Response to Anonymous Referee #1

The reviewer's comments are in black and our answers are in blue. Snippets of text from the submitted manuscript are in italics while modifications of the manuscript are shown in bold italics. The pages and lines reported here correspond to the submitted manuscript.

General comments: The paper titled 'Thin ice clouds in the Arctic: Cloud optical depth and particle size retrieved from ground-based thermal infrared radiometry' presents a new retrieval algorithm to estimate cloud optical depth and separate TIC1 vs TIC2 clouds based on the effective particle diameter. The paper contributes to the remote sensing field, is within the scope of AMT, and builds upon existing work that is well-referenced but some additional details are required. Results and conclusions are presented clearly and overall the paper is well-structured. Prior to publication I have several comments which need to be addressed:

We are grateful to this reviewer for the helpful comments. We provide below a point-by-point reply to his comments.

Specific comments:
-P.1-2: the introduction is well-structured but fairly brief. Please consider highlighting the relevance and importance of these observations to other communities (satellite, modelers, etc.) by describing additional applications (e.g., reference the satellite cloud climatology project Klein and Jakob, 1999; Webb et al., 2001).
Also, there have been previous studies using similar or even the very same instrumentation (FIRR, AERI) to measure the radiative effect of thin ice clouds. Describing these studies demonstrate the novelty of this paper's retrieval algorithm. See for instance Libois et al., 2016 (AMT), Blanchet et al., 2011 (SPIE), Mariani et al., 2012 (AMT), and related studies therein.

We have added more explanations about the relevance of ice clouds study in the introduction.
P1 L17: *Predictions of future climate change and its regional and global impacts require that a better understanding of the radiative transfer interactions between clouds, water vapor and precipitation be incorporated into appropriate models.* ***Recent model intercomparisons indicate large variability in ice cloud parameters (for example ice water content) amongst high-latitude models in the framework of CMIP5 (Coupled Model Intercomparison Project) (Jiang et al., 2012). Shortcomings in ice cloud parametrization (Baran, 2012) impact their representation of radiative effects as well as water cycles and leads to uncertainties in quantifying cloud feedbacks in the context of climate change (Waliser et al., 2009).*** *High-altitude thin ice clouds consisting of pure ice crystals, which cover between 20 to 40% of the Earth (Wylie and Menzel, 1999), can, for example, have opposing effects on the radiative properties of the Earth.*

P2L6: ***The advent of active sensors onboard satellites (for example CALIPSO/CloudSat) has enabled the application of considerably more resources for polar region ice cloud studies. This permits the evaluation of climate models (Jiang et al, 2012) and satellite cloud climatologies (Sassen et al., 2008). Long-term ground-based observations which are also essential for the validation of models and satellite climatology are, however, limited in their Arctic coverage (Heymsfield, 2017).***

P 2 L 21: ***An instrument designed to study thin ice clouds in the Arctic from space using far and thermal infrared channels (Blanchet et al., 2011) was recently tested during an airborne campaign in the High Arctic (Libois et al, 2016).***

-P. 2 l. 1-2 and l. 22-24: these statements require references.

P. 2 l. 1-2: *The macrophysical and microphysical properties of thin ice clouds determine which process dominates and hence determine the net forcing of thin ice clouds on the climate system* ***(Stephens, 2005)***.
P. 2 l. 22-24: *In this paper, we examine how multi-band thermal measurements of zenith sky radiance can be used to retrieve what are arguably the most critical extensive and intensive parameters influencing the radiative effects of ice clouds* ***(as in the early work on clouds from Nakajima and King, 1990):*** *cloud optical depth (COD) and effective particle diameter (D_{eff}).*

-P. 3 l. 1-5 these two statements require references.

P3 L1: *Water vapor and clouds are a significant climate modeling challenge since they represent major radiative forcing influences, while being the least understood components of the climate system* ***(Waliser et al., 2009; Jiang et al., 2012).***
P3. L3: Much of the recent research has been focused on aerosol-cloud interaction processes involving aerosols acting as ice and water cloud nuclei ***and their subsequent affect on*** *cloud microphysics, precipitation* and *radiation* ***(see for example, Feingold and McComiskey (2016) on recent ARM campaigns, Winker et al. (2010) and Illingworth et al. (2015) respectively, on the cloud remote sensing mandate of the A-Train and EarthCARE satellite missions and Jouan et al. (2013) as part of the NETCARE project).***

-P. 3 l. 11: Table 1 only lists the instruments used in this study. There are many more instruments operating at Eureka. Please clarify this.

This is true. We have changed the Table 1 caption. ***List of the instruments used for this article, which is a partial list of the instrumentation inventory of the PEARL observatory.***

-P. 5 l. 5: is there a reference for the CIMEL? An instrument paper is needed for the reader to understand the technical capabilities of the instrument.

A very similar instrument (we used a newer version with 2 additional channels) was fully detailed in Legrand et al. (2000), in terms of performances and error analysis. The companion paper (Brogniez et al., 2003) focused on its behavior in field campaigns and showed radiometric measurement accuracy of about 0.1 K. We have added those references in the manuscript. P5L5 :***(see Legrand et al. (2000) and Brogniez et al. (2003) for the description of a similar instrument).***

-P. 5 l. 6: why are the 10.2-10.9 and 11.8-13.2 channels not centered at the midpoint, but the other channels are? Please also clarify whether the exact same spectral ranges were used for the integrated P-AERI spectra.

By centered, we meant the peak wavelength of the spectral filter response. This was clarified in the manuscript. P.5 L.6: *... and* ***have a filter response peak value*** ~~***are centered***~~ *at 8.4, 8.7, 9.2, 10.7, 11.3 and 12.7 μm.* As shown in the figure below, the peaks are not always located in the middle of the channel.

The integration over the P-AERI spectra was weighted using the spectral filter response given by the manufacturer (see figure below). This was clarified in the text:

P.5 L.6: *In actual fact we had to simulate the response of this radiometer by* ***convolving the spectral transmittance of each filter with the*** *spectra of the Eureka Polar AERI (P-AERI) instrument* ***(****provided by Von Walden at the U. of Idaho and NOAA).*

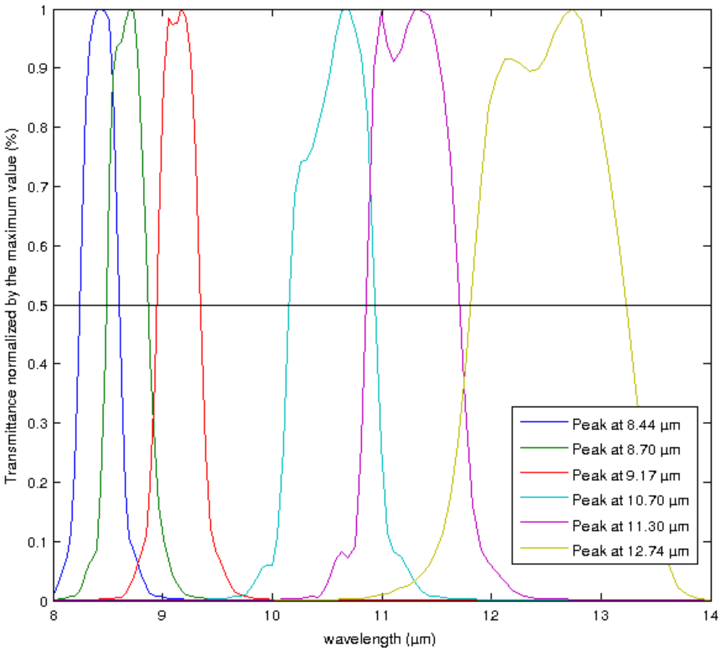

Figure 1: Transmittance of the 6 channels, normalized by their maximum value

-P. 5 l. 9-10: what are the implications of using P-AERI spectra to simulate CIMEL spectra? The impact of different spectral resolution, brightness temperature accuracy, instrument noise, and sampling time should be discussed. For instance, FIRR vs. AERI brightness temperature observations have statistically significant differences, possibly due to thermal affects. Is it possible to include results (if any) that indicate the level of agreement between the CIMEL and an AERI?

We agree that a comparison side-by-side of both instruments (P-AERI and CE-312) would be beneficial to better assess the performances of the radiometer. Unfortunately during field campaigns, the CE-312 wasn't ready for deployment and a slightly different instrument (CE-332), with only 3 bands, was used. The comparison with the 8.7 µm band (Figure 2 below) showed relatively good correlative agreement ($R^2=0.97$) except in the presence of low brightness temperatures (clear sky). The correlative statistics were similar for the 2 other bands (10.8 µm and 12.6 µm), resp. 0.98 and 0.99.

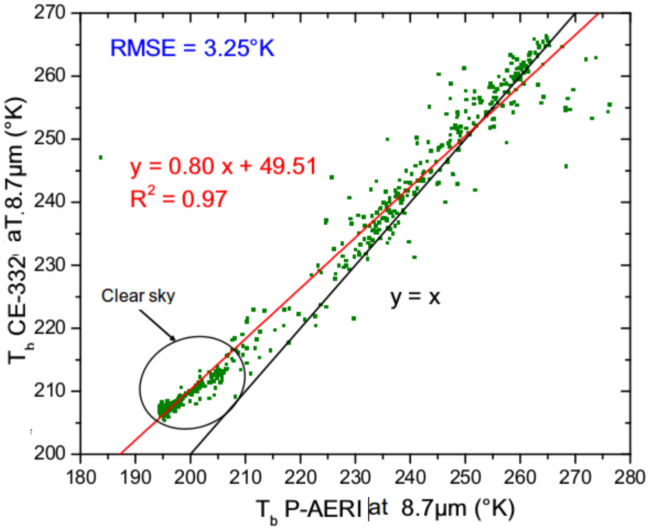

Figure 2: Brightness temperature comparison between integrated P-AERI spectra and the CE-332 8.7 µm channel during the field campaign in September 2007.

The P-AERI, which includes a highly accurate radiometric calibration system that employs 2 blackbody references, is expected to have a higher absolute accuracy (as an indicator of absolute differences relative to the P-AERI, we would note that the rms error relative to the "y = x" line on Figure 2 is 9.04 K for all the points and 5.23 K if the "Clear sky" points are not included). The noise equivalent temperature difference (NETD) is less than 30 mK, which can be compared with the value of 50 mK (at 20 °C) for the CE-312 instrument. In spite of the more moderate performance of the CE-332, we would remind the reviewer that the retrieval method incorporates the CE-312 measurement error. It is for this latter reason and the fact that we did not have a full, prototype, 6-band instrument in the field that we decided to not include a comparison of the CE-332 with the P-AERI directly in the text of the article.

-P. 7 l. 9-11: the reference case listed in Table 2 has different cloud base height and thickness values than what is listed in the 'average' row, but in the paper it is stated that the reference case was the set of mean parameters. Please clarify.

For the reference case, the cloud base height and thickness values were rounded to the nearest step of the MODTRAN vertical profiles for convenience. We added the following sentence to the legend to explain this: ***For the reference case, the cloud base height and thickness values were, for the sake of convenience, rounded to the nearest step of the MODTRAN vertical profiles***.

-P. 7: the reference case was for D_{eff} = 50 microns, which is a TIC2 cloud. Please comment on results for a TIC 1 cloud with D_{eff}< 30 microns.

We used a reference value that is common for ice clouds (Sourdeval et al., 2013). If we take a reference D_{eff} value of 15 µm, the sensitivity analysis is relatively similar with moderate differences of <~ 1 K (compare Figure 3 below with Figure 4 in the paper). We added the following sentence to the discussion of Figure 4 (P. 8 L9); ***We note that there was little sensitivity to the choice of a 50 µm effective diameter for the reference case: changing this typical TIC2 value to a value more representative of TIC1 particles produced differences in Figure 4 less than 1 K.***

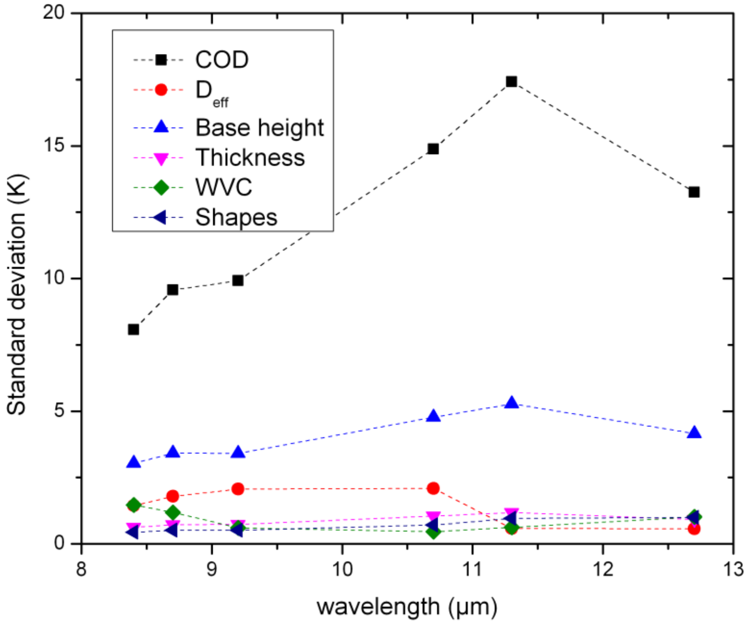

Figure 3: Sensitivity of T_b as a function of the six key radiative transfer parameters, when the reference D_{eff} is set as 15 μm.

-P. 7: this analysis is heavily dependent on MODTRAN'S ability to accurately simulate these cloud properties. Please comment on MODTRAN's reliability in this regard.

We used MODTRAN4 in this article since the 1 cm^{-1} resolution was adequate for our needs. Its multiple scattering capabilities are as accurate as the user requires: we employed this capability, with sensitivity tests, to ensure accurate calculations in the case of the thicker TICs. MODTRAN4 is flexible in the way it allows the user to configure the thermodynamical state of the atmosphere and the optical properties of complex scattering / absorbing constituents such as clouds. Thus, for example, it allowed us to incorporate the ice cloud properties recently parameterized by Baum et al., (2014) and to replace the standard MODTRAN vertical profiles by Eureka-specific radiosonde profiles of temperature and humidity. The layering capabilities allowed us to include cloud bottom and top height from our lidar profiles and to test the sensitivity of the radiative transfer computations to layer resolution.

-P. 8 l. 20: WVC in the Arctic has a large influence on thermal IR measurements depending on the spectral region (e.g., large influence at 20 microns) and season. Please clarify this.

We reinforced the Figure 4 evidence for weak WVC influence with the following modification of the text describing Figure 4. *P.8 L.20: Water vapor content (WVC) in the atmosphere, which remains relatively low* ***during the polar winter at Eureka, has a weak absorption influence on the CE-312 band*** ~~*in the Arctic, can also slightly influence thermal IR*~~ *radiance measurements* ~~*via band absorption*~~*.*

-P. 9-10: the discussion of errors requires extensive elaboration, particularly in order to defend the statement on p. 9 l. 2-4. For instance, the use of radiosonde data introduces several issues which need to be addressed, including: 1) dry bias, 2) impact of using soundings during cloud cover vs. clear sky on the retrieval, 3) interpolation of the +/- 12 hour radiosonde profile. Errors associated with the OEM retrieval, such as the Sa, Se, and error covariance matrices, should be described (perhaps in the appendix) to provide a sense of the magnitude of these errors. The a priori and its covariance matrix must be carefully selected due to their large impact on the retrieval's outcome – more detail is needed here.

1) The Vaisala radiosondes are known to be subject to dry bias which tends to underestimate the relative humidity by 2-8% (Wang et al., 2013), especially in dry conditions, which could be problematic in an arctic environment. This bias is less severe during nighttime (Turner et al., 2003) and by extension during the Arctic Winter. Some authors (Treffeisen et al., 2007; Rowe et al., 2008) have studied the bias in polar regions and have shown the bias could be up to – 10 % in the worst conditions. However, the 6 channels of the radiometer are far less sensitive to the WVC than to COD, as one can see in Figure 4, and are in an atmospheric window of water vapor. We agree that this could be more problematic for bands in the far infrared.
P10 L6: ***Radiosonde humidity sensors are known to be subject to dry bias especially in dry conditions and could underestimate the relative humidity up to 10 % (Rowe et al., 2008). The 6 channels are however far less sensitive to the WVC than to COD (see Figure 4) and therefore the bias is expected to be lower in cloudy conditions.***

2) and 3) To avoid the issue of interpolating radiosondes over extensively long periods of time, the cases were selected as close as possible to radiosonde launch times. Indeed, more than 40 % of the 150 cases occurred at a maximum of 3 hours before or after radiosonde profiles. In the case of temperature, the absolute value of the temporal variations between 2 radiosondes, averaged between 2 and 8 km, during the 3 polar winters, is about 1.72 °C, which means 0.14 °C/hour. The following sentences were added in the text: P10 L6: ***To avoid the issue of interpolating radiosondes over extensively long periods of time, the cases were selected as close as possible to radiosonde launch times.***

We agree that a careful definition of covariance matrix and errors is needed in the optimal estimation method (OEM). We have added more details about the covariance matrix in the appendix A.
P 20 L13: ***In our case, the reference case of Table 2 was used to define the a priori vector and its covariance matrix. … The measurement errors depend on the accuracy of the radiometer, which is assumed to be 0.1 K for each band (Brogniez et al., 2003), and we presumed the measurement errors are wavelength-independent. … The standard deviations of the components of S_e are close to 0.30 K (between 0.28 and 0.34 K), on the same order of magnitude than S_y.***

-P. 11 l. 9: please describe why this tolerance value was used.

The value of 10^{-15} 1/m/sr represents approximatively the minimum detectable reflectivity close to the surface, in the MMCR general mode. The minimum detectable reflectivity is an estimate of a minimally significant value that we determined from an analysis of MMCR profiles. The following change was made to the text;*… less than 10^{-15} m^{-1} sr^{-1}* ***(an empirically determined value of minimum detectability)*** *were eliminated from any …*

-P. 11 l. 29: there are several papers that state the wavelength range of the P-AERI is up to 20 microns. Please clarify this discrepancy.

It is true that the original P-AERI was designed to acquire measurements up to 20 µm (the measurements become noisy after 20µm). The text in the manuscript was changed to (P11 L29): *Although intervals of P-AERI spectra (wavelength range of 3 -* ***20 µm****)...*
More recent versions of the AERI (for example the Extended-AERI, see Mariani et al., 2012), have more far infrared capabilities.

-P. 14 l. 14: on p. 10 it is states that upper and lower cloud boundaries are obtained where 7 vertical samples (52.5 m) comply with the backscatter requirement. Please clarify this discrepancy (52.5 vs. 200 m).

The vertical resolution of 7.5 m was used in a previous version of this study and is now set as 30 m to smooth the lidar and radar profiles. The value of 200 m is set as the vertical step in the MODTRAN simulations. The value of 120 m (4 x 30 m) is needed to delimit cloud boundaries and therefore used to infer the COD and D_{eff} values from active instruments in the validation part of the manuscript. We didn't set the criteria to be 7 continuous pixels (= 210 m) because in some thin case (see for example in figure 6a, before 18:00), it happens that few pixels, in the vertical profile, don't match the threshold on the lidar signal.
P14 L 14: *... a cloud thickness greater than 200 m* ***(to comply with MODTRAN vertical step),*** *...*

-P. 15 l. 1-2: please clarify what is meant by “sufficiently accurate.”

By “sufficiently accurate.” we meant that there are very few cases (only 2) retrieved by lidar+radar which have a D_{eff} less than 50 µm. This means that the threshold between TIC1 and TIC2 (30 µm) was chosen in a conservative manner to reduce the crossover between TIC1 and TIC2. We made the following change to the text (P15 L1-2); *the* ***30 µm*** *crossover* ***criterion*** *from TIC1 to TIC2 is* ***sufficiently well delineated*** *to achieve acceptable classification accuracy*

-It would be interesting to see a comparison between MIXCRA and the Lidar-radar retrieval to provide a sense of how well the two established methodologies compare.

A comparison between MIXCRA and AHSRL/MMCR can be found below. But as this article focuses on the performances of the radiometer, we chose not to include a MIXRA and AHSRL/MMCR comparison.

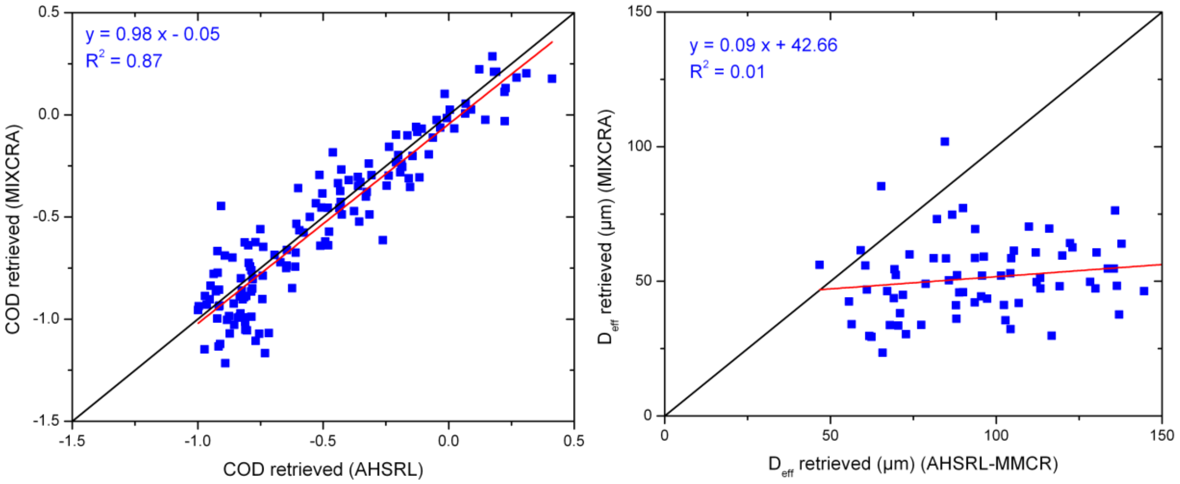

Figure 4: MIXCRA retrieval results compared with lidar derived COD (left) and with the lidar-radar D_{eff} retrieval product (right)

-P. 16 l. 15-on: please clarify whether “the comparison” is between MIXCRA and the AHSRL D_{eff} observations in the Turner and Eloranta paper and state their R-squared result.

P. 16 l. 15: The term “the comparison” was referring to the comparison between our retrievals and MIXCRA (Figure 7d). In actual fact, the paper of Turner and Eloranta (2007) doesn't include comparison of D_{eff} retrievals. To eliminate this source of confusion, we changed the sentence in question to; “*The comparison of the D_{eff} values* ***from our radiometer retrieval and the MIXCRA retrieval (Figure 7d)*** *shows a somewhat better absolute agreement relative to the comparisons* ***of our***

***radiometer retrieval** with the lidar-radar retrieval…*"

-The results discussed regarding Fig. 9 are important and yet left out of the conclusion– consider including them.

We added these sentences at the end of section 6.2 to expand the discussion, rather than in the conclusion, because we thought it would be more relevant: P18: L2. ***A long-term analysis would help to support the modeling conclusions on the impact of acid-coated ice nuclei on Arctic cloud as reported by Girard et al. (2013). These authors reported a mean downward longwave (negative) radiation anomaly at the surface of -3 -5 W/m2, close to Eureka.***

Technical corrections:

-P.2 l. 8-9: the word 'properties' is used three times in 12 words.

The sentence was rewritten: ***Numerous researchers have exploited the thermal IR behavior of the absorption and scattering efficiencies ~~properties~~ of cloud particles as a means of retrieving ~~those same properties~~ COD and particle effective sizes (e.g., Inoue, 1985).***

-P.2 l.18-19: please consider reordering your examples so that the references are listed in chronological order.

This was done in the manuscript.

-P.2 l. 27-29: the referenced work is not 'recent,' as your sources are 22 and 7 years old.

The first reference is important to understand the concept of the dehydration feedback. Since, observations from space (Grenier et al., 2009), airborne campaigns (Jouan et al., 2013) as well as laboratory simulations (Chernoff and Bertram, 2010) and climate model (Girard and Sokhandan, 2014) tends to confirm the impact of acid coating aerosols on cloud microstructure and radiative forcing over the Arctic during the cold season. In any case, we modified the sentence a bit to get rid of "recent"; "*This approach **was** motivated by **previously published** research that ~~work which shows that~~ **indicated** such a discrimination would play a key role in characterizing an important aerosol/cloud interaction process in Polar winter, namely precipitative cooling (**see, for example,** Blanchet and Girard, 1994; Grenier et al., 2009).*"

-P. 3 Eqn. 2: you have explained all variables except Dˆ2.

P4 L1: *where Q_{ext} is the extinction efficiency (extinction cross section per unit projected-particle-area) (Hansen and Travis, 1974)**, D is the particle diameter** and a(D) is the ice particle number density per unit increment in diameter.*

-P. 4 Fig. 1: no date and observation time is provided in the figure caption. There is also no color bar legend and units.

Corrected.

-P. 5 l. 12: the list of references is not complete. If you are citing examples of studies, then state this using ‘e.g.,’

Corrected.

-Fig. 2 and Fig. 4: the x-axis label ‘lambda’ should be changed to reflect what the physical quantity is, i.e., ‘Wavelength.’ The figure caption should clearly indicate whether this is simulated or observed values.

The term “lambda” was replaced by “wavelength” in the figures.

-Several places in the paper are missing a space. For instance, Table 2 caption, p.7 l.5, caption of Fig. 4.

Corrected.

-The text at the bottom right of Fig. 3 (b) should be moved into the figure caption.

Done.

-Fig. 4: please state the sample size of the simulation both in the figure caption and your discussion.

Done. Figure 4 caption: *Sensitivity of Tb as a function of six key radiative transfer parameters. The standard deviations (in units of K) are obtained by stochastically varying,* ***with a sample size of 1000****, the parameters of interest within the limits given in the Table 2.* P8L4: *… each parameter individually varied using a random number generator****, for 1000 samples****, with a normal probability distribution …*

-P. 11 l. 10: “mean’t” should be “meant.”

Corrected.

-P. 12 l. 7: avoid nested brackets if possible.

Corrected. *Within the scope of this current study, the cloud-phase determination from MIXCRA is used to ensure the comparison of ice-only cloud properties (i.e. those MIXCRA retrievals that yielded negligible liquid water path****,*** ~~*(i.e.*~~ ***LWP < 0.2 g.m−2***~~*)*~~***,*** *were taken as being pure ice-cloud cases). MIXCRA results are used here as an alternative point of reference for our retrievals.*

-P. 12 l. 12: “and demonstrate that our retrieval produces give physically” – please fix.

We removed the term “produces”.

-Fig. 6: titles should be moved next to the color bar (right-hand side). It should be clearly indicated that Fig. 6 (c) is Lidar-Radar retrieval in the figure and/or in the caption.

Done.

-Fig. 6: it is stated that only 8 of the 41 points from (b) passed the screening test. Please identify these points in the figure (perhaps a different color) and explain the distinction in the figure caption.

Done. The figure caption has been modified: ***The points surrounded by a star satisfied the criteria defined at the beginning of section 6.2 and were used in the validation part of this article.***

-Fig. 7: the equation (y=. . .) is missing in (b). The RMSE calculations are not shown in (b) and (d). The caption is also quite long – try to shorten and move parts to the discussion.

The equations and RMSE were added in (b) and (d). The caption was shortened.

-P. 20 l. 16: 'Environment Canada' is now 'Environment and Climate Change Canada.'

Corrected.

-P. 22 l. 11-15 and p. 24 l. 10-13: these references are out of order based on publication year.

Done.

References to be added to the article:

Baran AJ. From the single-scattering properties of ice crystals to climate prediction: a way forward. Atmos Res 2012;112:45–69.

Baum, B. A., P. Yang, A. J. Heymsfield, A. Bansemer, A. Merrelli, C. Schmitt, and C. Wang, 2014: Ice cloud single-scattering property models with the full phase matrix at wavelengths from 0.2 to 100 µm. *J. Quant. Spectrosc. Radiant. Transfer, vol. 146, 123-139.*

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Brogniez, G., C. Pietras, M. Legrand, P. Dubuisson, and M. Haeffelin, 2003: A High-Accuracy Multiwavelength Radiometer for In Situ Measurements in the Thermal Infrared. Part II: Behavior in Field Experiments. J. Atmos. Oceanic Technol., 20, 1023–1033, doi: 10.1175/1520-0426(2003)20<1023:AHMRFI>2.0.CO;2.

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