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Atmospheric Measurement Techniques Discussions

Interactive comment on "Use of spectral cloud emissivity to infer ice cloud boundaries: Methodology and assessment using CALIPSO cloud products" *by* Hye-Sil Kim et al.

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General comments) This study uses spectral cloud emissivity to derive information regarding the minimum and maximum values of cloud top height (CTH). Authors primarily use MODIS data to derive the relationship between brightness temperature (BT) or brightness temperature difference (BTD) and emissivity values to infer information of cloud top temperature (CTT), and then convert CTT into CTH. They used CALIPSO data to validate their products. Though such type of study is essential to improve our understanding regarding CTH retrieval accuracy by MODIS and other satellite sensors, this study needs more improvement to full this gap as explained in detail in the specific

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Discussion paper

comments below. The present version of the manuscript needs substantial revision. The presentation is not clear and discussion is relatively poor. The study method (Figure 2) is ambiguous. For example, what information do authors use from ice cloud pixels to determine the permissible ec?, what is the meaning of permissible ec ?, do authors use emissivity data or uncertainty in emissivity? There are a number of such confusions to the reader. Further, It is not clear how this study can address the problem of cloud vertical inhomogeneity as stated in the first line of abstract. It should be either removed or discussions are necessary to show how this study can address such problem. The discussions presented in the second half are relatively poor. For example, what are authors' view for relatively large difference in min(Hc) and CALIOP base height in Figure 9?. The English also needs to be improved.

Your detailed comments helped us to revise and improve our paper. We hope that this revised manuscript sufficiently addresses your comments and improves the clarity.

Specific comments

1. L63: Write the full form of NWP as it appears for the first time here.

Response: Done.

[lines 77–79] "The emissivities are used subsequently to estimate ranges of cloud height, which are found by converting the estimated cloud temperature ranges using a simple linear interpolation of the Numerical Weather Prediction (NWP) model products."

2. Section 2 : It is better to separate data and methodology in different sections.

Response: Done. Section 2 describes the data used in this study and Section 3 presents the methodology to infer cloud heights.

3. L95: Specify what method is used while remapping NWP fields to the resolution of satellite imaginary and interpolating to the time corresponding to satellite observation.

Response: The text was changed as follows:

[Lines 123–124] “The NWP fields are remapped to the resolution of satellite imagery by linear interpolation. We use the NWP products that are closest in time to the satellite observations.”

4. L140: Are ec and âU ÌŃ s Ìğ ec are obtained are SDS data of ‘cloud_emiss11_1km’ and ‘cloud_emission12_1km’ as expressed in L200. Are they the emissivity or emissivity uncertainties?

Response: The ec values from C6 MYD06, of which SDS data are ‘cloud_emiss11_1km’ and ‘cloud_emiss12_1km’, are cloud emissivity itself, not cloud emissivity uncertainties. We clarify definitions of the data in the revised version.

[lines 253–257] “Here we use the cloud emissivity values at 11 and 12-μm for each ice cloud pixel provided in MYD06, for which the Scientific Data Set (SDS) names are ‘cloud_emiss11_1km’ and ‘cloud_emiss12_1km’. The cloud emissivity for a single band is obtained by the following equation: e_c=(I_obs-I_clr)/(I_ac+T_ac B(T_c)-I_clr). (7) In Eq. (7), T_ac and I_ac are the above-cloud transmittance and the above-cloud emission (Baum et al., 2012), which are additional terms compared to the definition of the cloud emissivity in the infrared window regions in this paper (Eq. (2)). In spite of different definition of Eq. (7) from the Eq. (2), we use this cloud emissivity data since there the differences are small from the two different equations in the infrared window region.”

5. L140:L155: Make this section clear and easy to understand. For example, how do you constrain 11 micron cloud emissivity for an ice cloud pixel (L147), and how do you use this information with LUT values?

Response: We constrain 11-μm cloud emissivity from minimum to maximum values for an ice cloud pixel that are provided in the LUT values. We modified a paragraph located at lines 140–155 in the original manuscript, as below.

[lines 185–201] “In this study, we apply a range of spectral cloud emissivity values to infer cloud temperatures rather than an optimum value. In our approach, the cloud is considered as a number of plane parallel homogeneous cloud layers. The cloud layer temperature ranges, Tc, are estimated as a vector of possible Tc values given a range of the ec and ∆ec (hereafter, ec and ∆ec) such as ec = [e_cˆ1,e_cˆ2,âŃŕ,e_cˆn] and ∆ec =[∆e_cˆ1,∆e_cˆ2,âŃŕ,ãĂŰ∆eãĂŮ_cˆn] as shown in Fig. 2(b). The ec and ∆ec in Fig. 2(b) describes a range of possible spectral cloud emissivity values that can simulate the measured channel radiances. Thus, this study aims to produce Tc given the ec and ∆ec, and to examine how closely the retrieved Tc are to the actual vertical cloud structure. The differences between this study and Inoue (1985) are summarized as follows. Constraints in the iteration range for cloud emissivity are provided in look-up tables (LUTs) discussed in the next section, as opposed to considering the full range of possible values from 0 to 1. Emissivity differences (∆ec) are used, rather than a single value for the extinction coefficient ratio between two infrared channels. Given the range of emissivity differences (∆ec provided in LUTs), we obtain a range of Tc (and hence a range of cloud heights, Hc) that can be compared to CALIPSO products. The first step in the current method (Fig. 3) is to constrain 11-μm cloud emissivity ranges (ec|11) that an ice cloud pixel can have based on the brightness temperatures. To obtain a reasonable ec|11 boundary corresponding to the ice cloud microphysical properties, the LUTs are generated to provide ec|11 ranges characterized by brightness temperature (BT) for 11 μm (BT|11), BT differences (or BTD) between 11 and 13 μm (BTD|11, 13) and between 11 and 12 (BTD|11, 12) (the light gray box in Fig. 3).”

6. L197-L204: This paragraph is also confusing. The first line of this paragraph states that you derive an empirical relationship, however, the last section discusses about taking per centile values. Do you use empirical relationship or percentile values to define the minimum and maximum values of the emissivity?

Response: We removed the expression, ‘empirical relationship’ to avoid giving confusions to readers. Also we revised this paragraph located at L197–204 in the original manuscript.

[lines 253–267] “The final step is to find the possible ranges of ec and Δec in each of the bins of BTD|11,13, BTD|11,12, and BT|11. Here we use the cloud emissivity values at 11 and 12-μm for each ice cloud pixel provided in MYD06, for which the Scientific Data Set (SDS) names are ‘cloud_emiss11_1km’ and ‘cloud_emiss12_1km’. The cloud emissivity for a single band is obtained by the following equation: e_c=(I_obs-I_clr)/(I_ac+T_ac B(T_c)-I_clr). (7) In Eq. (7), T_ac and I_ac are the above-cloud transmittance and the above-cloud emission (Baum et al., 2012), which are additional terms compared to the definition of the cloud emissivity in the infrared window regions in this paper (Eq. (2)). In spite of different definition of Eq. (7) from the Eq. (2), we use this cloud emissivity data since there the differences are small from the two different equations in the infrared window region. Note that the cloud emissivity data from C6 MYD06 are retrieved under the assumption of the single-layered cloud. Here the possible ranges of ec and Δec are determined as the min/max(ec) and (Δec) among cloud emissivity values allocated by the bins of three parameters. To exclude extreme values, the min/max(ec) and (Δec) are defined as the 2nd /98th percentiles of the ec and Δec distributions when there are at least 5,000 pixels available for a given bin. When there are between 500 and 5000 pixels, the 5th /95th percentiles are chosen as the min/max(ec) and (Δec). In the rare case when there are between only 200 and 500 pixels, the 10th /90th percentiles are used. Any case with fewer than 200 ice cloud pixels is not included in the LUTs.”

7. Subsections 3.1 and 3.2 may be moved to data section.

Response: We moved subsections 3.1 and 3.2 to subsections 2.1 and 2.5 under the section 2 (the Data section).

8. L297: A brief description regarding the procedure of collocating CALIOP and MODIS is useful here.

Response: Done as follows:

[lines 353-354] "The computationally efficient method of Nagle et al. (2009) is used to collocate the simultaneous nadir observations (SNO) between two satellites. Following their approach, CALIOP is projected onto MODIS."

9. What are authors' view for deviated CBH and min(Hc)?

Response: The vector, Hc, provides a possible range of cloud heights for the observed channel radiances. When comparing to a lidar-based CBH, we also have to take note that the lidar signal attenuates as the COT increases.

10. Why not to write min_CTH or similar instead of min(Hc) ? Same for max (Hc) as well.

Response: Again, our products, Hc, provide a possible range of cloud heights for the observed channel radiances. Hc is not exactly same as the definition of cloud top height (CTH) or cloud base height(CBH).

11. The discussion of section 4 may be strengthen by referring past studies and/or putting authors' own logic.

Response: We added and modified the section 5 (section 4 in the original version of the manuscript). Most parts that were modified are paragraphs at lines 391–408, as below.

[Lines 404–421] "To better understand the potential biases of the current algorithm in comparison with CALIOP, we compare the mean(Hc) to the mean(CALIOP Hc) that are defined as 0.5·(max(Hc)+min(Hc)) and as 0.5·(CALIOP CTH + CALIOP CBH), respectively. Fig. 10 shows the frequency of occurrence of biases, that is, the mean(CALIOP Hc) minus the mean(Hc), as a function of CALIOP COT for the single-layer ice clouds during August 2015. In a comparison of the MODIS cloud mask with CALIOP, Ackerman et al., (2008) noted that the cloud mask performs best at optical thicknesses above about 0.4. The lidar has a greater sensitivity to particles in a column than passive radiance measurements. Based on this consideration, we limited our results to those pixels where the COT $\geq$ 0.5 in x-axis of Fig. 10. Fig.10 illustrates that our resulting single-layer ice clouds boundaries are consistent with CALIOP measurements, showing slightly negative biases except the region near 'COT$\leq$1.5'. These results suggest that our approach for applying a range of cloud emissivity values to estimate cloud boundaries has potential merit for using IR channels to produce cloud boundaries similar to those that the lidar observes, especially for optically thin but geometrically thick ice clouds which tend to have large uncertainties (Hamann et al., 2014). The negative biases of the mean(Hc) from CALIOP measurements are caused primarily by two factors: (1) The min(Hc) values for all cloud regimes tend to be higher than geometric cloud base, and (2) The max(Hc) values are sometimes slightly outside the actual cloud boundaries. Perhaps this is caused in part by the conversion of temperature to height using the NWP model product. Another source of error could be that the radiances have some amount of uncertainty that was not considered in our methodology. The notable point is that the boundary heights for optically thin cirrus (1.5<COT$\leq$3.5) show the lowest biases."

12. It is better to show the dependence of CTH or CBH difference between CALIOP and this study on CALIOP COT in Figure 10 instead of the mean value difference. What information do authors want to convey from the difference of C2 mean values?

Response: We understand your point here but we want to keep the figure the same for these reasons: (1) Fig. 10 would become more confusing if we show the dependence of the both of CTH and CBH difference between CALIOP. (2) What we intended to show is that for optically thin, but geometrically thick ice clouds, our cloud boundaries are consistent with CALIOP measurements. (3) As the results are shown for a limited optical thickness range, we feel it would not provide greater insight but would lead to a longer explanation necessary for understanding the min/max(Hc).

13. Figure 1:Make the caption clear. Write about Iclr and B in the caption.

Response: Done as below.

[20 pp.] “Figure 2: The conceptual model for (a) a plane parallel homogeneous cloud layer with no scattering, characterized by cloud emissivity (ec) and cloud emissivity differences between two infrared channels (Δec) at the cloud temperature (Tc) and (b) a number of plane parallel homogeneous cloud layers (the stripes box) with a possible range of ec and Δec such as ec = [e_cˆ1,e_cˆ2, âŃŕ,e_cˆn] and Δec = [ãĂŰΔeãĂŮ_cˆ1,ãĂŰΔeãĂŮ_cˆ2, âŃŕ,Δe_cˆn] corresponding to a possible range of cloud temperature, Tc = [T_cˆ1,T_cˆ2, âŃŕ,T_cˆn], where Iclr and B are the clear-sky radiance and the Planck's function, respectively. Arrows represent upwelling radiances.”

14. Figure 2: ‘The logo of Copernicus Publications’ should be removed from the caption. Response: We removed the ‘The logo of Copernicus Publications’ from the caption.

[21 pp.] “Figure 3: A flowchart for estimation of Tc and Hc corresponding to ec (from a light gray box that will be shown in Fig. 3) and Δec (from a dark gray box that will be shown in Fig. 4) which represent cloud microphysics uncertainty in a certain cloud thickness. We denoted functions for minimum/maximum values of a matrix, A, as min/max(A).” âĂČ 15. If COT is not used here, why do you use COT for y-axis title? Response: We removed the COT for y-axis title at the right side in Fig. 8, as below.

16. Table 1: What is IR cloud phase here?

Response: modified ‘IR cloud phase’ to the official name, ‘IR cloud thermodynamic phase’ (Baum et al., 2002), also added the reference for the product in the manuscript.

[lines 242–243] “Ice cloud pixels are identified by the MODIS IR cloud thermodynamic phase product in MYD06 (Baum et al. 2012) and where the pixels have a cloud top temperature $\leq$ 260K.”

17. Table 2: Why 700 and 705 appear in this table?

Response: This is a systematic problem, a conversion from ‘word’ to ‘PDF’. We corrected that problem in the revised manuscript.

Please also note the supplement to this comment:
https://www.atmos-meas-tech-discuss.net/amt-2019-148/amt-2019-148-AC4-supplement.pdf

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