The Role of Cloud Size and Environmental Moisture in Shallow Cumulus Precipitation

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ABSTRACT

Cloud models show that precipitation is more likely to occur in larger shallow clouds and/or in an environment with more moisture, in part as a result of decreasing the impacts of entrainment mixing on the updrafts. However, the role of cloud size in shallow cloud precipitation onset from global satellite observations has mostly been examined with precipitation proxies from imagers and has not been systematically examined in active sensors, primarily because of sensitivity limitations of previous spaceborne active instruments. Here we use the more sensitive CloudSat/CALIPSO observations to identify and characterize the properties of individual contiguous shallow cumulus cloud objects. The objects are conditionally sampled by cloud-top height to determine the changes in precipitation likelihood with increasing cloud size and column water vapor. On average, raining shallow cumulus clouds are typically taller by a factor of 2 and have a greater horizontal extent than their nonraining counterparts. Results show that for a fixed cloud-top height the likelihood of precipitation increases with increasing cloud size and generally follows a double power-law distribution. This suggests that the smallest cloud objects are able to grow freely within the boundary layer but the largest cloud objects are limited by environmental moisture. This is supported by our results showing that, for a fixed cloud-top height and cloud size, the precipitation likelihood also increases as environmental moisture increases. These results are consistent with the hypothesis that larger clouds occurring in a wetter environment may be better able to protect their updrafts from entrainment effects, increasing their chances of raining.

1. Introduction

Shallow cumulus clouds occur over all ocean basins; however, they are most prominent over the trade wind regions of the central ocean basins (Norris 1998; Eastman et al. 2011). These clouds impact both the atmospheric radiation budget (e.g., Zeng 2018) and the precipitation budget. As noted by Nuijens et al. (2017), observations reveal 20%–40% of oceanic shallow cumulus clouds produce rain, although warm rain is usually light, with typical intensities less than 1 mm day\(^{-1}\).

Climate models struggle to accurately simulate shallow cumulus clouds and their impacts, primarily because of coarse model temporal and spatial resolution (e.g., Stevens et al. 2002). The small-scale processes important for the development of these clouds, including turbulence and convection, must be parameterized to adequately represent the impact of shallow cumulus clouds on climate (e.g., Tiedtke 1989; Zhang and McFarlane 1995; Bretherton et al. 2004; Park and Bretherton 2009). For instance, Nam et al. (2012) found that climate models tend to underestimate low cloud cover, but they produce shallow clouds that are too reflective as a result of poorly simulating the impact of the environment on the vertical structure of low clouds. They hypothesize that precipitation efficiencies that are too weak could play a role in the overestimation of model shortwave cloud radiative effects.

For warm rain to occur, shallow cumulus clouds must have sufficient updraft strength, liquid water, and duration for the collision–coalescence process to produce rain droplets (e.g., Wood et al. 2009). Additionally, the drop size distribution is an important factor that influences warm rain production. Factors that may impact the drop size distribution include aerosols (e.g., Dagan et al. 2016; Jung et al. 2016b,a), convective organization (e.g., Zuidema et al. 2012), and entrainment (e.g., Korolev et al. 2016; Pinsky et al. 2016b,a). While entrainment can enhance the potential of warm rain production by broadening the drop size distribution (e.g., Beard and Ochs 1993; Derksen et al. 2009), mixing may also introduce new particles into a cloud.

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that could act as cloud condensation nuclei (CCN). While the introduction of a few large particles may help warm rain production (Cooper et al. 2013), overall an increase in CCN would suppress warm rain production by increasing the cloud droplet concentration (e.g., Derksen et al. 2009). However, Minor et al. (2011) analyzed the relationship between warm rain production and giant CCN concentration; they found that giant CCN concentrations are not as important as the spatial organization of shallow convection to warm rain production.

Entrainment mixing and the resulting evaporative cooling may also have competing effects at cloud edges. First, the cooling at a cloud’s lateral edges creates a humid barrier between the cloud and the environment (e.g., Heus and Jonker 2008; Heus et al. 2009). Schmeissner et al. (2015) showed that this barrier helps protect the cloud core from the negative impacts of entrainment on cloud microphysics and reduces the suppression of warm rain production. However, the mixing of dry air into a cloud may also cool the cloud core, resulting in the in-cloud air becoming less buoyant. As a result, weakened updrafts (e.g., Hernandez-Deckers and Sherwood 2018) within a cloud do not transport as much humid air to higher levels of the cloud inhibiting warm rain production.

Several studies have used cloud models to analyze the impact of entrainment on a cloud core and subsequent precipitation. Lu et al. (2012) used field campaign data to find that entrainment rates decrease as the distance from cloud core increases, which implies that the impact of entrainment on precipitation may decrease as shallow cumulus clouds increase in size (e.g., Jiang and Feingold 2006). Using a large-eddy simulation (LES), Heus and Jonker (2008) showed negative buoyancy is most likely to occur within a cloud’s core for the smallest shallow cumulus clouds due to mixing at cloud edges. As a result, cloud cores simulated by LES models and identified from limited field campaign observations are wider for larger shallow cumulus clouds (Kirshbaum and Grant 2012; Watson et al. 2015) and have a larger liquid water content. Similarly, Tian and Kuang (2016) found the influence of entrainment on cloud updraft velocity decreases as clouds become larger in an LES.

Other LES studies have found that larger shallow cumulus clouds are more likely to rain because their updrafts are more protected from entrainment (e.g., Kirshbaum and Grant 2012; Jähn et al. 2016). Watson et al. (2015) referred to this phenomenon as a “cloud size mechanism.” Burnet and Brenguier (2010) compared the life cycle of three different oceanic clouds and found one cloud larger and with a higher liquid water content than the other two. They conclude that the smaller clouds’ updraft cores were most affected by mixing, which resulted in those clouds collapsing on themselves before they could grow tall enough to produce precipitation. The larger cloud was able to sustain its updraft in spite of the influence of entrainment, allowing it to grow tall enough and sustain a high enough liquid water content to produce precipitation. Similarly, LES results from Jiang et al. (2010) showed that as clouds become larger, they are more likely to produce precipitation, regardless of aerosol loading.

It is well understood that developing convection requires a moist environment. One would expect that a dryer environment would impact a cloudy updraft more than humid environmental air because dry environmental air would dilute cloudy air more (e.g., Li et al. 2014; Lamer et al. 2015) and stabilize the updraft. LES results from Hernandez-Deckers and Sherwood (2018) recently found that buoyancy within a cloud core decreases faster for drier environments than for a more humid environment. Thus, it can be expected that a larger shallow cumulus cloud occurring in a moister environment has a higher likelihood of producing warm rain.

Most of the aforementioned studies are based on field campaign (e.g., Rauber et al. 2007; Zhou et al. 2015) or LES models (e.g., Nuijens et al. 2017; Dagan et al. 2018), which are limited to a small spatial domain for a short period. This limits the conditions over which clouds can be sampled and the effects of cloud size on precipitation can be examined. However, satellite observations provide a large sample of shallow cumulus clouds both occurring over different regions and in different stages of their life cycle. Previous satellite studies have used Tropical Rainfall Measuring Mission (TRMM) and/or GPM to investigate warm rain (e.g., Lau and Wu 2003; Liu and Zipser 2009); however, these precipitation radars that operate at Ku and Ka bands are not sensitive to the cloud-sized particles in the nonraining portion of a cloud and, as a result, cannot be used to analyze cloud size. While direct measurements of the entrainment impact on cloud updrafts are not possible, the higher sensitivity to clouds and light precipitation of CloudSat and CALIPSO instruments can be used to examine the relationship between cloud size and rain likelihood. Over a long enough time period, satellite observations provide a large cloud population to constrain this relationship and infer the likelihood of a cloud size mechanism and the role of the local moisture environment. We expect that larger clouds will have a higher likelihood of producing rain, and the relationship between cloud size and rain likelihood is modulated by the surrounding moisture environment. To test this, we identify individual warm shallow cumulus clouds for 4.5 years of...
global CloudSat observations and analyze their characteristics to investigate the relationship between rain likelihood and cloud size in various environments.

2. Data and methods

CloudSat and CALIPSO satellite data are used to identify individual contiguous shallow cumulus cloud objects. The CloudSat and CALIPSO missions both carry instruments capable of identifying the vertical distribution of cloud particles. The Cloud Profiling Radar (CPR; Tanelli et al. 2008) on CloudSat is a near-nadir-pointing 94-GHz radar that measures backscattered radiation from cloud particles and has a 1.7 km x 1.4 km horizontal resolution and 480-m pulse length oversampled by a factor of 2, giving 240-m vertical resolution. The CPR has two main limitations (Tanelli et al. 2008): attenuation in intense precipitation and ground clutter in the lowest three bins.

CALIPSO carries a lidar that measures backscatter from both cloud and aerosol particles. It is a non-scanning instrument, and in the lowest 8 km of the atmosphere, it is highly sensitive to small particles. It also has a high resolution of 333 m horizontally and 60 m vertically (Anselmo et al. 2007). CALIPSO also allows us to see cloudy pixels in the lowest part of the atmosphere otherwise obscured by ground clutter or that are too small to detect using CPR.

To identify cloud objects, we use the CloudSat level-2 “Radar–Lidar Cloud Geometrical Profile” product (2B-GEOPROF-LIDAR; Mace and Zhang 2014) layer-base and top-height variables. This product utilizes both CPR and lidar data to identify cloudy pixels, making it ideal for identifying individual cloud objects. A binary mask is then applied with all pixels having a cloud fraction greater than zero assigned a value of one. At least two cloudy pixels must be touching either vertically or horizontally for cloudy pixels to be considered contiguous. Additionally, a single cloudy bin that is not touching any other cloudy pixels is not considered contiguous and removed from this analysis. Each contiguous cloudy region is then stored as individual cloud objects and the median cloud-top height and along-track extent (hereby cloud extent) for each cloud object.

For this analysis, warm cloud objects are defined as any cloud object with cloud-top heights entirely below the freezing level designated in the CloudSat level-2 “Precipitation Column” (2C-PRECIP-COLUMN; Haynes et al. 2009) product. Figure 1 shows a sample cloud-object distribution for one orbit seen by CloudSat and CALIPSO.

Over the ocean, there are two primary warm cloud types: stratocumulus and shallow cumulus. Both cloud types generally form under different environmental conditions. Studies have found that shallow cumulus tends to develop in regions with a more unstable boundary layer than stratocumulus (e.g., Wood and Bretherton 2004). We use ECMWF-AUX (Cronk and Partain 2017) matched vertical temperature profiles to identify regions of weaker stability associated with
shallow cumulus cloud objects. Lower-tropospheric stability (LTS) = \( \theta_{700\text{hPa}} - \theta_{\text{surface}} \) (e.g., Slingo 2007; Klein and Hartmann 1993), where \( \theta \) is potential temperature, is often used to quantify the strength of the stable boundary layer and has been widely used by the scientific community (e.g., Nam et al. 2012; Medeiros et al. 2014) to separate stratocumulus and shallow cumulus cloud regimes. To accomplish this, the maximum LTS value is taken for each warm cloud object. First established by Klein and Hartmann (1993), we use an LTS threshold of 18.55 K to classify shallow cumulus cloud objects.

Figure 2 shows a violin plot for both the shallow cumulus and stratocumulus cloud-object along-track extents defined using a lower-tropospheric stability threshold of 18.55 K are presented as boxplots, indicating the median (white dots) and quartiles (thick black areas), with whiskers (thin black areas reaching up to 1.5 times the interquartile range). The violin-plot outlines illustrate kernel probability density; i.e., the width of the shaded area represents the proportion of the data located at that cloud-object extent.

Given the main goal of analyzing the impact of cloud extent and environmental moisture on the likelihood of rain, the precipitation flag product from 2C-PRECIP-COLUMN is used to separate raining and nonraining clouds. To identify raining shallow cumulus cloud objects, we tested three different combinations of flags (rain certain, certain and probable, and certain, probable, and possible) to determine whether rain is occurring.
within a CloudSat pixel within any shallow cumulus cloud object. All three flags are used to identify raining shallow cumulus cloud objects, with any cloud object containing at least one raining pixel being considered a raining cloud object. However, the overall findings of this study are similar no matter the combination of rain flags used.

Both this analysis (see Fig. 3) and others (e.g., Wood and Field 2011; Medeiros and Nuijens 2016) show that most warm shallow cumulus clouds occur within the subtropical and tropical ocean basins. For this reason, we further constrain our sample region to the global ocean basins confined within 60°S and 60°N. Measurements are also restricted to between August 2006 and December 2010, during which both instruments recorded observations during both the day and nighttime satellite overpasses. To classify environmental moisture, we use the average relative humidity (RH) below 3 km derived from ECMWF-AUX. Both cloud-top height and RH are used as control variables when determining the relationship between rain likelihood and cloud extent.

3. Results

We first analyze the spatial distribution of raining and nonraining shallow cumulus cloud objects by binning them to a 2.5° × 2.5° global grid. A similar binning method is applied to cloud-top height and cloud extent, and these results are discussed in detail below.

Figure 3a depicts the distribution of shallow cumulus objects over the global ocean basins and shows that a majority of these cloud objects are found within the trade regions of the central ocean basins, in particular, the intertropical convergence zone (ITCZ), South Pacific convergence zone, and the west Pacific warm pool. Previous studies have found similar results using different satellite (Wood and Field 2011) and field campaign (Medeiros and Nuijens 2016) observations.

Figure 3b shows the spatial distribution of raining shallow cumulus cloud objects over the global ocean basins. Similar to the distribution of all shallow cumulus cloud objects, most raining shallow cumulus cloud objects occur over the trade regions of the central ocean. In these regions, shallow convection tends to organize at cold pool boundaries (e.g., Seifert and Heus 2013) into cloud sheets, clusters, and arcs (e.g., Warner et al. 1979; Rauber et al. 2007) and to produce rainfall (e.g., Lau and Wu 2003; Schumacher and Houze 2003).

Figure 3c shows the likelihood of rain occurrence of shallow cumulus cloud objects within a given grid box. As implied in Fig. 3b, these results explicitly show a relatively small fraction of shallow cumulus cloud objects identified by CloudSat produce rain with the largest fraction of raining shallow cumulus cloud objects occurring over the central ocean basins, especially in large-scale convergence zones. Over this area, at most 15% of all shallow cumulus cloud objects within a given grid box produce rain, while only 5%–10% of shallow cumulus cloud objects in all other regions produce rainfall. Nuijens et al. (2017) found similar results, showing only 5%–10% of warm clouds produce rainfall globally. However, it should be noted that CloudSat only takes a snapshot of shallow convection at two times of the day. As a result, we may be oversampling raining shallow
cumulus cloud objects if the two times of day that happen to coincide with CloudSat’s orbit are also peaks in the diurnal cycle. However, this is not likely to be a large problem given the diurnal cycle in warm rain over oceans is weak (Liu and Zipser 2009).

It has long been established that shallow cumulus producing rainfall typically have top heights of 2 km or more (e.g., Short and Nakamura 2000). This study analyzes the impact of cloud-top height on the rain likelihood of shallow cumulus cloud objects using both the univariate and spatial distributions of all, raining, and nonraining shallow cumulus cloud objects. Table 1 shows shallow cumulus cloud-object statistics for all, raining, and nonraining cloud objects, respectively. To assume a normal univariate distribution, skewness values between $-2$ and $+2$ are considered to be acceptable (George and Mallery 2009). This criterion is used to analyze the overall characteristics of each distribution. In this paper, we use the median and mean absolute deviation (MAD) to describe the data; however, MAD and standard deviation (STD) are similar in cases in which the data can be assumed to be normal.

Figure 4a shows the cloud-top-height univariate distribution for all shallow cumulus cloud objects peaks at approximately 750 m and has a median shallow cumulus cloud-object-top height of $1.26 \pm 0.49$ km (see Table 1). Similar to our results, Rauber et al. (2007) found shallow cumulus cloud-top heights are generally below 1 km using a combination of radar, aircraft, ground, and ship-based measurements.

Figure 4b shows the distributions of both raining and nonraining shallow cumulus cloud-object cloud-top height with Table 1 showing that raining shallow cumulus cloud objects have a median cloud-top height of $2.07 \pm 0.63$ km, whereas nonraining shallow cumulus cloud objects are shallower by a factor of approximately 2, having a median of $1.19 \pm 0.42$ km. As shallow cumulus clouds grow deeper, it is well known that both the chance and intensity of warm rain increase (e.g., Short and Nakamura 2000; Rauber et al. 2007). Within the Caribbean Sea and Atlantic Ocean, Snodgrass et al. (2009) found that detectable rainfall was most likely for clouds with tops between 2.25 and 2.75 km. Considering that our definition of raining cloud objects is dependent on the “rain possible” flag, which has a reflectivity threshold of $-15$ dBZ (Haynes et al. 2009), we may be sampling cloud objects that are producing very light rain and light drizzle that evaporates before hitting the surface that are otherwise not included by

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Fig. 4. (a) The probability density function of cloud-top height for all shallow cumulus cloud objects, and (b) a comparison between the raining and nonraining cloud-top-height probability density functions.
the Snodgrass et al. (2009) 7-dB threshold used to identify precipitation.

Figure 5a shows the median cloud-top height at which at least 25% of cloud objects produce rain. Cloud objects are binned onto a 2.5° × 2.5° spatial grid, and any grid box containing no data is white.

Figure 5b shows the median cloud-top height at which at least 25% of cloud objects produce rain. Figure 5c shows top-height thresholds are smallest (<2.0 km) over the ITCZ and west Pacific warm pool regions. Outside these regions, the top-height threshold generally increases. This is most noticeable over the South Pacific Ocean trade region, where the top-height threshold to produce rainfall is greater than 2 km. Outside the ITCZ and western Pacific warm pool regions, environmental moisture tends to decrease. This implies that mixing is not as harmful to clouds occurring in the humid environments allowing shallower cumulus to sustain rainfall, whereas shallow cumulus in drier environments must grow deeper to sufficiently protect themselves from dry air mixing at cloud boundaries (e.g., Lu et al. 2012).

Another region of interest is the global coastlines, particularly the east coast of North America and the east coast of Asia. Over these regions, the top-height threshold required for at least 25% of cloud objects to rain is greater than 2 km (Fig. 5c). Given the high density of populated and industrial regions over eastern Asia and North America coupled with typically westerly atmospheric flow, the transport of polluted air from these regions over the ocean leads to a higher CCN concentrations (Rosenfeld 2000), which can increase the number of small droplets and decrease variability in the drop size distribution (e.g., Squires 1958). Both of these impacts reduce the chance of growing droplets large enough to fall out as rain (e.g., Albrecht 1989). A similar pattern exists west of the North African continent and southeast of Saudi Arabia, where dust has a similar impact (e.g., Koren et al. 2014).

If cloud depth was the main factor in determining precipitation likelihood, Fig. 5c would show little regional variability. From Fig. 5c, it is clear that rain likelihood is not entirely dependent on cloud depth, and that other processes such as aerosols, cloud extent, and environmental moisture are important. To determine the importance of cloud extent, we analyze the cloud-extent distributions of all, raining, and nonraining shallow cumulus cloud objects. Table 2 shows the overall
statistics of each cloud-extent distribution to determine how cloud size impacts the likelihood of precipitation. Figure 6a shows the univariate cloud extent for all shallow cumulus cloud objects. Most cloud objects are small with a median cloud extent of 4.45 ± 1.63 km (Table 2). Guillaume et al. (2018) recently investigated the differences in the horizontal cloud length scale for different cloud types using CPR data and found shallow cumulus clouds smaller than those identified by our study. These differences are likely due to their inclusion of single-bin cloud objects and their use of the CloudSat level-2 “Cloud Classification” product (2B-CLDCLASS; Sassen and Wang 2008), rather than the regime separation used here, to classify cumulus cloud objects.

Figure 6b shows the univariate cloud-extent distribution for both raining and nonraining shallow cumulus cloud objects, with raining shallow cumulus cloud objects being on the order of 2–3 times as large as nonraining cloud objects, with a median cloud extent of 9.92 ± 4.08 km (Table 2). This suggests that the cloud size mechanism may be detected in observations, with larger clouds being less effected by lateral entrainment and better able to maintain their updrafts longer, grow taller, and produce more intense rainfall. Liu and Zipser (2009) used the TRMM Precipitation Radar (PR) to show that 90% of all raining shallow cumulus typically have an area of <100 km². If we define the diameter of each cloud object using extent, then we find that 90% of all raining shallow cumulus cloud objects have an equivalent circular area that is less than 226 km², which is larger than those found by Liu and Zipser (2009). This discrepancy is expected because of the higher sensitivity and resolution of CloudSat/CALIPSO, with both CloudSat/CALIPSO able to identify cloudy area associated with small cloud particles (e.g., You et al. 2006) and CPR being better able to identify very light rainfall (e.g., Leon et al. 2008; Behrangi et al. 2014), neither of which can be detected by TRMM PR.

Figure 7a shows the spatial distribution of median cloud extent for all shallow cumulus cloud objects. These results show that cloud extent does not vary much across the global ocean basins, with an extent typically between 2 and 4 km. By comparing the spatial distribution of median raining shallow cumulus cloud-object extent to the spatial distribution of median cloud extent for all shallow cumulus cloud objects, Fig. 7b implies there is more variability in extent among raining cloud objects than nonraining cloud objects. Among raining cloud objects, Fig. 7b shows that extent increases from both poles to the equator and from the west to east over the global oceans. This can be attributed to a deepening boundary layer (Wood and Field 2011).

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resulting in the boundary layer decoupling from the surface (Bretherton and Wyant 1997) and smaller clouds (Wood and Bretherton 2006).

So far, our results identify two key characteristics of raining shallow cumulus cloud objects:

1) They are usually taller than nonraining shallow cumulus cloud objects.
2) They usually have a larger extent than nonraining shallow cumulus cloud objects.

Both of these conclusions support the overall hypothesis of this study: however, we have not explicitly shown if larger clouds in a wetter environment are more likely to rain. Next, we investigate the impact of both environmental moisture, cloud-top height, and cloud size on the likelihood of shallow rain by conditioning our shallow cumulus cloud-object dataset using cloud-top height and RH.

Figure 8 shows the likelihood of warm rain as a function of environmental moisture, cloud-top height, and extent. Focusing first on environmental moisture, Fig. 8 shows that shallow cumulus cloud objects that develop in a wetter environment are the most likely cloud objects to produce rainfall. This pattern is consistent among all shallow cumulus cloud objects and not dependent on cloud-top height. The dependence of rain likelihood on environmental moisture is largest for the shallowest cloud objects, with rain likelihood approximately 30% higher in the wettest environments for the largest cloud objects.

If we now focus on shallow cumulus cloud-top height, the change in rain likelihood is approximately linear and increases more slowly than the rain likelihood of objects with top heights of <2 km. This may be because cloud objects shallower than 1.5 km never reach the trade inversion, which can limit shallow cumulus growth (Wood and Field 2011). By limiting cloud-top heights to less than 1.5 km, we could also be heavily sampling clouds in the earliest development stages, which are less likely to rain. For top heights of >1.5 km, the relationship between rain likelihood shifts, with one power-law scaling distribution for cloud extents of <7–8 km breaking down to another power-law scaling distribution for cloud extents above 8 km, consistent with past literature (e.g., Kuo et al. 1993; Benner and Curry 1998; Neggers et al. 2003; Trivej and Stevens 2010; Neggers et al. 2019), of a double power-law scaling for cloud size distributions. Trivej and Stevens (2010) show similar behavior for the size of precipitating shallow cumuli with a break in the scaling at approximately 10 km². Assuming that one-half of the along-track extent represents the cloud radius, these data show that a break in rain likelihood occurs in the range of 9–17 km². Prior studies attribute the double power-law behavior to different regimes, where below the scale break small shallow cumulus can grow quickly up to the trade inversion where they become limited. Above the break, cloud objects are limited by environmental moisture conditions.

Examination of the cloud-top height and extent distribution for precipitating shallow cumulus in Fig. 9 further supports the idea that the double power-law relationship exists between top height and extent, consistent with previous tropical shallow cumulus work by Benner and Curry (1998). Below the break, top height and extent scale at approximately the 2:1 aspect ratio shown in previous studies (Benner and Curry 1998; Kuo et al. 1993) although slightly slower in the driest environments. Cloud objects in the driest environments rarely exceeding 1.7 km, while cloud objects occurring in the wettest environments can reach ≥2.4 km. Since boundary layer depth increases while trade inversion strength decreases as environmental moisture increases, this allows shallow cumulus that form in a more humid environment to grow larger and support more robust updrafts, increasing the chance of warm rain. Above the break, the relationship between height and extent depends strongly on the moisture environment. Trivej and Stevens (2010) found that environmental moisture is a key contributor to large shallow cumulus development. Combining Figs. 8 and 9 suggests that the general precipitating cloud size distribution follows scaling shown...
in previous studies; however, for a fixed cloud depth, the likelihood of precipitation depends on the size of the cloud and/or the moisture environment. For clouds with a similar depth, a larger cloud or a cloud in a moister environment is more likely to rain.

Figure 10 shows the median fraction of raining pixels within each cloud object conditioned on environmental moisture. It also shows a scale break and supports the idea that precipitation likelihood increases with environmental moisture, especially after the scale break where Trivej and Stevens (2010) suggest that cloud objects are limited by environmental moisture regime. For a fixed cloud extent greater than 7–8 km, the fraction of the cloud object that is raining is at least 10% greater when RH below 3 km is above 75% when compared with environments with RH 50% or below. This also suggests that cloud updrafts are less impacted by cloud edge mixing and may result in more vigorous updrafts, resulting in a higher rain likelihood and a larger raining cloud fraction, when the environment is moist.

4. Limitations

While we have attempted to mitigate as many limitations as possible, some limitations in the shallow cumulus identification scheme and precipitation identification scheme that could impact the results may still be present. The cloud-object identification scheme used by this study is limited by the 1.7-km along-track spatial resolution of CloudSat. As a result, the smallest cloud objects this study can sample have a minimum cloud extent of 1.7 km. There likely are raining cloud
objects that are smaller than this threshold. However, this limitation is unavoidable given CloudSat’s resolution.

Previous studies have used ground-based cloud radars to analyze shallow cumulus at a spatial resolution as high as 30 m (e.g., Kollias et al. 2003). Considering raining clouds may not always be large enough to fill CloudSat’s footprint, raining cloud objects may be missed if they lack a sufficient size and intensity necessary to trigger a rain detection by CloudSat. To test this, we performed sensitivity tests by setting a $0.1 \text{ km}^3$ grid within CloudSat’s footprint and assigning each subpixel reflectivity values ranging from clear to cloud to different rain intensities. We assumed a Gaussian shaped gain function and calculated the reflectivity that would be measured by CloudSat for varying subpixel reflectivities and rain fractions to determine the fraction of raining subpixels at a given intensity that would reach CloudSat’s thresholds for rain certain, rain possible and rain probable (Table 3). At the rain certain threshold of 0 dBZ, Table 3 shows that the rain rate must be $\geq 0.05 \text{ mm h}^{-1}$, and a rain shaft producing $0.05 \text{ mm h}^{-1}$ rain rates must be the entire size of CloudSat’s footprint (2.38 km$^2$) to trigger a rain detection. As rain rate increases, the minimum rain shaft size for a CloudSat rain detection decreases. Table 3 shows a similar pattern at both the rain probable and possible thresholds; however, any shallow cumulus cloud producing rainfall at rates of $>0.50 \text{ mm h}^{-1}$ only needs to be $0.01 \text{ km}^2$ (equivalent to one subpixel) to reach the rain possible threshold of $-15 \text{ dBZ}$. These results suggest potential beamfilling problems may impact our results and could contribute to the rapid increase in rain likelihood for the smallest cloud objects. Many previous studies, some of which use higher-resolution ground-based radar observations, showing similar double power-law relationships as cloud objects grow larger and scale breaks that occur at similar sizes (e.g., Benner and Curry 1998; Trivej and Stevens 2010) lends some confidence that our rain likelihood distributions are not purely due to sampling limitations.

Another consideration is any shallow cumulus cloud objects identified by CALIPSO within the ground clutter region of CPR are missed in the rain likelihood statistics. However, Rapp et al. (2013) estimated that around 0.6% of shallow clutter clouds may produce precipitation, suggesting relatively small impacts on our findings.

It is well established that as shallow cumulus grow they can modify the surrounding local environment through the vertical transport of latent heat. This can act to both increase environmental moisture and reduce LTS, allowing for subsequent growth and potentially rain (Johnson et al. 1999). Because we use ECMWF RH and LTS to classify the large-scale environment, cloud-scale modulation of the local environment is not considered. This limitation is unavoidable from a purely observational standpoint.

In addition, the environmental thresholds used here to classify shallow cumulus and stratocumulus cloud objects were initially developed using monthly averaged data. This may be why the environmental separation
scheme identifies cloud objects larger than the typical cumulus cloud (e.g., Rauber et al. 2007). As mentioned earlier, the largest 5% of shallow cumulus cloud-object sizes are removed from this analysis, although this has little impact on our overall findings.

5. Summary and discussion

Earlier studies have used cloud and LES models, constrained using field study data at select sites, to investigate the impact of shallow cumulus size on rain production. These studies concluded that as shallow cumulus clouds grow larger, the likelihood of rainfall increases. This was attributed to the influence of entrainment on larger shallow cumulus clouds decreasing, which allows for stronger updrafts. Given that global observations of shallow cumulus clouds are limited, it is essential that simulated clouds be compared to observations. This not only helps constrain shallow cumulus and their impacts on climate models but also our general understanding of warm rain production. This study developed a large global cloud-object dataset from CloudSat/CALIPSO observations to analyze the influence of cloud extent on rain likelihood. We then used LTS to identify shallow cumulus cloud objects. This approach allows us not only to analyze shallow cumulus cloud-object characteristics but also to identify any relationship between cloud size, rain likelihood, and the environment.

By binning the shallow cumulus cloud-object dataset onto a $2.5\degree \times 2.5\degree$ grid, results show that most shallow cumulus cloud objects (both precipitating and non-precipitating) are observed over the trade wind regions. These regions are generally associated with a weakly stable boundary layer and weak large-scale subsidence. As a result, the boundary layer can deepen and decouple from the surface, creating a favorable environment for shallow cumulus.

Most shallow cumulus cloud objects have cloud-top heights on the order of 1 km; however, raining shallow cumulus are generally about 2 times as tall, with the tallest occurring over equatorial regions. SSTs over these regions tend to be warm resulting in a wetter environment and deeper boundary layer, both of which are shown to enhance the likelihood of precipitation.

In general, shallow cumulus cloud objects are small with a cloud extent typically less than 5 km, but raining shallow cumulus cloud objects tend to be about 3 times as large as nonraining objects, lending support to the hypothesis that larger clouds are more likely to produce rainfall. Spatially, the largest shallow cumulus cloud objects tend to occur in the eastern ocean basins, while the smallest shallow cumulus cloud objects tend to occur over the west Pacific warm pool and the Indian Ocean.

To identify the relationship between cloud extent and rain likelihood, we constrained shallow cumulus cloud objects using cloud-top height and environmental moisture. For a fixed shallow cumulus cloud-object depth, the two main conclusions are that cloud objects with a larger extent are more likely to rain and that as environmental moisture increases rain likelihood becomes larger for smaller cloud objects.

For shallow cumulus cloud objects with top heights of $<1.5\mathrm{km}$, the change in rain likelihood increases approximately linearly with cloud-object size, with the slope dependent on the environmental relative humidity. One possible explanation is that the shallow cumulus cloud objects sampled with cloud-top heights of $<1.5\mathrm{km}$ are developing cumulus that have not yet reached the top of the boundary layer. For shallow cumulus cloud objects taller than 1.5 km, the change in rain likelihood shows a double power-law distribution with one scaling at extent values of $<7–8\mathrm{km}$ that breaks down and flattens into another scaling distribution at extent values that are greater than 8 km.

Trivej and Stevens (2010) show that the mean reflectivity as a function of cloud size also has this double power-law scaling, which explains why rain likelihood (based here on reflectivity thresholds) follows this distribution. Similar behavior is shown for the relationship between cloud-top height and extent and the raining fraction of clouds and extent, with the break
occurring at different top heights in different environmental regimes.

The shift in scaling of the rain likelihood distribution may be attributed to an environmental regime shift (Trivej and Stevens 2010). Small cloud objects are trade inversion limited and rapidly grow deeper and larger following the 2-to-1 size-to-height aspect ratios shown in earlier studies (e.g., Benner and Curry 1998) up to the capping inversion. As they grow larger, rain likelihood increases, suggesting that as cloud size increases they are less affected by entrainment and supporting the hypothesis that shallow cumulus become better protected from mixing as they grow larger (e.g., Heus et al. 2009; Burnet and Brenguier 2010).

Previous studies (i.e., Trivej and Stevens 2010) suggest that the breakpoint in the double power-law distribution is related to a shift in meteorological controls on convection, specifically changes in environmental moisture. Past the breakpoint, rain likelihood with cloud size increases more slowly but the rain likelihood at which the breakpoint occurs depends on the environmental RH. The same size cloud is more likely to produce precipitation in higher RH regimes, and the fraction of the cloud producing precipitation also increases. Both provide observational support for the idea that because of decreased evaporation at cloud edges, shallow cumulus updrafts are not as harmed by mixing in a humid environment. As a result, they can sustain larger droplets longer that may eventually fall out as rain.

Other potentially important factors important for the rain likelihood distribution with cloud size that were not examined here are the role of organization and aerosols. Our results suggest that aerosols near the coastlines likely play a role in limiting rain likelihood. However, Minor et al. (2011), found that spatial organization was more important than giant CCN concentration. Consistent with the suggested importance of spatial organization, Trivej and Stevens (2010) found that increasing shallow cumulus cloud size in precipitating shallow cumulus was coupled to an increase in cloud area fraction, which they attributed a moister environment more conducive to vertical and horizontal development. Precipitation in the trade regions has often been linked to convective organization (e.g., Zuidema et al. 2012; Seifert and Heus 2013; Stevens et al. 2020), with cold pools formed by previous convection initiating new shallow cumulus that can grow deeper and become more likely to rain. The break in the rain likelihood distribution with cloud size shown here could be related to a shift toward more spatially organized convection. We are currently expanding our cloud-object dataset to include additional metrics for cloud spacing and expect to use this dataset in the future to investigate the importance of shallow cumulus organization to precipitation likelihood.

Our results provide global observational support for previous modeling and limited field campaign studies hypothesizing that larger clouds or clouds in a more humid environment can protect their updrafts from entrainment and increase the likelihood of warm rain. Our results are encouraging; however, we cannot directly estimate entrainment using these observations. As a result, we can only speculate that larger shallow cumulus cloud objects are more likely to rain because their updrafts more protected from entrainment. Luo et al. (2010) identified a method that can be used to estimate entrainment in deep convective clouds using satellite data. This method uses estimates of moist static energy profiles throughout the depth of the cloud to estimate the entrainment rate. Future work could focus on developing similar satellite-based methods to estimate the entrainment rate in shallow cumulus clouds.

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Data availability statement: All CloudSat/CALIPSO data products used in this analysis were acquired from the CloudSat Data Processing Center and can be accessed online (http://www.cloudsat.cira.colostate.edu). For access to any other dataset created by the analysis, please contact the authors.

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