Response to Reviewer Comments for McCoy et al: *Increased Dynamic Efficiency in Mesoscale Organized Trade Wind Cumulus Clouds*

General:

Thank you for your detailed and thoughtful reviews. We appreciate you taking the time to provide extensive, constructive feedback and suggestions to help improve this manuscript. We have implemented the suggested changes, as described in more detail below. Reviewer comments are in blue and replies are in black with manuscript text in *italics* when crucial to include in the responses. See tracked changes for complete text updates as they are extensive.

Reviewer 1:

This paper investigated the dependence of cloud and updraft properties on mesoscale organization using doppler-wind lidar observations from the ATOMIC/EUREC4A field campaign. They split the days into more organized (MO) and less organized (LO) days based on satellite images. They show that MO have stronger and more variable updrafts, and this holds when constraining by size of updraft. They show that LO has distinct diurnal cycle in updraft properties whereas MO does not, suggesting MO is reinforced by dynamical processes associated with mesoscale organization, consistent with LES studies. They also show that the environmental differences between MO/LO (e.g. wind speed, lower tropospheric stability) are consistent with the previous studies using sugar/gravel/fish/flowers categories.

This is a well-written and thorough paper, with interesting results that should be read by everyone working on cloud organization of trade-wind cumulus. I have a few (very) minor comments below, but I am otherwise happy for this to be published without any further review.

Thank you for your exceedingly positive and helpful review of our paper. We are extremely pleased that you found this to be such a helpful contribution to the field. Thank you for your constructive comments, they have helped to improve the strength of the manuscript and refine our results.

- L250. The discussion from this sentence to me doesn't quite match up with what is shown in Fig. 4. The statistical tests show that there are significant differences between MO and LO, but to me the differences among different times within MO or LO don't always look significant. Particularly 4c, seems to indicate there is little to no significant diurnal cycle in W_cb,core. The statement that the largest mean in MO is 6-12UTC, could be 12-18 depending on where you look. Similarly the "gradual ramp up in mean and variance" for LO does not look so clear and depends on where you look

  Thank you for this comment. We agree that there is little cycle within the composites. We have modified this paragraph and clarified where differences are significant within the cycles. We have also added the cycle for the variance (f, right) which has a more robust difference (also seen in original panel b) diurnally for MO. We have also adjusted the other discussions about the potential connections with the environmental cycles to reflect this more accurate framing.

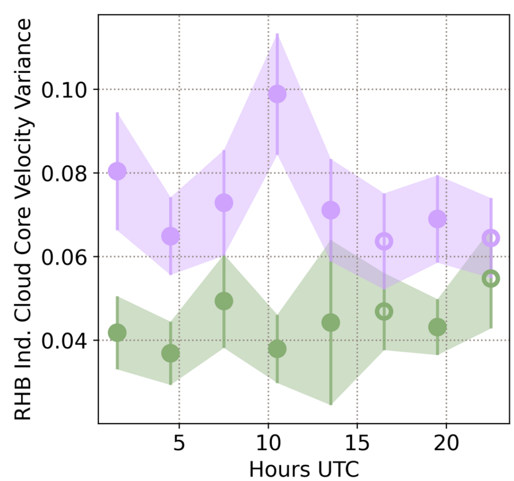


Figure 1 New Figure 5f

- L265. Could you just show the fraction successful. There still does appear to be a small right shift in L_plume,clear, even though the shift on L_plume,cloud is more apparent
  Thank you for this suggestion. We have added a panel (new Figure 6c, below) showing the fraction of successful plumes, taken as the ratio of the number distributions of the cloud-topped and clear-sky plumes: #cloud-topped plumes/#clear-sky plumes = plume success fraction. This comparison is much clearer, and the text has been updated accordingly.

- L306. The formatting of W_CB,Core and L_CB,Core is different. Lower case "B" and missing a space
  Thank you for catching this. We have corrected the formatting now.

- L328. You say likely from Feb 9th. Would it be possible to check. Replot the same curve with data from Feb 9th excluded
  Thanks for this question and the suggestion. Yes, if we remove February 9th, the pdfs are well separated (below). Text has been updated accordingly.

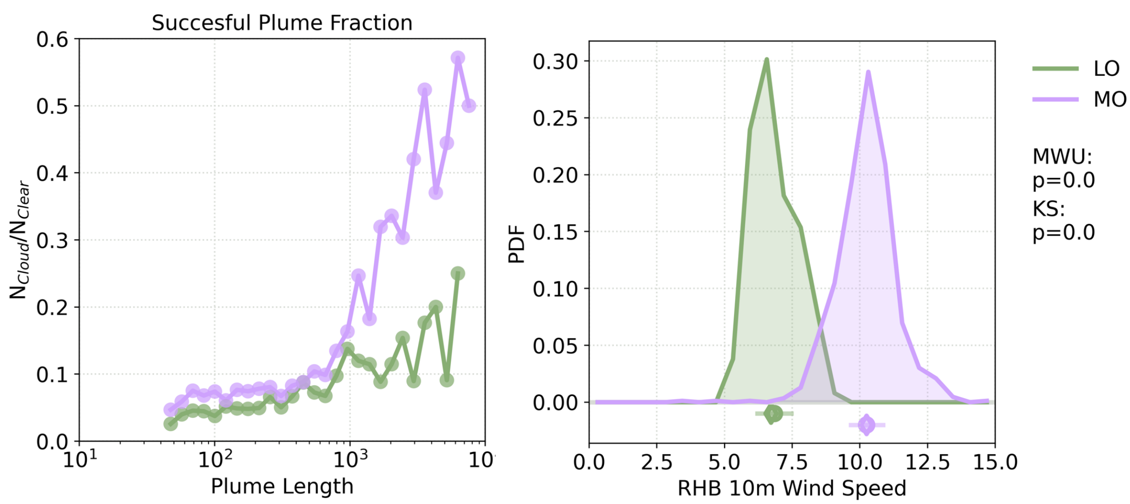


Figure 2 New Figure 6c (left) and test of dependence on February 9th, not shown in manuscript (right).

Reviewer 2:

General comments:

This manuscript uses ship-borne stabilized Doppler wind lidar measurements to study vertical motion underneath trade cumulus clouds over the tropical Atlantic during the ATOMIC/EUREC4A field campaign. It delivers an important, previously unrecognized finding: Their observations indicate that trade cumuli can achieve appreciable cloud-base mass flux variability at a constant thermal size, by varying the vertical velocity (wcbcore) per unit thermal witdth, especially in the upper sub-cloud layer. This “variability” is quantified by studying differences between scenes where the clouds are “less organized” (LO) and “more organized” (MO).

Additional conclusions are:

- The raised wcbcore in MO scenes relative to LO scenes increases as the cloud-base core sizes get bigger, because MO clouds continue to attain larger w as they grow, while LO clouds do not. The authors hypothesize that this can be explained by dynamics preventing the LO clouds to continue raising wcbore, and tie it to raised stability in the profile aloft.

- By quantifying the "environment" throughout the diurnal cycle, it is suggested that LO thermals and clouds are closely tied to the diurnal cycles in surface fluxes and winds, but MO wcbcore is kept high for other reasons. It is suggested that LO clouds are inhibited by stability aloft, and that MO clouds' heightened wcbcore create moist layers aloft at the expense of drying the subcloud layer.

This work is unique, novel and interesting to a large community studying the role of trade cumuli in climate, and I would recommend it be published, though I would request the authors consider a few modifications and thoughts.

Thank you for your comprehensive summary of our results and your extensive assessment. We have worked to address your concerns below and hope that the manuscript is more clearly tied to the theoretical framework in the literature and the results are better contextualized now. More detailed replies to your concerns are provided below.

First, I would ask the authors to explain more precisely how they distinguished "more/less organized" scenes (see comment line 187). Their interpretation throughout the paper leans entirely on this distinction, but while they do quantify it using measures of organization, they never actually explain how they distinguished one from the other. Presenting at least some typical examples of the different scenes would help readers relate to what they are actually quantifying the differences between.

Thank you for raising this concern. We agree that defining the organization is a very important part of this paper and is why we devoted Section 2.2 to discussing our methodology. We have now augmented this discussion with two new figures in the appendix to help clarify our rational in visually distinguishing between small cloud structures that are in organized patterns (all MO days shown in the new Figure A3) vs. those that are more randomly distributed (same for LO shown in new Figure A2). We have answered in more detail in your specific comments below and expanded on the motivating questions about early stages of organized cloud development we are trying to answer here.

Second, where I find the parts of the manuscript that quantify and present the results clear, I find the interpretations often to be less precise. Most of my specific comments address parts that I struggled to parse, so addressing them will help. Generally, I would suggest the authors present something like a conceptual picture, or framework, that ties their observations to the mechanisms they propose to connect them, or that they consider developing the ideas they hypothesize to explain their result more explicitly in the text. Here are a few concrete questions I was hoping to find answers to:

Thank you for this comment and critique of our paper. Because this is such a widespread concern about the paper, we have reworked the text to strengthen the connections to the underlying theoretical mechanisms for mesoscale organization that we think are occurring here (Bretherton and Blossey, 2017; Janssens et al., 2024, 2023; Narenpitak et al., 2021), summarized in new Section 3.1 and updated throughout including a new diagram that we use to connect our results with the theory (new Figure 2, below). More specific replies below and in the specific comments section.

- What (exactly) are moisture-convection feedback, "cloud-layer circulation" and how do the authors suggest they drive or feed back on the dynamically different MO/LO thermals?
  The moisture-convection feedback is the underlying framework that mesoscale organization operates on. The lifecycle will go something like this (also see Section 3.1, Figure 2):
  - A trade cumulus cloud forms on top of a thermal plume and heat is released as moisture condenses in the cloud, creating a moist and hot spot in the atmosphere

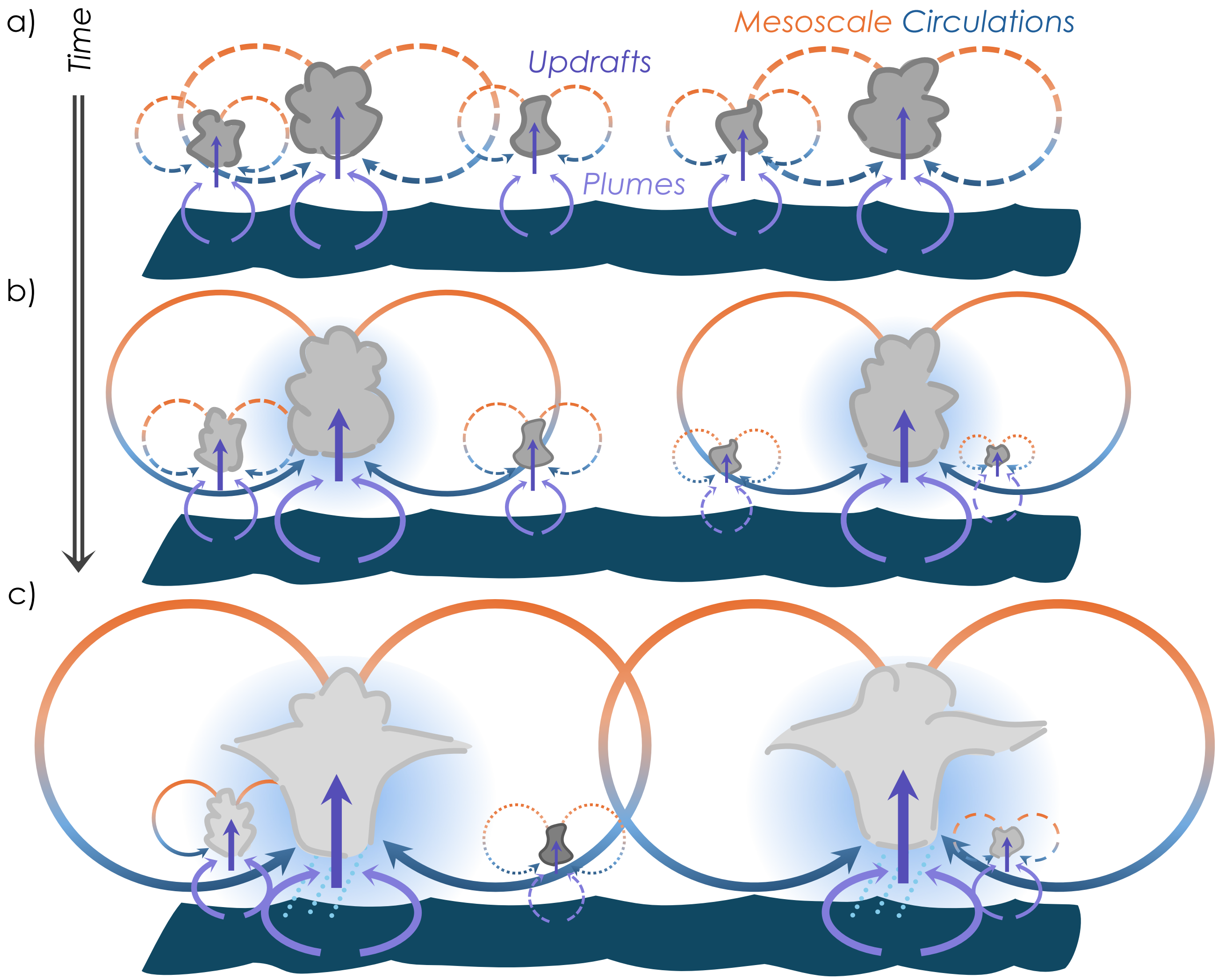


Figure 3 Diagram illustrating underlying theory of mesoscale organization driven by moisture-convection feedback. Results of our study are integrated into this figure, referenced throughout the analyses. Specifically, increased dynamic efficiency with strengthening organization is shown in the strengthening updrafts for similar core sizes (purple straight arrows).Plume widening and increased plume success in ascending branches are also shown.

  - BB17 argue that weak temperature gradient balance applies here, helping to explain the subsequent behaviors (Bretherton and Blossey, 2017).
  - J23, 24 expand on this theoretical framework for their non-precipitating cumulus study (Janssens et al., 2023) and more developed mesoscale organization study (Janssens et al., 2024).
- Heat generated through condensation will be expelled via gravity waves, i.e., approximately maintaining the weak temperature gradient (WTG). This is the initiation of mesoscale circulations, which are small at this stage.
- Circulations aggregate water vapor in their ascending branches, supporting cloud development. Clouds reinforce the circulations through their condensational heat release. This is the moisture-convection feedback.

- As moisture fluctuations become larger, the circulations become more extensive (i.e., length scale growth, J23), and the organization patterns develop larger cloud features (Bretherton and Blossey, 2017; Janssens et al., 2024; Narenpitak et al., 2021)
- Our observations in non-precipitating more and less organized small clouds led us to the "dynamic efficiency" hypothesis about the early stages of the moisture-convection feedback:
  - Once mesoscale circulations have been initiated in a cloud (through heat released from condensation triggering gravity waves, maintaining WTG), that circulation feeds back on the plume supporting the initial cloud as the ascending branch converges sub-cloud. This adds an extra boost to the cloud under organized states below and at cloud base in addition to the local buoyancy effect from condensation.
  - This increased dynamic efficiency (i.e., greater vertical velocity in updrafts for a given core size) strengthens the mass (moisture) fluxed into the cloud, generating more condensational heat release and strengthening the mesoscale circulations further.
  - Turbulence in MO clouds is also larger, consistent with the wider plumes. Plumes are more successful in these ascending branches, occurring in a moister environment and with the assistance of the returning, ascending circulation branch to cohere the plume into a stronger, successful updraft.
  - Thus, organization induced dynamic efficiency helps to explain how the moisture convection feedback helps to accelerate the process of mesoscale organization through strengthening vertical velocity in the ascending branch and increasing introduction of moisture into the cloud layer, generating more condensational heat release, strengthening circulations, and supporting the continued moisture-convection feedback.

- How can stability at 3000m explain the inhibition of LO (but not of MO) plumes at cloud base? If, as the authors hypothesize, stability controls LO's wcbcore, then can they be sure that the fact that the clouds are differently organized actually matters? After all, could LO's inhibition then be entirely controlled by stability, while it is merely a coincidence that the cloud scenes visually look different?

  Thank you for these questions, which we'll answer together here as well as addressing below and in the text.

  - The LO clouds experience higher and more temporally extensive stability (with LTS matching MO stability only during midday). We suggest that this makes it a harder environment for the LO clouds to establish themselves and flourish as they have to fight against greater tropospheric stability for longer. This likely impacts the success rate of the LO clouds. However, this may not impact the velocity at cloud base itself as much as it just sub-selects for clouds that are able to develop. The enhanced stability will likely impact how deep the LO clouds can grow, however, which we now discuss in more detail. MO clouds can grow deeper and likely contain greater liquid water given they are geometrically more extensive (Figure 12a). If this is the case, it means that they likely have greater condensational heat release which generates more buoyancy in the cloud locally and trigger more gravity waves. Compared to the shorter LO clouds, which cannot grow as deep and thus have less liquid water, they can achieve an extra boost from both the mesoscale circulations and the direct buoyancy increase from condensational heating.

- To address your second set of questions together, yes clearly you have co-variability between environmental controls and organization traits (Bony et al., 2020; Jansson et al., 2023; Schulz et al., 2021), making this a bit of a chicken and an egg problem. However, prior work in the literature directly addresses this (Narenpitak et al., 2021). They use LES to test whether a weakened stability case (WeakW, greater mesoscale vertical ascent) influences the development of Sugar into Flowers. While both the Control and WeakW cases develop into Flowers, the WeakW cases can produce larger cloud features. Environmental conditions can enhance organization and cloud traits, which we are not debating here. However, we are making the point that there is a multi-tiered process where the greater stability impairs the LO clouds from deepening, reducing the amount of buoyancy produced locally and impairing the mesoscale circulations enhancing the updrafts, thus weakening the relationship between wcbcore and Lcbcore.

I am not saying the authors need to answer these questions conclusively in this manuscript, I would simply ask them to consider placing the results more specifically in the context they have chosen.
Thank you for urging us to clarify our thinking. We have tried to do this and look forward to your evaluation.

Specific comments:
Introduction: Would the authors consider sharpening their broad introduction of several issues relating to shallow cumulus organisation, to knowledge gaps that their study fills? How does their "focus on observationally examining the influence that mesoscale organization has on the updraft velocities of wintertime trade Cu" relate to the motivating questions they introduce: i) cloud-radiative effects, ii) hydrological cycle changes, iii) cloud feedbacks?
Thank you for this comment. We agree the connection between these ideas and the study needed to be refined. All of these aspects are united through the process of mesoscale organization via the moisture-convection feedback. We are looking specifically at the early stages of this organization taking root and asking how this modifies the dynamics of the clouds, which impacts the amount of moisture imported into the cloud layer (i.e., how bright and moist they can grow, which impacts the radiative and moisture budget) and the potential sensitivity clouds have to the environment when organized (e.g., cloud feedback implications). We have also clarified the theoretical framework we are using to think about these results (Bretherton and Blossey, 2017; Janssens et al., 2024, 2023; Narenpitak et al., 2021), as mentioned in a different comment. We have emphasized the role of the moisture-convection feedback throughout the introduction now and added an explicit paragraph discussing these connections, copied here for clarity:
The potential key role of the moisture-convection feedback, and thus mesoscale organization, in controlling Cu impact on the radiative and hydrologic budget of the tropics motivates two questions: i) how does the moisture-convection feedback alter Cu updraft dynamics?; ii) at what organization state does this influence begin to appear? To answer these, our study focuses on observationally examining the dynamical differences between organization states of wintertime trade Cu cloud systems as they initially develop. Understanding the early-stage formation dynamics of organized systems allows us to evaluate whether there is a contribution of velocity variability to CB mass flux in less organized environments that grows with circulation scale-growth (i.e., Janssens et al. 2024). Impacts on CB mass flux from updraft dynamics has implications for how much moisture is brought into the cloud layer (i.e., influencing the moisture budget through charge cycles) and how bright these clouds can grow (i.e., influencing the radiative budget through deepening and brightening cloud structures). This also has potential implications for the sensitivity of cloud systems to their environment and whether early onset of

organization-driven differences in cloud dynamics helps to sustain organized cloud system formation and duration. While addressing these questions does not directly help improve Cu parameterizations within GCMs, it provides broader context for pinpointing processes important to capture in models (e.g., does mesoscale organization matter for capturing the mean cloud state and their environmental sensitivity?).

Line 99: I believe those authors find that vertical velocity variability only becomes important at large values of mesoscale vertical ascent, while cloud amount variability retains leading-order importance?
We have corrected this sentence as suggested, thank you.

Line 136: The two cloud fraction composites broadly agree, though there is a low bias in the doppler lidar-derived cloud fraction. Are these results sensitive to the "range-corrected intensity" threshold they mention? Is there additional salient information to be shared about this procedure?
Thanks for these questions. The ceilometer measurements at approximately similar cloud bases (now Figure A4 c, z≤800m) falls a little below the Doppler cloud base amount near the LCL (A4 a) and is on average the same statistically. We have clarified in the text that this is an approximate comparison between the ceilometer and Doppler measurements and that they will differ because of retrieval method and resolution. Specifically, i) the CBH cutoff for the ceilometer is approximately chosen to match the CBH distribution from the Doppler, not restricted to match the LCL±50m restriction, ii) the sampling rates are different between the Doppler (2Hz) and the ceilometer (10s), and iii) the Doppler does not include cloud samples of ≤10s in the cloud scene dataset as they are too small (≤20 measurements at 0.5s) but these are likely still included in the ceilometer. This comparison is provided as a sanity check to show that the filtered Doppler cloud scenes are capturing most of the clouds overpassing during these two periods.
For your questions about RCI, we have added more information about how the RCI threshold and cloud scene processing was conducted following previously developed methods for Doppler lidar retrievals in cumulus clouds (Lareau et al., 2018). Sensitivity tests were conducted on the RCI threshold early in the development of the RHB dataset and the RCI distribution was compared to the bimodal distribution in Lareau et al. (2018) that distinguishes between cloud and aerosol samples.
These details have now been worked into the methods section.

Line 140: So a "cloud scene" includes all points between -1.5 to 1.5 x/Lchord, with Lchord defined by the RCI thresholding, and 0-2 z/CBH, with CBH defined how? From the ceilometer? It might be worthwhile defining "cloud scene" explicitly, for a reader's convenience
Thank you for asking about the cloud scenes. We have revised this section to clarify what is a cloud scene (i.e., aggregated profile measurements that contain clouds). The CBH is calculated as the 25th percentile of all profile CBH included in a given scene. The CBH for each profile is determined as the lowest pixel (~0.5 s by 50 m) that satisfies the RCI threshold for cloud identification.
These details have now been worked into the methods section.

Line 150: What is the motivation for, and is there sensitivity to, choosing an hourly-averaged wind speed at cloud base to define Lchord? And what is the reason to choose a different wind, the surface wind, (also hourly averaged?) to scale the w-plumes?
Thanks for asking about this. Our methodology is to scale the feature of interest (i.e., CB length, plume length) by the windspeed that most directly corresponds to where the feature is occurring in the atmosphere. Because the plumes are both cloud-topped and clear-sky, we could not use the CB wind to

scale the plumes. As these are surface driven, it makes sense to use the near-surface wind speed for those features. Likewise, as we care about the length of the CB it makes sense to scale by the speed of the wind at that altitude as it could theoretically be moving at a different rate than lower down. As it turns out, there is negligible wind shear across the BL between the surface and CB in this study (e.g., Figure 9a) so the distinction between the plume and CB scaling is not important for these observations. We used the hourly average wind speed from the Doppler lidar as that was the vertical profile of horizontal wind speed that was available with the highest resolution (sondes are every 3-hours) and it had matching measurement characteristics (as from the same instrument) so would introduce less additional uncertainty.
These details have now been worked into the methods section.

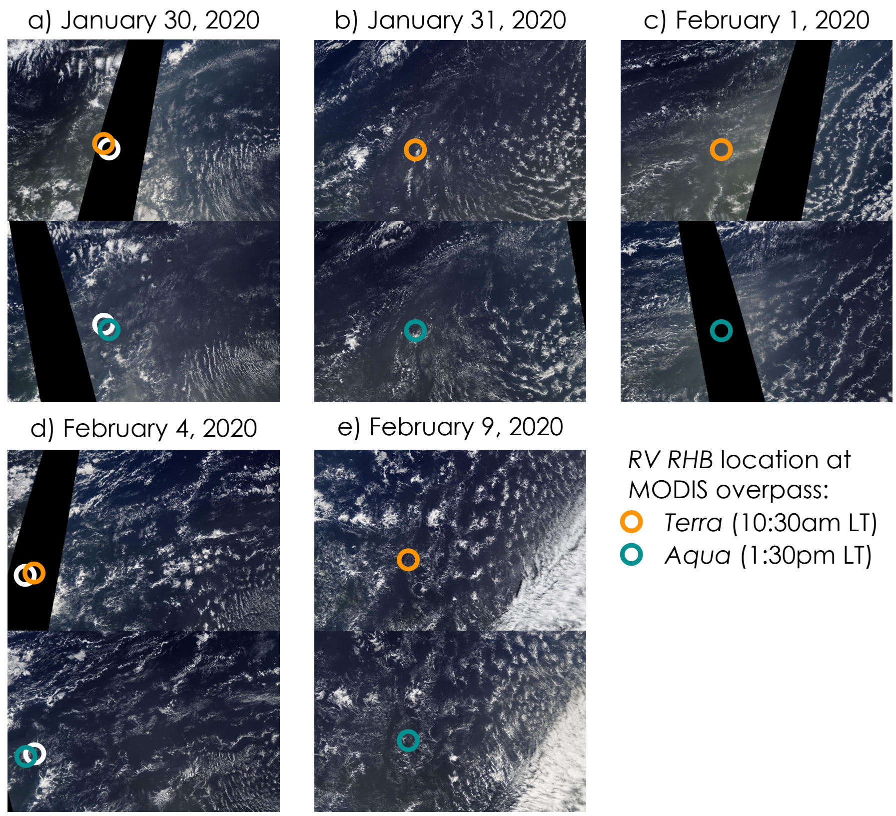
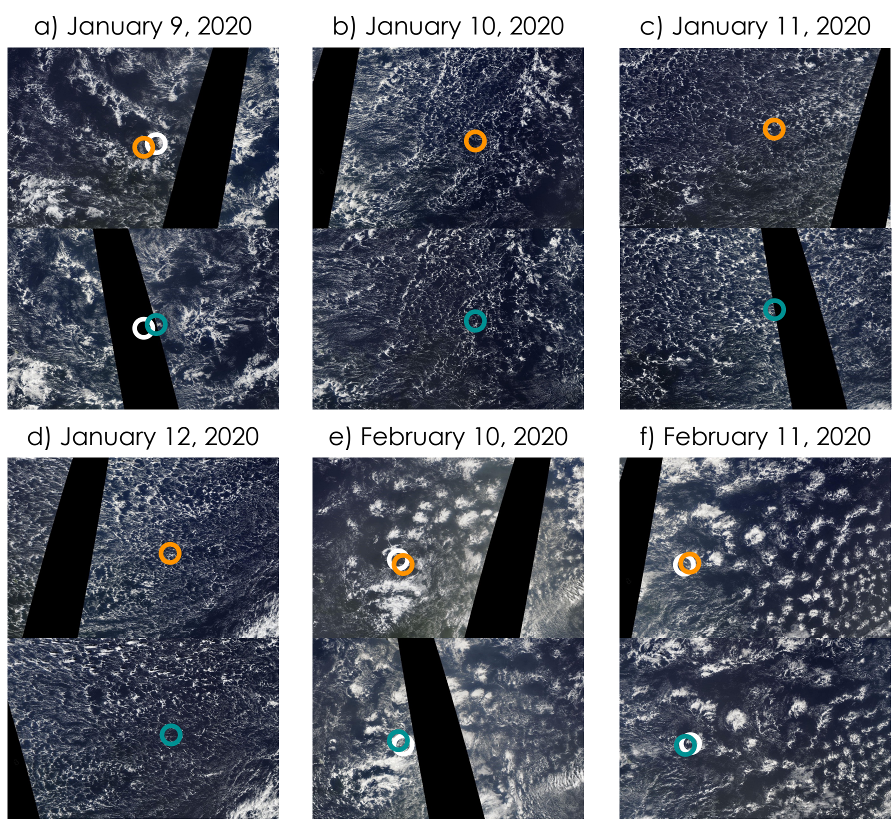


Figure 4 New Figure A2 for LO days (above) and New Figure A3 for MO days (below)



Line 187: Could the authors elaborate a little more on how they distinguish between LO and MO scenes from Terra/Aqua imagery? Purely by eye? They separate very nicely in their Iorg/S space, why then not just use a more objective distinction? And is the subjective distinction the classification that is used the rest of the paper? I would invest this effort, because it is presently not entirely clear what “more organized” and “less organized”, the fundamental distinction on

which the authors base their conclusions, are defined. I wonder if the results' interpretability would be enhanced if it is made clear what physical hypothesis underlies this distinction.
Thanks for raising this point. We have tried to clarify our method here and across the text and have added a diagram (Section 3.1, Figure 2) and further discussion of the physical hypothesis here and in the results (see your other comments) to help clarify our rational. To reiterate here for clarity, the dataset we are working with has a particularly good sampling of small clouds that, for the most part, are not-precipitating and are upwind of the rest of the EUREC4A sampling of more developed cloud systems near Barbados (George et al., 2023; Vogel et al., 2022). That provides a unique opportunity to evaluate the early stages of organizing clouds. Our work is focused on observationally evaluating the early stages of organization development and how the growth of mesoscale circulations modulate the behavior of clouds (e.g., though influencing their velocity profiles and mass fluxes). There are theoretical frameworks that help to contextualize the behaviors we observe: small, non-precipitating cloud systems develop mesoscale circulations due to dispersion of condensational heating in clouds through gravity waves (i.e., to satisfy the weak-temperature gradient), organizing cloud systems further into mesoscale patterns and developing a moisture-convection feedback (Bretherton and Blossey, 2017; Janssens et al., 2024, 2023; Narenpitak et al., 2021) that drives the circulations as the cloud systems are advected West. In our analysis, we are focusing on cases that have small, randomly spaced clouds (LO) and those that have begun to organize into patterns (MO), undergoing some amount of influence by mesoscale circulations and the moisture-convection feedback but not as much as is seen near Barbados.

To specifically address your questions about the organization identification that we use, we are using the by-eye identifications based on the MODIS Aqua and Terra imagery. We have added reference images for the MO and LO days showing the location of the RHB in the morning (Terra) and afternoon (Aqua) in the cloud fields (new Figure A2 and A3).
There are several reasons for why we did not use the objective metrics, even though ideally we would have preferred to do this. A big challenge in this analysis was how to unite a small, point source measurement with a large-domain, satellite organization identification. While this has been successfully done in prior studies (Schulz et al., 2021; Vial et al., 2021), we are too limited in data amount to have the quality control necessary for reliable statistics. Some of the issues:

- The Iorg and S dataset is centered on the 10x10° region near Barbados. The RHB was often sampling on the edge of the domain, not at its center, making the Iorg vs S assessment more approximate. To apply the objective method correctly, it would require calculating those metrics on a domain centered on the RHB. This computation is beyond the scope of the current project.
- Prior studies have been able to leverage their large data and have organization types occurring at all times over the diurnal cycle (Schulz et al., 2021; Vial et al., 2021). This was not possible for the small sample we had. Additionally, we know that organization fluctuates over the course of the day (Denby, 2023; Koren et al., 2024; Narenpitak et al., 2021). This confuses the problem as it subdivides the behaviors over a given day across multiple organization classes. To examine a cohesive signal in the diurnal cycle analysis to determine if there is a diurnal influence from the environment on these clouds, we did not want to subdivide the days and add additional noise from day-to-day environmental variation. This is potentially less of an issue in large data analyses although it should also be thought about there.

These details have now been worked into the methods section.

Line 215: Perhaps I missed this: Is "variance" horizontal variance at a height level, computed on single identified plumes, and then composite-averaged? I.e. is it really a composite measure of intra-plume turbulence?
Yes, that is correct. For each cloud scene, we identify the positive velocity sub-cloud and compute the mean and variance for each scene. These individual scenes are composited together. We show the mean and 2SE for each height bin from this composite, clarified in the text.

Line 235: Do the authors mean figure 2 ac?
Thanks for checking but no, this paragraph is describing Figure 4a,c (formerly 3) where the updraft profiles have been composited by the cloud base core length.

Line 241-245: This is an intriguing finding, and I wonder if the authors may wish to suggest more specifically how cloud-layer organisation influences the thermals. Are the authors suggesting that there may be pressure gradients extending down from the cloud layer, thus accelerating the thermals vertically? How would they be driven? Also pertains to discussion around line 270: How specifically would the cloud layer increase the success rate of the plumes in MO conditions? And 285: What specifically could a mesoscale ascending cloud layer do to thermals underneath? How is it related to "moisture-convection feedback"? And how does the test the authors perform (correlating Lplumecloud to Lcbcore and wcbcore) actually test these mechanisms? Finally, a "classical" reading of subcloud-layer thermals might involve a w*, defined solely on the basis of a surface buoyancy flux and relevant scales. My understanding is that most theories suppose this cannot change, so long as the surface forcing doesn't change. Are the authors suggesting that this velocity scale is no longer appropriate in MO situations, because there are cloud-layer forces controlling the velocity scale? It may be worthwhile for the authors to juxtapose their findings against such classical frameworks, to place their novel findings in context.
Thank you for highlighting these spots that needed more clarity. We have worked to explain the reasoning behind how we think the mesoscale circulations are enhancing updrafts and thermals. We added a theory section at the beginning of the results including a diagram of the mesoscale organization (Figure 2, detailed in the general responses above). For each of your highlighted lines we have clarified how the condensational heat-driven mesoscale circulations originating from the cloud layer influence the updrafts, plumes/thermals, and the relationship between the plumes and CB dynamics (which is what the Lplumecloud to Lcbcore and wcbcore comparisons are looking at). Specifically, the updated lines connected to your questions are:

- *Plume success increases with* L_{Plume} *for both organization types but the MO success rate increases far more rapidly, diverging from LO after 1 km. This organizational difference in success rate is another potential marker of cloud-layer driven mesoscale circulation, e.g., through the ascending circulation branch cohering plumes into stronger updrafts and lowering the LCL through converging moisture (Figure 2a, b). For a given plume width, MO clouds likely have deeper (e.g., Figure 12c) and moister clouds due to the moisture-convection feedback. As plumes increase in size, potentially through turbulent enhancement by mesoscale circulations, they can also support larger clouds. Thus, MO clouds for* $L_{Plume\ Cloud}$ *>1km have an exponentially greater potential to generate heat through condensation release, which will further reinforce mesoscale circulations, plume success rate, and organization.*
- *Organizational differences manifesting primarily in* $L_{Plume\ Cloud}$ *indicates plumes may be reinforced by a cloud-associated process, potentially including cloud-layer driven mesoscale circulations (i.e., Figure 4). The reinforced plumes likely feed back on clouds through supporting*

stronger cloud updrafts in the ascending branches of mesoscale circulations, increasing cloud success rate and helping to cluster clouds further through the moisture-convection feedback (i.e., by lofting more moisture into cloud, generating more condensation, and strengthening the moisture-converging, mesoscale circulations, Figure 2a, b).

- *To understand whether the organizational differences in plume behavior impact CB dynamics and thus CB mass flux, we contrasted the relationships between* $L_{Plume\ Cloud}$ *with* $L_{CB\ Core}$ *and* $w_{CB\ Core}$ *(Figure 7). Because of the different plume width distributions between LO and MO (Figure 6b), the CB core variables have been binned into quantiles by* $L_{Plume\ Cloud}$ *for ease of comparison. Linear regressions are performed on the underlying data. Hypothetically, for a given* $L_{Plume\ Cloud}$*, a stronger relationship with MO* $L_{CB\ Core}$ *would indicate that wider plumes support larger core area, e.g., through more cloud aggregation in ascending circulation branches. A stronger relationship with MO* $w_{CB\ Core}$ *would suggest that mesoscale circulations affect the updraft dynamics directly, e.g., contributing dynamically through strengthening the updrafts in ascending branches. Wider plumes associated with more organization could be supporting both of these effects, modifying CB mass flux in two ways.*
- *…Based on regressions on the quantile binned values, more variance is explained in* $L_{CB\ Core}$ *by* $L_{Plume\ Cloud}$ *for MO (73%) than LO (34%). While this indicates that plume width is more directly translating to core size in MO, the similarity in relationships between LO and MO suggests that core size has not been significantly modified by organization effects (e.g., cloud aggregation) at this stage of cloud development (Figure 2a, b). More organized stages beyond MO may see a larger impact (Figure 2c).*
- *…The offset between the LO and MO lines is a clear indication that for a given* $L_{Plume\ Cloud}$*, MO clouds have stronger* $w_{CB\ Core}$ *than in LO clouds. These comparisons mark an important finding: for a given plume width, and thus core length, MO clouds achieve stronger CB core velocities and have increased mass flux into the cloud layer. This may be a manifestation of returning cloud-layer driven mesoscale circulations boosting updraft strength in their ascending branches (Figure 2a, b).*
- *In short, we find that MO clouds are more "dynamically efficient": for a given core size, updrafts are much stronger for MO clouds compared to LO clouds. We hypothesize this is due to the returning, ascending branch of mesoscale circulations strengthening the updrafts of clouds as well as aggregating moisture and, potentially, widening turbulent plumes (Figure 2). The increasing separation with increasing* $L_{CB\ Core}$ *is consistent with the expectation that mesoscale variability contributions become more significant at larger cloud sizes (Janssens et al. 2024), emphasizing the importance of understanding organization influence on cloud behavior. We further see that, as suggested in* $L_{CB\ Core}$ *composites (Figure 4), LO* $w_{CB\ Core}$ *flattens out at larger* $L_{CB\ Core}$ *while MO continues to increase (though at a slower rate of increase than* $L_{CB\ Core}$ *<~250m), apparently less assisted by the cloud-layer driven phenomenon or less constrained by the environment. Whether this inhibition of LO may be set by its environmental conditions is examined in the next section.*

In regards to the classical reading of subcloud-layer thermals, recent LES work has shown that it is unlikely that mesoscale variability in surface buoyancy fluxes is driving mesoscale organization (Janssens et al., 2024). We reference this in the new Section 3.1 and discuss how our results, showing that LO and MO updrafts are relatively persistent diurnally despite large flux cycles (though similar mean surface temperatures), is consistent with that. Plumes are initially driven by the surface but we argue that the enhancement of updrafts in MO is associated with the mesoscale organization process helping the updrafts sub-cloud. An exact evaluation of how mesoscale buoyancy connects with surface buoyancy scaling in the context of the observed cloud behaviors is beyond the scope of this project and would likely require detailed modeling.

Line 413: How do the authors suggest that a stronger capping inversion could flatten the wcbcore-Lcbcore relation, even after subselection? That is, what does Lcbcore have to do with the response to stability? Also, could the authors motivate more clearly what they suppose the feedback is from the strength of the capping inversion to the clouds at cloud base? From the profiles in figure 10, it seems that the local stability of that layer is comparable between LO and MO, so what is the non-local influence from the inversion?

Thanks for your questions on this, we were not sufficiently clear in expressing our thoughts before. We went into more detail in reply to your general question above, but in brief the argument here is that greater stability means LO clouds can't grow as deep and contain as much liquid. This damps their condensational heat production, reducing the local buoyancy enhancement and the mesoscale circulations that may be enhancing updrafts here. The behavior diverges more for the larger cores/deeper clouds. We have added the following to expand our reasoning:

Specifically, greater stability in LO will restrain clouds from deepening as much as in MO conditions, reducing their geometric depth (Figure 12c) and liquid amount. We hypothesize that this damps their ability to release heat through condensation which impairs both the local buoyancy enhancement from heating and the generation of mesoscale circulations, resulting in less updraft strengthening for LO clouds than MO clouds (Figure 2a, b). The divergence between LO and MO curves grows with $L_{CB\ Core}$, consistent with deeper clouds being more enhanced. The opposite tendency has been shown in LES where a reduction in stability enhanced the transition from Sugar to Flowers and produced larger cloud features (Narenpitak et al. 2021). Further evaluation of the connection between environmental controls, dynamic efficiency, and mesoscale organization mechanisms is warranted.

Line 432: Can the authors conclude so strongly that the increased wcbcore in MO clouds supports their larger radiative impact? It seems logical that such systems, due to their increased dynamical contributions to cloud-base mass flux, produce deeper systems with larger coverage, but the result presented just contrasts MO and LO clouds, and these could differ in numerous other ways. For instance, if the MO cloud layers are indeed substantially moister, perhaps a lack of entrainment drying is decisive in deepening them. I do think attributing radiative impact to dynamical efficiency is an interesting direction for the authors to pursue further (in future work), perhaps with simple plume models rising through the observed environments.

Thank you for this suggestion and ideas. We have modified this paragraph accordingly:

Geometrically deeper clouds imply greater liquid water in the column and thus larger optical depth. ... We also find that the total BL cloud amount (ceilometer measured CBH≤3km, Figure A4d) is statistically larger for MO than LO (40±4% vs. 22±6%) despite their similar CB amounts, implying larger MO clouds potentially with detraining layers (a-c). Thus, MO clouds greater dynamic efficiency likely supports a larger radiative impact due to their greater optical depth as well as their larger cloud amount (e.g., Gravel vs. Sugar, Bony et al 2020). This potential connection between dynamic efficiency and impact on the radiation budget is worth investigating in future work.

Line 440: How do these observations square with the observations from the same field campaign, presented by George et al., (2022), which observe moister subcloud layers when the column is ascending at mesoscales (and so presumably a more organised cloud cluster is passing)? (The authors do not need to answer in the text, it just strikes me as a curious contrast)

Thank you for bringing this up, it's a valuable comparison to make. G23 (George et al., 2023) are studying a different region than the majority of samples from the RHB. The HALO circle examined in G23 is downstream, near Barbados, where the degree of organization is larger. While some organization has occurred, the strength of mesoscale circulations is not as fully established as in the more organized, downstream cases (e.g., Figure 2b vs. c). An interesting possibility here is that the strength of the updrafts in MO may be enough to pull moisture into the cloud but the mesoscale circulations have not developed to the magnitude needed to aggregate sufficient moisture to restore this export. Thus, you could potentially have this opposing result at this time in the Lagrangian cloud development (where the mesoscale systems are still relatively weak before kicking up towards Barbados). It would be interesting to evaluate this difference, i.e. between moisture behaviors dominated by local cloud processes (i.e., where moisture is being pumped into the cloud and mesoscale circulations aren't big enough to restore it yet) vs. mesoscale circulations (where the circulations are big enough to set up moisture gradients). Note that in G23, the converging anomaly does have a mean moisture anomaly that is positive, but the IQR crosses zero and overlaps with the diverging quantile IQR. We have added:
Note that on average the more organized systems downwind near Barbados exhibit the theoretically predicted moisture enhancement throughout their ascending circulation branches including sub-cloud (George et al. 2023). Contrasting cloud organization stages and their vertical moisture behavior could provide insights into processes dominating mesoscale evolution, i.e., between early stages dominated by local cloud processes and "dynamic efficiency" (MO, Figure 2b) vs. later stages where mesoscale circulations have strengthened enough to enhance moisture throughout the column and restore any previous depletion sub-cloud (Figure 2c).

Line 475: A central finding of this study is that the references in this paragraph have underappreciated the role of variability in vertical velocity when explaining variability in mass fluxes. Yet all these studies seem to have been rather successful at explaining mass flux variability without varying vertical velocity. It would be very interesting to see the authors reflect on how large the errors that the previous studies made were, and where the discrepancies come from (Did they not look? Did they have different tools? Sample different regions?).
Thanks for the question. The velocity variability associated with organizational differences is likely a second order effect while cloud amount dominates, at least up to a certain size of cloud and mesoscale ascent (Janssens et al., 2024). An aspect worth clarifying here is that the underlying assumption of the mass flux closure studies (George et al., 2021; Vogel et al., 2022) is that there is no velocity variability, leaving amount as the key controller. We agree that these studies have been successful in capturing that first order effect (Klingebiel et al., 2021) and producing reasonable mass flux magnitudes varying with environmental controls (George et al., 2021; Vogel et al., 2022). However, mass flux is calculated as a closure in these latter studies, so all variability not explicitly captured in the other mass budget terms is required to go into the mass flux term without distinguishing the source of that variability (i.e., whether updraft strength varies with organization). As discussed below and in the text, it is possible that dynamic efficiency is being inherently included in these evaluations as the calculated mass flux seems to depend more on the dynamic variables (Vogel et al., 2022). The underlying assumptions in the closure argument and the observations utilized are not able to explicitly measure mass flux or account for updraft behavior, making a one-to-one comparison with our analysis difficult. We agree that the closure results appear to outperform GCM parameterizations in capturing cloud behaviors (Vogel et al., 2022). For better process level understanding, however, explicitly accounting for the updraft contribution will be important for capturing how organization modulates updrafts and cloud development/evolution. Observations that facilitated direct mass flux and updraft measurements as well as large scale

measurements could be used to evaluate whether organizationally driven dynamic efficiency is being accounted for in these closure arguments and, if not, how this variability could be introduced into their formulation. This would allow explicit evaluation of the updraft strengthening contribution and address any potential errors. Potentially the long record at BCO would be a good basis for this comparison, although it would be skewed toward more organized structures later in their development. This assessment is beyond the scope of the current study.
We have modified the paragraph to reflect this (also see next comment):

Our results are the first observational demonstration that mesoscale organization modifies CB mass flux through impacting updrafts. This is a divergence from the idea that CB mass flux primarily depends on CB cloud amount, an important assumption in mass budget analyses (e.g., Klingebiel et al., 2021; George et al., 2021; Vogel et al., 2022). The closure arguments utilized in these studies produce reasonable mass fluxes that vary with environmental conditions, out-performing current GCM parameterizations in capturing Cu behaviors (e.g., Vogel et al., 2022). However, our results indicate that the organizational modulations of updraft strength and thus mass flux is an important process piece that may be missing from this framework. The greater dependence of mass flux on dynamic factors (e.g., mesoscale vertical velocity) in Vogel et al., 2022 may be an indication that the organizational contributions are being aliased in, accounting for the increased dynamic efficiency of organized clouds. By definition, all variability not captured by the other budget terms must go into the mass flux closure. However, explicitly accounting for the contribution from updraft strengthening as mass flux increases with organization would provide a key process-level insight for Cu development, informing our understanding of how organization modifies clouds in the trades even from their earliest development stages. Recent work indicates this contribution becomes increasingly important as Cu organizes: cloud velocity variations have an increased contribution to CB mass flux under strengthening mesoscale ascent (Janssens et al. 2024). Janssens et al. (2024) evaluations include a broader range of cloud structure sizes in their simulations while we focus on relatively small structures, early in their evolution across the Atlantic basin. However, the clear organizational differences already apparent in our results indicates that such differences will persist and likely grow larger as cloud systems evolve and grow in structure size across the basin, continuing to undergo mesoscale organization. Our results encourage future evaluations expanding this analysis to a longer observational record, larger organizational scales, and other mass flux calculation frameworks.

Line 479: Revisiting Vogel et al., (2022), it seems to me that there is plenty of variability even in their mass flux-cloud coverage relation (their fig. 3c); could that be directly attributable to variability in mass flux being explained by variability in vertical motion, rather than in cloud cover?
Thanks for highlighting this. In looking at our discussion again, we have made an error in our thinking by attributing skill to the RH inclusion. We agree with your framing that the influence from the mesoscale vertical velocity is potentially what is helping here (also see discussion in previous comment). See text above.

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