Properties of mid-latitude cirrus cloud from surface Ka-band radar observations during 2014-2017

by Juan Huo et al.

This paper presents an analysis of ice cloud properties (height, optical depth and horizontal extent) and formation mechanisms (in-situ or liquid origin) based on four years of surface millimetre wavelength radar measurements in Beijing, China. The results are proposed to serve as a reference for parameterization and characterization in global climate models.

I was also referee during the access review phase of the paper and recommended to consider some points before uploading the manuscript to ACPD, though they go in the direction of scientific comments. This review takes up this points again (it is an answer to the authors' response) since I am not content with the authors arguments and the changes they have made in the manuscript, as you will see in the new comments.

The original, first review of the manuscript is shown in black, the author's answers in blue and referees new responses in green.

We are very sorry that our last answers did not satisfy reviewer. Thanks to reviewer for giving us the opportunity to answer them again. The problems are focused on two aspects, one is the detection capability of Ka radar (the comment A), and the other is the selection criteria or definition of cirrus (the comment B). Our replies to the new comments are presented in orange. Revised portions, including all figures, in the revised manuscript are marked with red. We hope reviewer could be content with our new answers and revisions.

Overall I find the paper a well-made study on ice clouds, the four-year data set allows a comprehensive insight into the appearance of the clouds at the measurement site; so far there are not many observations from this region. The paper is well written, the illustrations are clear, the topic is appropriate for ACP.

Nevertheless, I would recommend a change to the manuscript before it appears in ACPD, which I describe in the following.

1) The description of the Ka-band radar is very brief. I miss information of the upper and lower detection limits, i.e. the detection range, as well as uncertainties. This should be placed in the context of the corresponding range of the observed variables in cirrus clouds, so that it can be seen whether the complete range of the cirrus is covered by the measurements.

1a) Sorry for that. More details about the Ka radar can be found in the paper of Huo et al. 2019 . Since there are detailed descriptions, we introduce it briefly ※ . Since there are detailed descriptions, we introduce it briefly in this manuscript. in this manuscript. According to referee's comments, we added the descriptions about the capability of the Ka radar (KPDR) (Please see the 1st paragraph in section 2.2).

I guess you meant the new text in Section 2.1 (not 2.2): *'It should be noted that KPDR is insensitive to very small particles and it is possible that KPDR will miss some clouds with reflectivity out range of the detection threshold. The missed percentage is inaccessible at present due to our incomplete understanding of cirrus clouds and limitations of observation condition; however, it should be small according to the* *radar capability.'*

New comments (A):

First, I want to mention in general that it would have been good to show the new text in the answer so that the referee does not have to - time consumingly - compare the two paper versions to find out what has changed. I recommend this method for the next time.

Second, the answer is not very informative. The detection threshold (lower limit) should be given here, even if they are mentioned in earlier papers. It could not be expected from the reader to read other papers to find important information.

Further, if you state that 'The missed percentage (of clouds) is inaccessible' you cannot conclude that 'it should be small'. The conclusion would be that it is not known. I insist on this point because to my opinion, for studies presenting general properties of clouds derived from a large data set from one instrument, then claiming that the observations can serve as a reference for parameterization and characterization in global climate models, it is essential to have a good knowledge if all occuring clouds are detected or not, and in case not, which part of the clouds are represented by the measurements.

– Couldn't it be possible to estimate from the definition of the radar reflectivity

$$Z = \int_{D_{min}}^{D_{max}} D^6 N_v(D) dD \quad (1)$$

which cirrus clouds are most probably out of the detection range of the Ka radar with the knowledge of the size distributions? Cirrus cloud size distributions in different temperature intervals are recently shown by Sourdeval et al. (2018), ACP, their Figure 2. These size distributions could be used to estimate Z, and I would highly recommend to perform such calculations.

– There is a recent study (Jiang et al. (2019): Simulation of Remote Sensi ng of Clouds and Humidity From Space Using a Combined Platform of Radar and Multifrequency Microwave Radiometers, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019EA000580; see also the EGU contribution: https://presentations.copernicus.org/EGU2020/EGU2020-20864_presentation.pdf) detecting ice clouds with remote sensing methods from space, where the sensitivity range o f the instuments is stated. Isn't such an analysis also possible for the ground b ased radar used here?

We understand that the detection capability of KPDR determines the quality of this study. We are very grateful to reviewer for providing us two options for testing the detection capabilities of KPDR. The first scheme calculates Ze based on the particle scattering theory combined with the knowledge of particle size distribution. The second scheme calculates Ze using a cloud model. The second scheme requires input cloud field data which should contain information of cloud micro-physical parameters such as cloud particle size and IWC, as so on. Relatively, the parameter conditions required by the first scheme are easier to meet, and its calculation accuracy is also sufficient to estimate the radar detection capability. Therefore, we decide to use the first option.

-- We first consider the extreme condition, assuming that the cloud particle size in a scattering target (radar bin) is a constant, then, calculate the Ze in terms of various Ni according to the equation (1) provided above by reviewer (see Fig. RC1).

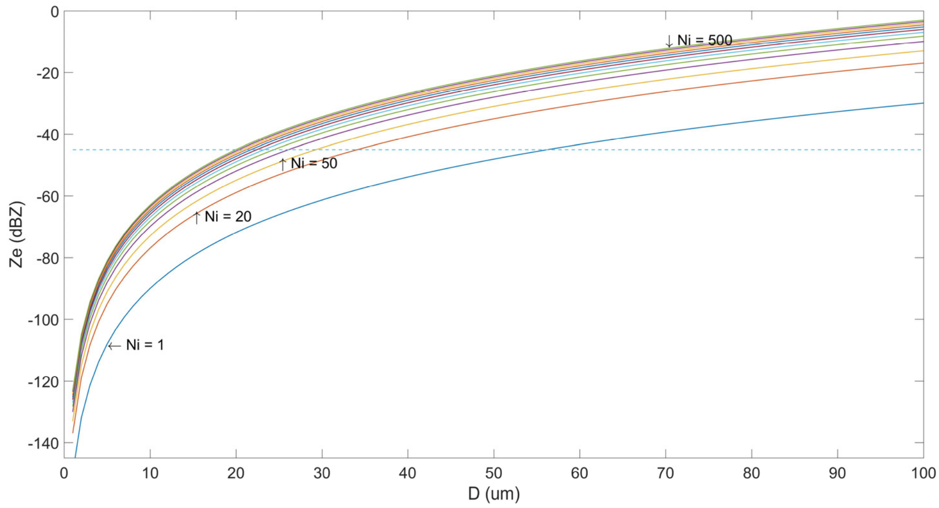


Fig. RC1. The reflectivity factor (Ze) in terms of and number density (Ni) when particle diameter (D) is a constant.

The lowest detectable value of KPDR is - 45dBZ. Generally, it is considered that the Ze of a scattering bin less than this value cannot be observed, otherwise it can be detected if Ze is above -45 dBZ. Taking the blue dotted horizontal line (Ze = -45dBZ) on the Fig.RC1 as a reference, under extreme conditions, when the particle size is equal to 20um, the Ze is less than -45dBZ even if the Ni is greater than 500 / L, meaning that KPDR cannot detect them. However, for the particles of which size is equal to 60um, KPDR can detect them only if Ni is larger than 1 / L. It can be concluded that that radar is more sensitive to large particles than small particles.

--Actually, the particle size of natural ice cloud is not constant, and the distribution function is much more complex than the above assumption, which is generally expressed by a modified gamma function. In addition, the Ze from ice particles is also related to the shape of particles. Deng et al. (2010, Fig. 4) simulated and calculated the distribution of Ze for several different shapes of ice crystals based on a modified gamma function and a particle size distribution (PDF) obtained by *in-situ* detections over mid-latitude region, respectively. For the convenience of reviewers, the relevant parts in Deng et al. (2010, Fig. 4) are posted here and shown as Fig.RC2:

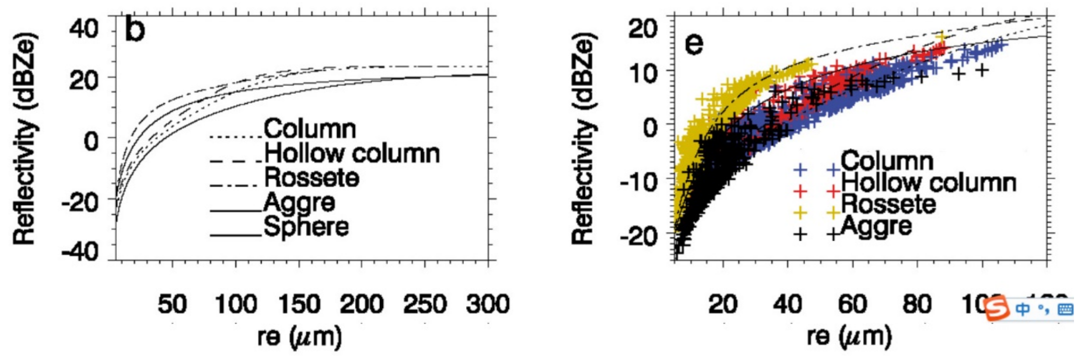


Fig.RC2 Left is the reflectivity (Ze) of five types of ice crystals calculated using modified the gamma function as the particle size function. Right is the reflectivity of four types of ice crystals calculated using the PDF obtained by *in-situ* measurement.

It can be seen from Fig.RC2 that the simulated reflectivity is above -30 dBZ. In addition, Deng et al. (2010, Fig. 11) also presented a comparison of detection ability between the CloudSat/CPR (radar) and CALIPSO/CALIOP (lidar). In order to facilitate reviewers, we also extracted the figure which is shown as Fig.RC3 below. Because the detection sensitivity of CPR is about -30 dBZ, a small part of the thin cloud observed by CALIOP is missed by CPR. The reflectivity of these "missed" thin clouds is approximately between -30 and -45dBZ.

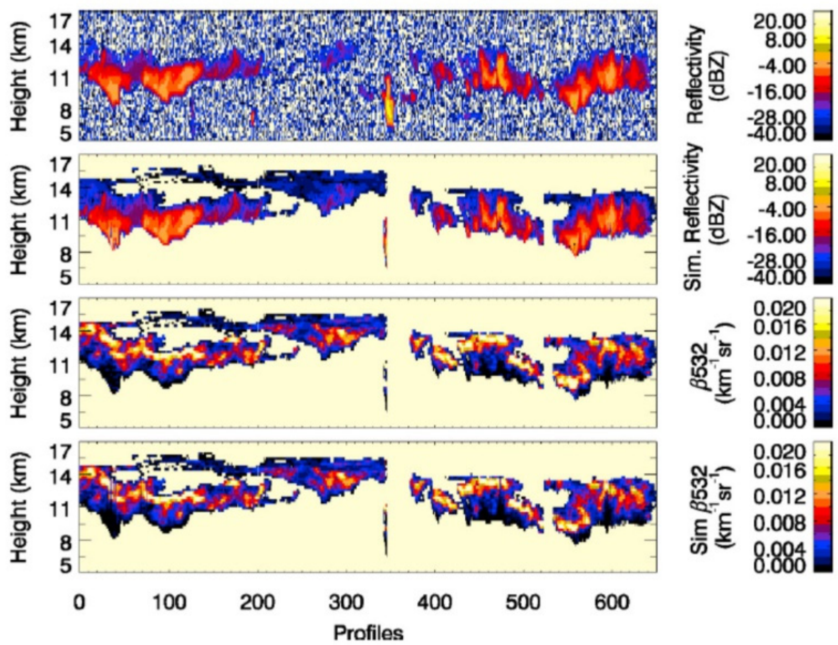


Fig. RC3 Retrieval example of 22 July 2007 CloudSat-CALIPSO case during the TC4 experiment. (a, b) Measured and simulated radar reflectivity, respectively. (c, d) Measured and simulated lidar back-scattering, respectively.

--Pokharel et al. (2011) compared the measured 94-GHz radar reflectivity in midlevel ice clouds with the reflectivity calculated using particle size distribution determined with a particle imaging probe. Below Fig.RC4 is cited from the figure 7 of Pokharel et al. (2011).

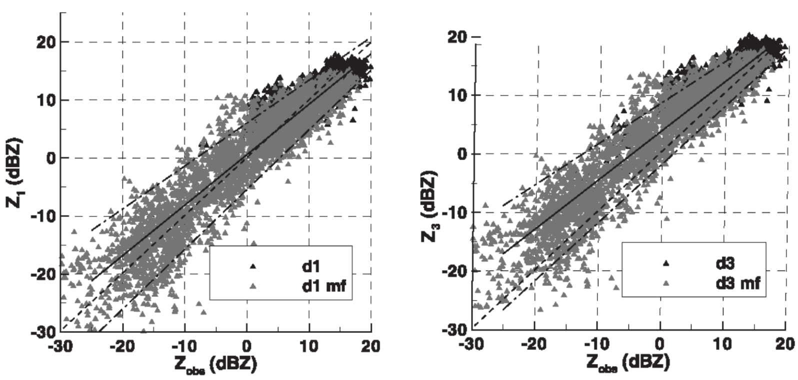


Fig.RC4 Scatterplots of the measured reflectivity Z_{obs} vs the calculated reflectivity for 1-Hz data. (left) The d1 density assumption. (right) The d3 density assumption (dark points).

--In the work of Martrosov et al. (2017, Fig.1), for those ice hydrometeor collected during aircraft flights in midlatitude (left) and subtropical (right) regions, the reflectivity is generally above -25 dBZ (shown below as Fig.RC5).

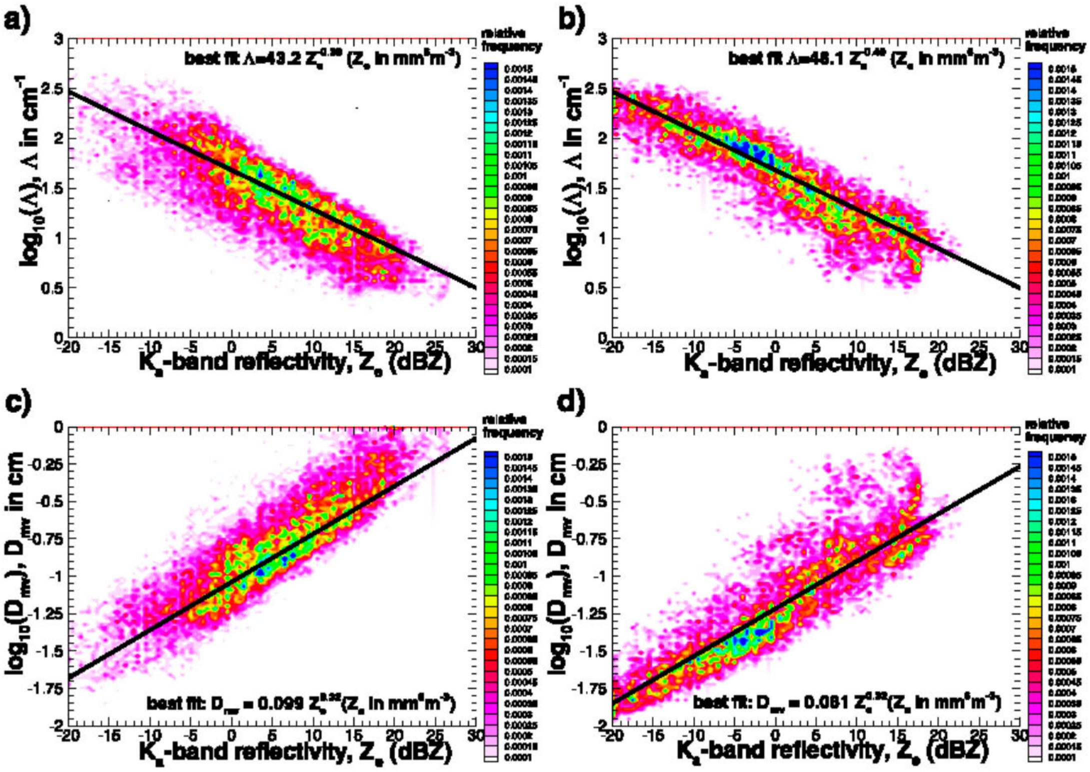


Fig.RC5 Scatterplots of K_a-band radar reflectivity vs (a),(b) the PSD slope parameter Λ and (c),(d) median volume particle size as derived from the (left) GCPEX and (right) CRYSTAL-FACE microphysical data.

Therefore, according to the calculations and measurements in previous and recent researches, KPDR should have strong capability in detecting most ice clouds in nature since its sensitivity is -45 dBZ.

Deng, M., G. G. Mace, Z. Wang, and H. Okamoto: Tropical composition, cloud and climate coupling experiment validation for cirrus cloud profiling retrieval using CloudSat radar and CALIPSO lidar, J. Geophys. Res. Atmos., 115, D00J15, doi:10.1029/2009JD013104,2010.

Pokharel, B. and G. Vali, Evaluation of collocated measurements of radar reflectivity and particle sizes in ice clouds: Journal of Applied Meteorology and Climatology, 2011. 50: p. 2104-2119.

Matrosov, S.Y. and A.J. Heymsfield, Empirical relations between size parameters of ice hydrometeor populations and radar reflectivity. Journal of Applied Meteorology and Climatology, 2017. 56(9): p. 2479-2488.

1b) Also, we added some statements (→i.e. cirrus cloud definitions) to make the information clearer (Please see the second paragraph in section 2.2).

Your new text: *'In some studies (Kr et al. 2016; Luebke et al. 2016; Heymsfield et al. 2017; Wolf et al. 2018), cirrus clouds are defined as ice clouds with lower temperature < -38°C. In this study, according to the Glossary of the American Meteorological Society (AMS,2019), the cirrus clouds are referred to all types of* *cirriform clouds (Ci, Cc and Cs clouds),which is determined by the reflectivity, temperature, height and depth.'*

New comment (B):

I do not agree with the idea that cirrus clouds can be defined so differently. The definition of Ci, Cc and Cs clouds also includes an altitude range, namely roughly > 5 km. Also, cirrus clouds are characterized as detached, thin ice clouds. Ac and As are reported up to altitudes of roughly 7 km; they are much thicker spatially and also optically and are mostly completely glaciated at higher altitudes.

At mid-latitudes, the altitude range 5-7km corresponds to temperatures between about -25° to -35°C (see Luebke et al., 2013, ACP, Fig. 4), where most of the ice clouds are glaciated mixed phase clouds, some might be fall streaks of cirrus clouds from above.

B-1: I strongly suggest that the authors reconsider the definition of the clouds they have observed. I recommend to define (throughout the manuscript, and already in the title) that ice clouds in the temperature range -15 to -55°C are detected (i.e. ice clouds in the mixed phase as well as the warmer part of cirrus cloud range). See also my new comments on 2).

B-2: I further suggest to change the title of the paper to‚Properties of mid-latitude **ice clouds** from surface Ka-band radar observations during 2014-2017'

There are different versions of cirrus clouds definition in previous articles. We initially thought that their differences may be due to the different scope of the definition, some may be a broad definition and the other may be a narrow definition.

Reviewer mentioned that cirrus covered the temperature range down to about –70^{o}C at mid-latitudes. We agree that. However, within mid-latitude regions, regional difference in temperature distribution should be considered. The coverage range of temperature would have local characteristics.

In the figure below (Fig.RC6), all the temperature profiles obtained by sounding measurements and downloaded from the hourly ERA5 dataset in Beijing in 2015 are presented. The dotted lines indicate the -70 ^{o}C. It can be seen that most temperature within 15km is above -70 ^{o}C, and -70^{o}C temperature occurs scarcely. Also, -65^{o}C temperature occupy very small percent. In the 5-7km altitude range, the temperature range is approximately -5 ~ -30 ^{o}C in Beijing. Thus, Beijing presents a distinct temperature distribution. Ice clouds over Beijing demonstrate a distinct temperature range.

In order to avoid confusions and consider the suggestions of reviewers, we decide to adopt the opinions of reviewers and define those clouds analyzed in our study as ice clouds. And in the revised document, in order to ensure 100% ice cloud, we increased the temperature threshold standard, and the cloud-base temperature is required to be below -10 ^{o}C. In addition, in the revised manuscript, the cirrus clouds are picked out from ice clouds according to cloud-base temperature less than -38 ^{o}C for a contrast. The occurrence frequency (see section 3.2) and formation type of cirrus (section 5) are analyzed.

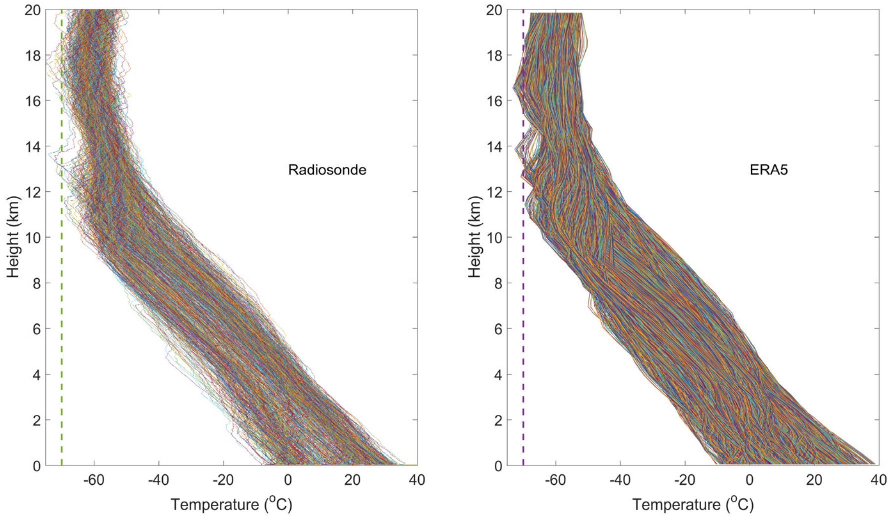


Fig.RC6 Temperature profiles at Beijing form radiosonde sounding (left) and ERA5 (right).

1c) The KPDR can detect the target of which reflectivity larger than -45 dBz due to its stronger transmitter, illustrating higher capability relative to other Ka radar, i.e., Ka radars with all-solid transmitter generally use reflectivity threshold of no more than -40 dBz. For the volume reflectivity, large particles normally contribute more than small particles. KPDR will miss small particles of which reflectivity lower than the -45 dBz. At present, it is hard to estimate the missed portions due to shortage of comparable measurements.

See my new comment (**A**)

2) This is of importance, because in the study cirrus clouds are reported only down to temperatures of -45°C, which is too high for cirrus clouds. Cirrus cover the temperature range down to about – 70°C at mid-latitudes and to about -90°C in the tropics (see e.g. Schiller et al.,2008, JGR; Luebke et al., 2013, ACP).

Further, cloud observations up to temperatures of -20°C are reported, which is definitively out of the cirrus temperature range. In newer studies, as for example Kramer et al. (2016, ACP), Luebke et al. (2016, ACP), Heymsfield et al. (2017, AMS Met. Monographs), Wolf et al. (2018, ACP; 2019, GRL), Kramer et al. (2020, ACPD), cirrus clouds are defined as ice clouds in the temperature range < -38°C, while in the range between -38°C and 0°C mixed phase clouds (liquid and/or ice) occur. The sorting of cirrus in the types of in situ and liquid origin (that have been succesfully used in the study – these are very good results!) is based on this temperature criterion, and, consequently it is found in the paper that at > -38°C the clouds are liquid origin. This shows on the one hand that the reflectivity based cloud origin sorting works well, but on the other hand that the chosen definition of cirrus is not suitable here. From my point of view, in this study clouds in the mixed phase range* as well as the warmer part of cirrus** are detected.

Thank the referee very much for the considered comments.

Yes. We have noticed that definitions of cirrus clouds differ among various references. In this study, cirrus clouds are defined and determined from the reflectivity distribution, height, depth and temperature. The classification accuracy is 86% when

compared with meteorological observer (Huo et al. 2019). After two temperature criteria (the cloud-top temperature should be less than −30°C and the cloud-base temperature should be less than 0°C added), about 15% cirrus clusters are filtered (from 7750 to 6649). Cirrus clouds in this study occur mostly within temperatures range of −15°C to −55°C, and are referred to all types of cirriform clouds (Ci, Cc and Cs clouds). If -38°C is used as criteria for cirrus determination, then about 60% cirrus clusters will not be considered. The occurrence frequency will reduce to 5% which is obviously different to the real distribution.
→ see new comment (**B**)
Does the cirrus lower than -70°C exist over Beijing? Or they are missed by the KPDR?
It is very likely that cirrus clouds down to -70°C exist above Beijing at mid – latitudes, because small and large scale temperature fluctuations will be present as in other regions. In this study, the coldest detected cirrus temperatures are -55C. The fact that cirrus clouds are getting thinner (with smaller ice crystals) at colder temperatures together with the knowledge that smaller ice crystals can not be detected by Ka band radar makes it very likely that the thinnest, highest and coldets cirrus are missed. → see also new comment (**A**)
Or cirrus cloud should be warmer than -38°C? →see new comment (**B**) More investigations are required to answer →I think we already have answers! . It was found that the temperature of cirrus clouds over North China from the CALIPSO/CloudSat 2C-ICE products were also far warmer than -38°C and above 98% of those cirrus clouds are ice particles (Fig.1, Huo et al. 2014※) . Since there are detailed descriptions, we introduce it briefly in this manuscript.) →I would call them ice clouds, see new comment (**B**). In addition, the origination type analysis in section 5 also show consistent features to the cirrus lower than -38°C.

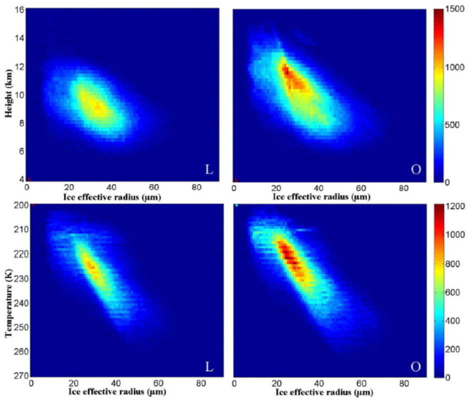
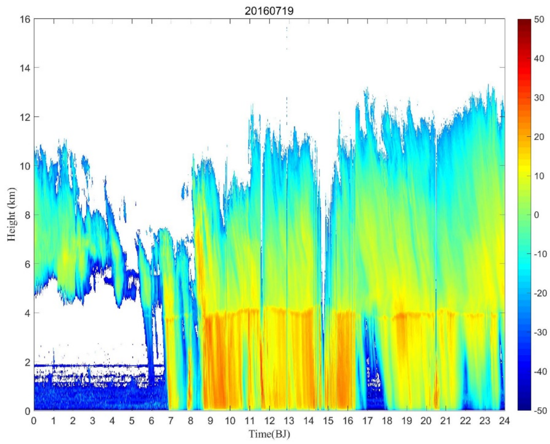


FIG. 5 Frequency of IER with (top) heights and (bottom) temperatures over the (left) L and (right) O area during 2007–10.

New comment (C): As I pointed out in 2) it is found in the paper (Section 5) that at > -38°C the clouds are liquid origin. Liquid origin cirrus are defined as glaciated mixed phase clouds that are lifted to altitudes where the temperature is < –38°C. Consequently, if you find ice clouds with this characteristics at temperatures > -38°C, these are glaciated mixed phase clouds.

In the revised manuscript, cirrus clouds (T_{base} < -38 °C) are picked out from ice clouds and their origin types are investigated in the revised section 5. We have got some new understandings, and we sincerely ask the reviewers to give some opinions about this part work.

Then, the definition in this study might be reasonable and we hope referee can accept our current cirrus classification approach. →see new comment to (**B**)
*: Can thick clouds also be detected with the Ka band radar or is there an upper limit ?
KPDR can detect thick clouds and clouds with depth larger than 10 km had been measured in past days (see a case in Fig.2).



**: the colder, thin cirrus are below the radar detection limit, yes ?
Theoretically, it is possible that the Ka radar will miss cloud bins with low number condensation and very small particles resulting in very small volume reflectivity. If colder and thin cirrus contain a few small particles, it may be missed by KPDR. At present, it is hard to estimate the missed percentage because there are no other comparable data sets at Beijing. It is hoped to get some achievements in the future as we have a lidar and Ka radar making coincident measurements at Tibet and Lidar is more sensitive to small particles.
→see new comment to (**A**)
3) Though this is already a part of the scientific discussion that usually takes place only in the open discussion, I recommend to consider these points already before uploading the paper to ACPD.
Yes. We agree. →however, I do not see that the suggested changes were made.