Authors Comment (AC)

On the Referee Comments (RC) #2

The Referee's comments were taken into consideration fully in the revised manuscript. We appreciate the points raised regarding the observations, and we made a conscientious effort to address all issues raised. Thank you. Item-by-item replies are in blue, whereas the Referee's comments are in black.

This study attempts to reach closure between simulated and observed relationships among CCN, cloud base updraft, drop concentrations, cloud mixing extent with ambient air, supersaturation at cloud base and above it, and condensation accommodation coefficient. This is a worthwhile and ambitious goal, but unfortunately the available measurements are insufficient for achieving any unambiguous closure. The authors are aware of this and attempt to supplement the missing measurements with assumptions that cannot be supported. This undermines the basis of the validity of the claimed closure.

The Referee's point regarding unambiguous closure in the classical sense due to limited data in our case is well taken. Indeed, such closure is not an objective of the work presented in the manuscript. The use of the "term" closure was referring to the comparison of cloud droplet spectra above cloud base simulated by the CPM and aircraft observations, not to the closure at/near cloud base as in classical analysis of aerosol measurements from field campaigns (e.g., Conant et al., 2004; Fountoukis et al., 2007). It was a confusing application of the term, and this has been corrected throughout the manuscript. We removed the term "closure" in the Abstract or elsewhere unless in the literature review and in its proper context.

We respectfully disagree with regard to assumptions made as explained below, throughout the Reply, and in the revised manuscript. The assumptions made are well justified by the integration of observations and model results, and follow relevant peer-reviewed literature as explained in the manuscript and in this Reply. Additional simulations were conducted assuming well-mixed conditions, and the results are included in the Supplementary Information. All our data including observations and model simulations will be available publicly at iphex.pratt.duke.edu. In this way, studies to reproduce our results and provide alternative analysis and interpretation will be possible, and we welcome the scrutiny.

The present manuscript describes a newly developed dynamic cloud parcel model to investigate aerosol-cloud interactions (ACI). It presents an application and sensitivity analysis for a case-study in the early development of the vertical microphysical structure of orographic cumulus congestus seen in the inner Southern Appalachian Mountains (SAM) during the Integrated Precipitation and Hydrology Experiment (IPHEx), and for which aircraft observations are available. The manuscript provides the first quantitative assessment of the physical parameters of ACI in controlling mid-day cumulus formation in complex terrain, which were not available before or from the IPHEx campaign in 2014. Because of IPHEx's emphasis on precipitation microphysics and specifically the vertical distribution of hydrometeors, aerosol measurements were limited compared to other campaigns when the focus has been strictly on aerosols, in particular near and at cloud base. In addition, collocated and concurrent radiosonde measurements were not available, and there was only one supersite where ground-based aerosol characterization was conducted. Consequently, high-resolution NWP simulations were conducted to obtain model soundings instead. Further, assumptions were made regarding the initial environmental conditions and model input parameters, and sensitivity tests were conducted accordingly to examine how variations in aerosol properties and microphysical processes influence the evolution and thermodynamic state of clouds over complex terrain. These assumptions relied on all quality observations that were available at the surface level and from aircraft, were informed by nearly ten years of field work and thus high familiarity with the region's meteorology, and high-resolution modeling for this study, and prior observations and modeling work in this region published in the peer-reviewed literature and referenced in the manuscript. Recognizing that limited measurements were available, no attempt at calibration was made. Instead, a detailed description of the model application, detailed rationale for all decisions, and a thorough discussion of the sensitivity analysis is presented. Emphasis is on examining the results from the perspective of cloud vertical development and the evolution of cloud droplet spectra with height.

The reference to "aerosol-cloud droplet number concentration (CDNC) closure" was meant to highlight the fact that there is **good agreement between aircraft measurements of cloud droplet spectra and model simulations**. The point of comparing simulated and observed cloud droplet spectra well above cloud base is to assess whether the model process-chain leads to realistic results. Motivated by the Referee's comment, it is apparent that our statements in the first version of the

manuscript were confusing. Consequently, we revised the writing and we refrain from using the term closure to avoid ambiguity as mentioned early.

Again, there are no measurements at cloud base or near cloud base proper in this study as the focus was on cloud microphysics during the field campaign proper. High-resolution model results show there is significant horizontal wind shear with 3D circulations including valley winds, thermal winds, ridge-valley circulations, and well defined southerly mesoscale mid-level transport patterns that result in complex horizontal and vertical wind structure very different therefore from the classical convective boundary layers in flat terrain. Whereas in the original manuscript we refrained from discussing flow dynamics in complex terrain to highlight aerosol-cloud processes that is the main topic of the manuscript, this was not helpful. Therefore, we revised the description of model set-up and initialization (Sect. 4.1) and added supplementary information (Sect. S3) to improve clarity and specificity and to avoid ambiguity and misleading interpretations. Several animations of WRF results, which capture the complex space-time evolution of wind fields, are available also. Replies to specific comments are addressed next.

1) Are these really cumulus congestus clouds? The nature of the clouds does not appear to be cumulus congestus, but rather deep precipitating clouds, at least by the radar data shown in Figure 2. Panel b shows an intense downdraft with Doppler folding velocity well exceeding 10 m/s. The reflectivity at that time, as shown in panel a, is so large that the radar echo at that time is fully attenuated above 3 to 4 km.

As shown in Fig. S9 in the revised manuscript (Fig. 6 in the original submission), the rising of warm air feeds the formation of cumulus clouds at the Maggie Valley (MV) supersite before 12:30 LT (local time) and the cloud top reaches around 4.5 km. The collocated raingauge at MV first reported rainfall around 12:37 LT and subsequently the W-band radar suffered significant attenuation due to the rainfall, especially at higher levels. The total sky imager at MV also provided photographs of sky conditions, showing the development of cumulus clouds at different stages and the subsequent rainfall event around 12:35 LT (see Fig. Add1). In addition to the W-band radar, the MV supersite and a nearby ridge location were also equipped with Ka-band vertical profilers, the NOAA X-pol radar was operating as well within the Pigeon River basin, and the ER2 aircraft also flew over the inner region. Thus, there are multiple observations over the region as described in the science plan (Barros et al., 2014), in addition to visual observations from scientists present

on site. Note that the W-band imagery was used strictly to provide a sense of the temporal evolution at a location relatively close to the target study region (IC) based on the aircraft measurements in the inner region, but these data are not used for the case-study proper. This is stated in the manuscript, but to avoid further confusion, the figure with W-band data at MV, old Fig. 6, was moved to Supplementary Material, and it is now Fig. S9.

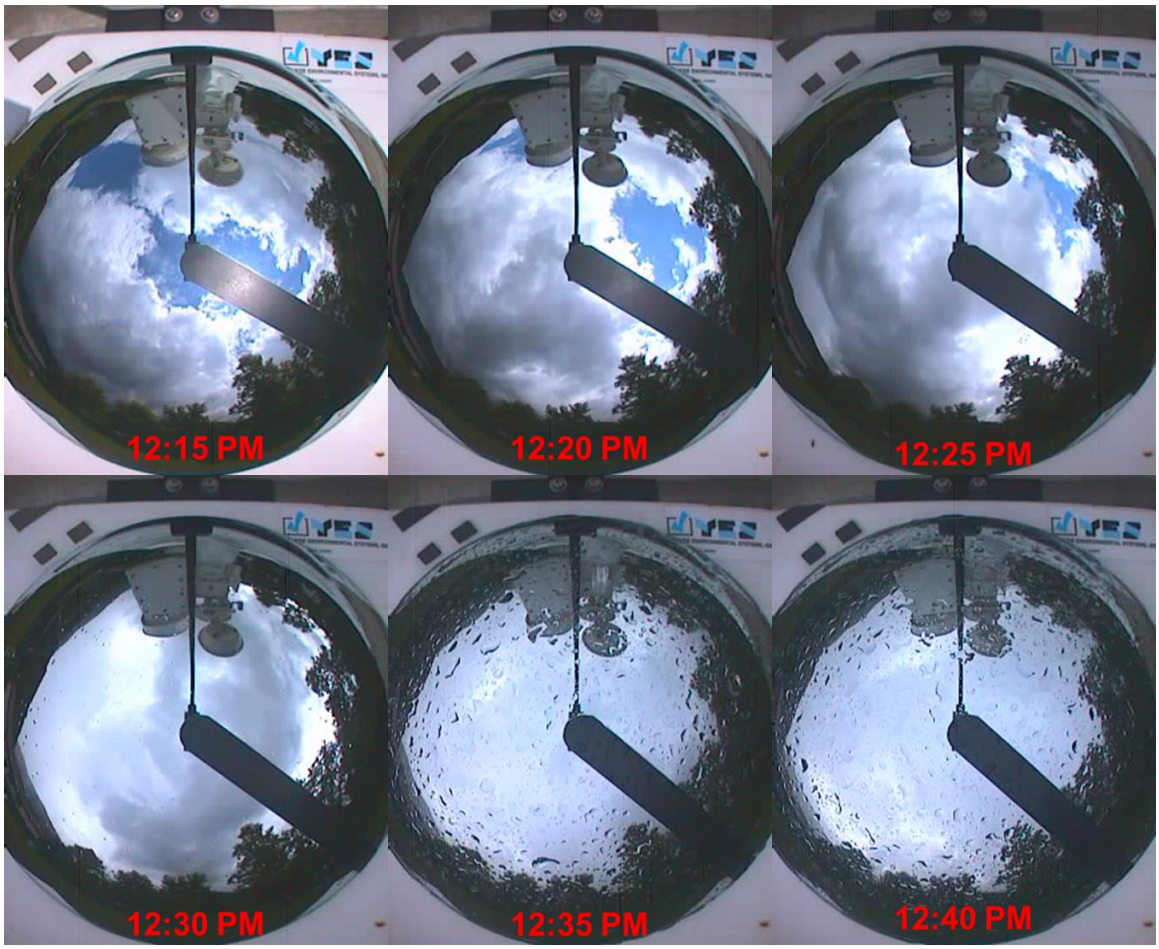

Figure Add1: Photographs of sky conditions around the flight period on 12 June 2014, observed by the total sky imager, located at the Maggie Valley (MV). Note timestamp of each image is indicated at the bottom.

The parcel model was applied to investigate the early stages of cumulus development. The targeted study region is the in-cloud (IC) region close to the MV site in the inner valley region of the SAM (see new Fig. 6a). The IC region was sampled by the aircraft during the first horizontal leg (flight period: 12:17 – 12:28 LT) when cumulus congestus were developing at MV as indicated by the W-band observations. A new figure (i.e., Fig. 7) was added and the corresponding discussion of this figure was added to the revised manuscript (Pg. 11, Lines 24 - 33). Figure 7 shows the airborne

observations of vertical velocities, cloud droplet concentrations and liquid water content (LWC) from the cloud droplet probe (CDP), and drop concentrations from the two-dimensional cloud (2D-C) probe (measuring hydrometeors with diameter between 105 μm and 2 mm). As shown in Fig. 7d, precipitation-sized drops were not observed in the IC region (highlighted in dark blue shade), indicating the early stage of cloud development in this region, which is suitable to set up the cloud parcel model simulation.

2) Is cloud base updraft 0.5 m/s? The cloud base updraft for convective cores should be taken as the peak and not average values. During the time before 12:31 they reach values between 1 and 2 m/s. Cloud base is where the green changes to white between 2.5 and 3 km MSL. The green indicates the fall velocity of the light precipitation from the clouds below their base.

The Referee is referring to the W-band data at MV, which as explained above though close to the IC region, it is actually located in a different valley and with different wind regime. As stated above in the Reply to point (1), the model simulation was conducted for the IC region, not at MV due to constrains by aircraft flight trajectory and timing. We rely on the W-band observations at MV to provide context for the model initialization at IC, but they do not reflect the actual cloud conditions at IC as explicitly stated in the manuscript. Rainfall was only reported at MV after 12:37 LT by the collocated raingauge. The initial updraft at cloud base for the reference simulation (0.5 m s^{-1}) is not based on the averaged value of the W-band vertical velocities at the MV. Instead, high resolution WRF model simulations were used for the reference run, and a substantive discussion regarding the 3D structure of mountain winds and interactions with mesoscale flow was added to Section 4.1 along with references to closely related studies, and supplementary figures and animations.

At cloud base, the initial temperature excess of the air parcel over the environment is assumed as 1.0 K (buoyancy). When rising, parcel velocity changes with height depending on environmental conditions and changes in the thermodynamic states of the parcel. The updraft velocity specified at cloud base in IC is strictly an initial condition. We recognize the uncertainty due to the lack of radiosondes, and the lack of aircraft observations at cloud-base level in IC. Thus, the sensitivity tests reported in the manuscript were conducted by varying the initial updraft velocity in the range of 0.1–1.5 m/s. This is consistent with the range of in-cloud vertical velocities observed by the

aircraft above cloud-base at the IC region, and with the WRF simulated vertical winds around the time of flight at IC, and generally everywhere in the inner mountain region with isolated cell being stronger (Figs S11-S13 and Animations SA1-SA4).

3) The updraft vertical profile. The stable stratification implies that the updrafts were forced mainly by orography and/or gust front from the nearby strong downdraft. Therefore, a parcel model of convective updraft is hardly applicable for this situation.

Note that the cloud parcel model concept has been widely used for studies of orographic precipitation (e.g., see references in Barros and Lettenmaier, 1993, and many others). Its application is tied to the notion of control volume in fluid mechanics, and how that control volume interacts with its environment, and it can be applied to general flow advection under well-defined conditions.

As stated above, the W-band data are only used to illustrate the cloud development at MV, not at IC. MV is relatively close to the IC region in terms of distance, but the situational context in the inner region is completely different with MV located on the foot slopes of a topographic divide in a lateral valley whereas IC is above a low hill in the middle of the main valley in the Pigeon River Basin (see Fig. 6a). Again, the parcel model simulates temporally and vertically evolving microphysics and buoyancy with entrainment above cloud base, and the focus in this study is on cloud vertical development.

The cloud base updraft at MV before 12:31 LT is about 1 to 2 ms^{-1} as indicated by the vertical velocity profiles. Indeed, at MV, strong mid-day convection led to the formation of cumulus congestus and strong downdrafts are observed after 12:30 LT (Fig. S9). At the study region IC, stronger updrafts (up to 2 m s^{-1}) were also observed at flight level in the convective core and weak downdrafts (< 1 m/s) in the periphery of IC during the first horizontal flight leg (see Fig. 7a), and there is no indication of a gust front. Similar to MV, IC clouds were formed by raising air which is suitable for the application of the cloud parcel model, though the structure of horizontal and vertical winds is complex, and the convective boundary layer (CBL) derived from WRF results is not well developed remaining below the LCL, which is not uncommon in complex topography (e.g., see for example Figs. 3, 5, and 11 for 2D flows and mountain CBL in De Wekker and Kossmann, 2015;Rotach et al., 2015). Thus other ventilating mechanisms must be considered that

vary in space and time with the mesoscale flow above the ridge, and local landform and elevation as shown in Figs S11-S13, Animations (SA1-SA4), and also illustrated for various other cases and times-of-day by Wilson and Barros (2015, 2017).

Note that there are also uncertainties associated with the need to reconcile the various spatial scales: the point-scale of the CPM, the effective resolution of the airborne measurements (90 m in this case), and the meso-β effective resolution of the WRF simulation that we are using to initialize the CPM. Even as the spatial resolution Δx is 250 m which brings the implementation to LES scale, due to model parameterizations and numerical implementation, the effective model resolution that preserves the observed scaling behavior of atmospheric kinetic energy ranges between $6\Delta x$ - $15\Delta x$, depending on stability conditions (e.g., Nogueira and Barros, 2014).

4) CCN concentrations at cloud base. The CCN at cloud base is not measured, but rather assumed. It is assumed that the surface measured CCN decays exponentially with height with a scale height of 1 km. However, in convective clouds the boundary layer must be well mixed, with a constant aerosol mixing ratio. It must be so with updrafts rooted near the surface in the solar heated boundary layer, if we take as a valid the assumptions of the convective parcel.

The parcel model is applied above cloud base. The specific conditions in the boundary layer are not necessary conditions to the application of the parcel model. As stated above, in addition to the east-west evolution, solar heating in complex terrain results in complex organization of ridge-valley circulations generally, which is further modulated locally by multiscale effects linked to regional moisture convergence patterns and landform leading to strong heterogeneity in the space-time distribution of clouds and the diurnal cycle of rainfall (e.g., Wilson and Barros, 2015, 2017). These processes are widely documented in the mountain meteorology literature as discussed in the reply to point (3) as above.

Given the complexity of the 3D circulations, especially the horizontal winds, the regional convergence patterns and the potential role of advective venting, and the nearly self-similar regional distribution of vertical velocities at the mesoscale, initial aerosol concentration at cloud base is extrapolated vertically from the surface aerosol number concentrations at MV by assuming an exponential decay with a scale height (H_S). This assumption is in keeping with previous studies using mesoscale models (Iguchi et al., 2008;Muhlbauer and Lohmann, 2008) and cloud parcel

models (e.g., Eichel et al., 1996) and consistent with differences in total aerosol numbers between the two horizontal flight legs at different heights over IC. The reference scale height (H_S = 1000 m) in this study is within the typical range (H_S: 550–1,100 m) for remote continental aerosol type (Jaenicke, 1993), which is a reasonable assumption.

However, to heed to the Referee's concerns and the uncertainty due to the lack of measurements of soundings and aerosol concentrations at cloud base, additional simulations were conducted using the surface aerosol concentrations as model input, thus assuming a well-mixed well-developed CBL. The results are presented and discussed in newly added Sect. S3 (see the Supplementary Data). Although agreement in total CDNC can be obtained between simulations and the airborne observations, large discrepancies exist between the predicted and observed activated spectra with implications for precipitation processes. Detailed discussion was added in the revised manuscript (Pg. 18, Lines 22 - 30).

5) The supersaturation in clouds. The authors report measured supersaturation (SS) in clouds. However, measuring SS in clouds is highly challenging, because in cloud temperature has to be measured at a very high accuracy as well as mixing ratio of water vapor. A major issue of measuring temperature in clouds is the effect of wetting of the temperature probe and the resultant evaporative cooling, which is far from being completely solved in reversal flow thermometer. To convince us that SS can be measured with a useful accuracy the authors have to provide the full description of the method of its calculation along with error calculation. They report SS=3% in a cloud with drop concentration of about 400 cmˆ-3 and updraft speed of nearly 1 m/s. This is physically impossible. The SS in such conditions must be a fraction of 1%.

The question of supersaturation must be addressed in two parts.

First, we thank the Referee for pointing out the measurement issue. The SS estimates using aircraft observations are indeed plagued with high uncertainty, and plotting them in the figure was a lapse as the data are not necessary and are indeed not relevant in this study. In the revised manuscript, a note about the supersaturation was added in the caption of Fig. 11b (Pg. 48, Lines 4 - 5). We also removed the supersaturation observations from Figs. 11b, B1a, B2a, and B3a and revised the relevant discussion accordingly.

Second, it is important to point out the difference between theory explaining fundamental physical processes, the CPM formulation and the inherent scale of the control volume underlying the spectral representation of cloud droplet population, and SS as a bulk property inherent to the control volume of measurement (or grid-size in a NWP models for example). At the scale of individual droplets, following Smirnov's (1971) kinetic model of droplet growth that explicitly accounts for feedbacks between latent heat and temperature, and the formation of a diffusive boundary layer around each individual drop, Fukuta (1993 and subsequent work) showed that theoretically maximum supersaturation can exceed 1%, and even be as high as 10% in convective clouds. Fukuta and others later used the diffusion-kinetic model to investigate condensation processes and explain low condensation values (e.g. Hagen et al. 1989).

6) The cloud drop size distribution widened in places unrealistically for convective clouds, as in ECR (Figure 8a). I strongly suspect that the clouds had precipitation falling from above, or recirculating cloudy downdraft air which had already produced precipitation. This increases the question about the applicability of a parcel model for these clouds.

The Referee points out the possibility of seeder-feeder interactions in ECR. ECR is not studied in this paper. Seeder-feeder interactions indeed play an important role in this region (Prat and Barros, 2010a, b;Wilson and Barros, 2014, 2015). However, in the day of the case-study, this was not the case in the inner region, and we are confident that this is so because of the multitude of observations available including personal observations by dozens of scientists in the field. It turned out that the summer of 2014 was much drier than normal especially in the eastern slopes and inner region of the SAM.

Further, as emphasized in the replies to points (1) and (2), only the cloud development at IC was simulated here. Precipitation-sized drops were not present in clouds in the IC region (highlighted in dark blue shade in Fig. 7d), thus conditions are suitable for applying the parcel model. Light precipitation was indicated over the ECR (highlighted in light blue shade in Fig. 7d), resulting in wide droplet spectra consistent with ground observations. This is also why ECR is not chosen for parcel model simulation.

Page 14 line 27: The text reads: "Consequently, smaller aerosol particles with high concentrations are activated due to a higher S_{max} further up from the cloud base, resulting in a direct increase in

cloud droplet numbers (Fig. 11c)." However, the parcel model shows a decreasing drop concentrations with height for all scenarios. There is no closure here. Furthermore, Smax is a property of cloud base, not well above it.

As stated above, the reference to "aerosol-CDNC closure" is removed from the revised manuscript due to the limited measurements from IPHEx, and the fact that the model simulations focused on the vertical development of cloud drop numbers and droplet spectra, not in the sense of aerosol-CDNC closure near cloud base. We recognize the critical importance of clear communication across sub-disciplines, and we corrected any potentially misleading statements. Due to the entrainment process, results from all simulations show decreasing in drop number concentrations with height. One key finding in this study is that the simulated drop numbers show good agreement with the observed CDNC (Fig. 11c) and droplet spectra (Fig. 12) collected roughly 300–500 m above cloud base. This is different from results from closure studies that are evaluated near cloud base without entrainment. We removed "further up from the cloud base" from the sentence (Pg. 15, Line 26)

Page 14 lines 30-33: There will be always a value of accommodation coefficient that matches the observed drop concentration. It can only be constrained if both cloud base updraft and CCN are known, because an increase in cloud base updraft has a similar result as of decreasing the accommodation coefficient. The same ambiguity applies to increasing CCN vs. decreasing the accommodation coefficient. A closure cannot be possibly reached with such uncertainties with respect to both cloud base CCN and updraft speed.

We emphasize again that no calibration of model parameters was attempted in this manuscript, as the focus is on understanding microphysical processes. Further, the simulation is dynamic so that cloud drop distributions evolve in time (with cloud height) and therefore cloud microphysical processes in the present modeling study are not cloud-base or near cloud-base processes. We regret having used the term "closure" which has very specific meaning in the context of classical aerosol field experiments and the adiabatic parcel model framework. Thus, statements referring to "aerosol-CDNC closure" were removed in the revised manuscript as pointed out above. In the present study, the role of individual parameters in a cloud parcel model with entrainment was examined exhaustively to characterize the sensitivity of ACI, and an evaluation against measurements above cloud base is presented. The model experiments reveal important findings

such as: 1) simulated spectra with a low value of condensation coefficient (0.01) are in good agreement with IPHEx aircraft observations around the same altitude and the estimated CDNC are consistent with the observations. This is in contrast with high α_c values reported in previous studies assuming adiabatic conditions. 2) Entrainment is shown to govern the vertical development of clouds and the change of droplet numbers with height, and the sensitivity analysis suggests that there is a trade-off between entrainment strength and condensation for the CDNC estimations. 3) Simulated CDNC also exhibits high sensitivity to variations in initial aerosol concentration at cloud base, but weak sensitivity to aerosol hygroscopicity. As indicated in the Summary and discussion Section, the next step will be to explore the global sensitivity in a multi-dimensional parameter space to investigate the non-linear interactions among ACI parameters using the fractional design method (Box et al., 1978). Finally, we cannot possibly emphasize enough the need for end-to-end field campaigns where concerted and comprehensive observations of aerosol, winds and thermodynamic structure of the atmosphere and rainfall processes are conducted. Thank you.

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