Response to Reviewers: "Cloud Regimes Over the Amazon Basin: Perspectives From the GoAmazon2014/5 Campaign" by Scott E. Giangrande, Dié Wang, and David B. Mechem

Author Comments/Summary of Changes (Prepared by S. Giangrande):

We would like to thank the reviewers for their helpful comments and suggestions. Overall, we agree with the reviewers on these comments and have responded to and/or incorporated nearly all suggestions into the revised manuscript. In addition to our detailed responses to each reviewer, we call reviewer attention to additional cross-cutting changes:

- **We improved manuscript language throughout, to also provide references for shallow-to-deep cloud transition topics, ideas that are later discussed by sections of the manuscript, and additional statements to caution potential readers on the limitations for this two-year dataset.**
- **Most manuscript figures have been modified for improved interpretation/clarity. New supplemental images provide larger-scale composite information at additional pressure levels (response to Reviewer 3).**
- **Several reviewers questioned our approach for select cumulative dataset plots, i.e., what was intended by 'ALL'/summary profiles? The 'all'-event behavior (includes every day, even those that did not match regime criteria, e.g., days having precipitation at 12 UTC). In general, we feel this way of including every event helps demonstrate whether cumulative regime properties missed significant cloud contributions from MCS.**

Once again, we wish to thank the reviewers for their efforts in improving this manuscript. We hope our responses meet with reviewer approval. All reviewer comments are provided in this document.

<u>Response to Reviewer 1</u>

Review by David K. Adams (dave.k.adams@gmail.com)

General Comments

I commend the authors for a well-written and interesting manuscript. There is nothing that really needs to be modified in terms of the general structure. One thing I think necessary is to provide a little more context for certain aspects of the study, such as the seasonality, diurnal cycle and the shallow-to-deep transition. For example, the definition of wet, dry and transition seasons should be put in a bit more context of the literature. Likewise the diurnal cycle. Your definitions may be very "GOAmazon centric", I.e, the peculiarities of those 2 years. Also, you mention the shallow-to-deep transition in passing, but this is actually a huge area of study in modeling as well as theory and observations. And many of the shallow-to-deep transition studies are based on Central Amazon conditions. So I would include a little more context to indicate to the interested reader where they may explore more these important ideas.

We thank this reviewer for their insights, as well as their many helpful comments and suggestions. We have attempted to address/answer several of these concerns below, and make the appropriate changes for our revised manuscript.

Specific Comments. Introduction

I think it is important to mention some of the previous work focusing on convection and surface atmosphere interactions as well as larger-scale forcing, such as WETAMC and TRMM-LBA. These studies provided data to examine another very important aspect of cloud development -- the inability of convective parameterizations to capture something resembling a shallow-to-deep transition (Betts and Jakob 2002a,b). And still to this day, the problem of the shallow-to-deep transition remains: what are *the physical mechanisms (e.g., cold pool collisions, moisture preconditioning above the PBL, moisture flux convergence, etc...)? And do models, even with convection "resolved", capture this transition in cloud development properly? There is a very large literature on this (Khairoutdinov, M., and D. Randall (2006), Hohenegger, C., and B. Stevens, (2013); Wu, C.-M., B. Stevens, and A. Arakawa, (2009).) And many of these studies actually focus the Amazon. This would go well with what you state in Lines 24-28 and with many of the ideas you mention further on in the manuscript.*

Thank you for the comment. Although the shallow-to-deep transition is not central to our study, it remains an ongoing challenge, and we agree it is useful to improve our introduction to include the relevant shallow-to-deep issues that we touch on and that have been the focus of much previous research. This is an especially good idea because these themes are consistent with many GoAmazon motivations, ongoing GoAmazon activities, and DOE ARM activities proposed for upcoming AMF deployments.

Line 34 Maybe write GCMs since otherwise it sounds like you are referring to a specific model called GCM.

Agree. Thanks.

Line 49-50 When you say "its" here you are referring to "changing nature of early transitions from dry and rainy seasons in the Amazon". It's a little bit awkward, maybe you might want to rephrase this.

We have reworded this portion of the introduction.

Line 83 "include estimates of" sounds better to my ears.

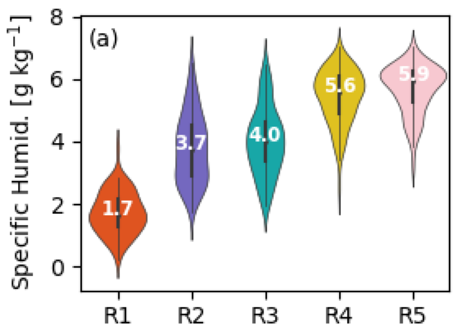
Agree. Fixed.

Line 83 low- (surface to 3 km). This seems very deep to me. The PBL (over the forests nearby) is typically about 500 to 1000m, lower in the wet higher in the dry. Can you give a little justification for choosing these layers? From one of my student's thesis and our paper (Lintner et al 2017), if you told me, I can only choose one variable that exercises the most control over deep precipitating convection in the Central Amazon, I would say 700 to 500mb in terms of specific humidity.

Agree. Thank you for the additional reference. We acknowledge that the approach was perhaps a bit arbitrary when selecting bulk layers of interest [e.g., 0--3 km, 3--6 km, 6--9 km, etc.], or choices of radiosonde thermodynamic parameters of interest. This was an attempt to provide options that may be of interest to multiple audiences, but in attempting to inform many, it is not well-aligned with any specific cloud/type. Initially, [0--3 km] was intended to coincide with the depth of the pre-convective cumulus layer, whereas the choice of the [3--6 km] layer was to gauge sensitivity of convection to mid-level RH / lapse rates. This approach was loosely aligned to previous studies, i.e., in their study of entrainment for cumulus congestus, Jensen and DelGenio (2006) use RH layers [2--4 km] and [5--7 km].

Jensen, M.P., and A.D. Del Genio, 2006: Factors limiting convective cloud-top height at the ARM Nauru Island climate research facility. J. Climate, 19, 2105-2117, doi:10.1175/JCLI3722.1.

For reference (though not included in the revised manuscript), we have plotted the specific humidity (700 mb to 500 mb) in a manner similar to the other figures in the manuscript:



Line 87 You should specify how you calculate CAPE, using a reversible or a pseudo-adiabatic and do you consider virtual temperature of the environmental profile in the vertical instead of just temperature. These can, in some conditions, may a pretty big difference.

Agree. We have attempted to correct inconsistencies with our statements on CAPE and its calculation. The section has been reworded. While there are differences among the different methods for calculating CAPE, we believe the relative relationships between the different regimes remains consistent with the descriptions we have provided in the text. Our assumptions follow a traditional parcel theory approach for CAPE calculation in Figure 4 and the values listed on the images in Figs 3 and 6:

1. **Condensation/evaporation of water vapor only (and no ice phase at all);**
2. **Parcel uses irreversible ascent;**
3. **The virtual potential temperature framework is used [Bryan and Fritsch (2002)].**

For demonstration purposes, the shaded areas on Figs 3/6 (CAPE) are calculated using air temperature, as according to Hobbs (1977); These are representative of traditional Skew-T plots.

Bryan, G.H. and J.M. Fritsch, 2002: A Benchmark Simulation for Moist Nonhydrostatic Numerical Models. *Mon. Wea. Rev.*, 130, 2917–2928, https://doi.org/10.1175/1520-0493(2002)130 <2917:ABSFMN>2.0.CO;2

Hobbs, P. V., and J. M. Wallace, 1977: Atmospheric Science: An Introductory Survey. Academic Press, 350 pp.

Line 95 I would say "Amazonia (SIPAM) radar located on south end of Manaus" since I think the military base would be considered in Manaus.

Agree. Thanks.

Line 103-4. I would disagree with this climatologically. The peak is typically around 2pm to 3pm, at least in terms of number of heaviest precipitation events. It rained much less frequently in Manaus around 12pm, and usually less intense. See Adams et al. (2013) and also Ludmila's paper (Tanaka et al. 2016). As I noted above, you may want to give a bit more context in terms of diurnal and seasonal cycles since they do vary a bit from study to study. In Adams et al. 2013, and Lintner et al. 2017, as well as Adams et al 2015, we choose Jan-Apr as wet, May-June wet-to-dry transition, July-Sept dry and Oct-Dec as dry-to-wet.

Agree. We have modified this line. These statements were informed by the specifics of the GoAmazon deployment, where the timing of precipitation is influenced by several larger-scale, regional, local factors - as well as the limitations for a two-year sampling that may not be fully representative of climatology.

Line 116 write " A simple cloud-type classification"

Agree.

Line 130-135. May give a little justification of these seasonal divisions.

Agree. We have added some support to these.

Line 195 When you say the authors, you mean you? Maybe put "we" if that is what you mean.

Agree. We have changed this line to make it less confusing.

Line 207-210. I am a bit surprised by this. I have found very little near surface humidity variability in the long-term Manaus sounding. And I imagine over the rainforest, even less so, humidity is essentially constant and high. Above the PBL, yes, there is where I think the important variability lies. The T3 site is an open pasture, I wonder if that accounts for lower atmo variability in water vapor. The Manaus sounding is fairly close to the river, so maybe that is responsible for the small variability in lower levels.

Agree. This was a poor choice of wording. Here, we are referencing the variability in the mid-to-upper level moisture, and have clarified this in the revised text.

Line 225 Definitely, April is rainy, it rains all the time and June is a transition month, not much rain, but cloudy a lot of the time (best time to visit Manaus for a tourist).

Yes. March and April are very interesting months with some of the more impressive events ARM collected during the campaign, though these months are sometimes ignored in the literature that considers 'wet' season conditions (aka, studies that only include DJF or DJFM). Again, this possibly speaks to why calendar-driven studies could be deficient.

Line 238 Yes, I would say this is true, and there is very little lightning in January to April. However, in Manaus, the locals call December “the lightning season”.

This is interesting to know. Thank you for providing the additional perspective. As before, this also speaks to the challenge when thinking of wet/transitional seasons in calendar terms as compared to those conditions conducive to storm electrification.

Line 276 “ as viewable by the current designations.” I think I know what you’re saying, but it sound odd.

Agree. Modified.

Line 291. Large-scale w is a very tough variable to measure. Strong positive w is associated with the in-cloud convective motions, as would be the latent heat release; however, the surrounding large scale atmosphere maybe still or subsiding. Even if the atmosphere is perturbed by a gravity or Kelvin wave, w is very small. As just an average measure of vertical motions it is o.k., but I wouldn’t try to estimate variables like moisture flux convergence based on this estimate.

Agree. The standard ARM single column model variational analysis products are provided as reference. However, we acknowledge that these products are sensitive to several factors including the precipitation fields (as noted in the manuscript), as well as use/location/number of radiosonde inputs. We have attempted to be in good communication with DOE/LLNL’s group (under ARM Translator S. Xie, those who generate these products for DOE ARM) on issues related to these datasets, variability as based on presence/absence of particular inputs. We do emphasize that the large-scale vertical motion W and the horizontal convergence (and moisture convergence) are all mutually consistent and variationally constrained by the observations and the mass continuity in the ECMWF model used in the variational analysis product.

Line 345 - 355. These are really a critical ideas about the STD that has implications far beyond this study. So you might want to emphasize this point in your paper and consider a bit more of the literature even if just superficially.

Agree. We have modified the text to acknowledge more of the existing literature on this topic, esp. some of the more recent studies coming out of GoAmazon2014/5.

Line 390 -394 Actually, see Figure 4 in Adams et al. 2015 that shows different behavior in the diurnal cycle of precipitable water vapor in and around Manaus.

Thank you for the additional reference.

Line 445-450 Yes, I would agree a lot of the convection in non-local forming most often to east of Manaus, and yes particularly during the transition and dry seasons.

Yes. As in our response to Reviewer 3, these MCS aspects are challenging to untangle. We suspect that follow-up deeper-dive 'regime 4' or similar activities would be beneficial -- our interests would be in refining which subsets of conditions within regime 4 promote MCS as compared to those conditions that do not.

Response to Reviewer 2

Review of "Cloud Regimes Over the Amazon Basin: Perspectives From the GoAmazon2014/5 Campaign" by Scott E. Giangrande, Dié Wang, and David B. Mechem

Alan K. Betts

This data analysis from GOAmazon is valuable. An upfront discussion of the limitations in drawing conclusions from 2 years of data would be useful. The main challenge I had as an outside reviewer is unclear definitions early in the paper. I also suggest a change of style introducing each Figure would improve the readability.

We thank the reviewer for their comments. We have reworked the introduction in parts (as also in response to Reviewer 1) and provide additional cautionary statements regarding the interpretation for the results from a 2-year dataset. We have also modified some of our text (i.e., in how we introduce figures) in response to the reviewer comments.

L84 LCL is missing from this list

Agree. Added.

L92 Regime breakdowns (clusters) is not defined – see below

L99 Cluster routines incorporate: use of cluster is unclear

L141 Finally you say: (Figure 1; Herein, we use the terms 'cluster' and 'regime' interchangeably). Looking back I see cluster is used in the abstract with no indication of what it is – derived from a model, described in section 2.2. The term is introduced in L 42-44. I recommend you rewrite L42-44 in the form

We classify the primary thermodynamic regimes that are associated with the cloud observations over Manaus, based on a cluster analysis, by applying a k-means clustering technique (refs), to the morning radiosonde launches collected during the GoAmazon2014/5 campaign. This also isolates the potential controls of large-scale conditions on convective regimes.

I find the use of 'breakdown' (as in L92 and elsewhere) confusing – perhaps because meteorologically it has been used for the breakdown of the dry season. Do you need it when you are simply describing the classification of days into regimes defined by the cluster analysis?
Eg L149-51 could be written clearly as (consistent with L130):

Figure 1 shows the cluster classification according to calendar-based Amazon definitions for the wet, dry and transitional seasons. The dry season months (Figure 1, bottom left panel) are predominantly associated with regimes 1-3, while the traditional Amazon wet season months (Figure 1, top right panel) are associated with regimes 4 and 5, with negligible contributions from the remaining regimes.

We agree with the above comments. We have reworked several portions of our manuscript to make changes as recommended.

Style. Generally I find texts much easier to read if each new Figure is always introduced with: Figure X shows. . . (rather than mentioned at the end of a sentence in parentheses)

Agree. We have reworded several figure references to avoid (whenever possible) this way of introducing our figures.

Figure 2 needs to reference Fig 1 for the cluster colors.

Agree. We have modified several manuscript figures, as also in response to Reviewer 3. We have added this specific detail to the figure caption.

Figure 11. How can the black plot for ALL be above all the regime classes at night? Isn't it an average of them?

In "ALL" event profiles/curves, we include every day in the dataset. Thus, this also contains all days having precipitation at 1200 UTC, i.e., not an average of all 'regime' days. This was done to demonstrate whether summary regime properties (profiles) miss any significant cloud contribution (e.g., clouds associated with propagating/MCS events, etc.). Recall that in order for an event to be labelled as part of any 'regime', it cannot have precipitation / must be clear at the time of the morning radiosonde. We had concerns prior to submission that a small number of events (days) may have a significant impact on one or more summary cloud behaviors. Here, the primary change is that removing these 12 UTC rain/contaminated sonde events mostly removed a more continuous lower-level cloud condition over the site.

Response to Reviewer 3

The authors present a k-means clustering analysis of thermodynamic conditions in the Central Amazon as represented by the radiosonde launches during the GOAmazon 2014/5 field campaign. They identified five regimes related to wet, transitional, and three dry types, respectively. Composite cloud and precipitation properties, convection statistics, large-scale circulation, and moisture advection related to these regimes are further contrasted. Finally, the authors discussed how these thermodynamic regimes can be linked to occurrence of different convection types. This manuscript is well written and it's interesting to see the clustering technique being applied to segregate local thermodynamic controls as compared to simple seasonal composite analysis in most previous studies. Overall, most of their conclusions are consistent with previous research efforts, but they also provide another angle to understand the relationship between the complex convection characteristic over the Amazon Basin and various types of seasonal thermodynamic controls. However, I do have a few relatively minor comments, which are mostly related to clarification of some points and improvement of figures. After addressing these I think this manuscript should be ready for publication in ACP.

We thank the reviewer for their comments. We have attempted to address all of the reviewer comments (either to the revised manuscript, supplemental, or reviewer-only through these responses in limited examples). We hope our changes/responses will satisfy the reviewer.

Major comments Selection of Radiosonde in Clear Conditions – section 2.1

In Line 99-100, the authors state that they only use radiosondes that launched in clear conditions. This is a very good practice for capturing pre-convection condition and studying shallow-to-deep convection transition.

As the reviewer is aware, a challenge when using the 1800 UTC radiosondes is that once precipitating conditions are present in the domain (e.g., congestus, convection associated with cold-pools, etc.), there is far less certainty/confidence that the conditions (even when 'clear' of clouds/precipitation at the AMF T3 site) are not partially influenced by that ongoing convection.

In Line 301-306, the authors also state that the enhanced moisture advection in regime 4 and 5 are not influenced by precipitation constrains since 1200 UTC is prior to significant precipitation. However, I think the one- hour constraint for clear condition is probably too short to reduce the influence from early morning convection on the 1200 UTC sounding, especially during the wet and transition seasons. I would suggest use clear condition for at least 3-6 hours prior to sounding time and 1 hour after that, or at least discuss how the nocturnal convection can influence the 1200 UTC sounding and your results, especially those related to moisture.

The reviewer correctly identifies the challenging interaction of scales in play in the Amazon environment, including the difficulty in cleanly separating the large-scale environment from the convection. The large-scale moisture advection will no doubt contain an influence from previous convective events, especially so for the regimes characterized by widespread precipitation and convective overturning (MCSs). Yet this is precisely the environment in which this convection forms. The best we can expect is to choose as our pre-convective periods those which minimize the immediate effects of convection, in particular cold pools. The 1200 UTC time seems to satisfy this ideal as close to possible, especially given the 6-hourly sounding interval.

For the benefit of the reviewer, we performed additional checks on these ideas (added notes, but opted not to make substantial changes to the manuscript). For the results presented in our study, approx. 93% of the radiosondes we labelled 'clear' were also 'clear' at 3 hrs prior (i.e., 0900 UTC to 1200 UTC) in the terms of surface precipitation (rain rate) measured by the ARM rain gauge. Most of

these events were found scattered throughout the regimes (mostly regime 4 and 5), though we would suggest the regimes classified on those days were typically consistent with the surrounding days. Note also that simply removing these ~7% events would not imply a noticeable shift in current manuscript figures.

K-means Clustering Method – section 2.2

In Line 141-142, the authors described the clustering process as "radiosonde temperature and wind information is input at . . ." following Pope et al. 2009b. I think it can be made clearer that how many variables go into the clustering process (temperature, eastward and northward wind speed?)? Also, I'm concerned about why humidity information is not included as input since humidity is also a very important aspect in thermodynamics, and it can be very different during different seasons in Amazon and show significantly influence on buoyancy profile (e.g. Zhuang et al. 2017; 2018). I think justify this point will help readers better understand your basis for clustering. Also, I did not find out if the author preprocess the data before inputting them to k-means clustering.

Yes, this was a great catch by the reviewer! It is hugely important that we forgot to mention that 'dew point temperature' was also included (listed this as 'temperature'). The input variables that are included into this k-means methodology are: temperature, dew-point temperature, U, V.

As far as preprocessing the data: The radiosonde data are interpolated to a relatively fine grid (~2 hPa) prior to identifying the 20 equally-spaced levels from 1000 hPa to 200 hPa. These details have been checked to make this point more obvious in the revised manuscript.

In Line 145-147, "Although the authors prefer the solution that does not use normalized inputs . . . select consequences are discussed when these inputs result in divergent solutions". I'm still confused here, what *kind of input is finally used to produce the final clustering results shown in the manuscript. I didn't find discussion about how this choice of input type would affect your results either. Perhaps it's better to move/add related discussion here or in the summary and discussion section. In addition, if you are using original or anomaly profile as input, did you assign weights for different variable? Would this affect your results? I'm asking this because these variables are in different units and the weighting can still have some influences even if the units are the same.*

As in the responses above, there may be some confusion because we did not specify 'dew point temperature' as an input. Thus, we understand if the Reviewer was surprised by the results achieved without such information.

As to the reviewer comments thereafter: we did not employ scaled or similar sorts of inputs, e.g., 'normalized' or 'standardized'-type inputs, to generate the regime clusters for the results that we presented in the primary body of the manuscript. This is consistent with the previous Darwin studies (e.g., Pope et al.) that did not employ scaled inputs or similar to the best we can determine. However, we did perform testing for standardized inputs to determine if there may be improved or different results depending on the use of these forms of inputs. We indicate in our manuscript and its supplemental images that such preprocessing appears to increase the relative importance of the wind inputs in the cluster outcomes, e.g., relatively lessens the importance for temperature/dew-point inputs. This change seems to allow certain transitional regime differences to be noted. Nevertheless, certain regimes (that is, the most extreme wet and dry event days) are suggested as robust or consistent across our input tests.

Overall, we include some changes to the text, as was also associated with our original manuscript (Sec. 2.2, Sec 2.3). We hope these details/discussions are useful to the Reviewer and/or readers who may attempt similar or improved breakdowns. We have clarified the associated discussion on

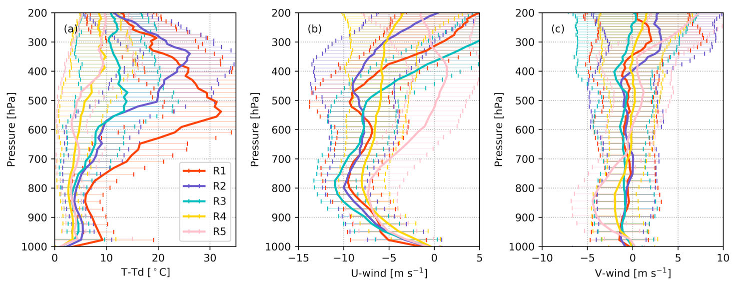
standardizing the inputs. Overall, we have found that these preprocessing efforts and potential sensitivities therein are not often well-communicated in the existing literature, and are sometimes non-obvious / not transparent.

Line 141-142, "input at 20 equally-spaced levels from the 1000 hPa to 200 hPa, . . .". I assume that this means equal weighting for different vertical layers. However, it seems to me the middle and upper level thermodynamics is much less important for convection than the lower troposphere. I'm wondering if some upper level thermodynamic disturbances could mask the lower level information and thus affect the clustering results. Maybe the authors can briefly comment this point. Also, the authors only show median profile in Figure 3, but I think a figure (either in the manuscript or the supplementals) showing both the mean/median and one standard deviation range of the input profiles in each regime would help address this point and show how well these five regimes represent the data.

This is an interesting comment. We tested the clusters to several factors that included different sets of inputs at different resolutions, e.g., whether 20-levels would faithfully reproduce the results we obtained from an entire radiosonde. When we include the full radiosonde or sub-sampling therein, there was not a significant change when compared to 20 coarsely-spaced levels. There are an infinite number of possibilities when considering how our intended audience may expand on these ideas to tackle specialized breakdowns. We agree with the reviewer that a focused set of inputs designed to explore the lowest-levels (as one example) may yield different results -- but, at the same time, we did not wish to unduly bias the regime identification with any preconceived notions such as minimizing the importance of middle-atmosphere stability. We do agree with the reviewer that such an effort (e.g., taking a deep dive into the regime 4 conditions to unravel MCS versus nonMCS) is potentially useful and something we wish to continue to explore when we begin idealized simulations on Amazon

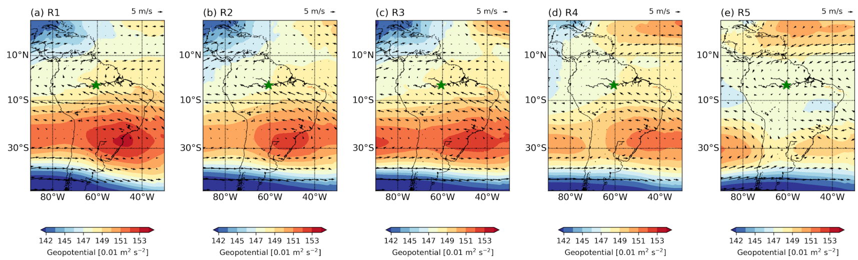
MCS events. One caution with such activities is that when one starts to fracture datasets into smaller subsets to interrogate for clues, there may not be sufficient data to perform efforts properly.

We have provided an image (below) for the benefit of the reviewer as a reference for the regime clusters as related to profile mean and spread of the conditions.



Large-Scale Synoptic Conditions – section 3.2 Please justify the use of 1000-hPa geopotential to represent large-scale circulation. For me, 1000-hPa is not a commonly used level for this kind of analysis, and I would prefer mean sea level pressure for surface system, 500-hPa or 200-hPa streamline for mid- to upper level circulation, 850-hPa wind for moisture advection analysis (consistent with many studies that low level moisture is more important for convection development and also your later results in Figure 7, 8 & 14).

This is a good comment. With ERA5 reanalysis, we are happy to provide 200hPa, 500hPa, and 850 hPa plots in the supplemental images (new Figures S5 - S7) to accompany the 1000 hPa plots in our manuscript. We feel the MSL pressure pattern is similar enough to the 1000 hPa geopotential heights that we have opted to retain the latter. Below is the regime breakdown for 850 hPa:



MCS in Regime 4 – section 4.3 Many studies (e.g. Williams et al. 2002, Zhuang et al. 2017) has shown that the transition season has a more unstable environment possibly contributed to its more intense convection than the wet season. It's also very interesting here (Line 441) to see that nearly half of the locally formed MCS are observed during the transitional regime. The authors have compared the thermodynamics between the nonMCS and MCS cases in regime 4 (Line 454-461), but I'm more interested about why regime 4 can produce about twice MCS cases as many as those in regime 5. Can the results from early sections be used to explain this? Perhaps some of the discussions from Line 238-247 can be moved here.

Yes. We would also like to better understand this! One motivation was to identify the larger-scale controls associated with GoAmazon MCS events, an attempt to inform our idealized/real-world modeling activities (ongoing projects to simulate several GoAmazon MCS events). It was encouraging that 'regime 4' conditions (instead of 'wet' and 'transitional' conditions on calendar dates) were those that significantly favored MCS during this study. This finding was bolstered when we accounted for 'propagating' events (found in all regimes), but are not assumed to be 'locally' forced. Interestingly, 'propagating' MCS events under 'regime 4' suggested weaker conditions compared to MCS events initiating 'local', and weaker than the typical "non-MCS" regime 4 environment.

The most complex detail was our inability to identify differences in large-scale conditions in regime 4 that differentiated MCSs from non-MCS events, a finding that might greatly benefit potential parameterization development/evaluation. Expecting that all different convective modes would cleanly fall along thermodynamic and flow differences at a single point was rather ambitious (or naive?). It is logical that a more detailed analysis of 'regime 4' conditions, including additional observations, is likely required. We argue that these regimes mainly represent a possible starting point in understanding the variability of convective organization in the Amazon region. As the Reviewer notes, there was variability found within regime 4 that we highlighted for the readers -- (i.e., Lines 238-247, and associated materials) that suggested potential for stronger updrafts in the Oct-Nov windows. This shift toward stronger instability parameters seemed quite consistent with previous studies on storm electrification. However, mapping the intra-regime variability to MCS/nonMCS likelihood was not as straightforward with the parameters/quantities we considered.

Overall, regime 4 conditions include relatively high RH conditions and higher wind shear favorable to deep/organized convection. However, clearly other factors, beyond those calculated from the morning pre-convective radiosondes, control/regulate the development of organized convection.

Summary and comparison of the results to broader literature – section 5

The summary section in the manuscript only lists some major findings throughout the previ- ous results section. This section should include a more detailed discussion about how the results relate to and differ from previous studies. The bullet points for major finds should also be shortened to be simpler and more precise. It is also worth mentioning the advantage of applying this clustering technique to study thermodynamic controls of Amazon convection compared to regular seasonal composite analysis.

Thank you for the comment. We have attempted to balance these reviewer comments, ideas with existing results, and references to the results of previous studies. Clearly, we agree with the reviewers that there are many recent GoAmazon studies in particular that we must acknowledge.

Minor comments

Abstract

Line 11: "three dry-season clusters". There are many places in the manuscript that use "dry season regime/cluster" or "drier season regime/cluster". I would suggest drop the "season" and simply use something like "dry regime/cluster" since these dry regime samples are also observed during the commonly defined wet or transition season. Also make sure the terminology is consistent throughout the manuscript.

We have attempted to modify some of these issues, also factoring the comments of Reviewer 2 regarding our use of 'cluster', 'breakdown', etc..

Line 12: ". . . for each regime for characteristic cloud frequency . . ." looks confusing. Please rephrase.

Ok.

Line 15: Again, what is "driest regimes". Is it just regime 1 or regime 1-3? Simply use "three dry regimes" if you were referring to regime 1-3?

Ok.

Line 15: What is “those” refer to? Line 15: “convective inhibition CIN”. No need to write down abbreviation here.

Modified.

Section 2

Line 138-139: Please provide references for these commonly defined seasons. Line 141: “is input” → “are input”

Ok.

Line 142: “over North Australia” → “over the North Australia”

Modified.

Line 165-166: This sentence looks weird and hard to follow. Do you mean in their studies, rainfall trends and onset measures indicate 2014-2015 wet season onset occurred later? How can rainfall trend relate to onset time? Please rewrite and make it clearer.

Ok. Modified.

Section 3

Line 206: This information should be also included in the caption of Figure 4.

Ok.

Line 212: Is it 4-6 m/s in the dry season versus 2-4 m/s in the wet season? The dry regime spread looks wider than wet regime in Figure 4f.

Yes. Good catch. We made a mistake and reversed the seasons. Corrected to be more specific.

Line 267: "composite westerly wind components over the MAO T3 site"? Where does this information come from? Figure 5e? I don't think the wind above the green star is significant westerlies.

Ok. We have revised these comments to be more consistent.

Line 267: Be consistent with site name. You used MAO site many times and MAO T3 a few times throughout the manuscript.

Thanks. We will address this inconsistency.

Line 268: Same as the previous comment, I don't find the wind field above MAO in regime 4 much different from regime 5. Also, as I pointed out in the major comment, I would suggest use 850 hPa if you want to use wind to indicate moisture transport. This is more consistent with previous studies and your results in Figure 7-8.

We have added 850/500/200 hPa into the supplemental images. We think there is a relative shift in the lower-level winds between regimes 4 and 5 (as in our radiosonde composite and parameter images), as well as the overall regional patterns, but we agree that the visual differences in ERA5 patterns over the MAO between Regimes 4 and 5 are not obvious.

Section 4

Line 312: How is Figure 9 correspond to Figure 7? If there is no specific link, I think you can simply drop "that correspond to Figure 7".

Rephrased, as we agree this may be confusing.

Line 353: "moister" → "wetter".

Ok.

Line 381: In Figure 11, why is the overall average rain rate higher than that of any regime during 03-12 UTC? Also, why is there no nocturnal precipitation here while there are significant clouds during late night and early morning in regime 3-5 in Figure 9. What is "regime-events having measurable precipitation"? Did you explain this before?

As in response to Reviewer 2, our 'ALL' conditions were intended to represent all conditions. These include events that we excluded, e.g., because they did not satisfy our requirement for 'clear' conditions at 12 UTC. We wanted an 'all' behavior to help provide confidence that our regimes (or requirements) were not necessarily excluding too many MCS events (i.e., overnight, propagating) or other significant instances associated with nonclear conditions at 12 UTC.

Line 385-386: You mentioned the uncertainty of radar estimated precipitation here. Can you also briefly introduce in the method section how the precipitation is derived from radar reflectivity (Z-R relation)? As I can recall, they only use the wet season Z-R relationship from the disdrometer to calculate all precipitation data. This information can be found in the ARM-MAO PI dataset.

Ok. We have provided additional details. For domain averages from the VARANAL products, we do not believe this would represent a major change in our plots, but we have noted that these issues may suggest that 'drier' season behaviors are likely over-estimated (see below).

A more detailed answer is that our previous rainfall efforts from GoAmazon have looked at the differences between the seasons w/r/t Z-R relationships and sensitivities therein (crude bootstrapping, etc.), as found in Table 2 of Wang et al. (2018 ACP). These results were obtained using that same disdrometer (Parsivel) over the entire campaign period. Overall, the implication when thinking of the specific (contingent) regime breakdowns would be that the 'drier' season coefficients would arguably carry 'larger' (a-coefficient) for same (b-coefficient) in Z = aR^b forms. This implies that 'dry' season rainfall is associated with a larger Z for a given R. This makes physical sense insomuch that this implies larger drop sizes / less 'tropical'/'oceanic' behaviors than for the 'wetter' seasons.

The overall implication when interpreting the accumulation that is derived from a product that only uses 'wet' behaviors is that rainfall estimates will likely 'overestimate' rainfall rate and accumulation in the dry season (i.e, for the same Z, R should be smaller) if compared to estimates that used seasonally sensitive Z-R relationships. We have noted this in the revised manuscript.

Wang, D., Giangrande, S. E., Bartholomew, M. J., Hardin, J., Feng, Z., Thalman, R., and Machado, L. A. T.: The Green Ocean: precipitation insights from the GoAmazon2014/5 experiment, Atmos. Chem. Phys., 18, 9121–9145, https://doi.org/10.5194/acp-18-9121-2018, 2018.

Line 394: "the most frequent clouds we observe are" → "the time with most frequent clouds are"

Ok.

Line 399: "lower-relative domain rainfall rate"? Do you mean lower domain rain rate?

Modified the text for clarity.

Line 426: "e.g., defined by a minimum area of Z>20dBZ of <200km2". If this is the definition you used for non-precipitating event, remove "e.g.,". Also, perhaps "minimum area of Z>20dBZ is less than 200 km2" is better. minimal area of Z>20dBZ of 200 km2? What is definition of isolated, and widespread precipitation event.

Ok. Fixed the corresponding text to improve clarity/interpretation.

Line 431: "km2". Use superscript for square. Also check elsewhere in the manuscript.

Ok.

Figures

Figure 1. Texts and numbers in this figure are too small. Consider increase the font size (also apply to some other figures), and use a legend like Figure 2 instead of listing R1, R2, . . . for all of the pie charts.

Ok. We added legends to Figures 1 and 13; Increased the font size for Figures 5, 6, 10, 13. Changes to Supplemental S1, S2 as well. Applied consistent changes to new supplemental figures as well.

Figure 2. Add a legend for different colors of dot in Figure 2a. Increase font size of R1, R2, . . . in Figure 2b. Also, to match the definition of seasons and make it easier for readers to understand the result in Figure 2b, please consider only use four main color tones to represent wet, dry, and two transitional seasons. For different month in one season, just use different levels of darkness of the same color.

Ok. We added the description of different colors in the Figure caption for Figure 2a, and we have changed the color of each month in Figure 2b (towards more of a wet-to-dry type of color scale that is less confusing than the previous rainbow colors).

Figure 4. Explain in the caption what's the thick black line in the middle of the density plot. Make the white number in bold font (also apply to Figure 12).

Ok.

Figure 7. "600-hPa/700-hPa" → "600-hPa (f-j) / 700-hPa (a-e)"

OK. Fixed.

Figure 8. What you plot is dash-dotted line not dashed line.

Thanks. Fixed.

Figure 9. Add unit to the colorbar. Why is tick numbers not aligned with the color?

Ok. Adjusted the colorbar and added the unit.

Figure 11. The shading areas look very narrow for standard deviation. Is it one standard deviation or standard error?

The shading areas are 1 sigma standard deviation.

Cloud Regimes Over the Amazon Basin: Perspectives From the GoAmazon2014/5 Campaign

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Abstract. Radiosonde observations collected during the GoAmazon2014/5 campaign are analyzed to identify the primary thermodynamic regimes accompanying different modes of convection over the Amazon. This analysis identifies five thermodynamic regimes that are consistent with traditional Amazon calendar definitions of seasonal shifts, which include a wet, transitional, and three dry-season regimes based on a k-means cluster analysis. A multisensor ground-based approach is used to project associated bulk cloud and precipitation properties onto these regimes. This is done to assess the propensity for each regime to be associated with different characteristic cloud frequency, cloud types, and precipitation properties. Additional emphasis is given to those regimes that promote deep convective precipitation and organized convective systems. Overall, we find reduced cloud cover and precipitation rates to be associated with the three dry regimes and those with the highest convective inhibition. While approximately 15% of the dataset is designated as organized convection, these events are predominantly contained within the transitional regime.

1 Introduction

A primary source of uncertainty in global climate or earth system model (GCM, ESM) predictions of possible climate change is the representation of cloud processes and associated cloud feedbacks that regulate Earth's energy and water cycles (e.g., Klein and Del Genio, 2006; Del Genio, 2012). One explanation for continuing deficiencies in climate model cloud-process representations points to uncertainties in how deep convection is parameterized. Unfortunately, the assumptions underpinning the parameterizations are often poorly constrained by observations. Formulating well-behaved convective parameterizations necessitates routine cloud observations, married to their associated meso- and synoptic-scale controls, and collected over the variety of global convective regimes. Untangling these cloud–climate controls in ways suitable to ongoing model development demands long-term, multi-scale, multi-sensor observations that often require challenging instrument deployments to capture cloud and precipitation properties in remote and under-sampled global regimes (e.g., Louf et al., 2019).

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As home to the largest tropical rainforest on the planet, the Amazon basin experiences prolific and diverse cloud conditions that vary according to pronounced changes in seasonal regimes. However, these clouds, regimes and their associated convective intensity are interconnected, with cloud properties (coverage, depth, precipitation) strongly influenced by (and influencing, via feedbacks) seasonal shifts in the thermodynamic forcing, as well as larger-scale atmospheric Hadley and Walker circulation variability (e.g., Fu et al., 1999; Machado et al., 2004; Misra, 2008). Recently, the ongoing struggle of GCMs and weather prediction models to represent aerosols, clouds and their interactions over this expansive tropical area motivated the 2-year US Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) campaign (e.g., Martin et al., 2016; 2017). As part of this effort, ARM deployed its Mobile Facility (AMF; e.g., Miller et al., 2014) downstream of Manaus, Brazil in the central Amazon. The facility enabled capture of the thermodynamic state, aerosol, cloud and precipitation properties in this location, through the deployment of multiple surface state and atmospheric profiling facilities (e.g., Mather and Voyles, 2013).

We classify the primary thermodynamic regimes that are associated with the cloud observations over Manaus using a k-means cluster analysis applied to the morning radiosonde launches collected during the GoAmazon2014/5 campaign. This is done to isolate the potential controls of large-scale conditions on convective regimes. Conceptually, this technique follows previous tropical clustering efforts such as Pope et al. (2009a, b) to examine the variability found in the North Australia monsoonal seasons. Their motivations were to promote objective methods to identify key monsoonal changes and establish cloud–precipitation regimes to evaluate the representation of these processes in global models (e.g., May and Ballinger, 2007). A similar opportunity is expected for Amazon studies, hinted at by several recent efforts (Marengo et al., 2017; Wright et al., 2017; Sena et al., 2018) that illustrate the complex cloud processes and the possible changing nature of yearly transitions from dry and rainy seasons in the Amazon. The clustering approach may also yield an improved understanding of the relationship between the intraseasonal variability and the different Amazon convective regimes (Betts et al., 2002; Ghate and Kollias 2016), as well as new insights into shallow-to-deep cloud transitions and model treatments therein (e.g., Khairoutdinov and Randall, 2006; Wu et al., 2009; Hohenegger and Stevens, 2013; Zhuang et al., 2017; Zhuang et al., 2018; Mechem and Giangrande 2018; Chakraborty et al., 2018; Chakraborty et al., 2020). Moreover, there is continuing need to identify particular seasonal, environmental or aerosol controls on Amazon convection and its intensity (Greco et al., 1990; Williams et al., 2002; Alcântara et al., 2011; Fan et al., 2018; Wu and Lee, 2019; Rehbein et al., 2019).

The proposed regime segregations are projected onto the large-scale synoptic patterns, forcing datasets, and remote-sensing cloud/precipitation observations for the GoAmazon2014/5 campaign. Although there are limitations when drawing conclusions from any two-year campaign dataset, these efforts are used to assess possible controls and convective-cloud predictors as related to i) the interpretation and consistency of these radiosonde clusters with previous wet/dry seasonal definitions for the Amazon, ii) bulk regime relationships to particular cloud presence/absence, the iii) precipitation properties for these regimes to include diurnal cycles, and iv) the propensity for regimes to promote extremes in precipitation such as

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null-event days or mesoscale convective systems (MCSs, Houze, 2004; Wang et al., 2019; Wang et al., 2020). The GoAmazon2014/5 datasets are briefly described in section 2. The clustering algorithm, displays of the regimes according to thermodynamic variability, and additional methodology sensitivity testing are described in sections 2 and 3. Section 3 also explores the relationships between these regimes and overarching synoptic patterns, as well as area-averaged and observationally constrained vertical profiles (e.g., horizontal moisture convergence) often used to force single-column models (SCMs). Summaries of cloud properties associated with these regimes are found in section 4. This includes discussion on the propensity for the regimes to promote precipitation, and the likelihood of MCS events initiating nearby the campaign facilities. Finally, key findings for this study are summarized in section 5.

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2 GoAmazon2014/5 Dataset and Processing Methods

Datasets for this study were collected by the U.S. DOE ARM facility during its "Observations and Modeling of the Green Ocean Amazon 2014–2015" campaign near Manaus, Brazil from January 2014 through December 2015 (herein, GoAmazon2014/5 or MAO; Martin et al., 2016; 2017; Giangrande et al., 2017). The primary datasets were from the routine ARM radiosonde launches during the campaign at the "T3" main AMF field site downwind of the city of Manaus, Brazil and near Manacapuru, Brazil. These radiosondes provide the thermodynamic quantities of interest and act as basis for regime clustering methods (section 2.2).

2.1 ARM GoAmazon2014/5 Products and Datasets

Details on ARM radiosondes, their preprocessing and convective parameter estimates, follow previous ARM studies (e.g., Jensen et al., 2015). The quantities of interest for this study include estimates of the convective available potential energy (CAPE), the convective inhibition (CIN), the Relative Humidity (RH) at low- (surface to 3 km), mid- (3 km to 6 km) and high-levels (above 6 km) of the atmosphere, the 0–5-km wind shear, the Level of Free Convection (LFC), the Lifting Condensation Level (LCL), and the 0–3-km Environmental Lapse Rate (ELR). Our CAPE calculations follow a traditional parcel theory approach (condensation/evaporation of water vapor only, assuming irreversible parcel ascent in a virtual potential temperature framework, e.g., Bryan and Fritsch, 2002). The originating parcels for CAPE/CIN estimates are defined by the level of the maximum virtual temperature in the lowest kilometer (below 700 hPa). Thus, the standard calculations for CAPE and CIN represent the most buoyant parcel in the boundary layer such that the reported values are comparable to 'most unstable CAPE/CIN' (herein, MUCAPE/MUCIN). Mixed-layer CAPE and CIN estimates (mean parcel properties over the lowest 500 m, which we take to be representative of the mixed layer) were also computed for comparison.

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Cloud properties were collected by collocated instruments at the MAO site, with additional information provided by observationally-constrained reanalysis datasets. For precipitation properties, surveillance S-band (3 GHz) radar observations were available to within 70 km of the MAO site as collected by the System for the Protection of Amazonia (SIPAM) radar located on the south end of Manaus (e.g., Ponta Pelada airport, Martin et al., 2016). These radar data were calibrated against satellite measurements, and subsequently gridded to a 2 km × 2 km horizontal grid at 2 km AGL (e.g., Schumacher and Funk, 2018).

Cluster routines incorporate only the morning (1200 UTC, 0800 local time) radiosondes that are launched in clear conditions. Clear conditions are defined as those having no rainfall at the MAO site according to rain gauge measurements to within an hour of launch time. Confirmation of precipitation-free conditions was also performed using SIPAM observations and manual checks for contaminated radiosondes. A more restrictive precipitation constraint (i.e., no rainfall at the gauge site between 0900 UTC and 1200 UTC) did not result in an appreciable change to the results that follow. A motivation for using the morning radiosonde was to capture pre-convective cloud conditions prior to the daily transition from clear skies to shallow cumulus to deep convection, given previous studies on the diurnal precipitation cycle for Manaus that peaks after local noon (e.g., Adams et al., 2013; Tanaka et al., 2014; Giangrande et al., 2017). Additional concerns are that earlier (0600 UTC) or later (1800 UTC) radiosonde launches are not representative of the pre-convective environment, and are more susceptible to existing clouds, overnight fog (e.g., Anber et al., 2015), precipitation and/or cold pool contamination. In total, 607 daily radiosondes from the campaign (out of 696, 12-UTC radiosondes in total) met these criteria, with 27 days removed due to missing radiosondes. Of the days flagged as contaminated or 'missing' at 1200 UTC, approximately 30-40 days were associated with radar-designated MCSs passing over MAO (section 4).

Time-height (column) cloud properties are provided by a hybrid cloud radar / radar wind profiler (RWP) product developed during GoAmazon2014/5 (Giangrande et al., 2017; Feng and Giangrande, 2018). The product combines the ARM multi-sensor (e.g., cloud radar, lidar, ceilometer, radiometer) Active Remote Sensing of CLouds (ARSCL; Clothiaux et al., 2000) cloud boundary designations with collocated 1290 MHz ultra-high frequency (UHF) RWP measurements (e.g., Giangrande, 2018; Wang et al., 2018), and gauge observations. The RWP improves the ARSCL cloud-boundary estimates of cloud echo top by sampling deeper precipitating clouds that otherwise attenuate/extinguish the cloud radar beam. A simple cloud-type classification is performed following McFarlane et al. (2013) and Burleyson et al. (2015). Observed clouds are classified into seven categories according to the height of the cloud and cloud thickness (Supplemental Table S1). These seven cloud categories are 'shallow', 'congestus', 'deep convection', 'altocumulus', 'altostratus', 'cirrostratus/anvil', and 'cirrus'.

Large-scale synoptic perspectives on the regimes are obtained using reanalysis fields from ERA5 (Hersbach and Dee, 2016) and the ARM variational analysis product (ARM-VARANAL). The VARANAL is derived from ECMWF analysis fields and ARM observations during GoAmazon2014/15 using the constrained variational analysis method of Zhang and Lin (1997). The

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product is available at 3-hour intervals on a regular vertical grid of 25 hPa over a domain of ~110 km radius around the MAO site (Xie et al., 2014; 2016). The product is also constrained by the domain-mean precipitation as observed by the SIPAM radar. Additional details on these products during GoAmazon2014/5 are found in Tang et al. (2016).

2.2 *K*-means Clustering Methods

Regime classification is accomplished using an open-source Scikit-learn's *k*-means algorithm applied to input radiosonde observations (toolkit from Pedregosa et al., 2011). The choice of *k*-means solutions over other configurations is done for simplicity and is consistent with previous radiosonde applications. While the sensitivity of proposed regime designations to different clustering approaches is not the subject of this study, applying alternate configurations did not alter relative clusters or composite interpretations.

One property of *k*-means clustering is that the number of clusters needs to be prescribed. One expectation from the Amazon convective literature (e.g., Williams et al., 2002) is that three to four regimes account for the bulk seasonal thermodynamic variability: i) a 'wet' season regime typically defined as December through April, ii) a 'dry' season regime from June through September, and iii) one or two 'transitional' regimes associated with the months leading into the wet and dry regimes, respectively. However, calendar definitions of the regimes vary in the literature (e.g., Zhuang et al., 2017), which may cause additional confusion when interpreting the findings across studies. From sensitivity testing (see section 2.3), we establish the number of clusters at five. Radiosonde temperature, dew point temperature and zonal/meridional wind information are input at 20 equally-spaced levels from 1000 hPa to 200 hPa, as similar to previous applications over Northern Australia (Pope et al., 2009a,b). This input resolution is coarser than the resolution of both the ARM radiosondes (~2 hPa), and that of the 25-hPa VARANAL resolution. Additional tests (not shown) indicate that, for this particular case, the *k*-means solutions are insensitive to improvements in the input radiosonde resolution (to the 2 hPa level), or input ordering of the data. Although the results for this study present cluster solutions that do not use standardized inputs (e.g., scaling all inputs to having a similar range, standard deviation), it is common practice in recent studies to scale inputs. Subsequent sections will comment on potential changes in cluster results when scaled inputs are substituted.

Figure 1 shows the cluster classification according to calendar-based Amazon definitions for the wet, dry and transitional seasons. The dry season months (Figure 1, bottom left panel) are predominantly associated with regimes 1-3, while the traditional Amazon wet season months (Figure 1, top right panel) are associated with regimes 4 and 5, with negligible contributions from the remaining regimes. The ambiguous transitional season (here, reflecting the months of May, October and November) indicates contributions from all regimes, though skewed towards regimes 4 and 5.

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In Figure 2, we plot the time-series of regime designations throughout the campaign (top panel), with the associated monthly breakdowns for the clusters (bottom panel). Qualitatively, the temporal coherenc of the individual clusters in the five-regime solution provides initial confidence in the appropriateness of this regime breakdown. Instances of regimes 4 and 5 are aligned with classical transitional and wet season periods, respectively, with regime 4 periods adjacent to regime 5 and not sporadically distributed within other regimes. The remaining clusters are interwoven within Amazon drier months. The observed cycling between these dry clusters is of immediate interest, as this variability may be indicative of intraseasonal synoptic pattern phases in the dry season.

The specifics of the GoAmazon2014/5 campaign and its particular representativeness in the context of historical Amazon records should be considered when assessing cluster appropriateness. As summarized by Marengo et al. (2017), climatological wet season onset for Manaus based on rainfall records is typically mid-November (e.g., Liebmann and Marengo, 2001). Their efforts indicate that traditional rainfall-based criteria and additional wet season onset measures such as outgoing longwave radiation indicators (e.g., Kousky, 1988) imply that the 2014-2015 wet season onset date occurred much later in the season (e.g., end of January, 2015). One explanation for the late onset, offered by Marengo et al. (2017), was that precipitation - the obvious indicator for wet-season onset -- was heavily influenced by the strengthening of the Madden–Julian Oscillation (MJO; Madden and Julian, 1994) and associated influences on Amazon rainfall. Based on cluster outcomes in Figure 2, we did not identify a prolonged cluster arguably associated with a presumed 'wet season' condition (e.g., regime 5) until early December 2014. This coherent shift in the frequency of radiosonde regime 5 designations coincides with an extended change-over in the upper-level winds, as also shown in campaign thermodynamic summary plots (e.g., Fig. 2 from Giangrande et al., 2017). Nevertheless, we record multiple instances of regime 5 as early as November 2014, coinciding with a pronounced dry-to-wet seasonal shift towards a deep-layer profile moisture (RH, see also Fig. 2, Giangrande et al., 2017). As before, the motivation for the k-means cluster method is not to 'pinpoint' an exact rainy season onset date (e.g., first appearance of a given cluster), rather to identify atmospheric regimes that may provide guidance towards subsets of attendant environmental conditions conducive to different bulk cloud properties.

2.3 Additional *k*-means Cluster Sensitivity Considerations

Establishing the number of clusters within *k*-means methods requires sensitivity testing. Too few clusters tends to overgeneralize and produce overly large intra-cluster variability; too many clusters lead to difficulty in interpretation, because there may be no physically meaningful distinction between clusters. Similar to justifications proposed by Pope et al. (2009a, b), we are interested in regimes associated with significant radiosonde variability, and therein, potential relationships to cloud variability. One criterion Pope et al. (2009a,b) recommended was that each cluster account for no less than 10% of the dataset. When adopting this approach, Amazon solutions having more than five clusters generated additional clusters that accounted for fewer than 10% of the days.

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When considering a six-cluster solution (supplemental Figure S1), the solution further subdivided the three drier regime clusters into four. However, the distinct separation between our wet (regime 5) and transitional (regime 4) clusters showed little difference when the number of clusters was increased from five to six. To be discussed in section 3, the wet and transitional regime separations predominantly differ from each other in their zonal/meridional wind structures. This does not suggest that there are not specific differences depending on whether the transition is wet-to-dry and dry-to-wet, only that these differences are not as pronounced as the drier intraseasonal shifts. In contrast, the four-cluster solution meets our basic criterion for determining the number of clusters (Supplemental Figure S2). However, with only four clusters, the regime 4 and 5 clusters are combined into a single, deep-moisture profile regime. We demonstrate in later sections that the 5-regime clustering is able to delineate useful details in convective transitions and organization compared to the 4-regime solution. Because of this, the authors settle on the five-cluster solution as it maintains a separate transitional regime that the authors believe is consistent with the literature.

3 Thermodynamic and Large-Scale Interpretation of Amazon Regime Clusters

3.1 Composite Regime Thermodynamic Profiles and Parameter Displays

In Figure 3, we plot the composite radiosondes for all five regimes classified in the previous section. Shaded regions provide reference to composite radiosonde MUCAPE (red shading) and MUCIN (blue shading). Values reported on these images are the median values of the MUCAPE/MUCIN calculated for each individual sounding. The probability density plots in Figure 4 report the median values, distribution, quartiles and 10th/90th percentile extremes for the convective parameters of interest calculated from the radiosondes. Differences in MUCAPE and MUCIN across the regimes are largely driven by differences in the mid-to-upper level moisture / dew point temperature rather than temperature, a result consistent with the understanding that horizontal temperature gradients over the tropics are small, and variability in tropical convection is predominantly associated with horizontal moisture gradients ("weak temperature gradient approximation," Sobel et al., 2001). For all regimes, the standard deviations for MUCAPE and MUCIN parameters are similar (1100 J/kg and –15 J/kg, respectively). For other fields, the standard deviations vary with regime, with greater variability in the traditional dry season time frames than in the wet season. For example, standard deviation for wind shear is 4–6 m/s in the drier regimes and regime 4 versus 2–4 m/s in the wetter regime 5 conditions. For mixed-layer CIN, median regime values become less negative (from -85 J/kg for regime 1, to -33 J/kg for regime 5); however, the relative distribution and regime rankings are similar. When considering mixed-layer CAPE distributions, the values estimated for regime 1 (the highest MUCAPE regime) are noticeably smaller than the other regimes (median values dropping to 550 J/kg), whereas the remaining regimes all have similar median mixed-layer CAPE

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values of approximately 1000 J/kg (similar relative rankings otherwise). This discrepancy in mixed-layer CAPE and more prohibitive mixed-layer CIN may explain the absence of deep convection under regime 1 conditions (section 4).

Temporal patterns for regime 5 align with calendar wet season definitions and deeper moisture conditions. As visible in Figures 3 and 4, regime 5 is associated with reduced values for MUCAPE, but favorable (less negative) MUCIN to promote frequent convection (e.g., Giangrande et al., 2016). Regime 5 also records the lowest LFC and LCL heights, and reduced distribution variability therein. Where regime breakdowns differ from traditional Amazon ideas is with these methods more frequently defining wet-to-dry season months such as April through June as 'transitional' regime 4 (Figure 3b) periods. As suggested by Figure 4f, the most significant difference we observe between the regime 4 and 5 composites are associated with profile winds, which includes increased lower-level wind shear in regime 4. A separation for wet and transitional regimes as according to wind shifts is consistent with ideas of transpiration or shallow convection 'preconditioning' an eventual wet season onset (e.g., Wright et al., 2017), e.g., favorable moisture conditions precede deeper cloud formation prior to regional scale wind shifts lending to wet season onset. However, this explanation would not apply for the reciprocal wet-to-dry transitional periods. Nevertheless, this dry-to-wet transition may bear some resemblance to the moistening and associated cumulus and congestus that occur as the MJO over the tropical western Pacific transitions from suppressed to active conditions (e.g., Johnson et al., 1999; Benedict and Randall, 2007; Mechem and Oberthaler, 2012, Zermeño–Díaz et al., 2015). Finally, while the differences in bulk wind shear are interesting between regimes 4 and 5, the magnitude of these differences are modest (to within 5 m/s). However, differences in mean shear within regime 4 may be indicative of differences in updraft structure (upright vs. tilted), convective cold pool circulations, and overall organization (e.g., Rotunno et al., 1988; Parker and Johnson, 2000; Weisman and Rotunno 2004).

Previous Amazon studies suggest that the dry-to-wet season transitional periods (e.g., September through November) are more conducive to storm electrification than wet-to-dry transitional periods (e.g., Williams et al., 2002). Our clusters do not distinguish differences between these periods (here, 'dry season' as traditionally defined, from June through September). Although the separations for regimes 1 (extreme dry) and 5 (extreme wet) are robust to our input tests, when *k*-means methods use standardized inputs, this change realigns five-cluster solutions towards 'pre' and 'post' dry season states (Supplemental Figure S3). While the authors did not pursue cluster solutions using standardized inputs for our primary examples, one suggestion is that standardized wind field inputs (to yield the same variability as the temperature and/or moisture fields) may help differentiate transitional periods. In our supplemental images, we provide composite properties for pre- (March through May) and post- (September through November) dry season regime 4 instances (supplemental Figure S4). Current regime 4 solutions exhibit enhanced MUCAPE for soundings collected during dry-to-wet periods that suggests those times as more conducive for vigorous updrafts (median MUCAPE values greater by ~700 J/kg).

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The remaining clusters are associated with months traditionally classified as the Amazon dry season. Shifts between the three drier clusters are attributed to radiosonde mid-to-upper level moisture, with only minor controls associated with shifts in winds. Regime 1 is the least-frequently observed for the Amazon campaign, but the most significant outlier in terms of thermodynamic parameters (e.g., Figure 4). Regime 1 is also associated with the driest overall profile conditions (at low- and mid-levels), the lowest mixed-layer CAPE, the highest LFC, and the most prohibitive MUCIN conditions. Regime 3 favors humid conditions at the low-to-mid levels when compared to regimes 1 and 2, and larger values of mid-to-upper level humidity. The enhanced humidity at low- and mid-levels in Regime 3 may aid in initiation and maintenance of deep convection, while enhanced upper-level humidity may promote saturated layers and ice-phase microphysical processes associated with stratiform precipitation. As widespread stratiform precipitation and MCSs have been reported also within the dry season (e.g., Wang et al., 2018; 2019), section 4 explores which dry season regime or regimes favor MCS.

3.2 Large-Scale Synoptic Conditions Projected into these Regimes

In Figure 5, we plot the means of the 1000-hPa geopotential height and wind field from the ERA5 (taken to represent the composite large-scale synoptic patterns) projected into each regime. Additional composites at the 200-hPa, 500-hPa and 850-hPa levels are found in the supplemental materials (Supplemental S5-S7). For the wet regime (regime 5), the composites show land-ocean contrasts, and composites carry strong impressions of the Chaco low over the continent (and/or Bolivian high at the upper levels). Signatures of the Bolivian high are present in the deep layer of prevailing southerly winds over the MAO site and are exclusive to regime 5 (Figure 3e). Unlike other composites, regime 5 also suggests 1000-hPa flows providing moisture convergence into the Amazon basin originating from the tropical belt (northern tropical Atlantic, e.g., Drumond et al., 2014), and associated calm or weak westerly low-level wind components over the MAO site. Although the 1200 UTC regime thermodynamic profiles did not indicate a pronounced difference between regimes 4 and 5 moisture characteristics, ERA5 composites suggest that regime 4 conditions are associated with different sources of moisture, with 1000-hPa winds over the Amazon basin shifting towards drier easterly zonal 1000-hPa flows. We speculate that the regime 4/5 shift visible in the large-scale composites may be associated with the positioning and strength of the South Atlantic Convergence Zone (SACZ) and its influences on the Amazon basin during the wet season (e.g., Carvalho et al., 2004). Drier season regimes have transitioned to southerly low-level flow suggestive of drier, colder air reaching the central Amazon. These patterns vary according to the positioning and strength of offshore features that, in turn, funnel increasingly drier, colder air from the southeast (e.g., tropical South Atlantic; Drumond et al., 2014).

GoAmazon2014/5 datasets recorded one complete transition from the dry season to the wet season. In Figure 6, we plot the composite 1000-hPa patterns associated with regime 5, with each panel corresponding to a different monthly composite between October and January. Noting that October contained few instances of regime 5 conditions, composite ERA5 maps suggest large-scale trends and flow patterns were reminiscent of regime 4 (e.g., transitional) composites (Figure 5d), and with

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weak indications for a continental surface low pressure or moisture inbound from southward latitudes. December composite patterns, in contrast, better reflect prevalent regime 5 composite behaviors (e.g., Figure 5e), that by January shift towards westerly low-level flow and are associated with low pressure and the SACZ. Westerly shifts in the central Amazon rainy seasons have been previously discussed as promoting a moist troposphere and frequent (albeit, not necessarily more intense) convection compared to easterly flow regimes near the beginning of the rainy season (e.g., Betts et al., 2002; Cifelli et al., 2002; Peterson et al., 2002).

To further explore attendant large-scale conditions and regime transitions, in Figure 7 we plot composite daily projections of horizontal moisture advection and vertical velocity from the VARANAL product. Estimated horizontal advection of moisture (e.g., $-V*\nabla q$; V is horizontal wind vector, q is water vapor mixing ratio; top row, green shading) is highest (positive) at the lower levels for the regime 4 and 5 clusters, and maximized at the lowest levels below 700-hPa around the 1200 UTC radiosonde launch time (dashed line). Note that the large-scale vertical velocity w (bottom row) is constrained by the domain-mean precipitation (assimilated SIPAM observations), with the strength of vertical motion adjusted by the diabatic heating derived from the SIPAM-estimated precipitation rates (e.g., Xie et al., 2014). Regimes with higher precipitation rates will indicate stronger ascending motion associated with greater diabatic heating during the afternoon precipitation periods. Interestingly, the large-scale w patterns during the morning hours are similar across regimes 2 through 5. Similarly, each regime indicates large-scale subsidence above 600-hPa that peaks around radiosonde launch time. However, regime 1 is an outlier and suggests substantial large-scale subsidence (above 600-hPa) and weak lower-level ascent around the morning radiosonde.

Finally, in Figure 8 we isolate the variational analysis profiles corresponding to the pre-convective radiosonde launches by plotting median profiles and $10^{th}/90^{th}$ percentile values at 1200 UTC. Regimes 4 and 5 share similar characteristics and enhanced moisture advection (lower levels) and larger-scale w in the mean and extremes (90^{th} percentile). Regime 4 also displays stronger upward motions from near the surface to 650-hPa, and stronger extremes in w from ~750-hPa upward. Since 1200 UTC is prior to significant domain-mean precipitation (section 4.2), these enhancements in regime 4 motions are not influenced by precipitation constraints. Similarly, moist regimes lack the extreme negative (dry) moisture advection (10^{th} percentile properties) found in regimes 1–3.

4 Regime Cloud and Precipitation Summaries, Likelihood for Precipitation Extremes

4.1 Cloud Frequency

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Cumulative cloud frequency and diurnal summaries are plotted in Figure 9. Note, the 'all' examples in Figures 9f,g represent the summary dataset behaviors that include all days including those having precipitation at 1200 UTC. The characteristics are in-line with monthly breakdowns previously available for the GoAmazon2014/5 campaign as reported by Collow et al. (2016). In Figure 10, we plot the frequency of specific cloud types for the periods following 1200 UTC (radiosonde launch) to 0000 UTC, to include the relative frequency of null conditions over the site. For the frequency plots in Figure 10, multiple cloud layers can be identified in the same column; therefore, individual cloud types and null conditions do not add up to 100%.

Cloud properties in Figures 9 and 10 indicate regime 1 is least favorable for cloud coverage (total, or daytime hours following the radiosondes). This is consistent with the least-favorable 1200 UTC convective parameters, moisture advection and subsidence as discussed in previous sections, as well as GoAmazon2014/5 dry-season studies on precipitation controls (e.g., Ghate and Kollias, 2016). During GoAmazon2014/5, regime 1 was the only regime where a majority of the daytime hours over the site were not populated with clouds (e.g., Figure 10b). When clouds were present, the most frequent cloud type was shallow cumulus ('shallow'). Upper-level cirrus clouds occupy a substantial fraction of the cloud observations under all regimes, and are the second-most frequent clouds observed for regime 1 conditions. Presumably, the prevalence of cirrus in regime 1 is attributable to cirrus generated remotely then being advected over the site. Interestingly, Figure 9 suggests there is an absence of cirrus and other cloud types in the periods around the 1200 UTC radiosonde launch. This provides confidence that the 1200 UTC radiosondes used as the basis of regime classifications are not contaminated by clouds. All regimes suggest large-scale subsidence at upper levels around 1200 UTC (e.g., Figure 7), which may explain the absence of cirrus.

The drier cluster cloud summaries in Figures 9 and 10 indicate increasing cloudiness from regimes 1 to 3, with cloud frequency positively associated with reduced MUCIN (lower MUCAPE) and higher column RH. Dry-season cloud frequency (regimes 1-3), including mid (congestus)-to-upper level (anvil, to include widespread/deep stratiform shields) cloud frequency, is significantly lower than observed for regimes 4 and 5 (Figure 9g). Among the drier regimes, regime 3 conditions are most conducive to clouds, although the relative cloud frequency as plotted in Figure 10 is similarly-scaled to the cloud types in regime 2. Moreover, diurnal cycles indicate that relative contributions from congestus are mostly absent from regime 1-3 mid-morning to afternoon periods (e.g., bimodal), and the increase in frequency between regimes 2 and 3 is attributed to enhanced shallow (echo tops < 3 km) and deeper (isolated) convection (echo tops > 8 km). There is weak evidence of overnight precipitating clouds during the dry season (e.g., Ghate and Kollias 2016), observed during the relatively moist regime 3.

MAO clouds are most frequently observed during the moist regimes (regimes 4 and 5), with increases in frequency attributed to contributions from all cloud types. Regime 5 indicates the highest frequency for shallow to mid-level clouds (e.g., 'shallow', 'congestus', and 'alto'), and the highest frequency overall as shown in Figure 9g. Diurnal plots suggest a gradual daytime shallow-to-deep cloud transition for regimes 4 and 5, consistent with previous arguments for increased water vapor in the lower troposphere as the primary factor responsible for triggering this transition (e.g., Ghate and Kollias 2016). Interestingly,

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the bulk timing of this transition is potentially contingent on the regime, as this is apparently occurring later in the day according to regime 5 composites. One explanation for the delayed timing is that this transition may be slowed by the reduced incident solar radiation associated with more frequent shallow clouds under regime 5 or wet season conditions (e.g., Zhuang et al., 2017). Variations in shallow-to-deep timing are also consistent with differences in surface energy balance partitioning, which are a strong function of soil moisture (e.g., Findell and Eltahir 2003a, b; Jones and Brunsell, 2009). Higher soil moisture values in the wet regime favor a partitioning of the surface net radiation toward more latent than sensible heat flux (i.e., smaller Bowen ratio). This partitioning leads to a wetter boundary layer, but weaker generation of turbulent boundary-layer growth that should foster a slower transition. Even in a tropical rainforest, the importance of moisture availability has been shown to have a large impact on Bowen ratio (Gerken et al., 2018), suggesting this as a possible mechanism for modulating the onset of deep convection.

Regime 5 indicates a trimodal distribution of convective clouds, as observed in previous tropical studies (e.g., Johnson et al., 1999). Over the tropical oceans, the congestus mode is associated with a mid-level stable layer near the melting (0°C) level (e.g., Johnson et al., 1999; Jenson and Del Genio 2006). This is thought to arise from radiative interactions accompanying intrusions of dry air from poleward latitudes (e.g., Mapes and Zuidema 1996; Redelsperger et al., 2002; Pakula and Stevens, 2009) or melting processes in organized stratiform precipitation (Mapes and Houze, 1995), though recent findings argue that the melting mechanism is not essential to creating the stable layer (Nuijens and Emanuel 2018). How these two possible mechanisms explain the presence of the congestus mode across the different Amazon regimes is not obvious. Regimes 1 and 2 are characterized by dry-air intrusions from poleward latitudes, yet exhibit the lowest frequency of congestus; this indicates that other factors are strongly suppressing the vertical development of congestus and cumulonimbus. The higher frequency for congestus during regimes 4 and 5 is accompanied by a greater incidence of organized convection (section 4.3); this suggests the possibility of the stratiform-cooling mechanism. To complicate matters, only the composite soundings for regimes 2 and 5 (as shown in Figure 3) exhibit indications of a mid-level stable layer (~700–550 hPa).

Finally, the bulk cloud characteristics as shown in Figure 10 are similar between regimes 4 and 5 during the morning to afternoon hours. However, an important shift in cloud properties under regime 5 is observed during the pre-radiosonde (overnight) periods, with regime 5 associated with more frequent congestus. From such depictions, it is unclear whether this shift in overnight cloudiness in regime 5 is associated with more frequent or resilient congestus, or possible contributions from MCSs. As discussed below, MCSs and/or radar-based indicators for widespread precipitation are more frequent for regime 4. This argues that the increase should be attributed to additional and/or more resilient congestus, and this explanation is consistent with the modest upper (anvil) peak for regime 4 and prominent congestus peak observed for regime 5.

4.2 Differences in Precipitation Behaviors Across Regimes

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Model evaluation often benefits from precipitation constraints that include comparisons to the diurnal cycle and other precipitation properties. In Figure 11, we plot the diurnal cycle of precipitation from the domain-mean precipitation rate used to constrain the 3-hourly VARANAL products, contingent on the regime-events having measurable precipitation. As in Figure 9, a summary campaign behavior ('all') that includes contributions from days having precipitation at 1200 UTC is also included. For these breakdowns, precipitation rate (in mm/hr) is based on SIPAM estimates for the domain within the 110-km radius of MAO site. The dotted lines on Figure 11 correspond to the domain-mean values, and the shading indicates a 1-sigma standard deviation for regime events. These standard deviations indicate the event-to-event variability; however, precipitation rates estimated by radar may carry at minimum 30% uncertainty (e.g., bias, or fractional root-mean-square error) owing to miscalibration or other factors (e.g., Xie et al., 2014; Giangrande et al., 2014). Note, the SIPAM rainfall estimates used in VARANAL assume a single radar-rainfall relationship based on disdrometer measurements collected under wet season conditions. This choice implies that the dry season rainfall rates are likely overestimated according to previous Amazon disdrometer studies performed for MAO during wet and dry season precipitation (e.g., Wang et al. 2018).

For radar-derived precipitation rates over the VARANAL domain as in Figure 11, the MAO location favors a pronounced daytime diurnal cycle, with peak occurring after local noon (e.g., 1800 UTC). The well-behaved diurnal cycle is consistent with climatologies over land from the Tropical Rainfall Measurement Mission (TRMM; Nesbitt and Zipser 2003; Yang and Smith 2006; Hirose et al., 2008), but this behavior may be fortuitous, since complex land surface cover, topography, or river / sea-breeze controls influence precipitation measurements in other parts of the Amazon basin and potentially mask a well-defined diurnal cycle (e.g., Adams et al., 2015; Burleyson et al., 2016; Machado et al., 2018). The cloudiest times over the MAO column do not perfectly align with domain-mean precipitation properties, but the times with the most frequent clouds we observe in Figures 9 and 11 are typically near 1800 UTC. Still, there are important shifts between various regimes. For example, regime 5 domain-mean precipitation from 2100 UTC into the overnight hours skews higher than the other regimes and is associated with an increased MAO column cloudiness (e.g., Figure 9e). Overall, moist regimes favor more intense rainfall rates, with the highest rainfall rates observed in regime 4, followed by regime 5. Although fewer clouds, smaller total convective area, and lower domain rainfall rates are observed during the drier season, the individual convective events (updrafts, precipitation) can be quite strong (Giangrande et al., 2016; Machado et al., 2018). This is evident by the relatively high domain-mean rainfall rates that are observed for regimes 2 and 3 for days when precipitation is recorded.

In Figure 12, we plot distributions for the maximum daily radar echo area after 1200 UTC (i.e., largest continuous area from any single radar scan, one assigned per day) occupied by various thresholds for the reflectivity factor, as proxies for deep convective core area coverage (Z > 40 dBZ) and widespread rainfall area coverage (Z > 20 dBZ). Thus, this measurement is a daily reference to the largest individual cell (any time), not a measurement for the total 'convective' area occupied by cells. Previous studies including Giangrande et al. (2016) and Machado et al. (2018) have indicated that rainy seasons favor larger total convective area coverage. In terms of allowance for singular deeper convective cores (Figure 12a), it is not surprising

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that regime 4 (e.g., transitional) is associated with the largest convective cells, as based on higher expectations for MCS. In terms of convective core properties associated with Z > 40 dBZ behaviors, multiple drier season distributions share comparable behaviors as to regime 5. This is consistent with suggestions that the dry season also promotes isolated, intense convection.

Regimes 4 and 5, in contrast, favor a substantially wider distribution of widespread precipitation coverage as shown in Figure 12b when compared to the drier regimes. An increase in widespread precipitation coverage (Z > 20 dBZ) is consistent with the arguments for more ubiquitous weak convection and/or MCS having trailing stratiform anvils (e.g., Romatschke and Houze, 2010). Interestingly, this may be interpreted as weaker cells/precipitation winning out over less frequent, but stronger cells. This is suggested as responsible for the reduced domain-mean precipitation rates compared to regime 2 (Figure 11 reflects only contributions from precipitation events). This view would also be consistent with regime 3 as associated with additional congestus and/or periphery stratiform precipitation, enabled through reduced MUCIN and greater humidity above 600-hPa.

4.3 Radar-based Null Event or MCS Event Frequency

In addition to compositing clouds by regime, we explore a simple Bayesian approach to query the likelihood a particular regime promotes different precipitation modes, information that is highly useful for convective parameterization and predictive efforts. If convection initiates for a given regime, what is the likelihood that the convection is nonprecipitating, isolated, or develops to a widespread precipitation event? In Figure 13, we break down the likelihood that precipitation events observed during GoAmazon2014/5 fall under nonprecipitating (NULL), isolated precipitating convection (ISO), and wide deeper convective (WDC) events. Among those WDC events, we identify those events having mature-stage MCS characteristics (i.e., MCS are a subset of the WDC events). For this study, NULL events are defined by a minimum area of Z > 20 dBZ that is less than 200 km^2. For mature MCS definitions, we follow the guidelines established in Houze et al. (2015) and Feng et al. (2018), where MCS are defined as having continuous 40 dBZ radar echo area exceeding 1000 km^2, with a continuous shield of 20 dBZ radar echo areas exceeding 10000 km^2. WDC events are defined as the precipitation events having a continuous, widespread shield of 20 dBZ echo exceeding 10000 km^2. For simplicity, ISO events are defined as the remaining events that did not fall within NULL or WDC categories (i.e., NULL + ISO + WDC = total events). For the analysis in Figure 13, 595 of the 607 rain-free radiosondes days were also well-observed by the SIPAM.

Overall, NULL precipitation days are rare, accounting for less than 4% of our two-year record (as shown in Figure 13, Table S2). NULL events were predominantly designated during the driest regimes, with regimes 1 and 2 accounting for 20 of the 23 (87%) instances. WDC events account for approximately 21% of the dataset, and commonly observed for regimes 4 and 5 (approximately 81%). Subsampling those WDC events, radar-based MCS events are relatively uncommon, accounting for approximately 8% of the dataset. As we plot in Figure 13, the majority of these MCS events were observed during the moist regimes (regimes 4 and 5 accounting for > 70% of the events), with approximately half of all MCSs observed during regime

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4. For completeness, the number of MCSs during GoAmazon2014/5 was approximately double those reported, but we have chosen to ignore radar-based MCS that produced rainfall over the MAO site at the time of radiosonde launch. Additional manual inspection of the WDC events also reveals that one-third of WDC events shared MCS-like characteristics, but fell short of study thresholds. Thus, potentially 20% of the campaign period was associated with MCS, although only half are considered for our analysis. Similarly, MCS designations are arbitrary, and we anticipate inconsistencies between this accounting and satellite tracking (e.g., Rehbein et al., 2019). One final consideration is that MCSs do not need to initiate locally (e.g., within the SIPAM radar domain ~ 500 km) to meet our radar-based definitions. We have inspected radar and satellite observations for 44/47 MCS events to manually identify MCS from our criteria that initiated to distances >500 km upstream, then propagated over the site. Supplemental Table S2 identifies two MCS categories, 'propagating', and 'local', as reminiscent of previous Amazon studies (e.g., Greco et al., 1990). By our breakdowns, MCS during the drier season are predominantly 'propagating' events, while moist regimes include contributions from both MCS categories.

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As the regime most associated with mature MCS events, in Figures S8 and S9 we plot composite radiosonde and parameter distributions (MUCAPE, MUCIN) for regime 4 'nonMCS', 'local' (13 events) and 'propagating' events (7 events). In Figure 14, we plot a similar MCS breakdown for 1200 UTC horizontal moisture advection and *w* from VARANAL. Overall, we do not observe any obvious difference between the composite properties among MCS and nonMCS events within regime 4. Similarities between MCS and nonMCS events are also reflected in the 1200 UTC variational forcing composites shown in Figure 14, with local MCS and nonMCS events reflecting comparable mean conditions. 'Propagating' MCS events are less representative of composite behaviors and suggest weaker thermodynamic conditions with the most favorable large-scale controls. However, these large-scale moisture/velocity enhancements are modest (e.g., vertical velocity increase of 2.5-to-5 hPa/h).

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5 Summary

To inform on the potential controls for clouds experienced over the Amazon basin, a cluster analysis was performed on routine radiosondes launched during GoAmazon2014/5. This effort follows similar applications of k-means cluster methods that attempt to objectively disentangle larger-scale cloud and precipitation controls from traditional calendar-driven wet/dry season definitions. We identified five primary thermodynamic regimes and explored these states in the context of traditional Amazon definitions, composite large-scale synoptic patterns, and model forcing datasets. Column and scanning radar observations were projected into these states, highlighting the propensities for each state to promote different cloud types, frequencies, and changes to precipitation. Emphasis was given to intra-regime conditions associated with organized convection in the transitional regime (regime 4) most favorable to MCS. Although caution is recommended when considering the findings established over a limited two-year GoAmazon2014/5 deployment, a summary of our key findings are as follows:

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- *k*-means clustering of the 1200 UTC radiosonde datasets yields five primary clusters. The three drier regimes relate different states of mid-to-upper level moisture associated with the strength of similar large-scale features that advect colder/drier air into the Amazon basin. The wet to transitional clusters exhibit similar deep moisture thermodynamic profiles, with regime 5 associated with evidence of moisture advection into the Amazon basin from the tropical belt.
- GoAmazon2014/5 cloud frequencies, cloud types and precipitation properties for the five regimes correspond well to bulk changes in the large-scale vertical air motion, moisture advection, local radiosonde thermodynamic composite profile and convective parameter shifts. Most regimes favor frequent clouds and intense precipitation during the early afternoon hours (after 1600 UTC), with precipitation following a single-peak diurnal cycle. These results are consistent with cumulative dataset results from the GoAmazon2014/5 deployment (e.g., Collow et al., 2016; Ghate and Kollias, 2016; Zhuang et al., 2017).
- The moist regimes were associated with modest MUCAPE, reduced MUCIN and higher humidity at all levels. The latter two controls are those suggested as most favorable in the Amazon for more frequent clouds, deeper convection, and widespread stratiform precipitation. These results are consistent with previous studies on the propensity for stronger updrafts during dry or dry-to-wet transitional seasons (e.g., Williams et al. 2002; Giangrande et al., 2016; Wang et al., 2019).
- Regimes 4 and 5 suggest prominent shallow-to-deep cloud transitioning (with trimodal cloud profile behaviors observed in regime 5), with the timing of these transitions potentially contingent on the regime. This later daytime transitioning under regime 5 may suggest the transition has been slowed by the reduced incident solar radiation (more frequent shallow clouds under regime 5), or higher soil moisture values (i.e., smaller Bowen ratio). This transition timing aligns with previous Amazon findings from Zhuang et al. (2017) for 'wet' and 'transitional' season conditions.
- The drier regimes reflect reduced column cloud frequency, bimodal instead of trimodal distributions in vertical profiles of cloud frequency, an absence of mid-level cloud contributions and shallow-to-deep transition signatures, and rainfall properties attributed to weak or isolated (infrequent) deep convection. Although convection is frequently observed during all regimes, dry-season regimes exhibit less-frequent clouds and rare Amazon NULL precipitation events.
- When precipitation is observed, SIPAM radar designations indicate most convection in isolated deeper convective cells. Organized convection was relatively frequent over MAO during this two-year GoAmazon2014/5 deployment (e.g., Rehbein et al., 2019), with approximately 10-20% of the convection observed over MAO associated with MCS. These MCSs were most frequently observed under moist profile conditions (regimes 4 and 5), and over the 1200 UTC to 0000 UTC period, with the best-defined MCSs observed during regime-4 GoAmazon2014/5 periods. Approximately half of the well-defined MCSs that passed over MAO fell outside of the typical diurnal cycle and/or were not associated with regime classifications.

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- When considering regime 4 favorability for deep convective events, it is suggested that intra-regime (pre- and post-dry season months) variability may account for shifts in favorability for enhanced storm updrafts and/or electrification. However, this study did not identify shifts in composite thermodynamic profiles or convective parameter distributions between MCS and nonMCS conditions. Additional checks of the large-scale synoptic patterns and forcing datasets under MCS and nonMCS conditions indicate that 'propagating' MCSs may favor an enhancement in the large-scale upward vertical motion (2.5-5 -hPa/h) and moisture tendencies during pre-convective windows that offsets weaker local thermodynamic environments. However, these factors were arguably less important when compared to overall regime 4 proclivity for MCS.

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Data Availability

All ARM datastream to include VARANAL, ARSCL, SONDE and other PI datasets used in this study can be downloaded at http://www.arm.gov and are associated with several "value added product" VAP streams and GoAmazon2014/5 PI datasets. Python machine learning codes were provided by Scikit-learn, as from Pedregosa et al., (2011). Radiosonde visuals were supported by the python package MetPy, as from May et al., (2020). ERA5 reanalysis products (production) are available at: https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production, as from Hersbach and Dee, (2016).

Author contributions. SEG, DW and DM designed the research; SEG and DW performed research; SEG and DM wrote the paper.

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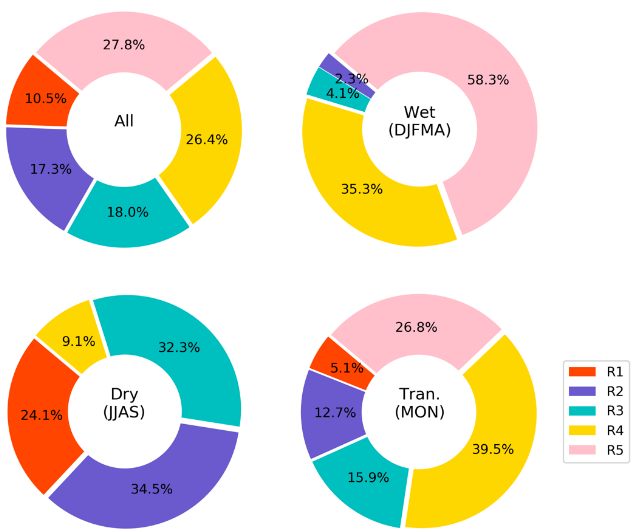

Figure 1. Breakdowns for the frequency to observe regime clusters (regimes 1 through 5 marked as R1 through R5) for the GoAmazon2014/5 radiosonde dataset (1200 UTC), as well as breakdowns for wet season (Dec., Jan., Feb., Mar., Apr.), dry season (Jun., Jul., Aug., Sep.), and transitional season (May, Oct., Nov.) radiosondes.

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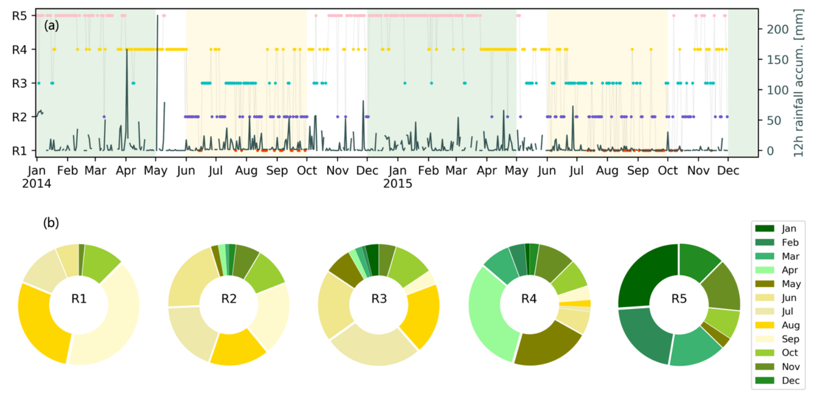

Figure 2. (a) Time series for Amazon regime cluster results (color-coded as also in Figure 1) with corresponding 12h (1200 UTC - 00 UTC) rainfall accumulation (from the MAO rain gauge). The green shading indicates the wet seasons and the yellow shading indicates the dry seasons according to calendar definition; (b) Relative breakdown for the frequency of each regime according to month.

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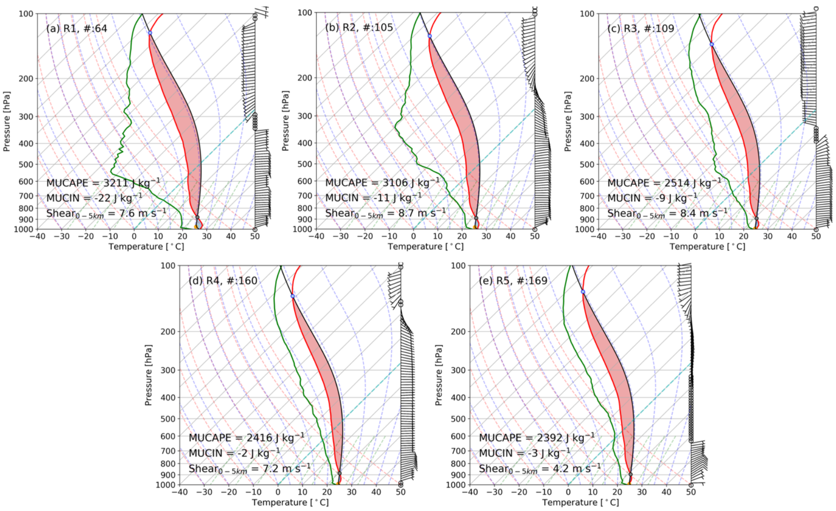

Figure 3. Composite 1200 UTC radiosondes for each regime. MUCAPE, MUCIN, and wind shear (surface to 5 km) parameters report regime-median values.

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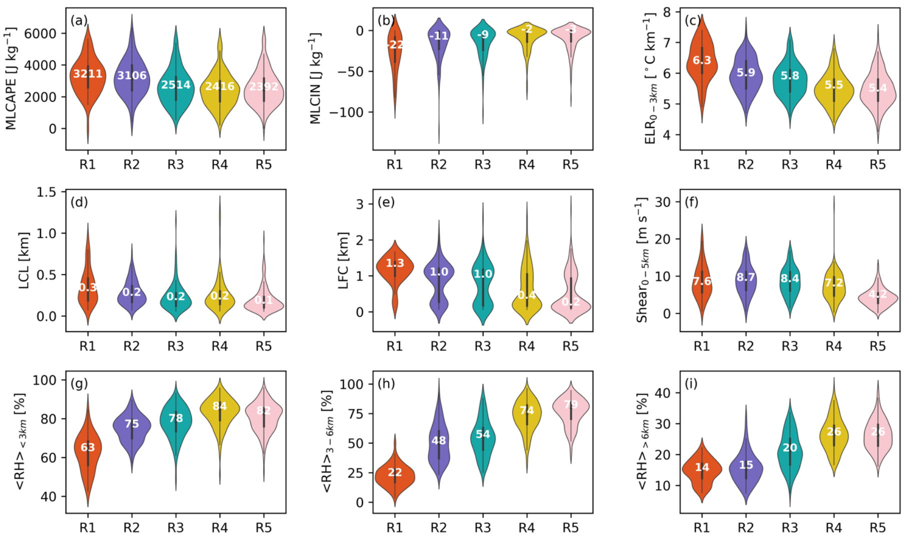

Figure 4. Shaded probability density plots for select thermodynamic quantities of interest estimated from the 1200 UTC radiosonde in each Amazon regime. The median values for each regime distribution are reported on each violin (white text). The interior black box shows the interquartile range and the thin black lines reflect the 95% confidence interval.

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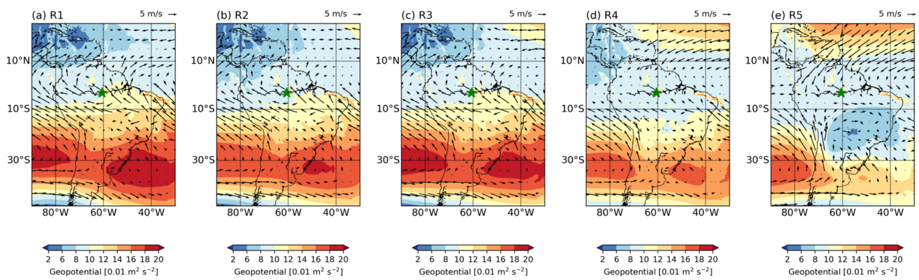

Figure 5. Composite large-scale synoptic patterns (geopotential heights in color [0.01 m2 s-2] and horizontal winds) projected into each regime, as from ERA5 for the 1000-hPa level. The green star indicates the ARM MAO site.

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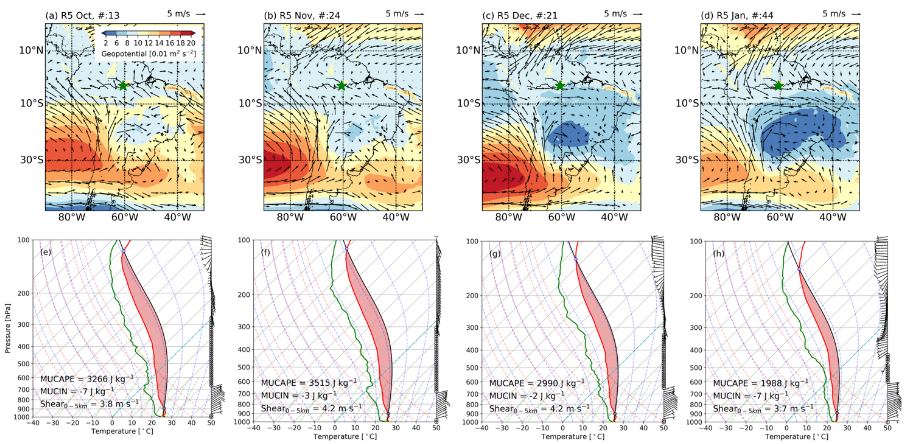

Figure 6. Composite monthly large-scale synoptic patterns at 1000 hPa (following Figure 5) and radiosondes, associated with regime 5. Plots correspond left-to-right to (a) October, (b) November, (c) December, and (d) January.

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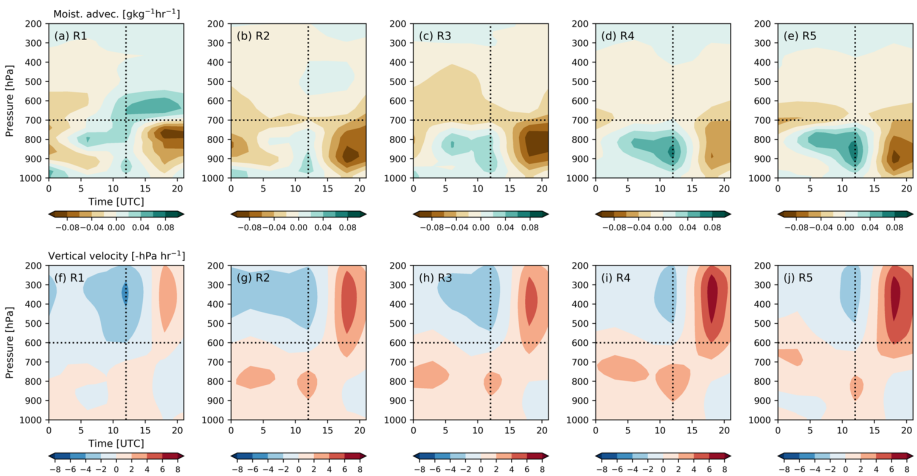

Figure 7. Composite diurnal (UTC) large-scale SCM variational forcing dataset (VARANAL) fields for (a-e) regime breakdowns of the horizontal moisture advection (green = positive moisture advection), and (f-j) large-scale background vertical velocity (red = upward vertical motion). 1200 UTC columns and 600-hPa (f-j)/700-hPa(a-e) levels are highlighted as dotted lines.

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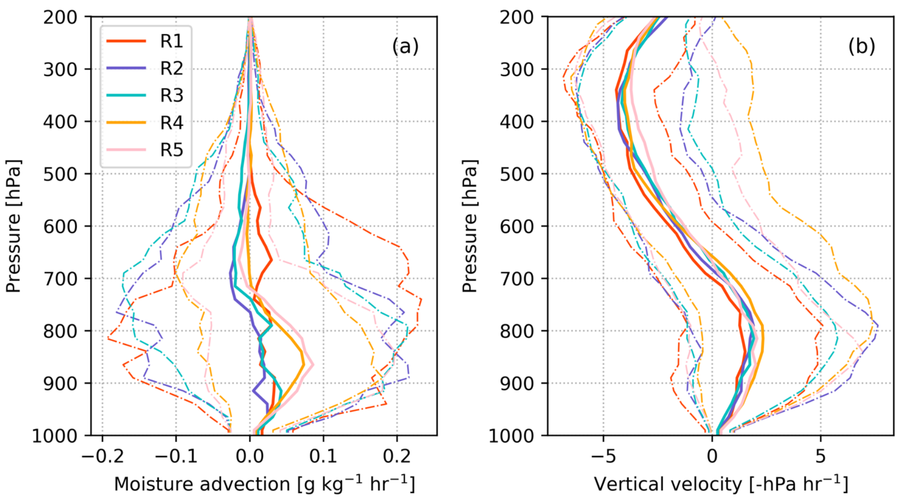

Figure 8. Median profiles (thick solid lines) of (a) horizontal moisture advection and (b) large-scale background vertical velocity (positive value = upward motion) for each regime at 1200 UTC. The 10th and 90th percentile ranges for the variational analysis fields are represented by the dashed-dotted lines.

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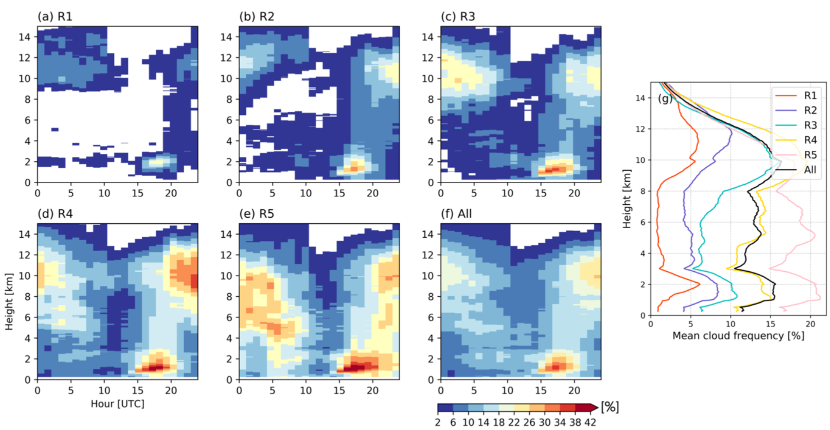

Figure 9. The diurnal cycle of hour-mean cloud frequency (when cloud coverage > 2%) as a function of height for each regime (a-f), as according to a multi-instrument cloud profiling retrieval. The mean 1h cloud frequency profiles are shown in (g).

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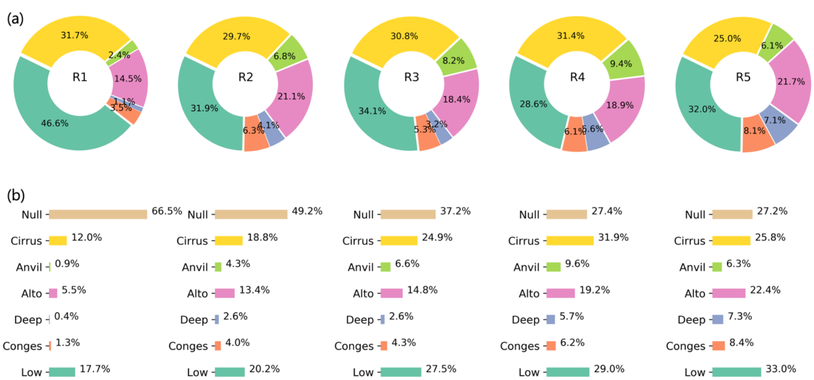

Figure 10. (a) Relative frequency of occurrence for specific cloud types in the column above the ARM MAO site for regime periods between 1200 UTC and 0000 UTC, and (b) percentages when compared to cloud-free conditions.

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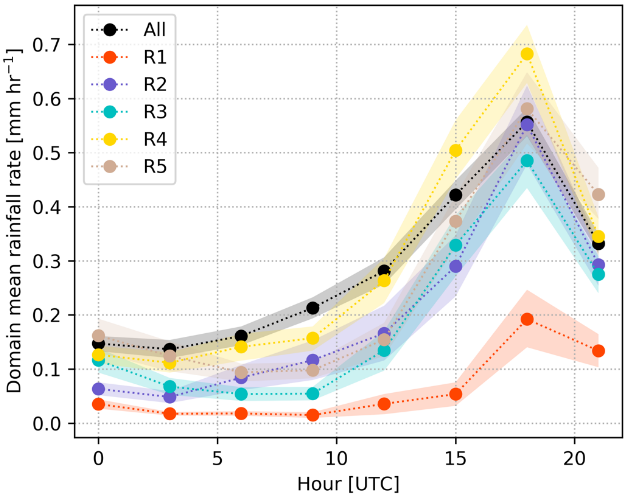

Figure 11. Domain-mean precipitation rate (for events with measurable precipitation) from the SIPAM radar to within a 110 km radius of the MAO site. The dotted lines report the dataset mean values, and the shading is 1-sigma standard deviation.

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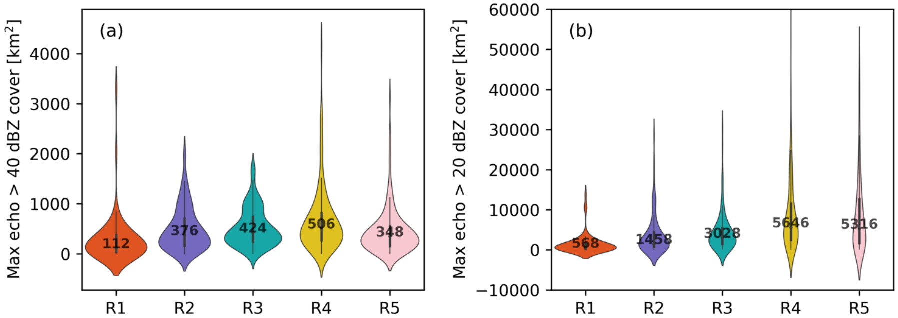

Figure 12. As in Figure 4, the maximum contiguous 2 km CAPPI radar echo coverage [in km^2] for any radar scan within a regime day that is occupied by radar echoes exceeding an intensity (a) Z > 40 dBZ, or (b) Z > 20 dBZ, for hours between 1200 UTC and 0000 UTC that day.

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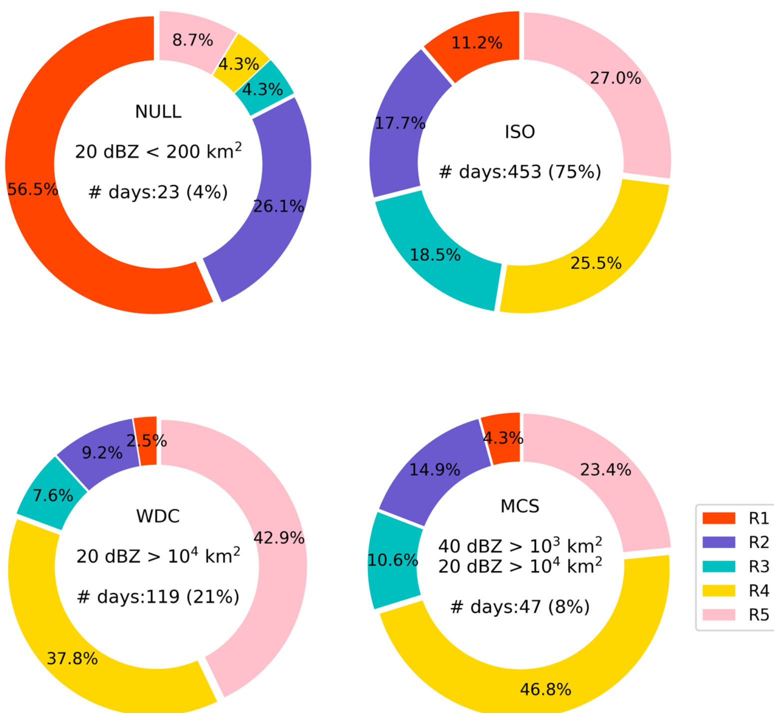

Figure 13. As in previous frequency plots, but for the percentage of (top left) NULL, (top right) ISOlated, (bottom left) wide deep convection (WDC) and (bottom right) MCS days associated with each regime cluster.

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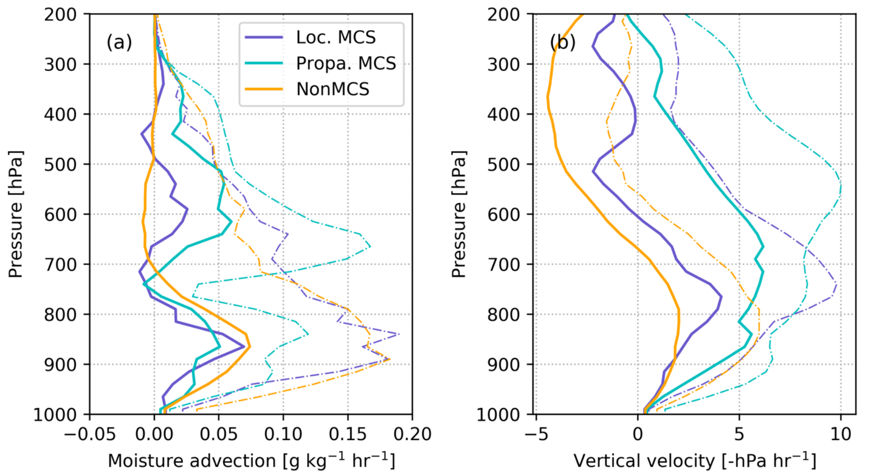

Figure 14. Variational forcing profiles at 1200 UTC for nonMCS, local MCS, and propagating MCS cases with rain rate less than 1.5 mm/hr. Profiles correspond to the regime 4 conditions. Solid lines are median profile values and dashed lines are the 95^{th} percentile values.

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