Anvil Productivities of Tropical Deep Convective Clusters and Their Regional Differences

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ABSTRACT

The anvil productivities of tropical deep convection are investigated and compared among eight climatological regions using 4 yr of collocated and combined CloudSat and CALIPSO data. For all regions, the convective clusters become deeper while they become wider and tend to be composed of multiple rainy cores. Two strong detrainment layers from deep convection are observed at 6–8 km and above 10 km, which is consistent with the trimodal characteristics of tropical convection that are associated with different divergence, cloud detrainment, and fractional cloudiness. The anvil productivity of tropical deep convection depends on the convection scale, convective life stage or intensity, and large-scale environment. Anvil ice mass ratio related to the whole cluster starts to level off or decrease when the cluster effective scales \( W_{\text{eff}} \) (the dimension of an equivalent rectangular with the same volume and height as the original cluster) increase to about 200 km wide, while the ratios of anvil scale and volume keep increasing from 0.4 to 0.6 and 0.15 to 0.4, respectively. The anvil clouds above 12 km can count for more than 20% of cluster volume, or more than 50% of total anvil volume, but they only count less than about 2% of total ice mass in the cluster. Anvil production of younger convection of the same \( W_{\text{eff}} \) is higher than that of the decaying convection. The regional difference in the composite anvil productivities of tropical convective clusters sorted by \( W_{\text{eff}} \) is subtle, while the occurrence frequencies of different scales of convection vary substantially.

1. Introduction

The trimodal characteristics of tropical convection (Johnson et al. 1999) indicate prominent stable layers that exist over the Pacific warm pool and the tropical eastern Atlantic, which are associated with trimodal distributions of divergence, cloud detrainment, and fractional cloudiness. Tropical mesoscale convective systems (MCS), defined as regions of deep convection with a precipitation region ~100 km in dimension (Zipser 1969, 1977; Houze 1977; Leary and Houze 1979; Houze 2004), are a fundamental mode of atmospheric variability. These phenomena redistribute heat and moisture between the tropical surface layer and the free troposphere. The stratiform anvil clouds of several MCSs can merge to form super clusters or mesoscale convective complexes (MCC; Maddox 1980) that can have horizontal scales of thousands of kilometers. Some fraction of hydrometers produced in convective updrafts of an MCS are transported into spatially large extensive mesoscale stratiform precipitating regions where their fate depends on an array of processes that cause this water to be redistributed between surface precipitation, residual cirrus, and water vapor (Gamache and Houze 1983; Pfister et al. 2001; Mace et al. 2006; Mullendore et al. 2009). The water budget of these stratiform regions

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is determined by the strength and duration of the active convective updrafts, the large-scale vertical motion, environmental wind shear, and background moisture profile (Mapes and Zuidema 1996; Mace et al. 2006; Cetrone and Houze 2009).

The anvil extent and anvil microphysical properties are important contributors to the atmospheric heating profiles and ultimately the water vapor transport, hence anvil properties influence global momentum budgets and radiative budgets, as highlighted in several studies (e.g., Hartmann et al. 1992; Massie et al. 2002; Schumacher et al. 2004; Alexander et al. 2004; Mace et al. 2011; Klein et al. 2013). Therefore, anvil clouds play an important role in cloud–radiative–dynamic feedbacks in the Earth climate system (Wielicki et al. 1995). For instance, Chou and Neelin (1999), Houze (1989), and Machado and Rosson (1993) showed that high cirrus fraction tends to increase strongly as deep cloud-top temperature drops, which is referred as the cirrus–detrainment–temperature (CDT) relation. This finding stimulated further investigations about climate feedbacks associated with cirrus clouds (Ramanathan et al. 1989; Ramanathan and Collins 1991; Chou and Neelin 1999; Lindzen et al. 2002; Hartmann and Larson 2002; Stephens 2005). However, in addition to the horizontal extent, knowledge of the vertical structure and microphysical properties of anvil clouds are important for understanding how the clouds evolve over time and influence their environment through heating and moistening (Klein and Jakob 1999). Understanding and simulating the water budget of extended tropical anvils remains a significant outstanding issue in modeling cloud feedbacks in the climate systems (Boing et al. 2012; de Rooy et al. 2013; Sherwood et al. 2014).

CloudSat and the other A-Train satellites have provided a new dimension of space-based observations of clouds and precipitation and the study of related processes (Stephens et al. 2008). Given the high sensitivity of the Cloud Profiling Radar (CPR) on board CloudSat to sense the nonraining anvil, the CPR has been widely used to study the relationships between anvil extent and the extent of parent convection (Cetrone and Houze 2009, Yuan and Houze 2010, 2011, 2013; Bacmeister and Stephens 2011). Anvil production is recently proposed in Yuan and Houze (2013). To quantify the anvil production for a convective system, two parameters are considered: the size of the system and the ratio of the raining core area to its overall area, which is related to the efficiency of a system to produce anvil clouds. It is found out that the ratio of raining area to the MCSs overall area decreases 0.8 to 0.3 as the system scale increases; that is, the ratio of anvil increases as the system scale increases. From CloudSat data, Yuan and Houze (2010) found that anvil clouds are mostly confined to within 1.5–2 times the equivalent radii (the radius of a circle with the same area of the convection) of the rain areas of MCSs, while over the western Pacific warm pool, they may extend out to ~5 times the rain area radii. The spatial statistics of convective clouds are also studied using CloudSat data in Bacmeister and Stephens (2011). They found that the detrainment index (Id, defined as the ratio of cluster maximum width to that of rainy base width) is a good indicator of convective cloud maturity. The anvil morphology of tropical convection over oceans has also been investigated in Igel et al. (2014) and Igel and van den Heever (2015) with CloudSat data. Igel et al. (2014) found that increased SST is associated with increased anvil thickness, decreased anvil width, and cooler cloud-top temperatures. However, a positive correlation of cloud-top height and anvil width is found in Igel and van den Heever (2015).

The Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on board CALIPSO can observe the cold tops of deep convection and optically thin cirrus layers in the upper troposphere. Cirrus clouds at 14–16 km tend to be too tenuous to be detected by CloudSat, whose occurrence can be as high as ~60% (Sassen et al. 2008). Deng et al. (2015) showed that tropical ice clouds colder than 220 K (~12 km) are mainly observed by CALIOP. The addition of CALIPS observation to CloudSat observation provides a full cross section of a deep convective system.

In this study we use the combined and collocated range-resolved CPR and CALIOP data to characterize the horizontal and vertical structures of tropical convection clusters and their composite anvil productivities, which is defined as the amount of anvil clouds generated from tropical deep convection at certain scale. To quantify it, the ratios of anvil scale and cross section volume to its attached convective cluster are investigated. Moreover, taking the advantage of the up-to-date CloudSat 2C-ICE product (Deng et al. 2010, 2013, 2015) of ice cloud microphysical properties, ice mass rather than radar reflectivity (Ze) is also examined to provide a unique view of ice cloud microphysics and ice mass transport in convective regions.

Regional differences are explored among eight tropical climatological regions including ocean, land, and Maritime Continent regions as well. The anvil productivity of tropical deep convection depends on several factors including surface temperature, convection life stages, and upper-troposphere humidity. A sensitivity study of anvil productivity of tropical deep convection to those parameters is performed.

This paper is organized as follows. In section 2, data and cluster identification method are described. The
cluster sorting method and the properties of tropical deep convection clusters are discussed in section 3. The anvil productivity of tropical convective clusters and its sensitivity to surface skin temperature, life stages, and upper-troposphere humidity are investigated in section 4. A final discussion and conclusion is presented in section 5.

2. Data and methodology

a. CloudSat data products

In this study we use the combined and collocated CloudSat and CALIPSO data collected between 2007 and 2010. The CALIOP and CPR provide complementary observations to cover clouds from those optically thin cirrus clouds in the upper troposphere to precipitation near the surface. Several CloudSat standard products from combined CPR and CALIOP measurements are used here. Cloud geometrical profile from 2B-GEOPROF-lidar (Mace et al. 2009; Mace and Zhang 2014) provides the cloud boundaries. Cloud scenario classification from 2B-CLDCLASS-lidar (Sassen and Wang 2008) provides cloud phase (liquid, ice, or mixed phase) determination for each cloud layer and classify it as one of eight basic cloud types, so that downstream retrieval algorithms or assumptions can be applied to the conditions for which they are considered valid.

Ice cloud microphysical properties are from CloudSat 2C-ICE product (Deng et al. 2010, 2013, 2015), which is a synergetic ice cloud retrieval created by optimally combining the CPR and the CALIOP measurements using a variational method to provide the profiles of extinction coefficient, ice water content (IWC), and effective radius (re) for ice particles. Attenuation due to ice particle distributions is included in the radar and lidar forward models. The Mie scattering effect of nonspherical large particles is calculated in the forward model lookup table according to a discrete dipole approximation (DDA) by Hong (2007). 2C-ICE data have been compared with in situ data and other retrieval datasets such as CloudSat 2B-CWC_RVOD (Austin et al. 2009) and radar/lidar (DARDAR; Delanoë and Hogan 2008) in Deng et al. 2013. They find that the mean ratios of the retrieved IWC and re in 2C-ICE to that estimated from in situ data are 1.12 and 1.05, respectively. The 2C-ICE retrieval agrees reasonably with the DARDAR results in the radar region, which includes the radar–lidar overlap and radar-only regions, while the 2C-ICE retrieval in the lidar-only region has somewhat better agreement with in situ measurement than DARDAR since 2C-ICE takes the extra constraint that Ze is below the detection threshold of the CPR near ~30 dBZ. In addition, an additional constraint is applied using a parameterization of Ze in the lidar-only region compiled from a climatology of ground-based cloud radar and lidar data (Deng et al. 2015).

Deep convective clouds are identified as mixed-phase cloud layers by 2B-CLDCLASS-lidar, where the CALIOP signal is quickly attenuated at the cold top. Since the CPR is mostly sensitive to ice particles rather than supercooled liquid, 2C-ICE assumes that the CPR signal is dominated by ice particles above the melting layer and the contribution of the possible supercool water can be neglected. Therefore, 2C-ICE provides estimates of ice properties in both anvil clouds as well as the ice properties above the melting layer in the deep convective cores. Matrosov (2015) evaluated 2C-ICE retrievals of total ice content in precipitating cloud systems with ground-based operational radar measurements. Results showed that the ice water path (IWP) derived from 2C-ICE is in a relatively good agreement with the IWP from a method developed specifically for thick ice clouds that accounts for ice hydrometers nonsphericity (Matrosov and Heymsfield 2008).

The CloudSat ECMWF-AUX product is created by the Generic-AUX Interpolate-to-Reference algorithm (http://www.cloudsat.cira.colostate.edu/dataSpecs.php?prodid=6) to provide the skin temperature and profiles of atmospheric temperature, pressure, and specific humidity fields, from which the relative humidity with respect to ice (RH_ice) is calculated. The ECMWF-AUX may mix potentially important subgrid variability in boundary layer and midtropospheric humidity, but it provides a reasonable large-scale humidity background (Bacmeister and Stephens 2011).

b. Tropical convective cluster identification and anvil partition

We use CloudSat and CALIPSO two-dimensional (2D) transects across tropical cloud clusters to define the parameters of our study. We assume that these transects are random with respect to the spatial structure of the convective cluster. We further assume that the cloud clusters in this study do not possess systematic anisotropy relative to the A-Train track. With these assumptions and enough events, the 2D sampling should not produce major statistical biases in the spatial statistics considered here. Other studies using cloud photographs and MODIS imagery have indicated a mean cloud horizontal aspect ratio of around 2 with no systematic orientation of features (Benner and Curry 1998; Bacmeister and Stephens 2011). The effects of A-Train along-track sampling and noncircular geometric anvils in the horizontal plane have been investigated in Igel.
and van den Heever (2015). Their results show that the measured radii should be decently representative of the characteristic radius of anvil individual object. We assume, therefore, that the effects of 2D sampling along the satellite track have minimum influences on the cloud morphology statistics that we compile.

We use a cluster-based approach to analyze the convection clusters along the A-Train track as Bacmeister and Stephens (2011) and Igel et al. (2014). First the convection cluster is defined as a group of radar and/or lidar detected and horizontally or vertically connected cloud layers in GEOPROF-lidar that contains deep convective clouds classified by 2B-CLDCLASS lidar. Only the deep convective clusters with cluster top higher than about ~9 km above mean sea level (MSL) are selected in this study, while convection in Bacmeister and Stephens (2011) includes shallower convective clusters. Connected thin cloud layers above 14 km are discarded if there is a lower-level cloud with cloud top higher than 10 km, because this thin cloud layer may be dynamically or radiatively related to the convection, but may not be directly detrained from the current deep convective cluster (Garrett et al. 2003).

To be defined as a deep convective cloud cluster, the following criteria must also be met:

1) The cloud cluster base (the lowest hydrometer base) is below 2 km above ground level (AGL), which is very important for cluster identification over the land. The cloud top is 9 km above MSL so that the convective cluster has a decent vertical extent.

2) Given the A-Train sample along the track and the likelihood of the transect being random relative to the center of the convective cluster, the cloud cluster must have at least 10 continuous profiles classified as deep convection (Dc) or nimbostratus (Ns) in the 2B-CLDCLASS-lidar product so that this cluster is unambiguously sampled as a likely convective cluster.

3) The anvil edges can be connected among clusters. A mass continuity check is performed for each identified cluster. If a minimum of ice water depth less than 2 g m⁻² (optical depth at about 0.1) is found between two convective rainy cores, which is identified as the Dc and Ns parts of the cluster as determined by the CLDCLASS-lidar product so that this cluster is unambiguously sampled as a likely convective cluster.

4) The preexisting anvil clouds can connect with the anvil edge of another developing convective cluster, which will artificially increase the anvil length compared to the actual anvil length generated by the convective cluster. To avoid such artifacts, the detrainment index \( I_d \) is required to be less than 4, which is close to the upper limit of the anvil spreading ratio reported in Yuan and Houze (2011). This criterion removes about 30% of the total identified clusters from consideration.

Figures 1a,b show the CALIPSO backscattering coefficient and the CPR radar reflectivity \( Z_e \) of an example cluster. The CPR \( Z_e \) decreases to the noise level above 13 km. While there is certainly attenuation in the liquid precipitation below 5 km between profiles 250 and 350, we see strong attenuation in \( Z_e \) at about profile number 310. The region of this layer classified as nimbostratus and deep convection (Fig. 1c) is what we define to be the rainy cores of these clusters. Note that CALIOP is quickly attenuated near the layer top but it identifies a higher cloud top to about 15 km.

For each convective cluster such as illustrated in Fig. 1, the convective cluster rainy core is first identified as the Dc and Ns parts of the cluster as determined by the CLDCLASS-lidar product and assigned as the rainy cloud base width \( W_{cb} \). If there are multiple rainy cores, then \( W_{cb} \) is the summation of all cores. While the number of cores and the average core width \( W_{core} \) in the convective cluster are also calculated and recorded. Traditionally, these convective rainy cores include the convective rain and stratiform rain. Because of strong attenuation and Mie scattering, it is very hard to separate convective and stratiform rain from CPR data using the method developed from ground cloud radars (Deng et al. 2014). Therefore, they are included together as the convection rainy core. Low-level cumulus clouds are discriminated from this deep convective cluster. The anvil clouds are composed of the connected altostratus (As), altocumulus (Ac), and high clouds in the convective clusters. The maximum cluster scale or width \( W_{cluster} \) is the horizontal length from cluster edge to edge as reported by the CPR and CALIOP, the anvil width is \( W_{anvil} = W_{cluster} - W_{cb} \), and vertical depth of the convective cluster \( D \) is determined from the minimum base \( H_{base} \) to the maximum height of the cluster top \( H_{top} \). For each cluster, the location and the skin temperature from ECMWF data are averaged over its rainy core.

To study the vertical structure of the cluster, the cluster can be thought as a stack of horizontal slices of 480-m thickness (twice that of CloudSat sample resolution) in Fig. 1c. The corresponding cross section area \( V \) and ice mass (IM) of the cluster and anvil clouds in every 480 m height interval with center height \( Z_i \) are noted as
$V_{\text{cluster}}(z_i), IM_{\text{cluster}}(z_i)$ and $V_{\text{anvil}}(z_i), IM_{\text{anvil}}(z_i)$, respectively, and defined as

\[ V_{\text{cluster}}(z_i) = N_{\text{cluster}}(z_i) \times \Delta x \times \Delta z, \quad \text{and} \quad (1) \]
\[ IM_{\text{cluster}}(z_i) = \sum IWC_{\text{cluster}}(z_i) \times \Delta x \times \Delta z, \quad \text{and} \quad (2) \]

and

\[ V_{\text{anvil}}(z_i) = N_{\text{anvil}}(z_i) \times \Delta x \times \Delta z, \quad \text{and} \quad (3) \]
\[ IM_{\text{anvil}}(z_i) = \sum IWC_{\text{anvil}}(z_i) \times \Delta x \times \Delta z, \quad \text{and} \quad (4) \]

where $N_{\text{cluster}}$ and $N_{\text{anvil}}$ are the number of CPR bins of the cluster and anvil clouds within the 480-m height interval, respectively. To convert these bin numbers to cross section area, we multiply $N_{\text{cluster}}$ and $N_{\text{anvil}}$ with CloudSat along-track spacing between profiles $\Delta x \approx 1.079 \text{ km}$ and CloudSat vertical range bin separation $\Delta z \approx 240 \text{ m}$. The cross-sectional area ($\text{km}^2$) is referred to as the cross section volume following Bacmeister and Stephens (2011) to avoid confusion with the cloud horizontal area from MODIS imagery as in Yuan and Houze (2013).

Similarly, $\sum IWC_{\text{cluster}}(z_i)$ and $\sum IWC_{\text{anvil}}(z_i)$ are the summation of 2C-ICE retrieved IWC of the cluster bins and anvil cloud bins within the 480-m height interval, respectively. We multiply them with the CloudSat sample volume $\Delta x$ and $\Delta z$ to get ice mass (IM; g m$^{-1}$) of the cluster and anvil. We can also calculate the average profiles of reflectivity, re, IWC, RH_ice in every 480-m slice for the cluster, and the corresponding rainy core or anvil clouds. In such a way, the two-dimensional structures of each cluster in Fig. 1 are recorded in one-dimensional vertical arrays.

We can then calculate the total cross section volume and ice mass of the cluster and anvil clouds by adding the slices together as

\[ V_{\text{cluster}} = \sum_{H_{\text{base}}}^{H_{\text{top}}} V_{\text{cluster}}(z_i), \quad (5) \]
\[ IM_{\text{cluster}} = \sum_{H_{\text{base}}}^{H_{\text{top}}} IM_{\text{cluster}}(z_i), \quad (6) \]
\[ V_{\text{anvil}} = \sum_{z_i}^H V_{\text{anvil}}(z_i), \quad \text{and} \]
\[ \text{IM}_{\text{anvil}} = \sum_{z_i}^H \text{IM}_{\text{anvil}}(z_i). \]

From the cluster total volume and depth we determine an effective width for the cluster \( W_{\text{eff}} = V_{\text{cluster}} / D \), the dimension of an equivalent rectangular with the same volume and height as the original cluster) as Bacmeister and Stephens (2011). Take the cluster in Fig. 1 for example: \( W_{\text{cb}}, W_{\text{anvil}}, \) and \( W_{\text{cluster}} \) are about 100, 325, and 425 km, respectively. The resulted \( W_{\text{eff}} \) is about 200 km, which means the anvil clouds account for 75% of the cluster scale but only 50% of the volume.

To consider the anvil productivity, we define the total anvil scale ratio \( (r_w) \), anvil volume ratio \( (r_v) \), and anvil ice mass ratio \( (r_m) \) to the whole cluster as

\[ r_w = \frac{W_{\text{anvil}}}{W_{\text{cluster}}}, \]
\[ r_v = \frac{V_{\text{anvil}}}{V_{\text{cluster}}}, \quad \text{and} \]
\[ r_m = \frac{\text{IM}_{\text{anvil}}}{\text{IM}_{\text{cluster}}}. \]

For its vertical structure of anvil productivity, anvil volume ratio by height \( r_v(z_i) \) and anvil ice mass ratio by height \( r_m(z_i) \) are defined as the ratio of anvil volume (anvil ice mass) at every 480-m slice to the total cluster volume (total cluster ice mass); that is,

\[ r_v(z_i) = \frac{V_{\text{anvil}}(z_i)}{V_{\text{cluster}}}, \quad \text{and} \]
\[ r_m(z_i) = \frac{\text{IM}_{\text{anvil}}(z_i)}{\text{IM}_{\text{cluster}}}, \]

respectively. We also calculate the cumulative anvil volume \( r_{v, \text{cum}}(z_i) \) and anvil ice mass ratios, and \( r_{m, \text{cum}}(z_i) \), from the cluster top to a certain level as

\[ r_{v, \text{cum}}(z_i) = \sum_{z_j}^{\text{Top}} r_v(z_j) \quad \text{and} \]
\[ r_{m, \text{cum}}(z_i) = \sum_{z_j}^{\text{Top}} r_m(z_j), \]

respectively. The cumulative anvil volume and mass ratios at the cluster base equal to the total anvil volume and mass ratios as defined in Eqs. (10) and (11).

3. Convective clusters results

a. Geographical distribution of convective clusters and sorting criteria

Figure 2a shows the global distribution of identified convective clusters at a 5° × 5° grid resolution. Here and throughout the analysis we combine the 0130 and 1330 local time CloudSat data. The IT CZ and South America are the most active deep regions in terms of convective cluster occurrence. This pattern is similar to the TRMM monthly mean rainfall in Liu et al. (2008a), their Fig. 4. The geographical pattern of tropical deep convective cluster occurrence is well correlated with the sea surface temperature (SST) pattern shown in Fig. 2b from NCEP 2007–10 reanalysis data. Eight regions that are similar to Yuan and Houze (2010) are selected for more in-depth analysis: tropical Africa (AF), Indian Ocean (IO), Maritime Continent (MC), western Pacific (WP), eastern Pacific (EP), southern Pacific (SP), South America (AM), and Atlantic (AT). The deep convection occurrence statistics for these eight regions and corresponding SST are listed in Table 1. IO and MC are the warmest regions, while EP and AT have the lowest SSTs. It is known that the large-scale atmospheric dynamics and radiative processes strongly affect the life cycle of deep convective systems in the tropics. For example, the diurnal heating of the tropical atmosphere and ocean surfaces provides a favored condition in the afternoon for the formation and growth of mesoscale cloud systems before dawn (Chen and Houze 1997; Nesbitt and Zipser 2003). Over land, the precipitation maximizes in the later afternoon while over water, tropical convection reaches a peak a few hours before sunrise (Liu et al. 2008b). Since CloudSat and CALIPSO pass over a location at ~0130 and ~1330 local time, the data we analyze is collected a few hours earlier than the respective day and night maxima in tropical convection. Therefore, the clusters that we analyze may tend to be somewhat weaker or younger than what would have been observed a few hours later in the local day.

The sorting criteria of the convective clusters depend on the research question being posed. To test the sensitivity of tropical convection anvil productivity to sea surface temperature as in Igel et al. (2014), skin temperature from CloudSat ECMWF-Aux is used. To be compared with Igel et al. (2014), our identified clusters over the eight regions are sorted by skin temperature for their occurrence, anvil width, effective width, cluster-top height, and relative humidity at 12 km in Figs. 3a–e. The skin temperature over MC, WP, EP, and AT has a narrow distribution and a higher peak around 300 to 303 K than other regions. The anvil width seems to increase and the cluster-top height over EP, WP, AT, and
SP decreases as the skin temperature decreases, which seems consistent with Fig. 11 in Igel et al. (2014). However, these correlations are not linear and have large standard deviations (black vertical bar) at a given skin temperature.

Given the broader distribution skin temperature over land than those over ocean and large standard deviation in Figs. 3b–e, sorting by skin temperature is not desirable here. The convective rainy core width ($W_{cb}$) or the cluster scale ($W_{cluster}$) can be considered as an objective parameter to sort the clusters. However, the convective clusters of the same $W_{cb}$ but at the decaying stage might have a larger anvil fraction than those at the developing stage. The resulted sorting relation with $W_{cb}$ might be controversy. On the other hand, $W_{cluster}$ tends to be contaminated by the attached decaying anvil clouds if they are not all discarded.

Following Bacmeister and Stephens (2011), we use cluster effective width ($W_{eff}$) for sorting to count for both rainy core and anvil clouds. The attached anvil clouds are usually thinner than the convective rainy core, but it still contributes partially to $W_{eff}$. The

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**TABLE 1.** Summary of sea surface temperature, deep convective clusters, and their anvil productivity in selected eight regions labeled in Fig. 1. Total cluster volume is total cloudy bins in the cluster. The total ice mass is the total ice water content in the clusters. Sample volume $\Delta x \sim 1.079 \text{ km and } \Delta z \sim 0.240 \text{ km need to be multiplied to calculate the absolute value in Eqs. (5) and (6).}

<table>
<thead>
<tr>
<th>Region</th>
<th>SST (K)</th>
<th>No. of clusters</th>
<th>Cluster scale (km) (anvil ratio)</th>
<th>Cluster volume (bin) $\times 10^3$ (anvil ratio)</th>
<th>Total ice mass (g m$^{-3}$) $\times 10^3$ (anvil ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF (land)</td>
<td>—</td>
<td>4685</td>
<td>124 (0.49)</td>
<td>6.7 (0.28)</td>
<td>1.30 (0.10)</td>
</tr>
<tr>
<td>IO (mixed)</td>
<td>302.0</td>
<td>2451</td>
<td>185 (0.48)</td>
<td>10.1 (0.27)</td>
<td>1.51 (0.10)</td>
</tr>
<tr>
<td>MA (mixed)</td>
<td>302.7</td>
<td>7836</td>
<td>150 (0.49)</td>
<td>8.1 (0.27)</td>
<td>1.28 (0.09)</td>
</tr>
<tr>
<td>WP (ocean)</td>
<td>301.9</td>
<td>4241</td>
<td>129 (0.47)</td>
<td>7.0 (0.25)</td>
<td>1.29 (0.09)</td>
</tr>
<tr>
<td>EP (ocean)</td>
<td>300.3</td>
<td>5118</td>
<td>124 (0.49)</td>
<td>6.7 (0.26)</td>
<td>1.35 (0.10)</td>
</tr>
<tr>
<td>SP (ocean)</td>
<td>301.2</td>
<td>5078</td>
<td>151 (0.48)</td>
<td>8.2 (0.26)</td>
<td>1.44 (0.10)</td>
</tr>
<tr>
<td>AM (land)</td>
<td>—</td>
<td>6418</td>
<td>115 (0.46)</td>
<td>6.3 (0.25)</td>
<td>1.18 (0.09)</td>
</tr>
<tr>
<td>AT (ocean)</td>
<td>300.4</td>
<td>3211</td>
<td>106 (0.49)</td>
<td>5.7 (0.26)</td>
<td>1.12 (0.10)</td>
</tr>
</tbody>
</table>
calculated $W_{\text{eff}}$ of all clusters is highly correlated with $W_{\text{cluster}}$ ($r^2 = 0.90$) and $W_{\text{cb}}$ ($r^2 = 0.85$). Compared to $W_{\text{cluster}}$, $W_{\text{eff}}$ is less affected by possible extensive tropopause cirrus clouds, if they are not all eliminated. On the other hand, $W_{\text{eff}}$ can sort the convective clusters with the same $W_{\text{cb}}$ but with different anvil detrainment. Therefore, $W_{\text{eff}}$ sorting enables the tropical convective clusters to be characterized on a reliable scale basis.

The occurrence, anvil width, skin temperature, cluster-top height, and relative humidity at 12 km of convective clusters are sorted by $W_{\text{eff}}$ in Figs. 3f–j. We find out that there is a decent sample of convection clusters over the $W_{\text{eff}}$ scale for all regions. Given the geographic variation for the eight regions, the normalized PDFs in Fig. 3f show that convection in IO and MC has a higher probability to form super clusters (connected MCSs or MCC) of 1000 km wide. Convection at EP and AT are very similar with a narrow scale range between 100 and 500 km. The distribution of convection at AM and AF are very similar in terms of $W_{\text{eff}}$.

Anvil width, cluster-top height, and RH_ice at 12 km increase with $W_{\text{eff}}$. The relations are monotonic with smaller standard deviations than the skin temperature sorted relations in Figs. 3b,d,e. The skin temperature of clusters over WP is hottest. The skin temperature of clusters over AF and AM decreases with increasing $W_{\text{eff}}$. We speculate that the skin temperature decreases over
land is related to the increased rainy core of convective clusters, while the rain affects less over ocean owing to larger heat capacity of water. The positive correlation of cluster-top height and anvil width with RH_ice at 12 km indicates the close relation between large-scale environment and convection development and anvil detrainment, which will be investigated more in the anvil productivity sensitivity section.

b. Convective rainy core properties

The composite mean numbers of rainy cores and mean rainy core width ($W_{\text{core}}$) in each convective cluster are shown in Figs. 4a and 4b, respectively. The larger the convection clusters, the more and larger rainy cores in the cluster are found. They have one or two rainy cores with average width less than 50 km when $W_{\text{eff}}$ are less than 100-km width. For clusters larger than 100 km, the number of rainy core increases from 2 to more than 10, and each rainy core width increases from 50 km to more than 100 km. Among the eight regions, convective clusters with the same $W_{\text{eff}}$ over AF, EP, and AT have less but wide rainy cores, while WP, MC, and IO have more but narrow rainy cores, which is consistent with the finding in Nesbitt et al. (2000) that the size of precipitation features with ice scattering and with an MCS from TRMM is about 1.5–2 times larger comparing the east Pacific to the continental regions such as the western Pacific and South America.

The maximum height reached by particular $Z_{\text{e}}$ values is a common parameter to estimate the peak convective vigor. Figure 5 shows the intensity of convective rainy cores in terms of composite $Z_{\text{e}}$ vertical distribution. For convective clusters with $W_{\text{eff}}$ less than about 100 km, $Z_{\text{e}}$ above 5 km increases as $W_{\text{eff}}$ increases for the eight regions, and the maximum heights of certain $Z_{\text{e}}$ over AF, AM, IO, and MC is relatively higher than those over WP, EP, SP, and AT.

But for convective clusters with $W_{\text{eff}}$ larger than about 100 km, the maximum height of certain $Z_{\text{e}}$ above 5 km decreases as $W_{\text{eff}}$ increases, while the maximum radar echoes between 5 and 7 km increase as $W_{\text{eff}}$ increases. There is an extended layer of W-band $Z_{\text{e}}$ larger than 10 dBZe around or below 5 km. The $Z_{\text{e}}$ peak at the melting layer might be caused by the phase transition...
and indicates these cluster rainy cores are dominated by stratiform rain (Deng et al. 2014). Those two opposite patterns for narrow and wider convective clusters may indicate the rainy cores transit from dominant convective rain to dominant stratiform rain or the systems at different stages.

The composite vertical distribution of re and IWC above 5 km in convection rainy cores are studied with 2C-ICE data and shown in Figs. 6a and 6b, respectively. For convective clusters less than 100 km wide, IWC and re in the rainy core generally increase at all levels as $W_{eff}$ increases. Assuming that convection rainy cores of less than 50 km are mainly contributed by convective rain, this indicates that those convective cores become more intense with stronger updraft to pump high ice mass with larger ice particles as the convection scales increase. Among the eight regions, the value of maximum heights of certain Ze, re, and IWC in Figs. 5 and 6 in the AF and AM regions are slightly higher than those in the other regions, which is consistent with discussion by Liu et al. (2007) that typical updrafts of convection less than 100 km over AF and AM are much stronger, lofting larger particles high into the storm.

As the convective clusters become wider than 100 km, IWC in the rainy cores decrease at all levels as the cluster scale increases. The effect radius re increases between 5 and 8 km, and re decreases above 8 km as $W_{eff}$ increases. Sedimentation of large particles in weak updrafts or downdraft of the stratiform rain is speculated to cause re to decrease above 8 km, which may partially result in increased re and radar echo between 5 and 7 km (Deng et al. 2014).

c. Vertical distribution of convective clusters

In this section, the tropical deep convective clusters are examined in terms of their vertical and horizontal scales, vertical volume distributions, and their associated large-scale humidities.

The composite mean $V_{cluster}(z)$ is shown in Fig. 7a for the eight regions. First we see that, for all eight regions, the convective clusters become taller as their horizontal scale increases. The cluster-top height (also see Fig. 3i) increases from 10 km to more than 16 km, and cluster-top temperature decreases from 230 to 190 K. At the same $W_{eff}$ scale, the convective clusters over EP, AT, and SP tend to have lower cloud tops than other regions.

Second, we see that the volume increases at all height levels as $W_{eff}$ increases. Third, cross section volume has two prominent peaks in the vertical profiles. The first is right above the melting layer or at 6–8 km. This peak becomes less obvious as $W_{eff}$ increases. The second peak is above 10 km and becomes prominent as $W_{eff}$ increases. Its corresponding peak height increases as $W_{eff}$ increases. The composite mean cross section volume by height from CloudSat CPR-only is shown in Fig. 7b. The comparison between Figs. 7a and 7b shows that the second prominent volume peak above 10 km is less obvious in the CPR-only measurements, which is expected.
since ice clouds above 12 km are mainly observed by CALIOP (Deng et al. 2015). Except that $W_{\text{eff}}$ from CPR-only is smaller, the sorted cross section volume distribution below 10 km in Figs. 7a and 7b and cluster base height and skin temperature (not shown) as a function of $W_{\text{eff}}$ are similar between CPR-only and CPR/CALIOP combined datasets, which indicates that the effect of possible tropopause thin cirrus clouds by including CALIOP observation, if not all removed, on the convective scale sorting is negligible, while the contribution of CALIOP observations on the detection of upper part of convection is very important for anvil productivity study.

The composite corresponding ECMWF RH_ice of convective clusters as a function of $W_{\text{eff}}$ is shown in Fig. 8. As $W_{\text{eff}}$ increases, the lower troposphere becomes more moist, the midtroposphere becomes more moist as well, and the RH_ice at about 220 K or 15 km increases from 0.75 to supersaturation. This pattern is very similar to the convection–humidity relations in general circulation model as illustrated in Fig. 10 of Del Genio et al. (2012), where convection is sorted by convection rainfall to study the moisture preconditioning in MJO development. It is not coincident, since $W_{\text{eff}}$ in this study is positively related to convective rainy base width ($W_{\text{cb}}$) or rainfall. It is speculated that the moist boundary layer becomes thicker to form more organized convection. The entrainment of dry air in the midtroposphere dilutes the convection buoyancy but the detrainment moistens the middle–lower troposphere. A more humid free troposphere and a favorable boundary environment lead eventually to the onset of widespread deep convection. The saturated air in the clouds in the upper troposphere, which is also observed in Soden (2000), Gierens et al. (2004), and Comstock et al. (2004), is closely associated with massive anvil clouds detrained.

FIG. 6. Composite-averaged (a) re and (b) IWC profiles of the rainy core in the convective clusters as a function $W_{\text{eff}}$ for eight regions.
from the convection. Among the eight regions, the middle and upper troposphere over AF, EP, and AT are relatively drier than those over other regions.

4. Regional analysis of anvil productivity

The anvil productivity of tropical deep convection is critical for the prediction of atmospheric sensitivity due to global warming in climate models (Ramanathan et al. 1989; Stephens 2005). The quantitative nature of anvil cloud detrainment is a very important aspect of convection parameterization in numerical models (Petch 2006; Del Genio et al. 2012). With the combined CRP/CALIOP measurements, anvil production features are explored here. In section 4a, we first examine the composite ratios of scale, cross section volume, and ice mass of total anvil cloud to its parent convection cluster \( r_w, r_y, \) and \( r_m \) in Eqs. (9), (10), and (11) in Fig. 9. Then in section 4b the anvil productivity is resolved vertically to determine the favored convection detrainment level.

a. Fractions of scale, volume, and ice mass of all anvil to the whole convection cluster

We can see in Fig. 9a that the average \( r_w \) increases from about 0.4 to 0.55 as \( W_{eff} \) increases up to about 500 km. The corresponding anvil spreading ratio \( [W_{cluster}/W_{cb} = W_{cluster}/(W_{cluster} - W_{anvil})] \) as in Yuan and Houze (2011) or the detrainment index as in Bacmeister and Stephens (2011) is about 1.5–2.2. The detrainment index limit of 4 for cluster sampling in section 2b is equal to an anvil scale ratio of 0.75, which is the upper limit of the standard deviation in Fig. 9a. The

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Fig. 7. Composite cross section volumes (total cloudy bins in every 480-m level). Sample volume \( \Delta x \sim 1.079 \) km and \( \Delta z \sim 0.240 \) km need to be multiplied to calculate the absolute value in Eq. (1) as a function of \( W_{eff} \) for the eight regions: (a) from combined CloudSat and CALIOP observations and (b) from CloudSat only.
The mass ratio $r_m$ increases from 0.05 to 0.15 as $W_{eff}$ increases until about 200 km, then decreases or levels off with $W_{eff}$. The variations of those ratios among the regions are much smaller than the standard deviations. The total mean scale, volume, and ice mass ratio for the eight regions are listed in Table 1. Next, we explore the vertical distributions of anvil volume and ice mass ratio.

**b. Vertical anvil volume ratio to its convection cluster**

The anvil volume ratio by height $[r_y(z_i)]$ represents the main anvil detrainment level in the convective cluster and is shown in Fig. 10a. We can see that for all eight regions, there is a dominant detrainment layer between about 12 and 15 km, whose volume ratio and its peak height increase as the convective clusters become extensive in terms of $W_{eff}$. For this detrainment layer, detrained anvil clouds at MC, IO, and AF tend to have a relatively large volume ratio in their clusters than those at EP, SP, and AT. Moreover, this dominant detrainment layer over AF, IO, MC, WP, and AM can extend to heights in excess of 14 km, while those over EP, SP, and AT maximize below 14 km.

There is another detrainment layer centered at about 6–8 km in Fig. 10a, which is more noticeable when convective clusters are less than 100 km wide. This is consistent with the vertical distribution of cluster volume in Fig. 7a. For ocean regions at WP, EP, SP, and AT, this detrainment layer seems in transition gradually to the higher dominant detrainment layer at 12 km. Luo et al. (2009) suggested that this transient layer at 6–8 km may play a role in determining the cloud height. For the mixed land and ocean regions at IO and MC and the land regions at AF and AM, this anvil detrainment layer at 8 km counts less of the total cluster volume.

We also calculate the cumulative anvil volume ratio to the convective cluster volume from the cluster top to

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**Fig. 8.** Composite-averaged relative humidity in respect to ice (RH_{ice}) of identified convection clusters as a function of $W_{eff}$ for eight regions.

**Fig. 9.** Composite mean of (a) anvil scale ratio ($r_w$), (b) cross section volume ratio ($r_y$), and (c) ice mass ratio ($r_m$) of total anvil to the whole convective cluster for the eight regions. Vertical black bar lines are the standard deviations of clusters at AF.
certain level $r_{v,\text{cum}}(z_i)$ in Fig. 10b to see the exact anvil volume fraction detrained from the convective cluster. As $W_{\text{eff}}$ increases from about 10 km until about 100 km, $r_{v,\text{cum}}(z_i)$ at each height level increases quickly, or the height of certain $r_{v,\text{cum}}(z_i)$ increases quickly with $W_{\text{eff}}$. For example, the height of ratio of 0.16 (light blue color) in Fig. 10b increases from 6 to 12 km. Then the volume ratio increases slowly with $W_{\text{eff}}$. By then, the anvil above 12 km counts for about more than 20% of the convective cluster or 50% of the total detrained anvil clouds.

The height of ratio 0.16 (light blue color) in Fig. 10b over MC and IO regions is slightly higher than other regions, which indicates that convective clusters with the same $W_{\text{eff}}$ at MC and IO detrain more anvil clouds to higher levels. The anvil volume ratio below 10 km decreases fastest over WP and SP when $W_{\text{eff}}$ is larger than about 500 km in Fig. 10a, causing a quick decrease of cumulative anvil volume ratio with $W_{\text{eff}}$ in Fig. 9b.

c. Vertical anvil ice mass ratio to its convection cluster

The vertical distribution of those detrained anvil ice mass is shown as anvil ice mass ratio by height $r_{m}(z_i)$ in Fig. 11a. We can see that the anvil ice mass layers are mainly located below 12 km. The anvil ice mass ratio seems to increase at all levels until $W_{\text{eff}}$ increases to about 100 km. This increasing ice mass ratio is consistent with the increased vigor of convection in Figs. 5 and 6 with strong updrafts that transport water upward and detrain into the anvil as the convection becomes wider. Then anvil ice mass ratio decreases below 12 km as $W_{\text{eff}}$ increases; the height of the anvil ice mass ratio maximum decreases to 8 km. This vertical ice mass
distribution explains the level off and decrease of total anvil ice mass ratio as $W_{\text{eff}}$ increases to larger than 200 km in Fig. 9c. Even the anvil volume ratio of the dominant detraining layer at about 10–14 km increases as $W_{\text{eff}}$ increases as shown in Fig. 10a, the anvil ice mass ratio of that layer changes very little. The increased volume versus constant mass ratio may indicates decreased mean ice water content of anvil cloud with $W_{\text{eff}}$, which is reasonable as the anvil is detrained far away from the convention center. The detailed ice cloud properties distribution in the anvil clouds in respect to the distance to their parent convection is under study.

Figure 11b shows the cumulative anvil ice mass ratio above certain level [$r_{m,\text{cum}}(z_i)$]. The cumulative ice mass ratio increases at all height levels as $W_{\text{eff}}$ increases until about 100 km. Then it starts to decrease below 12 km as $W_{\text{eff}}$ increases. Even though the anvil clouds above 12 km contribute more than 20% of cluster volume (bright green in Fig. 10b) when $W_{\text{eff}}$ reaches 1000 km, they only account for about 2% of total ice mass in the cluster (the light blue color contour in Fig. 11b). This 2% ratio seems negligible compared to the convective cluster itself. However, the water mass in the anvil clouds can affect the infrared radiation budget and water vapor field in the upper troposphere and potentially contribute to the exchange of air between the stratosphere and troposphere in the tropics and local cirrus formation later on, which can contribute to the global climate change (Holton et al. 1995; Holton and Gettelman 2001).

d. Sensitivities to skin temperature

The above composite mean anvil productivity of tropical convection is generated for certain $W_{\text{eff}}$.  

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**Figure 11.** (a) Composite mean ratios of anvil ice mass at a certain level to the total convective cluster ice mass [$r_m(z_i)$] and (b) composite mean cumulative ice mass ratios of anvil above certain height level to the total cluster ice mass [$r_{m,\text{cum}}(z_i)$].
However, anvil productivity of the convective clusters of the same $W_{\text{eff}}$ depends on the convective life stages and the large-scale dynamical and thermodynamical environments. In Fig. 12, the sensitivities of anvil productivity and rainy core properties to skin temperature are examined by comparing convective clusters with the same $W_{\text{eff}}$ but with skin temperatures above and below the average for land, ocean, and land/ocean mixed regions. We can see that, compared to those with below-average skin temperature, convective clusters with warmer skin temperature have taller but narrower rainy cores, and the scale, volume, and ice mass ratio of detrained anvil clouds are systematically larger.

**e. Sensitivities to convection stages**

If any observation can follow the convection, anvil productivity in its parent convection life cycle would be shown on the $W_{\text{eff}}$ scale axis. Therefore, the composite mean along with the $W_{\text{eff}}$ scale would represent the composite life cycles of all clusters. However, A-Train observation only gets a single look at each cluster. At a certain $W_{\text{eff}}$ scale, the sorted clusters may be at different stages of their life cycles. For convective clusters in their developing stages, the cluster rainy cores are dominated by convective cores with strong updrafts. For the mature or decaying convective clusters, the convective cores are diluted and the cluster rainy cores are dominated by stratiform rain. The radar echo enhancement due to ice melting at about 5 km is a strong indicator of stratiform rain. Therefore, the $Ze$ at 5 km ($Ze_{5km}$) of developing convection may be smaller than those of mature or decaying convection with extensive stratiform rain. Figures 13a and 13b show the mean $Ze$ of the rainy profiles in the convective clusters of the same $W_{\text{eff}}$ but with $Ze_{5km}$ above average and below average by one standard deviation, respectively. For the convection less than 100 km wide with lower than average $Ze_{5km}$ (Fig. 13b), the maximum height of 8 dB$Ze$ is higher than those with above average $Ze_{5km}$ (Fig. 13a). This result further confirms us that the convective clusters less than 100 km with lower $Ze$ at 5 km are likely at their developing stages, which loft upward more relatively larger particles since radar reflectivity is positively related to the largest particle sizes.

Figure 14 shows the sensitivity of anvil productivity and rainy core properties to the convective life stage using $Ze_{5km}$ as a proxy. We can see that the convective clusters with below average $Ze_{5km}$ have more but narrower rainy cores but the same cluster-top height. The anvil scale, volume, and ice mass ratio for both groups increase with scales. But the anvil ratios of scale, cross section volume, and ice mass in convective clusters at the developing stage can be 10% more, probable because the younger clusters have no time to develop the stratiform rain yet and that the ice that will soon form rain is still in the anvil.

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**FIG. 12.** Anvil scale ratio, volume ratio, ice mass ratio, rainy core number and width, and cluster-top height as a function of $W_{\text{eff}}$ for land (black), ocean (blue), and mixed regions (red) for convective clusters of the same $W_{\text{eff}}$ but with skin temperature above average (solid) or below average (dashed) with one standard deviation.
f. Sensitivities to relative humidity

The sensitivity of anvil productivity of tropical convection to large-scale humidity environment is shown in Fig. 15. For two groups of convective clusters with RH_ice at 12 km above and below average, the rainy core number and width are very similar but the cluster-top height in moist environment is higher. The anvil ice mass ratio is almost the same, but the anvil scale ratio can be more than 10% higher in the moist environment. The differences become smaller as $W_{\text{eff}}$ increase because the variation of RH_ice at 12 km becomes smaller as shown in Fig. 3j. A more humid upper troposphere and a favorable boundary environment would lead to the onset of wide spread deep convection. On the other hand, the massive anvil clouds detrained from the convection would lead to saturated air in the clouds in the upper troposphere, which is also observed in Soden (2000), Gierens et al. (2004), and Comstock et al. (2004).

5. Discussion and conclusions

From 4 yr of combined and collocated CloudSat and CALIPSO data, the convection horizontal and vertical structures are examined and compared that for all eight climatological regions. We found the following:
1) When the convective clusters become wider, the convective clusters become deeper. The clusters tend to be composed of multiple rainy cores and each core becomes wider. Among the eight regions, convection of the same $W_{\text{eff}}$ over eastern Pacific and Atlantic Ocean tends to have fewer but wider rainy cores, while those over the western Pacific, Maritime Continent, and Indian Ocean regions tend to have more but narrower rainy cores. For the convection at the same scale, African, South American, and mixed land and ocean regions over the Indian Ocean and Maritime Continents and tend to have higher cloud top than those over open ocean. The quantitative value of the rainy core would be the benchmark for model evaluation and development.

2) Sorted convection and anvil properties based on $W_{\text{eff}}$ have smaller standard deviations than those from skin temperature sorting (Igel et al. 2014) and have monotonic relations with $W_{\text{eff}}$, indicating the importance of the scale analysis of tropical convection.

3) For convective clusters less than about 100 km wide, the larger $Z_e$, $r_e$, and IWC in rainy cores are found at higher levels as the cluster scales increase, implying that more ice mass of larger particles are transported to the mid- and upper troposphere in strong updrafts. As the convection clusters become larger than 100 km wide, the rainy core is probably dominated by stratiform rain. Ice water content at all levels and $r_e$ above 8 km in the rainy core decrease as the $W_{\text{eff}}$ increases, probably as a result of sedimentation or/and evaporation, while $Z_e$ and $r_e$ increase between 5 and 8 km with $W_{\text{eff}}$.

4) The vertical cluster volume shows that there are two main detrainment layers at about 6–8 km and between 10 and 16 km, which is consistent with the trimodal characteristics of tropical convection. The contribution of CALIOP observations is very important to the identification of the strong detrainment layer above 12 km for tropical anvil productivity study, while the effect of the possible tropopause thin cirrus clouds on the scale sorting is negligible.

5) The $W_{\text{eff}}$ sorted RH has a similar pattern with the GCM simulations sorted by convection rainfall in Del Genio et al. (2012) for moisture preconditioning in MJO development. The coincidence indicates that the convection becomes more and more organized as the midtroposphere humidity increases. As the convective clusters become more organized, the convection itself becomes deeper and reaches the dominant detrainment layer above 10 km and hence increases the anvil productivity in terms of anvil size, volume, and ice mass.

To sum up, the anvil productivity of tropical convection depends on the convection scale, convective life stage, convection intensity, and large-scale environment.

1) Average anvil ice mass ratio increases from 0.05 to 0.15 with $W_{\text{eff}}$ until $W_{\text{eff}}$ is larger than 200 km. The decreases of anvil scale and cross section volume ratio delay. As $W_{\text{eff}}$ increases until about 500 km, the average ratio of anvil scale increases from 0.4 to 0.6, and the average anvil volume ratio increases from 0.15 to 0.4.
2) The anvil clouds above 12 km can count for more than 20% of cluster volume, or more than 50% of total anvil volume, but they only count less than about 2% of total ice mass in the cluster.

3) Compared to those with below-average skin temperature, convective clusters with warmer skin temperature have taller but narrower rainy cores, and the scale, volume, and ice mass ratio of detrained anvil clouds are systematically larger. Anvil production of convections at developing stage is 10% higher than that of the decaying convection of the same $W_{ett}$. The moist upper troposphere is positively correlated with convection vertical development and anvil horizontal spreading.

4) The difference in the composite anvil productivities of tropical convective clusters sorted by the effective width among the eight climatological regions is subtle, while the occurrence of different scales of convection varies a lot. Convection at Indian Ocean Maritime Continents have the higher probability to form MCSs and MCCs.

The occurrence of different-scale convections leads to the variant anvil amount detrained at different levels causing different radiative effects, which are very important for cloud–radiation feedbacks in the climate system. The anvil volume and ice mass distributions among the convective clusters in this study provide a comprehensive structure of anvil clouds across the tropics, which are very valuable to evaluate model simulations of tropical convective clouds, mass transport, and cloud radiative feedback.

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