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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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review of manuscript AMT-2019-148

In this manuscript, a relatively simple scheme for inferring the location of the upper and lower boundaries of clouds based mainly on infrared window channels is suggested and demonstrated. The idea is novel and as a suggested scheme for the remote sensing of clouds, it is highly relevant to Atmospheric Measurement Techniques. In general, the results of the new scheme are impressive and interesting. However, there are a number of clarifications that I suggest would be helpful to the reader, as follows.

We greatly appreciate your detailed comments, which we used to revise and improve our paper as shown below.

(1) Given that at least ten different techniques already exist for retrieving cloud top heights with passive infrared radiation, it might be better to make the title more specific. Perhaps something like "A relatively simple scheme for inferring ice cloud boundaries using spectral cloud emissivity and its uncertainty..." would better emphasize the uniqueness of the current method as compared to the ones that already exist. See also my comment number 5.

Original title: Use of spectral cloud emissivity to infer ice cloud boundaries: Methodology and assessment using CALIPSO cloud products

Potential new title: A relatively simple scheme for inferring ice cloud boundaries using spectral cloud emissivity and its uncertainty: Methodology and assessment using CALIPSO cloud products

A second potential new title: Inference of cirrus layer boundaries using spectral cloud emissivity and its uncertainty: Methodology and assessment using CALIPSO cloud products

A third potential new title: Use of spectral cloud emissivities and their related uncertainties to infer ice cloud boundaries: Methodology and assessment using CALIPSO cloud products

In the revised version, we chose the third potential new title, 'Use of spectral cloud emissivities and their related uncertainties to infer ice cloud boundaries: Methodology and assessment using CALIPSO cloud products', since the spectral cloud emissivities and their uncertainties are unique factors to infer ice cloud boundaries in this paper.

(2) lines 7-8: "...generally assume a plane-parallel homogeneous cloud exists in each field of regard, or pixel, but this assumption ignores vertical homogeneity." – Strictly speaking, the plane-parallel assumption only ignores horizontal homogeneity within

each pixel and does allow for vertical homogeneity. The more relevant argument here is that similar schemes additionally assume that the cloud is optically thin to the extent that there is only one value of cloud emissivity and only one value of cloud temperature per cloud in each pixel.

Response: We agree that the relevant argument here is that even when optically thin ice clouds are present, operational retrievals provide only one value of cloud emissivity and one each of height/temperature/pressure per pixel. The text will be changed to reflect that we are assuming horizontal homogeneity with a given pixel but allowing for vertical inhomogeneity (that is, finding cloud boundaries).

[lines 8–12] “Satellite imager-based operational cloud property retrievals generally assume that a cloudy pixel can be treated as being plane-parallel with horizontally homogeneous properties. This assumption can lead to high uncertainties in cloud heights, particularly for the case of optically thin, but geometrically thick, ice clouds. This study demonstrates that ice cloud emissivity uncertainties can be used to provide a reasonable range of ice cloud layer boundaries, i.e., the minimum to maximum heights.”

(3) line 14: “single-layer thin and thick ice clouds, and multi-layered clouds” – The distinction between these three categories is not precise. To be clear, I would write “single-layer thin ice clouds, single-layer [geometrically or optically?] thick ice clouds, and multi-layer clouds”. This is true here and throughout the manuscript (e.g., lines 64-65).

Response: We clarified the three categories, “single-layer optically thin ice clouds, single-layer optically thick ice clouds, and multi-layer clouds” as follows throughout the manuscript.

[lines 15–16] “We estimate minimum/maximum heights for three cloud regimes, i.e., single-layered optically thin ice clouds, and single-layered optically thick ice clouds, and multi-layered clouds.”

[lines 79–81] “Cloud boundary results are presented for three cloud categories, i.e., single-layered optically thin ice clouds, single-layer optically thick ice clouds, and multi-layered clouds, and these results are assessed with measurements from a month of collocated CALIOP Version 4 data.”

the subtitle of section 4.1 [line 288] 4.1.1 A scene for single-layered optically thin ice cloud (19 August, 2015, at 0320 UTC) [line 323] 4.1.2 A scene for single-layered optically thick ice cloud (19 August, 2015, at 1530 UTC)

[line 289] “Figure 6 is a scene analysis for single-layered optically thin ice clouds for a granule at 0320 UTC on 19 August, 2015.”

[line 324] “The second case is the single-layered optically thick ice clouds (Fig. 7) at 1530 UTC on 19 August 2015.”

[lines 368–370] “Fig. 9 shows the joint histogram of the max/min(Hc) (y-axis of left/right panels) as a function of the CALIOP CTH/CBH (x-axis) for single-layered optically thin (Fig. 9(a)) ice cloud, single-layered optically thick (Fig. 9(b)) ice cloud, and multi-layer (Fig. 9(c)) cloud.”

[27 pp.] A caption of Fig. 9: “Joint histograms of three cloud categories; (a) single-layered optically thin ice clouds, (b) optically thick ice clouds, and (c) multi-layer clouds during August 2015.”

[32 pp.] A caption of Table 4, and categories in Table 4: “Comparison of max(Hc) (min(Hc)) to the CALIOP CTH (CALIOP CBH) for all cloud pixels and three cloud regimes; single-layered optically thin ice clouds, optically thick ice clouds and multi-layered clouds for August, 2015.”

(4) line 18: “become larger” – Cite how large here.

The range of biases of single-layer optically thick ice clouds and multi-layered clouds are specified as follows.

[line 19–20] "For optically thick and multi-layered clouds, the biases of the estimated cloud heights from the cloud top/base become larger (0.30/–1.71 km, 1.41/–4.64 km)."

(5) Section 1 Introduction – In general, I think it would be helpful to the reader if the authors put the need for their scheme into better perspective. For example, it would be helpful to know from the outset under what circumstances non-window schemes, such as CO2 -slicing, can and cannot be used for the same purpose. Likewise, is the scheme suggested in the current study expected to provide an advantage over CO2 -slicing (a) because there an issue of availability of appropriate channels for implementing CO2 -slicing with wide enough spatial and temporal coverage, (b) because there is some issue of reliability with the CO 2 -slicing technique, (c) because CO 2 -slicing suffers from similar biases in that the cloud is assumed to be at a single altitude and to possess a single temperature, or (d) because the current scheme is just simpler? See also my comment number 14.

Response: We revised introduction as you suggested. [lines 25–35] "Satellite sensors provide data daily that are essential for determining global cloud properties, including cloud height/pressure/temperature, thermodynamic phase (ice or liquid water), cloud optical thickness, and effective particle size. These variables are essential for understanding the net radiation of the earth and the impact of clouds (L'Ecuyer et al. 2019). In particular, cloud heights at the top and base levels are necessary to determine upwelling and downwelling infrared (IR) radiation (Slingo and Slingo, 1988; Baker, 1997; Harrop and Hartmann; 2012). Additionally, cloud heights are used to derive atmospheric motion vectors that are important for most global data-assimilation systems (Bouttier and Kelly, 2001) affecting the accuracy of the global model forecast (Lee and Song, 2018). However, in most operational retrievals of cloud properties, only a single cloud height is inferred for a given pixel, or field of view. The goal of this study is to develop an algorithm to infer cloud height boundaries for semi-transparent ice clouds using only IR measurements for its applicability of global data regardless of solar illumination. Where this study could provide the most benefit is for the case where an ice

cloud is geometrically thick but optically thin."

[lines 61–73] "There is a retrieval approach to infer optically thin cloud-top pressure that uses multiple IR absorption bands within the 15-μm CO2 band (e.g., Menzel et al. 2008; Baum et al. 2012), called the CO2 slicing method. These 15-μm CO2 band channels are available on the Terra/Aqua MODIS imagers, the HIRS sounders, and with any hyperspectral IR sounder (IASI, CrIS, AIRS). MODIS is the only imager where multiple 15-μm CO2 channels are available. Zhang and Menzel (2002) showed improvement of the retrieval of ice cloud height when they take into account spectral cloud emissivity that has some sensitivity to the cloud microphysics. As the goal of our work is to develop a reliable method for inferring ice cloud height from geostationary data, we are limiting this study to the use of the relevant IR channels, i.e., measurements at 11- 12-, and 13.3-μm. To complement the use of IR window channels, the addition of a single IR absorption channel, such as one within the broad 15-μm CO2 band, has been shown to improve the inference of cirrus cloud temperature (Heidinger et al., 2010). Their study shows how adding a single IR absorption channel at 13.3 μm to the IR 11- and 12-μm window channels decreases the solution space in an optimal estimation retrieval approach and leads to closer comparisons in cloud height/temperature with CALIPSO/CALIOP cloud products."

(6) lines 77-78: Briefly mention what scheme is used to retrieve cloud emissivity in the C6 MYD06 product.

Response: We mentioned briefly explanation how cloud emissivity for each band was retrieved in the C6 MYD06 product, as follows.

[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)"

(7) line 115: “a parameterization is adopted” – I believe that at these wavelengths, where scattering (by molecules) is negligible, exp($-\ \kappa$z/μ) is considered an accurate expression for the transmissivity based on the Beer-Lambert law and not a parameterization.

Response: The text “a parameterization is adopted” has been removed and revised the sentence as below.

[lines 157–158] To relate the effective emissivity between two channels, Inoue uses the relation of the cirrus emissivity to the optical thickness.

(8) line 118: “the quantity κz/μ is called the optical thickness...” – I believe that κz is considered to be the optical thickness, rather than κz/μ.

Response: You are correct. The sentence now states; [line 160] “..the quantity κz is called the optical thickness and is also wavelength dependent.”

(9) line 139: Tc is already in bold font, but it would be a good idea to emphasize in the text that this is a vector of possible values of cloud temperature rather than a single value.

Response: We emphasize Tc is a vector, not a single value in the text.

[lines 186–188] “The cloud layer temperature ranges, Tc, are estimated as a vector of possible Tc values given a range of the ec and Δec (hereafter, ec and Δec) 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).”

(10) lines 151-152: In other words, one does not need to assume a ratio of cloud optical depths between the two channels, such as the ratio 1.08 in Equation 5, or is there some similar implicit assumption?

Response: Your interpretation is correct, and there is no implicit assumption either. To clarify the meaning of the sentence on lines 151-152, we revised them as the sentences

on lines 193-197.

[lines 203-207] “The third step is to find Tc values that satisfy the three equations, i.e., Eq. (2) at 11 μm, Eq. (2) at 12 μm, and the equation for cloud emissivity differences (Eq. (4)) between 11 and 12 μm with constraints in ec|11 and Δec|11,12. That is, the last equation among the three equations in our method is different from Inoue’s method (Eq. (5)) where e_c |_11=e_c |_12+ ãĂŰ∆eãĂŮ_c |_(11,12). (6)”

(11) line 155: “we obtain two T c values...” – Actually, a list of possible Tc values, including the minimum and maximum possible values, is obtained, correct?

Response: You definitely understand our intention. We clarify the sentence as below.

[lines 209–211] “That is, we obtain two Tc values as the minimum and maximum temperatures that an ice cloud pixel can have, corresponding to min/max(Δec|11,12).”

(12) lines 156-157: “... by a dynamical lapse rate...” – Does this mean that it is assumed that Tc varies within the cloud layer, or does the lapse rate only apply to the atmospheric layers outside of the cloud layer?

Response: We used the expression of ‘a dynamical lapse rate’ for an antonym of ‘a fixed lapse rate’ in the text. We added how we calculated a dynamical lapse rate in this study.

[lines 212-213] “The dynamical lapse rate on each grid is calculated from differences in temperatures between 200 and 400 hPa per differences in heights between 200 and 400 hPa.”

(13) line 158: “any cloud height is not allowed...” – “no cloud height is allowed...”

Response: Corrected as noted.

[lines 214] “In this study, no cloud height is not allowed to be higher than tropopause, which is provided in the GFS NWP model product.”

(14) lines 163-166: “In fact, ... day and night.” – These sentences belong in the Introduction. Refer also to my comment number 5.

Response: These lines are changed in the introduction as below.

[lines 32–34] “The goal of this study is to develop an algorithm to infer cloud height boundaries for semi-transparent ice clouds using only IR measurements for its applicability of global data regardless of solar illumination.”

(15) lines 97-98: “... based on an empirical relationship...” – Does this mean that the authors’ Equation 4 is not used, or is the empirical relationship related to Equation 4?

Response: We removed this expression that would give confusions to readers.

(16) lines 264-266: “It is interesting that...” – I think that this should be emphasized better. It is not an interesting side note but an impressive demonstration of the concept suggested in this paper.

Response: We changed the word “interesting” to “remarkable” and added the sentence as below.

[lines 314–316] “It is remarkable that the max(Hc) corresponding to uncertainties of cloud emissivity tends to occur at or slightly above the cloud top as indicated by CALIPSO, higher than the EEL and MODIS CTH. The max(Hc) on the cloud edges and the edges of the eye of the Goni varied from the base of cloud mask and tropopause height.”

[lines 317–319] “These results show the feasibility of inferring single-layered ice cloud boundaries from spectral cloud emissvity and its uncertainties by IR measurements.”

(17) line 266: “... and the eye of the Goni...” – It does not seem that there are data points right in the eye, only at the edges of the eye, correct? Also “scattered from” is not the best wording here and throughout the discussion.

Response: we changed “the eye of the Goni” to “surrounding the eye of Goni”, and

“scattered” to “varied”

[lines 319–321] “The max/min(Hc) on the cloud edges and the edges of surrounding the eye of the Goni have relatively large biases from the top/base of the cloud.”

(18) lines 267-269: Again, I think the success of the authors’ method should be emphasized better here. These sentences explain the difference between the results of their method and the other data in the regions of the cloud edges and the eye of the hurricane. However, given that the left side of the image appears to contain multiple cloud layers that are likely moving, the fact that the authors’ results and the CALIOP VFM data exhibit similar variation and similar values near the tropopause actually demonstrates a rather decent qualitative correspondence between the two.

Response: We changed some expressions and added the sentence to emphasize our results as below.

[lines 313–322] “Note that the max(Hc) (blue circles) is close to the top of clouds except in the region of cloud edges and the eye of Goni. Bias between the cloud top and the max(Hc) is 0.46 km, that is –4.5 K in the aspect of temperature. It is remarkable that the max(Hc) corresponding to uncertainties of cloud emissivity tends to occur at or slightly above the cloud top as indicated by CALIPSO, higher than the EEL and MODIS CTH. The height of the min(Hc) (green circles) also follows the base of the cloud layer with a bias of -1.58 km (10.6 K in temperature), slightly lower than EEL and MODIS CTH. These results show the feasibility of inferring single-layered ice cloud boundaries from spectral cloud emissvity and its uncertainties by IR measurements. The max/min(Hc) on the cloud edges and the edges of surrounding the eye of the Goni have relatively large biases from the top/base of the cloud. Those regions show relatively large STD(Iobs|11) and small COT and contain multiple clouds. To sum up, our resulting cloud heights corresponding to cloud emissivity uncertainties are likely to exhibit similar variations to the CALIOP VFM, except the cloud edges and multiple cloud regions.”

(19) lines 278-279: Once again, I think the success of the authors' method should be emphasized better here. The bias for min(Hc) from the cloud base is larger than that of optically thin clouds, but it is still better than the EEL, which is what would have been predicted.

Response: We changed the sentence as below.

[lines 331-332] "The bias for min(Hc) from the cloud base is larger than that of optically thin clouds, –2.69 km (19.4 K), but the min(Hc) still exhibit similar variation to CALIOP VFM."

(20) line 315: "... minimum value" – Was "maximum value" intended here?

Response: Good catch. We correct the sentence which you pointed out.

[lines 373–375) "This implies that maximum value of cloud height ranges corresponding to ec and Δec are close to the cloud top for single-layer clouds as determined from CALIOP."

(21) Figures 6-8: The orange contours are barely visible. Perhaps they are not necessary to include. Also, a closing parenthesis seems to be missing from the end of each of the three figure captions.

Response: Corrected as you suggested from Fig. 6–Fig. 7 as below. However, we keep the Fig. 8 as the previous version, since there are some water cloud pixels as the multi-layered clouds.

Please also note the supplement to this comment:
https://www.atmos-meas-tech-discuss.net/amt-2019-148/amt-2019-148-AC2-supplement.pdf

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