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LETTER

The impact of rain rate, raining patch size, and spacing on southeastern Pacific cloud fraction transitions

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Abstract

Rain-induced cold pools are one mechanism by which transitions in cloud fraction in marine stratocumulus over the southeast Pacific occur. We use CloudSat/CALIPSO to identify raining patches within stratocumulus over the southeast Pacific, and then calculate the cloud fraction surrounding each raining patch, nearest-neighbor distance (spacing), mean rain rate, and raining patch size (extent). The spatial patterns show that as cloud fraction decreases and rain rate increases from east to west, a minimum in spacing exists between 80°W-100°W, but the maximum extent occurs further west. Holding spacing constant, cloud fraction decreases with rain rate but increases with extent. Additionally, cloud fraction is generally lower between 80°W-100°W when cells are large. This behavior is consistent with the idea that heavier rainfall associated with larger cells may result in possible cold pool interactions that could drive lower cloud fractions around the largest cells producing the most intense rainfall.

1. Introduction

Just off the west coasts of the major continents, large stratocumulus cloud decks that gradually transition from contiguous cloud layers to broken-cell trade cumulus toward the equator are common. These large cloud decks have a pronounced cooling effect on the surface (e.g. [1]), therefore it is important to understand how the extent of these clouds may change in response to climate change (e.g. [2]). Historically, the advection of humid subtropical air to warmer waters east of the major stratocumulus regions which results in a deeper boundary layer, has been viewed as a primary driver of stratocumulus transitions (e.g. [3–7]). As cool moist air is advected westward, it travels over progressively warmer water and regions with weaker subsidence aloft. Below the cloud layer, more stable air coupled with deeper and more unstable air within the cloud layer decouples the surface from the cloud layer, allowing more vigorous updrafts to form within the cloud layer. These updrafts are able to penetrate the top of the boundary layer and mix drier air into the cloud layer, helping to break it apart (e.g. [7]).

Modeling and regional observational-based studies have also hypothesized that rainfall can drive the development of closed to open cell transitions within stratocumulus decks. Rainfall induced transitions can occur by two mechanisms: 1) by removing cloud water from the cloud layer [8] and 2) by cold pool collisions [9–13]. Focusing on the second mechanism, the evaporation of drizzle and light rainfall induces downdrafts which spread out at the surface as cold pools. These cold pools may then collide and mechanically produce more intense updrafts that can induce turbulence at cloud top which mixes drier air down into the cloud layer from above the boundary layer helping to thin it out (e.g. [9]).

During the VAMOS Ocean–Cloud–Atmosphere–Land Study Regional Experiment over the southeast Pacific, Terai and Wood [14] used aircraft observations to show that measurable cold pools typically do not form until rain rates exceed 1 mm day$^{-1}$. However, Yamaguchi and Feingold [13] found that single raining patches producing locally heavy rainfall are insufficient in driving transitions in a cloud model. Specifically, Yamaguchi and Feingold [13] found the distance between raining patches of stratocumulus important in determining if a transition to open-cell stratocumulus will occur. Observational cold pool horizontal sizes in this region are typically smaller than 50 km and rarely exceed 100 km [14]. This implies that raining patches must typically be...
closer than 100km for cold pool interactions that may drive transitions to occur. If nearest-neighbor distance between raining (spacing) between cells is large, Yamaguchi and Feingold [13] found that transitions occur slower, but only if the raining patches are producing heavy enough rainfall and/or raining patches are large enough for cold pool interactions to occur.

Most studies have used either cloud models (e.g. [10, 13, 15]) or field-campaign observations (e.g. [16–18, 14]) to analyze the influence of rainfall on stratocumulus transitions. Although modeling and field-campaign studies may be better for investigating individual physical processes driving transitions, this limits analyses to specific regions and short time frames and may not be representative of climatological transitions. Satellite observations can provide a large enough sample size over a long enough time frame to analyze variability between raining patch characteristics and cloud fraction transitions over the southeast Pacific stratocumulus to shallow cumulus climatological transition region. CloudSat, in particular, is highly sensitive to the light precipitation produced by these clouds, and in conjunction with CALIPSO can provide a more holistic view of total cloud fraction over this region. Rapp [19] used CloudSat and CALIPSO observations to investigate the influence of rainfall on these transitions and found cloud fraction changes faster around raining clouds than non-raining clouds within the southeast Pacific transition region. However, the relationship between raining patch size, spacing, intensity, and these cloud fraction transitions was not investigated. To fill these gaps, this study will use CloudSat and CALIPSO observations to test the hypothesis that raining cell spacing minima, raining patch size maxima, or rain intensity maxima are present across a stratocumulus to shallow cumulus cloud fraction transition over the southeast Pacific.

2. Data and methods

CloudSat and CALIPSO are used to identify contiguous cloudy regions over the stratocumulus cloud fraction transition region in the southeast Pacific. CloudSat carries a near-nadir pointing 94-GHz radar (Cloud Profiling Radar (CPR); [20]) with a 1.7 × 1.4km² horizontal resolution and a 480 m pulse-length oversampled by a factor of 2 giving a vertical resolution of 240 m. The CPR is sensitive to both cloud and rain droplets, however, ground clutter in the nearest three bins [20] to the surface limit its usefulness closest to the ground. CALIPSO carries a lidar that has a higher resolution than CloudSat in the lowest 8km, with a horizontal resolution of 333 m. CALIPSO is highly sensitive to small cloud droplets that would otherwise be missed by CPR and can sense droplets in the lowest part of the atmosphere that occurs in the ground clutter region. Using both CloudSat and CALIPSO to identify cloudy regions gives a more holistic view of where clouds are occurring at any given time.

We use the layer-top and layer-base products from 2B-GEOPROF-LIDAR [21] to identify contiguous cloudy regions. This product stores up to 5 cloud-layers on any given pixel, but we only include single-layer clouds in this analysis, and we do consider a single-cloudy bin as contiguous.

Once we identify contiguous cloudy regions, we further subset the data into contiguous raining regions by only including regions where 2C-RAIN-PROFILE [22] rain rates are >0mm hr⁻¹. Contiguous raining regions must be both over the ocean and have cloud-top temperatures entirely above 273 K. This is done by matching cloud-top height to the freezing level identified using ECMWF [23] temperatures matched to CloudSat’s track, which is stored in 2C-PRECIP-COLUMN [24], and matching the navigation flag from 2B-GEOPROF [25] to each pixel for the separation between land and ocean. Each contiguous raining region is stored as an individual raining patch along with the mesoscale cloud fraction, raining patch along-track size (extent), maximum rain patch top height, and mean rain rate for each raining patch. spacing is defined as the minimum nearest neighbor distance from one raining patch edge to the nearest other raining patch edge along CloudSat’s orbit. The mesoscale cloud fraction surrounding the center pixel of each raining patch is calculated by averaging the ratio of cloudy pixels to the total number of pixels within a window between the raining patch edge and the nearest raining patch edge on either side. Raining patch extent is defined as the number of contiguous raining pixels multiplied by CloudSat’s along-track resolution of 1.4 km, and maximum top height is defined as the highest altitude obtained from the 2B-GEOPROF-LIDAR layer-top product within each raining patch.

As shown in figure 1, this study focuses on the southeast Pacific between longitudes of 80 °W and 120 °W and latitudes between 10 °S and 25 °S. Analysis of stratocumulus transitions over the southeast Pacific has been investigated extensively by prior literature (e.g. [3, 11, 19, 26–28]). Measurements are constrained to June 2006—December 2010 because CloudSat stopped taking night time measurements after 2010 due to a battery anomaly [29].
3. Results

3.1. Entire southeastern pacific domain

To analyze spatial patterns in the distribution of cloud fraction, rain rate, spacing, extent, and top height, raining patches are binned to a $2.5° \times 2.5°$ grid over the southeast Pacific, and each statistic is averaged within each bin. Figure 1 (a) shows that the number of raining patches sharply increases from the South American coast through $80°W$, increasing from below 100 samples to $>500$ samples, with the largest number of raining patches occurring between longitudes of $80°W$—$120°W$ and latitudes of $5°S$–$25°S$, before gradually tapering off towards the trade cumulus region. Focusing on cloud fraction, figure 1 (b) shows that cloud fraction decreases from east to west, with cloud fraction surrounding each raining patch $>0.9$ closest to the coast decreasing to values $<0.7$ west of $120°W$. As shown in figure 1 (c), the gradient in rain rates is aligned with the gradient in cloud fraction, however, the magnitude of rain rate increases from east to west with rain rate exceeding 1 mm hr$^{-1}$ east of $105°W$. Figure 1(d) shows that there is a minima in cell spacing between $80°W$ and $110°W$ and north of $25°S$, with values $<50$ km. Figure 1(e) shows small variations in size with the largest values approaching 7 km west of $105°W$ and then decreasing again to the west. The local minima in cell spacing across the climatological cloud fraction transition is consistent with our hypothesis; however, the local maxima in extent is east relative to the largest cloud fraction gradient.

The location of the local maxima in extent (figure 1(e)) also appears to be co-located with the spatial maxima in rain rate. To identify any relationship between rain rate and extent, figure 2(a) shows median rain rate as a function of extent. We find that rain rate and extent are positively correlated, with a correlation coefficient of 0.36. As a result, rain rates are generally below 0.02 mm hr$^{-1}$ when raining patches are smaller than the median size (4.2 km), and rain rate does not exceed 0.5 mm hr$^{-1}$ until raining patches reach a size of approximately $7\text{ km}$.
The spatial gradient in top height (figure 1f) is generally aligned with the gradient in both rain rate and cloud fraction, with top heights increasing from about 1.5 km near the coast to about 2.6 km at the western edge of the domain. Focusing on the relationship between top height and rain rate, this suggests that, similar to extent, top height is positively correlated with rain rate. Figure 3(b) shows that top height and rain rate are indeed positively correlated, with a correlation coefficient of 0.37. This result shows that both the tallest and/or raining patches with the largest extent are more likely to produce more intense rainfall.

Even though rain rate is correlated with both extent and top height, that does not necessarily mean that they influence cloud fraction in the same way. To test this, figures 3(a) and 3(b) show median cloud fraction as a function of rain rate, conditioned by extent and top height respectively. We then use a monte carlo algorithm to simulate a sample distribution of medians at a given rain rate by resampling the cloud fraction distribution with replacement at a given rain rate 100,000 times and then classify median error as one standard deviation in the sample median distribution.

Focusing on extent, figure 3(a) shows cloud fraction increases around raining cells when extent is larger. This is opposite from what is expected if raining extent were important for cloud fraction transitions. However, cloud fraction decreases with increasing rain rate for all patch sizes, although the effects appear to be larger for the smaller patch sizes. Figures 2(a) and 3(a) imply that the intensity of precipitation may be more related to the surrounding cloud fraction than the patch size, despite the positive correlation between the two.
Focusing on top height, figure 3(b) shows cloud fraction is lowest when raining patches are deeper than 2 km, but the relationship between cloud fraction and extent shown in figure 3(a) disappears, with cloud fraction remaining relatively constant as rain rate increases. Considering the similar orientations of the spatial gradient in cloud fraction, rain rate, and top height in figure 1, this suggests that these relationships may be driven by geographic variations, with the deepest raining patches producing the most intense rainfall over the western portion of the domain where cloud fraction is lowest and the opposite over the eastern portion of the domain.

To further test the relative importance of patch size versus intensity, we calculate cloud fraction anomalies relative to the climatological mean surrounding a rain cell within each 2.5° × 2.5° gridbox. We then average the anomalies for raining patches above and below the median patch size. Figure 4(a) shows the mean cloud fraction anomalies are negative between 80°W–100°W and 10°S–25°S, while anomalies are positive west of 100°W when raining patches are above the median size. The region of negative anomalies is generally co-located with the region of the closest raining patches (figure 1(d)). Figure 4(b) shows that, even though mean rain rates are generally >0.4 mm hr⁻¹ spatially over the entire domain when raining patches are larger than the median size, the region of negative cloud fraction anomalies are generally aligned with the sharpest gradient in rain rate. Figure 4(c) shows opposite patterns in mean cloud fraction anomalies to those shown in figure 4(a) when raining patches are smaller than the median size. However, figure 4(d) shows rain rates are relatively constant from the coast to 105°W with values generally below 0.1 mm hr⁻¹. These results suggest that over the eastern portion of the domain, rain rate may be more related to the surrounding cloud fraction than extent because we would expect positive cloud fraction anomalies over this region when raining patches are largest if extent is driving the relationship.

Given the diurnal nature in cloud fraction and rain rate over the southeast Pacific [e.g. 6, 8, 9], we also analyzed the daytime and nighttime data separately. We found that 61% of the raining patches were sampled at night, implying that the overall results in this study would primarily reflect the nighttime results. Comparing the nighttime-only data to the entire dataset, the general relationships between the variables do not change, with the only major difference being cloud fraction is generally higher at night than during both day and night.

Figure 4. The spatial distribution of mean cloud fraction anomalies within each 2.5° × 2.5° gridbox for raining patches ≥ 4.2 km and those < 4.2 km are shown in panels A and C respectively. The spatial distribution of mean rain rate within each 2.5° × 2.5° gridbox for raining patches ≥ 4.2 km and those less than < 4.2 km are shown in panels B and D respectively. The dashed box represents the eastern region (10°S–25°S; 80°W–100°W), while the dotted line represents the western region (10°S–25°S; 100°W–120°W).
composited together. Therefore, we analyze the composite data for the remainder of this study to maximize the number of samples.

3.2. Eastern and western southeastern Pacific regions

Figure 3(b) establishes that extent and rain rate have opposite relationships with cloud fraction across the southeast Pacific domain, and cloud fraction anomalies shown in figures 3(a) and c suggest that rain rate may be more related to changes in surrounding cloud fraction east of 100 °W than extent. To further analyze regional importance of extent and rain rate to changes in cloud fraction, the remainder of this analysis focuses on two subregions, an eastern domain (80 °W and 100 °W; 10 °S and 25 °S) and a western domain (100 °W and 120 °W; 10 °S and 25 °S). Even though there is slight overlap in the typical ranges of top height over the eastern and western regions, with top heights generally between 1.65 km and 2.15 km over the eastern region and top heights between 2.02 km and 2.64 km over the western region, raining patches are generally taller over the western region. Therefore, we do not analyze any influence of top height on rain rate, spacing, or cloud fraction in this section because using an east/west separation already loosely controls this analysis for top height.

To isolate the relative importance of rain rate to changes in cloud fraction over both regions, figure 5 shows median cloud fraction as a function of spacing conditioned by extent (figures 5(a) and (b)) and rain rate (figures 5(c) and (d)), and, similar to figure 3b. Over the western region, figure 5(a) shows that cloud fraction decreases with spacing but varies little with extent. Comparing the eastern and western regions, figures 5(a) and 5b show that cloud fraction decreases faster over the western region than the eastern region, with cloud fraction approaching 60% over the western region and cloud fraction ranging between 75% and 85% over the eastern region.

Figure 5. Median cloud fraction as a function of spacing over the western (80 °W–100 °W) portion of the southeast Pacific are shown in panels A and C. Median cloud fraction as a function of spacing eastern (100 °W–120 °W) portion of the southeast Pacific domain are shown in panels B and D. Shades of red represent raining patches that are separated by size, while shades of blue represent raining patches that are separated by rain rate. The errorbars represent ±1 standard deviation of a sample distribution of cloud fraction medians at a given spacing which are calculated using a Monte Carlo error estimation.
region for spacing of 120 km. Conversely, over the eastern region, figure 5(b) shows cloud fraction decreases faster with increasing spacing when raining patches are larger than the median size than it does when they are smaller, with cloud fraction differences approaching 3% as spacing approaches 100 km. Figure 5(c) shows the relationship between cloud fraction and spacing is relatively independent of rain rate, with cloud fraction decreasing at approximately the same rate during the most and least intense rainfall over the western region. Over the eastern region, figure 5(d) shows cloud fraction decreases faster with spacing during the most intense rainfall, with differences of approximately 5% between cloud fraction surrounding raining patches producing the most and least intense rainfall as spacing approaches 100 km. Given the infrequency of raining patches being further than 50 km apart with the number of samples being fewer than 300 at spacings >50 km, the argument that cloud fraction decreases quicker with spacing when raining patches are larger and/or producing more intense rainfall is further supported by the spread in median cloud fraction does not overlap for spacing between 40 km and 100 km. The curves shown in figures 5(a) and b look similar to those shown in figures 5(c) and d. This suggests that decreases in cloud fraction with extent at given spacing over both regions are actually masking the importance of rain intensity, because of the positive correlation between rain rate and extent (Figure 3a) and the opposite influences of rain rate and extent on cloud fraction (figure 3b).

Until this point, we have not made any inferences about the relative importance of the spacing between raining patches to surrounding cloud fraction. Figure 6(a) and b show the joint relative frequency distributions of raining patches at a given spacing and rain rate over the western and eastern regions respectively. Over the eastern region, figure 6(b) shows that raining patches most frequently produce either very light drizzle, with values below 0.03 mm hr$^{-1}$, or moderately heavy rainfall, with rain rates between 0.3 and 2 mm hr$^{-1}$, and are most frequently spaced within 100 km of each other. Relating this to cloud fraction, figure 5(d) shows that cloud fraction decreases at approximately the same rate for rain intensities above and below 1 mm hr$^{-1}$ until spacing reaches approximately 45 km, and once spacing exceeds 45 km, cloud fraction decreases faster when rain rate is highest. If we assume that cold pools typically do not develop until rain rates exceed 1 mm hr$^{-1}$ and cold pool sizes generally range between 10 and 100 km [14], figure 6(b) suggests that raining patches may be close enough together for cold pool interactions to occur [13] over the eastern region, which may help explain the cloud fraction differences between the least and most intense rainfall shown in figure 5(d) once spacing exceeds 45 km. Figure 6(a) shows that most raining patches are within 100 km of each other over the western region as well. If this is the case, why are patterns shown in figure 5(c) and (d) inconsistent? To address this, figure 5(c) shows that cloud fraction is generally lower for any given spacing than that over the eastern region (figure 5(d)). For raining patches within 100 km of each other, this implies that rain rate may not be as important to changes in cloud fraction because cloud fraction is lower, which may mean that the raining patches are simply too far apart for cold pool interactions to occur or stratocumulus transitions have already occurred.

Even though most raining patches are within 100 km of each other over the western region, figure 6(a) shows that a larger fraction of raining patches are further than 100 km apart than over the eastern region (figure 6b). To directly compare subregions, figure 6(c) shows the percent difference between relative frequency over the eastern and western regions. It shows more raining patches over the western region produce rain rates >1 mm

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**Figure 6.** The relative frequencies (%) of spacing as a function of rain rate over the western (100 W–120 W) and eastern (80 W–100 W) portions of the southeast Pacific domain are shown in panels A) and B). Note that, relative frequency is defined as the percentage of raining patches occurring within each bin. Panel C) shows the percent difference between relative frequency over the eastern and western regions $\left(\frac{\text{East}}{\text{West}} \times 100\right)$. 

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**Figure 3a**

**Figure 3b**

**Figure 3c**

**Figure 3d**

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**Figure 4a**

**Figure 4b**

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**Figure 5a**

**Figure 5b**

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**Figure 6**
hr$^{-1}$ than over the eastern region, but they tend to be further than 100 km apart. This implies that, although rain rates tend to be higher, raining patches are also more likely to be too far apart for any potential cold pool interactions to occur over the western region [13].

4. Summary and discussion

To test the hypothesis that raining cell spacing minima, raining patch size maxima, or rain intensity maxima are present across a stratocumulus to shallow cumulus cloud fraction transition over the southeast Pacific, we identify and analyze individual contiguous raining patches along CloudSat/CALIPSO’s orbit. We then calculate the cloud fraction surrounding each raining patch, minimum spacing, maximum extent, maximum top height, and mean rain rate and analyze the relationships between them. Contrary to our hypothesis that increasing rain extent would be related to regions with lower cloud fractions, cloud fraction increases with extent; however, it does decrease with increasing rain rate. This decrease in cloud fraction with rain rate was also shown in Rapp [19] with the cloud fraction surrounding raining CloudSat pixels being approximately 5% lower when rain rate is highest than when it is the lowest. Additionally, we find that the spatial gradient in top height is oriented similar to rain rate and cloud fraction over the entire domain, with top height increasing as rain rate increases and cloud fraction decreases from east to west. As hypothesized, a local minimum in raining patch spacing exists between 80 °W and 110 °W with raining patches generally <50 km apart, and this minima in cell spacing is co-located with sharpest gradient in rain rate. Unlike spacing, extent remains relatively constant across the cloud transition region. This may be partially because most raining patches are smaller than 8.4 km, and Cloudsat cannot resolve fine enough horizontal scales to adequately capture the small-scale variability in extent due to its along-track resolution of 1.4 km.

Wood and Hartmann [30] used a neural network to classify the mesoscale organization of cellular convection into closed, open, and organized, and they found that cellular organization transitioned from closed cell stratocumulus closest to the coast to organized open pockets of shallow cumulus between 85 °W and 100 °W to unorganized shallow cumulus west of 100 °W over the southeast Pacific. Rapp [19] and Smalley and L’Ecuyer [31] identified a similar region west of the South American coast between 80 °W and 100 °W where cloud fraction surrounding raining CloudSat pixels decreases faster than cloud fraction surrounding non-raining pixels. We found anomalously low cloud fraction surrounding larger raining patches occur in a similar region to that shown by these studies. Rapp [19] hypothesized that, between the regions of organized closed stratocumulus and unorganized shallow cumulus [30], precipitation is intense enough, raining patches are large enough, and/or raining patches are close enough together for cold pools to interact and cloud fraction transitions to occur. Focusing on the relationship between rain rate and extent, we find that cloud fraction anomalies are negative here and co-located and oriented with the gradient in rain rate when raining patches are large. Given the positive correlation between extent and rain rate, this suggests that rain rate may be more important to changes in cloud fraction because rain rate is positively correlated with extent, and we would expect rain rate to drive cold pool strength [13, 14]. If rain rate is driving transitions, our results imply that cold pool interactions do not begin until raining patches are approximately 40km apart, which is within the typical range of cold pool sizes found by Terai and Wood [14]. However, because CloudSat orbits are generally not aligned with the climatological wind trajectories [32], if there are differences in the along-wind and across-wind cell evolution and spacing, it is possible we may not be adequately sampling spacings below 40km if closer spacings occur in the along-wind direction of the cloud fraction transition [32].

Over the western region, cloud fraction anomalies are almost always positive when raining patches are large, even though rain rates are on average higher than the eastern region. Not only are cloud fractions typically lower but distances between raining patches are larger here, which could imply that cold pool interactions are less likely to occur [13]. This, coupled with the deepest raining patches producing the most intense rainfall, suggests it is more likely that lower cloud fractions result from the boundary layer decoupling from the surface due to daytime heating [33] west of 100°W, which would be correlated with both more intense rainfall and lower cloud fractions (e.g. [7]).

Considering extensive literature has shown that both cloud fraction and rain rate have a seasonal (e.g. [27, 34, 35]) dependence, it is reasonable to expect similar seasonal patterns in our results. Cloud fraction is highest with the furthest westward extent during southern hemispheric winter [27], while rainfall is most frequently closest to the coast [35]. Further analysis is needed to analyze the seasonal differences in rain rate, extent, and spacing; however, it will need to be cleverly designed to minimize CloudSat/CALIPSO sampling issues or will need to rely on another dataset.

Similar to the seasonal variability in cloud fraction and rain rates, earlier studies found a pronounced diurnal cycle in stratocumulus (e.g. [17, 33, 36]), with larger cloud fractions and most intense rainfall occurring over a much wider area during the night [33, 35, 36]. The highest cloud fractions recede toward the coast and rain rates
recede towards the western portion of the region during the day. Any analysis of precipitation induced transitions is more difficult during the day because daytime heating also acts to uncouple the boundary layer [33] which can thin stratocumulus but also lead to deeper, more intense raining patches. During the night, it is easier to isolate the influence of rainfall on transitions due to the lack of solar heating. It is more difficult to do a similar analysis for day and night due to sampling limitations, but we do not think that day/night differences influenced our results since most raining patches were sampled during the night.

Stratocumulus transitions remain difficult to represent within climate models (e.g. [37]). Recent studies have improved parameterizations to better capture stratocumulus transitions in response to changes in temperature and boundary layer depth which have been applied to climate models [38, 39], however, climate models struggle to simulate the impact of mesoscale organization on transitions due to inadequate parameterizations of sub-scale features responsible (e.g. [40, 41]). Our study adds to prior observational work suggesting that organization of precipitation, specifically the relationship between rain intensity and spacing between raining patches, is important to cloud fraction transitions (e.g. [19, 30, 31]). As a result, we speculate that climate model parameterization representations of sub-grid scale mesoscale organization in response to precipitation must be improved to better represent its influence on cloud fraction transitions.

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