

In this manuscript, a relatively simple scheme for inferring the location of the upper and lower boundaries of clouds based
5 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.

10 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
15 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

20 **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

25 **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
30 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
35 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
40 (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

45 *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).

50 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.”*

60 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)*

65 [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.”*

70 [lines 368–370] *“Fig. 9 shows the joint histogram of the max/min(H_c) (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(H_c) (min(H_c)) 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.”*

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

Response: 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

90 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 CO₂ -slicing technique, (c) because CO₂ -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.

95 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:

$$e_c = (I_{obs} - I_{ctr}) / (I_{ac} + T_{ac}B(T_c) - I_{ctr}). \quad (7)''$$

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(7) line 115: “a parameterization is adopted” – I believe that at these wavelengths, where scattering (by molecules) is negligible, $\exp(-\kappa z/\mu)$ 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.

135

[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 $\kappa z/\mu$ is called the optical thickness...” – I believe that κz is considered to be the optical thickness, rather than $\kappa z/\mu$.

140

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: T_c 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.

145

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

[lines 186–188] “The cloud layer temperature ranges, T_c , are estimated as a vector of possible T_c values given a range of the e_c and Δe_c (hereafter, e_c and Δe_c) such as $e_c = [e_c^1, e_c^2, \dots, e_c^n]$ and $\Delta e_c = [\Delta e_c^1, \Delta e_c^2, \dots, \Delta e_c^n]$ as shown in Fig. 2(b).”

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(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.

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[lines 203-207] “The third step is to find T_c 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 $e_{c|11}$ and $\Delta e_{c|11,12}$. That is, the last equation among the three equations in our method is different from Inoue’s method (Eq. (5)) where

$$e_{c|11} = e_{c|12} + \Delta e_{c|11,12}. \quad (6)$$

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

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

165

[lines 209–211] “That is, we obtain two T_c values as the minimum and maximum temperatures that an ice cloud pixel can have, corresponding to $\min/\max(\Delta e_{c|11,12})$.”

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

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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.”

175

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

Response: Corrected as noted.

180

[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.

185

[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.*”

190

(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.

195

(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.

200

[lines 314–316] “*It is remarkable that the $\max(H_c)$ 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 $\max(H_c)$ 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 emissivity and its uncertainties by IR measurements.*”

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(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”

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[lines 319–321] “*The $\max/\min(H_c)$ 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.*”

215

(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.

220 [lines 313–322] “Note that the $\max(\mathbf{H}_c)$ (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 $\max(\mathbf{H}_c)$ is 0.46 km, that is -4.5 K in the aspect of temperature. It is remarkable that the $\max(\mathbf{H}_c)$ 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 $\min(\mathbf{H}_c)$ (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 emissivity and its uncertainties by IR measurements. The $\max/\min(\mathbf{H}_c)$ 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 $STD(I_{obs}|_{11})$ 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.”

230 (19) lines 278-279: Once again, I think the success of the authors’ method should be emphasized better here. The bias for $\min(\mathbf{H}_c)$ 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.

235 [lines 331-332] “The bias for $\min(\mathbf{H}_c)$ from the cloud base is larger than that of optically thin clouds, -2.69 km (19.4 K), but the $\min(\mathbf{H}_c)$ 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.

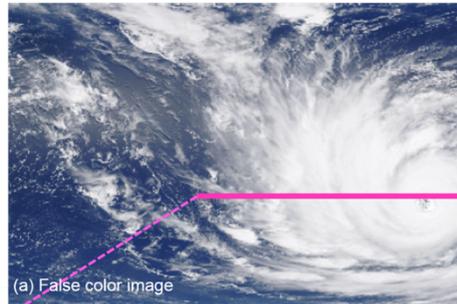
240 [lines 373–375] “This implies that maximum value of cloud height ranges corresponding to e_c and Δe_c are close to the cloud top for single-layer clouds as determined from CALIOP.”

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

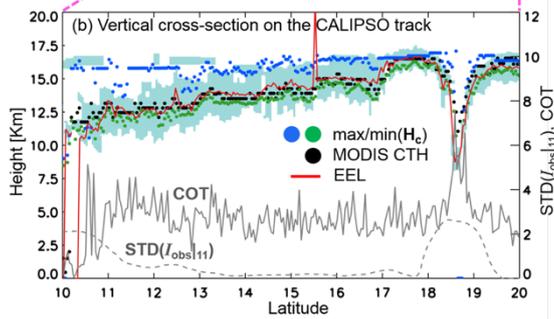
Response: Corrected as you suggested from Fig. 6–Fig. 7 as below. However, we keep the Fig. 8 as the previous version, since
there are some water cloud pixels as the multi-layered clouds.

Fig. 6)

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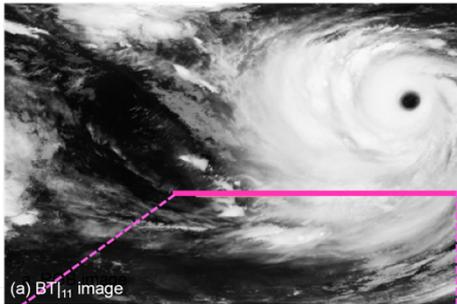


260

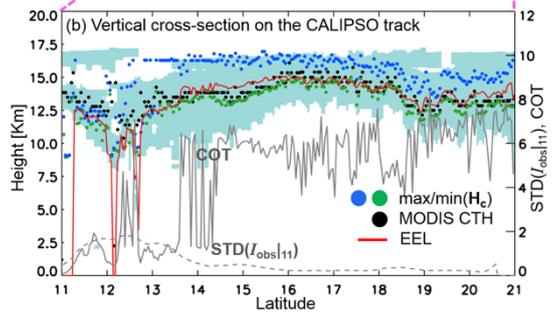
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Fig. 7)

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General comments: This paper described a method to estimate the height of ice clouds from satellite measurements of three infrared channels. The paper is well written and includes useful information for researchers in the field of satellite remote sensing. However, it was difficult to understand how the vertical inhomogeneity of ice clouds was considered in this method. The reviewer concluded that additional explanation is necessary in the manuscript before AMT publication. Specific comments are addressed below.

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

(1) Page 5 line 138-140 and Fig.1: What does e_c^i ($i=1\hat{N}$ rn) in Fig.1b mean? Why e_c and T_c represent inhomogeneous layer? In the reviewer's understanding, e_c (and T_c) describes a range of possible cloud emissivity (and temperature) that can simulate the measured channel radiances assuming a homogeneous cloud layer.

Response: Modified as suggested.

[Lines 188–190] “The e_c and Δe_c 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 T_c given the e_c and Δe_c , and to examine how closely the retrieved T_c are to the actual vertical cloud structure.”

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[the caption of Figure 2, 20 pp] Figure 2: The conceptual model for (a) a plane parallel homogeneous cloud layer with no scattering, characterized by cloud emissivity (e_c) and cloud emissivity differences between two infrared channels (Δe_c) at the cloud temperature (T_c) and (b) a number of plane parallel homogeneous cloud layers (the stripes box) with a possible range of e_c and Δe_c such as $e_c = [e_c^1, e_c^2, \dots, e_c^n]$ and $\Delta e_c = [\Delta e_c^1, \Delta e_c^2, \dots, \Delta e_c^n]$ corresponding to a possible range of cloud temperature, $T_c = [T_c^1, T_c^2, \dots, T_c^n]$, where I_{clr} and B are the clear-sky radiance and the Planck's function, respectively. Arrows represent upwelling radiances.

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(2) Page7 line 197-200: I suppose that the LUT for the empirical relationship between cloud emissivity and BT/BTD is a key of the proposed method. Does the author assume the dataset MYD021KM and MYD06 provide the relationship for vertically inhomogeneous cloud layer? I think that the author should express the basic idea of your approach for inhomogeneous cloud layer in the manuscript.

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Response: The LUTs for the relationship between cloud emissivity and BT/BTD were constructed using MYD021KM and MYD06 products. Even MYD06 products are retrieved under the assumption of the single-layer cloud, they are useful to express uncertainties in cloud emissivity due to diverse cloud microphysical properties that are likely to exist in the vertical cloud structure.

Thus, we explicitly stated that vertical inhomogeneity was not considered in the generated LUTs and also explained how those LUTs can work to infer uncertainties in cloud emissivity in the vertical cloud structure in the revised manuscript as below.

310

[Lines 261–267] “Note that the cloud emissivity data from C6 MYD06 are retrieved under the assumption of the single-layered cloud. Here the possible ranges of e_c and Δe_c are determined as the min/max(e_c) and (Δe_c) among cloud emissivity values allocated by the bins of three parameters. To exclude extreme values, the min/max(e_c) and (Δe_c) are defined as the 2nd /98th percentiles of the e_c and Δe_c 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(e_c) and (Δe_c). In the rare case when there are between

315

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.”

320 (3) Page 8 line 233-237 and Fig.5: The reviewer could not understand what does the author intend to show in Fig.5a and 5b. What does the region of large differences of $I_{\text{clr}|11}$ - $I_{\text{clr}|12}$ in Fig.5b suggest?

Response: Our intent for Figs. 5a and 5b (Fig. 1a and Fig. 1b in the revised manuscript) is (hopefully) more clear in the text and replicated as follows.

325 [lines 126–137] “The MODIS pixels identified as being clear-sky are used to generate a gridded clear-sky map, which is another ancillary product required for our method. To simplify the generation of this map, the MODIS data with 1km resolution are converted to 5 km resolution. Monthly composites of clear-sky radiances (I_{clr}) at $0.1^\circ \times 0.1^\circ$ resolution are generated by choosing the maximum value among radiances for three months of August (2013–2015) in each $0.1^\circ \times 0.1^\circ$ grid box. To confirm the availability of the generated I_{clr} , we present the spatial distribution of I_{clr} at $11 \mu\text{m}$ ($I_{\text{clr}|11}$, Fig. 1(a)), from 8 to $11 \text{ W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$. The largest $I_{\text{clr}|11}$ values are shown over the northwestern region of the domain, whereas the smallest $I_{\text{clr}|11}$ values are shown over the southeastern region of the domain. The pattern of $I_{\text{clr}|11}$ is similar to the spatial distribution of the monthly average of sea surface temperature in 2015 (<https://bobtisdale.wordpress.com/2015/09/08/august-2015-sea-surface-temperature-sst-anomaly-update/>). Also, we show the spatial distribution of differences of $I_{\text{clr}|11}$ from $I_{\text{clr}|12}$ in Fig. 1(a), examining the reliability of the generated $I_{\text{clr}|12}$. Note that the differences of $I_{\text{clr}|11}$ and $I_{\text{clr}|12}$ are positive over the domain, because water vapor absorption is stronger at $12 \mu\text{m}$ than at $11 \mu\text{m}$. Large differences are shown in the western region, near the Philippines (green-colored contours in Fig. 1).”

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(4) Page 22 Fig.6b and Page 8 Fig.8b: What is the enhancement of EEL at latitude 15.6° of Fig. 6b? Similar enhancement is also appeared at latitude 25.7° in Fig. 8b.

Response: Added the explanation about the enhancement of EEL shown in Fig. 6b and Fig. 8b, as detailed below.

340 [Line 311–312] The enhancement of EEL at approximately 15.6°N in Fig. 6(b) is caused by an extraordinary value of Q_e provided in the CALIOP V4.

[Line 340–341] The enhancement of EEL at around 25.7°N in Fig. 8(b) is also caused by an extraordinary value of Q_e provided in the CALIOP V4 product.

345

[Reviewer #3]

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 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 ϵ_c ?, what is the meaning of permissible ϵ_c ?, 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 $\min(H_c)$ and CALIOP base height in Figure 9?. The English also needs to be improved.

360

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

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

Response: Done.

370

[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.*”

375

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.

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

Response: The text was changed as follows:

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[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.*”

390

4. L140: Are ϵ_c and ΔU 's, ϵ_c 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 ϵ_c 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:

$$e_c = (I_{\text{obs}} - I_{\text{ctr}})/(I_{\text{ac}} + T_{\text{ac}}B(T_c) - I_{\text{ctr}}). \quad (7)$$

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, \mathbf{T}_c , are estimated as a vector of possible T_c values given a range of the e_c and Δe_c (hereafter, e_c and Δe_c) such as $e_c = [e_c^1, e_c^2, \dots, e_c^n]$ and $\Delta e_c = [\Delta e_c^1, \Delta e_c^2, \dots, \Delta e_c^n]$ as shown in Fig. 2(b). The e_c and Δe_c 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 T_c given the e_c and Δe_c , and to examine how closely the retrieved T_c are to the actual vertical cloud structure.

The differences between this study and Inoue (1985) are summarized as follows.

1. 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.
2. Emissivity differences (Δe_c) are used, rather than a single value for the extinction coefficient ratio between two infrared channels.
3. Given the range of emissivity differences (Δe_c provided in LUTs), we obtain a range of T_c (and hence a range of cloud heights, \mathbf{H}_c) that can be compared to CALIPSO products.

The first step in the current method (Fig. 3) is to constrain 11- μm cloud emissivity ranges ($e_{c|11}$) that an ice cloud pixel can have based on the brightness temperatures. To obtain a reasonable $e_{c|11}$ boundary corresponding to the ice cloud microphysical properties, the LUTs are generated to provide $e_{c|11}$ 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 e_c and Δe_c 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:

$$e_c = (I_{\text{obs}} - I_{\text{ctr}})/(I_{\text{ac}} + T_{\text{ac}}B(T_c) - I_{\text{ctr}}). \quad (7)$$

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
435 retrieved under the assumption of the single-layered cloud. Here the possible ranges of e_c and Δe_c are determined as the min/max(e_c) and (Δe_c) among cloud emissivity values allocated by the bins of three parameters. To exclude extreme values, the min/max(e_c) and (Δe_c) are defined as the 2nd /98th percentiles of the e_c and Δe_c 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(e_c) and (Δe_c). In the rare case when there are between only 200 and 500 pixels, the 10th /90th percentiles are used.
440 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).

445 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.”

450

9. What are authors’ view for deviated CBH and min(H_c)?

Response: The vector, H_c , 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.

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

Response: Again, our products, H_c , provide a possible range of cloud heights for the observed channel radiances. H_c 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 strengthened by referring past studies and/or putting authors’ own logic.

460 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(H_c) to the mean(CALIOP H_c) that are defined as $0.5 \cdot (\max(H_c) + \min(H_c))$ and as $0.5 \cdot (\text{CALIOP CTH} + \text{CALIOP CBH})$, respectively. Fig. 10 shows the frequency of occurrence of biases, that is, the mean(CALIOP H_c) minus the mean(H_c), 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 $\text{COT} \geq 0.5$ in x-axis of Fig. 10.

470 Fig.10 illustrates that our resulting single-layer ice clouds boundaries are consistent with CALIOP measurements, showing slightly negative biases except the region near ‘ $\text{COT} \leq 1.5$ ’. 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).

475 *The negative biases of the mean(H_c) from CALIOP measurements are caused primarily by two factors: (1) The min(H_c)*
values for all cloud regimes tend to be higher than geometric cloud base, and (2) The max(H_c) 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
480 *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
485 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(H_c).

490 13. Figure 1: Make the caption clear. Write about Iclr and B in the caption.
Response: Done as below.

Response:

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

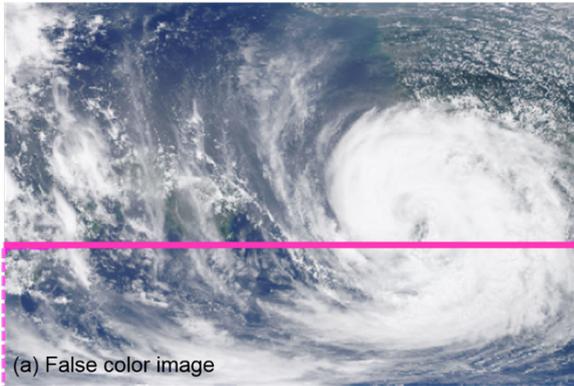
[21 pp.] *“Figure 3: A flowchart for estimation of T_c and H_c corresponding to e_c (from a light gray box that will be shown in*
Fig. 3) and Δe_c (from a dark gray box that will be shown in Fig. 4) which represent cloud microphysics uncertainty in a certain
cloud thickness. We denoted functions for minimum/maximum values of a matrix, A , as $\min/\max(A)$.”

500

15. If COT is not used here, why do you use COT for y-axis title?

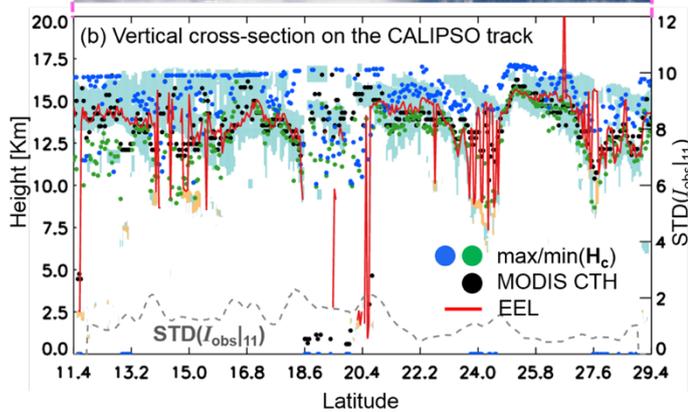
Response: We removed the COT for y-axis title at the right side in Fig. 8, as below.

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

530 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 $\leq 260K$."

535

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.

540

Use of spectral cloud emissivity emissivities and their related uncertainties to infer ice cloud boundaries: Methodology and assessment using CALIPSO cloud products

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Abstract. Satellite imager-based operational cloud heightproperty retrievals generally assume that a cloudy pixel can be treated
550 as being plane-parallel with horizontally homogeneous cloud exists in each field of regard, or pixel, but thisproperties. This
assumption ignores vertical inhomogeneity, which is of particular importance can lead to high uncertainties in cloud heights,
particularly for the case of optically thin, but geometrically thick, ice-clouds composed of ice particles. 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. Here ice cloud emissivity uncertainties are obtained for three IR channels centered at 11, 12,
555 and 13.3 μm . The range of cloud emissivities is used to infer a range of ice cloud temperature/heights, rather than a single
value per pixel as provided by operational cloud retrievals. Our methodology is tested using MODIS observations over the
western North Pacific Ocean during August 2015. We estimate minimum/maximum heights for three cloud regimes, i.e.,
single-layerlayered optically thin ice clouds, and single-layered optically thick ice clouds, and multi-layered clouds. Our results
are assessed through comparison with CALIOP Version 4 cloud products for a total of 11873 pixels. The cloud boundary
560 heights for single-layerlayered optically thin clouds show good agreement with those from CALIOP; biasbiases for maximum
(minimum) heights versus the cloud top (base) heights of CALIOP are 0.13 km (–1.01 km). 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). The vertically resolved boundaries for ice clouds can contribute new information for data assimilation efforts for weather
prediction and radiation budget studies. Our method is applicable to measurements provided by most geostationary weather
565 satellites including the GK-2A advanced multi-channel infrared imager. The vertically resolved heights for ice clouds can
contribute new information for studies involving weather prediction and cloud radiative effects.

1 Introduction

In this study, we develop an algorithm to infer cloud height for ice clouds using only infrared (IR) measurements for its
applicability of global data regardless of solar illumination. Although the Satellite sensors provide data daily that are essential
570 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.

Although our approach will be applied to geostationary satellites in future work, the algorithm is developed for the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor for two reasons: (1) our resulting cloud temperatures can be compared to those from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation/Cloud-Aerosol Lidar with Orthogonal Polarization (CALIPSO/CALIOP) active lidar Version 4 products for verification and (2) further comparison can be made to the MODIS Collection 6 cloud products. The approach adopted in our study for the inference of ice cloud height has a basis in the work of Inoue (1985), who developed this approach using only the split-window channels on the Advanced Very High Resolution Radiometer (AVHRR). The goal of the Inoue (1985) approach was to improve the inference of cloud temperatures for semi-transparent ice clouds. Heidinger and Pavolonis (2009) further improved this approach and generated a 25-year climatology of ice cloud properties from AVHRR analysis.

For satellite-based cloud height retrievals based on passive IR measurements, the radiative emission level is regarded as the cloud top. When the emissivity is 1, the cloud is emitting as a blackbody and the cloud top is at, or close to, the actual cloud's upper boundary. As the emissivity decreases, the cloud top inferred from IR measurements will be lower than the actual cloud top level. This is demonstrated in Holz et al. (2006), who ~~compare~~compared the cloud tops from aircraft Scanning High-Resolution Interferometer Sounder (S-HIS) measurements to those from co-incident measurements from the Cloud Physics Lidar (CPL). They ~~find~~found that the best match between the cloud tops based on the passive S-HIS measurements and the CPL ~~occurs~~occurs when the integrated cloud optical thickness is approximately 1. This implies that the differences of cloud ~~top~~stop heights by IR measurements from those by CALIOP are expected since the IR method reports the height where the integrated cloud optical thickness, beginning at cloud top and moving downwards into the cloud, is approximately 1 while CALIOP reports the actual cloud top to be where the first particles are encountered.

With regard to geometric differences of IR cloud tops from the actual cloud tops, optically thin but geometrically thick clouds show the largest bias, since the level of which the integrated optical thickness reaches 1 is much lower than the height at which the first ice particles occur. In a review of different ten satellite retrieval methods for cloud top heights by IR measurements (Hamann et al., 2014), the heights inferred for optically thin clouds are generally below the cloud's mid-level height. When lower-level clouds are present below the cirrus in a vertical column, the inferred cloud height can be between the cloud layers, depending on the optical thickness of the uppermost layer.

605 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
610 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, ~~can~~has been shown to improve the inference of cirrus cloud temperature (Heidinger et al., 2010). Their study
615 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.

~~There are also retrieval approaches that use multiple IR absorption bands within the 15- μm CO₂ band (e.g., Menzel et al. 2008; Baum et al. 2012). Zhang and Menzel (2002) showed improvement of the retrieval of ice cloud height when they take~~
620 ~~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 .~~

Rather than ~~infer~~inferring a single ice cloud temperature in each pixel, we ~~first~~ infer a range of ice cloud temperatures (minimum to maximum temperature per each ice cloud pixel) that correspond to uncertainties in the cloud spectral emissivity.
625 We note that the spectral cloud emissivity, which can be obtained using measurements at 11, 12, and 13.3 μm , has some dependence on the ice cloud microphysics. 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 profiles. Cloud boundary results are presented for three cloud categories, i.e., single-~~layer~~layered optically thin ice clouds, single-layered optically thick ice clouds, and multi-layered clouds, and these results are
630 assessed with measurements from a month of collocated CALIOP Version 4 data. The focus area for the data analysis and resulting analyses is the western North Pacific Ocean for the month of August 2015.

The paper is organized as follows. Section 2 ~~discusses~~describes the data ~~and used in this study~~. Section 3 presents the methodology and the generation of the relevant look-up tables (LUTs) for the radiances/ and brightness temperatures used in our analyses. Section 3.4 provides results for the western North Pacific Ocean during August 2015, and comparisons with
635 CALIOP. Section 4.5 discusses the results and Section ~~5~~concludes. 6 summarizes this paper.

2 Data and Methodology

2.1 AQUA Study domain

640 The study domain is the western North Pacific Ocean (0°N–30°N, 120°E–170°E) during three months of August from 2013–2015. Two of these months (August 2013 and August 2014) are used for generating the LUTs, while the month of August in 2015 is used for testing and validating the current algorithm. The reason for restriction of the study domain is to obtain a clear relationship between radiances/brightness temperatures and spectral cloud emissivity. In the western North Pacific Ocean, the ice clouds can be generated from diverse meteorological conditions including frequent typhoons.

2.2 Aqua/Moderate Resolution Imaging Spectroradiometer (MODIS)

645 The MODIS is a 36-channel whisk-broom scanning radiometer on the NASA Earth Observing System Terra and Aqua platforms. The Aqua platform is in a daytime ascending orbit at 1330 LST. The MODIS sensor has four focal planes that cover the spectral range 0.42–14.24 μm . The longwave bands are calibrated with an onboard blackbody. The Table 1 shows the Aqua MODIS products used in this study; these products include the Collection 6 1-km Level-1b radiance data (MYD021KM), geolocation data (MYD03), and the cloud properties at 1-km resolution (MYD06). In this study, the radiances and brightness temperatures at 11, 12, and 13.3 μm (channels 31, 32, and 33, respectively) are taken from the C6 MYD021KM data. Latitude/longitude information for each granule is from C6 MYD03. The C6 MYD06 product provides cloud emissivity values in the IR window (8.5, 11, and 12 μm) and also cloud top height (CTH), all at 1-km spatial resolution; these parameters were not included in earlier collections (Menzel et al., 2008; Baum et al., 2012). The cloud emissivities at 11 and 12 μm are used in this study.

2.2.3 CALIPSO/CALIOP

655 The CALIPSO satellite platform carries several instruments, among which is a near-nadir-viewing lidar called CALIOP (Winker et al. 2007, 2009). Originally, CALIPSO flew in formation with NASA's Earth Observing System Aqua platform since 2006 and was part of the A-Train suite of sensors. At the time of this writing, it is no longer part of the A-Train but flies in formation with CloudSat in a lower orbit. CALIOP takes data at 532 and 1064 nm. The CALIOP 532-nm channel also measures the linear polarization state of the lidar returns. The depolarization ratio contains information about aerosol and cloud properties. This study uses CALIPSO Version 4 products that were released in November 2016. With the updated radiometric calibration at 532 and 1064 nm (Getzewich et al., 2018; Vaughan et al., 2019), cloud products such as cloud-aerosol discrimination and extinction coefficients show significant improvement relative to previous versions (Young et al., 2018; Liu et al., 2019). CALIPSO products are used to validate our retrievals, including CAL_LID_L2_VFM-Standard-V4 which provides cloud vertical features, CAL_LID_L2_05kmCPro-Standard-V4 and CAL_LID_L2_05kmCLay-Standard-V4 which provide cloud top and base temperature (height), extinction coefficients and temperature profiles (Table 1).

665

2.34 Numerical weather model product

The Global Forecast System (GFS) model is produced by the National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) (Moorthi et al. 2001). GFS provides global ~~Numerical Weather Prediction (NWP) model output/outputs~~ at 0.5° resolution at 3-hour forecast intervals every 6 hours: that are available online (<https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forecast-system-gfs>). We use two variables from the NWP ~~product/products~~, temperature profiles and geopotential heights, with cloud heights provided for 26 isobaric layers that are related to cloud temperatures. These data are used for the conversion of cloud temperatures to cloud heights. The NWP fields are remapped to the resolution of satellite imagery ~~and also interpolated to the~~ by linear interpolation. We use the NWP products that are closest in time ~~corresponding~~ to the satellite ~~observation times~~ observations.

2.42.5 Clear-sky maps generated from MODIS

The MODIS pixels identified as being clear-sky are used to generate a gridded clear-sky map, which is another ancillary product required for our method. To simplify the generation of this map, the MODIS data with 1km resolution are converted to 5 km resolution. Monthly composites of clear-sky radiances (I_{clr}) at 0.1°×0.1° resolution are generated by choosing the maximum value among radiances for three months of August (2013–2015) in each 0.1°×0.1° grid box. To confirm the availability of the generated I_{clr} , we present the spatial distribution of I_{clr} at 11 μm ($I_{clr|11}$, Fig. 1(a)), from 8 to 11 $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$. The largest $I_{clr|11}$ values are shown over the northwestern region of the domain, whereas the smallest $I_{clr|11}$ values are shown over the southeastern region of the domain. The pattern of $I_{clr|11}$ is similar to the spatial distribution of the monthly average of sea surface temperature in 2015 (<https://bobtisdale.wordpress.com/2015/09/08/august-2015-sea-surface-temperature-sst-anomaly-update/>). Also, we show the spatial distribution of differences of $I_{clr|11}$ from $I_{clr|12}$ in Fig. 1(a), examining the reliability of the generated $I_{clr|12}$. Note that the differences of $I_{clr|11}$ and $I_{clr|12}$ are positive over the domain, because water vapor absorption is stronger at 12 μm than at 11 μm . Large differences are shown in the western region, near the Philippines (green-colored contours in Fig. 1).

3 Methodology

3.1 Cloud retrieval algorithm

The basis for the retrieval algorithm is provided in Inoue (1985). Figure 42(a) shows the plane parallel homogeneous cloud model with no scattering. The ice cloud layer at a given height has a corresponding ice cloud temperature (T_c) and an associated cloud emissivity (e_c). The observed upwelling radiance (I_{obs}) at the cloud top is composed of two terms: the first depending on the upwelling clear-sky radiance (I_{clr}) at the cloud base and the other depending on the radiance ($B(T_c)$) computed for a cloud emitting as a blackbody:

$$I_{obs} = (1 - e_c)I_{clr} + e_c B(T_c), \quad (1)$$

where $B(T_c)$ is the Planck emission for a cloud computed at T_c (Liou, 2002). All terms in Eq. (1) are wavelength dependent except for the T_c . I_{obs} is determined from the satellite measurements, and I_{clr} can be found from clear-sky conditions in the imagery or computed by a radiative transfer model given a set of atmospheric profiles of temperature, humidity, and trace gases. However, e_c and T_c are unknown.

700 Eq. (1) can be rearranged to solve for the emissivity:

$$e_c = (I_{obs} - I_{clr}) / (B(T_c) - I_{clr}). \quad (2)$$

One can relate two channels by taking a ratio of the radiances, similar to that of the CO₂ slicing method (e.g., Menzel et al. 2008) and assuming that the emissivity between two channels spaced closely in wavelength are the same. However, Zhang and Menzel (2002) showed improvement of the retrieval of ice cloud pressure by accounting for differences in the spectral cloud emissivity.

705

Inoue (1985) discusses the range of uncertainties in both T_c and e_c and further suggests that use of multiple IR channels can reduce the uncertainties. To relate the effective emissivity between two channels, ~~a parameterization is adopted that relates~~Inoue uses the relation of the cirrus emissivity to the optical thickness. The e_c is a function of the absorption coefficient (κ) and the cloud thickness (z),

710
$$e_c = 1 - \exp^{-\kappa z / \mu}. \quad (3)$$

The term μ in Eq. (3) is a cosine of the viewing zenith angle; the quantity $\kappa z / \mu$ is called the optical thickness and is also wavelength dependent. Given a value for e_c , the T_c can be obtained by Eq. (2). The estimate of e_c from an IR measurement will have inherent uncertainties due to the diversity of ice particle size distributions (i.e., cloud microphysics), sensor calibration, and in the cloud vertical inhomogeneity.

715 Another way to constrain these uncertainties is by using multiple IR channel measurements, specifically the spectral emissivity differences between two IR window channels (Δe_c). We can express the Δe_c between two IR channels by:

$$\Delta e_c = \exp^{-\frac{\kappa' z}{\mu}} - \exp^{-\frac{\kappa z}{\mu}}. \quad (4)$$

In Eq. (4), κ' is the absorption coefficient at 'another' IR window channel. That is, the Δe_c is determined by $(\kappa - \kappa')/z$ which depends on the cloud particle size and cloud thickness (Kikuchi et al., 2006). Many studies have adopted this, or a similar, approach to apply the representative relations of spectral cloud emissivity relying on cloud types to retrieve the T_c (e.g., Inoue, 1985; Parol et al., 1991; Giraud et al, 1997; Cooper et al, 2003; Heidinger and Pavolonis, 2009).

720

For the case of two IR channels, Inoue (1985) formulated the retrieval of the cirrus cloud temperature and effective emissivity by setting up three equations with three unknowns (specifically referring to Inoue's equations 5, 6, and 7): Two equations are same as Eq. (2) at 11 and 12 μm in this paper, and the last equation is as follows.

$$725 \quad e_{c|12} = 1 - (1 - e_{c|11})^{1.08}, \quad (5)$$

where $e_{c|11}$ and $e_{c|12}$ represent cloud emissivity for 11 and 12 μm -, respectively. In Inoue (1985), the extinction coefficient ratio between the 11- and 12- μm channels is set to a constant value of 1.08. The cloud temperature is determined by assuming a cloud emissivity at one wavelength, calculating the emissivity at the other wavelength, and modifying the emissivities until a consistent cloud temperature is found for both wavelengths. The initial assumed 11- μm cloud emissivity begins with a value of 0 and increases by a value of 0.01 until T_c converges.

Inoue's (1985) approach for developing the spectral cloud emissivity relationship improved the accuracy of the cirrus temperature retrievals. More recent studies explored the extinction coefficient ratio between the 11 and 12- μm channels for various cloud types (Parol et al., 1991; Duda and Spinhirne, 1996; Cooper et al., 2003). Heidinger et al. (2009) uses an optimal estimation method that employs extinction coefficient ratios using pairs of the 8.6, 11, 12, and 13- μm channels to infer cloud heights for GOES-16/17.

In this study, we design an approach as shown in Fig. 2 where more apply a range of spectral cloud emissivity values to infer cloud temperatures rather than two channels can be used an optimum value. In this study, we examine the feasibility for estimating ice cloud our approach, the cloud is considered as a number of plane parallel homogeneous cloud layers. The cloud layer temperature ranges, T_c , are estimated as a vector of possible T_c values given the uncertainties a range of the e_c and Δe_c (hereafter, \mathbf{e}_c and $\Delta \mathbf{e}_c$) such as $\mathbf{e}_c = [e_c^1, e_c^2, \dots, e_c^n]$ and $\Delta \mathbf{e}_c = [\Delta e_c^1, \Delta e_c^2, \dots, \Delta e_c^n]$ as shown in Fig. 1(b)-as shown in Fig. 2(b). The \mathbf{e}_c and $\Delta \mathbf{e}_c$ 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 T_c given the \mathbf{e}_c and $\Delta \mathbf{e}_c$, and to examine how closely the retrieved T_c are to the actual vertical cloud structure.

The differences between this study and Inoue (1985) are summarized as follows.

- 745 4. Constraints in the iteration range for cloud emissivity ranges (\mathbf{e}_c) in the different channels 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.
5. Emissivity differences ($\Delta \mathbf{e}_c$) are used, rather than a single value for the emissivity extinction coefficient ratio between two infrared channels.
6. Given the range of emissivity differences ($\Delta \mathbf{e}_c$ provided in LUTs), we obtain a range of T_c (and hence a range of cloud heights, \mathbf{H}_c) that can be compared to CALIPSO products.

The first step in the current method (Fig. 23) is to constrain 11- μm cloud emissivity for ranges ($e_{c|11}$) that an ice cloud pixel and use $e_{c|11}$ values that are provided in can have based on the brightness temperatures. To obtain a reasonable $e_{c|11}$ boundary corresponding to the ice cloud microphysical properties, the LUTs (the light gray box in Fig. 2). The input parameters of LUTs are generated to provide $e_{c|11}$ ranges characterized by brightness temperature (BT) for 11 μm ($\text{BT}_{|11}$), BT differences (or BTD) between 11 and 13 μm ($\text{BTD}_{|11,13}$) and between 11 and 12 μm ($\text{BTD}_{|11,12}$) (the light gray box in Fig. 3).

The second step is to constrain cloud emissivity differences between 11 and 12 μm for an ice cloud pixel, $\Delta e_{c|11,12}$ that are also provided in LUTs (the dark gray box in Fig. 23) with identical input parameters as in the first step. Then the The third step

is to find T_c values ~~that satisfy~~satisfying the three equations, i.e., ~~a solution for~~ Eq. (2) at 11 μm , Eq. (2) at ~~both 11 μm and 12 μm~~ , and ~~the equation for cloud emissivity differences (Eq. (4) using)~~ between 11 and 12 μm with constraints in $e_c|_{11}$ and $\Delta e_c|_{11,12}$. That is, the last equation among the three equations in our method is different from Inoue's method (Eq. (5)) where

$$e_c|_{11} = e_c|_{12} + \Delta e_c|_{11,12}. \quad (6)$$

The initial assumed 11- μm cloud emissivity begins with a value of $\min(e_c|_{11})$ and increases by a value of 0.01 until T_c converges. Notice that the T_c value, an element of available ice cloud temperatures set, as T_c , depends on $\Delta e_c|_{11,12}$ in Eq. (4). That is, we obtain two T_c values ~~corresponding to min/max($\Delta e_c|_{11,12}$)~~. ~~We define those two T_c values~~ as the minimum and maximum temperatures that an ice cloud pixel can have, ~~corresponding to min/max($\Delta e_c|_{11,12}$)~~. Finally, we estimate cloud height ranges, H_c , relating to $\min/\max(T_c)$ ~~by using~~ a dynamical lapse rate calculated from GFS NWP temperature profiles provided for 26 isobar layers. 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. In this study, any cloud ~~height is~~heights are not allowed to be higher than tropopause, which is provided in the GFS NWP model product.

3.2.5 Generation of look-up tables (LUTs)

For our method, relevant information for the western North Pacific Ocean is stored in look-up tables (LUTs). The LUTs include the $\min/\max(e_c)$ and $\min/\max(\Delta e_c)$ values for three indices: $\text{BTD}|_{11,13}$, $\text{BTD}|_{11,12}$, and $\text{BT}|_{11}$. The reason for selecting these three indices is that they are linked with cloud optical thickness, cloud effective radius, and cloud temperatures, respectively. ~~In fact, the vertical evolution in~~ Both solar and infrared radiances have been used to investigate cloud microphysics ~~has studied by~~ using passive satellite measurements, ~~especially using solar channels~~ (e.g., Freud et al., 2008; Lensky and Rosenfeld, 2006; Martins et al., 2011). ~~Note that further discussion of the inherent assumptions and limitations is provided in Martins et al. (2011)~~. A primary benefit of using IR measurements is that the ice cloud temperature and emissivity do not depend on solar illumination, so the cloud properties are consistent between day and night.

First, the $\text{BTD}|_{11,13}$ ~~largely depends on~~ is sensitive to the presence of mid- to high-level clouds and the cloud opacity ~~height~~. While both the 12- and 13.3- μm measurements are both affected by CO_2 absorption, the 12- μm channel is at the wing of the broad 15- μm CO_2 band and ~~is~~ has less ~~affected~~ CO_2 absorption than the 13.3- μm channel. Additionally, the peak of weighting function for the 13.3- μm ~~band~~ channel is ~~around in the vicinity of 700-800 hPa~~ so that the observed radiance at 13.3 μm represents ~~middle and low atmosphere~~ the lower tropospheric temperature. Thus, the BT at 13.3 μm is generally colder than that of the two other IR window channels. The $\text{BTD}|_{11,13}$ is larger for clear-~~sky~~ pixels than for ice clouds, but $\text{BTD}|_{11,13}$ depends on degree of cloud opacity. The $\text{BTD}|_{11,13}$ has been applied by Mecikalski and Bedka (2006) to monitor changes in cloud thickness and height for signals of convective initiation.

Second, the $\text{BTD}|_{11,12}$ depends in part on the microphysics and cloud opacity, i.e., the number and distribution of the ice particles; the imaginary part of the refractive index for ice varies in the IR region under study. The $\text{BTD}|_{11,12}$ has been used to

identify cloud type (Inoue, 1985; Pavolonis and Heidinger, 2004; Pavolonis et al.,2005). Prata (1989) used the $BTD_{|11,12}$ to discern volcanic ash from non-volcanic ash-absorbing aerosols. Recently, adding BTD from 8.6 and 11 μm , the $BTD_{|11,12}$ is also applied to infer cloud phase (Strabala et al.,1994; Baum et al., 2000, 2012).

Finally, $BT_{|11}$ values can provide cloud height information, at least for optically thick clouds including low-level clouds. For optically thick clouds, the $BT_{|11}$ values approximate the actual cloud temperature, since at 11 μm the primary absorber is water vapor and there is generally little absorption above high-level ice clouds. As noted earlier, the $BT_{|11}$ for optically thin clouds includes a contribution from upwelling radiances from the surface and lower atmosphere.

The LUTs are compiled for e_c and Δe_c by three input parameters, i.e., $BTD_{|11,13}$, $BTD_{|11,12}$, and $BT_{|11}$ from information in the C6 MODIS products. Data used in generating our LUTs are summarized in Table 1. The procedure first step is to collect all ice cloud radiances at 11, 12, and 13.3 μm from MYD021KM over the western North Pacific Ocean (~~0°N–30°N, 120°E–170°E~~) during the recurring period of the August 2013 and 2014. 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 ≤ 260 K. The spatial and temporal domain is restricted to obtain a clear relationship between spectral cloud emissivity and three IR parameters underfor the constraints of atmosphere and surface conditions. case study analyses that will be presented in Section 4.

The second step is to categorize the ensemble of ice cloud pixels with ice cloud temperature ≤ 260 K are filtered by the IR cloud phase product in MYD06. Data used in generating LUTs are summarized in Table 1. For those ice cloud pixels belonging to each category of three input parameters, the LUT uses the cloud emissivity values $BTD_{|11,13}$, $BTD_{|11,12}$, and $BT_{|11}$. The collected cloud pixels are separated into cloud types linked with cloud microphysical properties. We convert radiances centered at 11, 12, and ~~12~~13.3 μm to BT by the inverse Planck's function and stores the then calculate $BTD_{|11,13}$, $BTD_{|11,12}$, and $BT_{|11}$ for each pixel. Subsequently the ice cloud pixels are sorted into range bins defined for the three parameters as follows: $BT_{|11}$ values in a range from 190 K to 290 K in increment of ~~5~~5 K; $BTD_{|11,13}$ values in a range from -2 K to 30 K in increments of 2 K; and $BTD_{|11,12}$ values ranging from -1 K to 10 K in increments of 0.5 K (Table 2). For example, the first category is $190 \text{ K} \leq BT_{|11} < 195 \text{ K}$, $-2 \leq BTD_{|11,13} < 0$, and $-1 \leq BTD_{|11,12} < -0.5$.

The final step is to find the possible ranges of e_c and Δe_c 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:

$$e_c = (I_{obs} - I_{ctr}) / (I_{ac} + T_{ac}B(T_c) - I_{ctr}). \quad (7)$$

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 e_c and Δe_c are determined as the $\min/\max(e_c)$ and (Δe_c) among cloud emissivity values allocated by the bins of three parameters. To exclude extreme values, the $\min/\max(e_c)$ and (Δe_c) are sorted into percentiles. The $\min/\max(e_c)$ and (Δe_c) are defined as the 2nd/98th percentiles of each ice cloud emissivity distribution for the three cloud categories the e_c and Δe_c distributions when there are at least 5,000 pixels selected available for a given bin. When there are between 500 and 5000 pixels, the 5th/95th percentiles are chosen as the $\min/\max(e_c)$ and (Δe_c) . 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 pixel numbers pixels is not included in the LUTs.

Fig. 34 shows examples of LUT values for e_c belonging to the specific category for $230 \text{ K} \leq \text{BT}|_{11} < 235 \text{ K}$ (Fig. 34(a)) and $270 \text{ K} \leq \text{BT}|_{11} < 275 \text{ K}$ (Fig. 34(b)), which imply the presence of optically thick and thin ice clouds, respectively. The minimum (the left panel) and maximum (the right panel) values of the e_c are shown as colors in the space of $\text{BTD}|_{11,12}$ (x-axis) and the $\text{BTD}|_{11,13}$ (y-axis). In Fig. 34(a), the e_c values range from about 0.8 to 1.1. The e_c generally ranges from 0 to 1, but a non-physical e_c value over 1 might occur in case of an over-shooting cloud (from strong convection that briefly enters the lower stratosphere) that has colder temperature than surrounding environment temperature (Negri, 1981; Adler et al., 1983). As for optically thin clouds, the e_c values of Fig. 34(b) range from around 0.3 to 0.8. In general, e_c values are low when cloudy pixels have large values of $\text{BTD}|_{11,12}$ and $\text{BTD}|_{11,13}$.

Fig. 45 shows examples of LUT values of Δe_c for optically thick (Fig. 45(a)) and thin (Fig. 45(b)) ice clouds as shown in Fig. 34. The Δe_c ranges from -0.12 to 0.04 . The Δe_c shows a more complex relationship with $\text{BTD}|_{11,12}$ and $\text{BTD}|_{11,13}$ than with e_c does. It is notable that similar patterns Δe_c are repeated on the optically thick (Fig. 45(a)) and thin ice cloud (Fig. 45(b)). One reason for this could be that Δe_c are more sensitive to particles sizes, whereas e_c values are more directly linked with cloud opacity (refer to Eq. (3) and Eq. (4)). The optically thin ice cloud cluster tends to be more sensitive to $\text{BTD}|_{11,12}$, showing larger variations of Δe_c than the thick ice cloud cluster.

34 Results

3.1 Study domain

Both case study and monthly The current algorithm analyses are performed over the Western study domain, the western North Pacific Ocean, in August 2015. The analysis domain coincides with where MODIS data are used to populate the LUTs. In the Western North Pacific, the ice clouds can be generated from diverse meteorological conditions including frequent typhoons. Note that the typhoon ‘Goni’ formed on 13 August and dissipated on 30 August, 2015, affecting and affected East Asia. Case studies involving Typhoon Goni scenes are provided in Section 3.3.

850 3.2 Clear-sky maps generated from MODIS

855 ~~Much~~4.1. Quantitative analysis and comparison of the input and auxiliary data for the tests are available from the radiances and our results with CALIOP cloud products are described in the MODIS C6 (Table 2). The I_{obs} and BT at 11, 12, and 13.3 μm (channels 31, 32, and 32) are taken from the C6-MYD021KM data. Two ancillary data products are also necessary. One is an estimate of I_{clr} that is required in Eq. (2). The MODIS pixels identified as being clear-sky are used to generate a gridded clear-sky map, which is the second ancillary product required for our method. To simplify the generation of this map, the MODIS data are subsetted to 5 km resolution. Monthly composites of I_{clr} at $0.1^\circ \times 0.1^\circ$ resolution were generated by choosing the maximum value among radiances for three months of August (2013–2015) in each $0.1^\circ \times 0.1^\circ$ grid box. Fig. 5a presents spatial distribution of I_{clr} at 11 μm ($I_{clr|11}$, Fig. 5(a)), from 8 to 11 $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$. Then Fig. 5b presents spatial distribution of differences of $I_{clr|11}$ from $I_{clr|12}$. Large differences are shown in the western region, near the Philippines (green-colored contours in Fig. 5). Ice cloud pixels are identified using the IR cloud phase product in the MYD06, which in turn uses the MODIS cloud mask product MYD35. For each ice cloud pixel selected, application of the methodology shown in Fig. 2 results in the min/max(T_c). Section 4.2.

860 3.34.1 Comparison of min/max- $T_c(H_c)$ with CALIPSO for three granules

865 3.34.1.1 A scene for single-layered optically thin ice clouds (19 August, 2015, at 0320 UTC)

870 Figure 6 is a scene analysis for single-layered optically thin ice clouds for a granule at 0320 UTC on 19 August, 2015. Fig. 6(a) is a MODIS false color image that captures Tropical Cyclone Goni. Note that the image is rotated 90 degrees left to simplify comparison with CALIPSO. The heavy pink line (Fig. 6(a)) is the south-to-north CALIPSO track at the closest time to the MODIS observation time. The CALIPSO made a near-eye overpass of the cyclone. The CALIOP track measures a cross section of the cyclone, from the eyewall to the outer bands. Fig. 6(b) is a cross section from CALIOP data (Table 3) at the time of the overpass, that shows the horizontal (x-axis) and vertical (y-axis at the left side) locations of all cloud layers. The CALIOP vertical feature mask (VFM) indicates the presence of randomly-oriented ice and horizontally-oriented ice (sky-blue), and water (orange) cloud phase in the scene. The y-axis at the right side are is for two supplementary data shown as gray lines. The gray solid line is the CALIOP COT at 532 nm, for the opacity of ice clouds. The gray dashed line is the standard deviation of the MODIS $I_{obs|11}$ ($\text{STD}(I_{obs|11})$) on the collocated path with the CALIOP track, calculated over a 5×5 pixel array centered at each cloud pixel. The $\text{STD}(I_{obs|11})$ includes cloud feature information (Nair et al., 1998). For example, pixels at cloud edges or fractional clouds have relatively large $\text{STD}(I_{obs|11})$. The $\text{STD}(I_{obs|11})$ values are used to filter overcast cloud pixels. The data in Fig. 6 are primarily of single-layered ice clouds with horizontal homogeneity as demonstrated by the low value of $\text{STD}(I_{obs|11})$.

880 For comparison with CALIPSO, the min/max(T_c) are converted to max/min(H_c) and are shown from our method (blue/green circles) to the VFM in Fig. 6(b). Also provided is the MODIS CTH (black circles) for reference. For these comparisons, we converted temperature to height using a dynamical lapse rate from GFS NWP temperature profiles. When the cloud pixel

temperature is colder than the tropopause temperature, it is changed to be that of the tropopause and is converted to the tropopause height provided by GFS NWP. The solid red line indicates where the CALIOP COT is about 0.5. This line is a reference for the position where the passive remote sensing retrievals will place the cloud (Holz et al. 2006; Wang et al., 2014), well known as the radiative emission level. The radiative emission level should be thought of more as a guideline since the matched COT values can be different depending on cloud types or algorithm methods. To determine this depth in the cloud layer, we integrated the extinction coefficient, CALIOP Q_e (Table 3), from the top of the cloud downwards until the COT reached about 0.5. Hereafter, we call that layer as the effective emission layer, EEL. The enhancement of EEL at approximately 15.6°N in Fig. 6(b) is caused by an extraordinary value of Q_e provided in the CALIOP V4.

Note that the $\max(\mathbf{H}_c)$ (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 $\max(\mathbf{H}_c)$ is 0.46 km, that is -4.5 K in the aspect of temperature. It is interesting/remarkable that the $\max(\mathbf{H}_c)$ 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 $\max(\mathbf{H}_c)$ on the cloud edges and the eye of the Goni are scattered from the base of cloud mask and tropopause height. Those regions show relatively large $\text{STD}(I_{\text{obs}|11})$ and small COT. The height of the $\min(\mathbf{H}_c)$ (green circles) also follows ~~to~~ the base of ~~clouds~~ the cloud layer with a bias ~~=of~~ -1.58 km (10.646 K in the aspect of temperature), slightly lower than EEL and MODIS CTH. These results show the feasibility of inferring single-layered ice cloud boundaries from spectral cloud emissivity and its uncertainties by IR measurements. The $\max/\min(\mathbf{H}_c)$ 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 $\text{STD}(I_{\text{obs}|11})$ 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.

3.34.1.2 A scene for single-layered optically thick ice clouds (19 August, 2015, at 1530 UTC)

The second case is the single-layered optically thick ice clouds (Fig. 7) at 1530 UTC on 19 August 2015. Here we show the $\text{BT}|_{11}$ image instead of RGB image (Fig. 7(a)) since this is a nighttime scene. Fig. 7(a) is also rotated 90 degrees left. For this overpass, CALIOP observed clouds farther away from the center of Goni, and inspection of the cross-section in Fig. 7(b) suggests that most of cloud pixels are optically thick with COT values higher than 5, about where the CALIOP signal attenuates, and have relatively low $\text{STD}(I_{\text{obs}|11})$ as indicated by the gray solid/dashed line in Fig. 7(b). In the comparison with the CALIOP VFM, the $\max(\mathbf{H}_c)$ tends to occur at or slightly below the cloud top as indicated by CALIPSO, still higher than the EEL and MODIS CTH. The bias for the $\max(\mathbf{H}_c)$ from the top of clouds is 2.38 km (-13.222 K), which is larger than that of optically thin ice clouds. The $\min(\mathbf{H}_c)$ is close to the MODIS CTH and the EEL, but The bias for $\min(\mathbf{H}_c)$ from the cloud base is larger than that of optically thin clouds, -2.69 km (19.404 K), but the $\min(\mathbf{H}_c)$ still exhibit similar variation to CALIOP VFM. The passive IR measurements have an upper COT limit as shown in earlier studies (Heidinger et al. 2009; 2010). The height boundaries from our method brackets both the CALIPSO measurements and the MODIS retrievals.

3.34.1.3 A scene for multi-layerlayered cloud (8 August, 2015, at 0520 UTC)

915 The third case also involves a cross-section of Goni, but this scene is more complex in that there is evidence of both multi-layered and less homogeneous ice clouds on the southern boundary of the typhoon (Fig. 8a). Note that the STD ($I_{\text{obs}|11}$) on the CALIPSO track show relatively large variances, compared to the previous two cases (Fig. 8(b)). The CALIOP COT is omitted given the high fluctuations in the values. The CALIOP vertical feature mask (VFM) indicates the presence of randomly-oriented ice and horizontally-oriented ice (sky-blue) including water (orange) cloud phase. The enhancement of EEL at around

920 25.7°N in Fig. 8(b) is also caused by an extraordinary value of Q_e provided in the CALIOP V4 product. In the region of 10°N–20°N, the max/min(H_c) in this region are often outside the boundaries of the VFM. The max(H_c) (blue circles) ~~are~~ scattered ~~varied~~ from near the second cloud layer to the top of the first cloud at the tropopause. Some pixels of the min(H_c) (green circles) values are also outside the range of the VFM. There is more than one reason causing these increased ~~scatters~~ variances, including the fact that the uppermost cloud layer is optically thin (over half of all pixels have COT < 1.5)

925 and there are indications of lower cloud layers. In the region of 20°N–30°N, clouds on the top layer are relatively thick (on average, COT = 3.5). In that case, heights of the max(H_c) on the multi-layer pixels tend to be close to the EEL, which is much lower than the top of clouds. This is to be expected for the case of a geometrically thick but optically thin cloud. Note that the value of the min(H_c) on the multi-layered cloud pixels sometimes reach almost to the second cloud layer, rather than near the first layer. Further thought needs to be given to these cases.

3.4.2 Comparison of max/min H_c with CALIPSO for August 2015

In this section, the max/min(H_c) is compared with the cloud top/base height (CTH/CBH) from CALIOP over the ~~Western~~ western North Pacific during August 2015. The ~~procedure~~ computationally efficient method of Nagle et al. (2009) is used to collocate the simultaneous nadir observations (SNO) between two satellites. Following their approach, CALIOP ~~with~~ is projected onto MODIS ~~is described in Nagle et al. (2009).~~

935 First, we qualitatively examine the max/min(H_c) with the cloud layer vertical cross-section from CALIOP/MODIS matchup files (Table 3) in Fig. 6-Fig. 8. Second, we quantitatively investigate the max/min (H_c) for all ice clouds against CALIOP CTH/CBH during the month. The extinction coefficients profiles, cloud phase and their quality flags, and the number of cloud layers are extracted from CALIOP and used in this analysis (Table 3).

The matchup data are filtered as follows: only ice cloud phase pixels are chosen that have the highest quality (CALIOP QC for cloud phase = 1), where CALIOP COT > 1.5 and STD($I_{\text{obs}|11}$) from MODIS ≤ 1 , which helps to remove cloud edges and fractional clouds. The relationship is investigated between the max/min(H_c) and CALIOP CTH/CBH for three cloud regimes; (1) single-layerlayered optically thin ice clouds, (2) optically thick ice clouds, and (3) multi-layerlayered clouds where the uppermost layer is optically thin cirrus. The CALIOP/MODIS matchup clouds are separated into single-layerlayered and multi-layered cloud groups using the number of layers found (NLF) from CALIOP (Table 3). The multi-layered cloud group includes

945 two or more cloud layers, excluding single-layered clouds. Among single-layerlayered cloud pixels, we define optically

thin/thick cloud groups as CALIOP COT which is less/greater than 3.5, referring to the ISCCP cloud classification (Rossow et al., 1985; Rossow and Schifer, 1999).

950 Fig. 9 shows the joint histogram of the max/min(H_c) (y-axis of left/right panels) as a function of the CALIOP CTH/CBH (x-axis) for single-layered optically thin ice cloud (Fig. 9(a)), single-layered optically thick ice cloud (Fig. 9(b)), and multi-layered clouds (Fig. 9(c)). Table 4 provides all statistical quantities for Fig. 9 as correlations (corr), differences of the mean value (bias), and root mean square differences (rmsd). Additionally, all statistical quantities in terms of temperature are in the unit of K and are given in the round brackets in Table 4. For single-layered clouds, the majority of max(H_c) values are scattered about the one-to-one line. The statistical values are corr = 0.61, bias = 0.13 km, rmsd = 0.91 for thin clouds. This implies that minimum/maximum value of cloud height ranges corresponding to e_c and Δe_c are close to the cloud top for single-layered clouds as determined from CALIOP.

955 However, the scatter is higher for optically thick clouds, with corr = 0.65, bias = 0.30 km, rmsd = 1.08 (Table 4). As for the max(H_c) for multi-layered clouds, the majority of scatter points are on the lower right side of the one-to-one line, with corr = 0.25, bias = 1.41 km, and rmsd = 2.64. The lowest correlation and the largest bias for multi-layered clouds are shown, as expected given the assumption of the single-layered clouds in our method.

960 The comparisons of the min(H_c) (y-axis of right panels in Fig. 9) to the CALIOP CBH (x-axis) for all cloud categories show relatively large correlations, at least over 0.48. Scatter points in three joint histograms for all cloud types are parallel to the one-to-one line, but show negative biases implying higher heights than CALIOP CBT. As with the cases of the max(H_c), bias of the min(H_c) increases from single-layered optically thin ice (-1.01 km), to optically thick ice (-1.71 km) and multi-layered clouds (-4.64 km).

965 4.5 Discussion of Results

The results in Figs. 6–9 show the comparisons of the ice cloud height ranges obtained based on the ice cloud emissivity uncertainties with both MODIS C6 products and vertical cross sections of clouds from CALIOP. We investigated minimum and maximum of the estimated ice cloud heights perfor each cloud pixel for three cloud regimes during August 2015: (1) single-layered optically thin clouds, (2) optically thick ice clouds, and (3) multi-layered clouds.

970 Overall, the maximum values of the estimated ice cloud height ranges for single-layered optically thin/thick ice clouds show some skill in comparison with the cloud tops from CALIOP: corr = 0.61/0.65, bias = 0.13/0.30 km. In particular, we note that the upper height boundary for optically thin clouds derived from our method are very close to the geometric cloud tops. For multi-layered clouds, the maximum heights are occasionally much lower than the uppermost cloud layer as observed by CALIOP, showing the highest bias at 1.41 km. Higher biases are expected in our method given the assumption of single-layered clouds in each pixel. Additionally, the skill of our method decreases when the upper cloud layer is composed of optically thin (having very low COT values) and fractional clouds; in some cases, the method cannot determine an emissivity range from the LUTs, which were generated for single-layered ice clouds.

The minimum heights for single-layered optically thin ice clouds reach near the base of cloud, with $\text{corr} = 0.83$, $\text{bias} = -1.01$ km. However, those for thick/multilayer, the biases became larger, at most -4.64 km. That is, the minimum heights for thick clouds became much higher than the CALIOP-~~the~~ observed cloud bases. This indicates that the IR method has an optical thickness limitation and is more useful for lower optical thicknesses, which has been noted previously (e.g., Heidinger et al. 2010). Even with large biases of minimum heights, it is notable that correlation coefficients between minimum heights and the cloud base for all three cloud regimes are sufficiently large, at least 0.48.

To better understand the potential biases of the current algorithm in comparison with CALIOP, we compare the mean(H_c) to the mean(CALIOP H_c) that are defined as $0.5 \cdot (\max(H_c) + \min(H_c))$ and as $0.5 \cdot (\text{CALIOP CTH} + \text{CALIOP CBH})$, respectively.

Fig. 10 shows the frequency of occurrence of biases, that is, the mean(CALIOP H_c) minus the mean(H_c), as a function of CALIOP COT for the single-layered ice clouds during August 2015. ~~Here mean(CALIOP H_c) is defined as simple average of upper and lower cloud boundary such as $0.5 \cdot (\text{CALIOP CTH} + \text{CALIOP CBH})$. The mean(H_c) is also defined as $0.5 \cdot (\max(H_c) + \min(H_c))$.~~ 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 $\text{COT} \geq 0.5$ in x-axis of Fig. 10.

Fig.10 illustrates that our resulting single-layered ice clouds boundaries are comparable to consistent with CALIOP measurements, showing slightly negative biases except the region ~~of~~near 'COT ≤ 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(H_c) from CALIOP measurements are ~~mainly~~ caused primarily by two factors: (1) The $\min(H_c)$ values for all cloud regimes tend to be higher than geometric cloud base, and (2) The $\max(H_c)$ 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 ($1.5 < \text{COT} \leq 3.5$) show the lowest biases, ~~which current algorithms by passive imageries have difficulties to produce accurately.~~

Fig.10 also addresses the ~~weakness~~weaknesses of our method. In the region of $\text{COT} \leq 1.5$, biases of mean(H_c) from CALIOP are largest and positive. This region might be relevant to fractional clouds or cloud edges. We infer that relationship of cloud emissivity at 11 and 12 μm , the key controller in our method, might not be optimal in the fractional clouds or cloud edges, resulting in lower heights.

A limitation of this study is that the LUTs are generated for spectral emissivity using IR sensor observations and level-2 products that still have errors and uncertainties. It would be interesting to extend this preliminary research by generating LUTs for spectral emissivity using CALIOP, not IR sensors. If we can obtain more diverse ice cloud emissivity in vertical cloud

thickness, it could result in improvements in the resulting cloud temperatures/height ranges. Also, the LUTs based on CALIOP data/products could be used to reduce errors in inferring cloud temperatures for multi-layered clouds.

5.6 Summary

015 The intent of our study is to demonstrate that ice cloud emissivity uncertainties, obtained from three IR channels generally available on various satellite-based sensors, can be used to estimate a reasonable range of ice cloud temperatures as verified through comparison with active measurements from CALIPSO. For satellite-based retrievals with heavy data volumes, the general assumption is that the cloud in any given pixel can be treated as plane parallel, which simplifies the retrieval algorithms. However, for ice clouds and particularly optically thin ice clouds known as cirrus, the plane-parallel assumption breaks down because cirrus tends to ~~have greater vertical inhomogeneity than lower-level water clouds. Cirrus are~~ optically thin but ~~are~~ often geometrically thick, ~~which is different with lower-level liquid water clouds.~~ For ~~these cases~~ cirrus, the inference of a cloud-top temperature for a given measurement may not be optimal. In our approach, a range of spectral ice cloud emissivity is calculated from which is, in turn, used to infer a range of cloud temperatures. These temperatures are converted to heights and subsequently compared to active lidar measurements provided by CALIPSO/CALIOP products.

020
025 This study provides a methodology to infer a range of spectral cloud emissivity for each cloud pixel. The range in emissivity represents uncertainty in the cloud microphysics to some degree. In our approach, we generate two LUTs for cloud emissivity at 11 μm and cloud emissivity differences between 11 and 12 μm using the brightness temperatures at 11, 12, and 13.3 μm . The 11- μm channel is a window channel where the primary absorption is caused by water vapor. The 12- μm channel is impacted by both H₂O or and CO₂, while the 13.3- μm channel has more absorption by CO₂ than by water vapor. The benefit of a method that relies of IR channels is that it does not depend on solar illumination, so the cloud heights can be obtained consistently between day and night.

030 We estimate a range of ice cloud temperature corresponding to the ice cloud uncertainty generated by three IR channels centered at 11, 12, and 13.3 μm by MODIS C6. The focus area is ~~northwestern~~ the western North Pacific Ocean during August 2015. We verified the estimated ranges of ice cloud temperature for three cloud categories, i.e., single-layered optically thin ice and optically thick ice clouds, and multi-layered clouds, against the vertical feature mask for CALIOP. We show that the minimum/maximum values for the estimated range of ice cloud heights agree with CALIPSO measurements fairly well for single-layered optically thin clouds. However, for optically thick and multi-layered clouds, the biases of the minimum/maximum values for those ranges from the cloud top/base became larger.

035 This approach can be applied to the new geostationary satellites, such as Himawari-8 (launched in 2015), GOES-16/17 (launched in 2016 and 2017), and GK-2A (launched in 2018). The new features of ice cloud temperatures from base to top by geostationary IR observation could contribute to improved accuracy of weather prediction and cloud radiative effects.

040 In future work, we intend to improve upon this methodology by developing lookup tables for spectral cloud emissivity uncertainty with CALIOP. Above all, it is required to study for global area for applying this method to the new geostationary

satellites. Also, further study is required to add more infrared channels to resolve more accurate spectral cloud emissivity uncertainties.

045 *Author contributions.* HSK built, tested, and validated the algorithm, and wrote the manuscript. BB contributed to complete the algorithm and to review/edit the manuscript carefully. YSC provided initial idea for the algorithm and guidance of this study. All authors were actively involved in interpreting results and discussions on the manuscript.

Competing interests. The authors declare no conflict of interest.

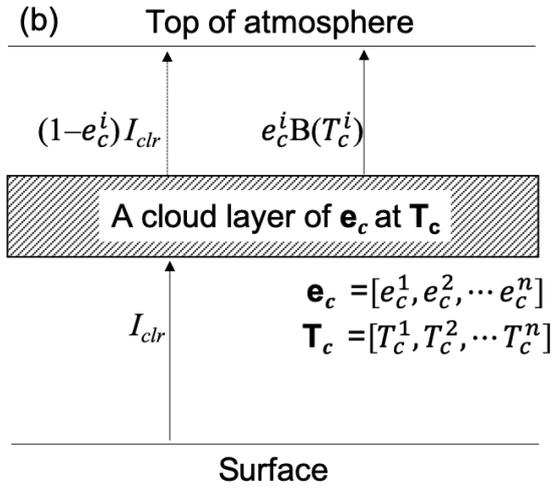
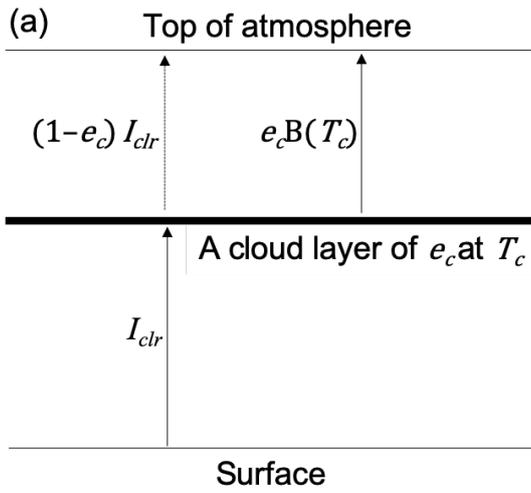
050 *Acknowledgments.* This work was supported by the “Development of Cloud/Precipitation Algorithms” project, funded by ETRI, which is a subproject of the “Development of Geostationary Meteorological Satellite Ground Segment (NMSC-2019-01)” program funded by the National Meteorological Satellite Center (NMSC) of the Korea Meteorological Administration (KMA).

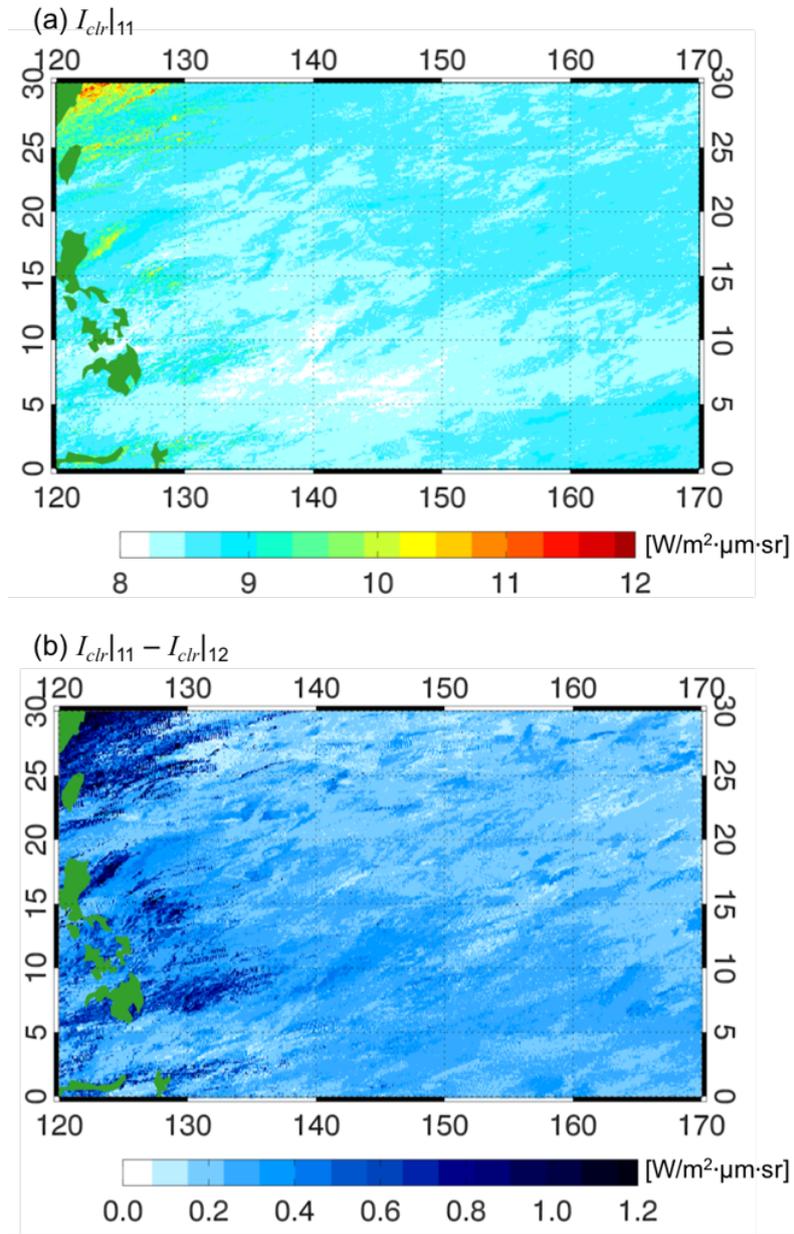
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Figure 1: Conceptual cloud model shown: The estimated clear sky radiance map at $0.1^\circ \times 0.1^\circ$ resolution for (a) $11 \mu\text{m}$ ($I_{clr|11}$) and (b) differences of $11 \mu\text{m}$ from $12 \mu\text{m}$ ($I_{clr|11} - I_{clr|12}$) in the unit of $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$. $I_{clr|11}$ and $I_{clr|12}$ are the maximum values among MODIS C6 radiances for three months of August (2013–2015) in each $0.1^\circ \times 0.1^\circ$ grid box. Green-shaded contours over the map show land, which is generally from the Philippines.

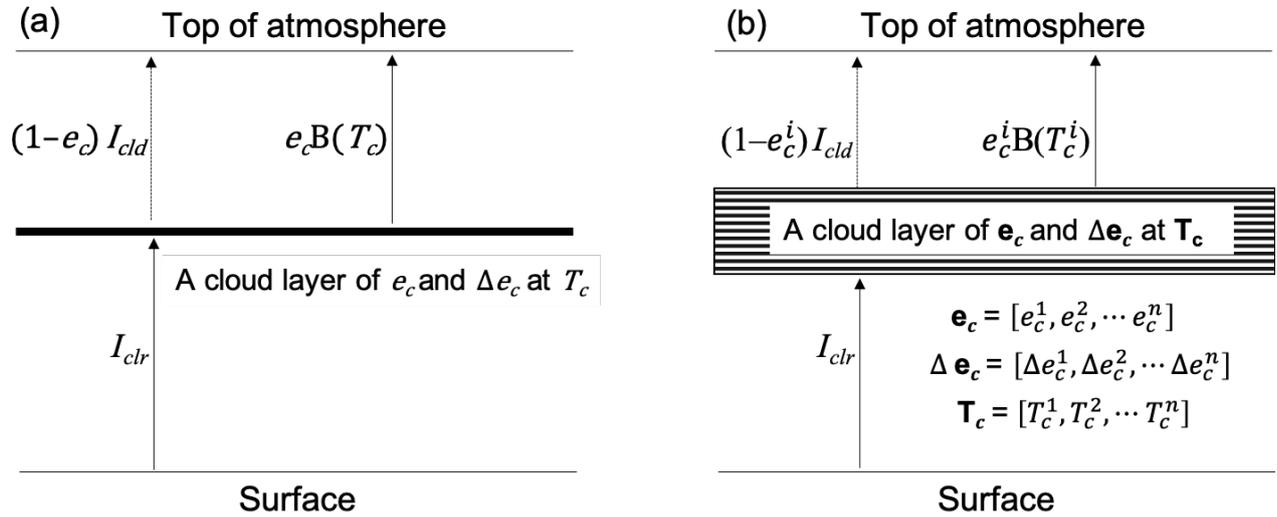
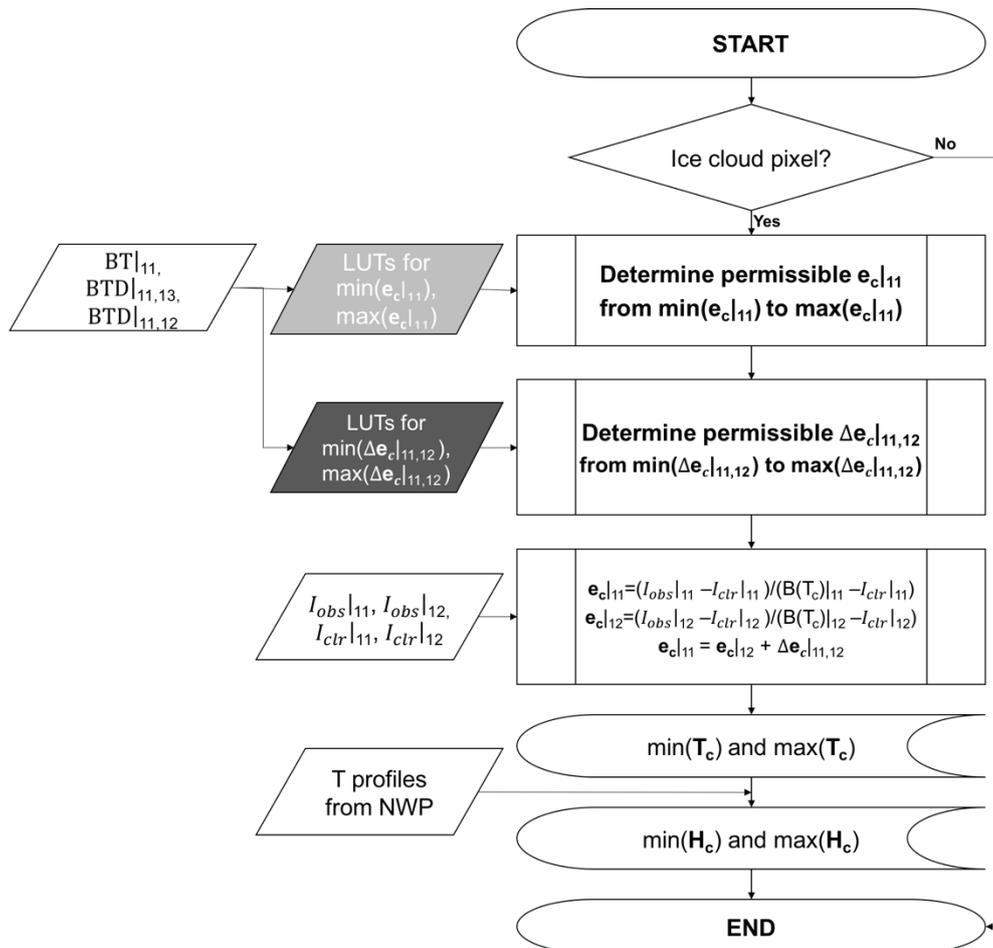


Figure 2: The conceptual model for (a) a plane parallel homogeneous cloud layer with no scattering, characterized by cloud emissivity at $11 \mu\text{m}$ (e_c) and cloud emissivity differences between 11 and $12 \mu\text{m}$ two infrared channels (Δe_c) at the cloud temperature (T_c) and (b) a number of plane parallel inhomogeneous layer homogeneous cloud layers (the stripes box) with uncertainties in a possible range of e_c and Δe_c such as $\mathbf{e}_c = [e_c^1, e_c^2, \dots, e_c^n]$ and $\Delta \mathbf{e}_c = [\Delta e_c^1, \Delta e_c^2, \dots, \Delta e_c^n]$ in a certain $\Delta e_c^1, \Delta e_c^2, \dots, \Delta e_c^n$ corresponding to a possible range of cloud temperature ranges, $\mathbf{T}_c = [T_c^1, T_c^2, \dots, T_c^n]$, where I_{clr} and B are the clear-sky radiance and the Planck's function, respectively. Arrows represent upwelling radiances.



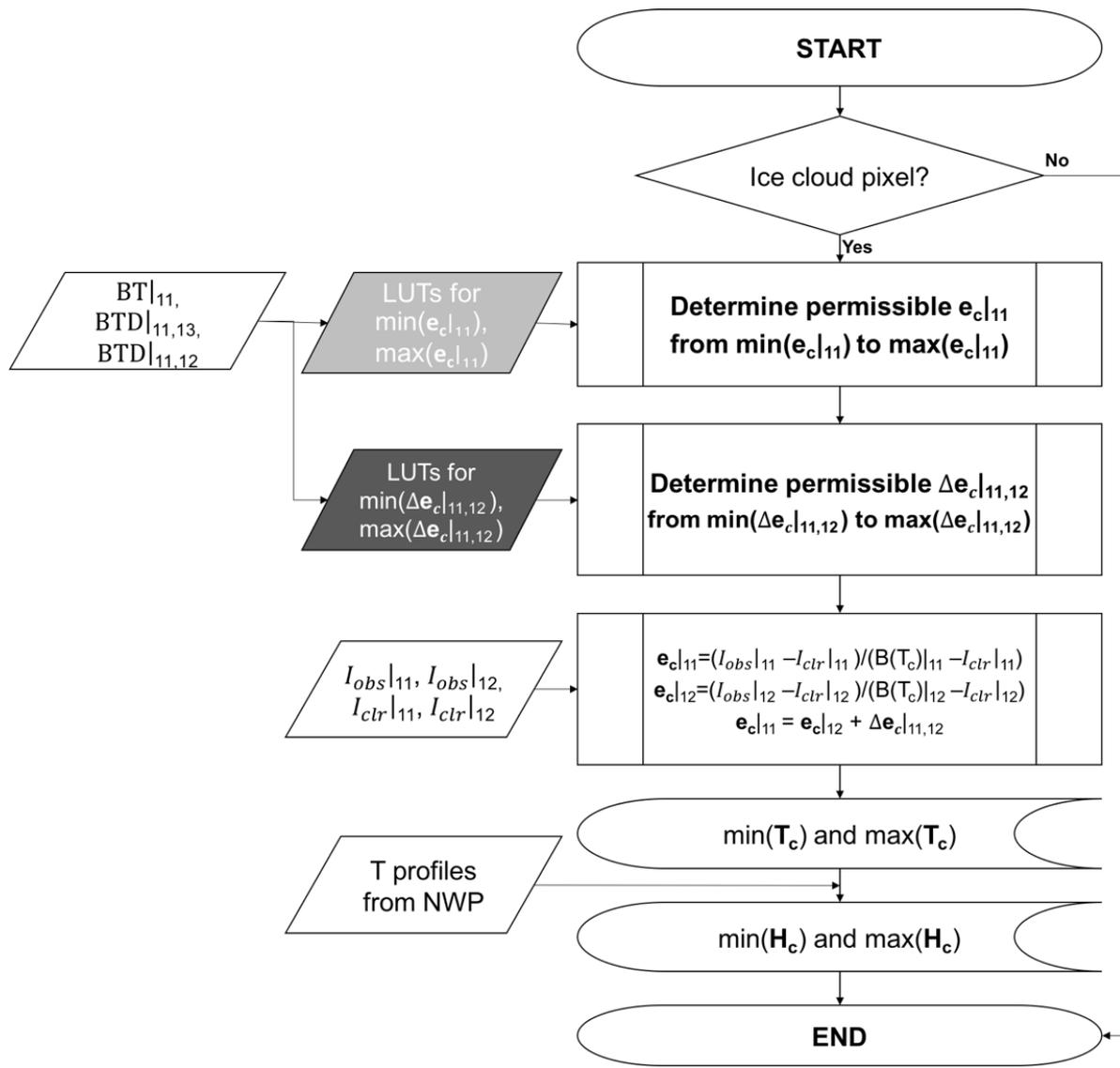
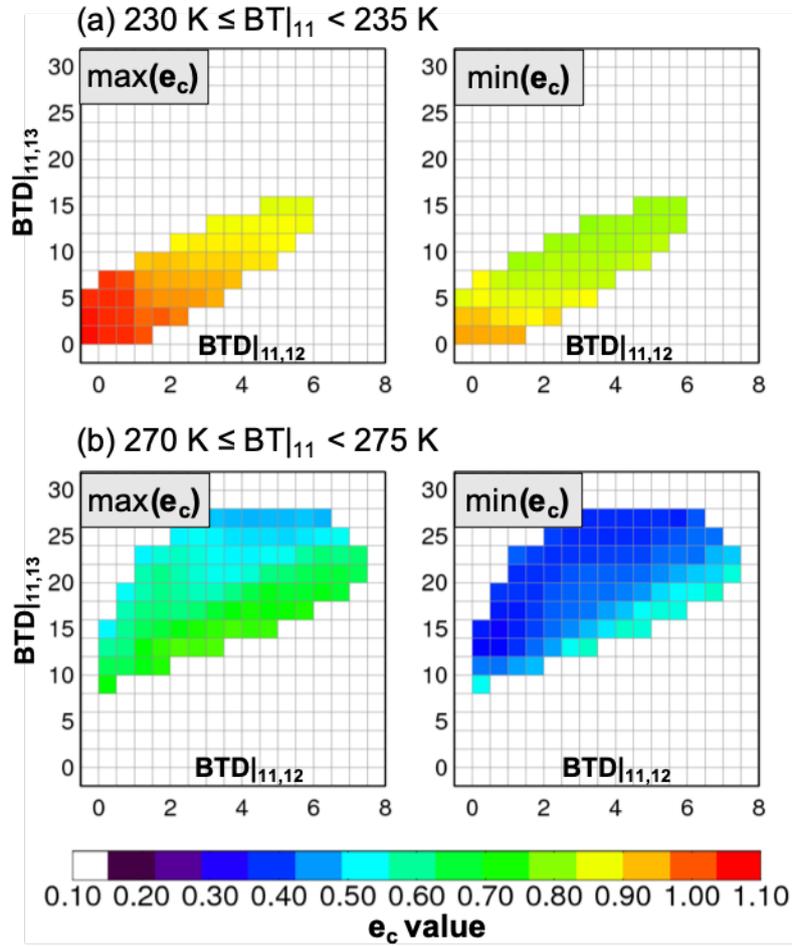
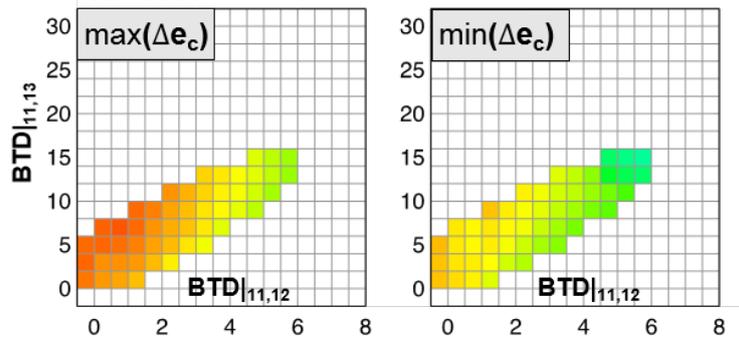
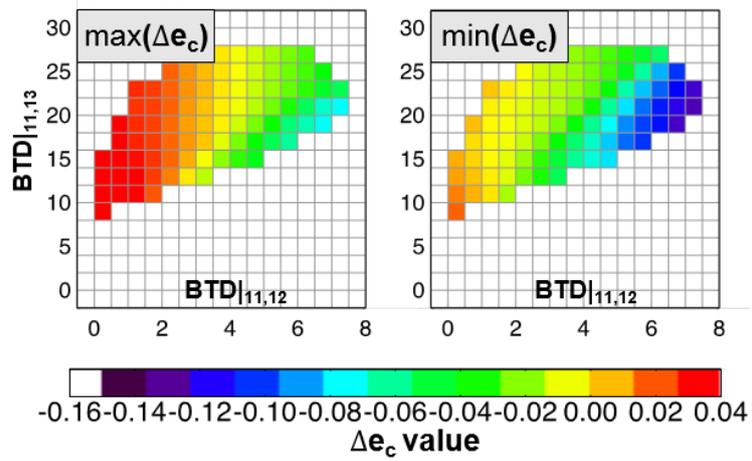


Figure 2: The logo of Copernicus Publications.3: A flowchart for estimation of T_c and H_c corresponding to e_c (from a light gray box that will be shown in Fig. 34) and Δe_c (from a dark gray box that will be shown in Fig. 45) which represent cloud microphysics uncertainty in a certain cloud thickness. We denoted functions for minimum/maximum values of a matrix, A, as $\min/\max(A)$.



(a) $230 \text{ K} \leq \text{BT}|_{11} < 235 \text{ K}$ (b) $270 \text{ K} \leq \text{BT}|_{11} < 275 \text{ K}$ 

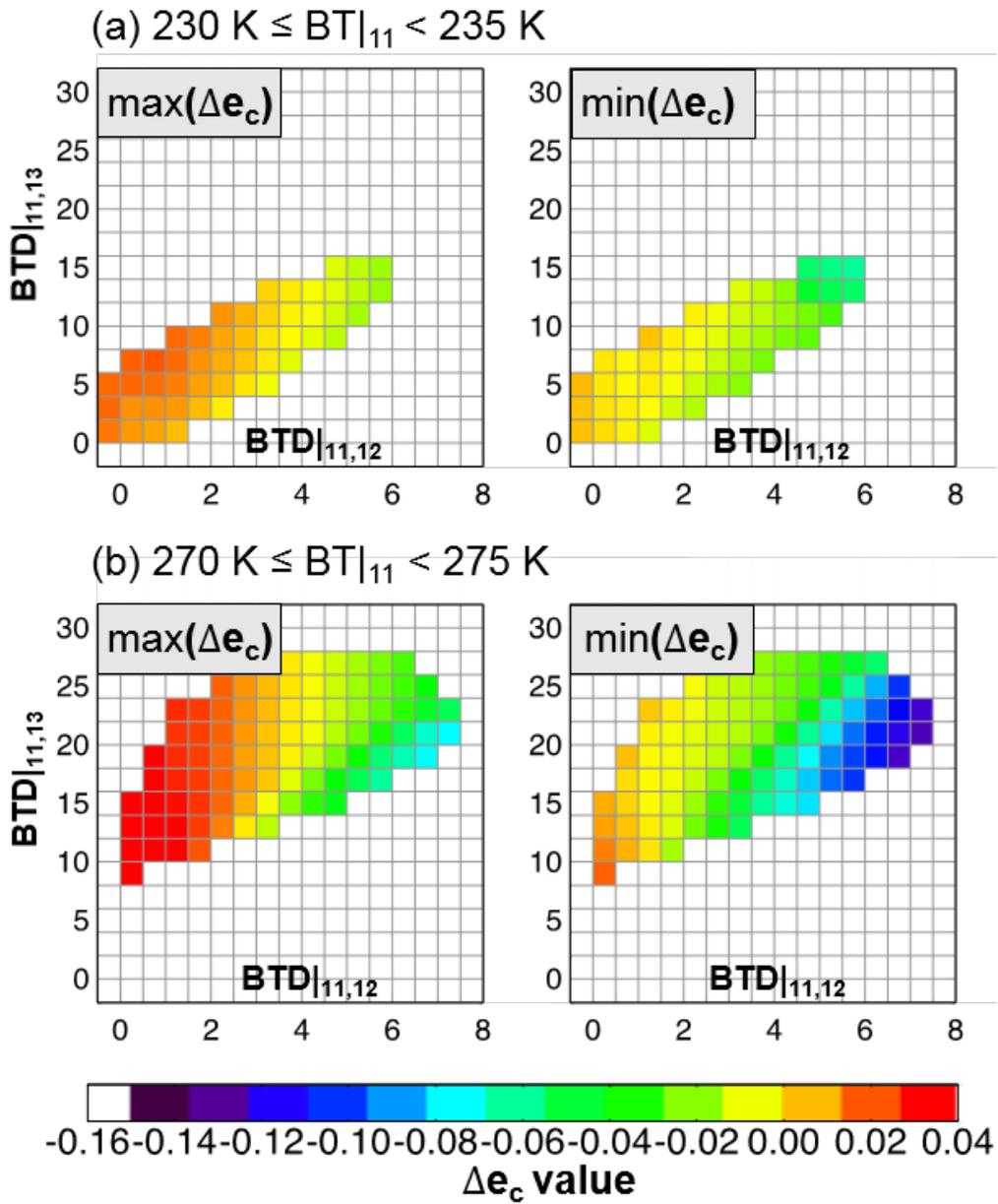
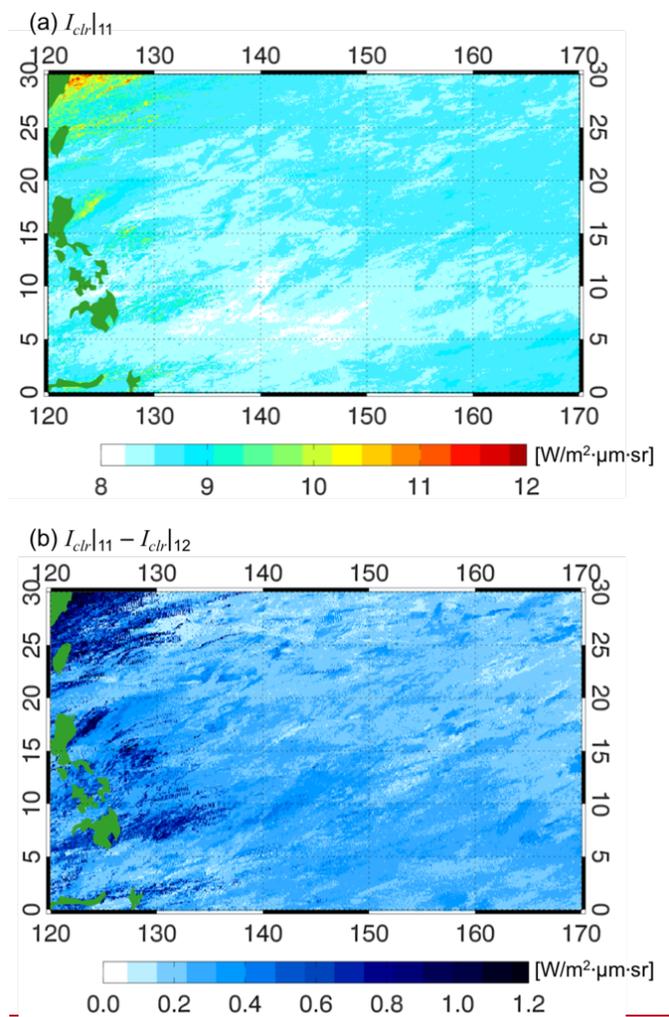


Figure 45: Look-up tables for min/max(Δe_c) (left/right panel in colors) by $\text{BTD}_{|11,12}$ (x-axis) and $\text{BTD}_{|11,13}$ (y-axis) for (a) $230 \text{ K} \leq \text{BT}_{|11} < 235 \text{ K}$ and (b) $270 \text{ K} \leq \text{BT}_{|11} < 275 \text{ K}$. Identical data as in Fig. 34 are used to generate these look-up tables, except cloud emissivity differences between 11 and 12 μm come from MODIS C6 (referring to Table 1 and Table 2).

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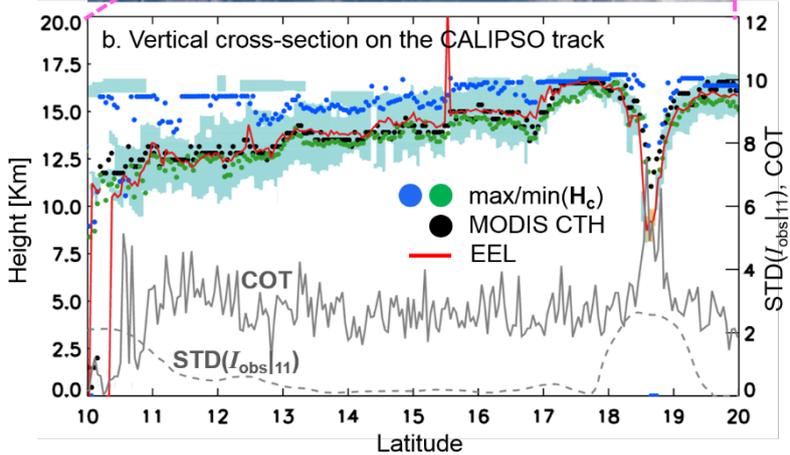
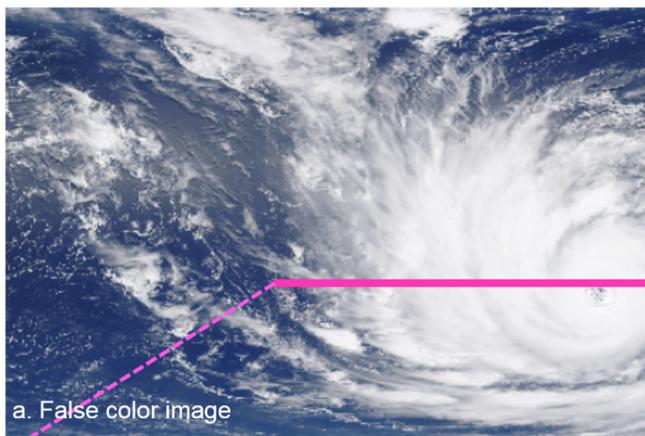
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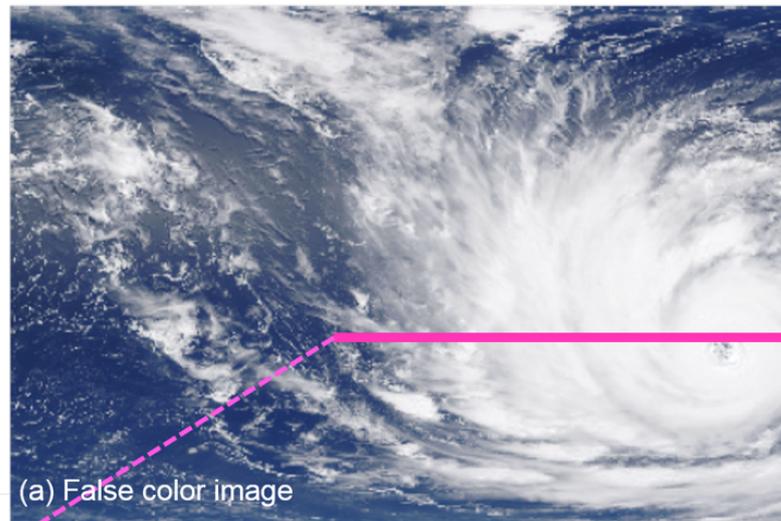


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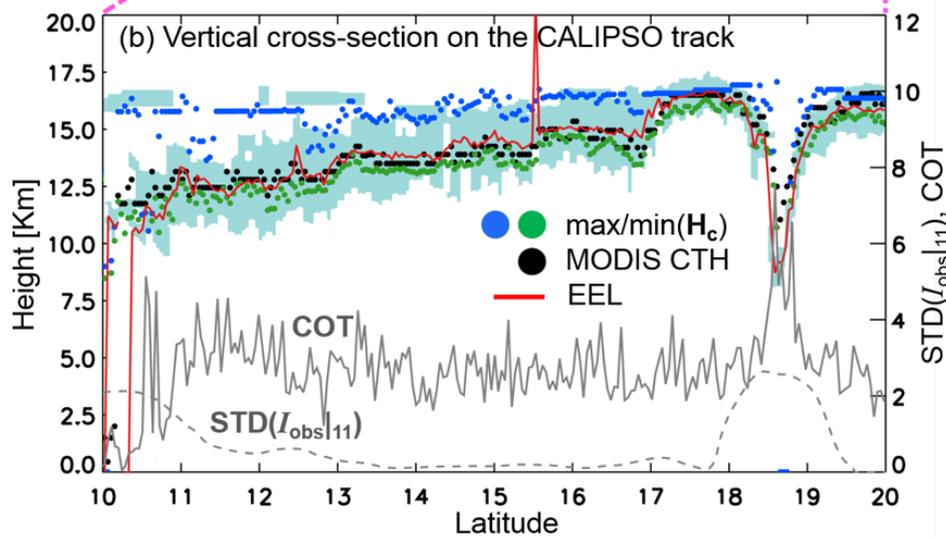
Figure 5: The estimated clear sky radiance map at $0.1^\circ \times 0.1^\circ$ resolution for (a) $11\text{-}\mu\text{m}$ ($I_{clr|11}$) in the unit of $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$, and (b) $I_{clr|11} - I_{clr|12}$. $I_{clr|11}$ and $I_{clr|12}$ are the maximum values among MODIS-C6 radiances for three months of August (2013–2015) in each $0.1^\circ \times 0.1^\circ$ grid box. Green shaded contours over the map show land, which is generally from the Philippines.

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(a) False color image



(b) Vertical cross-section on the CALIPSO track

● max/min(H_c)
 ● MODIS CTH
 — EEL

COT

STD($I_{obs|11}$)

STD($I_{obs|11}$), COT

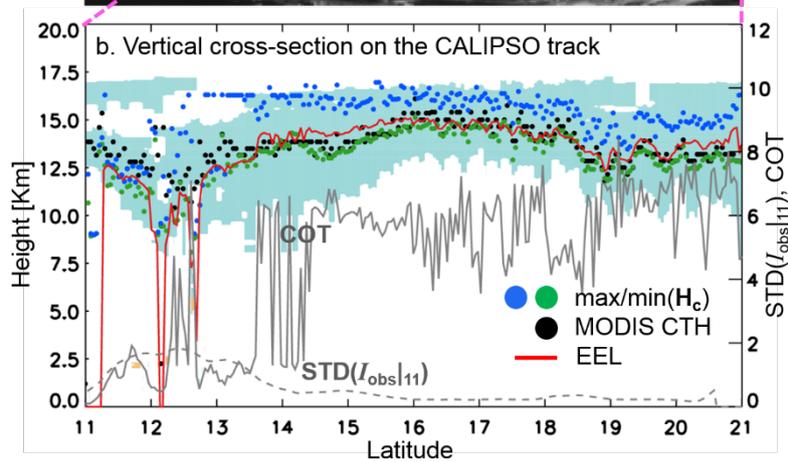
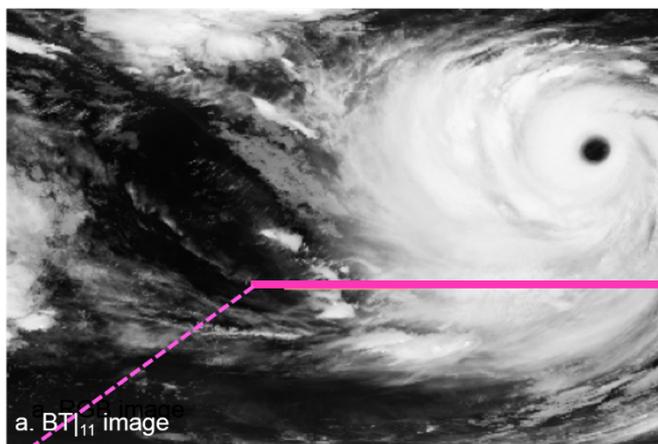
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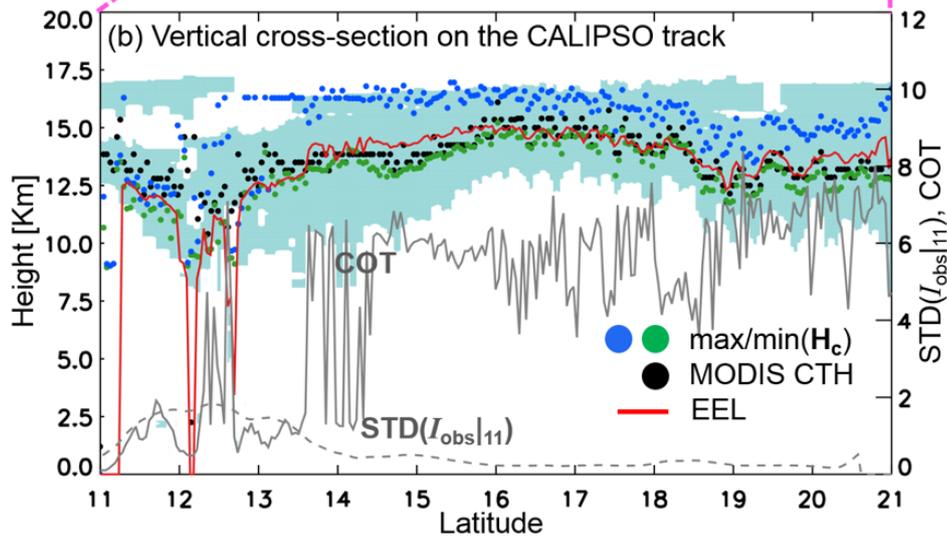
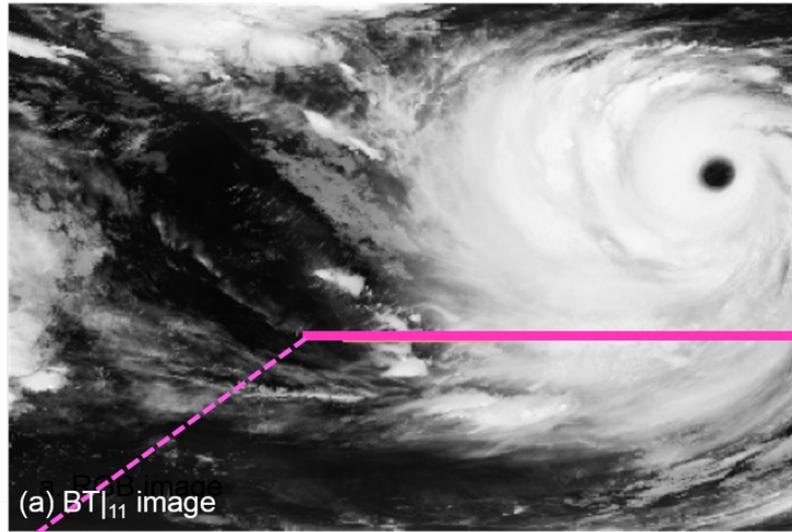
Latitude

Figure 6: (a) MODIS false color image (rotated 90 degrees left) at 0320 UTC 19 August 2015. This scene captures part of Typhoon Goni. The heavy pink line on the image shows CALIPSO track at the closest to MODIS observation time. (b) Vertical cross-section of the CALIPSO track designated by the heavy pink line in Fig. 6(a). The vertical feature mask is shown as sky-blue and orange contours (randomly and horizontally oriented ice, and water). The red solid line shows where the layer COT (integrated Q_e at 532 nm from CALIOP) reaches a value of 0.5. The green/blue and black circles are the min/max(H_c) and MODIS CTH, respectively. The gray solid (dashed) line on right side y-axis is the column COT from CALIOP (standard deviation of 11- μ m radiances from MODIS).

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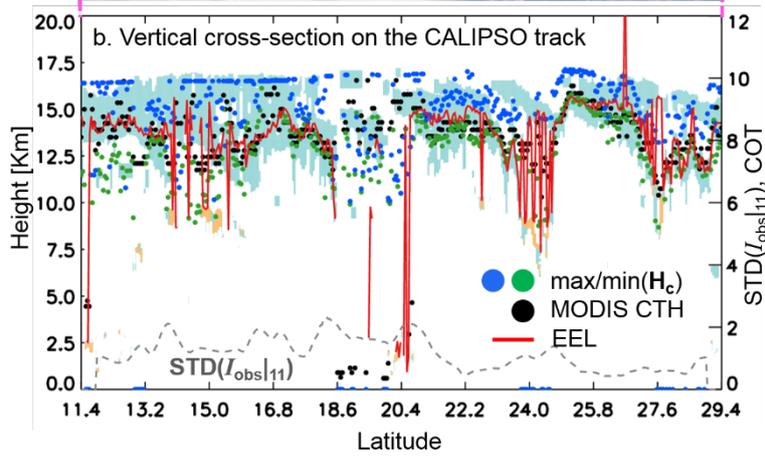
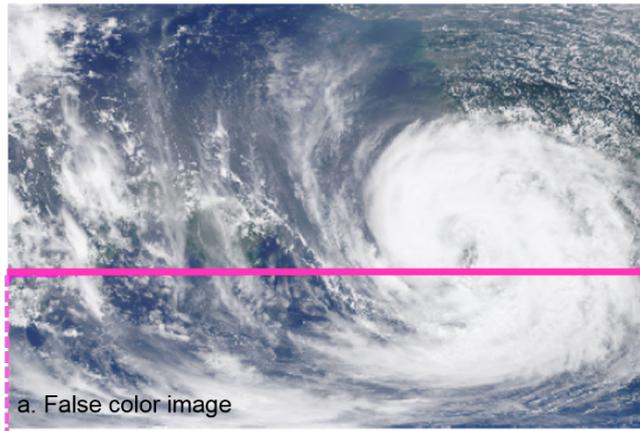
300

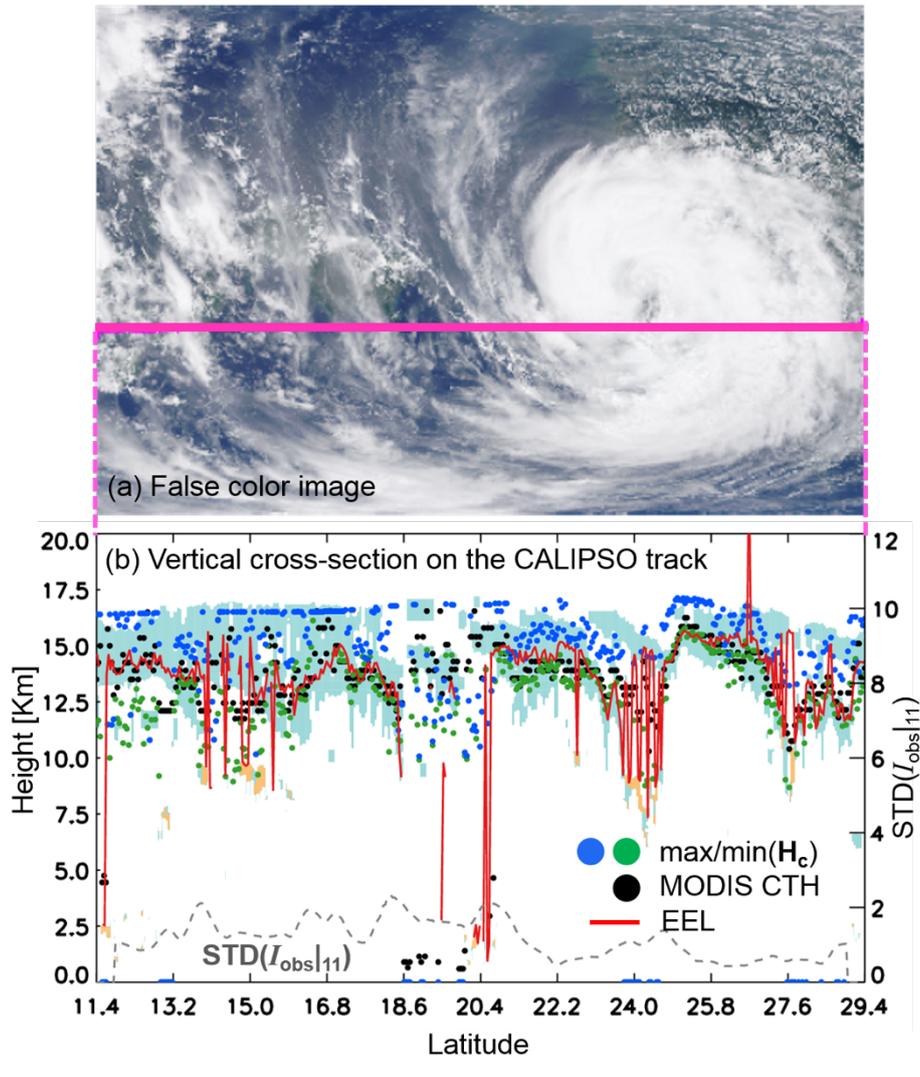
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Figure 7: (a) $BT|_{11}$ image from MODIS (MYD021 C6) at 1530 UTC on 19 August 2015. This scene captures part of Typhoon Goni. The heavy pink line on the $BT|_{11}$ image shows CALIPSO track at the closest to MODIS observation time. (b) Vertical cross-section of the CALIPSO track designated by the heavy pink line in Fig. 7(a). The vertical feature mask is shown as sky-blue and orange contours (randomly and horizontally oriented ice, and water). The red solid line shows where the layer COT (integrated Q_c at 532 nm from CALIOP) reaches a value of 0.5. The green/blue and black circles are the min/max(H_c) and MODIS CTH, respectively. The gray solid (dashed) line on right side y-axis is the column COT from CALIOP (standard deviation of 11- μ m radiances from MODIS).

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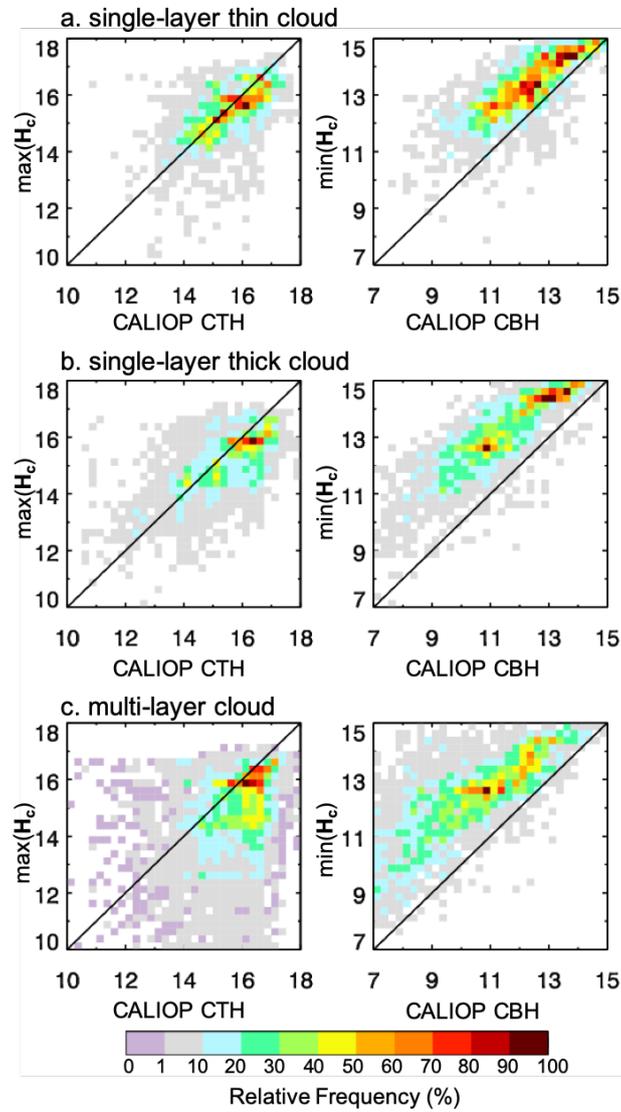




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Figure 8: (a) MODIS false color image (rotated 90 degrees left) at 0520 UTC on 8 August 2015. This scene captures part of Typhoon Goni. The heavy pink line on the image shows CALIPSO track at the closest to MODIS observation time. (b) Vertical cross-section of the CALIPSO track designated by the heavy pink line in Fig. 8(a). The vertical feature mask is shown as sky-blue and orange contours (randomly and horizontally oriented ice, and water). The red solid line shows where the layer COT (integrated Q_c at 532 nm from CALIOP) reaches a value of 0.5. The green/blue and black circles are the min/max(H_c) and MODIS CTH, respectively. The gray solid (dashed) line on right side y-axis is the column COT from CALIOP (standard deviation of 11- μ m radiances from MODIS).

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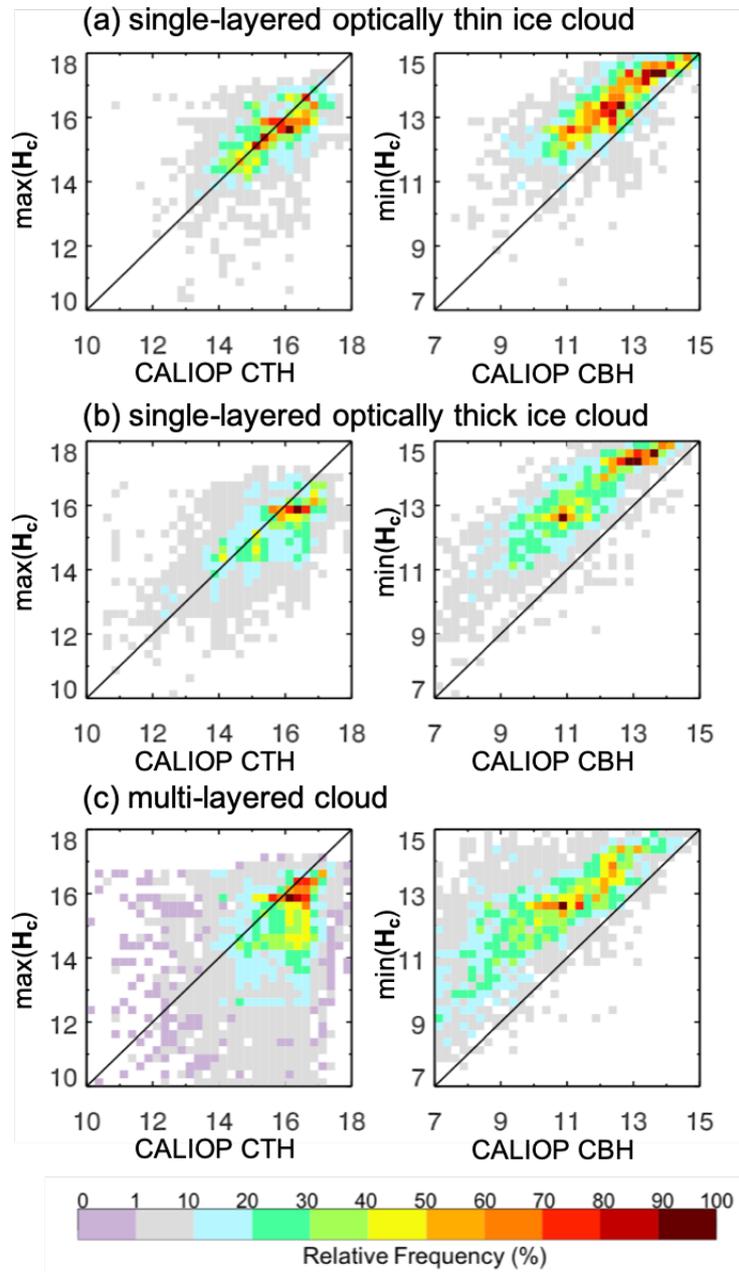
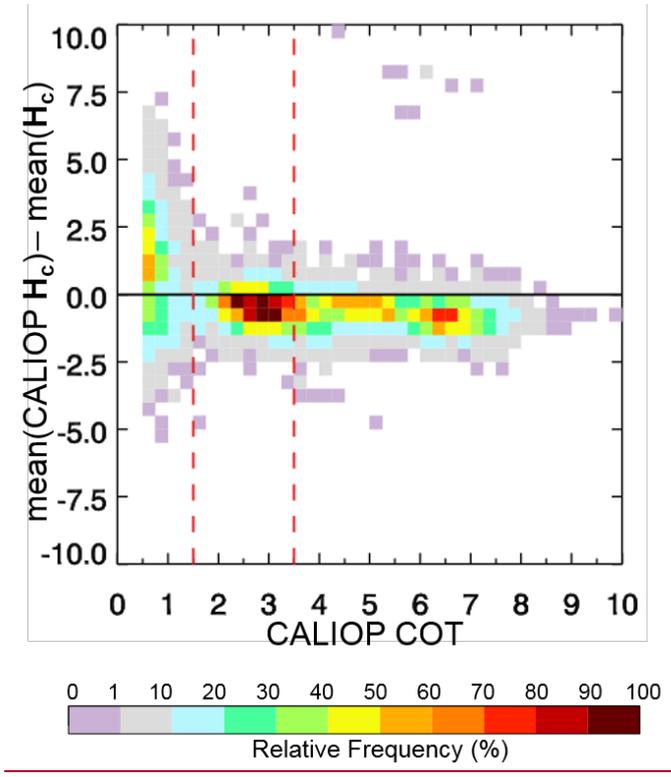


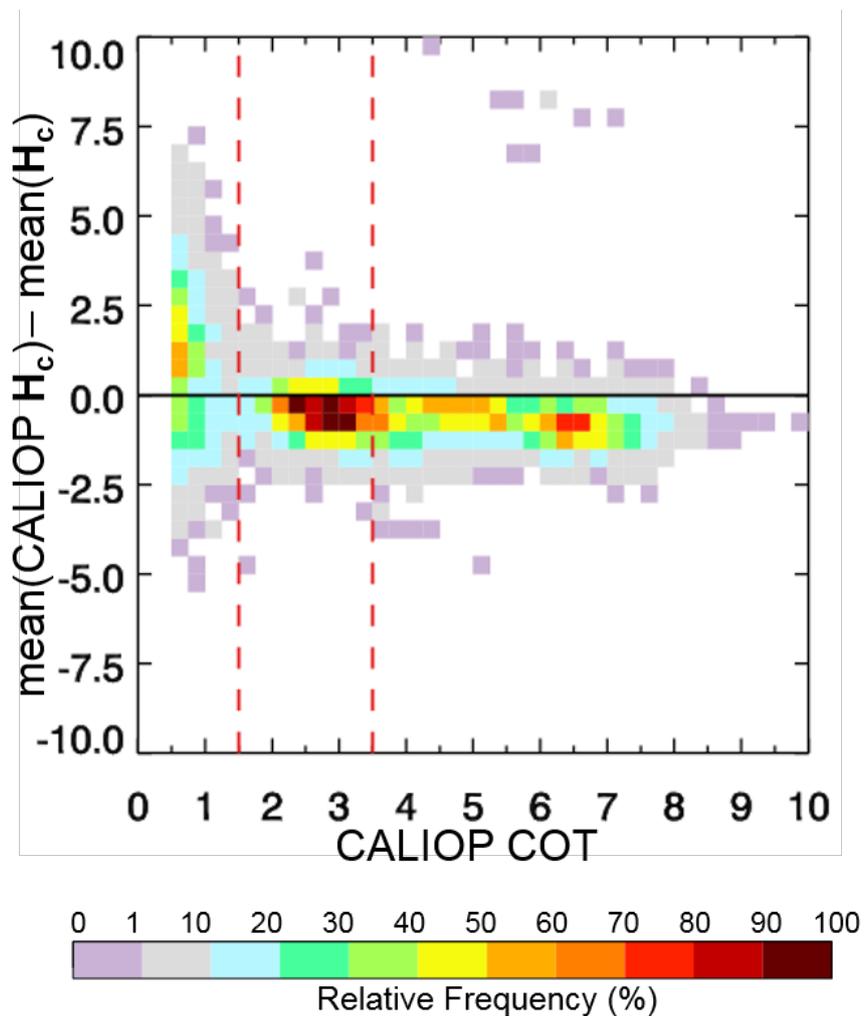
Figure 9: Joint histograms of three cloud categories; (a) ~~single-layered~~ single-layered optically thin ice cloud, (b) optically thick ice cloud, and (c) ~~multi-layer cloud~~ multi-layered cloud during August 2015. The first column show CALIOP CTH (cloud top height, x-axis) versus max(H_c) (y-axis), the second column shows CALIOP CBH (cloud base height, x-axis) versus min(H_c) (y-axis).

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Figure 10: A frequency of biases of $\text{mean}(H_c)$ from $\text{mean}(\text{CALIOP } H_c)$ as a function of CALIOP COT during August 2015. The $\text{mean}(\text{CALIOP } H_c)$ implies the average of upper and lower cloud boundary, simply defined as $0.5 \cdot (\text{CALIOP CTH} + \text{CALIOP CBH})$. The $\text{mean}(H_c)$ is also the average of cloud heights by our method, defined as $0.5 \cdot (\min(H_c) + \max(H_c))$. The red dotted lines are references for single-layered optically thin ($1.5 < \text{COT} \leq 3.5$) and optically thick ($\text{COT} > 3.5$) ice clouds in this study.

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	Variables	MODIS C6 products	Period	Domain
Input data	BT ₁₁ BT ₁₂ BT ₁₃	Band 31, 32, and 33 in MYD021	August 2013/2014	Western North Pacific (0°N-30°N, 120°E-170°E)
Output data	min/max(e_c) min/max(Δe_c)	Cloud products in MYD06		
Auxiliary data	IR cloud <u>thermodynamic</u> phase			

Table 1: The detailed information used to generate empirical look-up tables (LUTs) of min/max(e_c) and min/max(Δe_c). MODIS bands 31, 32, and 33 have spectral wavelengths ranges of 10.78–11.28, 11.77–12.27, and 13.185–13.485 μm , respectively.

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Input parameters	Value ranges	Increment
$BT _{11}$	190 K – 290 K	5 K
$BTD _{11,13}$	-2 K – 30 K	2 K
$BTD _{11,12}$	-1K –10 K	0.5 K

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Table 2: Parameter ranges and discretization of parameters in the LUTs for e_c (Fig. 34) and Δe_c (Fig. 45)

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	Variables	Data/products used in Sec. 3	Period	Domain
Input data	$I_{obs} _{11}$ $I_{obs} _{12}$ BT $ _{11}$ BT $ _{12}$ BT $ _{13}$	Band 31, 32, and 33 in C6 MYD021	August 2015	Western North Pacific (0°N-30°N, 120°E-170°E)
	Auxiliary data		$I_{clr} _{11}$ $I_{clr} _{12}$	
IR cloud <u>thermodynamic</u> phase		Cloud products in C6 MYD06	August 2015	
References for scene analysis	T/P profiles	GFS NWP products	August 2015	
	MODIS CTT/CTH	Cloud products in C6 MYD06	August 2015	
	VFM	CAL_L1D_L2_VFM-Standard- V4		
	CALIOP cloud phase			
	Q_e			
	T/P profiles	CAL_LID_L2_05kmCPro- Standard -V4		
COT				
References for statistical analysis	Number of layer found	CAL_LID_L2_05kmCLay- Standard-V4		
	CALIOP CTH/CBH			
	CALIOP CTT/CBT			

425 **Table 3: Data used for the tests shown in Fig. 23.** Input and auxiliary data are taken from the MODIS C6 cloud products and from CALIOP V4 cloud products. The abbreviations, CTT/CBT, CTH/CBH, COT, T/P, and VFM refer to cloud top/base temperature, cloud top/base height, cloud optical thickness, temperature/pressure, and vertical feature mask. The vertical profile of the extinction coefficient at 532 nm is denoted as the Q_e .

Category	Criteria	Count	CALIOP CTH vs. max(H_c) (CALIOP CTT vs. min(T_c))			CALIOP CBH vs. min(H_c) (CALIOP CBT vs. max(T_c))		
			Corr	Bias	Rmsd	Corr	Bias	Rmsd
All ice		11873	0.31 (0.29)	0.88 (-6.15)	2.07 (15.21)	0.67 (0.70)	-3.17 (22.40)	4.54 (30.20)
Single- layerlayered optically thin ice cloud	NLF = 1 $1.5 < \text{COT} \leq 3.5$	2237	0.61 (0.57)	0.13 (-0.62)	0.91 (6.12)	0.83 (0.83)	-1.01 (8.02)	1.31 (10.66)
Single- layerlayered optically thick ice cloud	NLF = 1 $\text{COT} > 3.5$	3067	0.65 (0.66)	0.30 (-1.53)	1.08 (7.12)	0.87 (0.87)	-1.71 (13.96)	1.92 (15.53)
Multi- layerlayered cloud	NLF > 1	6569	0.25 (0.23)	1.41 (-10.18)	2.64 (19.53)	0.48 (0.48)	-4.64 (31.22)	5.95 (38.69)

Table 4. Comparison of max(H_c) (min(H_c)) to the CALIOP CTH (CALIOP CBH) for all cloud pixels and three cloud regimes; single-~~layerlayered~~ optically thin ice ~~cloudscloud~~, optically thick ice ~~cloudscloud~~ and multi-~~layerclouds~~layered cloud for August, 2015. Pixel numbers (count), correlation coefficients (corr) and differences of the mean values (bias), root mean square differences (rmsd) are provided. Additionally, comparison of min/max(T_c) to the CALIOP CTT/CBT are also shown as numbers of round brackets.