Response to Anonymous Referee #2

Referee #2: This manuscript describes a method to track convective systems in the tropics using a so-called 'variable-BT' method. The tracked objectives are evaluated against observations by comparing object drifting speed and direction with those observed from three ARM sites. Contributions of convective activities to precipitation and anvil amount are discussed. I think the topic can be a good contribution to the community by bringing a more flexible tracking framework. However, I believe this manuscript needs substantial improvements before it can be considered for publication.

Response: We thank anonymous referee for reviewing our manuscript and very helpful comments to modify the manuscript. We have responded to all comments and carefully improved the representation of the manuscript accordingly.

Major:

1. ***Grammar and Readability:***

There are numerous grammar errors that make the manuscript difficult to read. The author should do a thorough proof-reading or seek help from a professional editing service before submitting the revised manuscript. Particular attention should be paid to the abstract, as a readable abstract is more likely to attract readers' interest in the method developed and can help increase the paper's impact.

Response: Professional editing service has been used to correct the grammar mistakes and unclear descriptions. Careful proofreading has been done by authors. To improve the readability, the revised manuscript has been reorganized with more subtitles for showing the goal of analyses.

The abstract has been reorganized into two paragraphs, to introduce the innovation of the tracking algorithm; and the convective processes revealed by the novel tracking algorithm. It has been reedited as: "The convective processes of precipitation and the production of anvil clouds determine the Earth's water and radiative budgets. However, convection could have very complicated convective organizations and behaviors in the tropics. Many convective activities in various life stages are connected in complex convective organizations, and it is difficult to distinguish their behaviors. In this work, on the basis of hourly infrared brightness temperature (BT) satellite images, with a novel variable-BT tracking algorithm, complex convective organizations are partitioned into organization segments of single cold cores as tracking targets. The detailed evolution of the organization structures (e.g., the variation in the cold-core BT, mergers and splits of cold cores) can be tracked, and precipitation and anvil clouds are explicitly associated with unique cold cores. Compared with previous tracking algorithms that focused only on variations in areas, the novel variable-BT tracking algorithm is capable of documenting the evolution of both the area and BT structures. For validation, the

tracked motions are compared against the radiosonde cloud-top winds, with mean speed differences of -1.6 m/s and mean angle differences of 0.5°.
With the novel variable-BT tracking algorithm, the behaviors of oceanic convection over the tropical western Pacific Ocean are investigated. The results show that the duration, precipitation and anvil amount of the lifecycle accumulation all have simple loglinear relationships with the cold-core-peak BT. The organization segments of the peak BT values less than 220 K are long-lived, with average durations of 4-16 hours, whereas the organization segments of the warmer-peak BT values disappear rapidly within a few hours but with a high occurrence frequency. The decay process after the cold core peaks contributes to more precipitation and anvil clouds than does the development process. With the core peaking at a colder BT, the differences in the accumulated duration, precipitation and anvil production between the development and decay stages increase exponentially. Additionally, the occurrence frequency of mergers and splits also has a loglinear relationship with the cold-core-peak BT. For the lifecycles of the same cold-core-peak BT, the lifetime-accumulated precipitation and anvil amount are strongly enhanced in complicated lifecycles with the occurrence of mergers and splits compared with those with no mergers or splits. For the total tropical convective cloud water budget, long-lived complicated lifecycles make the largest contribution to precipitation, whereas long-lived complicated and short-lived simple lifecycles make comparable contributions to the anvil cloud amount and are both important.”

2. ***Introduction:***

The author spent most of the space describing the importance of segmenting convective systems, but the motivation for the work in this manuscript is not well articulated. While there are already quite several tracking algorithms in the community, why is the tracking method developed here a necessary contribution? What are the major differences/advantages of your tracking method over others? Why is it important to have the extra features (if any) from your tracking algorithm? This information should be added to either the introduction or the discussion.

Response: A paragraph has been added to introduce the motivation of this work and the advantages of the tracking algorithm developed in this work, as follows: “In this work, complex convective organizations (CCOs) are segmented into simple structural components of single cold cores and tracked separately according to variable-BT11 identification and dynamic overlap. Compared with fixed-threshold tracking, the variable-BT11 tracking algorithm has the advantages of documenting more detailed convective evolution in CCOs. Although several variable-BT11 tracking algorithms have been proposed, the tracked lifecycle is still described mostly by the variation in areas and lacks of the BT11 structural information. By the novel variable-BT11 tracking algorithm developed in this work, the tracked lifecycle is described by the cold-core BT11 variation in the CCO structural components. The precipitation and non-precipitating anvil clouds are explicitly associated with unique cold cores.”

3. ***Flow and Logic:***

The flow and logic of the manuscript need improvement. For example, the paragraph starting from L245 and Figure 5 should be moved up to before Figure 3 or even earlier. The L245 paragraph introduces one of the key novelties of the method developed in this manuscript compared to previous fixed-BT tracking methods, and thus should be introduced and highlighted earlier before demonstrating and evaluating the results in Figure 4 and Figure 3, respectively.

Response: The flow and logic of the Section 3 has been reorganized. Figure 5 has been moved to be the subfigure (f) in the revised Fig. 1. And the L245 paragraph has been introduced and highlighted earlier before the discussing the results of Fig. 3 and 4.

Overall, for readability, subtitles in section 3 have been added to help grasp the goal of analyses and the step of establishing the tracking algorithm, as follows:

(1) Segmenting CCOs into the OSs of single cold cores;

(2) Tracking the displacement of OSs on the basis of cross correlation;

(3) Tracking OSs via dynamic overlaps;

(4) Quality control and validation of variable-BT11 segment tracking;

(5) Comparison with conventional fixed-threshold tracking.

The key novelties of the tracking method developed in this manuscript in comparison to the fixed-threshold tracking are highlighted at the start of the subsection (5) as: "The fundamental difference between fixed-threshold and variable-BT11 tracking is target selection. With the fixed threshold of the BT11, the connected convection of multiple cold cores is recognized as tracking targets, and only the area information is accessible. With the OS as tracking targets, variable-BT11 tracking is capable of documenting the detailed evolution of each OS within CCOs, such as the developing depth, connecting conditions, and contributions to precipitation and anvil clouds.".

4. ***Limitations in ARM observations***

MMCR is a millimeter wavelength radar, and the signal attenuates quickly when observing deep convective clouds, especially in convective core and stratiform regions. The cloud top heights from MMCR in these regions are thus underestimated if relying on ARSCL data for detection. Cloud fraction profiles are also significantly impacted in the upper part of the convective systems. This will likely contribute to the discrepancies in the comparison between the HCS-drift winds and radiosonde cloud-top winds in Figure 3.

Response: Thanks. This limitation due to the beam attenuation has been clarified in the clarified in the main text: "some bias might be attributed to the uncertainty in the cloud-top heights. For its detection, the MMCR might underestimate the cloud top height since its signal would attenuate quickly for deep convective clouds (Hollars et al., 2004). In the convective systems, the motion of air is highly organized (Houze, 2004); thus, system movement might be inconsistent with the observed winds at the cloud-top height.”.

Minor:

Is BT the only parameter used in identifying segments? How did you segment the objects from the BT thresholds? Was it a watershed-type segmentation? The author does not demonstrate well how the ‘variable-BT11’ method works, with details lacking and thus making it hard to evaluate the method’s appropriateness.

Response: Yes, the BT is the only parameter used in identifying segments. Figure 2 in the revised manuscript (as shown below) has been added to illustrate how to segment the objects.

The details of the segmentation have been clarified as in the revised manuscript as: “For segmentation, the pixels lying outside the centers are assigned to the connected neighborhood OSs by the 1-K interval. To be specific, all BT11 contours of the 1-K interval between the cold-center BT11 and 260 K need to be found first. The assignment of the pixels outside the centers is conducted in the order from cold to warm BT11 contours of the 1-K interval. The initial OS is just the center and it is updated after every 1-K-interval assignment. An example illustration of the 1-K-interval assignment is shown in Fig. 2. On the basis of the 8-point-connected neighborhood in which the 8 surrounding points are recognized as the connected neighborhood to the center point, the distance between two pixels is computed as the number of necessary pixels connecting them. According to the nearest linear distance, as shown in Fig. 2a, some of the pixels assigned to OS2 (those light green pixels in Fig. 2a) are disconnected from OS2 but connected to OS1. After the assignment, OS2 is composed of two disconnected parts. For an organized convective system, the assigned pixels outside the center can also be understood as outflowing anvil clouds from the center. It would be strange that the outflowing anvil clouds from OS2 are not connected with its original OS2 but connected with OS1. To avoid these conditions, the distance of the nearest route is used to determine the pixel assignment. Here, the route of OS1 and OS2 to reach a pixel (the blue and red arrows in Fig. 2b) is confined to within the 1-K-interval contour. Pixels of the same distance to OS1 and OS2 are randomly assigned. In Fig. 2b, the assignment of the pixels on the basis of the distance of the nearest route is more reasonable than that in Fig. 2a on the basis of the nearest linear distance. Thus, in every 1-K-interval assignment, the distance of the nearest route is used to accomplish the segmentation and the OSs are updated with these newly assigned pixels iteratively until all the pixels within the CCO are assigned.”.

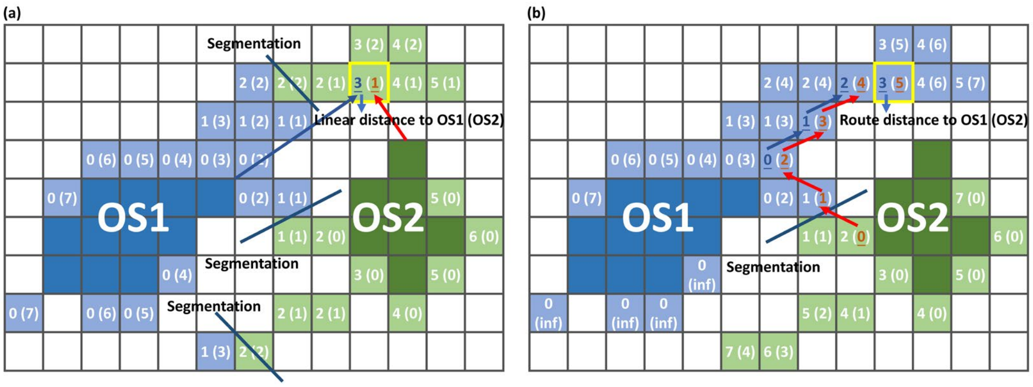

Figure 2. Illustrations of segmentation according to the nearest linear distance (a) and the nearest route distance (b). The dark blue and green pixels represent the OS1 and OS2 centers, respectively. The colored pixels outside the centers are the pixels to be assigned in the contour of the cold-center BT11 plus 1 K. The light blue and green pixels are assigned to OS1 and OS2, respectively. The numbers inside those pixels indicate the number of necessary pixels to connect with OS1 and OS2, respectively. The arrows in (a) and (b) represent the nearest distances of OS1 and OS2 to reach the yellow-edge pixel, as examples to illustrate the computations of the linear distance and the route distance, respectively.

The 'feature-matching displacement' section 2.5, how is this matrix used in the method?

Response: The section 2.5 has been reorganized into the section 3 and a cartoon subfigure has been added into Fig. 1 to illustrate how the feature-matching displacement is used (as shown below).

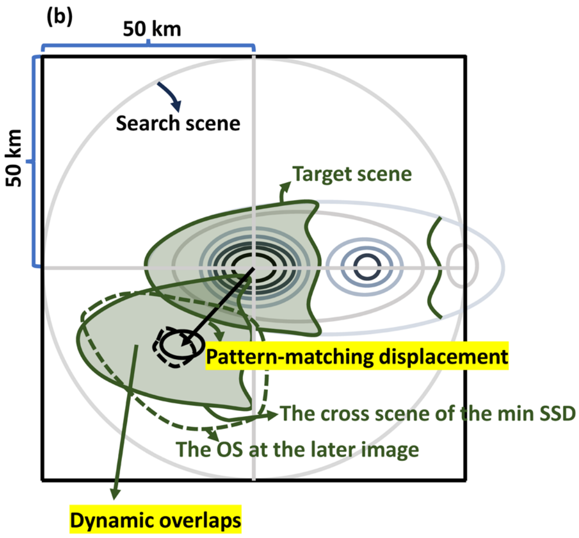

Figure. 1b in the revised manuscript. (b) Example illustrations of tracking the OS by combining cross correlation and the overlap in areas. The OS is moved according to the displacement predicted by cross correlation and then overlaps with the OSs in the later images.

In the main text, it has been clarified as: "In Fig. 1b, to track the temporal evolution of OSs, the OS is moved to the location predicted by cross correlation and then overlaps with the OSs in the later image. In this way, the dynamic overlaps can be used to tolerate the fast-moving OS in tracking.".

What is the minimum temporal resolution required to perform the tracking? You mentioned in Section 2.1 the 1-hour resolution BT images from CERES. Are those the images you used for tracking?

Response: The minimum temporal resolution is 1 hour. Yes, the 1-hour GEO BT11 images from the CERES project are used for tracking. If the missing time gap between two continuous images exceeds 2 hours, the OSs in these two images and all lifecycles including these OSs are excluded from analyses. Additionally, the OS touching the image edges and all lifecycle including the OS touching edges are excluded. This has been clarified in the revised manuscript.

Specific:

L80: GEO should be defined.

Response: It has been defined at the line 50 in the revised manuscript: "geostationary satellites (GEOs)".

L83: Only data from the year 2006 was used?

Response: Yes, only data from the year 2006 was used in this work.

L130: The symbols in the formulas should be explained.

Response: It has been explained as "Here, the mean speed and angle bias, the mean vector difference (MVD), the standard deviation (SD) of the MVD and the root-mean-square error (RMSE) of the tracked cloud motions compared with the observational cloud-top winds were computed. U and V are the x- and y-component winds, respectively. The subscripts i and r indicate an individual sample of the tracked cloud motion and the corresponding reference cloud-top winds of radiosondes, respectively, and N is the total number of samples.".

L138-140: This sentence is unclear. Please rephrase it. When you say 'irregular segments', how do you determine the irregularity? What about segments with relatively regular shapes like convective core regions?

Response: The newly added Fig. 1b (as shown above) in the revised manuscript might be helpful to explain the irregularity. Here, the irregularity means the target scene in the cross correlation is not the regular square box but the segmented organization components with irregular shapes.

This sentence has been rephrased as: "As shown in Fig. 1b, the target scene is the OS BT11 pattern. The search region is centered at the core centroid of the target and confined to a radius of 50 km, which corresponds to a maximum OS motion of 50 km/hour (Merrill et al., 1991). The cross scene has the same shape as the OS target and refers to all possible scenes to match the OS target within the search region. The BT11 pattern of the target scene is normalized, and so is the BT11 pattern of each cross scene. The patten-matching displacement is determined by the minimum of the sum of squared differences (SSD) of the normalized BT11 between the OS target scene and the cross scene.".

Figure 2: How was this figure generated? Is it from hypothetical data or satellite observations? How many years of data are used? Can you add the sample number to the figure?

Response: The cloud-top winds are derived by combing the radar and radiosonde observations at those sites (see more details in Sect. 2.3) as the observational reference to examine the tracked OS motions from the hourly satellite images in 2006. To collocate the observations from the ground-based sites and satellites, the tracked OS-drift winds from the GEO observations that are closest to the time of the cloud-top wind observations and nearest to the site locations are used to compare with the cloud-top winds at those ground-based sites. The observational time difference is no more than one hour and the tracked OS core centroid is within 150 km of those ARM site locations. These are consistent with the previous studies for examining the performance of cloud-drift winds (Nieman et al., 1997; Santek et al., 2019; Daniels et al., 2020). This has been clarified in the revised manuscript.

It is from the satellite observations and not from the hypothetical data. One-year data in 2006 is used. The sample number has been added in the top left-hand corner.

L184: What is the difference between cold-core BT and cold-center BT? The previous paragraph does not seem to describe the terminology well.

Response: Figure 1a has been revised to better illustrate the terminology definitions and Table 1 has been added to summarize these definitions for easily checking (as shown below).

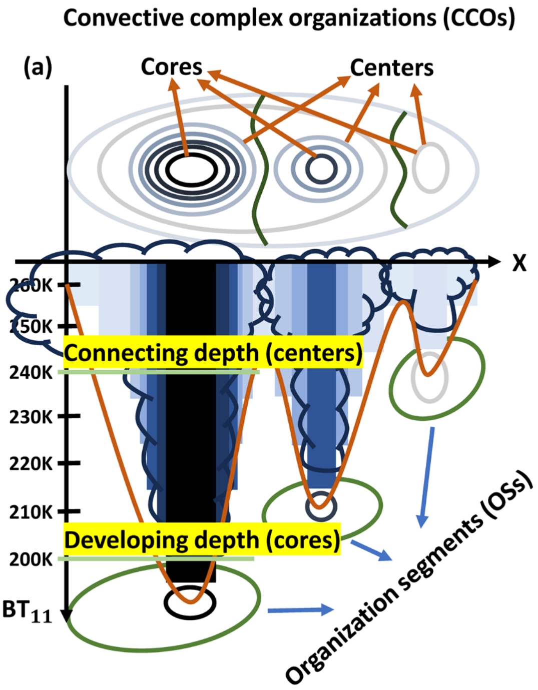

Figure. 1a in the revised manuscript. (a) Example illustrations of segmenting the CCO into single-core OSs as tracking targets. The CCO 3-dimensional structures in x, y and BT11 are identified by the adaptive variable-BT11 thresholds. The cold-core BT11 indicates the depth of development. The cold-center BT11 indicates the depth of the connection.

The innermost ring of the local coldest BT11 is defined as the cold core for the most active vertically developing region in the OS. The BT11 of the cold core represents the OS developing depth. The isolated ring of the warmest BT11 is the cold center and the OS would be connected (disconnected) to the surrounding OSs outside (within) the center. Thus, the cold-center BT11 can be used to indicate the connecting condition between the OSs in the CCO. The complexity of convective organizations can be inferred from the cold-center BT11 of OSs. Only when the cold-center BT11 is 260K, the OS is the isolated convective body and disconnected with other OSs. These descriptions have been added in the main text.

Table 1. Summary of the key definitions for variable-BT_{11} tracking developed in this study

Name	Definition
Complex convective organizations (CCOs)	The contiguous area of the BT_{11} colder than 260 K.
Organization segments (OSs)	The segmented single-core structural component of CCOs.
Cold-core BT_{11} (OS developing depth)	The local coldest BT_{11} contour in OSs.
Cold-center BT_{11} (OS connecting depth)	The local warmest isolated BT_{11} contour of only enclosing one core in OSs.
CCO BT_{11} (CCO developing depth)	The coldest cold-core BT_{11} of multiple cores in the CCO.
Anvil cloud	The non-precipitating (precipitation less than 1 mm/hour) region of each OS.
Dynamic overlapping rates (DORs)	The OS is moved to the location predicted by cross correlation and then overlaps with the OSs in the later image.
Merger and split BT_{11}	The BT_{11} of the merged cold core and the BT_{11} of the splitting cold core.
Cold-core-peak BT_{11}	The coldest cold-core BT_{11} in lifecycles, representing the convective peaking strength.
Development and decay stages	The stage before and after the time of the cold core peaking at the coldest BT_{11} (if there are multiple cores of the same BT_{11}, the one of the largest core areas is selected).
Lifecycle-accumulated duration, precipitation and anvil cloud amount	The accumulated time, precipitation and anvil cloud amount in the lifecycle.

Figure 6: Did you explain how you define the development and dissipation stages somewhere? Are the results shown in Figure 6 (and subsequent figures) from above the three ARM sites, or from the tropics in general as specified at the beginning of Section 2.1? Can you add sample numbers to either the figure or the caption?

Response: The development (decay) stage is defined as the stage before (after) the time of the cold core peaking at the coldest BT11 with the largest core area. It has been clarified in the manuscript and the definition can be checked in Table 1.

The results in Section 4 from Figs. 6-10 are all from the tropical western Pacific Ocean. It has been clarified in the beginning of Section 4 as: "The warm pool of the tropical western Pacific Ocean (130°W-170°E, 20°S-20°N) is a typical region of oceanic convection precipitating and producing anvil clouds (Wall et al., 2018). In this section, only the OS lifecycles over the oceans in this region are considered for investigating the behaviors of the oceanic convection precipitating and producing anvil clouds."

Figure 6 has been added (as shown below) in the revised manuscript to show the sample number of the tracked lifecycles in tropical western Pacific (130°W-170°E, 20°S-20°N) in 2006.

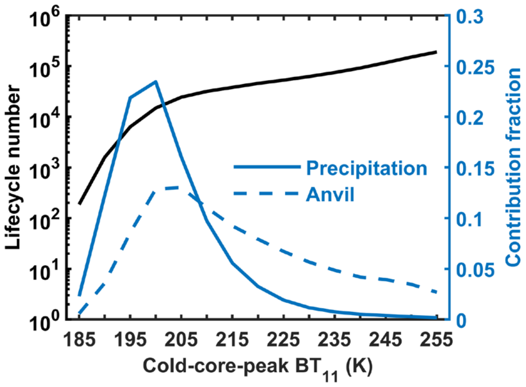

Figure 6. Sample numbers of tracked OS lifecycles with cold-core-peak BT11 values from 185-255 K in the tropical western Pacific (130° W-170°E, 20°S-20°N) in 2006. The contribution fraction of the OS lifecycles to the precipitation and anvil cloud amount is shown on the right axis.