



Increased Dynamic Efficiency in Mesoscale Organized Trade Wind Cumulus Clouds

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Abstract. Mesoscale organization of boundary layer clouds modulates low cloud radiative properties and contributes to the tropical hydrologic cycle. Trade-wind cumuli have varying organization and are a notable source of uncertainty in global climate models (GCMs). The linkage between cumulus development and dynamics is difficult to capture, impacting low cloud feedback estimates. We investigate the relationship between mesoscale organization and updraft dynamics in the wintertime trades using ship-borne observations, including a motion-stabilized Doppler-wind lidar. We contrast two periods with similar cloud structure sizes but different clustering: more (MO) and less (LO) organized clouds. MO are dynamically more efficient than LO clouds: for a given core size, MO have stronger sub-cloud and cloud base updrafts, leading to greater vertical moisture transport. Despite similar background environmental plume distributions, cloud-topped plumes are wider for MO than LO. MO updraft strength is less responsive to diurnal variations in environmental factors than LO although both are enhanced during early morning surface flux maximization. Once established, MO clouds may be maintained through the assistance of cloud-layer circulations that facilitate increased dynamic efficiency through reinforcing plumes. Dynamic efficiency is likely a key contributor to the mesoscale moisture-convection feedback critical to these regimes. The influence of mesoscale organization on cloud dynamics through increased velocity variability is another unresolved factor in GCM parametrizations. Understanding this efficiency, and the potential environmental resilience of MO clouds, will be informative for simulating cumulus behaviors under current and future climates.

1 Introduction

Clouds occurring over the ocean in the planetary boundary layer (BL, up to ~ 3 km in altitude) are key components of the climate system. They are important reflectors of sunlight back to space, acting to cool the planet, and can contribute to regional hydroclimate through persistent drizzle modifying the moisture budget (Hartmann and Short, 1980; Wood, 2012). Marine BL clouds organize into mesoscale patterns ($O(100$ km)) of clustered cloud structures that vary across the globe (Atkinson and Zhang, 1996; Wood, 2012). This occurs through a process of mesoscale circulations reinforcing cloud development and per-



sistence, converging moisture into the ascending cloudy branches and drying the subsiding branches (Bretherton and Blossey, 2017; Narenpitak et al., 2021; Janssens et al., 2023; George et al., 2023). This mesoscale moisture-convection feedback is reinforced through longwave cloud top cooling in subtropical stratocumulus (Sc) clouds (Bretherton and Blossey, 2017; Zhou et al., 2018; Zhou and Bretherton, 2019a, b) and assisted by gravity waves in tropical trade wind cumulus (Cu) (Bretherton and Blossey, 2017; Janssens et al., 2024a).

Globally, mesoscale organization modulates the radiative properties of BL clouds by separately changing both the amount and optical thickness of clouds (McCoy et al., 2023; Eastman et al., 2024). As clouds evolve from subtropical Sc decks to the west of continents toward the tropics, they transition from more (Sc) to less (Cu) organized clouds (e.g., Eastman et al., 2021, 2022; Sandu and Stevens, 2011; Bretherton et al., 2019; Muhlbauer et al., 2014). Across this transition, the opacity of clouds decreases with an increase in the generation of precipitation-driven, optically-thin cloud features at the trade-wind inversion (O et al., 2018b, a; Wood et al., 2018; McCoy et al., 2023; Eastman et al., 2024). Once in the tropical, trade-wind region, cloud amount becomes the key factor in controlling low cloud radiative effects (Bony et al., 2020). Effectively, this is a shift from a cloud widening (Sc) to a cloud deepening (Cu) regime (Feingold et al., 2017), altering the fundamental relationship between cloud brightness and amount (Feingold et al., 2017; Bender et al., 2017). This relationship is something that general circulation models (GCMs), used for climate projections, fundamentally struggle to reproduce (e.g., Engstrom et al., 2015; Bender et al., 2017; Konsta et al., 2022).

Whether mesoscale organization in the trades has a net influence on the radiative budget is an open question. Observations indicate more clustered trade-wind Cu are optically thicker (Alinaghi et al., 2024) and have fewer optically-thin cloud features (Eastman et al., 2024). When normalized by cloud amount, more organized Cu also have larger radiative effects (Alinaghi et al., 2024). This indicates that mesoscale organization increases both cloud amount (Bony et al., 2020) and opacity in the trades (Alinaghi et al., 2024), thus impacting the overall radiative budget of the region. However, idealized large-eddy simulation (LES) ensembles indicate that mesoscale organization results in a small net influence on the regional budget because of offsetting effects across the mesoscale circulations: cloud radiative effects are enhanced in ascending branches (i.e., moisture convergence, clouds are more clustered) but they are dampened in descending regions (i.e., moisture divergence, less clustered) (Janssens et al., 2024b).

In addition to their potential radiative impacts, organized shallow trade-wind clouds play a role in the energetic discharge-recharge cycles that facilitate deep convective precipitation in the tropics (Wolding et al., 2024). Tropical clouds undergo a shallow discharge-recharge cycle that builds up both heat in the ocean and moisture in the BL, deepening convection toward the free troposphere (FT). Specifically, as trade Cu clouds organize into wider, more Sc-like clusters, convection and moisture deepen in the BL and extend to the FT (Wolding et al., 2024). This is consistent with the moisture convergence and cloud enhancement that occurs in the ascending branches of mesoscale circulations (i.e., the moisture-convection feedback, Janssens et al., 2024a; Narenpitak et al., 2021; Bretherton and Blossey, 2017; Zhou and Bretherton, 2019b). Simultaneously, ocean heat content slowly builds, despite the rapid surface heat flux conversions to atmospheric moist static energy (Wolding et al., 2024). Under the right conditions, the combined BL moistening and deepening of shallow convection (e.g., moisture-convection feedback) and enhancement of ocean heat content and surface fluxes (e.g., surface forcing) leads to a self amplification of

shallow convection (Wolding et al., 2024; Janssens et al., 2024a). This enables a transition from shallow to deep convection and the start of a new, deep phase of the discharge-recharge cycle, leading to extensive precipitation through mesoscale convective systems (Wolding et al., 2024). In this way, the organization of shallow clouds plays a critical role in setting the moisture budget of the tropics.

How low clouds will respond to climate change is a topic of great concern, as is constraining the representations of low clouds and their feedback in GCMs (e.g., Sherwood et al., 2020; Zelinka et al., 2020; Myers et al., 2021). Subtropical Sc have a substantial positive shortwave feedback on the climate while the trades have a much smaller, near-zero but still positive feedback, ultimately amplifying the warming from increased concentrations of well mixed greenhouse gases (GHGs) (Myers et al., 2021; Scott et al., 2020). Mesoscale organization may modulate this shortwave cloud feedback through regional shifts in morphology occurrence frequency, influencing cloud optical thickness (and likely amount) in the process (McCoy et al., 2023). This shift in occurrence frequency has already been seen since 1971 in the low cloud-dominated, trade-wind dry-season (Eastman et al., 2025). Under increased stability, due to uneven warming across the atmospheric column, surface observers have seen an increase in low cloud amount and rain gauges have documented more precipitation. In combination, these observations indicate a climatological shift toward more Sc-like clouds with more optically thin features. This implies a potential negative feedback associated with morphology that may suppress warming and drying in the Caribbean under future climate change (Eastman et al., 2025). Recent work has also found enhanced trade Cu cloudiness over positive sea surface temperature anomalies on the submeso-to mesoscale as a result of convective updrafts driven by increased surface fluxes (Chen et al., 2023, 2024). Idealized LES simulations projecting two specific Cu types into the future suggest that mesoscale circulations themselves may be hindered due to increased GHGs, further complicating this issue (Kazil et al., 2024).

GCMs project a much larger, positive feedback in the tropics than observations suggest (Myers et al., 2021; Vogel et al., 2022), over-emphasizing trade Cu's response to environmental changes (Nuijens et al., 2015a, b). One explanation for this is over-drying of the BL and cloud base (CB) because of increased lower tropospheric mixing, entrainment, and large scale circulations in a warmer world (Sherwood et al., 2014; Zhao, 2014; Brient et al., 2016). Observational and LES studies indicate that trade Cu are actually more resistant to environmental changes (Bretherton et al., 2013; Blossey et al., 2013; Vogel et al., 2016; Nuijens et al., 2014, 2015a). In particular, cloud at CB (i.e., near the lifting condensation level, LCL) is relatively invariant in the trades and controls the overall low cloud amount (Nuijens et al., 2014, 2015a, b). The "cumulus-valve" mechanism (Neggers et al., 2006) has been used as a conceptual framework to help explain the apparent resistance of CB cloudiness to environmental changes: CB amount is proportional to the mass flux through CB (i.e., the updraft velocity scaled by cloud amount and, often, air density). GCMs tend to emphasize thermodynamics (i.e., relative humidity, Quaas, 2012) more than dynamics (i.e., CB mass flux) in their trade Cu dependencies (Vogel et al., 2022). Cu feedback is understandably difficult to simulate as it is a multi-scale problem: their cloud radiative effect is primarily dependent on cloud amount (Bony et al., 2020) but it is being reinforced by mesoscale circulations (Narenpitak et al., 2021; Janssens et al., 2023; George et al., 2023; Janssens et al., 2024a) that are not represented in GCMs. Indeed, GCMs poorly capture differences between trade Cu organization regimes, both in their absolute behavior and diurnal evolution (Vial et al., 2023). This likely impacts their ability to capture an accurate trade Cu feedback and contributes to uncertainties in climate sensitivity.



The cumulus-valve theory has provided leverage for investigating this multi-scale problem, often by focusing on the relationship between CB amount and mass flux. Progress has been made through observationally constraining this relationship (Vogel et al., 2020; Klingebiel et al., 2021; George et al., 2021; Vogel et al., 2022; George et al., 2023), by investigating how well GCMs capture the relationship (Vogel et al., 2022), and evaluating its response to future environmental conditions (Vogel et al., 2022; Kazil et al., 2024). Typically in these evaluations, the variability in mass flux is dominated by the variability in cloud amount (e.g., Vogel et al., 2020; Klingebiel et al., 2021; George et al., 2021; Vogel et al., 2022). However, a recent LES ensemble of trade-wind Cu indicates this assumption begins to break down as mesoscale structures become sufficiently large: the contribution to CB mass flux from CB velocity variability becomes more consequential at larger scales (Janssens et al., 2024a). This implies clouds of different organizational states will have different degrees of mass, and thus moisture, transported into their cloud layers, affecting how moist the BL can become (e.g., influencing their energetic charge-discharge cycling) and the longevity of clouds (e.g., the persistence of their radiative effects and lack of sensitivity to environmental changes). Mesoscale organization influence on cloud dynamics through increased velocity variability is likely another unresolved factor in GCM parametrizations that is worth considering.

In this study, we focus on observationally examining the influence that mesoscale organization has on the updraft velocities of wintertime trade Cu cloud systems. We utilize ship-borne measurements taken upwind (approximately one day's advection, Figure A1) of Barbados (a benchmark for evaluating tropical cloud behavior, e.g., Medeiros and Nuijens, 2016)). We focus on a unique observational dataset from a motion-stabilized Doppler-wind lidar that facilitates a detailed examination of the updraft dynamics and their associated plume characteristics for different mesoscale organization states (Section 2). We categorize the observed organization states (Section 2.2) before characterizing their differences in dynamics (Section 3.1). Due to sampling strategy, our analysis focuses on smaller cloud structures that have relatively little precipitation. This allows us i) to investigate the behavior of clouds relatively early in their lifetimes as they progress across the ocean, clustering further as their mesoscale organization develops (Eastman et al., 2024; Schulz et al., 2021) and ii) to isolate the influence of local processes rather than synoptic influences (Aemisegger et al., 2021). We gather further insights about the development of organized clouds from examining their associated environmental controls and thermodynamic behaviors (3.2) before discussing the implications of (Section 4) and summarizing (Section 5) the results.

2 Methods

2.1 Ship-borne Observations

We utilize *in situ* observations gathered during the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC) (Quinn et al., 2021) which was the United States contribution to the international Elucidating the Role of Clouds Circulation Coupling in Climate Campaign (EUREC⁴A) (Bony et al., 2017; Stevens et al., 2021). The NOAA RV *Ronald H. Brown* (RHB) sampled between January 7th and February 13th, 2020 in a region of the ocean between Barbados (60°W) and 51°W, the location of the Northwest Tropical Atlantic Station (NTAS) mooring (Figure A1). Local time is approximately UTC-4. Generally, the RHB stayed between 16 and 13°N. We used thermodynamic measurements made on the RHB to investigate



125 the surface and near surface conditions; ceilometer measurements to understand the cloud base height (CBH) behaviors; and radiosondes launched every three hours to investigate the thermodynamic profiles of the atmosphere.

Primarily, we utilized the vertical velocity measurements captured by the motion-stabilized Doppler-wind lidar from NOAA's Chemical Sciences Laboratory (more instrument details in Schroeder et al., 2020; Quinn et al., 2021, 2022). Vertical velocity measurements were gathered at a rate of 2 Hz and with a vertical resolution of 33.6 m. Once every hour, the lidar performed
 130 a conical ~ 2 min scan at 15° from zenith to retrieve horizontal wind information before returning to its motion-stabilized vertical position. Lidar vertical pointing is stabilized within 0.03° (1σ standard deviation) of zenith, enabling accurate measurements of vertical velocity. Our analysis was focused on the profiles of vertical velocity (w) up to CB, a region that was reliably and consistently observed across the campaign. The lidar signal to noise ratio becomes too low above this height due to attenuation by clouds or, when clouds are not present, lack of aerosol above the boundary layer. Individual cloud scenes
 135 from the Doppler lidar measurements were identified using a threshold in range corrected intensity (RCI). Successive clouds occurring within 10 seconds and 50 m were aggregated as one cloud scene. CB amount from the individual scenes was comparable in magnitude and diurnal cycle to the approximate CB amount from the ceilometer (Figure A2a, c). Ceilometer CB amount was derived from $CBH \leq 800$ m (the upper quartile of MO CBH, Figure 11b) for this comparison. This indicates that the sampling of the identified cloud scenes is comprehensive for this period for low, active clouds.

140 Vertical velocity data around each cloud scene were stored as normalized matrixes for later calculations: length normalized by total cloud length at CB or chord length (-1.5 to 1.5 in x/L_{Chord}), and height normalized by CB (0 to 2 in z/CBH). Figure 1a shows an example normalized w matrix for a cloud scene identification, highlighting a plume connecting from the surface to CB and observable partway into the cloud before attenuation. The sub-cloud and CB updraft region (-0.5 to 0.5 in x ; 0 to 1 in z) where our analysis is focused is marked for reference. Because we were interested in the behavior of developing or
 145 active clouds, we further restricted our dataset to cloud scene identifications with a CBH within 50 m of the LCL. The reference CBH of the individual cloud was taken as the 25th percentile of CBH across the aggregated profiles composing the total scene. This method produced a CBH that agreed well with the ceilometer observations (Figure 11a, Quinn et al., 2021). The LCL was determined from an adiabatic parcel model initialized with thermodynamic observations from the RHB.

We were additionally interested in the dimensions of the clouds and thermal plumes sampled by the lidar. The length of a
 150 given identified cloud was defined as the duration of the cloud sample scaled by the horizontal wind speed at CB, which is interpolated from the hourly horizontal velocity measurements from the lidar (L_{Chord}). A plume is defined as a contiguous region where $w > 0.05 \text{ m s}^{-1}$. The plume horizontal length is taken as the maximum diameter of the plume measured in seconds and converted to meters using the surface wind speed (L_{Plume}). Note that this analysis is agnostic to the number of plumes contributing to the maximum plume length as, due to the nature of the cross sectional sampling of the lidar, we are not
 155 able to robustly distinguish between multiple overlapping plumes and one wide plume contributing to the contiguous plume. Plumes are labeled as cloud-topped if the plumes occur within one minute of a cloud identification that has a positive updraft at CB ($L_{Plume \text{ Cloud}}$). Otherwise, they are assigned to be clear-sky (i.e., "unsuccessful" plumes, $L_{Plume \text{ Clear}}$).

We further restricted the cloud identification data to examine clouds with active CB cores ($w_{CB} > 0$). We defined the CB core updraft for individual clouds ($w_{CB \text{ Core}}$) as the mean of CB values that satisfied $w_{CB} > 0$. The corresponding CB core

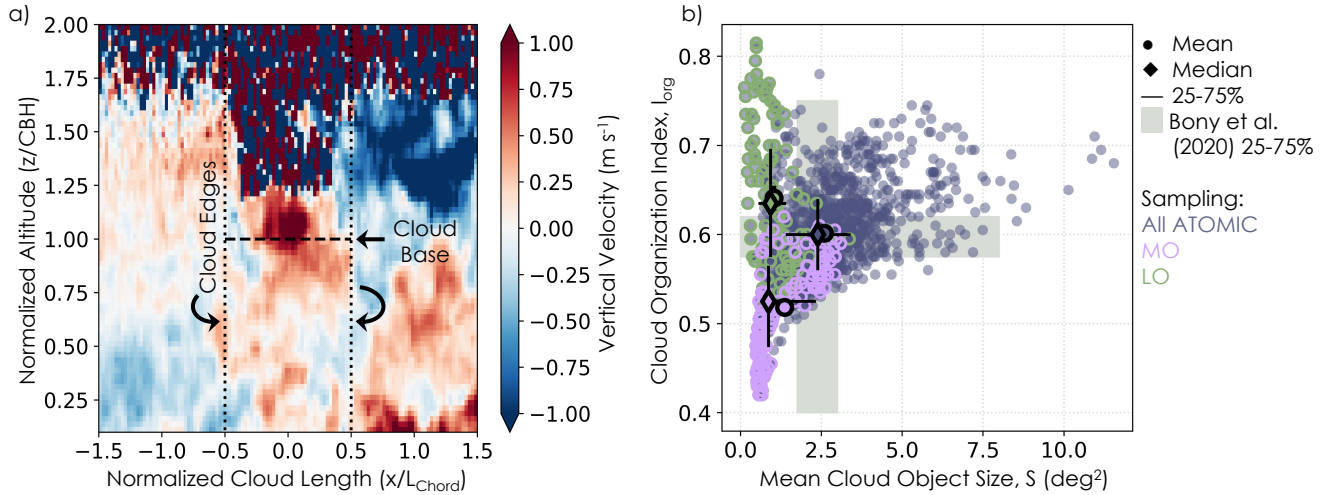


Figure 1. a) Individual cloud vertical velocity measurement example shown in normalized altitude (by cloud base height) and cloud length (by chord length) space. Cloud edges and base are marked for reference. b) Campaign days (dark purple) in I_{org} vs. S space with MO (purple) and LO (green) highlighted. Mean (circle), median (diamond), and 25-75% (lines) for the MO, LO, and total campaign data composites are included. Gray shading in the background shows the interquartiles ranges used to define the SGFF quadrants in Bony et al. (2020) for reference, as in Schulz (2022).

length ($L_{CB\ Core}$) for individual clouds is defined as the total cloud length, L_{Chord} , scaled by the fraction of the samples that contribute to the active CB core. In the example w matrix in Figure 1a, the plume noticeably strengthens near CB and in cloud, marking the core updraft. In addition to the CB core observations, we analyzed updraft profiles sub-cloud ($w > 0$). We do not include the samples outside of cloud (i.e., < -0.5 and > 0.5 in x , Figure 1a) as they may be contaminated by nearby clouds. For this reason we also do not analyze downdrafts as they are likely incomplete, falling largely outside of the sub-cloud range.

We are not able to sample in heavily precipitating conditions. This did not pose a significant issue as there were few instances of precipitation recorded on the RHB (Quinn et al., 2021). The RHB tended to sample much further upwind compared to the other platforms during EUREC⁴A, observing earlier in the evolution of clouds, before precipitation and their accompanying cold pools developed (Touzé-Peiffer et al., 2022). This suggests that these observations are particularly well suited for investigating the early stages of Cu clouds in this region, adding context to their early behaviors before the clouds reach the main EUREC⁴A domain and Barbados.

2.2 Cloud Organization Identifications

The goal of our comparison is to contrast organized cloud structures with unorganized ones. Distinguishing by organization was a non-trivial task. Mesoscale structures have been variously categorized in recent years (e.g., Wood and Hartmann, 2006; Rasp et al., 2020; Yuan et al., 2020; McCoy et al., 2023; Janssens et al., 2021; Denby, 2020; Lang et al., 2022; Chatterjee et al., 2024;



Warren et al., 2011) to investigate their influence on the climate system. One such methodology (Rasp et al., 2020) developed a neural network to categorize four archetypal cloud types based on expert assessments (*SGFF*: *Sugar*, *Gravel*, *Flowers*, and *Fish*) to aid trade Cu investigations (e.g., Stevens et al., 2019; Bony et al., 2020; Schulz et al., 2021; Vial et al., 2021). This algorithm, along with hand identifications from the EUREC⁴A team, were applied to GOES-16 and MODIS satellite scenes over the EUREC⁴A region and campaign period to develop the C³ONTEXT dataset (Schulz, 2022). Our initial analysis utilized C³ONTEXT *SGFF* identifications collocated to the location and time of RHB sampling (see Hovmöller diagram, Figure A1). However, many cloud samples could not be confidently labeled as one of the *SGFF* types, leading to a large number of unclassified (Schulz, 2022) or "None" types dominating the sampling (Figure A1). This presented a problem for analyzing the comparatively sparse campaign sampling, unlike analyses based on multi-year satellite climatologies (e.g., Bony et al., 2020; Schulz et al., 2021; Vial et al., 2021).

To maximize the number of cloud scene identifications utilized, ensuring more reliable statistical sampling, we developed a more general classification methodology: hand-identifying clouds into two categories, less (LO) and more (MO) organized structures. We relied on MODIS *Aqua* and *Terra* satellite imagery to identify the daily cloud field where the RHB was sampling. The LO category comprised days where only scattered structures occurred (January 30, 31, and February 1, 4, and 9; 1356 lidar cloud scene identifications, 1275 cloud-topped plumes, and 27040 clear-sky plumes). The MO category comprised days where more discernibly clustered structures as well as some smaller structures occurred (January 9, 10, 11, 12 and February 10 and 11; a total of 2539 cloud scenes, 2492 cloud-topped plumes, and 29284 clear-sky plumes). LO days included *Sugar* dominated cloud scenes and MO included *Gravel* and a few *Flowers*-like cloud scenes. Different LO and MO sample sizes are accounted for by utilizing standard error to determine confidence in the mean and statistical tests for determining distribution differences at 95% confidence. Days where very large cloud structures associated with the decay of mid-latitude cold frontal cloud systems (i.e., *Fish*, Schulz et al. (2021); Aemisegger et al. (2021)) were not included in our analysis to focus on locally-driven cloud systems, as previously noted.

To confirm that this coarse LO-MO separation distinguished measurements by organization as intended, we additionally compared these categorizations with two objective classifiers also included in the C³ONTEXT dataset: the mean cloud object size (*S*) and the organization index (*I_{org}*, which compares the distribution of nearest-neighbor distances between centroids to a random distribution) (Schulz, 2022). This phase space has been reliably utilized to classify trade Cu (e.g., Bony et al., 2020; Schulz, 2022; Janssens et al., 2021). *I_{org}* and *S* were calculated on 10×10° brightness temperature-defined scenes of cloud amount (as in Bony et al., 2020), approximately centered on the EUREC⁴A region. They were then collocated to the location and time of the RHB sampling (Figure 1b). The inter-quartile ranges corresponding to the *SGFF* archetypes in Bony et al. (2020) are shown for reference following Schulz (2022). The LO data tends to fall in the *Sugar* quadrant (lower *S*, higher *I_{org}*) while the MO data tends to fall in the *Gravel* quadrant (lower *S*, lower *I_{org}*). The apparent greater organization of LO (*I_{org}* > 0.5) follows the behavior of *Sugar* discussed in Bony et al. (2020). This counterintuitive behavior is likely a feature of the brightness temperature thresholds, which are more sensitive to the sparsely distributed deeper clouds in these scenes than the dominate low clouds. Overall, this comparison indicates that i) the visual categorization described above successfully separates observations by organization to the first order (y-axis) and ii) both LO and MO will span similar cloud structure

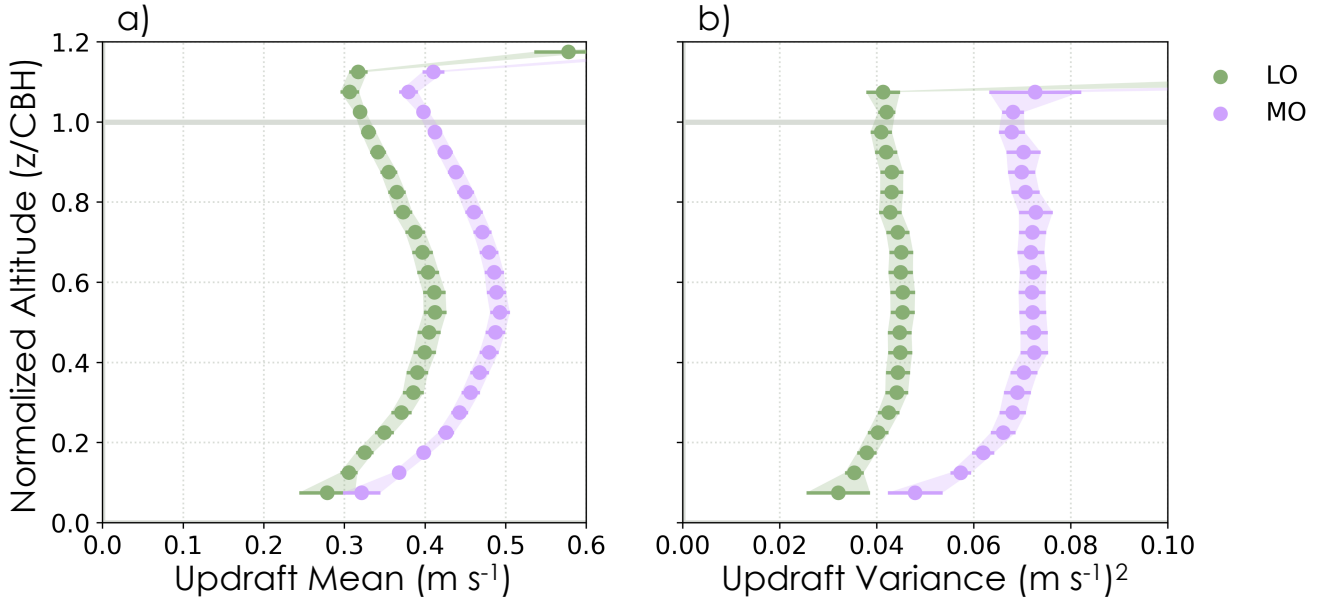


Figure 2. MO (purple) and LO (green) composites of updraft profiles of a) mean and b) variance of vertical velocity. Shading and horizontal lines represent 2SE in the mean (circles) for vertically binned data. Filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

210 sizes (x -axis). This is fortuitous as it allows us to focus on organization without the additional complexity of structure size contributing to cloud behavioral differences.

3 Results

3.1 Dynamic Efficiency of Organized Clouds

The central goal of this work is to identify whether there is a detectable difference in cloud dynamics across mesoscale organizational states. We began by comparing the MO and LO composites of updraft velocity means (a) and variances (b) (Figure 2). For each composite, here and throughout the paper, the mean and confidence in the mean (twice the standard error, 2SE) are shown for each vertical bin (either in altitude or normalized altitude space, z/CBH , as shown here). We apply the Mann-Whitney U-test for each bin to test whether the non-parametric distribution of the MO and LO data is statistically likely to have come from the same population at 95% confidence. As shown, MO clouds have larger mean updrafts that are from a statistically different population than the LO cloud updrafts throughout the sub-cloud layer, CB, and into the observable lower cloud layer prior to lidar attenuation (Figure 2a). This is also true for the mean variance in the updrafts (Figure 2b), indicating that MO clouds have greater turbulence than LO in addition to having more powerful updrafts.

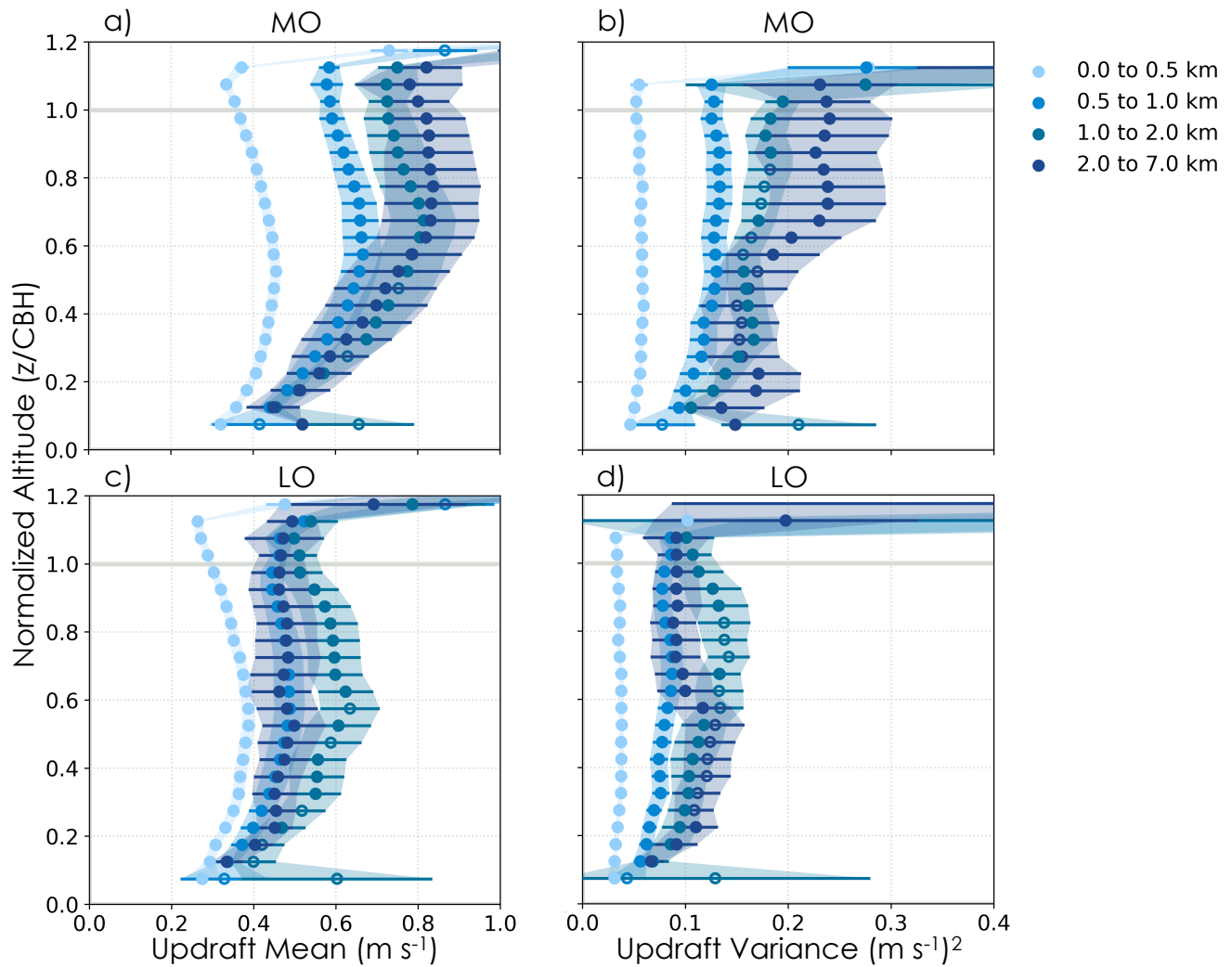


Figure 3. MO (a-b) and LO (c-d) composites of updraft mean (a, c) and variance (b, d) profiles for different cloud core sizes. Shading and horizontal lines represent 2SE in the mean (circles). Filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test for the given $L_{CB\ Core}$ range.



In Figure 2, all cloud sizes are included in the organization composites. On average structure sizes are similar between MO and LO (Figure 1b) but it is worth testing for variations in behavior across cloud size. For example, the mean MO-LO separation could be influenced if there was disparity in updraft region size and the subsequent core area of the cloud. Additionally, if one organization state tended to have larger updraft regions their cores may be more protected, increasing the number of strong updrafts and shifting the mean to larger values compared to the other organization states. To address both of these issues we composited MO and LO clouds by $L_{CB\ Core}$ ranges (Figure 3), which is also generally informative of cloud size separation (e.g., Figure 5c-d) assuming minimal horizontal expansion and tilting with height (e.g., Figure 14 for *Sugar* and *Gravel*, Schulz et al., 2021). The selection of $L_{CB\ Core}$ ranges is based approximately on the quantiles of the distribution of cores across the data such that similar amounts of low cloud are captured for each core range. In both organization states, a majority of clouds occur in the 0 to 500 m and 500 m to 1 km ranges and progressively fewer occur in the 1 to 2 km and 2 to 7 km (Figure 5d). This indicates that the total mean results (Figure 2) are weighted toward the smaller clouds, which makes their substantial differences even more notable.

The resulting profiles for updraft mean (Figure 3a, c) and variance (b, d) provide three insights. First, MO updraft mean and variance are larger and significantly different at 95% than LO updrafts for all $L_{CB\ Core}$ ranges across the majority of the cloud and subcloud altitudes. The few exceptions to this are likely impacted by sampling as they occur at the surface and in the larger $L_{CB\ Core}$ ranges, exhibiting wider 2SE bars. For the mean updrafts, the 1 to 2 km range has several bins in the lower half of the sub cloud layer where MO and LO are not statistically different. For the updraft variance, 1 to 2 km and 2 to 7 km composites have several bins in the upper and lower half of the sub cloud layer, respectively, that are not statistically different. This overlap pattern leads to the second insight. With increasing organization, cloud-topped plumes increase in updraft strength but strengthening appears to occur more in the upper sub cloud layer and CB region. This suggests that there may be an organization-dependent cloud-layer influence on the updrafts. For example, updrafts may be assisted through cloud-layer circulations that increase with organization, part of the moisture-convection feedback due to mesoscale circulations increasing organization over time. Third, with progressively larger $L_{CB\ Core}$ ranges, updraft magnitudes increase. The LO composite is an exception to this, decreasing from the second largest to the largest $L_{CB\ Core}$ range. This discrepancy in behavior between LO and MO is intriguing, suggesting that the LO $w_{CB\ Core}$ may be more constrained by other factors, such as its environment (Section 3.2), while the MO can continue to strengthen with increasing cloud core size.

Similarly, we evaluate the behavior of the updrafts across the diurnal cycle (Figure 4). For all times of day, MO updraft mean and variance are larger and come from a statistically different population than LO updrafts at 95% confidence. For MO, the largest mean and variance occur at the end of the night (between 6 and 12 UTC, or 2-8 AM local). MO is relatively persistent outside of this, dipping overnight before recovering. For LO, there is a more gradual ramp up in mean and variance across the day, peaking marginally sub-cloud and at CB (c) between the late afternoon and after sunset (18 to 24 UTC, or 2-8 PM local) before also decreasing over night (0 to 6 UTC). MO and LO clouds have different sensitivities to the diurnal cycle: LO appears more tied to the solar influence while MO may be more influenced by nighttime factors. Time of peak LO velocity lags between the mid-plume height ($0.5 z_{CBH}$, 0 to 6 UTC) and CB, indicating a potential lag between the surface influences

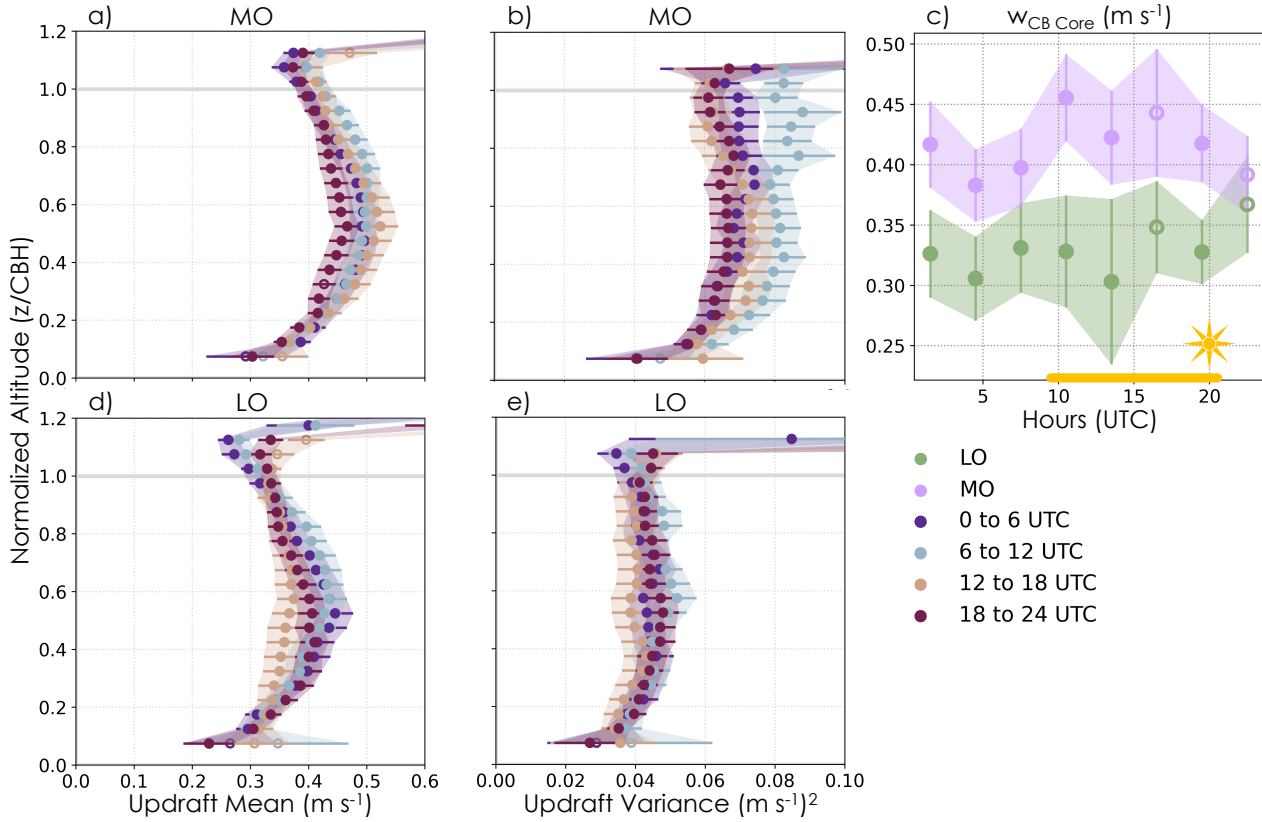


Figure 4. MO (a-b) and LO (d-e) composites of updraft mean (a, d) and variance (b, e) profiles for different times of the day in UTC. The diurnal cycle for mean updraft velocity at the CB for MO (purple) and LO (green) is shown in (c). The local daytime (yellow line, sun) is shown for reference on (c). Shading and horizontal lines represent 2SE in the mean (circles). Filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

and their impact on clouds. This lag is not apparent for MO, suggesting the cloud layer may support the plume strength when surface influences are declining. We will return to this in Section 3.2.

To gain a more holistic understanding of the updraft differences, we also evaluated the differences in plume and cloud size characteristics across organization states. First, we contrasted the distribution of the plume maximum horizontal lengths in clear-sky (a, "unsuccessful", $L_{Plume\ Clear}$) and cloud-topped (b, "successful", $L_{Plume\ Cloud}$) conditions (Figure 5). L_{Plume} exponentially decays with size for all cases, changing in slope around 2 to 3 km. For a given organizational state, unsuccessful plumes occur more frequently than successful ones across all lengths (a vs. b). This is consistent with relatively low CB cloud fractions. Diurnal mean cloud amount is $\sim 9.5\%$ for LO and $\sim 13\%$ for MO with 2% 2SE for both (Figure A2a, c). For a given L_{Plume} , MO has more successful plumes compared to LO (Figure 5b). While the mean CB amounts are statistically similar, this plume difference may be a marker of their diurnal cycle behaviors: LO cloud amount minimizes between 8 and

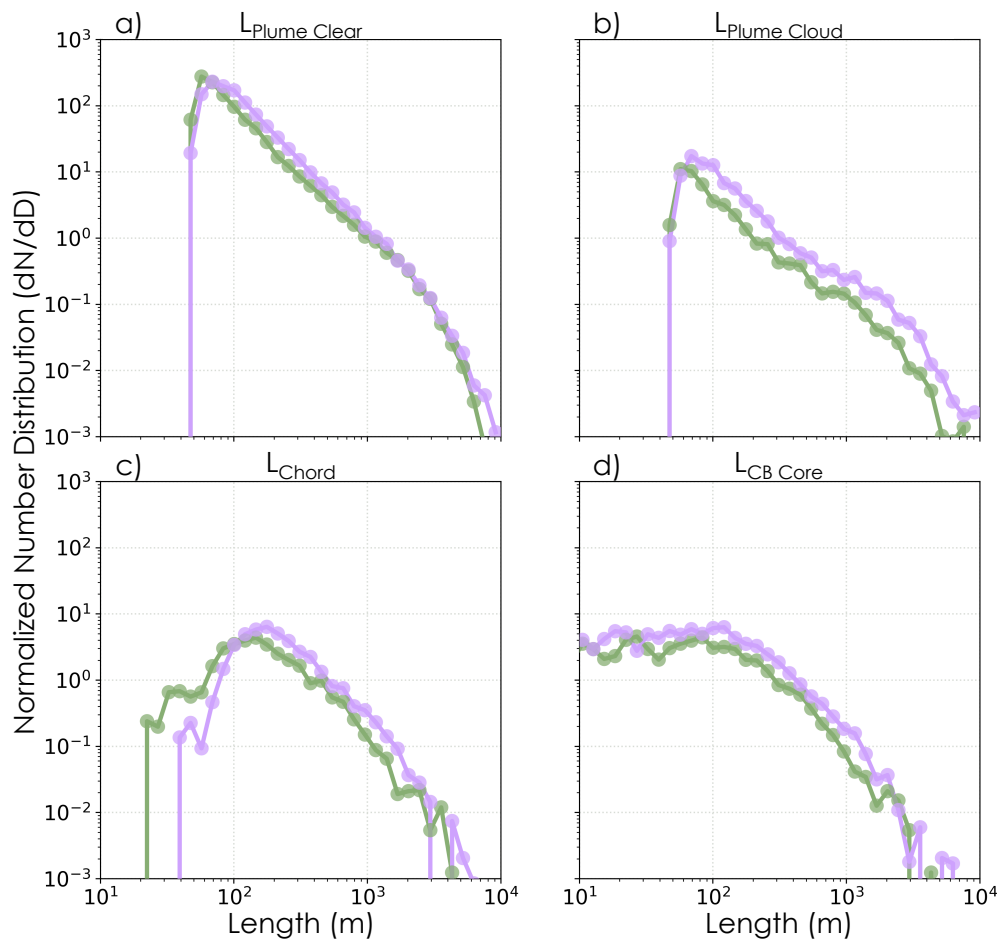


Figure 5. MO (purple) and LO (green) normalized size distributions for clear-sky (a) and cloud-topped (b) plume widths and the cloud chord (c) and core (d) lengths. MO and LO distributions are different at 95% confidence based on both the Mann-Whitney U-test (rejecting the null hypothesis that the underlying distributions are the same) and the Kolmogorov-Smirnov test (rejecting the null hypothesis that the data were drawn from the same distribution).

16 UTC while MO holds steady (Figure A2). Additionally, the successful MO plumes tend to occur more frequently with larger $L_{Plume\ Cloud}$ compared to LO (i.e., the distribution is shifted to the right, Figure 5b), with their respective curves diverging after ~ 100 m. Notably, this difference is not apparent in the unsuccessful, $L_{Plume\ Clear}$ distributions (a), which
 270 further indicates that cloud layer influence on plumes may differ across organizational states.

Second, we evaluated the total (c, L_{Chord}) and CB core (d, $L_{CB\ Core}$) lengths and found organizational differences apparent in their distributions as well. Specifically, MO clouds tend to be generally larger than LO clouds but with substantial overlap. MO occur more frequently with larger L_{Chord} and less frequently with smaller L_{Chord} than LO (i.e., MO shifted to the right



of LO, c). This also holds for $L_{CB\ Core}$ with large cores occurring more frequently for MO (d). The CB core cloud amount
 275 from $L_{CB\ Core}$ ($\sim 7 \pm 2\%$ for LO and $8.9 \pm 0.6\%$ for MO, Figure A2b) is, as expected, smaller than the amount derived from
 L_{Chord} but both CB and CB core amounts are statistically similar between MO and LO on average and both exhibit persistent
 MO and an apparent solar burn-off/recovery cycle for LO. Note that $L_{Plume\ Cloud}$ tends to be wider than the cloud and core
 lengths they support (i.e., L_{Chord} , $L_{CB\ Core}$ distributions are shifted left relative to the plumes, b-d; relationship is not 1:1 in
 Figure 6a). Recall that $L_{Plume\ Cloud}$ pertains to the maximum width of the contiguous region, not the plume core, and likely
 280 includes turbulent tendrils.

The tendency toward larger L_{Chord} and $L_{CB\ Core}$ for MO clouds is consistent with the expectation that they have undergone
 more organization. Organizational differences manifesting primarily in $L_{Plume\ Cloud}$ indicates plumes may be reinforced by
 a cloud-associated process, potentially including cloud-layer driven circulations (i.e., Figure 3). The reinforced plumes likely
 feed back on clouds through supporting stronger cloud updrafts in the ascending branch of mesoscale circulations, helping
 285 them to cluster further through the moisture-convection feedback. To test this, we compared $L_{Plume\ Cloud}$ with $L_{CB\ Core}$
 and $w_{CB\ Core}$ (Figure 6). Because of the different plume width distributions between LO and MO (Figure 5b), 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.

It is apparent that both LO and MO clouds have statistically indistinct linear relationships between $L_{Plume\ Cloud}$ and
 290 $L_{CB\ Core}$ (Figure 6a; L_{Chord} has similar behavior, not shown, with R^2 (p)=0.594 (0.0) and 0.25 (0.006) for MO and LO,
 respectively). The increased frequency of larger $L_{Plume\ Cloud}$ for MO (i.e., wider quantile distribution and Figure 5b) is con-
 sistent with the marginally more frequent occurrence of larger $L_{CB\ Core}$ (Figure 5d). 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%).

The organizational differences are much larger in the relationship between $L_{Plume\ Cloud}$ and $w_{CB\ Core}$ (Figure 6b). Best fit
 295 linear regressions are statistically distinct between LO and MO for the range encompassed by the majority of the observations
 ($L_{Plume\ Cloud}$ through ~ 6 km). The variance explained in the quantiles is substantial for both MO (74%) and LO (60%). 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.

300 Finally, we evaluated these organizational differences in cloud behavior using the classic cumulus-valve phase-space from
 the literature (e.g., Klingebiel et al., 2021; Vogel et al., 2022): $w_{CB\ Core}$ vs. $L_{CB\ Core}$ (Figure 7). Because the range of
 $L_{CB\ Core}$ is more similar than $L_{Plume\ Cloud}$ (Figure 5b vs. d), we can use the same quantiles for LO and MO $L_{CB\ Core}$ and
 use the Mann-Whitney U-test to statistically evaluate distribution overlap in each quantile. This strategy is also advantageous
 since the $L_{CB\ Core}$ vs. $w_{CB\ Core}$ relationship is distinctly non-linear. Note that linear regression fits are statistically well
 305 separated for MO and LO. Regression on quantiles for LO and MO indicates 40% and 59%, respectively, of the variance in
 $w_{CB\ Core}$ is explained by $L_{CB\ Core}$ (Figure B1).

We find, in agreement with prior evaluations (Section 1), that stronger $w_{CB\ Core}$ is associated with more cloud at CB (i.e.,
 greater $L_{CB\ Core}$). However, there are two important nuances revealed in Figure 7: i) MO clouds have consistently larger

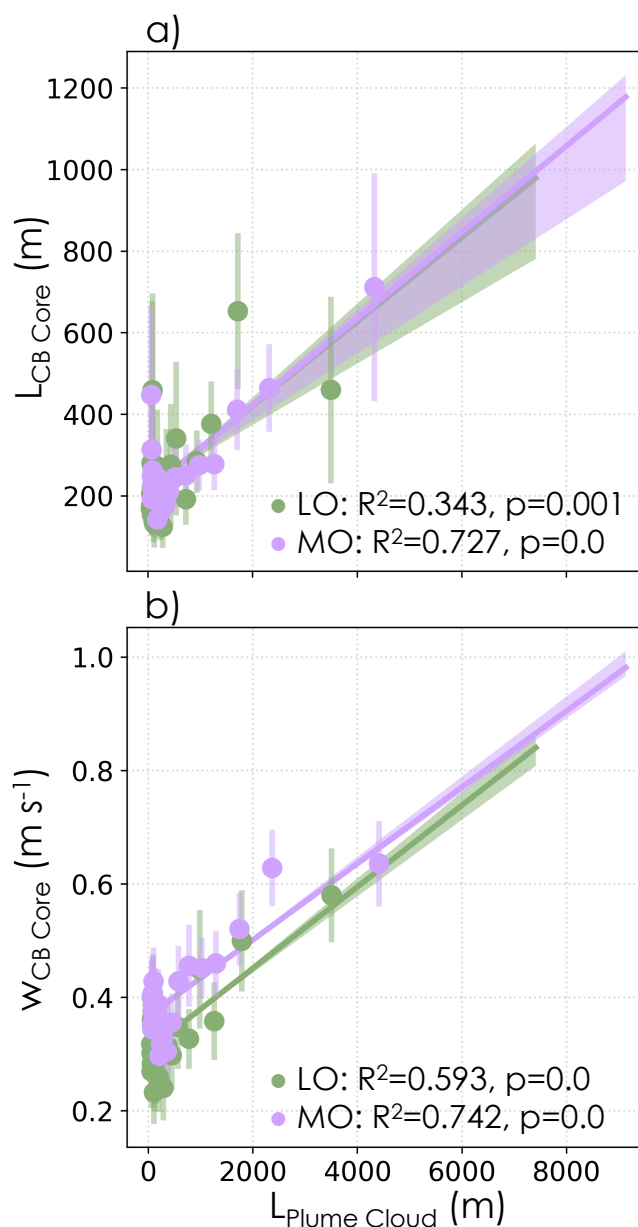


Figure 6. MO (purple) and LO (green) comparisons between cloud-topped plume widths and (a) CB core velocity and (b) lengths. Best fit linear regressions are computed on the underlying data with confidence intervals (min and max, shading) calculated using the jackknife method (Tukey, 1958). Mean (dot) and 2SE (vertical shading) for quantiles of plume width illustrate the distribution of data. Correlation coefficients for quantile relationships are significant at 95% confidence.

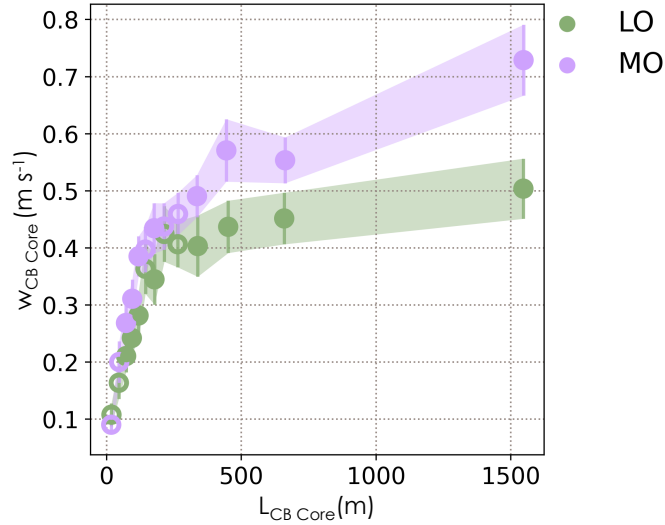


Figure 7. MO (purple) and LO (green) composites of CB core size ($L_{CB\ Core}$) vs. velocity ($w_{CB\ Core}$). Mean (circle) and 2SE (shading, vertical lines) of $w_{CB\ Core}$ are plotted in quantiles of $L_{CB\ Core}$ computed from the combination of LO and MO distributions. Filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

mean core updrafts (i.e., the MO curve is higher than the LO curve, consistent with Figures 5d and 6b); and ii) the relationship
 310 between $L_{CB\ Core}$ and $w_{CB\ Core}$ increasingly diverges across organization states with increasing $L_{CB\ Core}$. The MO and
 LO populations are statistically distinct at 95% for the majority of the $L_{CB\ Core}$ bins, especially for core lengths greater than
 ~250m. The increasing separation with increasing $L_{CB\ Core}$ is consistent with the expectation that mesoscale variability con-
 tributions become more significant at larger cloud sizes (Janssens et al., 2024a), emphasizing the importance of understanding
 organization influence on cloud behavior. We further see that, as suggested in $L_{CB\ Core}$ composites (Figure 3), LO $w_{CB\ Core}$
 315 flattens out at larger $L_{CB\ Core}$ while MO continues to increase, apparently less constrained (though at a slower rate of increase
 than $L_{CB\ Core} < \sim 250\text{m}$). Whether this inhibition of LO may be set by its environmental conditions is examined in the next
 section.

3.2 Characteristics of Organized Environments

In this section, we contrast thermodynamic and environmental conditions across organizational states. This allows us to infer
 320 how these conditions may be conducive to supporting dynamically more efficient organized clouds. We focus on cloud control-
 ling factors that are likely influential to Cu: wind speed, heat fluxes, air and sea temperatures, stability, and vertical moisture
 profiles. We additionally examine diurnal variations for indications of causality in the mesoscale organization cycle. While this
 is a correlative framework, understanding the evolution of cloud dynamics and their environment across the diurnal cycle is
 insightful for interpreting some causal aspects of the cloud systems.



MO clouds occur at higher wind speeds throughout the depth of the BL (a) extending to the near surface (d, e) (Figure 8). MO and LO have statistically different distributions at every altitude at 95% confidence (a, d). Surface wind speed differences are consistent with climatological *Sugar* (i.e., LO) and *Gravel* (i.e., MO) behaviors (Bony et al., 2020; Schulz et al., 2021). LO has a bimodal shape including a small probability of higher surface wind speeds aligning with the MO mode. This is likely from February 9th (e.g., Figure 4, Quinn et al., 2021) before LO clouds transition toward MO clouds. However, the LO and MO distributions are still statistically distinct and LO is lower on average (d).

Wind speed increases sharply from the surface, then stays relatively constant until above the mean CBH (horizontal lines) where it begins to decrease with height (a). This indicates there is no shear in the subcloud layer 100 m above the surface, allowing plumes to develop with limited interference for both MO and LO. Backwards shear manifests in the cloud layer and above: ~ 2 m/s/km between 1 and 3 km (typical for this season in the trades, e.g., Helfer et al., 2020). Shear has a small amount of diurnal variability but is statistically indistinct between MO and LO (not shown). Wind direction is dominated by westward flow with some diurnal variability (not shown). Directional variation is also seen with height (Savazzi et al., 2022), becoming more easterly and northerly (veering North for LO while MO maintains more southward).

The LO and MO composite profiles (b-c) and surface (e) winds are statistically distinct for all hourly ranges across the diurnal cycle. Notably, LO surface winds tend to increase gradually over the day while MO winds are highest at night, declining over the day. This is consistent with 10-m wind speed cycles observed at the NTAS buoy for *Sugar* and *Gravel*, respectively, although MO has a higher magnitude and later peak than *Gravel* (Vial et al., 2021). Surface wind patterns are similar to the $w_{CB\ Core}$ for LO but the opposite cycle behavior for MO (Figure 4). However, the MO wind speed profile and surface peak at the end of the night (6-12 UTC) which does align with the peak MO $w_{CB\ Core}$ (Figure 4a-c).

The stark wind speed differences are translated into the heat fluxes (Figure 9): MO PDFs are shifted to larger latent (LHF, a) and sensible heat fluxes (SHF, b) compared to LO. This is also true for their combined buoyancy flux (Figure C1a-b, same PDF and cycle shape as SHF). We find that MO PDFs and diurnal cycle composites are statistically distinct from LO distributions. The shape of the LHF and SHF diurnal cycles are more distinct than those of the wind speed (Figure 8e), peaking at the end of the night for MO (~ 7.5 UTC) and LO (~ 10 UTC). SHF has a sharper cycle and larger relative amplitudes compared to LHF, maintaining a magnitude offset between MO and LO but their phases are more alike than for LHF.

The shape of the LHF and SHF cycles are a result of the conflation between the air-sea temperature difference (Figure C1d), surface humidity (Figure 12e), and the wind speed cycle (Figure 8e). Air temperature responds more promptly to the diurnal cycle (peaking ~ 12.5 UTC, Figure C2b) while sea surface temperature (*SST*) lags behind, likely due to a larger heat capacity, and is warmest at day end and overnight (Figure C2d). While the magnitudes are higher, these cycles are generally consistent with the climatological cycles seen for *Sugar* and *Gravel* (Vial et al., 2021). Their combination leads to an air-sea temperature difference that peaks at the end of the night and is a minimum around ~ 12.5 UTC for MO and LO (Figure C1d). LHF has a more gradual cycle and follows wind speed more closely. LO and MO specific humidity at 10m (q_{10m}) is a minimum at the end of the night (Figure 12e), aligning with the peak in wind speed and thus LHF. LO LHF is relatively constant over the course of the day while MO LHF decreases before its night time increase.



MO LHF (SHF) is larger than for LO due to the combination of both larger magnitudes and diurnal cycle phase alignment between U_{10m} and q_{10m} ($SST - T_{10m}$ for SHF). The SHF and LHF early morning peak matches the location of the $w_{CB\ Core}$ peak for both MO and LO, suggesting that there is some boost to the updrafts from these turbulent energy fluxes. However, there is evidently another contributor to the MO cycle that helps to maintain the relatively constant MO $w_{CB\ Core}$ during periods of declining fluxes and winds (Figure 4c). The LO $w_{CB\ Core}$ cycle, which increases over the day, seems to align more with its associated wind and LHF cycles suggesting a greater tie to environmental controls.

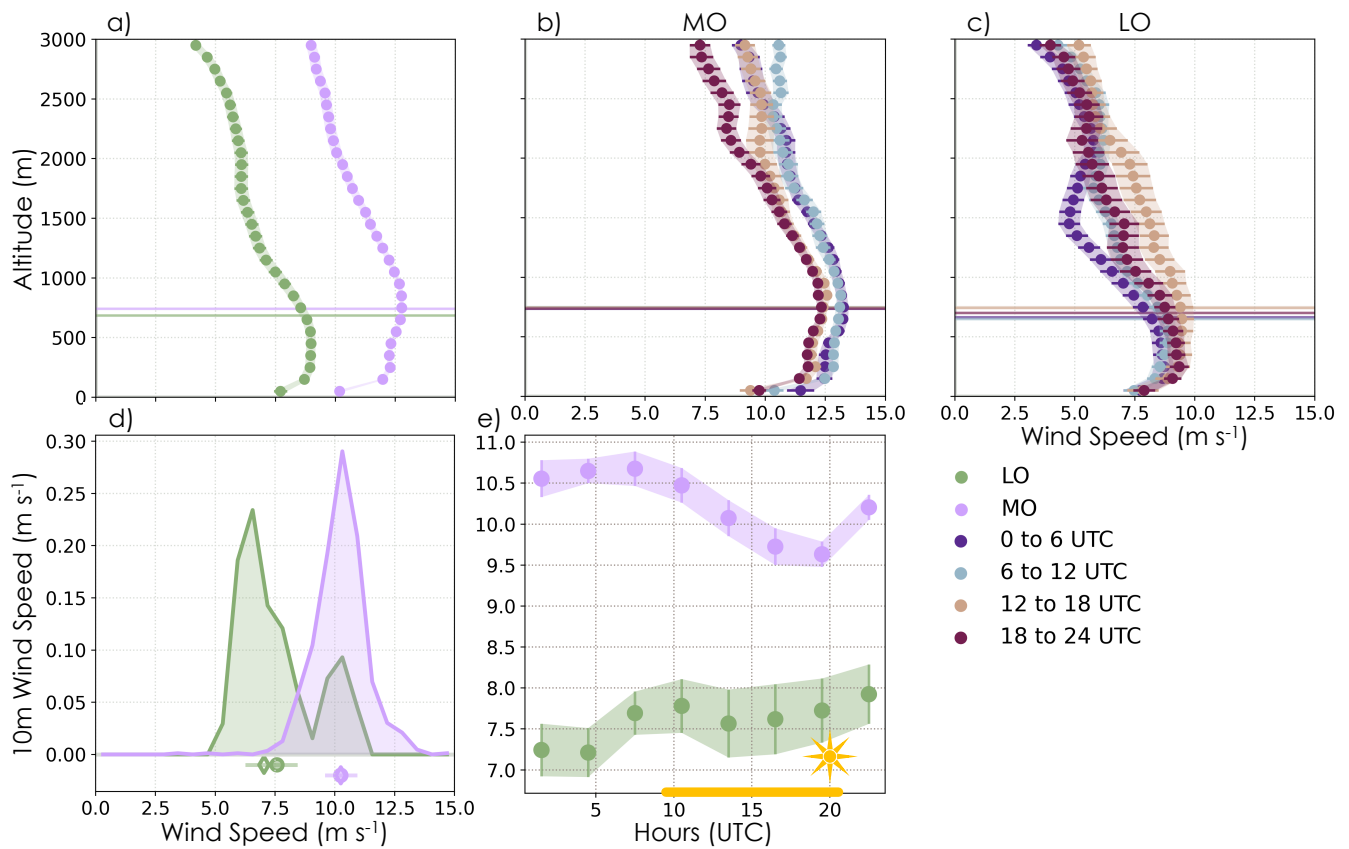


Figure 8. MO (purple and b) and LO (green and c) composites of radiosonde horizontal wind speed (a-c) and surface wind speed at 10m (d-e). Mean profiles are composited absolutely (a) and in UTC ranges (b-c). Absolute PDF and statistical comparisons for surface wind speed are shown in (d) with mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line) statistics. The corresponding diurnal cycle is shown in (e). (a-c, e) Shading and lines represent 2SE in the mean (circles) and filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test. Composite mean (horizontal line) and 2SE (shading hidden by line) lidar CBH is shown for reference (a-c).

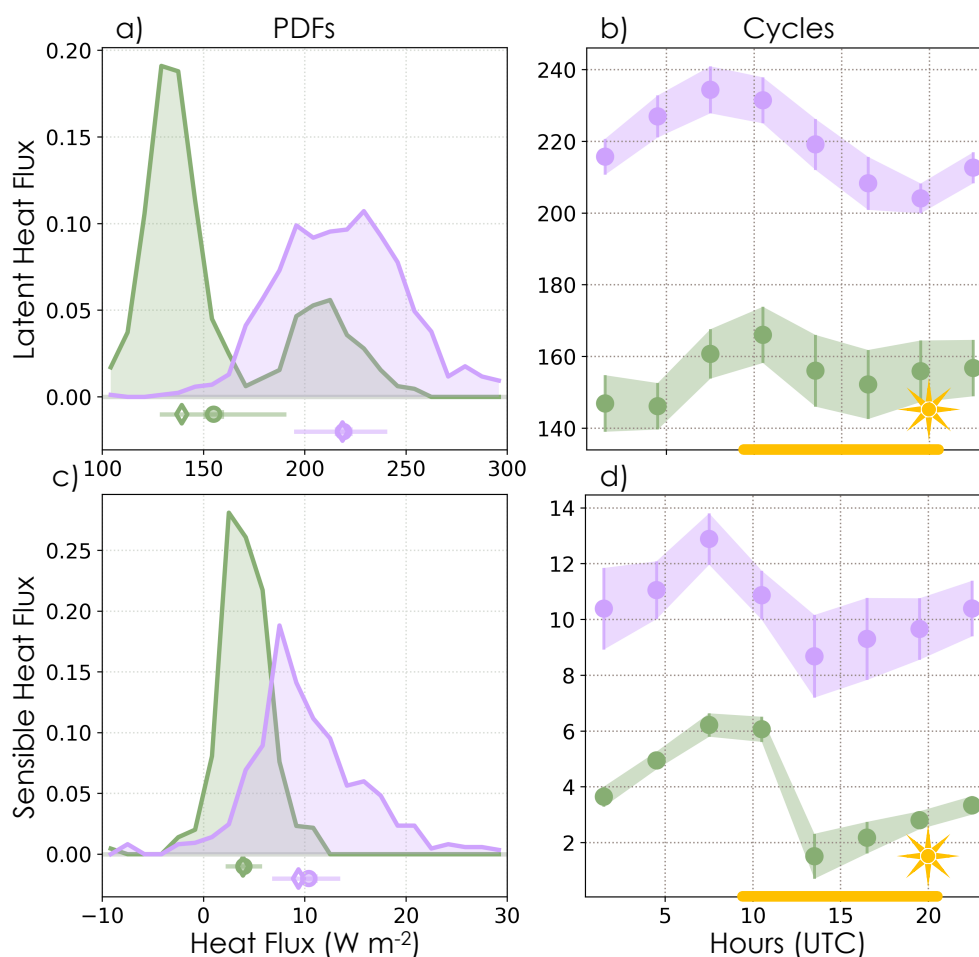


Figure 9. MO (purple) and LO (green) composites PDFs (a, c) and diurnal cycles (b, d) for latent (a-b) and sensible (c-d) heat fluxes. Variable statistics for each composite are shown below the PDFs: mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line). PDFs and diurnal cycle (filled circles) MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

365 Thermodynamic profiles modulate cloud systems ability to develop and persist. We find that SST and T_{10m} are both larger for LO and statistically distinct from MO distributions (Figure C2b). These temperature differences are also consistent with the climatological separation between *Sugar* (i.e., LO) and *Gravel* (i.e., MO) (Bony et al., 2020; Schulz et al., 2021; Vial et al., 2021). Higher SST s are often associated with increased dry-air entrainment and reduced low cloud amounts in stratocumulus regions (e.g., Klein et al., 2017; Scott et al., 2020). This appears to hold here as well (Figure 5c). The combination of higher
 370 SST but smaller air-sea temperature differences, thus smaller fluxes, likely damps LO plume strength (e.g., Figure 5b). The MO-LO temperature offset extends through the depth of the BL with LO clouds tending to occur in warmer environments, with larger and statistically distinct potential temperatures compared to MO (Figure 10a-c). LO cloud development is likely



impaired through entrainment of warm, relatively drier air compared to MO (e.g., Figure 12a, discussed more later). Note that both MO and LO sub-cloud layers are well mixed (i.e., constant θ with height until after CB), facilitating cloud development through even moisture distribution. MO θ profiles are relatively consistent across the diurnal cycle (b). However, LO above ~ 1 km has a substantial diurnal cycle with θ increasing over the day (Figure 10b), peaking at 18-24 UTC and minimizing at 6-12 UTC. This aligns with the T_{10m} cycle but is a much larger magnitude (Figure C2b). The relative magnitudes and cycles are consistent with θ profiles derived from reanalysis for *Sugar* and *Gravel* clouds (Vial et al., 2021).

The amplification of the LO θ cycle above cloud may be associated with increased shortwave absorption from increased concentrations of absorbing aerosol on most of the LO days (recall LO on January 30-31, February 1, 4, and 9). Specifically, Quinn et al. (2022) identified a layer of absorbing aerosols aloft (January 29-February 3rd and February 9th) that were a mixture of biomass burning and dust transported from Africa to the RHB between 1 and 3 km in altitude. This aerosol layer gradually mixed into the BL as it was transported toward Barbados, increasing aerosol extinction throughout the atmospheric column and absorbing aerosol concentrations at the surface (e.g., Figure C4a-c) (Quinn et al., 2022). January 29-31 and February 1-3 were the exception to this with lower correlations between aerosol properties at the surface and aloft (Quinn et al., 2022). More absorbing aerosols aloft could increase the amount of shortwave absorbed over the diurnal cycle, heating above cloud and stabilizing the BL. Narenpitak et al. (2023) found in their LES study that the aerosol layer present on January 31 - February 2 also deterred organization through longwave effects. During EUREC⁴A, low-level, longwave radiative cooling was found to depend on the ratio of relative humidity between the BL and FT and was influenced by moist intrusions at the mid-levels (Fildier et al., 2023).

Sub-cloud air temperature is more complicated to understand. There was no precipitation at the RHB during the LO period (Figure C4d-e), enabling the aerosols to persist in the sub-cloud layer. If sufficient shortwave made it through the aerosol and cloud layers aloft, this could contribute to the larger LO T_{10m} cycle (Figure 10c, C2b). LO has lower total BL CF (Figure A2d) along with higher surface humidity (Figure 12a, c, e), potentially assisting in warming the sub-cloud more than for MO. The result of these effects may be the sharper daytime increase in LO LCL, and thus CBH (Figure C3a-b, horizontal lines on Figure 10c), which would further deter cloud development. In contrast, the MO period was dominated by marine, non-absorbing aerosols (Quinn et al., 2022) that experienced some precipitation removal (e.g., coinciding with times of increased precipitation over the diurnal cycle, Figure C4b, d-e), higher CF, and lower specific humidity, potentially damping any atmospheric heating signatures.

No matter the driver of the diurnal cycle in θ , it has a notable effect on the lower tropospheric stability cycle ($LTS = \theta_{700hPa} - \theta_{SLP}$, Klein and Hartmann (1993), Figure 10e). LO environments are more stable and statistically distinct from MO environments when examined in aggregate (d), consistent with the climatological *Sugar* (i.e., LO) and *Gravel* (i.e., MO) comparisons (Bony et al., 2020; Schulz et al., 2021). The MO and LO cycles are also similar to the *Gravel* and *Sugar* cycles, respectively, but have larger differences in magnitude and a less varied cycle for MO (Vial et al., 2021). Notably, MO and LO have the same stability at the beginning and middle of the day (~ 10 -15 UTC, e). This overlap corresponds to the period of increased winds and fluxes and occurs before re-stabilization of the LO BL, whose inversion appears to have degraded overnight.



Increased stability over the majority of the day presents an additional deterrent to LO clouds developing as their plumes will need to be sufficiently energetic to reach the simultaneously lifted LCL (Figure C3a) and form a cloud. The brief drop in stability likely allows LO plumes to have some success early in the day, shortly after the winds and fluxes have peaked and more turbulent energy is available in the system. Similar behavior has been seen in the southeast Atlantic in the presence of smoke in the BL (Zhang and Zuidema, 2019). This also implies that persistent LO clouds are likely sub-selected for stronger $w_{CB\ Core}$ that can better resist this environmental deterrence (Figure 4c). Even with this sub-selection, the stronger capping inversion for LO clouds may explain the flattening of the $w_{CB\ Core}$ vs. $L_{CB\ Core}$ curve (Figure 7). A more detailed evaluation of the LO evolution during the January 30-February 2 period at the RHB, highlighting the aerosol impacts mentioned here, is in development. The nuances of meteorology-aerosol co-variability impacts on organized cloud systems, including the prevalence of LO clouds occurring under mixed dust and biomass burning aerosol conditions, is worth future investigation (e.g., using the long record at BCO and following Zhang and Zuidema, 2019).

MO clouds exist in consistently more unstable environments (Figure 10d-e), which is conducive to the development of deeper clouds and likely reinforces their moisture-convection feedback through facilitating lofting of humidity into the upper BL. A marker of the deeper MO clouds can be seen through comparing CBH measurements from the Doppler wind-lidar and the ceilometer (Figure 11b-c). MO Doppler lidar CBH PDFs tend to be larger and statistically distinct from LO, with most CBH falling between ~ 600 -800 m for both (Figures 11b, also 4b and sonde plots throughout). However, Doppler cloud identifications are restricted to have CBH near LCL (a), effectively removing any information about detraining cloud layers at the top of clouds or cloud edges as clouds tilt with height under shear. In contrast, the ceilometer CBH measurements are not restricted and capture a significant tail at upper levels for both MO and LO (Figures 11c). This tail is more extensive for MO than LO, indicating that they consistently achieve greater heights (up to ~ 2.5 km) compared to their less organized counterparts (~ 1.5 -1.8km). Relative humidity profiles (Figure C5) roughly support these cloud depths (Figure 11c): 80% until ~ 2 km for MO and ~ 1.3 km for LO on average. Merging of convective updrafts in organized tropical deep convection enables deeper clouds (Glenn and Krueger, 2017), consistent with the wider plumes and deeper extent of MO clouds. We also find that the total BL cloud amount (ceilometer measured $CBH \leq 3$ km, Figure A2d) is statistically larger for MO than LO ($40 \pm 4\%$ vs. $22 \pm 6\%$) despite their similar CB amounts (a-c). Thus, MO clouds greater dynamic efficiency supports their larger radiative impact (e.g., *Gravel* vs. *Sugar*, Bony et al., 2020).

To evaluate the prevalence of the moisture-convection feedback for MO cases and the type of air being entrained in both organizational states, we next examine the specific humidity profiles (Figure 12). Unlike other variables, q has distinctly different organizational tendencies in the upper and lower BL (a). Above ~ 1.3 km, MO q is much larger and from a statistically distinct distribution compared to LO. Moisture FT (700 hPa) environments have also been seen for *Gravel* (i.e., MO) than *Sugar* (i.e., LO) (Schulz et al., 2021). Moisture advection likely does not explain the increased q aloft for MO vs. LO. Three-day Lagrangian back trajectories of q_{700hPa} are persistently drier for *Gravel* than for *Sugar* up until the final ~ 12 hrs before the cloud observation (Schulz et al., 2021).

In the sub-cloud layer the opposite behavior is true: MO is substantially drier than LO below CB. This is particularly apparent in q_{10m} (d-e). These statistically distinct separations hold across the diurnal cycle at the majority of altitude bins (b-c) and at

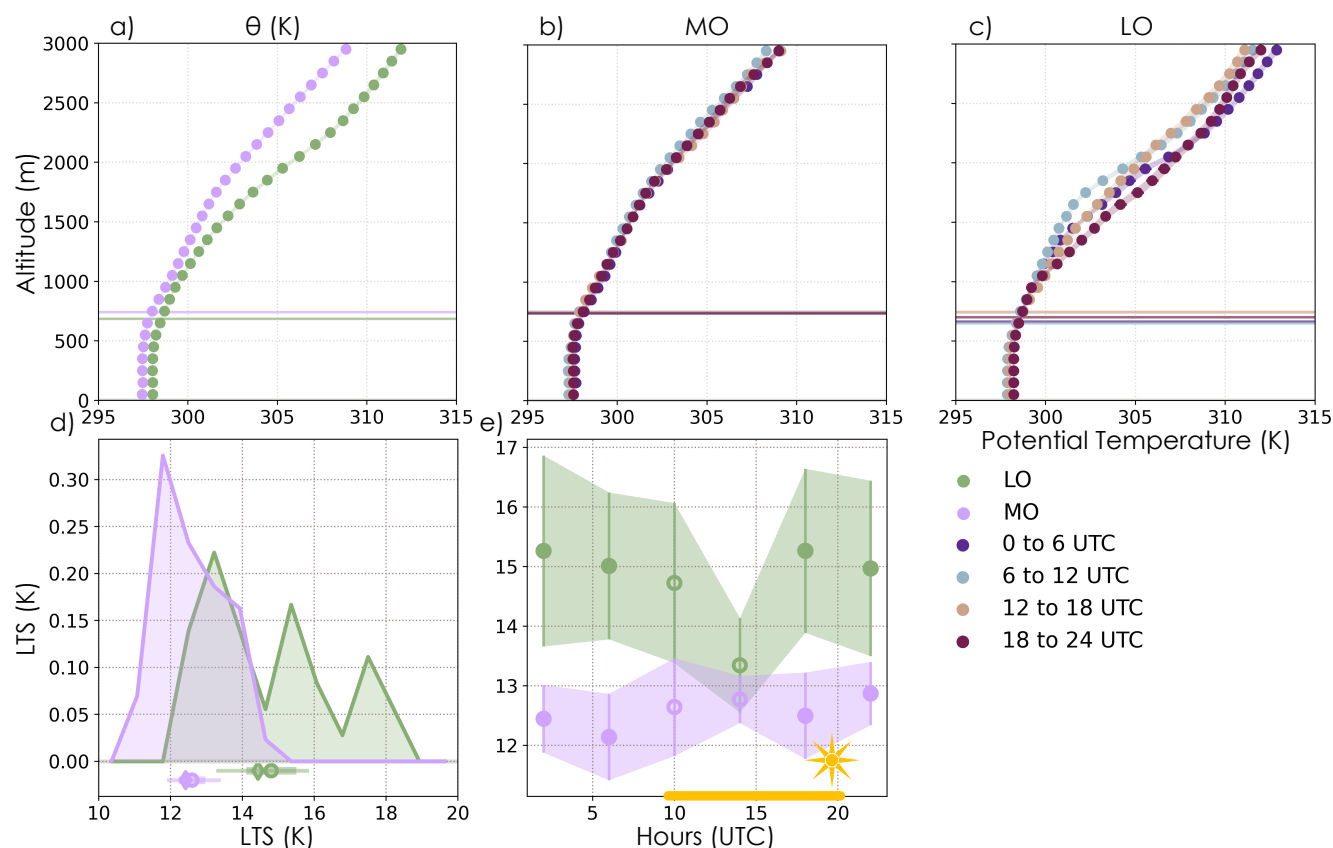


Figure 10. MO (purple and b) and LO (green and c) composites of radiosonde potential temperature (a-c) and lower tropospheric stability (d-e). Mean profiles are composited absolutely (a) and in UTC ranges (b-c). Absolute PDF and statistical comparisons for LTS are shown in (d) with mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line) statistics. The corresponding diurnal cycle is shown in (e). (a-c, e) Shading and lines represent 2SE in the mean (circles) and filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test. Composite mean (horizontal line) and 2SE (shading hidden by line) lidar CBH is shown for reference (a-c).

the surface, with LO recovering more than MO by the end of the day (e). MO has a smaller magnitude but similar diurnal cycle amplitude as LO at the surface and below CB, with both gaining the most moisture by the end of the day (18-24 UTC). MO q has a roughly similar diurnal cycle above CB as below (b). In contrast, LO q peaks by the end of the day in the sub-cloud layer and between 0-12 UTC in the middle BL. This may be linked to the period of greatest instability, facilitating more active lofting of moisture. A drier upper BL for LO clouds means that cloud top entrainment will introduce more dry air than in MO clouds, additionally deterring LO cloud development. On the other hand, entraining moister air will help to maintain MO

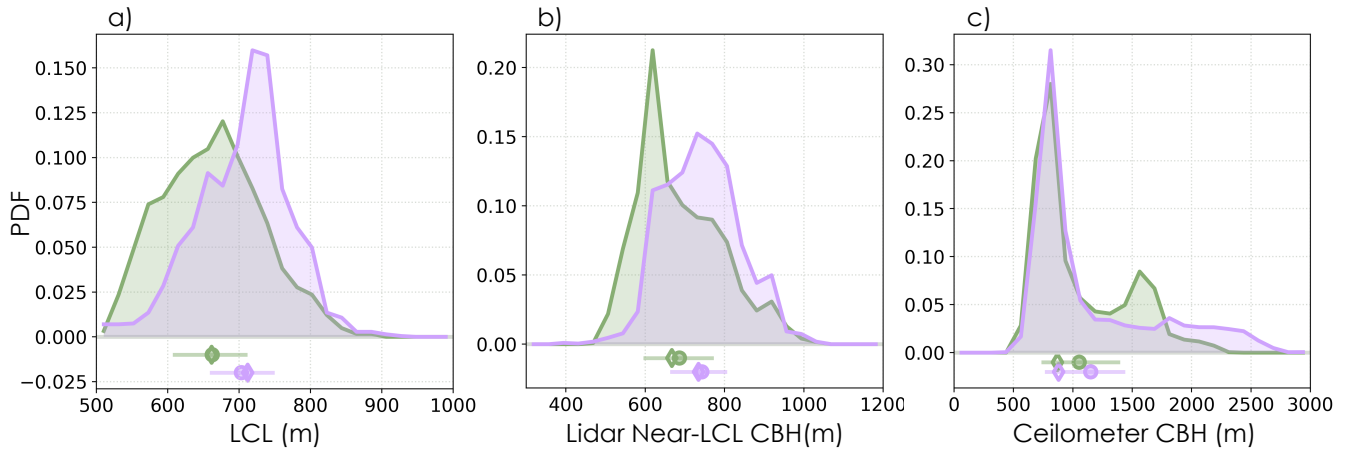


Figure 11. MO (purple) and LO (green) composite PDFs of (a) lifting condensation level (LCL), (b) Doppler lidar CBH for individual cloud scenes, restricted to within 50 m of the LCL, and (c) ceilometer CBH for shallow and mid level clouds (below 3km). Variable statistics for each composite are shown below the PDFs: mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line). The MO and LO distributions are different at 95% confidence based on the Mann Whitney U-test.

clouds for longer. Increased dry air entrainment for LO clouds is also consistent with the previously discussed expectations associated with the higher *SST*s for LO clouds.

450 The deeper and persistently moister layer aloft for MO is consistent with more moisture lofted into the upper BL through increased $w_{CB\ Core}$ due to greater dynamic efficiency. This coincides with a critical part of the moisture-convection feedback, increasing aggregation of moisture into the ascending, cloudy branch as organization increases. Our analysis highlights a further nuance: the MO subcloud layer is drier than for LO clouds. This presents an additional barrier for MO clouds as it raises their LCL compared to LO clouds (Figure 11a, C3a). The relative decoupling index ($CBH-LCL/LCL$, Kazil et al., 2017; Jones et al., 455 2011) is marginally higher for MO than LO although it is less diurnally variable (Figure C3d). However, the average relative decoupling instances are both well below 0.1, indicating MO and LO are both well coupled to the surface and that this is a small albeit statistically significant disadvantage. While the challenge for MO clouds to develop may be marginally increased, this could be ultimately helpful for increasing the strength of the CB updrafts (e.g., environments with higher LCL have wider, deeper, and stronger cloudy updrafts, Mulholland et al., 2021). In summary, the opposing q tendency in the upper and lower 460 BL across organizational states is potentially an indication of the efficiency of moisture export to the upper BL through the stronger MO cloud updrafts, which are more effectively removing sub-cloud moisture over time compared to the LO clouds.

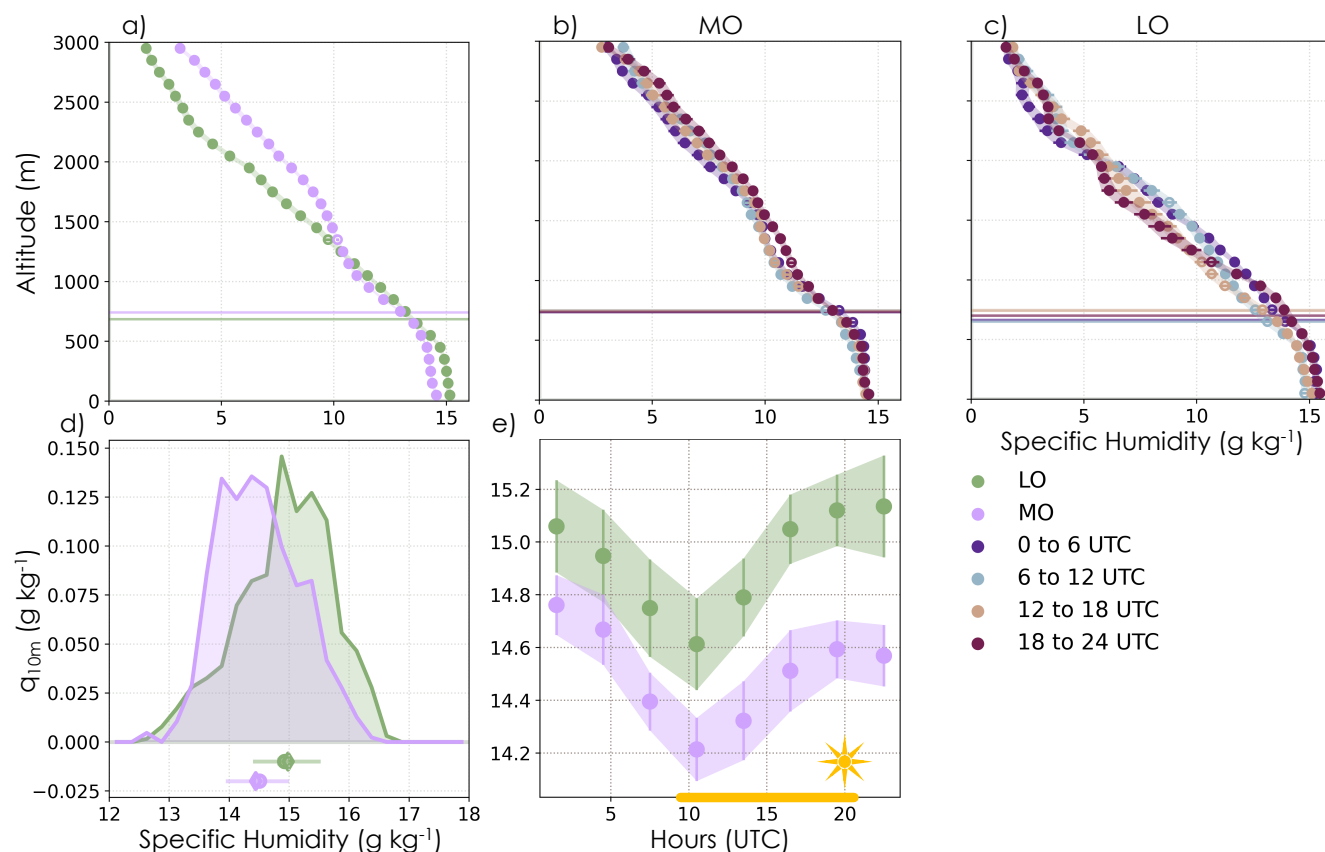


Figure 12. MO (purple and b) and LO (green and c) composites of radiosonde (a-c) and 10m (d-e) specific humidity. Mean profiles are composited absolutely (a) and in UTC ranges (b-c). Absolute PDF and statistical comparisons for 10m specific humidity are shown in (d) with mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line) statistics. The corresponding diurnal cycle is shown in (e). (a-c, e) Shading and lines represent 2SE in the mean (circles) and filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test. Composite mean (horizontal line) and 2SE (shading hidden by line) lidar CBH is shown for reference (a-c).

4 Discussion

It is evident from this analysis that there are organizational differences in the dynamics of trade-wind Cu and that organization modifies the fundamental relationship between CB cloud amount and mass flux. Specifically, we have demonstrated that clouds with more mesoscale organization are dynamically more efficient: wider plumes produce stronger CB core updrafts through a given core size. We also show that these organizational differences increase with the size of cloud cores and are likely self-maintained by cloud-layer driven circulations, staying relatively resistant to diurnally varying environmental factors. Increased dynamic efficiency has important implications for MO clouds as they form: stronger updrafts through a given core results in



more mass and moisture moved into the cloud system and the upper BL, increasing its moisture over time. Cloud top entrain-
 470 ment will introduce moister air, helping to sustain MO clouds. This is consistent with mesoscale organization mechanisms
 where a moisture-convection feedback converges water vapor into the circulations ascending, cloudy branch and strengthens
 the overturning circulation proportional to the updraft strength (e.g., Janssens et al., 2024a). The increased strengthening of
 updrafts near the cloud layer is supportive of cloud-layer driven circulations being essential in this process (Narenpitak et al.,
 2021).

475 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 depends mainly 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 additional inclusion of
 relative humidity in Vogel et al. (2022) may alias in the organizational contribution by indirectly accounting for the increased
 dynamic efficiency of MO clouds (e.g., higher humidity due to stronger mass fluxes that are not accompanied by an increase
 480 in core size, Figure C5a-b). Our results are more in accordance with the organizational differences seen in recent, idealized
 LES ensembles: mesoscale velocity variations have an increased contribution to CB mass flux under strengthening mesoscale
 ascent (Janssens et al., 2024a). Janssens et al. (2024a) 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, using detailed ship-
 borne observations. However, the clear organizational differences already apparent in our results indicates that such differences
 485 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 and
 larger organizational scales.

Eventually, it is likely that the dynamic efficiency facilitating the moisture-convection feedback loop will be broken once
 clouds are sufficiently organized to precipitate. The accompanying cold pools that are generated along with their associated
 490 downdrafts will reverse the circulation direction, breaking the feedback cycle. The dynamic efficiency may also slow with
 time as the sub-cloud layer moisture is depleted. The small cloud structures examined here have limited (MO) to no (LO)
 precipitation (Figure C4d-e) and thus no cold pools (rarely seen at the RHB, Touzé-Peiffer et al., 2022)). These results are thus
 applicable to the development stage of the cloud cycle rather than the decay. However, we do see that the MO vs. LO cloud-
 topped plume width and cloud size distributions (Figure 5b-c) are consistent with the oscillations in cloud size and thermals
 495 in the literature that evolve between states with relatively more small clouds (e.g., LO) and states with relatively more large
 clouds (e.g., MO) (Feingold et al., 2017; Oh and Austin, 2024). These oscillations are driven by aggregation of small clouds
 and thermals into larger clouds and thermals before breaking up, operating on a faster timescale (1.5 to 2 hours, Feingold et al.,
 2017; Oh and Austin, 2024) than the meoscale organization that is likely influencing the separation here (e.g., 12 hours to a
 day, Narenpitak et al., 2021). However, it is a useful behavioral comparison to make against the eventual evolution of the clouds
 500 through their organizational states: LO to MO to eventual collapse and return to LO. This type of organizational cycling may
 further influence the energetic discharge-recharge cycle: the MO dynamic-efficiency phase could potentially moisten the cloud
 and upper BL enough to enable the transition from the shallow to the deep cycle, kicking off deep convection development



(Wolding et al., 2024). To investigate the full cloud life cycle would require examination of LES or geostationary satellite analysis.

505 None of the tested cloud controlling factors sufficiently explained the persistence of MO CB core updrafts and amount across the diurnal cycle. Nor was there such a factor controlling the sub-cloud enhancement of updrafts that occurred with increasing core size. Instead, cloud-layer driven circulations operating as part of the mesoscale moisture-convection feedback may help to sustain MO clouds once they are formed through reinforcing plumes and strengthening $w_{CB\ Core}$. Such coupling and re-
 510 and moisture through the sub cloud layer have been seen historically (e.g., LeMone and Pennell, 1976). There has also been a climatological shift toward more frequent occurrences of Sc-like clouds in this region (i.e., MO) (Eastman et al., 2025) which is projected to continue under future SST and stability changes (McCoy et al., 2023), leading to a negative feedback associated with cloud morphology that may suppress Caribbean warming and drying (Eastman et al., 2025; McCoy et al., 2023). Taken together, these results have important implications for future trade Cu: climatologically more frequent MO clouds may be
 515 less susceptible to environmental perturbations as their moisture-convection feedback may be more resilient to environmental changes. However, a recent LES case study showed that increased greenhouse gases under future conditions damp mesoscale circulations in the larger, more organized *Flower* clouds, leading to a more positive tropical Cu feedback (Kazil et al., 2024). The multi-scale complexity of these mesoscale systems encourages continued examination of organization influence on vertical velocity profiles and the resulting cloud system sensitivity to environmental conditions. This is especially important to
 520 undertake in order to improve Cu representation in GCMs for robust climate projections.

5 Summary

In this study, we utilized a unique, ship-borne observational dataset taken in the wintertime trades upwind of Barbados during the 2020 ATOMIC (Quinn et al., 2021) and EUREC⁴A (Stevens et al., 2021) joint campaigns. Our primary source of data was a motion-stabilized Doppler wind-lidar aboard the RV *Ronald H. Brown* that we used to examine the dynamics of trade Cu and
 525 their associated plume behaviors. We additionally used thermodynamic and environmental measurements collected onboard and from ship-launched radiosondes. These observations were composited based on hand-identified classifications into more (MO) and less (LO) organized boundary layer cloud structures on the mesoscale ($O(100\text{ km})$). Organization classifications were validated against objective measures of mesoscale clustering (following Bony et al., 2020), indicating that MO and LO have similar cloud structure sizes but substantially different degrees of clustering.

530 We find that MO clouds have larger and statistically distinct updraft vertical velocity mean and variance compared to LO clouds. This holds across ranges of cloud base (CB) core size and the diurnal cycle. Updraft strength increases with CB core size for both MO and LO but the organizational difference widens substantially. MO cloud updraft strength increases without apparent constraint while LO clouds plateau at larger core sizes, potentially due to capping from their larger tropospheric stability. The increases in MO updraft strength with core size particularly manifests in their upper sub-cloud layer, implying
 535 cloud-layer driven circulations may be reinforcing cloud updrafts. Unsuccessful, clear-sky plumes are similar across organiza-



tional states, further pointing to cloud-driven processes reinforcing organizational differences in dynamics. MO clouds tend to have wider cloud-topped plumes than LO but MO and LO have the same positive relationship between plume width and core size. However, the positive cloud-topped plume width relationship with CB core updraft strength is significantly stronger for MO than LO clouds and statistically distinct. We conclude that MO clouds have greater dynamic efficiency than LO clouds: organized sub-cloud and CB core updrafts are substantially stronger for a given plume width, and thus core size, leading to larger CB mass flux for organized clouds.

MO and LO environments are statistically distinct, helping to shape their cloud development and persistence. Fluxes contributed to the peak in CB core updrafts at the end of the night for both MO and LO clouds. LO updraft strength coincides with increased subcloud warming over the day, likely energizing the thermal plumes that drive these more environmentally coupled clouds. Stronger diurnal updrafts enabled LO clouds to overcome daytime (and potentially absorbing aerosol-induced) stability and lifting condensation level increases. MO clouds have higher wind speed and fluxes and lower stability environments on average. However, their sub-cloud and CB core updrafts, as well as cloud amount, were persistent and not significantly assisted or deterred by diurnally varying environmental factors. This lack of diurnal coupling additionally supports the idea of cloud-layer driven circulations maintaining MO clouds once they have been formed. Notably, MO clouds have much higher specific humidity in and above the cloud layer and lower humidity sub-cloud compared to LO clouds. This, along with the deeper and wider extent of MO clouds in the BL, is likely a marker of the mesoscale moisture-convection feedback taking effect in MO clouds. Increased dynamic efficiency of MO clouds imports more moisture into the cloud layer and upper BL. This leads to reduced sub-cloud moisture over time and helps maintain MO clouds through moistening air entrained at cloud-top.

The organizational differences in cloud efficiency identified in this study likely play a fundamental role in the mesoscale moisture-convection feedback, enabling MO cloud persistence and furthering mesoscale organization of trade Cu. We have observationally demonstrated for the first time that organization impacts CB mass flux through modulating updrafts, a departure from the expectation that mass flux is controlled by CB cloud amount (e.g., Klingebiel et al., 2021; George et al., 2021; Vogel et al., 2022). Our results are more consistent with recent modeling evidence of mesoscale velocity variability becoming increasingly important under greater mesoscale ascent (Janssens et al., 2024a). Greater dynamic efficiency in MO clouds likely facilitates the energetic discharge-recharge cycle that controls precipitation in the tropics, increasing the amount and depth of moisture in the BL that initiates the transition from shallow to deep convection (Wolding et al., 2024). MO clouds, once established, are driven more by cloud-layer circulations and are resilient to diurnal changes in environmental controls, unlike the diurnally-driven LO clouds. This has important implications for the potential susceptibility of MO clouds to climate change. Combined with the trend toward MO clouds in the Caribbean since 1971 (Eastman et al., 2025), our results suggest that tropical Cu may be more resilient to future environmental changes than previously thought due to their tendency toward increased mesoscale organization. These results encourage the continued assessment of mesoscale organization impacts on the climate system and evaluation of whether representing their characteristics in GCM parametrizations is valuable for reducing future climate uncertainty.



Data availability. All data are available at NOAA's National Center for Environmental Information (<https://www.ncei.noaa.gov/archive/accession/ATOMIC->

570 2020) and on the PMEL Atmospheric Chemistry data server (<https://saga.pmel.noaa.gov/data/>).

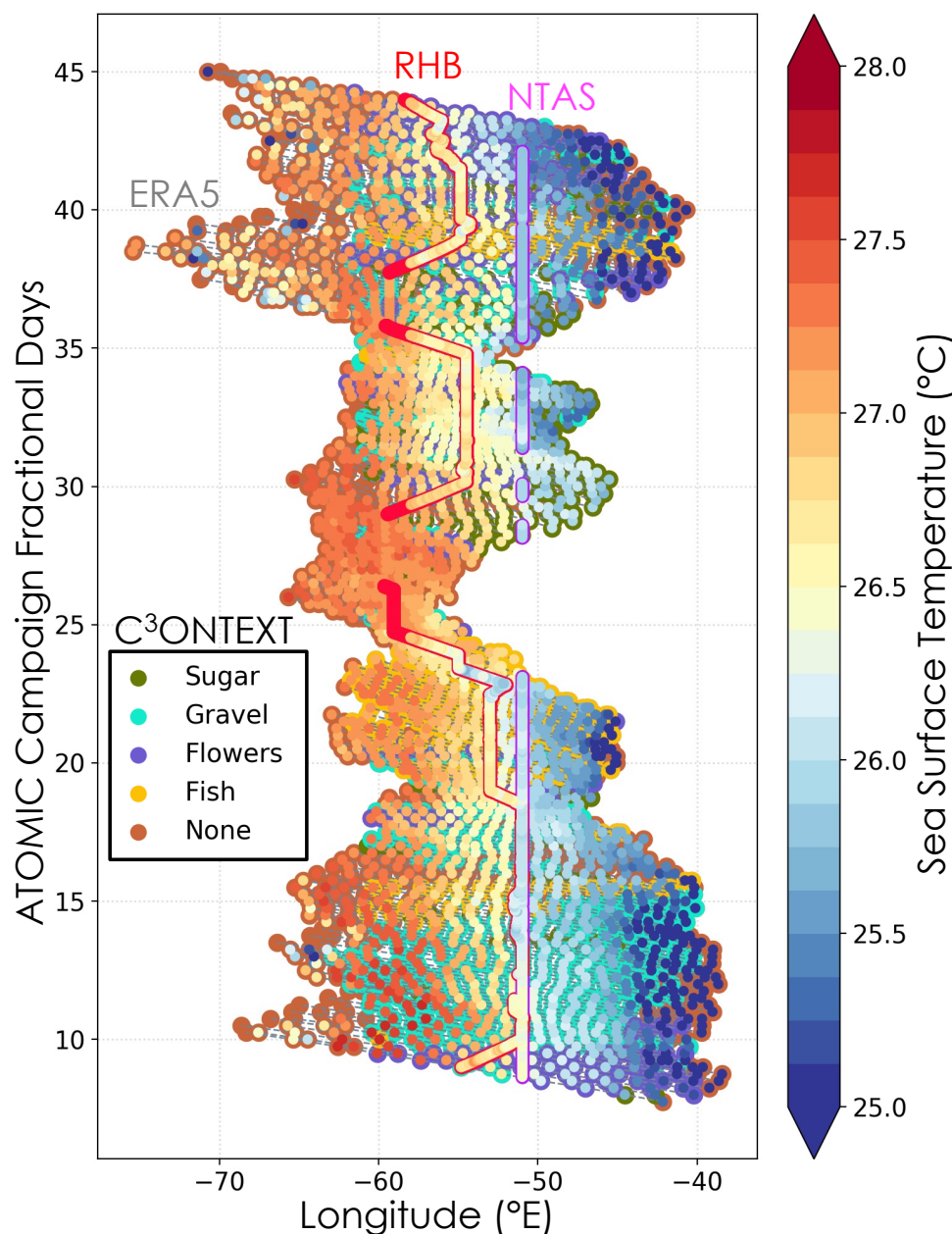


Figure A1. Hovmüller diagram of cloud organization evolution during the ATOMIC Campaign. Dashed lines are 30-hr forward and 30-hr backward Lagrangian trajectories originating from the RV Ronald H. Brown (c/o Ryan Eastman). ERA5 sea surface temperature is extracted at each 3-hr point along the trajectories. Observations within 100 km and 3 hr of trajectory point are extracted and overplotted for the RHB (red) and NTAS (pink) platforms. Morphology patterns are identified for each trajectory point from C³ONTEXT (Schulz, 2022) and plotted behind observations. If the point cannot be confidently labeled (i.e., fraction $\geq 50\%$), they are marked as "None".

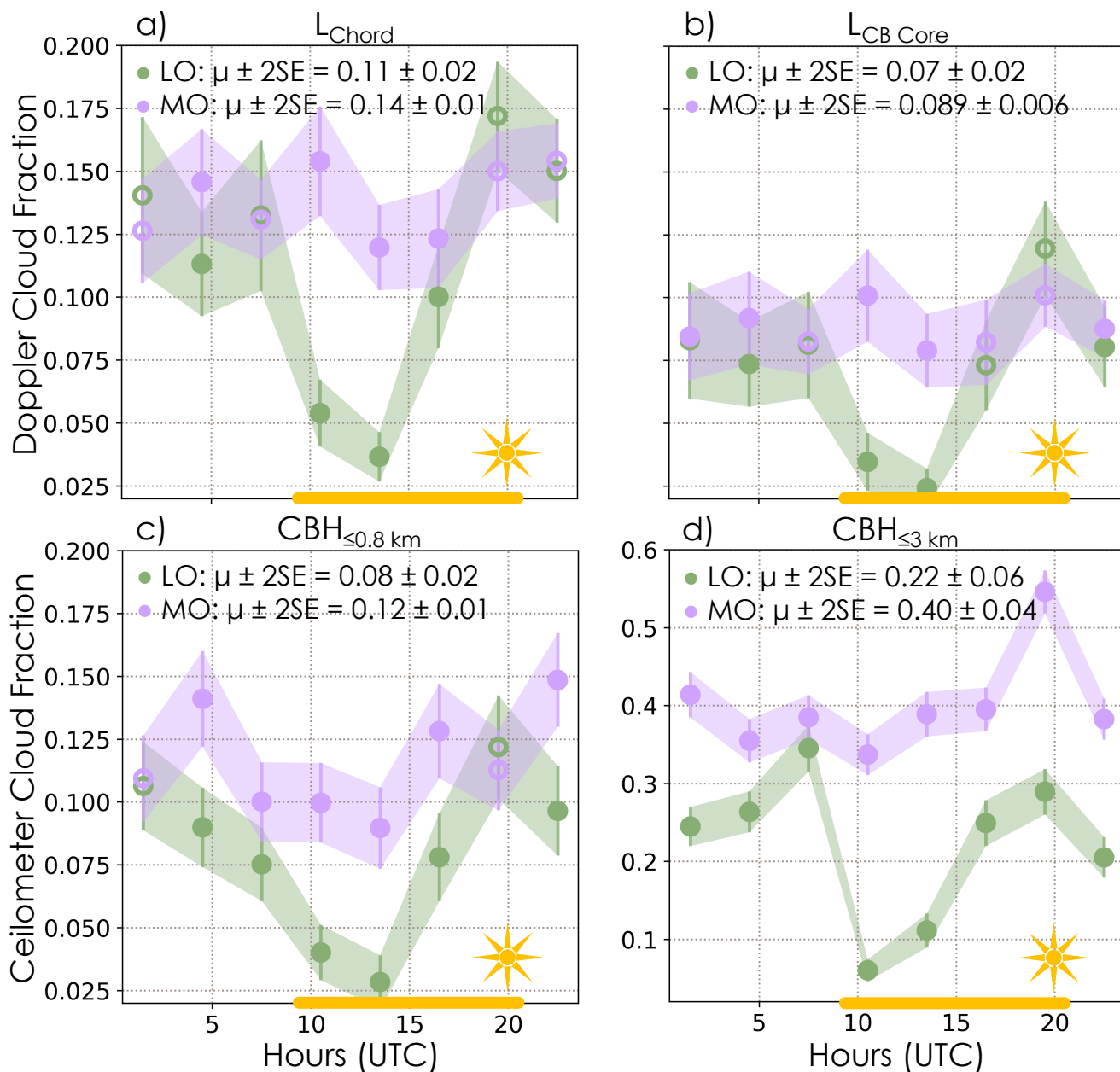


Figure A2. MO (purple) and LO (green) composites diurnal cycles of cloud fraction computed using identifications from the Doppler-wind lidar cloud duration for chord length (a), core length (b) and from the ceilometer for approximate CB (c, $CBH \leq 800m$) and total BL (d, $CBH \leq 3km$). Filled circles indicate where MO and LO distributions for a given 3-hour bin are different at 95% confidence based on the Mann-Whitney U-test. Doppler-wind lidar estimates are derived from the duration (in seconds) scaled by the amount of observations averaged into a given bin divided by the total number of observations over the composite. Diurnal mean and 2SE are provided for reference.

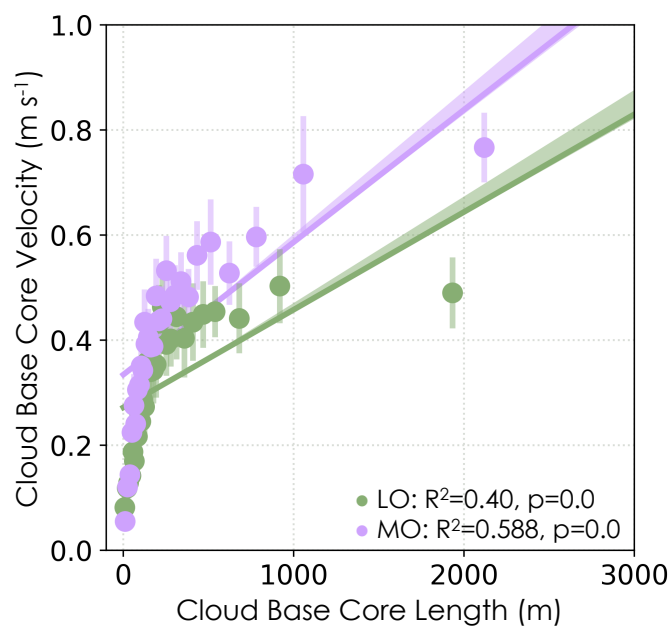


Figure B1. MO (purple) and LO (green) composites of CB core size ($L_{CB\ Core}$) vs. velocity ($w_{CB\ Core}$). Best fit linear regressions are computed on the underlying data with confidence intervals (min and max, shading) calculated using the jackknife method (Tukey, 1958). Mean (dot) and 2SE (vertical lines) of $w_{CB\ Core}$ are plotted in quantiles of $L_{CB\ Core}$ to illustrate the distribution of data. Correlation coefficients for quantile relationships are significant at 95% confidence.

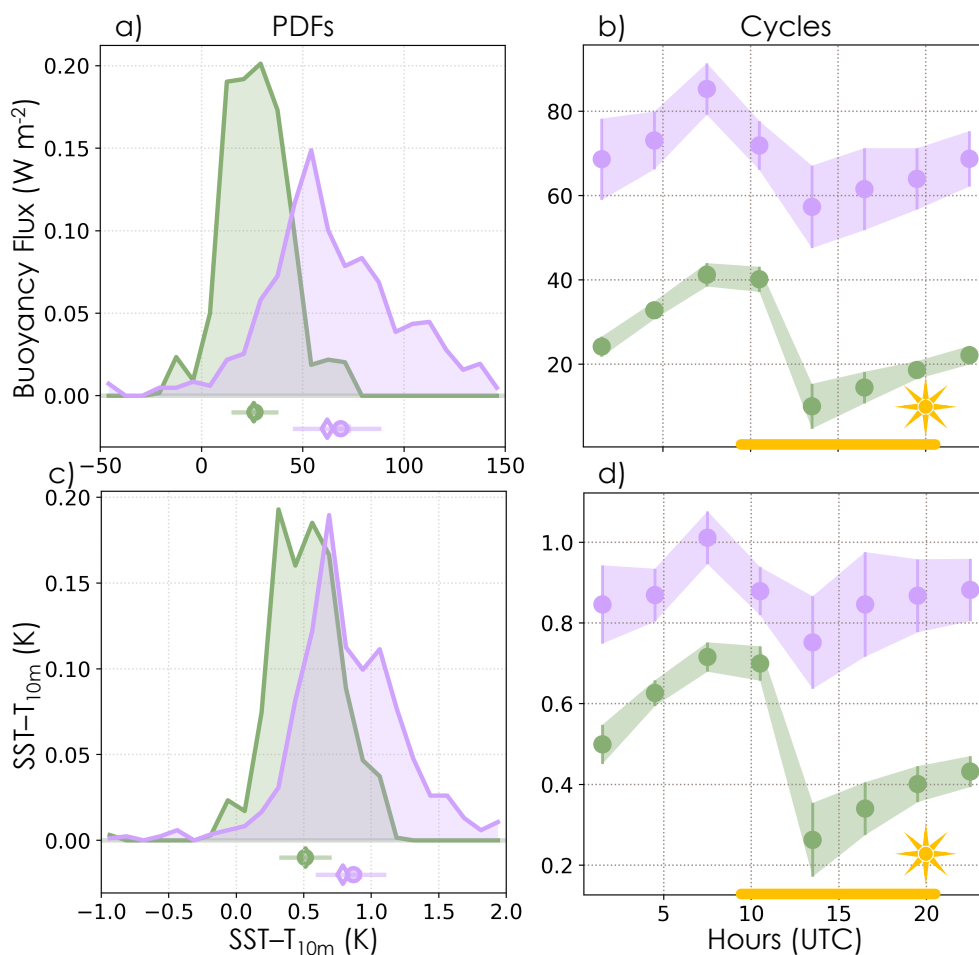


Figure C1. MO (purple) and LO (green) composites PDFs (a, c) and diurnal cycles (b, d) for buoyancy flux (a-b) and temperature difference between the sea surface and 10m air (c-d). Variable statistics for each composite are shown below the PDFs: mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line). PDFs and diurnal cycle (filled circles) MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

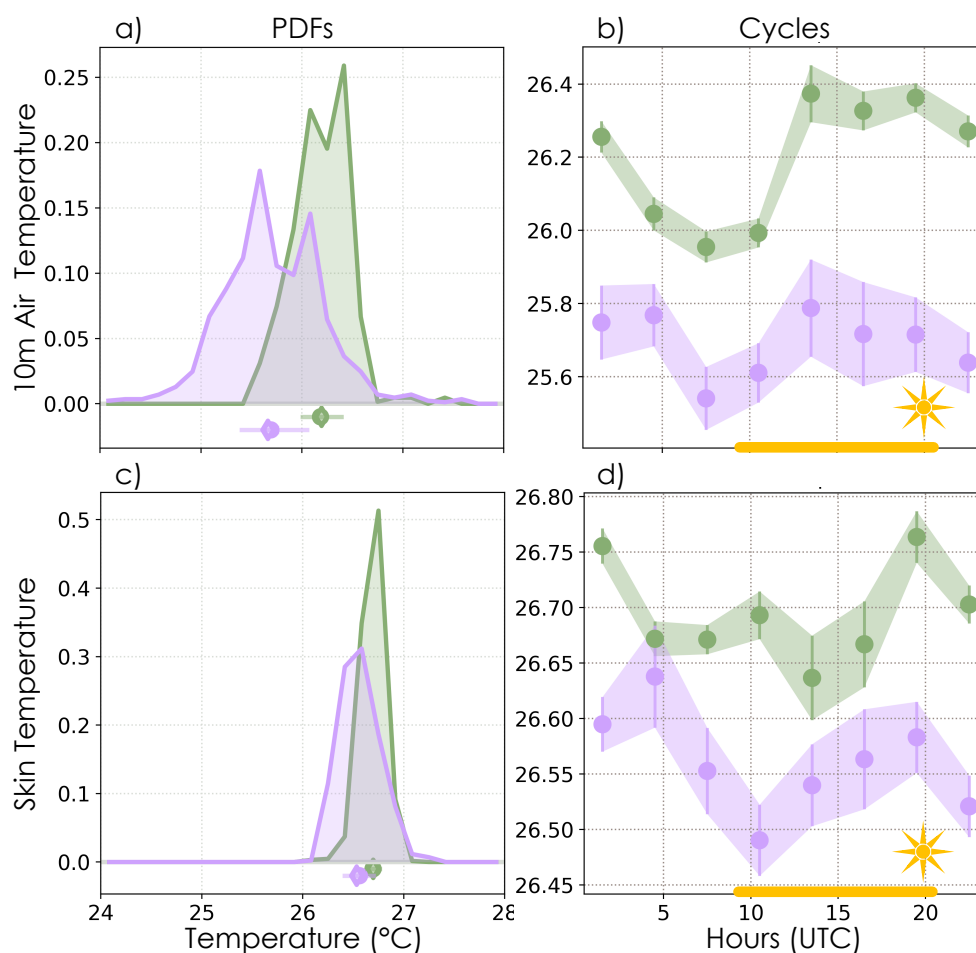


Figure C2. MO (purple) and LO (green) composites PDFs (a, c) and diurnal cycles (b, d) for 10m air (a-b) and sea surface skin (c-d) temperatures. Variable statistics for each composite are shown below the PDFs: mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line). PDFs and diurnal cycle (filled circles) MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

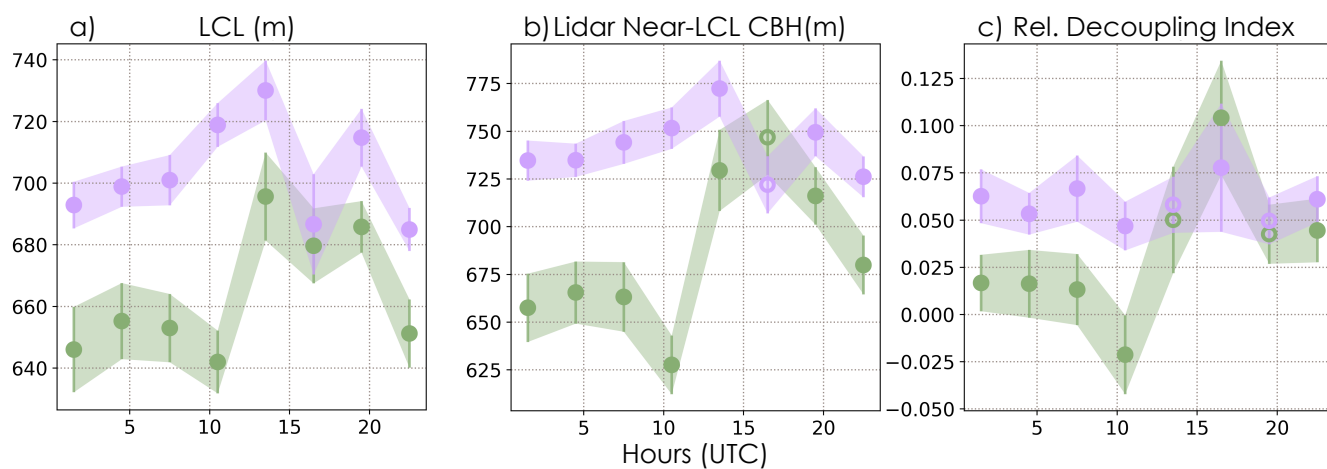


Figure C3. MO (purple) and LO (green) composite diurnal cycles for lifting condensation level (a), near-LCL CBH (b), and relative decoupling index (c) for individual cloud observations from the lidar. Mean (dot) and 2SE (vertical lines, shading) are shown for each hour range. MO and LO distributions (filled circles) are different at 95% confidence based on the Mann-Whitney U-test.

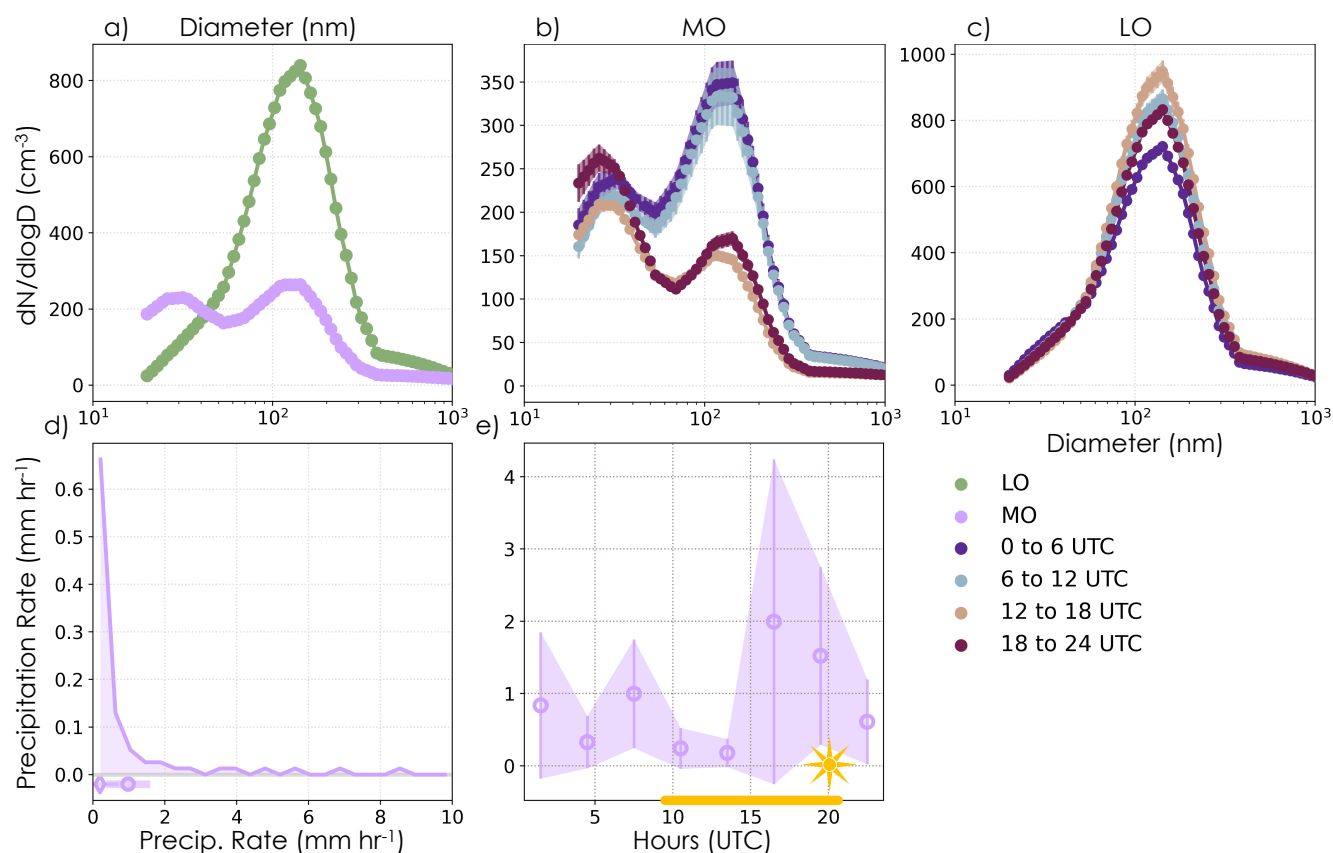


Figure C4. MO (purple and b) and LO (green and c) composites of merged and log-normal fitted DMPS and APS Quinn et al. (2022) number distributions (a-c) and precipitation rate (d-e). Mean distributions are composited absolutely (a) and in UTC ranges (b-c). Absolute PDF and statistical comparisons for precipitation rate are shown in (d) with mean (circle), median (diamond), 2SE (thick line), and 25-75% (thin line) statistics. The corresponding diurnal cycle is shown in (e). Note that precipitation only occurred during MO periods, which appear to help deplete accumulation mode aerosol during hours of more frequent precipitation (12-24 UTC). (a-c, e) Shading and lines represent 2SE in the mean (circles) and filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test.

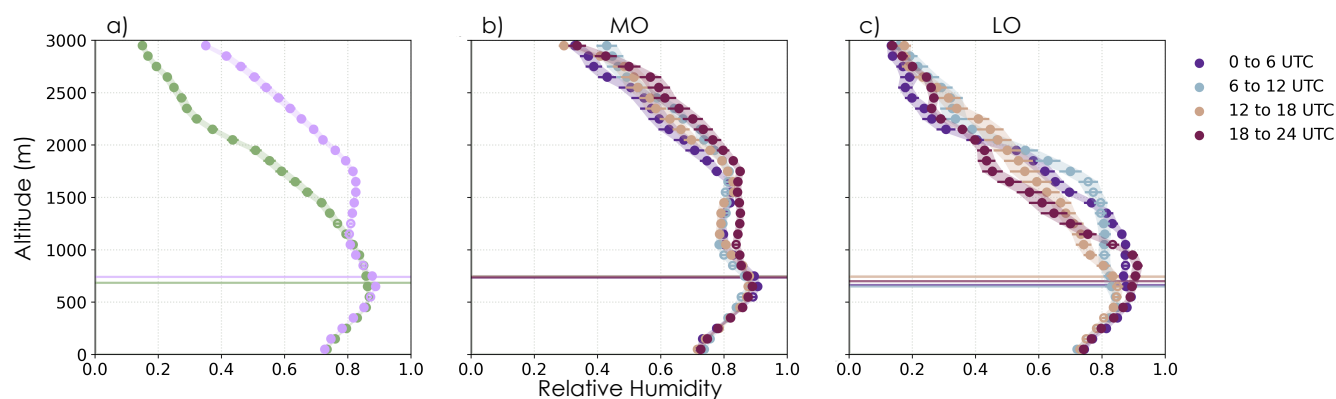


Figure C5. MO (purple and b) and LO (green and c) composites of radiosonde relative humidity (a-c). Mean profiles are composited absolutely (a) and in UTC ranges (b-c). Shading and lines represent 2SE in the mean (circles) and filled circles are where the MO and LO distributions are different at 95% confidence based on the Mann-Whitney U-test. Composite mean (horizontal line) and 2SE (shading hidden by line) lidar CBH is shown for reference (a-c).



Author contributions. ILM originated the concept of this study in discussions with PZ, led the project, analyzed the data, and wrote the paper. SB, AB led the effort to take the RHB vertical velocity measurements during ATOMIC. SB developed cloud and plume products for this study and contributed extensive insights on their interpretation. PZ, JK, WA, and GF provided guidance throughout the project. All authors contributed to the interpretation of the results and edited the manuscript.

575 *Competing interests.* At least one of the (co-)authors is a member of the editorial board of Atmospheric Chemistry and Physics. The authors are aware of no other conflicts of interest.

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