Reply to Referee #1

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We thank the reviewer for pushing us to better quantify the link between SCVVFs and SCDDs and pointing out a number of clerical errors. This, together with comments from the other reviewer led to a significant revision of the manuscript. We believe that the revised manuscript is easier to read, more consistent throughout, and provides conjecture and explanations that are better supported by the observations presented.

Below, comments provided by the reviewer are in black, our responses are in red.

Reviewer Comments

The paper uses in-situ observations of dynamics and microphysics to link the formation of supercooled drizzle drops to specific dynamical conditions.
Main comment: While the in depth interpretation of the flight leg data and back of the envelope discussion calculations were interesting, to me it seems that this qualitative investigation of this flight is the first part of the study**. The hypothesis proposed is that scvvf are required to form scdd**. I think it would be useful and necessary to generate some quantification of the observations to test this hypothesis using the rest of the flight data available from the campaign.

The bolded statement above mis-represents the intent of this manuscript. Through this work we aim to demonstrate that the presence of SCVVFs *enhance* drizzle formation and growth and therefore can influence where drizzle may form within clouds. This by itself is not surprising or novel. Throughout the introduction we present several previous studies linking the production of drizzle, in both supercooled clouds and in warm clouds, to atmospheric phenomena such as wind shear, turbulent mixing, cloud top instabilities, etc., which act to broaden the DSD. Further restrictions may be placed on *SCDD* development such as low CCN to grow larger droplets and INP concentrations to inhibit ice growth. The previous works focus on drizzle production predominantly at *cloud top.* Here we demonstrate that SCVVF layers can lead to drizzle initiation in the middle of a cloud, and need not occur at cloud top if the conditions are right. The observations presented from this case coupled with the concepts derived from earlier studies set up our hypotheses and eventual conclusions: that SCVVFs (1) can enhance collision-coalescence growth in a macroscopic sense (inferred from vertical reflectivity gradients), (2) can influence the vertical location of collision-coalescence onset in cloud (first occurring where SCVVFs are present), and (3) fundamentally affect the cloud microphysical response by condensation (subadiabatic w'-CWC' relationship). It is not our intent to suggest that SCVVFs are a necessary condition for SCDD production. In fact, we present observations from leg 2 showing the presence of drizzle despite the *absence* of SCVVFs. This is similarly true near the far eastern end of leg 1, where drizzle is present without SCVVFs. In these cases, drizzle initiation is presumably occurring near cloud top. Care has been taken in the revised manuscript to make this point more clear to the reader.

Based on the qualitative hypothesis it would seem reasonable to try and define thresholds for the following conditions: 1. T<0 and T>Tmin 2. ice_conc < min_ice_conc 3. are scvvf present? Need some metric based on w' ? 4. are scdd present? Need some metric based on cloud probes. and then combine these to quantify how well the scvvf-scdd hypothesis works. 1 and 2 have previously been suggested as controlling factors (as pointed out in the paper), while 3 is the new part explored here. So, if(1 & 2 & 3) is true, is 4 also true? This can be assessed for different thresholds and metrics across the flight campaign. Such an approach could also be used to assess the frequency and usefulness of the S anticorrelation seen to be indicative of scdd. I think this level of quantification would be very useful for other researchers and have application in aviation safety.

While we agree with the reviewer that such a study would be very interesting and useful, it is completely separate from the work presented here. The case-study approach used here aims to provide insight into the mechanisms important for influencing SCDD formation and growth. One expects that this in turn can be used to inform and validate future detailed modeling studies that aim to reproduce SCDD development in case clouds. A subsequent, campaign-wide examination of the role of SCVVFs in hydrometeor growth should help inform us regarding their overall role in SCDD formation in general, but provides little insight into the mechanism(s) responsible.

Specific Comments

l46 - S* and CCN not defined
The symbol S* is removed in the revised manuscript. CCN now defined in paragraph 3 in the Introduction: "(i.e. with lower numbers of cloud condensation nuclei; CCN)"
Care has been taken throughout the revised manuscript to ensure all symbols and abbreviations are defined.

l55 - and riming....
Riming has been included in the revised manuscript. We also note the following sentence captures this by stating: "....else ice will more rapidly scavenge the available vapor and cloud water." Paragraph 4 of Introduction in revised manuscript.

l68 - what mechanism? Is it shear induced turbulent enhancement?
Changed to explicitly indicate "turbulent broadening or mixing". Middle of paragraph 5 of the Introduction in revised manuscript

l85 - what gradient? Number concentration with temperature or horizontal distance?
This entire paragraph has been removed in the revised manuscript.

l151 - could report the frequency (Hz) of the data here for the size distributions, concentrations and condensed water estimates.
Change made, revised manuscript now reads: "From these 1 Hz size spectra…" in describing the size distributions and derived water content estimates. Paragraph 5, Section 2 of the revised manuscript.

L212: confirmed by the 2dp - was shape recognition used for the 2dp, or was the 99th percentile based on a size threshold?
The resolution (200 μm) of the 2DP is too coarse for reliable shape recognition. Rather, 2DP measurements were only used for particles with diameters greater than 1 mm (Paragraph 5, Section 2). Visual inspection of 2DS images failed to reveal any obvious liquid drops, *i.e. very circular particles,* with diameters larger than about 500 μm. Therefore, we presume that any particles larger than 1 mm, detected by the 2DP are likely ice. Regardless of whether these particles are liquid or ice, it does not change the conclusion that the concentration of ice particles was less than 0.1 L^{-1} in legs 1 and 2 and 0.3 L^{-1} in leg 5.

L218: "suggesting ice" - can liquid be ruled out? The doppler velocity would seem to be a potential evidence stream, but the text following this line seems to suggest it would be ambiguous.
We thank the reviewer for pointing this out. We often observed a significant decrease in Doppler velocity within about 1 km of the surface (Fig. 4e and 4f, for example, 20 to 40 km downwind of PJ). This decrease occurs at a similar location to a corresponding increase in the radar reflectivity, further bolstering the conjecture that liquid is being transformed to ice and that subsequent growth leads to enhanced reflectivity near the surface. This has been included in the revised manuscript. Paragraph 2 of Section 3.2.

L232: it seems that the plots and analysis could be passed through a high-pass filter to remove the terrain induced larger scale fluctuations and just concentrate on the smaller scale variations.
l271 - okay fig5b has w', but it is not clear what the nature of the filtering was of w to derive w'.
In order to calculate perturbation vertical velocity (i.e. *w'*), we took the measured vertical velocity and subtracted a simple high-pass filtered field that had been processed with a 10-s boxcar moving average. Several different size filters were tried, and the 10-s filter seemed to adequately capture the perturbations of interest. The details of this calculation are now included in the caption of Fig. 5 in the revised manuscript.

L274: to me the correlation between Ncld and w' looks poor - can you plot scatter plots and give correlation coefficients - or even do lagged correlations given the discussion at the end of the paper? fig5d shows the mvd and Ncld to have an almost linear anticorrelation, suggesting that Ncld is proportional to LWC^(-0.5). I don't know if that is a coincidence or if it means something significant...
Both reviewers commented on the correlations between droplet number concentration/liquid water content and perturbation vertical velocity. This also plays into the development of the conceptual model, presented as figure 13 in the manuscript. In order to address both reviewers, we provide additional analysis showing computed lagged correlations and follow-on discussion at the end of each review response (see below).

To the reviewer's other comment--there is clearly a strong anticorrelation between cloud droplet number concentration and mean-volume diameter, although what is not clear from the figure is whether it is linear. In the case of a linear (or near linear) relationship, we wonder if this demonstrates a balance between growth through condensation, collision-coalescence, and removal of drops through scavenging/collection and sedimentation. Exploring this in future work, particularly using detailed parcel model frameworks may be worthwhile.

l332 - the hypothesis was posed earlier on that the SCVVFs were responsible for the SCDD, but now this observation seems to counter that. See my main comment above.

We point out again, that the hypothesis is that SCVVFs may *enhance* drizzle production, but are not *required* (or responsible) for the initiation of SCDDs. However, in the example referenced here (leg 5), SCVVFs are indeed present and SCDDs are sampled at flight level. The principal difference in leg 5 compared to leg 1 is just that the SCVVF's are contained within a thin layer just above flight level. The SCVVFs in leg 5 are described in the second-to-last paragraph in section 3.4

L351: can you quantify this S correlation pattern to use it automatically?
That is an interesting question...given the observations from this single case study, it would not be possible to derive a quantification to be applied automatically. However, it may be worth exploring in a broader study that uses many cases (across the entire SNOWIE campaign, for instance) to look for a robust signal. Such an effort is beyond the scope of this study, but could be folded into a subsequent campaign-wide examination of SCVVFs as noted in an earlier response.

l373 Ncdp is this the same as Ncld?
All reference to Ncld and Ncdp has been removed from the text and replaced with the more explicit "cloud droplet number concentration" in the revised manuscript.

L407: is it possible to show a figure like 13 but from the actual data? I find it difficult to identify this behaviour in the current figures. It's difficult to see, but do the doppler velocity and reflectivity fields also show this lag effect?
Based on the results of the lagged correlations (below) this figure has been significantly revised. We acknowledge that the original figure was difficult to interpret and the connections between the ideas represented in the figure and the observations were not well represented. The revised figure is much simpler, and these connections are more apparent. We also note that the observed behavior supporting this model is best seen in the flight level data because of the noted complexity of the Doppler velocity data.

Condensational Inertia and Conceptual Model

R1: To me the correlation between Ncld and w' looks poor - can you plot scatter plots and give correlation coefficients - or even do lagged correlations given the discussion at the end of the paper?
R2: The schematic diagram presented in Fig. 13 is interesting, but I believe that the condensational inertia theory of why the LWC and Nd estimates are not in quadrature is insufficient. As the authors argue, the condensational delay may be around 10 seconds (phase relaxation timescale), yet the time between wave crests is substantially longer than this (probably 100 s or more for wind speeds of 10-20 m/s and wavelengths of 1-2 km).
Both referees indicated a desire for better quantification of the relationship between w' and CWC'/N_{cld}'. For referee 1 this had to do with some suggested N_{cld}/CWC relationship while for referee 2 it concerned the time/spatial scales and the lack of time series signals being in the expected quadrature relationship as per the proposed conceptual model (Fig. 13). To examine these relationships more quantitatively, the higher (5 Hz) resolution w', CWC', and N_{cld}' time series for were detrended and filtered of frequencies smaller than 0.1 Hz (wavelengths longer than 1 km). These time series were lagged by 0.2 s increments over a full 10 s period and correlated with a Pearson autocorrelation function to determine the correlation coefficients at each time lag. The results are presented below:

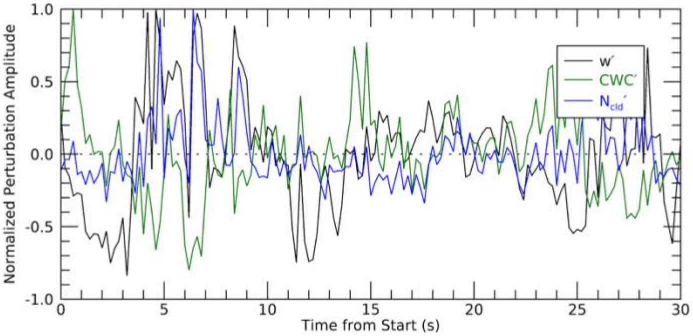

Figure 1: Normalized perturbation time series for selected kinematic and microphysical measurements. Measurements have been de-trended and filtered of frequencies lower than 0.1 Hz (corresponding to wavelengths longer than ~1 km).

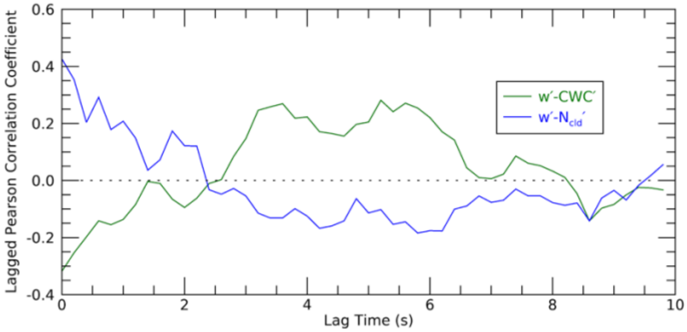

Figure 2: Lagged Pearson correlation coefficients for the time perturbation quantities in Fig. 1.

The lagged correlations (with maxima at position 0) clearly indicate that these condensational kinetic responses are zero-lag, with w'-CWC' being anticorrelated and w'-N_{cld}' positively correlated. Zero-lag correlations in this context likely indicate that cloud parcels are moving with(in) the kinematic pattern as opposed to through it as the latter should result in some spatial lag corresponding to the motion of parcels relative to w' pattern. This analysis has led us to modify the conceptual model presented in the original conceptual model with a more simple one. The analysis, while discrediting the original model, otherwise strengthens the suggested microphysical response. Furthermore, for the phase relaxation time to have led to a spatial lag exactly in quadrature now seems obviously unlikely, and we thank the referees for asking us to quantify these relationships. A new conceptual model incorporating this insight is proposed with perturbations caused from kinetic responses to a vertical velocity couplet more closely resembling the overturning cells suggested in HM05 to avoid the flow continuity issues that arise from this vertical parcel motion framework (e.g. when considering the location of maximum vertical displacement of parcels).

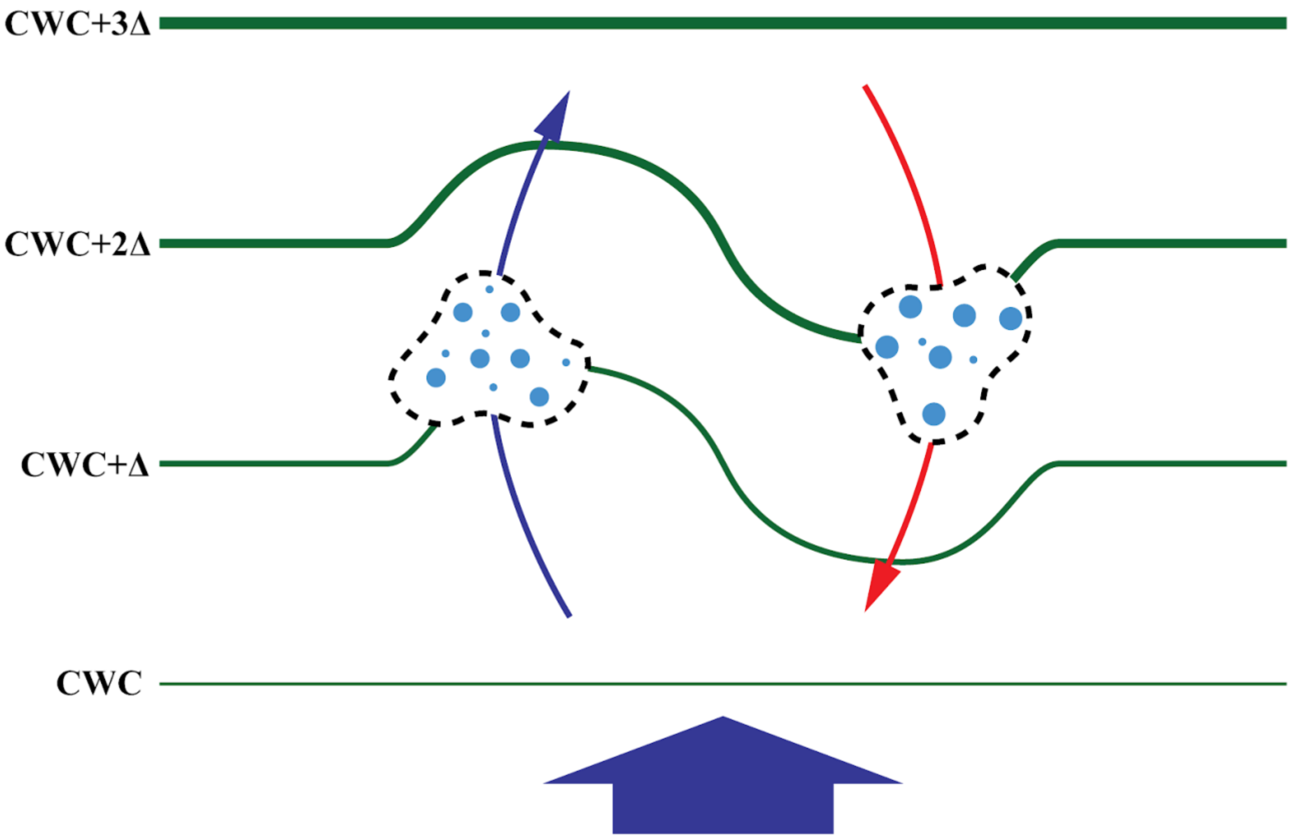

Figure 3: Revised conceptual model: simplified schematic of spatial responses to the perturbation updraft (blue) and downdraft (red) pattern superimposed on broader orographic lift (broad blue arrow bottom). The colored trajectories indicate the approximate path of parcels passing through the kinematic pattern following the schema of Houze and Medina (2005). Lines of constant cloud water content (green) indicating the expected deformations due to condensational kinetic effects, with line weight corresponding to relative condensate mass. Cloud parcels circulate within the vertical velocity perturbation pattern and more and smaller drops are located in perturbation updrafts than downdrafts. CWC contours appear flat and unperturbed above and below the vertical velocity fluctuation pattern as they are determined by the adiabatic ascent in the broader uplift pattern.

References

Houze, R. A. and S. Medina, : Turbulence as a Mechanism for Orographic Precipitation Enhancement, J.Atmos.Sci., 62, 3599-3599-3623, https://doi.org/10.1175/JAS3555.1, 2005.