Response to Anonymous Referee #1

Referee #1: This study presents a novel convective cloud data product called GATM, which distinguishes individual MCSs from complex organizations and combine GEOs satellite image with A-Train satellites, making it possible to investigate the anvil production of MCSs and its association mechanisms. Overall, I find the manuscript well written and clearly structured, and I believe it will be a valuable contribution to the literature. I only have minor comments as listed below.

Response: I thank the anonymous reviewer's efforts for reviewing the manuscript. I am very grateful for his/her insightful and helpful comments to improve the clarity and representation of the results. I have carefully taken these comments into account to revise the manuscript accordingly.

Comments:

- *When combining GEO satellite images and A-Train satellites, how would an MCS be counted if the A-Train satellite orbit and the center of the MCS are offset (e.g., the MCS1 scenario in Figure 1)? Are there any special procedures in place to address this situation, and would that introduce any uncertainty to the product?*

  Response: For the MCS1, the A-Train-observed cross section consists of multiple profiles. These profiles are all counted to be the MCS1-related profiles. For each profile, its organization and lifecycle information are derived from the GEO-based MCS tracking.

  Specifically, the procedures of constructing the GATM are as follows:

  (1) Matching the A-Train-observed profiles with GEO image pixels: According to the longitude and latitude of each profile in the A-Train orbit and the satellite overpass time, the A-Train profile is matched with the nearest GEO image pixel, with the distance no more than 3 km and the observational time difference no more than half an hour. As illustrated in Figure 1, the orbit of the A-Train corresponds to four GEO-observed MCSs (MCS1-3 are connected and MCS4 is isolated). By matching the A-Train orbit with the GEO image pixels, the association of these A-Train profiles with the GEO-observed MCSs is distinguished.

  (2) Deriving the organization and lifecycle information from the GEO for the A-Train-observed profile: The organization and lifecycle information for the A-Train and GEO matched profiles in the first step is further derived from the GEO-based MCS tracking. As illustrated in Figure 1, for the MCS1, the A-Train-observed cross section consists of multiple MCS1-related profiles. The GEO provides a full picture of the MCS1 spatial organization structure and its life cycle. In this work, for each MCS1-related profile, the information derived from the GEO includes: a) the distance to the cold-core centroid, which corresponds to its relative position in the MCS; b) the cold-core BT and cold-center BT, which represent the MCS organization structure; c) the cold-core-peak BT, its life stages (developing, peaking or decaying) and the time relative to the convective peaking time, which reflect the MCS life cycle. In this way, these A-Train and GEO matched profiles receive a Lagrangian perspective from the GEO-based MCS tracking.

The GATM combines the advantage of the GEO radiometer imagers in tracking and the advantage of the A-Train active sensors in detecting cloud vertical structures and radiance. In essence, the GEO-based adaptive variable-BT segment tracking data set (Section 2.1) and the A-Train CCCM data set (Section 2.2) are collocated in the GATM. For the GEO-A-Train matching process, a limitation might result from the difference in the temporal resolution between the GEO and A-Train satellites. The GEO images have hourly resolution, whereas the A-Train-observed profiles are instantaneous. Although the observational time difference between the GEO and A-Train satellites is constrained no more than half an hour for matching, clouds could vary significantly during this half an hour. The temporal resolution of the new-generation GEO has achieved 2.5 mins (e.g., Himawari-8 launched in 2014) and benefits tracking in recent years (Daniels et al., 2020; Yang et al., 2023), but the best observational period of the A-Train Constellation is during the year 2006-2011 (Kato et al., 2011). Thus, in this work, to take advantages of the A-Train Constellation, the GEOs of the same period during 2006-2011 are used to construct the GATM.

Overall, the GATM provides a unique perspective to capture the process-level convective anvil outflow in 4 dimensions of space (x, y and z) and time. If only using the CloudSat, the identification of the convective anvil depends on the whether the convective pillar is observed (Igel et al., 2014; Takahashi and Luo, 2012; Deng et al., 2016; Hu et al., 2021). In other words, if the overpass of the CloudSat is not through the core of the MCS, the anvil cannot be determined. As a result, the anvil identification is limited by the satellite orbit. When producing statistics of the convective cloud structure by only using the CloudSat, the core structure of the MCS is composited by more cloudy samples and fewer clear-sky samples, whereas the edge of the MCS away from the core is the composite of fewer cloudy samples and more clear-sky samples. This might lead to a bias in the composited anvil structure further from the core, since it is mixed with a large number of clear-sky samples. On the other hand, by combining the GEO that provides a full picture of the convective system, even though the overpass of the A-Train is not through the core of the MCS, the convective anvil still can be identified (e.g., MCS1 and MCS4 in Figure 1). In this way, for the composites of the anvil structure, none of clear-sky samples is included and thus the composites of the anvil radiative heating structure further from the core is not biased by clear-sky samples.

These descriptions have been added in the revised manuscript.

- *I like how the author discusses the two mechanisms with simple yet clear analyses, but I think the conclusions regarding the two mechanisms and their impact on diurnal cycle of MCSs could be slightly revised for improved clarity* *(e.g., L304-308). My takeaway is that both mechanisms contribute to anvil production of MCSs. Daytime MCSs are primarily dominated by the lapse rate mechanism with a small contribution from differential radiation mechanism, whereas nighttime MCSs are largely driven by clear-sky convergence with almost no contribution from vertical destabilization. Thus, daytime MCSs produce much stronger anvil clouds than nighttime MCSs, leading to the diurnal cycle.*

Response: Many thanks for your very helpful insights. The conclusions at L304-308 have been revised as: "Overall, the lapse-rate and differential radiation mechanisms both can contribute to the MCS anvil production. In Figure 5e, at 13:30 LT, the MCS divergence directly driven by the radiative destabilization (the rapid decline of the net radiative heating with height) is much stronger than the clear-sky convergence (the differential radiation mechanism). This might imply that daytime MCS anvil production is primarily dominated by the lapse-rate mechanism with a small contribution from the differential radiation mechanism. In Figure 5f, at 01:30 LT, the MCS divergence driven by the radiative destabilization (the increase of the net radiative cooling with height) is smaller than the clear-sky convergence. This might imply that the nighttime MCS anvil production is largely driven by the clear-sky convergence with a small contribution from the vertical radiative destabilization. On the diurnal time scale, the divergence determined by the radiative destabilization at 13:30 LT is much stronger than the divergence driven by the clear-sky radiative cooling through the circulation at 01:30 LT. As a result, daytime MCSs produce much stronger anvil clouds than nighttime MCSs, which leads to the diurnal variation shown in Figure 3.".

- *Figure 8: The conclusion presented in the diagram is unclear based on the accompanying text. While there is more anvil clouds in daytime MCSs compared to night-time MCSs, the existence of night-time MCSs still trap LW radiation and reduce outgoing LW radiation (compared to a clear-sky scenario), thereby contributing to a net warming effects on the Earth. How does "less anvil" lead to "more outgoing LW radiation"? Is the author suggesting less anvil and more outgoing LW radiation over time?*

Response: It means that less anvil leads to less trapped outgoing LW radiation. Figure 8 has been modified as shown below.

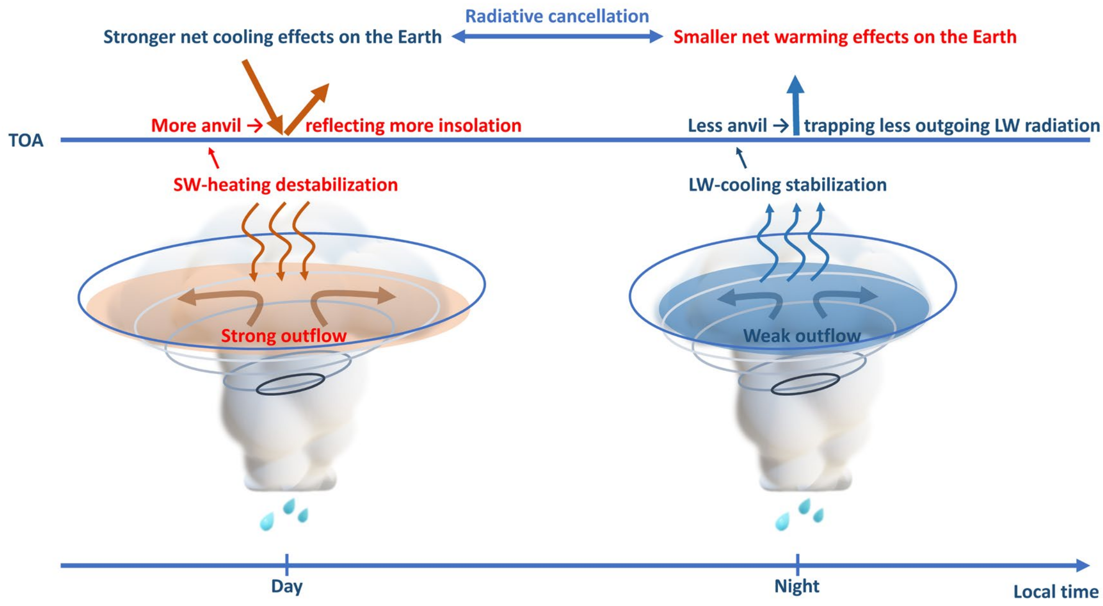

Figure 8. Illustrations of the anvil-radiation diurnal interaction processes.

Minor comments:

- *Fig 2c: If Figure 2c shows the accumulated anvil production of MCSs over the development/decay periods, should the unit be km^2 instead?*

Response: The unit of the anvil area in each BT image is km^2. The time gap of the GEO BT image is 1 hour. Here, the accumulation of anvil areas for the tracked MCS durations is computed as:

$$Accumulated\ anvil\ area = \sum_{i=1}^{D}(A_i \times \delta t), \quad (6)$$

where A represents the anvil area associated with the tracked MCS in each GEO image, and the subscript "i" represents the i-th image for the MCS duration. D represents the MCS duration. δt corresponds to the observational time interval and in this work is 1 hour. As a result, the accumulation of anvil production over a period of time has the unit of km^2*hour.

This has been clarified in the revised manuscript.

- *L229 "Here, the hourly anvil producing efficiency refers to the hourly anvil area produced in the MCS decay process.": Since the unit is in %, shouldn't it be further divided by the mean value instead?*

Response: Yes, it is further divided by the mean value for quantifying their relative variation on the diurnal time scale.

It has been further clarified in the revised manuscript as: "For the accumulated anvil area produced by MCSs, the hourly mean anvil production and duration are two major contributing factors for its diurnal variation. Here, the hourly mean anvil production is defined as the accumulated anvil area divided by the lifetime during the decay stage, which represents the hourly mean anvil area produced in the MCS decay process. In Figure 3, by constraining the cold-core-peak BT, the diurnal variation of the accumulated anvil area, hourly mean anvil production and duration are shown. Here, for the same convective peak BT, the diurnal variation is quantified by the diurnal anomalies at different local times divided by the mean value.”.

- *How does the clear-sky region define when calculating clear-sky radiative cooling?*

Response: The clear sky refers to no clouds above 7 km based on the CCCM data.

This has been clarified in the revised manuscript.

- *L317 “imposes a strong forcing on the Earth radiative energy budget”: Forcing usually refers to external factors acting on the system, such as increasing carbon dioxide concentration, aerosols, etc. Recommend changing the term to something like “plays an important role in Earth’s energy budget’ or something similar.*

Response: It has been revised as: “plays an important role in Earth’s radiative budget”

- *L376: It seems that the unit “W m-2 K-1” is incorrect as it’s inconsistent with the conclusion (L426, W m-2). In addition, it is somewhat unclear how this value should be compared with the high-cloud altitude and tropical anvil cloud area feedbacks from Sherwood et al (2020) and how the difference should be interpreted. This seems to be an apple-to-orange comparison as the unit differ, and the feedback values from Sherwood et al (2020) should already be weighted by the ratio of regional area to global area.*

Response: This sentence has been revised as: “Although the diurnal-cycle climate feedback and its relevant mechanism are still missing in current climate studies, cloud-resolving models and observations both suggested that the diurnal cycle of cloud coverage could have a positive phase shift with surface temperature rising (Yin and Porporato, 2019; Gasparini et al., 2021; Wang et al., 2022). Nevertheless, recent studies have suggested that the diurnal-cycle features of clouds (e.g., diurnal-cycle amplitude and phase) simulated by climate models have significant biases compared against that in the observation (Yin and Porporato, 2017; Chen et al., 2022; Zhao et al., 2023). As a result, predicting the diurnal-cycle climate feedback remains challenging but might be important for understanding the climate sensitivity. Here, diurnal-cycle climate feedback can be largely determined by multiplying the response of the diurnal cycle to the surface temperature by the sensitivity of the radiative budget to the changes in the diurnal cycle. The response of the diurnal cycle is still an uncertain aspect in the future climate, whereas the radiative sensitivity to the diurnal cycle can be assessed."

- *L381: It would be helpful to provide an estimate of the phase shift in response to warming based on previous literatures, such as an order of magnitude or an estimated range.*

Response: Thanks for your suggestion. The sensitivity of NetCREs to the diurnal-cycle phase of convective anvil outflow is approximately -1 W m^{-2} hr^{-1} when the phase shift is in the range between -4 and 8 hr (otherwise the sensitivity has the same magnitude but positive). Notably, the radiative sensitivity to the diurnal-cycle phase is proportional to the diurnal-cycle amplitude amplification ratio (λ) in Figure 7b, with the regression coefficient of approximately 1. As the diurnal-cycle amplitude is stronger with the amplification ratio λ, the radiative sensitivity to the phase shift would be amplified by multiplying by λ. As a result, if the climate response of the diurnal cycle of the convective anvil outflow to the temperature can be known, the sensitivity that is assessed here might be useful for inferring to its feedback strength.

Text:

- *L107: should be "and" rather than comma (i.e., cold cores and cold centers).*

Response: It has been corrected as: "i.e., cold cores and cold centers"

- *L159: Jule -> July*

Response: It has been corrected as: "July".

- *L379: "The" should be lowercase*

Response: It has been corrected as: "the".