppresses peak LWP and delays cloud breakup. This is likely true, but you may want to qualify it a bit here, since you're only working with five trajectories. It is difficult to make broad inferences with such a small sample size. This does motivate an enlarged study using this technique, which would be an excellent goal.

We fully agree. We have reworded this sentence, which now reads *L11-12"Delayed cloud breakup during the 29 March 2022 event is consistent with a shift from precipitation- to entrainment-driven cloud breakup under high N_d conditions."*

Although references to Turnow (2025) and Sorooshian (2023) are clearly made in the data section, I think it would help to give a little bit more attention to environmental factors such as surface winds, vertical winds within and above the PBL, and inversion strength. It would strengthen the paper to add a figure showing the breakdown of a few fundamental CCFs over time (maybe the Scott 2020 CCFs?) for each STE trajectory.

We fully agree! The figure that shows these CCFs over time along MCAO trajectories is actually the old Fig. 7. However, we realized this needs to be shown and illustrated upfront before diving into process discussions. Therefore, we now show and discussion large-scale meteorological evolutions along MCAO trajectories at the beginning of Section 3 (i.e., Section 3.1), and we have added more CCFs to the figure (**new Fig. 4**).

L191-193"Further contextual large-scale meteorological conditions during these MCAO events are described Section 3.1, as well as in Table 2 of \citet{Sorooshian23} and in \citet{Tornow25}."

We have also added a **new Fig. 2**, demonstrating the steadiness of large-scale meteorological conditions along instantaneous trajectories.

L175-181"To further demonstrate the validity of the `space-time exchange', we examine gradients in additional large-scale meteorological conditions beyond surface winds, including SST, LHF, SHF, buoyancy flux, the M-index, and subsidence and RH at 700 hPa, along instantaneous trajectories for each MCAO event (Fig. 2). Diurnal variations (between 14-20 UTC; denoted by colors in Fig. 2) are minimal for most meteorological conditions, with subsidence and RH at 700 hPa exhibiting the strongest diurnal variability. The steady gradients in surface buoyancy flux and temperature support the applicability of the `space-time exchange', while diurnal variations in the dynamical environment are used to interpret the observed diurnal variations in process fingerprints discussed in Section 3.6."

Should section 4.2 be in the results, and not the discussion? This is quite a bit of new work added, and it seems much more in-line with a core result than what is normally mentioned in a discussion section.

Thanks for the suggestion. We have moved Section 4.2 to the results (new Section 3.5).

Introduction: Paragraph beginning on line 28: I can't tell if you're describing the Sc-Cu transition and closed-open transition as separate processes or the same process. It would be wise to make it clear that these two transitions are very different from one-another, then settle on a consistent set of terms that are used throughout.

We agree. In the revised manuscript, we have streamlined these introductory remarks with consistent terminologies throughout to avoid ambiguities.

L28-44"Morphological transitions of boundary layer clouds, particularly the transition from overcast to broken cloud fields have been extensively studied to understand the processes governing cloud evolution and their profound radiative impacts \citep{McCoy17,Goren22}. These transitions are typically associated with a deepening marine boundary layer (MBL) driven by gradients in sea surface temperature (SST). One such example is the stratocumulus-to-cumulus transition, which occurs as clouds are advected from subtropical ocean upwelling regions toward warmer tropical waters \citep{Albrecht95,Bretherton92,Sandu10}. Another distinct class of transitions is associated with marine cold-air outbreaks (MCAOs), in which cold continental air masses are advected over relatively warm ocean surfaces \citep{Brummer96,Brummer99,Fletcher16a,Fletcher16b,Pithan18}. During MCAO events, strong temperature contrasts between the ocean surface and the overlying cold air generate intense buoyancy fluxes that rapidly deepen the MBL. This rapid expansion of the MBL entrains free-tropospheric air, which can eventually decouple the cloud layer from the surface moisture sources and lead to cloud breakup \citep{Tornow23}. Concurrently, cloud thickening during MCAOs leads to rapid accumulation of liquid condensate, enhancing collision-coalescence processes and eventually triggering precipitation-driven cloud breakup \citep{Abel17}. Furthermore, subfreezing cloud-top temperatures are common during MCAO events, making frozen hydrometeors prevalent. As a result, mixed-phase processes such as riming can further accelerate condensate removal and, thereby, cloud breakup \citep{Abel17,Tornow21,Karalis22,Chellappan24}. Consequently, accurately capturing cloud morphological transitions during MCAOs remains challenging even for process-resolving models, owing to the strong sensitivity of transition onset to the representation of microphysical processes \citep[e.g.,][]{Abel17,deRoode19}."

Figure 7, caption: Do colors indicate max Nd or CTT?

Thanks for catching this, it should be max N_d. We fixed it in the revision.