**Response to David Mitchell:**

**We thank Dr. Mitchell for his careful reading and thoughtful comments, which will improve the manuscript. Our responses and text modifications are shown in bold. Line numbers refer to the original manuscript currently under discussion.**

General Comments:

This paper uses a sophisticated parcel model to investigate likely ice formation mechanisms and growth processes responsible for conditions in deep convective clouds associated with commercial and military jet aircraft engine failures (i.e. engine power loss, flameouts and damage). While the parcel model is not capable of realistically simulating all relevant cloud processes, and thus is not robust enough to unambiguously identify these processes associated with jet engine problems, it represents a useful first step towards identifying these processes. That is, it identifies processes that are more likely associated with engine problems, and vice-versa, thus laying the groundwork for more comprehensive 3-D cloud resolving modeling to determine the likely processes associated with engine problems.

While this paper focuses on deep convective cloud conditions (in the transition region between the convective and stratiform regions) at the -40°C level, this temperature level is associated with a minority of the engine problem events documented in Mason et al. (2006). Unless this is no longer true, this point should be stated in the paper, and the authors should explain why they chose to focus on this temperature level.

**Mason et al. (2006) indeed document that less than 1/10 of reported engine events occurred at temperatures colder than -40°C. However, events at cold temperatures are more common in later compilations, as will be clarified in new text on line 10 of p. 16554:**

> **"These cold temperatures were the focus of the Airbus flight tests, in part because over a third of the engine events reported by Gryzch and Mason (2010) occurred at temperatures colder than -35°C (and over a quarter at temperatures colder than -40°C). The importance of such cold temperatures is further supported by the latest Boeing engine icing event database of 162 events occurring at a median temperature of -36°C (Bravin et al., 2015)."**

**In light of the latest Boeing engine icing database being published since our manuscript was submitted, we will also replace "more than 100 incidents" on line 4 of p. 16553 with "more than 160 incidents" and on line 7 of the same page add "Bravin et al., 2015" after "Mason and Grzych, 2011".**

It is interesting that capped columns appear to be the dominant ice crystal shape associated with aircraft engine problems, as it suggests that the ice may have formed in the temperature regime associated with isometric (i.e. quasi-equal axis) ice crystals (-8 to -10°C). Ice crystal diffusional growth rates depend on the vapor gradient and the ice surface kinetics (i.e. the accommodation coefficient), and these isometric ice crystals have unique surface kinetics such that the efficiency by which water vapor molecules incorporate into the ice crystal lattice is minimal; see Chen and Lamb (1994, JAS) for more detailed information. It is not clear whether the parcel model used accounted for these unique surface kinetics or "inherent growth ratios"; this should be mentioned.

**While capped columns are common in the particle imagery, it was incorrect for us to imply that capped columns are predominant. We will replace the sentence that begins on line 23 of p. 16555:**

> **"This identification appears consistent with the Airbus measurements, characterized by the presence of unrimed capped columns (Figure 1), a habit found elsewhere in tropical deep convection outflow (cf. Heymsfield et al., 2002; Lawson et al., 2010)."**

**with the following:**

> **"This identification appears consistent with the common presence of capped columns in the Airbus measurements (Figure 1), a habit found elsewhere in tropical deep convection outflow (cf. Heymsfield et al., 2002; Lawson et al., 2010). The majority of crystals in the Airbus measurements appear irregular and are generally of insufficient clarity to distinguish rime or other morphological details."**

**And on line 15 of p. 16563 we will replace "prevalence" with "common appearance".**

**The model does not account for unique surface kinetics. It is already stated on line 14 of p. 16559 that diffusional growth of ice particles is treated using the capacitance method assuming spheroids, and we will insert a clarification on line 16 of that page:**

> **"The accommodation coefficient for diffusional growth is assumed to be unity."**

Surface kinetics could be important since this produces anomalously low growth rates for isometric ice crystals (see Takahashi & Fukuta 1988, J. Met. Soc. Japan; Takahashi et al. 1991, J. Met. Soc. Japan), resulting in less ice surface area for water vapor uptake in the cloud updraft. Hence, conditions may exist (e.g. low updraft case) where supersaturations are initially determined by the available ice surface area and updraft speed, and new ice surface area cannot be produced rapidly enough to balance the production of supersaturated water vapor, leading to conditions where supersaturations eventually exceed water saturation. Such relatively high supersaturations may subsequently affect the cloud microphysics in interesting ways, and it is important to know whether these effects are treated in the parcel model.

**While we do not include a treatment of unique surface kinetics, the loss of particle surface area for condensation and deposition is sufficient in many of our simulations that include rain to drive substantial supersaturations with respect to liquid water, as seen in figures 10, 12, 13, 15, 19, and 20, and discussed on pp. 16568, 16569, 16571,16573, 16576, and 16578.**

The paper is well written and organized and the figures are of good quality. Relevant literature has been cited.

Specific Comments:

1) Page 16563, 1st paragraph: The Hallett-Mossop process also depends on the cloud droplet size distribution (i.e. the numbers of droplets having d > 23 microns). What do the estimated ice splinter production rates imply about the cloud droplet spectra?

**We will add the following text on line 6 of p. 16563:**

> **"On the basis of laboratory measurements (Mossop and Hallet, 1974; Mossop, 1976), Pruppacher and Klett (1997, p. 358) also note that approximately 1 splinter is produced for every 100 to 250 water drops larger than 24 μm diameter accreted by graupel at -5°C, and thus 0.5 $cm^{-3}$ (~1 std $cm^{-3}$) of splinters would require 50 to 125 $cm^{-3}$ of such drops. At levels corresponding to the Hallett-Mossop temperature range, effectively all drops are larger than 24 μm diameter, and the required drop number concentrations ($N_d$) exceed $N_d$ at that level for the slow updraft, and brackets $N_d$ for the baseline and strong updrafts. However, our crude representation of splinter production does not consume drops as real riming would, and a substantial sink of drops can readily drive supersaturations that activate new drops (as seen in a number of simulations below), which might provide sufficient numbers of additional drops if riming were represented more physically, as well as providing a supply of droplets smaller than 13 μm diameter that are also required for ice production from rime splintering (Pruppacher and Klett, 1997, p. 358)."**

2) Page 16567, lines 6-9: This study addresses conditions characterized by anomalously high IWCs. Since ice particle aggregation rates are directly related to the ice mass flux (e.g. Mitchell 1988, JAS), aggregation rates should be relatively high

under these high IWC conditions. It is not clear why collisions between ice particles are expected to be inefficient (low aggregation efficiencies) under the modeled conditions; side planes have complex structures and form between -20 and -40°C (Bailey & Hallett 2009, JAS). The neglect of aggregation may be unavoidable for this modeling framework, but it does not appear to be a realistic assumption.

**The topic of aggregation between ice particles is not neglected, as that process is the focus of section 4.8. To clarify this point, on line 9 of p. 16567 we have replaced "sensitivity tests discussed below" to "sensitivity tests discussed in Section 4.8."**

3) Page 16567, line 26: The process of raindrop breakup has not been discussed.

**The treatment of raindrop breakup is described in the first paragraph of Section 4.7.**

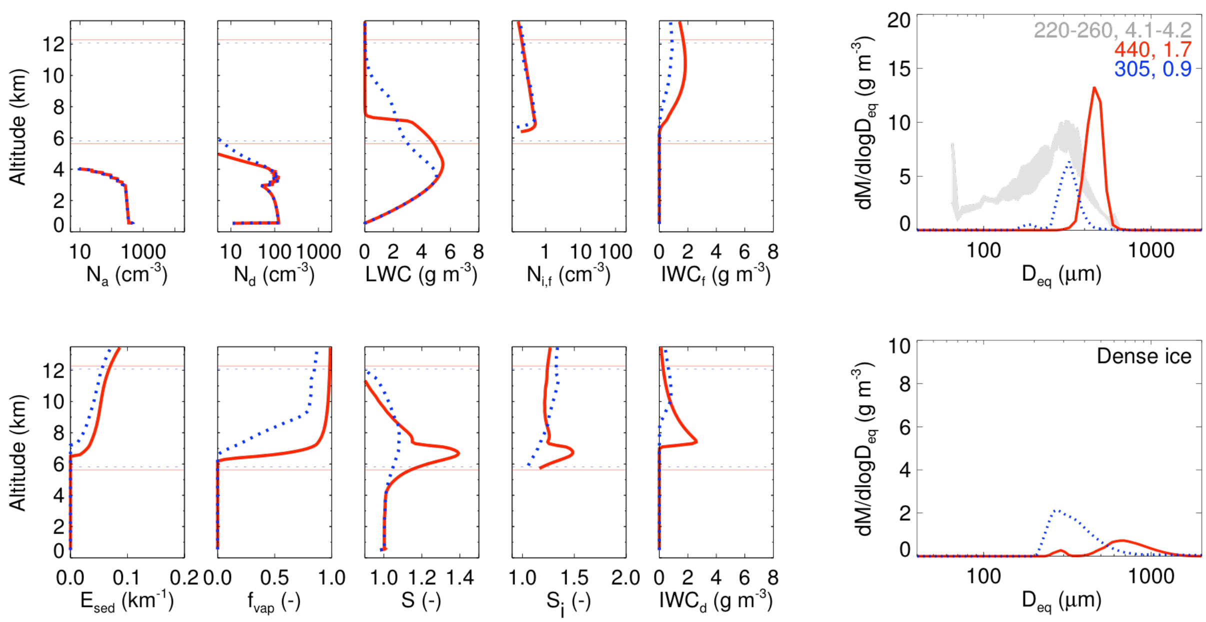


***Figure caption: Panels as in fig. 10 for simulations including gravitational collection for parcel depth of 1 km with (red solid line) and without (blue dotted line) raindrop breakup.***

**Simulation results with and without raindrop breakup are provided in the figure here. Because the manuscript is rather lengthy and already includes 20 figures, instead of adding another figure we will append the following sentence to the paragraph ending on line 2 of p. 16569:**

> **"We note that breakup of raindrops contributes to the large supersaturations, as when that process is omitted, sedimentation depletes LWC faster, fewer raindrops collect smaller water drops, and more smaller water drops increase**

**competition for water vapor, thereby reducing supersaturations (not shown)."**

4) Page 16573, line 17: Based on the PSD in Fig. 13, the green dashed curve ($f_{sh}$ = 50) is not markedly bimodal, but it exhibits a shoulder deviating from unimodal behavior.

**We will replace "markely bimodal with" with "the development of a second mode is suggested by a shoulder for" on that line.**

5) Page 16573, line 27: What does the current literature support for $f_{sh}$?

**Published laboratory studies have indicated that $f_{sh}$ < 2 (cf. Fridlind et al. 2007). However, since we submitted this manuscript, another publication focused on droplet shattering during freezing has appeared, so we will replace the original text on lines 26-27 on p. 16573:**

> **"As discussed by Fridlind et al. (2007), even a modest net multiplication factor of $f_{sh}$ = 5 is substantially greater than that supported by current literature. Hereafter, immersion IFN and drop shattering during freezing are neglected and only a pseudo-Hallett–Mossop source is considered."**

**with the following:**

> **"A net multiplication factor of $f_{sh}$ = 50 is substantially greater than $f_{sh}$ < 2, which is the maximum value supported by published laboratory studies (cf. Fridlind et al. 2007). However, Lawson et al. (2015) recently combined microphysics measurements obtained within tropical cumulus clouds with a column model to derive an implied secondary ice particle production rate from drop shattering of 1000 $mg^{-1}$ of freezing drops[1], which is about three times the Hallett-Mossop rate of 350 $mg^{-1}$ (as discussed in Section 4.5). Whereas their model is initialized with primary ice particles based on measurements, here primary ice particles are produced by IFN activation, for which we assume an abundance 100 times that of the Demott et al. (2010) parameterization; to the extent that a secondary source such as Hallett-Mossop rime splintering is also active, the required IFN abundance could be reduced. Although a pseudo-Hallett-Mossop source is used in the remainder of this study for convenience, possible alternatives include abundant IFN combined with copious drop shattering during freezing (with $f_{sh}$ >> 2) or some other multiplication process.**
>
> **[1]Note that on p. 2442 of Lawson et al. 2015, the optimized fragmentation factor should be $10^{9}$ $kg^{-1}$ instead of $10^{-9}$ $kg^{-1}$ as published (Paul Lawson, personal communication)."**

**We will also append "or alternatively a combination of abundant IFN and copious drop shattering during freezing or some other multiplication process" to the sentence ending on line 12 of p. 16580.**

Minor Comments:

1) Page 16568, line 23: repetition of “aloft”

**We will correct the typo.**

2) Page 16571, line 6: Does parcel desiccation occur through precipitation?

**To avoid the apparent implication that warm rain completely desiccates the parcel we will modify "desiccate a parcel" to "deplete LWC".**

3) Page 16571, line 9: Suggest replacing “under” with “during” to avoid confusion (e.g. under-saturated conditions).

**We will make the suggested replacement.**

4) Page 16606, Fig. 13: In 3rd line of caption, it seems $cm^{-3}$ should be $L^{-1}$ based on the text.

**The units were incorrect in the text; we will change $L^{-1}$ to $cm^{-3}$ on lines 8 and 16 of p. 16573.**

**REFERENCES**

**Bravin, M., Strapp, J.W. and Mason, J., An Investigation into Location and Convective Lifecycle Trends in an Ice Crystal Icing Engine Database, Tech. Rep. SAE Technical Paper 2015-01-2130, SAE International, Warrendale, Pennsylvania, doi:10.4271/2015-01-2130, 2015.**

**Lawson, R. P., Woods, S. and H. Morrison, The microphysics of ice and precipitation development in tropical cumulus clouds, J. Atmos. Sci., 72, 2429-2445, 2015.**

**Mossop, S. C. and Hallett, J.: Ice crystal concentration in cumulus clouds: Influence of the drop spectrum, Science, 186, 632-634, 1974.**

**Mossop, S. C.: Production of secondary ice particles during the growth of graupel by riming, Q. J. Roy. Meteor. Soc., 102, 45-57, 1976.**