Response to Anonymous Referee #1

Referee #1: The paper by Zhenquan Wang presents a new tracking algorithm for tropical convective systems and uses the algorithm to answer a few science questions about convective storms. Most of the paper is devoted to the tracking algorithm, in which variable brightness temperature (BT11) thresholds are used to identify cloud systems, segment them into convective cores and anvil clouds, and track the evolution, merging, and splitting of the segments over time. One of the main results is that colder BT11 is associated with a greater frequency of mergers and splits. In the last part of the paper, the algorithm is used to examine cloud lifetime, precipitation, and anvil cloud area. These properties tend to display log-linear relationships when plotted against BT11.

This is an interesting study and reflects an impressive amount of work by the author. I have no doubt that the tracking algorithm developed here is well motivated and well executed, and it seems like it could produce an interesting dataset from which many questions about convective cloud systems could be examined.

However, there are serious issues regarding the clarity of presentation in this paper. I found much of the writing and descriptions of the methodology to be very unclear, and the terminology used for the tracking algorithm was confusing and difficult to grasp. For these reasons, I do not feel equipped to evaluate the appropriateness of the methodology or to understand what the scientific conclusions really mean. So, please excuse me for being unable to provide much constructive feedback here. I would be happy to do so in the future once the presentation has been clarified. Some general comments are below, followed by line comments.

Response: We thank the anonymous reviewer for his/her efforts of reviewing our manuscript. We are very grateful for his/her valuable comments to help us improve the representation of the results. We have carefully taken these comments into account and accordingly revised and reorganized the manuscript to clarify the writing and descriptions of the methodology.

1. Unclear terminology. *Cold-core, cold-center, segmentations, HCSs, organizations, organization segments, mergers & splits. Some of these terms are more clearly defined than others, but the precise meanings need to be clarified (especially HCS). Fig 1a was helpful for understanding centers vs cores…perhaps a similar schematic would help for the other terms.*

Response: The definitions of these terminologies have been specifically clarified in the main text. Figure 1 has been revised by adding more cartoon subfigures to help to understand these terminologies and the steps of establishing the variable-BT11 tracking algorithm (as shown below). Table 1 has been added to summarize these terminology definitions for easily checking (as shown below).

The terminology definitions can be checked as follows for how they have been revised in the manuscript:

(1) Terminology used in the target identification:

Complex convective organizations (CCOs): the contiguous area of the BT11 colder than 260 K.

Organization segments (OSs): the OS and the high cloud system (HCS) have exactly the same meaning and both represent the CCO segment of a single cold core, which is the target of the variable-BT11 tracking. It represents the structural component of CCOs. To avoid misunderstanding, in the revised manuscript, only the terminology of "OS" is used.

Cold cores: the local coldest BT11 contour within the OS. The cold-core BT11 represents the developing depth of the OS.

Cold centers: the local warmest isolated BT11 contour of the OS, which encloses only one cold core. The cold-center BT11 represents the warmest BT11 of it disconnecting from other OSs.

Segmentations: the OS outlines. The OS BT11 structure is simply characterized as the core and OS outlines. In the revised manuscript, "segmentations" has been replaced with "the OS outlines".

Anvil: the non-precipitating (precipitation less than 1 mm/hour) region in each OS.

(2) Terminology used in the target tracking:

Dynamic overlapping ratios (DORs): the OS is first moved to the locations predicted by the cross correlation and then overlaps with the OSs at the later moment. For the OS with single cores, three DOR indices are considered to determine the associations of two OSs at different times for whether they are the same object, including the DOR between cores, the DOR between OSs and the DOR between cores and OSs. In the revised manuscript, a cartoon illustration of the dynamic overlaps has been added as Fig. 1b.

Mergers and splits: Notably, the OS is not necessarily associated with only one OS. Mergers and splits are allowed and identified as the many-to-one and one-to-many OS associations, respectively. The mergers and splits in the fixed-BT11 and variable-BT11 tracking are very different. Mergers and splits in fixed-threshold tracking are dependent on the selection of the BT11 threshold. Owing to the selection of the fixed BT11 threshold, the identified targets are usually connected under a warmer threshold but are disconnected under a colder threshold. As illustrated in Fig. 1f, if under the fixed threshold of 260 K, no mergers or splits occur. If under the fixed threshold of 220 K, the cutoff of the CCO by 220 K is the connected complex of multiple cores or two disconnected parts at different times. This change in the connecting conditions over time under the selected fixed threshold results in mergers and splits in fixed-threshold tracking. If under the fixed threshold of 200 K, the mergers and splits of cold cores are captured. It manifests that mergers and splits in fixed-threshold tracking can be attributed to many reasons: the threshold selection, the change in the connecting conditions and the variation in cold cores over time. In contrast, in variable-BT11 tracking, mergers and splits are not influenced by changes in the connecting conditions over time but is only related to the variation in cold cores as illustrated in Fig. 1e-f. In the revised manuscript, a cartoon illustration of Fig. 1e has been added to show the mergers and splits in the variable-BT11 tracking. Fig. 5 of the previous manuscript has been moved to Fig. 1f to illustrate the difference of the mergers and splits between the fixed-BT11 and variable-BT11 tracking.

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.

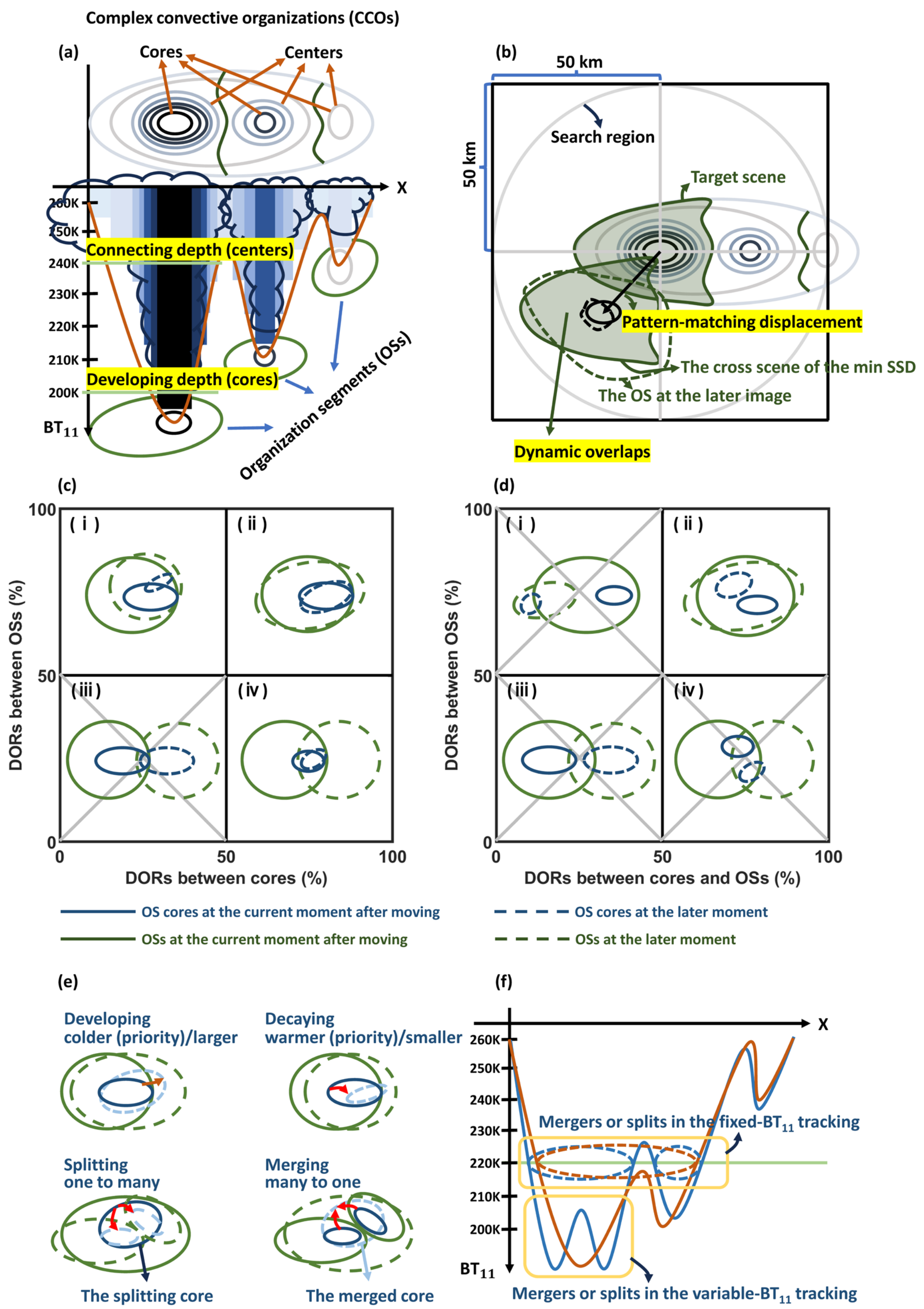

Figure 1. Illustrations of the variable-BT11 segment tracking algorithm. (a) Example illustrations of segmenting the CCO into single-core OSs as tracking targets. The CCO 3-dimensional structures in x, y and BT11 are identified by the adaptive variable-BT11 thresholds. The cold-core BT11 indicates the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

two OSs of different moments when their cores have overlaps and no overlaps, respectively. The solid blue and green lines indicate the OS core and segmentation outlines of the current moment at the location predicted by cross correlation, respectively. The dashed blue and green lines indicate the OS core and segmentation outlines of the later moment, respectively. The gray cross indicates the non-association between OSs. (e) Examples illustrating tracked OS evolution (i.e., development, decay, mergers and splits). The red arrows indicate the evolution of the OS with time. (f) Illustrations of the difference between the variable-BT11 and fixed-BT11 tracking for mergers and splits. The solid red and blue lines are the CCO BT11 structures at different times captured by the adaptive variable-BT11 thresholds. The dashed red and blue contours are the mergers and splits captured by the fixed threshold of 220 K.

2. Clarifying the methodology. *The description of pattern-matching and the tracking algorithm were both quite confusing to me. The goals of each part of the analysis should be clearly laid out at the beginning of each section. It is confusing how segmentations, mergers, and splits are defined. I wish I could point to more specific aspects that I did not understand, but I am finding it difficult to do so at this point.*

Response: The description of pattern-matching and the tracking algorithm has been reorganized according to the steps of establishing the tracking algorithm with subtitles to indicate the goals of each step, 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.

Fig. 1 has been revised to help to understand the terminology definitions and steps of the tracking algorithm. In the revised Fig. 1, Fig. 1a illustrates the target identification by adaptive variable-BT11 thresholds. Fig. 1b illustrates the target tracking by the pattern-matching and dynamic overlaps; Fig. 1c-d illustrate the dynamic overlapping conditions. Fig. 1e-f illustrate the difference of the variable-BT11 tracking with the conventional fixed-BT11 tracking. Overall, Fig. 1 shows the flowchart of the tracking algorithm by cartoons.

The descriptions have also been revised according to the following minor comments. Please see more details in the responses to minor comments or in the revised manuscript.

Table 1 has been provided to summarize the terminology definitions for easily checking (see the response to the major comment #1). The mergers and splits have been illustrated in the revised Fig. 1e. Mergers and splits are identified as the many-to-one and one-to-many OS associations, respectively.

The goal of the section 3 is to introduce the variable-BT11 tracking algorithm and its difference with the conventional fixed-BT11 tracking algorithm. The goal has been clarified at the beginning of section 3 as follows: "To distinguish the behaviors of clustered convective activities in CCOs, the organization segments (OSs) of single but variable-BT11 cold cores (Fig. 1a) are partitioned as tracking targets and are tracked by combining the cross correlation and the area overlap (Fig. 1b) based on the hourly infrared satellite images. This novel variable-BT11 segment tracking algorithm and its difference from the conventional fixed-threshold tracking algorithm are introduced in this section as follows.".

3. Mergers & Splits statistics. *Another thing to clarify is how statistics are computed for mergers and splits (e.g. Fig 7 and 8). How is a PDF of mergers and splits as a function of BT11 calculated? What if the two merging cores have different BT11? Which of the merging cores do the precip and anvil statistics represent? This was all very unclear.*

Response: In Fig. 7 and 8, the BT11 of mergers and splits refers to the merged cold-core BT11 and the splitting cold-core BT11, respectively, as illustrated in revised Fig. 1e. In this way, the BT11 of mergers and splits is represented by one splitting or merged core to compute the PDF as a function of BT11. The precipitation and anvil in Fig. 8 are the lifecycle-accumulated precipitation and anvil amount, which represent the accumulated precipitation and anvil of all OSs in a lifecycle. It has been clarified in the main text and the definitions have been summarized in Table 1.

4. Cloud property results.

- *I cannot find a description of how the anvil area is computed. Is it just the entire nonprecipitating area of each individual segment?*

  Response: Yes, the anvil is defined as the non-precipitating (precipitation less than 1 mm/hour) region of each OS.

  It has been clarified in the revised manuscript as "The OS can be further separated into precipitating and non-precipitating (precipitation less than 1 mm/hour) regions on the basis of the GPM. The non-precipitating area is identified as the anvil cloud. By segmentation, those precipitation and anvil pixels are explicitly associated with unique cold cores.".

  The definition can also be checked in Table 1.

- *The study region is (20S-20N, 90E-170E), which I find to be interesting from a cloud property perspective. I imagine this choice was largely motivated the availability of different observations, especially the ARM sites. The region* *includes some of the western Indian Ocean and Bay of Bengal, the entire Maritime Continent region, and some of the west Pacific warm pool. The characteristics of convective systems can differ significantly between the maritime continent, where land -based convection dominates, and the oceanic regions, where larger mesoscale convective systems are typical (see Fig 9 in Yuan & Houze 2010, doi:10.1175/2010JCLI3671.1). Does it make sense to aggregate the precipitation, duration, and anvil area statistics across this entire region? I imagine there would be considerable differences between the Maritime Continent and the oceanic regions, with smaller cloud systems and fewer mergers/splits for land-based convection. The author could consider stratifying the results by region, or at the very least acknowledging what I imagine are very large spreads within each BT11 bin for the cloud property statistics.*

Response: In consideration of the significant difference of the convective systems between the maritime continent and oceanic regions, we only focus on the oceanic regions in Section 4 in the revised manuscript. The warm pool of the tropical western Pacific Ocean (130°W-170°E, 20°S-20°N) is a typical region of the oceanic convection precipitating and producing anvil clouds (Wall et al., 2018). In Section 4, only the OS lifecycles over oceans of this region are considered for investigating the behaviors of the oceanic convection precipitating and producing anvil clouds. This has been clarified at the beginning of Section 4.

5. Grammar and Structure. *As a native English speaker, I found this paper quite difficult to understand at times, and this is likely a major reason for the perceived lack of clarity. I simply want to share that thought with the author, so that they can adjust and edit as they see fit. If editing services are available at the author's institution, they may wish to pursue them. This is simply a suggestion, and I do not consider it necessary for the paper to be published, as long as the necessary components are greatly clarified.*

Response: Thanks. To improve the readability, the revised manuscript has been better structured by adding more subtitles for showing the goals of each analysis. The descriptions have been adjusted and reedited with more examples and details to improve the clarity according to comments from referees. Editing services have been used to help to correct grammar mistakes and to revise the unclear descriptions. Careful proofreading has been done by authors.

More Minor Comments:

- *What is meant by "organization segments"…does this just mean the different structural components of the storm?*

Response: Yes, the OS is the segmented single-core structural component of the complex organizations. The OS is the tracking target of the variable-BT11 tracking algorithm.

It has been clarified in the revised manuscript as "As illustrated in Fig. 1a, the CCO is the complex organization of multiple connected convections and is identified as the contiguous area of the BT11 that is colder than 260 K. The 260-K threshold can enclose 95% of deep convective clouds and as much of the anvil cloud as possible but with the least contamination from lower-level clouds (Yuan and Houze, 2010; Yuan et al., 2011; Chen and Houze, 1997). The segmented single-core structural component of CCOs is identified as the OS to be used as the tracking target."

A cartoon in Fig. 1a might be helpful to understand the OS definition.

- *Line 30: "due to **the fact** that the…"*

Response: It has been corrected.

- *Line 43-46: the author cites three papers as evidence that convective organization and precipitation efficiency (PE) are related, but I am not sure these references are correct. Bao & Sherwood (2019), https://doi.org/10.1002/2018MS001503, seems like a more appropriate reference here. Choi et al (2017) found that greater PE (by their definition of PE) was associated with reduced cirrus cloud area, but this is not the same thing as convective organization. Lindzen et al (2001) and Mauritsen & Stevens (2015) hypothesized about the relationship between PE and anvil cloud area, but did not present any evidence of a relationship between organization and PE.*

Response: It has been corrected.

- *Line 51: what are the two distinct modes of convection being referred to here?*

Response: The two distinct modes are in terms of the BT11 and refer to the deep convective clouds and anvil clouds.

This sentence has been corrected as: "From the images of the brightness temperature at 10.8 μm (BT11) of geostationary satellites (GEOs), pixels of thin cirrus clouds cannot be accurately distinguished from cloudless pixels, but the major structure of the organized convection, consisting of the deep convective clouds and the associated anvil clouds, can be observed continuously in time and used for tracking".

- *Line 81: replace "190 W" with "170 E"*

Response: It has been corrected.

- *Line 128: the equation for the speed bias (eq 1) is incorrect. The subscripts are switched around. See eq 4 in Nieman et al (1997)*

Response: It has been corrected.

- *Line 128: latter -> later*

Response: It has been corrected.

- *Section 2.5: this section was very unclear to me. Please provide some context for what the goal of this pattern matching is and how it fits in to the tracking algorithm*

Response: The goal of the pattern matching based on the cross correlation is to predict the displacement of OSs. The OS is moved to the location predicted by the cross correlation and then overlaps with the OSs in the later image. In this way, the dynamic overlaps by combining the cross correlation and the overlap in areas are used for tracking the OS, which avoids the mistakes in tracking the fast-moving OS.

To better introduce the goal of the pattern matching and how it fits the tracking algorithm, this subsection has been rephrased and is reorganized into the Section 3 of the tracking algorithm in the revised manuscript. And a cartoon subfigure has been added as Fig. 1b for explaining how the pattern matching is achieved and how it fits the tracking algorithm. The pattern matching is a necessary step to find the OS movement for accomplishing the dynamic overlap.

  - *Line 142: "normalized BT11"…normalized in what sense?*

    Response: The BT11 in the target scene and the BT11 in each cross scene are normalized, respectively. 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.

    This has been clarified in the revised manuscript as: "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”.

- *Define “target scene” and “cross scene”*

Response: The definitions of the target and cross scenes have been added in the main text: “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.”.

Fig. 1b has been added for illustrating these definitions.

- *Line 145-146: “for the areas larger…” what areas are you talking about?*

Response: It is the area of the tracking target. The organization segment of irregular shapes is selected as the tracking target. For large (small) targets, a lower (higher) threshold for the pattern correlation is used to examine the pattern matching. It has been clarified in the manuscript.

- *It seems that SSD would be minimized if the BT11 field does not change at all from one time to the next. Are the fields adjusted in space to overlap? Is this what normalization refers to? This was generally quite confusing.*

Response: Yes, if the BT11 field does not change at all, the SSD is minimized when the displacement is zero. The BT11 fields are not adjusted to overlap, but the location of the target is adjusted according to the predicted displacement and then to overlap. The normalization refers to that the BT11 in the target scene and the BT11 in each cross scene are normalized, respectively, then are matched to calculate the SSD.

A cartoon figure has been added as Fig. 1b, which could be helpful to understand the cross correlation. The target scene refers to the OS with irregular shapes. The cross scene has the same shape to the target scene, and is within the search region of the radius 50 km. The BT11 in the target scene and the BT11 in the cross scene are normalized, respectively, and then are matched to calculate the SSD. Then, the location of the target is adjusted according to the displacement predicted by cross correlation and then overlaps with the OSs in the later image.

The flowchart is as follows:

(1) Segmenting the complex organizations into the organization segment (OS) of single cores (Fig. 1a);

(2) Tracking the displacement of the OS based on the cross correlation (Fig. 1b);

(3) Moving the OS to the locations predicted by the cross correlation and then computing the overlaps with the OSs at the later moment (referring to dynamic overlaps) (Fig. 1b).

(4) Tracking the OS by the dynamic overlaps (Fig. 1c-d).

For clarity, the main text has been reorganized according to the flowchart and each part has been added a small title to clarify the purpose.

- *Fig 1:*
  - *the font size in panel 1a is too small at the top of the figure ("centers" and "cores"). The green font color for "connecting depth" and "Developing depth" is hardly visible.*

Response: The font size of Fig. 1a has been enlarged. The font color has been modified.

  - *What does "after moving" mean in the legend? Aren't you showing two moments in time, with the dotted lines indicating the later moment? Aren't the solid lines then showing the "before moving" picture?*

Response: "after moving" means that the tracking target is moved to the predicted location by the cross correlation (the solid lines) and then overlaps with the targets in the later images (the dash lines). Yes, the solid and dash lines indicate the targets at the current and later moments, respectively. But, by the cross correlation, the displacement of the current target is predicted and the target is first moved to the predicted location and then overlaps with the targets in the later images.

A more detailed illustration of dynamic overlaps has been added as Fig. 1b.

- *Panels b,c: do the displacements between the solid and dotted lines reflect displacement over time? Or have the later moments been pattern-matched and adjusted for maximum overlap?*

  Response: The displacement between the solid and dotted lines does not reflect the displacement over time. The location of the target at the current moment has been adjusted by the cross correlation before overlapping with the targets at the later images. Fig. 1b has been newly added and could be helpful to explain how the dynamic overlaps are computed. As shown in Fig. 1b, the dynamic overlaps refer to the overlap between the cross scene of the min SSD and the target at the later image.

- *Line 180: If I am understanding correctly, the algorithm detects the full cloud segment by expanding out from the core in 1K BT11 intervals. I imagine there is some ambiguity at times, in which it is not obvious which core a piece of anvil cloud should be assigned to? How is this dealth with?*

Response: 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.

This has been clarified in the revised manuscript.

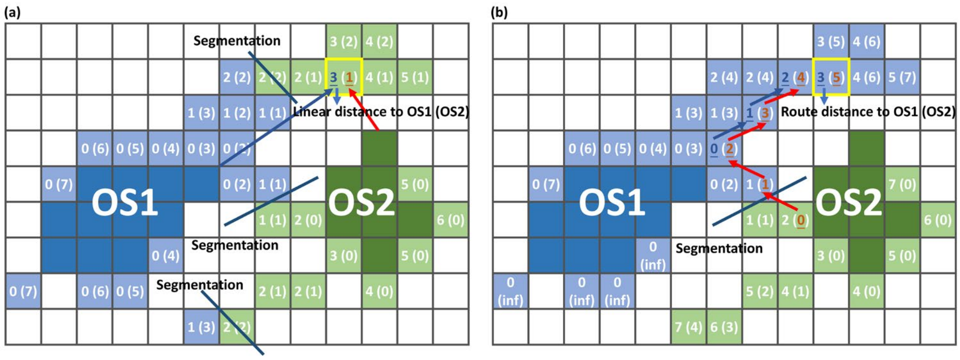

Figure 2. Illustrations of segmentation according to the nearest linear distance (a) and the nearest route distance (b). The dark blue and green pixels represent the OS1 and OS2 centers, respectively. The colored pixels outside the centers are the pixels to be assigned in the contour of the cold-center 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.

- *Lines 185-190: this paragraph was quite confusing to read, and I had to read it about 5 times to understand the details here. Cold-center BT11, complex BT11, and cold-core BT11 should be more clearly defined somewhere…at the moment they are buried in Fig 1a.*

Response: Table 1 has been added to provide a summary of the key definitions in this study.

- *Line 200: for clarity, specify "The core-core and segmentation-segmentation DORs are relative to the minimum area… The core-segmentation DORs are relative to the core area"*

Response: These definitions have been clarified in the main text as "For the OS with the core structure, three indices of the dynamic overlapping ratio (DOR) are considered to determine the associations of two OSs at different times for the same object, including the DOR between cores, the DOR between OSs and the DOR between cores and OSs. The DOR between cores is the ratio of their overlaps in cores relative to the minimum area of the cores to represent the degree of core overlap. The DOR between OSs is the ratio of the OS overlap relative to the minimum area of the OS to represent the degree of OS overlap. The DOR between cores and OSs is the ratio of the overlap of the OS to the core relative to the core area, representing the degree of the core overlapped by the later or previous OS.".

- *Lines 198-205 – this paragraph is also confusing to read. Does "temporal associations" mean that the you consider it to be the same storm at different times?*

Response: Sorry about that. Yes, the temporal associations indicate the same storm at different times. It has been explained in the main text.

This paragraph has been rephrased as "Two OSs of different moments are associated in time and considered the same object when these two OSs overlap sufficiently. The overlapping situations of two OSs are distinguished by whether their cores overlap with each other (Fig. 1c) or not (Fig. 1d). Those pairs of OSs in situations (ⅰ), (ⅱ) and (ⅳ) in Fig. 1b all sufficiently overlap with the DOR between either cores or OSs greater than 50% and thus are associated in time to reflect the OS evolution with time. The situation (ⅲ) in Fig. 1c with DORs of both cores and OSs less than 50% indicates that these two OSs have no associations. In Fig. 1d, when the cores of two OSs do not overlap, the determinant of the OS association relies on the DOR between OSs and the DOR of OSs to cores. In those cases, the OSs are associated in time only in situation (ⅱ) in Fig. 1d, with those two DOR indices both larger than 50%. Those pairs of OSs in the other situations in Fig. 1d are obviously not associated. Overall, if the DORs of two OSs satisfy the overlapping conditions of (ⅰ), (ⅱ) and (ⅳ) in Fig. 1c and (ⅱ) in Fig. 1d, they are associated in time.".

- *Fig 2 middle row: the arrows were a bit confusing, maybe it could be equally effective to just put red and white dots on each panel (optional suggestion).*

Response: The arrows have been replaced with dots.

- *Line 241: unclear: "thus ends by less disconnected convection complex". It looks less connected, not less disconnected.*

Response: It has been corrected as "The major branch (the red line in the middle panel of Fig. 5) begins with the large complex organization of connected convections but ends with only one of disconnected parts."

- *Line 244: "evolution of the system structures but not the variations of the connections?"…what does this mean?*

Response: Mergers and splits in fixed-threshold tracking are dependent on the selection of the BT11 threshold. Owing to the selection of the fixed BT11 threshold, the identified targets are usually connected under a warmer threshold but are disconnected under a colder threshold. As illustrated in Fig. 1f, if under the fixed threshold of 260 K, no mergers or splits occur. If under the fixed threshold of 220 K, the cutoff of the CCO by 220 K is the connected complex of multiple cores or two disconnected parts at different times. This change in the connecting conditions over time under the selected fixed threshold results in mergers and splits in fixed-threshold tracking. If under the fixed threshold of 200 K, the mergers and splits of cold cores are captured. It manifests that mergers and splits in fixed-threshold tracking can be attributed to many reasons: the threshold selection, the change in the connecting conditions and the variation in cold cores over time. In contrast, in variable-BT11 tracking, mergers and splits are not influenced by changes in the connecting conditions over time but is only related to the variation in cold cores as illustrated in Fig. 1e-f.

Examples are shown in Fig. 5. In the fixed-threshold tracking of 210K (the middle panel of Fig. 5), the mergers and splits are caused by the variations of whether convections are connected or not under the 210-K threshold. In the variable-BT11 tracking (the bottom panel of Fig. 5), the tracked mergers and splits are the mergers and splits of cold cores and are not influenced by the variations in the connecting conditions with time. This explanation has been added to the revised manuscript.

- *Figure 5 is completely lost on me – I do not know what this figure is trying to show, and the caption is not very helpful here. Please explain this figure.*

Response: Figure 5 has been modified to be the Fig. 1f in the revised manuscript. The caption has been revised as "Illustrations of the difference between the variable-BT11 and fixed-BT11 tracking for mergers and splits. The solid red and blue lines are the CCO BT11 structures at different times captured by the adaptive variable-BT11 thresholds. The dashed red and blue contours are the mergers and splits captured by the fixed threshold of 220 K."

In the main text, it has been explained as "mergers and splits in fixed-threshold tracking are dependent on the selection of the BT11 threshold. Owing to the selection of the fixed BT11 threshold, the identified targets are usually connected under a warmer threshold but are disconnected under a colder threshold. As illustrated in Fig. 1f, if under the fixed threshold of 260 K, no mergers or splits occur. If under the fixed threshold of 220 K, the cutoff of the CCO by 220 K is the connected complex of multiple cores or two disconnected parts at different times. This change in the connecting conditions over time under the selected fixed threshold results in mergers and splits in fixed-threshold tracking. If under the fixed threshold of 200 K, the mergers and splits of cold cores are captured. It manifests that mergers and splits in fixed-threshold tracking can be attributed to many reasons: the threshold selection, the change in the connecting conditions and the variation in cold cores over time. In contrast, in variable-BT11 tracking, mergers and splits are not influenced by changes in the connecting conditions over time but is only related to the variation in cold cores as illustrated in Fig. 1e-f."

- *Figure 6*
    - *It would be nice to add a panel showing the sample size for each cold-core-peak BT11 bin.*

Response: Figure 6 has been added in the revised manuscript to show the sample size for each cold-core-peak BT11 bin, as shown below.

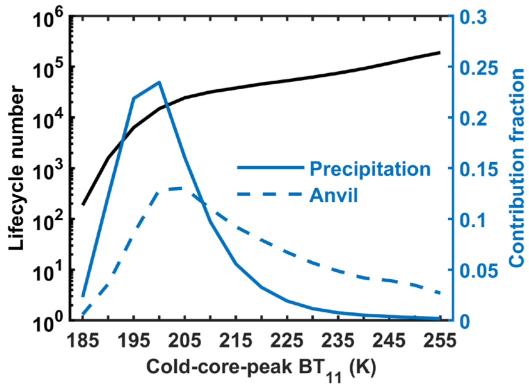

Figure 6. Sample numbers of tracked OS lifecycles with cold-core-peak BT11 values from 185-255 K in the tropical western Pacific (130°W-170°E, 20°S-20°N) in 2006. The contribution fraction of the OS lifecycles to the precipitation and anvil cloud amount is shown on the right axis.

- *it would be nice to see the spreads in duration, precip, and anvil amount for each cold-core-peak BT11 bin. The t-test for the mean is nice, but I imagine these is a very large spread on these quantities, since convective systems vary greatly in size. It would be good to show the spread if there is a simple way to do so.*

Response: The PDFs of the lifecycle-accumulated duration, precipitation and anvil amount for each cold-core-peak BT11 have been added in Figure. 7a-c in the revised manuscript, as shown below.

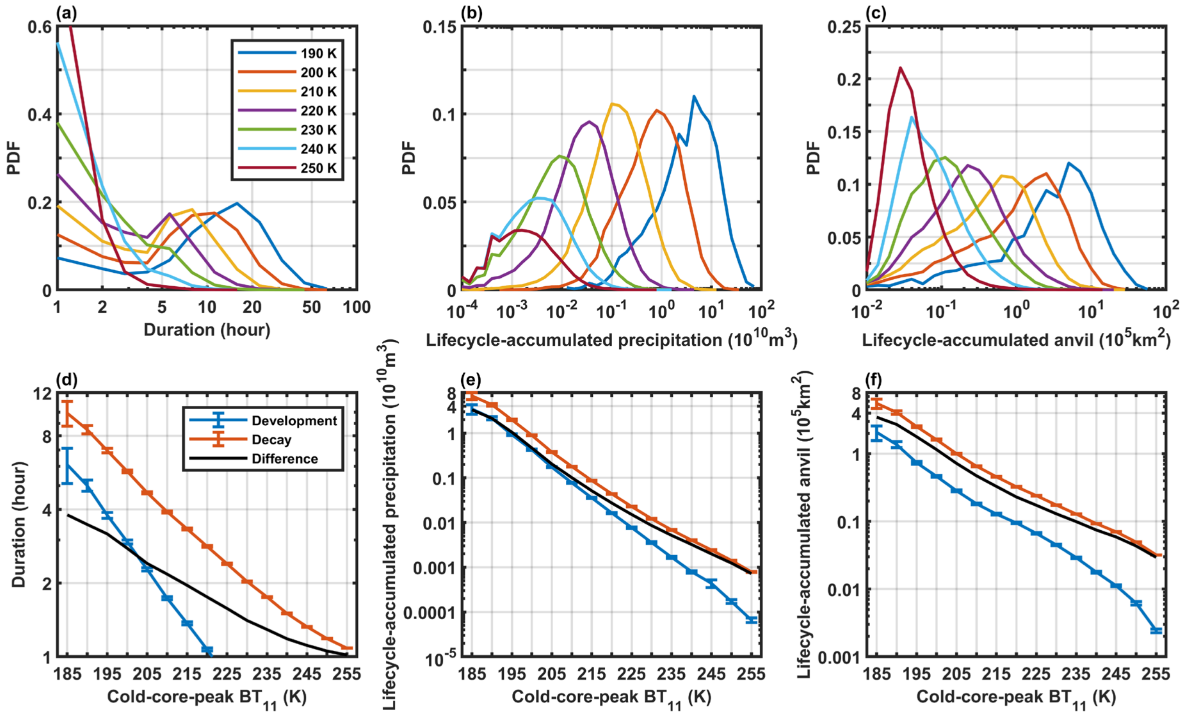

Figure 7. PDFs of the accumulated duration (a), precipitation (b) and non-precipitating anvil amount (c) of the OS lifecycles of different cold-core-peak BT11 values from 190-250 K. The mean accumulated duration (d), precipitation (e) and non-precipitating anvil amount (f) contributed by the development (blue lines) and decay stages (red lines) as a function of the cold-core-peak BT11 from 185-255 K. The black lines represent the differences in the accumulated duration, precipitation and anvil between the development and decay stages in (d-f), respectively. The error bars indicate the 95% confidence intervals of the means based on the t test.

- *Line 269-270: "and the difference of the duration, precip, and anvils between two stages has exponential increases with the core peaking at colder BT11." I am struggling to see how this is the case in Fig 6. It does not seem like the difference between the orange and blue lines is exponentially greater at lower BT11, although it is hard to tell because of the log scale.*

Response: The difference of the duration, precipitation and anvils between two stages has been shown in Figs. 7d-f by the solid black lines. It can be seen the difference roughly has an exponentially increase with the core peaking at colder BT11.

- *Lines 278-281: this sentence is not clear, please revise. Will be helpful once HCS is clearly defined. For example, how do mergers and splits create more HCS? My initial thought was that HCS referred to the entire system BT11<260, including many segmentations?*

Response: The HCS in the previous manuscript is just the segmented single-core structural components. To avoid misunderstandings, we directly use the "organization segments (OSs)" to replace the "HCS". Here, we mean that the mergers and splits would create more OSs in the lifecycle to increase the precipitation and anvils.

- *Equations 7 & 8: what is N exactly? The definition of HCS seems to be very important here. Is it the number of segments? Also, it would be helpful to explain what the point of this sort of analysis is before showing the results.*

Response: The N is the lifecycle-accumulated number of OSs. Yes, it is the number of segments. It has been clarified in the revised manuscript as: "N is the accumulated OS number in the lifecycle".

The purpose of this analysis has been clarified at the beginning before discussing the results as: "How do mergers and splits influence the lifecycle-accumulated precipitation and anvil cloud amounts? There are two possible mechanisms: the hourly precipitation and anvil production of each OS in the lifecycle are enhanced, and the accumulated number (N) of OSs in the lifecycle is increased.".

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.”.

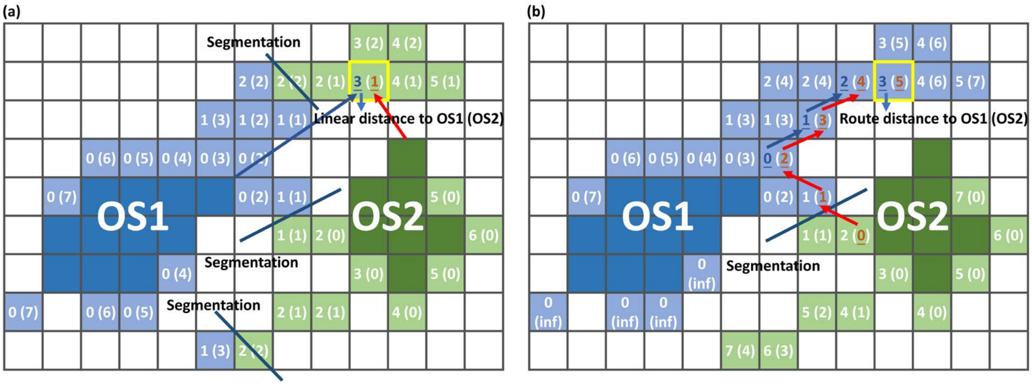

Figure 2. Illustrations of segmentation according to the nearest linear distance (a) and the nearest route distance (b). The dark blue and green pixels represent the OS1 and OS2 centers, respectively. The colored pixels outside the centers are the pixels to be assigned in the contour of the cold-center 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).

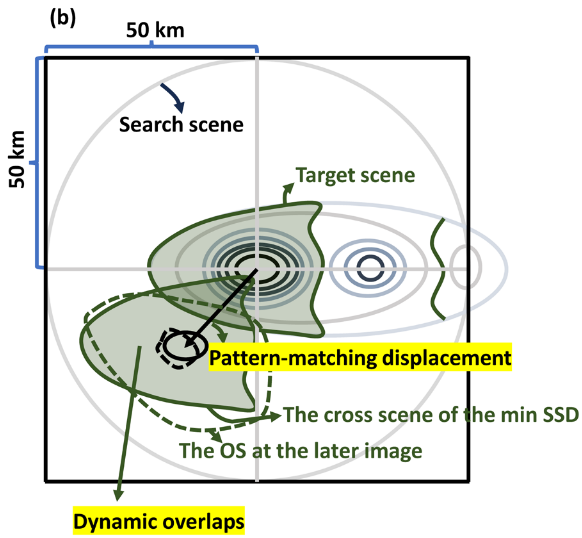

Figure. 1b in the revised manuscript. (b) Example illustrations of tracking the OS by combining cross correlation and the overlap in areas. The OS is moved according to the displacement predicted by cross correlation and then overlaps with the OSs in the later images.

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).

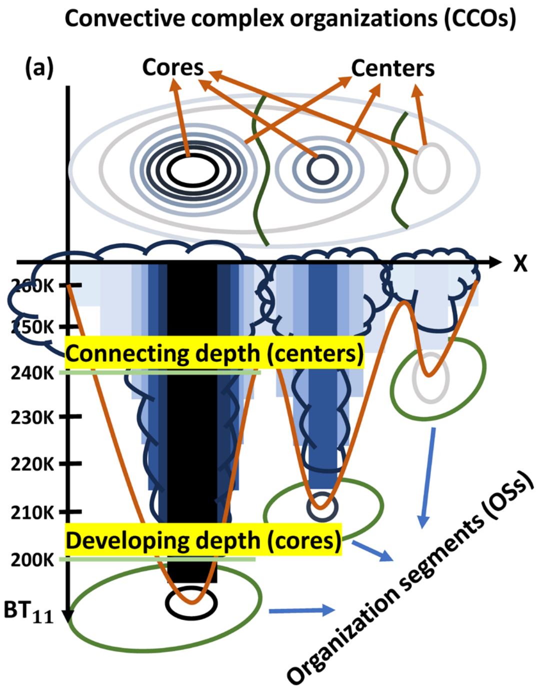

Figure. 1a in the revised manuscript. (a) Example illustrations of segmenting the CCO into single-core OSs as tracking targets. The CCO 3-dimensional structures in x, y and BT11 are identified by the adaptive variable-BT11 thresholds. The cold-core BT11 indicates the depth of development. The cold-center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

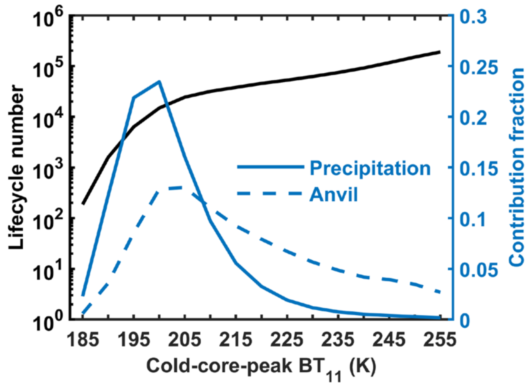

Figure 6. Sample numbers of tracked OS lifecycles with cold-core-peak BT11 values from 185-255 K in the tropical western Pacific (130° W-170°E, 20°S-20°N) in 2006. The contribution fraction of the OS lifecycles to the precipitation and anvil cloud amount is shown on the right axis.