Reviewer's comments in black, replies in blue.

The authors found that the observed PSDs in fresh developing convective clouds is narrower than predicted. They argued that this is due to the fact that the freezing time for large drops is longer than that for small drops. The idea is interesting, but it is not convincing for me.

Answer: We appreciate your insightful comments and suggestions. The manuscript is revised accordingly, and is much improved based on your comments. We believe the revised manuscript is now more convincing.

1. Based on the observational data, the "first ice" is small. But this might be due to secondary ice production or sampling statistical problem, which has been well discussed in Lawson et al. (2015). The authors did not discuss those possibilities and this would lead misleading if the readers are not familiar with this field.

Answer: We appreciate the insightful comment. Ice generation in convective clouds is complicated, and we agree that some of the observed small ice at about -8 C may be due to secondary ice production. If that is the case, it means there were large drops that freeze and then produce the secondary ice. These large freezing drops may be at the early stage of freezing, so they are spherical or quasi-spherical. When these large freezing drops are not fully frozen, and contain more liquid mass than ice mass, they may be not regarded as ice based on shape. However, in the model, drop freezing is assumed instantaneous, and freezing drops are added to the ice PSD as soon as they are nucleated (please see reply to Comment 2), this is not true for large drops in real clouds at relatively warm temperatures, and thus may be a source of uncertainty in model simulations. For example, instantaneous freezing results in the sudden release of a large amount of latent heat, while time-dependent freezing results in a gradual release of latent heat. The objective of this study is not to deal with first ice or ice generation, but focusing on understanding the freezing time for large drops and its possible consequences in interpreting observations and modelling ice generation in the models.

The sampling statistical problem is also very important in studying the ice PSDs in convective clouds. In this study, we focus on relatively warm temperature, with 14 penetrations between -7 C and -10 C, and 6 penetrations between -10 C and -12 C. The samples size is relatively small, but the observations are useful for studying ice generation in tropical maritime developing convective clouds, and can provide very useful information of the PSDs, at least for the clouds sampled by Learjet during ICE-T. Currently, there are not many measurements of PSDs in tropical maritime developing convective clouds with strong updraft cores, especially for small ice PSDs, so more field measurements are needed in the future. These points have been added to the revised manuscript.

2. The modeled PSD strongly depends on the ice nucleation parameterizations. By changing to another microphysical scheme, it is possible that the simulated PSD might be better or worse compared with observations. It is difficult to say whether the simulated broader PSDs is because the model does not consider the time-dependent drop freezing or the microphysical scheme.

Answer: We totally agree that the modelled PSD strongly depends on the ice nucleation parameterizations, and we apologize for the unclear discussion on this point in the original manuscript. To confirm that the modelled broader PSD is because time-dependent drop freezing is not considered, we conducted two simulations, as seen in Fig. R1 below, in the left panels, all of the ice physics implemented in the SBM are included; in the right panels, liquid-ice collision is excluded. If liquid-ice collision is excluded, most of the modelled ice is small at warm temperatures, consistent with observation (Fig. 1h and i), only a very low concentration of large ice is found, which is from immersion freezing. If liquid-ice collision is included, the concentration of large ice suddenly increases by 2 orders of magnitude at temperature between -7 C and -10 C (Fig. 1c and d), indicating these large ice are from liquid-ice collision process, and are added to the ice PSD as soon as they are nucleated in the bin microphysical scheme we used, which is widely use for WRF simulations. Taking into account the long freezing time of large drops, these particles actually are at the freezing stage, but not fully frozen. This discussion has been added to the revised manuscript.

3. In Fig. 4 and 5, the authors show results for 10, 15 20 m/s, but it is very rare that such high velocity can exist for 120 s in real clouds. For example, as shown in Fig 6, also mentioned by the authors, "the maximum updraft velocity is 7 m/s and mean updraft velocity approximately 3 m/s". It would be good to see the modeling result for low velocity. In addition, it is also useful to add the value of vertical velocity at different levels in Figure 1 a-e. I guess the velocity is smaller than 10 m/s, if so, the influence of low velocity on freezing time would be small, or even ignorable.

Answer: Great idea! We have added the observed mean vertical velocity and averaged maximum vertical velocity in Fig. 1, please see Fig. R1 below. We also modified Fig. 3, 4 and 5 based on the observed vertical velocity, please see Figs. R3, R4, R5 below. As seen in Fig. R1, the observed mean vertical velocity is approximately 10 m/s between -6 C and -10 C, the averaged maximum vertical velocity is approximately 15 m/s between -6 C and -10 C. The strong updraft at temperatures warmer than -10 C can transport large supercooled drops to higher levels. For example, in Fig. R3, if a supercooled drop in 500 microns in radii starts freezing at about -8 C, it is fully frozen at about -10.18 C. This is also confirmed in Fig. R4c and d, due to the relatively long freezing time and strong updraft, drops larger than 400 microns in radii which start freezing at -8 C or -6 C are fully frozen at temperatures 2–3 C colder than the nucleation temperature. At temperatures colder than -10 C, the observed updrafts are weaker, so large supercooled drops can stay at the same level for a long time, and the freezing temperature is similar to the nucleation temperature.

We totally agree that if the vertical velocity is weaker, the influence of vertical velocity on the freezing temperature would be smaller. The purpose of Fig. 6 is to support this point. In Fig. 6, the cloud has a relatively weak updraft, and large particles may stay at the same level for a long time or may fall through the updraft from aloft, so graupel and frozen drops were observed at temperatures as warm as -5 C, this is different than Fig. 1, which is plotted for much stronger updrafts. In another study (Yang et al. 2016), we plot the PSDs for all the updrafts stronger than 1 m/s sampled by C-130 during ICE-T, the results also support that large ice are observed at warm temperatures in developing convective clouds with relatively weak updraft.

Reference:

Yang, J., Wang, Z., Heymsfield, A. J., and Luo, T.: Liquid-Ice Mass Partition in Tropical Maritime Convective Clouds. J. Atmos. Sci., 73, 4959-4978, 2016.

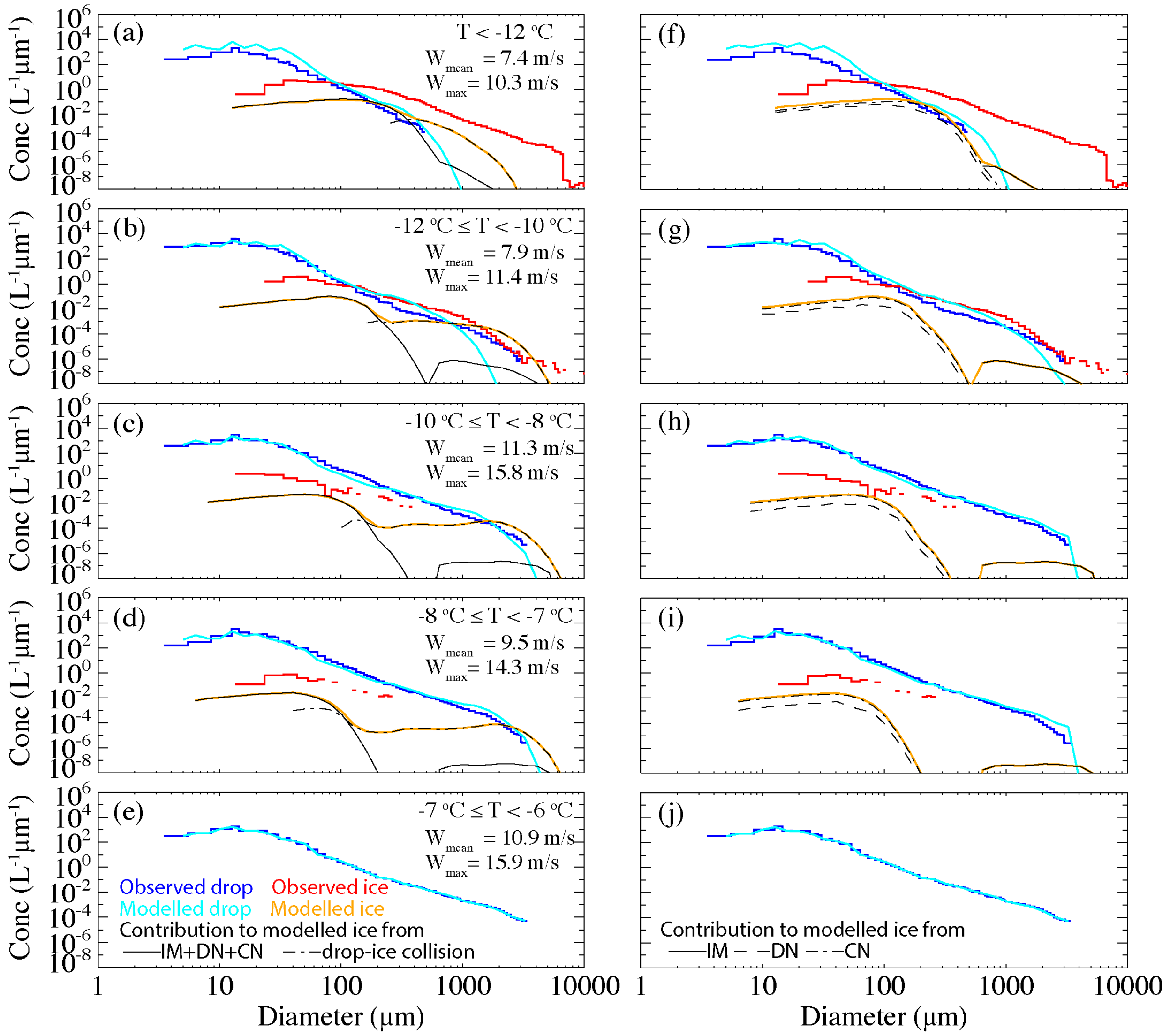

Figure R1. Particle size distributions in fresh developing convective clouds observed by the Learjet during ICE-T and those modeled using a parcel model with SBM. In (a)-(e), all of the ice physics implemented in the SBM are included; in (f)-(j), drop-ice collision is excluded. The black solid, dashed, and dashed-dotted lines in (f)-(j) represent the contributions from immersion freezing (IM), deposition/condensation nucleation (DN), and contact nucleation (CN), respectively, to the modeled ice size distributions. The black solid and dashed-dotted lines in (a)-(e) represent the contributions from primary ice nucleation (IM+DN+CN) and drop-ice collision, respectively, to the modeled ice size distributions. The observed mean vertical velocity (W_{mean}) and averaged maximum vertical velocity (W_{max}) are shown in (a)-(e).

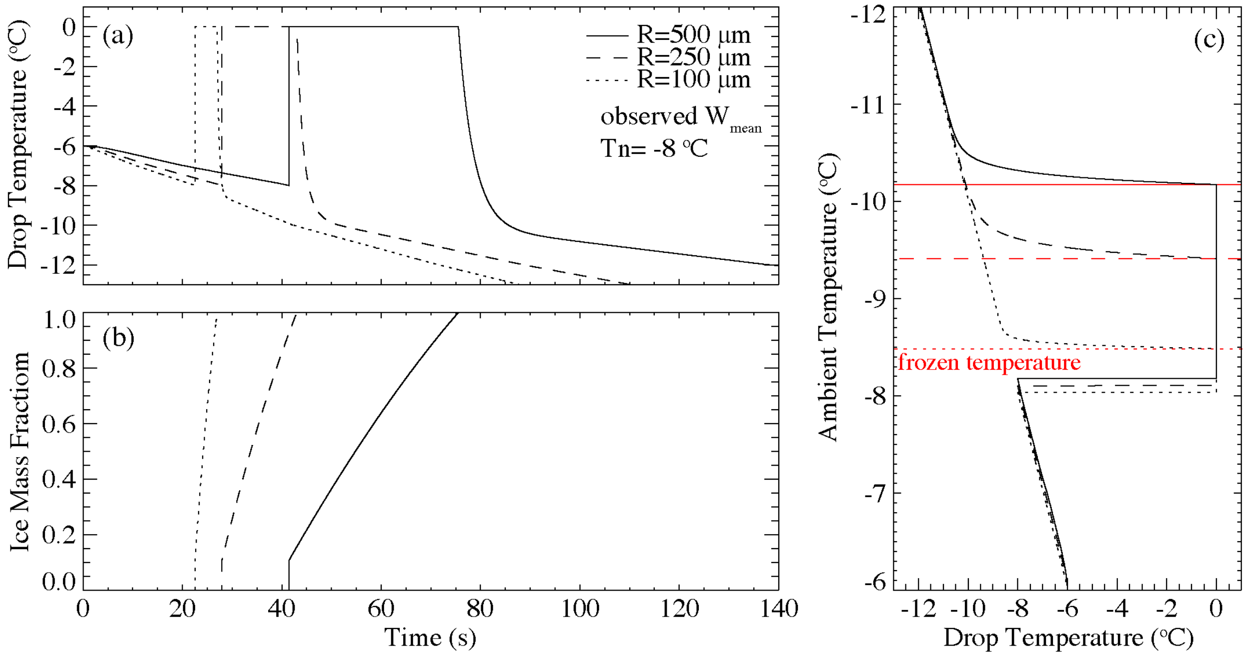

Figure R3. (a) Changes in drop temperature over time for drops with different radii based on the observed mean vertical velocity, which is temperature-dependent. Nucleation temperature (Tn) is -8 °C; (b) same as (a) but for ice mass fraction; (c) ambient temperature versus drop temperature for drops with different radii. The red solid, dashed and dotted lines indicate the frozen temperature for drops with radius of 500 μm, 250 μm and 100 μm, respectively.

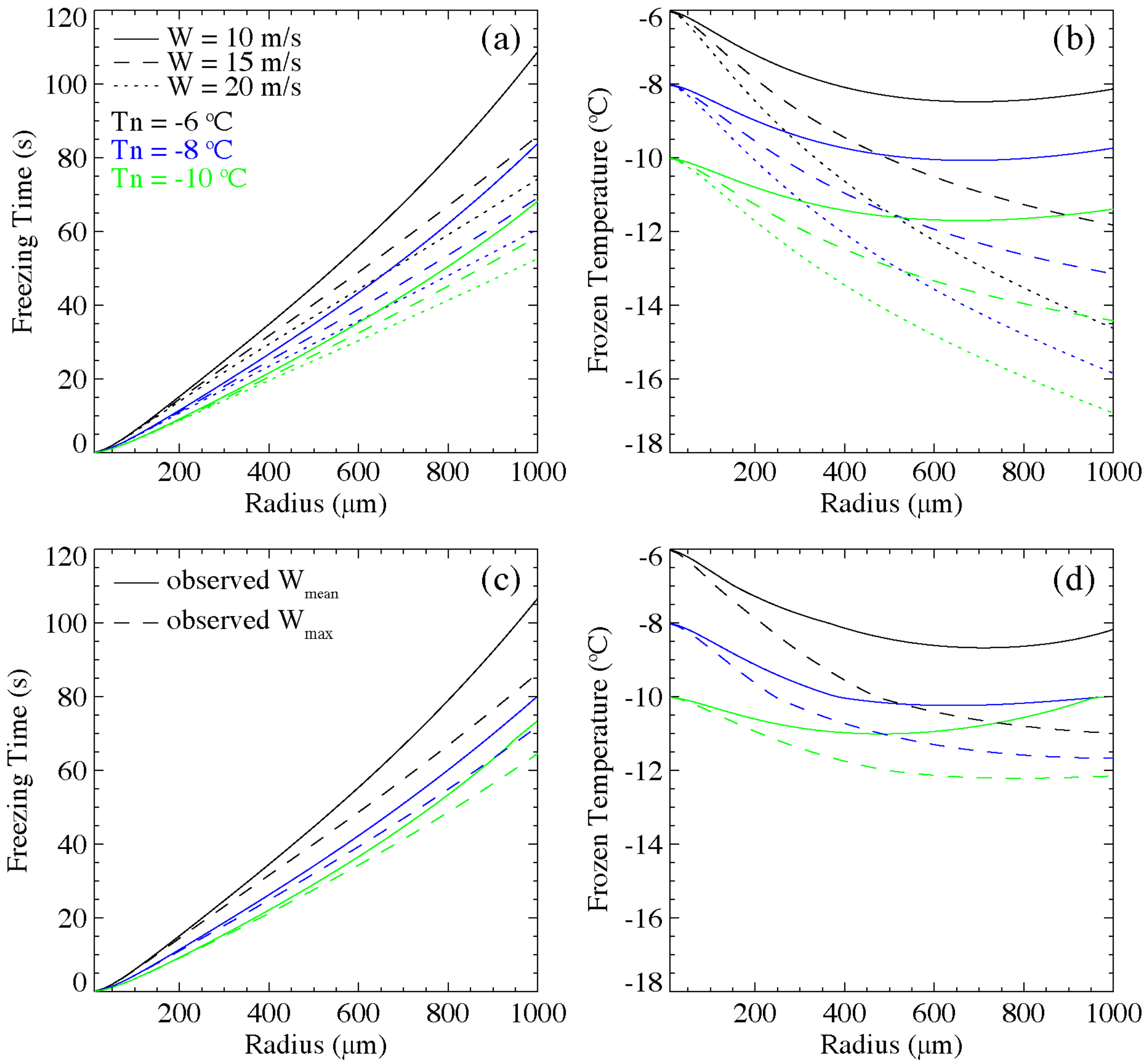

Figure R4. (a) Freezing time and (b) frozen temperature as functions of drop radius for different values of vertical air velocity (W) and nucleation temperature (Tn). (c) and (d) are the same as (a) and (b) but for the observed mean vertical velocity (W_{mean}) and averaged maximum vertical velocity (W_{max}), which are temperature-dependent.

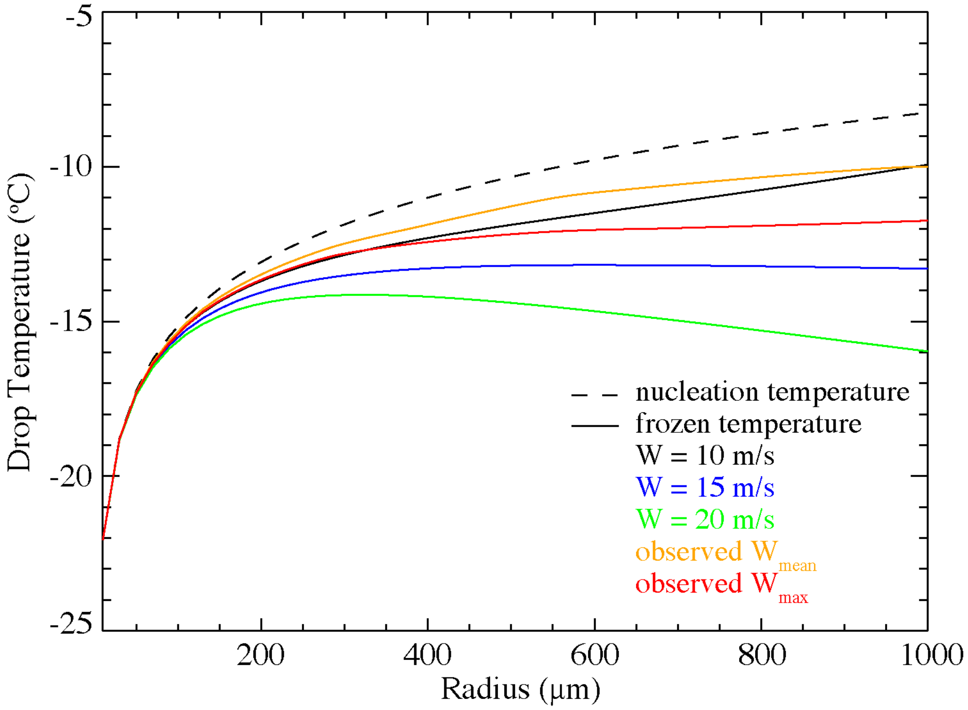

Figure R5. Drop temperature as a function of drop radius for different vertical air velocity (W) values, including the observed mean vertical velocity (W_{mean}) and averaged maximum vertical velocity (W_{max}), which are temperature-dependent. The nucleation temperature is the temperature at which drops have a 10^{-4}% probability of freezing, as determined based on Bigg's parameterization for immersion freezing.

To sum up, the main conclusion of this paper that the observed “first ice” is due to the effect of time-dependent freezing time is not convincing for me. Secondary ice production and sampling statistics which can explain the observed “first ice” are not well discussed in this paper. I’m afraid that this would lead the effect of freezing time not-very-strong speculation or even wrong explanation. In addition, the simulation results might strongly depend on the parameterizations, which makes the comparison (to observational data) less convincing. The vertical velocity used in the model is also too strong compared with the real case, which might enhance the effect of time-dependent freezing process.

Answer: We appreciate your insightful comments and suggestions. The manuscript is revised accordingly. The objective of the paper is not to focus on "first ice" or ice generation but to focus on understanding the freezing time of large drops and its possible consequences in interpreting observations and modeling ice generation in the models. Discussion about secondary ice production and sampling statistics are added. The impact of ice microphysics in the model simulations is better discussed to confirm that the modelled broad ice PSD is due to the instantaneous drop freezing. Fig. 1, 3, 4, and 5 are modified based on the observed vertical velocity, and text is revised accordingly. The revised manuscript is much improved based on these comments, and we believe the results is more convincing now.