Author response to Referee #2:

Dear Referee,

We sincerely thank you for your thoughtful and constructive comments, which have greatly helped us improve the manuscript. Below, we provide our point-by-point responses to each comment. All changes made to the manuscript according to the comments of the three reviewers have been carefully highlighted in the revised version.

General comments:

This study investigates the latent and radiative heating fields of tropical cloud systems using synergistic satellite observations. The artificial neural network (ANN) regression is used to generate 'observational data' based on limited satellite observations and meteorological reanalyses. This work could be useful for understanding tropical cloud systems, particularly mesoscale convective systems. Overall, the paper is well-written. However, the presentation and analysis need improvement before the paper is suitable for publication.

Recommendation: Major revision

Major comments:

- Some conclusions are not well supported by the presented results. For example, in lines 515-518, it is stated that "The smaller CIRS-retrieved height may be interpreted as anvils of convective systems having descended at a later stage of their life cycle or as relatively thick clouds with diffusive tops, for which the retrieved (radiative) height may be deeper within the cloud because of very small ice water content in the upper part of the cloud." However, the authors do not provide any related analysis to support this conclusion.

  Thank you very much for your valuable comment.

  *Indeed, these were plausible explanations, which are not easy to prove. Therefore, we wrote '**may be interpreted**'. We have provided references for the latter (diffusive cloud top) in section 5.1, lines 436-437: e.g. Liao et al. 1995; Stubenrauch et al. 2010, 2017, and we have added one reference which suggests a descend of anvils with life time (Fig. 5.15 of Strandgen 2018) in line 435. We did not repeat these references in the conclusions, but since these are only possible explanations and they are not very clear and not so important, we have removed them from the conclusions.*

  To improve the manuscript, we have made substantial revisions to the conclusion section, as well as other parts of the text where the explanations were unclear.

- Lines 144-145: "The rain intensity classification (no rain, light rain, heavy rain), determined by an ANN trained with precipitation data from CloudSat, considers light rain to be < 5 mm h^{-1} and heavy rain > 5 mm h^{-1} (Stubenrauch et al., 2023)."
  a) The GPCP and TRMM precipitation data are widely used by the community. Could you provide a justification for why you chose to use CloudSat precipitation data? Also, please include the link to the CloudSat precipitation data in the Data Availability Statement.

  If we wanted to use information on the rain intensity or rain fraction in the training, we needed to use data which are available over the whole production period (2004-2018) for each of the AIRS and IASI footprints. Since we have used CloudSat-CALIPSO data earlier to expand the radiative heating rates (Stubenrauch et al. 2021), we used CloudSat precipitation rate data (2C-PRECIP-COLUMN, Haynes et al. 2009) to expand information on precipitation (Stubenrauch *et al. 2023). Since the distribution of precipitation rate is highly skewed, we were not able to do an ANN regression of this precipitation rate, but we succeeded to build an ANN classification, separating no-rain, light-rain and heavy-rain scenes (Stubenrauch et al. 2023). In this article, we have also shown that this scene identification was more powerful to separate TRMM SLH latent heating rates than cold brightness temperature.*

We could not use TRMM data, because as we have shown, before, these are only available for less than 5% of the AIRS and IASI footprints. There may be a possibility to use GPCP data, but again the L2 data would have been needed to collocate with the complete AIRS and IASI datasets in time and space, and we are not sure if there is a 100% overlap. Since we have had already this CIRS-ML rain intensity classification, we pursued this path.

During this review, we have analysed the complete collocated dataset further, and we found indeed some noise linked to the difference between fraction of certain rain from CloudSat (using CIRS-ML) and from TRMM, but the CIRS-ML dataset seems to be coherent with the certain rain fraction, though it was not used as input for the ANN (see replies to referee #1).

In this article we have shown one method to expand the latent heat with CIRS data; there may be better ways, but since the whole procedure took quite an effort, it was not possible to pursue two paths in parallel. It would be nice if this work inspires other researchers to improve the methods to get a complete 3D dataset of UT cloud systems.

Thanks for your valuable comment. We have completely revised the last paragraph of section 2.3, and we have added the comparison between TRMM and CIRS-ML certain rain fraction to section 3.2..

b) How did you handle data when the rain rate is exactly 5 mm h^{-1}?

Actually, these thresholds are valid for the CIRS-ML rain intensity classification at the AIRS footprint scale. We have now completed the description by including the propagation to the 0.5° grid cells. At the 0.5° scale, the threshold should be more around 2.5 mm/h. Since we use always the same scene identification, for training and production, the categorization should be still coherent. All thresholds are <= for light and > for heavy rain.

- Could you please provide the definitions of UT and UT clouds in this study? How are the CRE and ACRE calculated, given that they represent the clouds' impact on radiative heating?

UT clouds were defined in line 331 (previous version): "We consider UT clouds with P_{cld} < 350 hPa…"

High-level clouds were defined in line 118 (previous version): "CIRS cloud types are defined according to p_{cld} and ε_{cld} as high clouds (P_{cld} < 440 hPa)…"

Since the definition of UT clouds is introduced much later, it may cause confusion with high-level clouds. To address this, we added the sentence "UT clouds with P_{cld} < 350 hPa are part of the high cloud category." at line 149 in revised manuscript.

Indeed, there was a confusion in the manuscript. The training of the ANNs was separately done for high-level clouds and mid- and low-level clouds. We have changed 'UT clouds' to 'high-level clouds' in both the figures and the text, mostly in section 2.

When moving to the analysis of mesoscale convective systems, we use the definition of UT clouds.

The cloud radiative effect (CRE) is calculated as the difference between all-sky radiative heating rates and clear-sky radiative heating rates, with the unit K/day. We use the clear sky identification of CIRS as in (Stubenrauch et al. 2021). The atmospheric cloud radiative effect (ACRE), already defined for example by Li et al. (2015) and Harrop and Hartmann (2016) as the difference in cloud radiative effects between the TOA and the surface, and corresponds to the vertically integrated CRE, with unit W/m².

To clarify this point, we have revised the sentence on line 61 (previous version) to:

"In our analyses, we use the following definitions: LH refers to the latent heating profile; LP denotes the vertically integrated latent heating; Qrad represents the radiative heating profile; CRE (cloud radiative effect) refers to the difference between all-sky and clear-sky radiative heating rates, expressed in units of K/day; and ACRE (atmospheric cloud radiative effect) represents the vertically integrated CRE, with units of W/m²."

- Different time periods are selected for analysis (e.g., Fig. 2 (2008-2013), Fig. 3 (2004-2013/2007-2010), Fig. 9 (2004-2018)). Why were these specific time periods chosen?

  For the ANN training in Section 2 we used collocated data. While the CIRS-ML AIRS data are available from 2004 on, the CIRS-ML IASI data are available from 2008 on. Since we preferred to use complete years for the collocation, and in 2014 there were two months missing for TRMM, we used the period until 2013.

  The CIRS-ML LH production was done over the complete periods of CIRS-AIRS (2004-2018) and CIRS-IASI (2008-2018), as explained in the beginning of section 3.

  After verifying the coherence between original TRMM-SLH LP, including the diurnal cycle, and ML-predicted LP at the different observation times in Figure 5, we decided to use only CIRS-AIRS data over ocean for our analysis. To maximize the statistical reliability, we utilized the entire CIRS-AIRS dataset (2004-2018).

- Line 336: "An MCS is defined as an UT cloud system with at least one convective core and the presence of precipitation." How did you distinguish between an MCS and an isolated deep convective cloud system?

  Isolated deep convective systems would be smaller. We look at a scale of grid cells of 0.5°, which leads to a size of about 2500 km^2. But indeed, the definition of a MCS is the scale of 100 km and larger. So, we changed it in the text to convective systems. However, for the analysis of mesoscale organization we excluded convective systems which are built of less than 5 grid cells, so these are MCSs.

- Line 293-295: "In summary, the increasing slopes of the relationship between LP of CIRS–ML and TRMM suggest that our ML-expanded LH dataset is suitable at scales larger than about 2.5° (with a slope of 0.7)."
  a) It would be better to present a plot with the 2.5° scale in Figure 6.
  b) Line 501: "with slopes of 0.68 and 0.76 for 2.5° and 5°, respectively." Please check the slope for the 2.5° scale: is it 0.68 or 0.7?

  Thanks for your comments, we have added the plot for the 2.5° scale to Figure 6, as suggested. For the slope of 2.5° scale, you are correct that it is 0.68, not 0.7. We appreciate your careful attention to this detail, and the correction has been made in the revised manuscript.

- Figure 11 shows negative ACRE when LP < 200 W/m² for precipitating UT clouds over the ocean. However, Figure 10b shows positive ACRE when LP < 200 W/m² for precipitating UT clouds over the ocean. Why is there a discrepancy?

  Thank you for this thoughtful comment.

  Fig.10b: LP is divided into multiple bins, and the average ACRE within each bin is calculated.

  Fig.11: A 2D histogram (pcolormesh) is used to divide the spatial distribution of LP and ACRE into small grids, and the average value of the variable within each grid is calculated. This method captures more detailed local variations and distribution characteristics.

  The discrepancy is because:

  In Fig.10b, for LP < 200 W/m², the ACRE is positive because each bin contains multiple data points, and negative values are masked by the averaging process.

  In Fig.11, each small grid may contain only a few data points, allowing negative ACRE values to be displayed.

  Indeed, the comparison between Figures 10b and 11 shows that there are only few cases with a negative ACRE. These cases occur exclusively in cool-dry environments. In the text (lines 413-414, previous version) we explained that these should be thin cirrus with lower precipitating clouds underneath. The ACRE of these scenes leads to a slightly negative ACRE (Stubenrauch et al. 2021). The CIRS retrieval only identifies the uppermost cloud layer in the case of multi-level clouds.

Minor comments:

- Line 101-102: "Its spectral coverage spans 2378 radiance channels within the wavelength range of 3.7–15.4 µm (650–2700 cm^{-1})"
  What does "650–2700 cm^{-1}" represent?

  The range 650–2700 cm^{-1} represents the wavenumber range, which is another way to express the wavelength range 3.7–15.4 µm.

  Wavenumber (cm^{-1}) is the number of wave cycles per centimeter and is commonly used in infrared spectroscopy. It is related to wavelength (µm) by the formula:

  Wavenumber = 10^4 / wavelength (µm)

  3.7 µm corresponds to ~2700 cm^{-1}, and 15.4 µm corresponds to ~650 cm^{-1}.

  Since this is of no importance for our article, we took out the wave numbers. We have updated line 102 to make this clearer and avoid any confusion.

- Line 214-215: "In all cases, the real data reveal a large variability between 600 and 800 hPa, which may be linked to the variability between stratiform and convective rain within the 0.5°." Why?

  Depending on the fraction of convective and stratiform rain within the 0.5° grid cells, and because the stratiform and convective shapes of the LH profiles are very different (e. g. Schumacher et al. 2004), the shapes vary.

- Line 232: "The minor cooling observed at approximately 550 hPa is attributed to the melting process" Why does melting induce cooling in the radiative longwave (LW) heating profile?

  The cooling observed at approximately 550 hPa due to melting is a result of latent heat absorption. When solid precipitation (such as snow or ice) melts, it requires energy to transition from a solid to a liquid state. This energy is drawn from the surrounding atmosphere in the form of latent heat, which leads to a cooling effect in the local environment. In the radiative LW heating profile, this cooling appears because the absorbed energy lowers the local temperature (Yasunaga et al., 2008), reducing the thermal emission in the longwave spectrum.

- Figure 5: Why does the vertically integrate LH still have the units of K/day? Which lines represent 9:30 AM/PM?

  Thanks for these questions.

  In Figure 5, both y-axes originally showed vertically integrated latent heating (in W/m^2) and averaged latent heating (in K/day), by using a conversion factor. To avoid confusion, we have removed it and kept only the W/m^2 axis.

  The new Figure 5 only shows vertically integrated LH (LP) in W/m^2. We have also simplified the figure for clarity. Since our main focus is the coherence between TRMM–SLH LP and ML-predicted LP, we removed details about SW and LW radiative effects and related text to reduce complexity. After the revision, Figure 5 presents zonal averages of original TRMM LP, including the diurnal cycle, and LP from ML regression using CIRS-AIRS and CIRS–IASI at four observation times of 1:30 and 9:30, each AM and PM.

- Figure 7: "10-year (2008–2018 JAN) averages" Should it be 11 years instead?

  Thank you for catching this. You are correct, it should be 11 years instead of 10. We have updated this in the text.

- Figure 8: Can you show the plot of the difference between CIRS-ML and TRMM/GPCP? The title of the label bar should be LP instead of LH.

  Figure 8 is an illustration to show that the CIRS-ML LP captures the geographical distributions. We have already shown before (Figures 3 and 6 and also new Figures in the supplement) that CIRS-ML regression leads to a smaller range of LP, meaning that small LP is slightly overestimated and larger LP may be largely overestimated. Instead of showing a difference plot in addition, we show a ratio (new Figure S13), which should reflect the slopes given in Figure 6.

  Thank you for your careful review. We have corrected the mistake in the title of the label bar, which has been changed to "LP" in the revised manuscript.

- Line 348: "Figure 9 presents profiles of latent heating and radiative heating…." The label of Figure 9b indicates that the cloud radiative effect (CRE) is presented.

  We apologize for the confusion. The plot actually shows the cloud radiative effect (CRE), which is the difference between all-sky radiative heating rates and clear-sky radiative heating rates. To clarify, we have corrected this in the text. Thank you for pointing it out.

- Line 440: circulation Stephens et al. (2024) -> circulation (Stephens et al. 2024).

Thank you for pointing this out. The error has been corrected to "circulation (Stephens et al., 2024)." We appreciate your attention to detail.

- Line 405: “Humid environments increase the buoyancy of convective clouds, which allows clouds to reach greater heights (Holloway and Neelin, 2009), confirmed by Fig. 10b”. However, Fig. 10b does not provide any information about cloud heights.

  We apologize for the mistake. The correct reference should be Fig. 10c, not Fig. 10b. We have corrected this in the text. Thank you for pointing it out.

- Line 461: “20 km^2” -> “20 W m^{-2}”

  Thank you for catching this error. It has been corrected to "20 W m^{-2}." We appreciate your careful review.

- “LP” is used to represent two different physical variables in one study.
  a) Line 60: “In our analyses, we use the following definitions: LH for latent heating profile, LP for vertically integrated LH”
  b) Line 453: “The relationship between precipitation intensity (LP) and radiative enhancement (ACRE)”

  Thank you for your thoughtful comment. In this study, LP is consistently defined as vertically integrated latent heat. However, we use LP as a proxy for precipitation intensity. To avoid confusion, we have clarified this usage in the revised text (line 547)：

  " ...less organized and larger, more organized MCSs at similar average rain intensity (using vertically integrated latent heating LP as a proxy).

References:

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Yasunaga, K., Hashimoto, A., & Yoshizaki, M.: Numerical simulations of the formation of melting-layer cloud. Monthly weather review, 136(1), 223-241, 2008.