Rain on small tropical islands

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[1] A high-resolution rainfall climatology based on observations from the Tropical Rainfall Measuring Mission's Precipitation Radar (PR) instrument is used to evaluate the influence of small tropical islands on climatological rainfall. Islands with areas between one hundred and several thousand km^2 are considered in both the Indo-Pacific Maritime Continent and Caribbean regions. Annual mean climatological (1997–2007) rainfall over each island is compared with that over the surrounding ocean region, and the difference is expressed as a percentage. In addition to total rainfall, rain frequency and intensity are also analyzed. Results are stratified into two 12 h halves of the diurnal cycle as well as eight 3 h periods, and also by a measure of each island's topographic relief. In both regions, there is a clear difference between larger islands (areas of a few hundred km^2 or greater) and smaller ones. Both rain frequency and total rainfall are significantly enhanced over larger islands compared to the surrounding ocean. For smaller islands the enhancement is either negligibly small, statistically insignificant, or, in the case of Caribbean rain frequency, negative. The enhancement in total rainfall over larger islands is partly attributable to greater frequency and partly to greater intensity. A diurnal cycle in island enhancement is evident in frequency but not intensity, except over small Caribbean islands where the converse is true. For the larger islands, higher orography is associated with greater rainfall enhancements. The orographic effect is larger (percentagewise) in the Caribbean than in the Maritime Continent. Orographic precipitation enhancement manifests more strongly as increased frequency of precipitation rather than increased intensity and is present at night as well as during the day. The lack of a clear diurnal cycle in orographic enhancement suggests that much of the orographic rainfall enhancement is attributable to mechanically forced upslope flow rather than elevated surface heating.

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1. Introduction

1.1. Motivation

[2] A central goal of atmospheric dynamics is a better understanding of what controls the distribution of deep convection in space and time. One undeniably important control, if still an imperfectly understood one, is the nature of the lower boundary, particularly the spatial distribution of land and sea.

[3] Much literature on the monsoons argues (or takes for granted) that land-sea contrast plays an important role in the development and maintenance of the monsoons. Some recent work has questioned whether the land-sea contrast is as important as had been thought [e.g., *Gadgil*, 2003], but it is almost certain that it plays some role. While some early work posited that land-atmosphere interaction is important to the intraseasonal variability of the monsoon [*Webster*, 1983], some more recent authors [e.g., *Sobel et al.*, 2008, 2010] have argued instead that the presence of land inhibits that variability. The role of topography in monsoons is similarly debated. Numerical model experiments tend to suggest that the Tibetan plateau has a strong influence on the South Asian monsoon [*Kutzbach et al.*, 1993], but this may be due more to the insulation of the South Asian continent from the colder, drier extratropical flow [*Boos and Kuang*, 2010] than to elevated heating over the plateau [*Molnar and Emanuel*, 1999].

[4] One way to develop an improved understanding of the roles of land-sea contrasts and orography in controlling deep convection is to start small. Small islands can be thought of as localized perturbations to an otherwise oceanic lower boundary [*Williams et al.*, 2004]. An isolated island whose horizontal extent is small compared to horizontal scales of interest in the atmosphere (the deformation radius, advective length scales, etc.) will be unable to induce a continental climate. Instead, it will provide a spatially fixed, highly localized forcing within an otherwise oceanic, uniform atmospheric environment. As such, it provides a simple test bed for our understanding of atmospheric convection.

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[5] In this study we provide observational constraints on precipitation over islands which might serve as targets for theory and modeling. Our interest is in to what extent rainfall over islands differs from that over the surrounding ocean. We study this difference as a function of island area, elevation, and diurnal cycle. We use a high-resolution precipitation climatology based on data from the Precipitation Radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite. We focus on islands in the Indo-Pacific Maritime Continent and Caribbean regions. In both regions, convection is relatively frequent and islands are numerous, allowing adequate sample sizes for statistical intercomparison.

1.2. Background

[6] It has long been recognized that islands and mountain ranges are focal points for the development of tropical convection [e.g., *Holland and Keenan*, 1980]. *Nullet and McGranaghan* [1988] used observations from a dense network of rain gauges on the Hawaiian islands to investigate the enhancement of rainfall over those islands compared to the surrounding ocean (whose annual rainfall was assumed to be 700 mm) and found that the enhancement was nearly a factor of 3. Some more recent studies have illuminated the role of larger Indonesian islands in controlling the distribution of rainfall using data sets based on infrared and passive microwave observations [*Qian*, 2008; *Ichikawa and Yasunari*, 2008]. For smaller islands the picture is less clear. *Reed* [1980] performed an analysis whose intent was similar to ours for islands in the tropical North Pacific using gauge data, but the paucity of observations over ocean to which to compare the island data rendered the resulting island-ocean differences controversial [*Dorman*, 1982] and led *Reed* [1982] to comment that satellite observations would be necessary to resolve the issue.

[7] The TRMM satellite has created new opportunities to study convection over islands. Building on the work of *Williams and Stanfill* [2002], *Williams et al.* [2004] used data from the Lightning Imaging Sensor (LIS) instrument aboard the TRMM satellite to determine the lightning flash rate over many tropical islands. Their scatter plots of flash rate (number of lightning flashes per unit area per unit time) versus island area showed that sufficiently small islands had flash rates indistinct from that of the oceanic background, while larger islands had larger flash rates, increasing with island size. The transition from the more oceanic regime (low flash rate, presumably indicating relatively weak updrafts) to a more nearly continental one (high flash rate, stronger updrafts) occurred in the island area range 100–1000 km^2. In the present study, we perform an analysis broadly similar to that of *Williams et al.* [2004], but focusing on rainfall rather than lightning. Unlike lightning, rainfall over tropical oceans is not generally small compared to that over land, so rather than analyzing the absolute value of rainfall, we focus on the difference between the areal mean climatological rainfall over each island and that over the ocean region immediately surrounding it.

[8] Some early theoretical studies addressed the dynamics of island sea breezes using dry models [e.g., *Neumann and Mahrer*, 1974; *Mahrer and Segal*, 1985]. Recent theoretical and numerical studies with moist models shed more direct light on the physics of convection over tropical islands and provide further motivation for our work. *Robinson et al.* [2008] performed idealized simulations in both a linear dry model and a moist nonlinear cloud-resolving model forced by localized surface heating. They found that the response to the surface heating maximizes when the surface heating has a particular horizontal scale, due to a resonant interaction of convection with gravity wave dynamics at that scale. This suggests a prediction that precipitation (and other measures of convective intensity) should also maximize at a particular scale. For realistic parameters, the resonant scale corresponds to several hundred to perhaps 1000 km^2. *Kirshbaum and Smith* [2009] performed large-eddy simulations of precipitation over the Caribbean island of Dominica, motivated by the observational study of *Smith et al.* [2009], and interpreted their results using a simple linear model. They found that precipitation over the upwind side of Dominica is strongly enhanced by shallow convection forced by orographic uplift. Surface heating plays no role in this mechanism, consistent with the weak to nonexistent diurnal cycle observed in precipitation over Dominica [*Smith et al.*, 2009]. The physics described by *Robinson et al.* [2008] and *Williams et al.* [2004], on the other hand, involves surface heating in a central way and should thus lead to a strong diurnal cycle. One aim of the present study is to examine the diurnal cycle as well as the role of topography over a large sample of islands, to determine the relevance of these different mechanisms to a broader spectrum of island configurations and climate regimes.

[9] Our study focuses on the most immediate and easily definable aspect of the island influence on rainfall, namely differences between the spatial mean climatological rainfall over the island and that over the ocean region immediately surrounding it. If the goal were to compare the island rainfall to that over true open ocean, one might also need to consider to what extent the oceanic region adjacent to an island is influenced by the island's presence, and not representative of the oceanic environment. Focusing on the diurnal cycle in particular, *Kikuchi and Wang* [2008] classify the Maritime Continent region as "coastal," but most of the Caribbean as open ocean. We do not consider this issue further in any detail here. We do limit our study to relatively small islands which are not in close proximity to larger ones, expecting that the oceanic environments around such islands are more representative of the open ocean than would be those near larger islands or continents.

[10] We restrict our analysis only to the areal mean and annual mean climatological rainfall over each island (within the resolution of the PR). Climatological rainfall may vary strongly from one part of an island to another, particularly when there is significant orography. Similarly, the enhancements may be different in different parts of the seasonal cycle. To some extent, these two effects may compensate, as seasonal wind changes cause windward slopes to become leeward or vice versa. Variations within individual islands are important from many points of view, but a proper treatment of them requires attention to the particular orography of each island and is outside the scope of this broad statistical study.

2. Data and Methods

[11] We use several TRMM orbit data products (1C21, 2A23 and 2A25) derived from measurements made with the

TRMM Precipitation Radar (PR) [*Kummerow et al.*, 1998a] for the period 1997–2007.

[12] The TRMM PR data set has a number of properties which make it particularly suited for our purpose. The high spatial resolution (5 km × 5 km) is ideal for analysis of fine-scale features such as precipitation enhancements over small islands. TRMM's temporal sampling strongly limits our ability to study temporal variability on these spatial scales, so we restrict the present study to the spatial structure of the climatology. The relatively direct relationship between radar reflectivity and precipitation, and the relative insensitivity of radar retrievals to the nature of the underlying surface, makes radar superior to passive microwave for studying land-sea contrast. The difficulty of characterizing the surface microwave emission makes microwave retrievals more problematic over land, and requires major differences in retrieval algorithms over land, coast, and ocean [*Kummerow et al.*, 1998b; *McCollum and Ferraro*, 2000]. While the PR retrieval algorithms do have some differences over land and ocean [*Meneghini et al.*, 2000; *Kozu et al.*, 2001; *Meneghini et al.*, 2004], these are relatively minor compared to those necessary for passive microwave retrievals. Rain gauges are at best sparse over ocean, making them poorly suited for the study of land-sea differences. Infrared emission measured from satellites (i.e., cloud-top temperature) is not nearly as directly related to precipitation—particularly on the small scales of interest here—as is radar reflectivity [*Yuter and Houze*, 1998].

[13] Detailed comparisons of TRMM PR from 1998 to 2001 to an active radar calibrator on the ground indicate that the PR's absolute calibration is within ±1 dB and that the instrument was stable over the 4 year time period [*Takahashi et al.*, 2003]. A 1 dB offset is equivalent to ~15% in rain rate [*Houze et al.*, 2004]. The TRMM PR is considered to be such a stable reference that it is used to calibrate ground radars used in the TRMM Ground Validation program [e.g., *Wang and Wolff*, 2009]. *Bowman* [2005] compared TRMM PR precipitation retrievals to rain gauges on oceanic buoys in the TRITON/TAO array in tropical Pacific. He compared TRMM PR 4 year average rainfall over 1° × 1° areas each containing a single open ocean buoy and using from 55 to 614 overpasses (the number of overpasses is primarily dependent on the availability of buoy data). Use of a 6 h period of gauge data centered on the overpass time yielded a correlation coefficient $r^2 = 0.92$ [*Bowman*, 2005]. Using ground-based radar and gauge data on Kwajalein Atoll, a region of small islands in the western tropical Pacific that is included in this study, *Schumacher and Houze* [2000] found good agreement within the sensitivity threshold of the PR ($Z \geq 17$ dBZ). Based on 50 TRMM PR overpasses, the ratio of area-integrated precipitation at 3 km altitude and 4 km × 4 km interpolated spatial resolution between the Kwajalein ground-based S-band radar and the TRMM PR for echo >17 dBZ was 0.99 with a correlation of 0.96. The minimum sensitivity threshold restricts the PR's ability to detect rain rates less than ~0.4 mm h^{-1}. Even with this limitation, *Schumacher and Houze* [2000] found that less than 3% of near surface stratiform rain <0.4 mm h^{-1} was missed by the PR.

[14] From the TRMM data set we produce climatologies of a number of variables, based on the surface rain rate. TRMM products use the terminology "near surface" to refer to the lowest usable radar measurement, usually less than 1.5 km altitude, and "estimated surface" to refer to an estimate based on the near surface measurement and assumptions about the vertical profile of rainfall. We refer to TRMM's "near surface rain" values as "surface rain" in this study. Reflectivity at a set of fixed altitudes from the surface to 6 km has also been analyzed, and the results are qualitatively similar to those obtained from surface rain (not shown). This demonstrates that the results are not artifacts of the rain rate retrievals.

[15] We bin the data from each individual orbit onto a regular grid with spacing 0.05 degrees in both longitude and latitude. The files produced from each individual orbit are then accumulated over the entire record to produce climatologies, either daily mean or diurnally stratified. The resulting climatologies are very similar to those of *Nesbitt and Anders* [2009], who discuss some features of the data set including sampling issues.

[16] Our analysis focuses on three statistics computed from the instantaneous surface rain rate product. The first is the mean rain rate, computed simply as the sum of the instantaneous rain rate over all observations in the record (including zeros) for pixels within a given area (i.e., an island or region of ocean around an island), divided by the number of such observations. The second is the conditional rain rate, or average rain intensity (hereafter simply intensity), which is the average rain rate over only those pixels where the rain rate was greater than or equal to 0.4 mm h^{-1} corresponding to the minimum sensitivity of the TRMM PR. The third is the percentage of rainy pixels, or rain frequency (hereafter simply frequency), which is the fraction of pixels in the sample whose rain rate was above the 0.4 mm h^{-1} threshold. In each case, the value of the quantity in question was averaged over each island. To obtain an ocean value for comparison to the island average, an ocean area was determined by computing the maximum width of the island in any direction, and finding the circle whose radius was 1.5 times that width centered on the center of the island. The variable in question was computed over the oceanic part of that circular area, whose area is typically around 3 times that of the island. This gives an oceanic area whose size is somewhat greater than that of the island to improve sampling, while at the same time not so large that it is very likely to enclose other islands. The results are not sensitive to the details of this procedure. The difference between the island and ocean values was normalized by the average value over the combined area of the two to produce a percentage difference.

[17] Island locations and areas were found using the GLOBE elevation data set [*Hastings et al.*, 1999] coarsened to the resolution of the TRMM PR sensor (~0.05°). Any pixel containing an elevation value greater than zero was considered to be land. Island area was found by summing the areas of contiguous pixels (0.05° × 0.05°, ~5.5 km × 5.5 km) belonging to the individual island. Islands within 12 pixels (~65 km) in any direction of a much larger land mass (larger being defined as having an area >6150 km^2) were eliminated from the study to prevent contamination from the larger land mass' climate. These specific criteria, though applied objectively, were chosen subjectively to eliminate islands which visual inspection showed to be

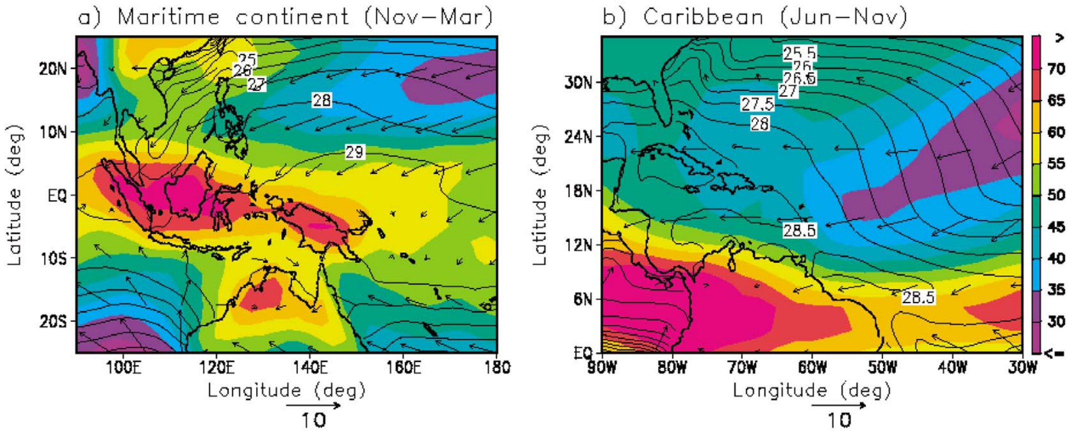

Figure 1. Climatological mean sea surface temperature (contours, °C), relative humidity at 700 hPa (color shading, percent), and surface wind (vectors, m s^{-1} (a) during the November–March in the Indo-Pacific maritime continent region and (b) during June–November in the Caribbean. Wind and relative humidity are from the NCEP/NCAR Reanalysis 2, available from January 1979 to July 2010, while sea surface temperature is from the Optimum Interpolation Sea Surface Temperature data set *Reynolds and Smith* [1995]; *Smith and Reynolds* [1998], available December 1981 to August 2010. Figure courtesy of Daehyun Kim.

clearly influenced by coastal rain enhancements offshore of the largest Indonesian islands. The minimum island size was chosen to be 4 contiguous GLOBE pixels (~120 km^2), between 4 and 5 TRMM PR pixels. The maximum island size was set as 200 contiguous pixels (~6150 km^2). The number of islands larger than this cutoff is relatively small, and on these large islands the rainfall distribution tends to be more inhomogeneous and the areal mean less representative than it is for smaller islands. These large islands (>6150 km^2) are more suited to study on an individual basis rather than statistically as part of a large group.

[18] Island elevation values were obtained from the Shuttle Radar Topography Mission data set (SRTM) [*Farr et al.*, 2007]. Elevation values were calculated at an approximate resolution of 0.025° × 0.025° (meaning the minimum island size of 4 GLOBE pixels contained approximately 16 elevation values from the SRTM data set). The elevation value was matched to its respective island obtained from the GLOBE data using a centroid matching technique. In the Caribbean, islands that did not have an exact match (i.e., centroids not within one pixel) were matched by hand. In total there were 52 islands in the Caribbean region and 141 islands in the Indo-Pacific region that met all of the size and location criteria and had reliable elevation estimates.

3. Results

3.1. Characterization of the Regions

[19] The large-scale climates of the two regions studied here differ substantially. We may expect the influence of small islands on rainfall to be modulated by these larger-scale climatological differences, so we briefly characterize them here before presenting our results from the PR. Figure 1 shows climatological sea surface temperature (SST), relative humidity at 700 hPa, and surface wind for the respective rainy seasons of the two regions (further details given in Figure 1 caption). While our PR results below are from the entire year, the larger part of the rain falls during the seasons shown in Figure 1. We see that the Caribbean has lower SST, lower relative humidity in the lower free troposphere, and stronger surface winds than does the Maritime Continent. While there are spatial variations in the climatology within each of the regions, these for the most part are smaller than the differences between the two regions. Thus while our analysis is done explicitly as a function of island area, topography and the diurnal cycle, by separating the data into two regions with different mean environmental characteristics we are to some degree conditioning our results on these large-scale climatological features as well. To the extent that our results for the Maritime Continent and Caribbean differ systematically, we interpret those differences as being due to the large-scale differences shown in Figure 1.

3.2. Sample Map

[20] We show a representative map of the PR surface rain climatology to give a visual impression of the character of the data set. Figure 2 shows the climatological mean daily rainfall accumulation (mm) during the hours 0000–1200 UTC (approximately daylight hours) for the Indo-Pacific Maritime Continent. The inset at upper right shows a subset of the region with greater magnification. The data set is clearly able to resolve differences in rainfall between relatively small islands and the surrounding oceans, as well as many topographic, coastal, and other features. However, even this 10 year climatology appears noisy at the high spatial resolution we use here, related to poor temporal sampling (over 70 h between TRMM PR overpasses near the equator) and the large natural variability in rainfall at the spatial scales of interest. Other work (in progress, to be submitted for publication in due time) will focus on a more in-depth analysis of features on and near the larger islands. Here, our interest is in the statistical properties of the island-

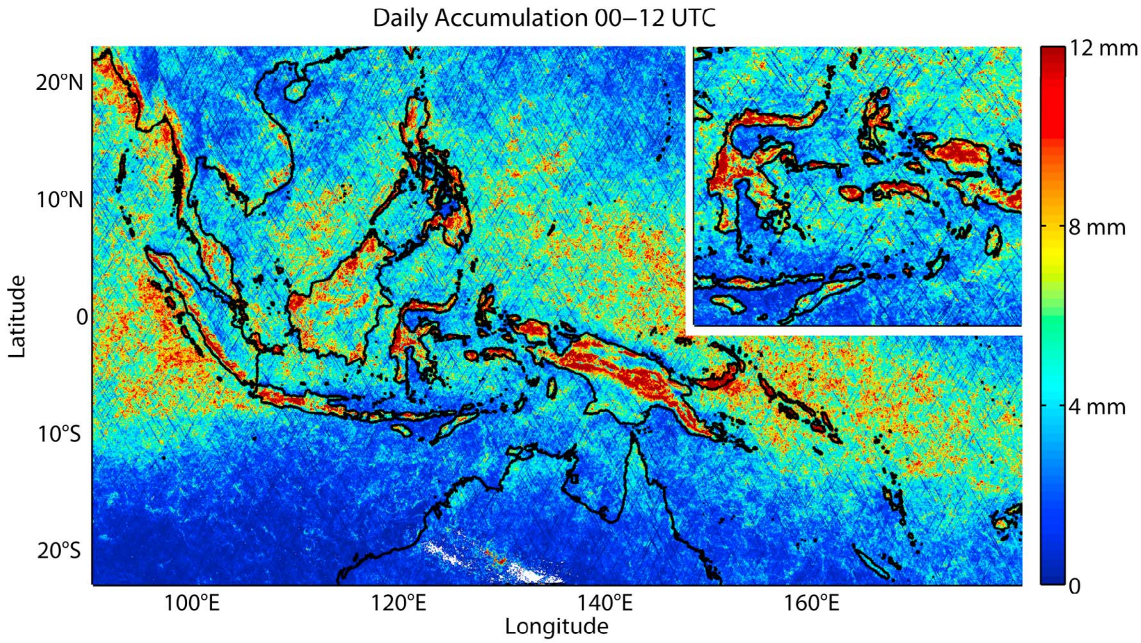

Figure 2. Climatological mean daily rainfall accumulation (mm) during the hours 0000–1200 UTC (approximately daylight hours) for the Indo-Pacific Maritime Continent region. Inset shows a subset of the region at larger magnification.

ocean differences in rainfall over a large sample of relatively small islands.

3.3. Diurnal Mean

[21] Figure 3 shows the enhancements in mean rain rate, frequency, and intensity, for each island in the Indo-Pacific Maritime Continent region, plotted as a function of island area. Figure 4 shows the same thing for the Caribbean. In both cases, island area is plotted on a logarithmic scale, and the axes in all panels of Figures 3 and 4 are the same for comparison.

[22] In both regions, for islands smaller than a threshold value, somewhere around 500 km^2, the rain rate enhancements are scattered approximately evenly about zero, while for larger islands there is a clear enhancement. In the Indo-Pacific, the scatter decreases with increasing island size, presumably due to the area averaging. It is not clear whether the smallest islands in our sample truly have no rain rate enhancement compared to the surrounding ocean, or whether they have a modest enhancement which is dwarfed by sampling noise. The scatter in the rain rate enhancements

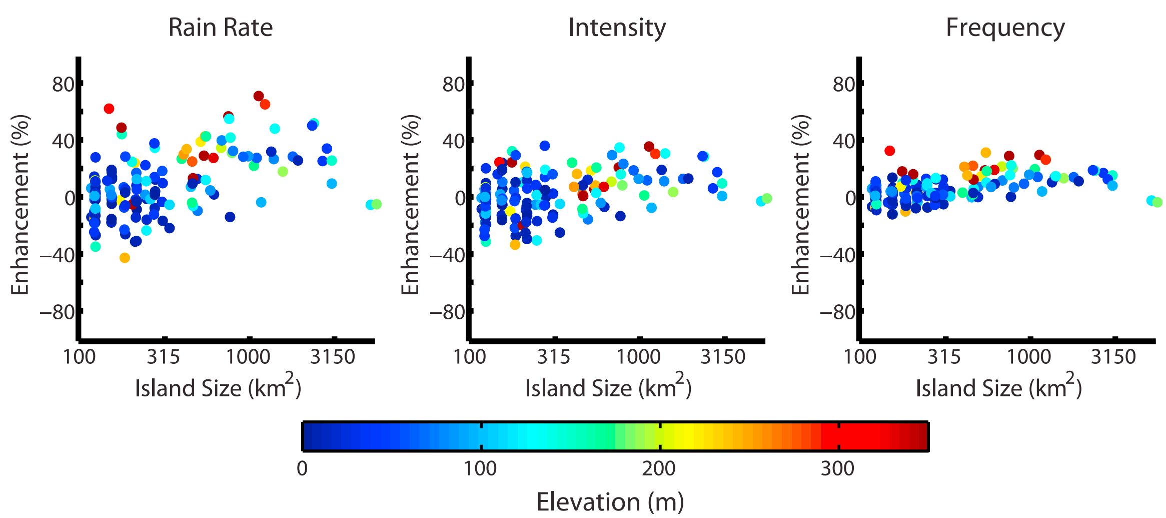

Figure 3. Scatterplots for the Indo-Pacific region of island size, on the *x* axis (km^2) versus island enhancements (%) in (left) climatological annual and daily mean total rain rate, (middle) conditional rain rate, and (right) rain frequency. Each point represents one island, colored by the 75th percentile of island elevation at 0.025 degree resolution (see text for details).

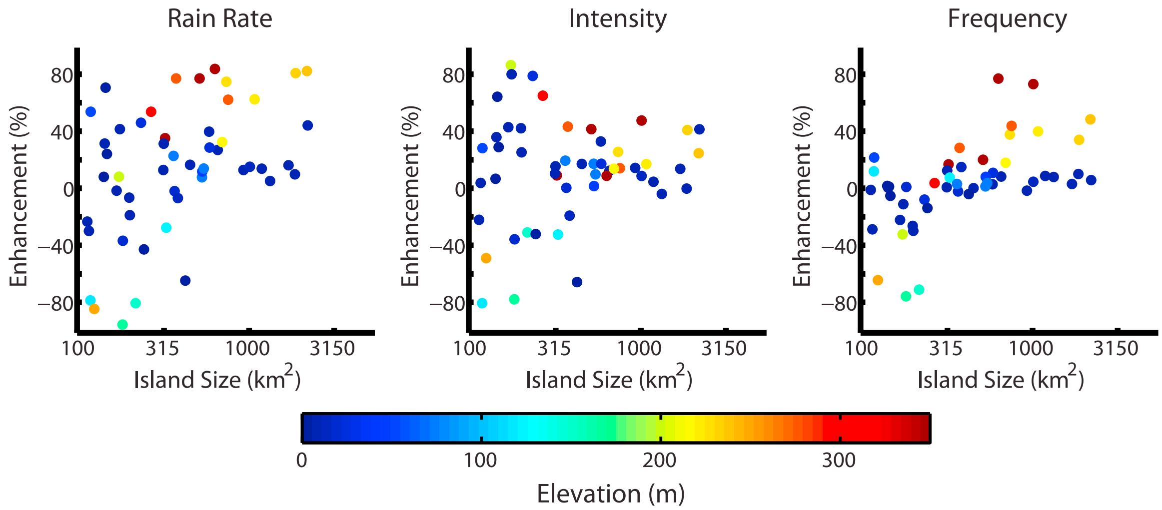

Figure 4. Same as Figure 3 but for the Caribbean region.

in the Caribbean is greater than that in the Indo-Pacific, however, for both small and large islands.

[23] The plots for intensity and frequency in Figures 3 and 4 show similar structure to that of those for total rain rate, but with smaller enhancements for the larger islands, as appropriate since the total rain rate can be thought of as a product of frequency and intensity. The percentagewise enhancements for larger islands in intensity and frequency are of comparable magnitude. This is consistent with the notion that on climatic time scales, variations in frequency and intensity tend to be correlated so that frequency itself can be a good proxy for mean rainfall [e.g., *Morrissey et al.*, 1994].

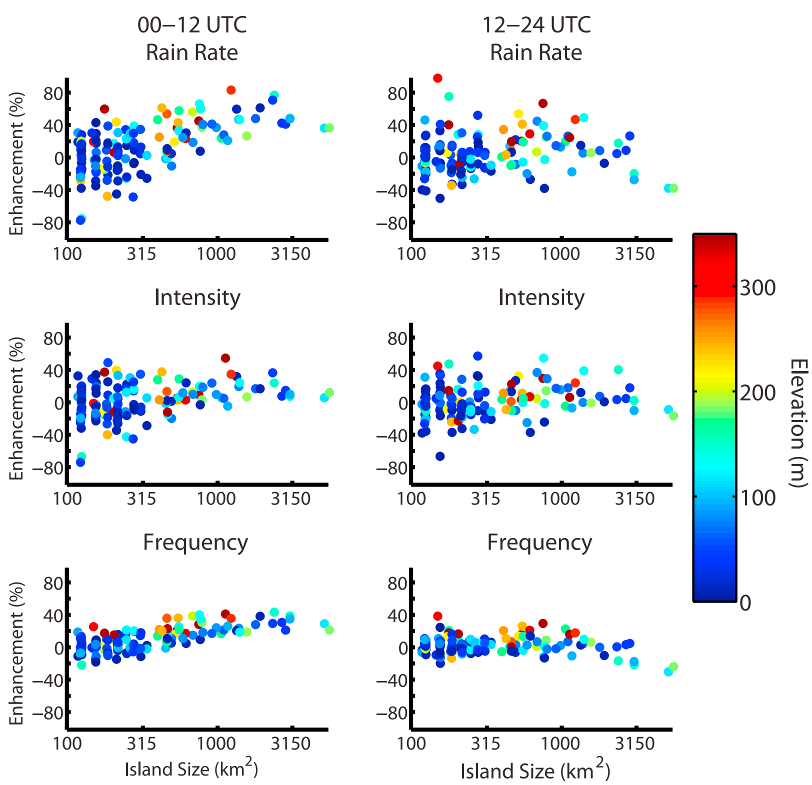

Figure 5. Scatterplots for the Indo-Pacific region of island size, on the *x* axis (km^2) versus island enhancements (%) in (top) total rain rate, (middle) conditional rain rate, and (bottom) rain frequency, for the hours (left) 0000–1200 UTC and (right) 1200–2400 UTC. In this region, 0000–1200 UTC (left column) corresponds approximately to daylight hours, while 1200–2400 UTC (right column) corresponds approximately to night. Each point represents one island, colored by the 75th percentile of island elevation at 0.025 degree resolution (see text for details).

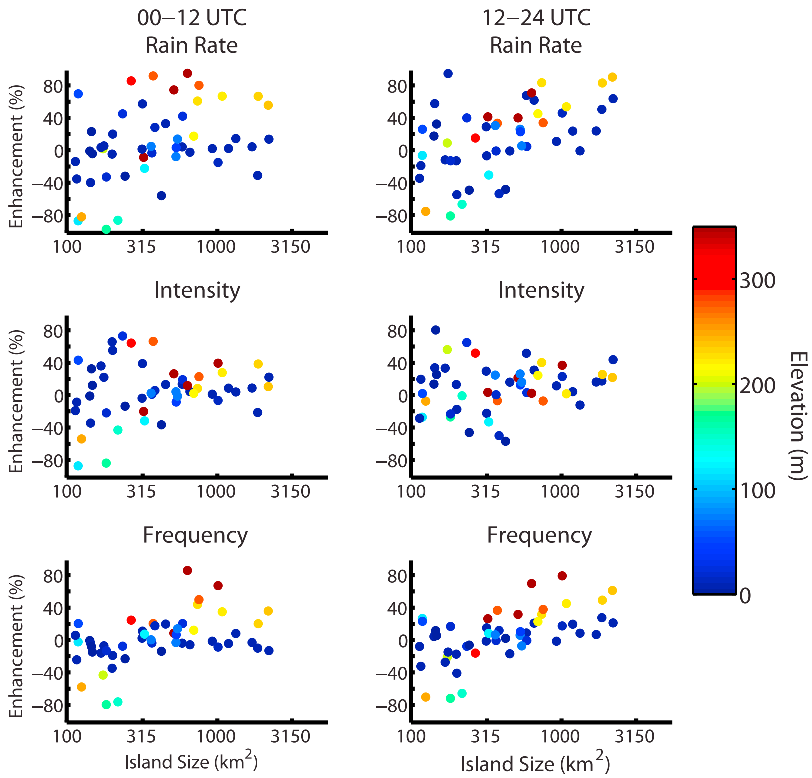

Figure 6. Same as Figure 5 but for the Caribbean region. In this region, 0000–1200 UTC (left column) corresponds approximately to night, while 1200–2400 UTC (right column)) corresponds approximately to day. Each point represents one island, colored by the 75th percentile of island elevation at 0.025 degree resolution (see text for details).

[24] In Figures 3 and 4, each point is colored according to the 75th percentile of the island's elevation. That is, for each island the distribution of elevations is constructed from all grid points in the digital elevation data at 0.025 degree resolution, and the value corresponding to the 75th percentile of that distribution is chosen; choosing a somewhat different elevation statistic does not qualitatively change the results. For mean rain rate, there is a clear tendency in the Caribbean for the largest enhancements to occur for those islands with higher topography. Intensity shows little or no such tendency. Frequency shows it quite clearly: of the points on the upper side of the size range in Figure 4 (right) with the largest enhancements (~40% or greater) all are ones with warm colors, indicating the largest topographic relief. In the Indo-Pacific, a qualitatively similar role of topography is seen. Frequency, in particular, shows the largest enhancements for islands with higher topography (Figure 3, right), though the scale used for the *y* axis—chosen for consistency with Figure 4—is not optimal for revealing it. Below we focus on this feature more directly.

3.4. Diurnal Cycle

[25] Figures 5 and 6 contain plots similar to those in Figures 3 and 4, except that they are stratified by the half of the diurnal cycle during which the observations were taken. Enhancements in rain rate, intensity and frequency are shown for the Indo-Pacific in Figure 5 and for the Caribbean in Figure 6, for the periods 0000–1200 and 1200–2400 UTC. In the Indo-Pacific, 0000–1200 UTC corresponds fairly closely to daylight hours, and 1200–2400 UTC to local night, while (coincidentally) the converse is approximately true in the Caribbean.

[26] Figure 5 shows that the Indo-Pacific enhancements for larger islands in all three fields—total rain rate, and its components frequency and intensity—are more pronounced during the day than at night. This indicates that the enhancement in total rainfall seen in Figure 3 is primarily due to surface heating by solar radiation, which results in larger daytime surface temperature increases on islands than over the ocean due to the smaller heat capacity of land compared to that of the ocean mixed layer.

[27] The daytime enhancement in convection over tropical islands (particularly those with significant orography) has long been known [e.g., *Leopold*, 1949]; for small islands in the maritime continent in particular it can be seen in visible imagery [*Holland and Keenan*, 1980] or in retrievals based on infrared and passive microwave satellite observations [*Qian*, 2008]. As discussed above, radar observations are particularly well suited to quantifying this effect.

[28] Data for the Caribbean islands, as shown in Figure 6, show a considerably less clear diurnal signal. The largest enhancements of rainfall by far tend to occur over the few large islands with the highest topography, and are perhaps somewhat enhanced during the day (1200–2400 UTC), but not greatly. The flatter islands (indicated by the cooler colors) do show an increasing trend with island size, to a greater extent during day than night.

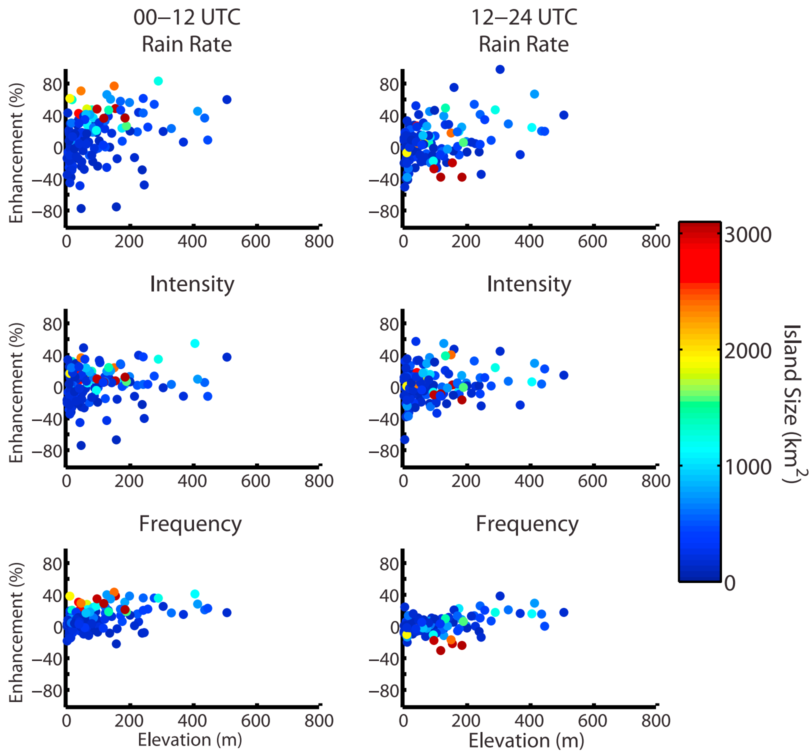

Figure 7. Scatterplots for the Indo-Pacific region of island elevation (measured by the 75th percentile), on the *x* axis (*m*) versus island enhancements (%) in (top) total rain rate, (middle) conditional rain rate, and (bottom) rain frequency, for the hours (left) 0000–1200 UTC and (right) 1200–2400 UTC. In this region, 0000–1200 UTC (left column) corresponds approximately to daylight hours, while 1200–2400 UTC (right column) corresponds approximately to night. The color of each point represents island area in km^2.

[29] Figures 7 and 8 focus more directly on the role of topography over the diurnal cycle. The format of Figures 7 and 8 are similar to Figures 5 and 6, with two changes. First, the representations of orography and island area are switched, so that the *x* axis shows orography (again the 75th percentile of island elevation at 0.025 degree resolution) while the colors show island area. Second, only islands with areas greater than 315 km^2 are shown. Qualitatively, the behavior as a function of orography for this subset of larger islands is similar to that as a function of size for the entire set of islands. Islands with larger orography (greater than 50–100 m by this statistic) show enhancements in all measures compared to the flatter islands, but beyond the 50–100 m threshold, there is little dependence on orographic height. Daytime upslope valley winds related to solar heating do not appear to intensify rainfall with increasing mountain elevation for the spatial scales of islands we examine. Figures 7 and 8 also make clear that for the largest islands with the highest orography, the total rain rate enhancements are significant—greater than 50%.

[30] It is of interest to study the diurnal cycle with a resolution finer than 12 h. As we increase the resolution, however, the number of observations within each time bin decreases, increasing the sampling error. We can reduce this again by averaging islands together. Figures 9 and 10 present the diurnal cycles of island enhancements in rain rate, frequency and intensity with 3-hourly resolution, averaged over islands in two island size categories: islands with areas less than 315 km^2 are considered "small," while islands with areas greater than 315 km^2 are considered "large"; the left column compares these two categories. The right column looks at the effect of topography, again with two categories: islands whose 75th percentile of elevation is greater than or less than 50 m are labeled "tall" and "short," respectively, and averages are computed over these two sets. The *x* axis is local rather than universal time; our data are averaged into 3 h bins in universal time, then data from each such bin are placed in the 3 h local time bin that is closest for each island. Doing the analysis in universal time leads only to modest, not qualitative differences in the results. In Figures 9 and 10, the red curves on the right panels show the mean values of each variable averaged over all oceanic points surrounding the islands, as a reference to the relative enhancements given. The oceanic diurnal cycles in frequency and rain rate are stronger in the Indo-Pacific than the Caribbean, and have broad maxima from late night to early afternoon of the following day and a minima in late afternoon and evening, consistent with the classification of the Maritime Continent as coastal [*Kikuchi and Wang*, 2008].

[31] The island enhancements shown in Figures 9 and 10 are broadly consistent with those in Figures 3–8. In the Indo-Pacific, we see a significant enhancement in frequency and rain rate over large islands but not small ones (left column). The enhancement occurs almost entirely during daytime hours. As this corresponds fairly closely to the 0000–1200 UTC period over the whole domain, this suggests that the 12-hourly grouping used in Figures 5 and 7 is

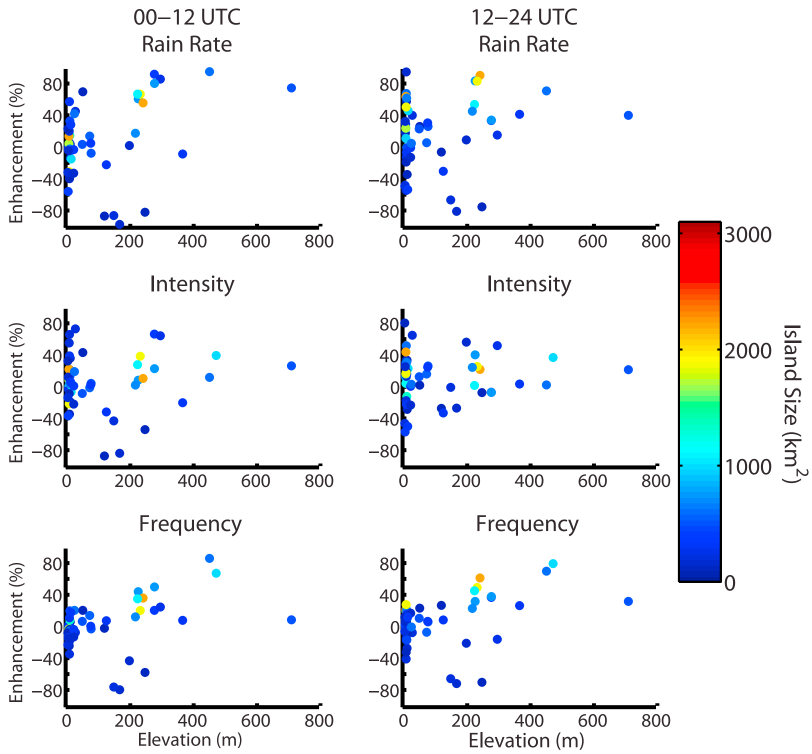

Figure 8. Scatterplots for the Caribbean region of island elevation (measured by the 75th percentile), on the *x* axis (*m*) versus island enhancements (%) in (top) total rain rate, (middle) conditional rain rate, and (bottom) rain frequency, for the hours (left) 0000–1200 UTC and (right) 1200–2400 UTC. In this region, 0000–1200 UTC (left column) corresponds approximately to night hours, while 1200–2400 UTC (right column) corresponds approximately to day. The color of each point represents island area in km^2.

adequate for capturing the gross features of the diurnal cycle. The diurnal enhancement in intensity is weak. The diurnal cycle in orographic enhancement (right column, compare green and blue curves) is substantial for rain rate, with tall islands significantly more enhanced than short ones during daytime hours. This is partly attributable to a slightly greater daytime enhancement in frequency for tall islands, but also to an apparent relative suppression (or at least lack of any significant enhancement) for short islands at that time. Overall, the diurnal cycle for short islands appears small and not particularly coherent.

[32] As with the 12-hourly resolution, the diurnal cycle of enhancement in the Caribbean with the 3-hourly grouping is less pronounced than in the Indo-Pacific. Frequency and rain rate are significantly greater over large islands compared to small islands throughout the entire diurnal cycle, but the day-night contrast for a given size category is less than in the Indo-Pacific region, suggesting a reduced role of solar heating in inducing convection in the Caribbean. As in the Indo-Pacific, the diurnal cycle for small islands appears small and not particularly coherent. Orographic enhancement of rain rate in the Caribbean is again shown to be stronger in the Caribbean than the Indo-Pacific, with the enhancement being primarily a function of a greater frequency of precipitation over the islands with greater topography. Overall, despite the addition of sampling error, the analysis of 3-hourly mean enhancements confirms the results demonstrated above using the 12-hourly data.

3.5. Summary Statistics

[33] Table 1 shows statistics computed from the values shown in Figures 2–7. The averaged percentage island enhancements in total rain rate, frequency, and intensity are shown for both regions and both phases of the diurnal cycle as well as the daily mean. Results are stratified into the two island size categories used above: those with areas less than 315 km^2 are "small" and shown in the left entry in each column, while those with areas greater than 315 km^2 are "large" and shown in the right entry in each column. Bold typeface indicates values that are both positive and significantly different from zero at the 95% confidence level according to a one-sided Student's *t* test. We also use a two-sample Student's *t* test to determine if differences between day versus night and tall versus short islands are greater than zero to the 95% confidence level. Significant differences based on the two-sample Student's *t* test are discussed in the text but are not highlighted with a different typeface in Tables 1 and 2.

[34] Daily mean enhancements in all three variables are significant and positive for large islands in the Indo-Pacific: 24.9% for rain rate, 13.2% for frequency, 9.9% for intensity. For small Indo-Pacific islands, enhancements are negligibly small, no more than two or three percent (the enhancements in frequency, however, despite being this small, are statistically significant). The results are similar for large Caribbean islands: enhancements in daily mean rain rate, frequency, and intensity are 31.2%, 17.5%, and 12.6%, respectively.

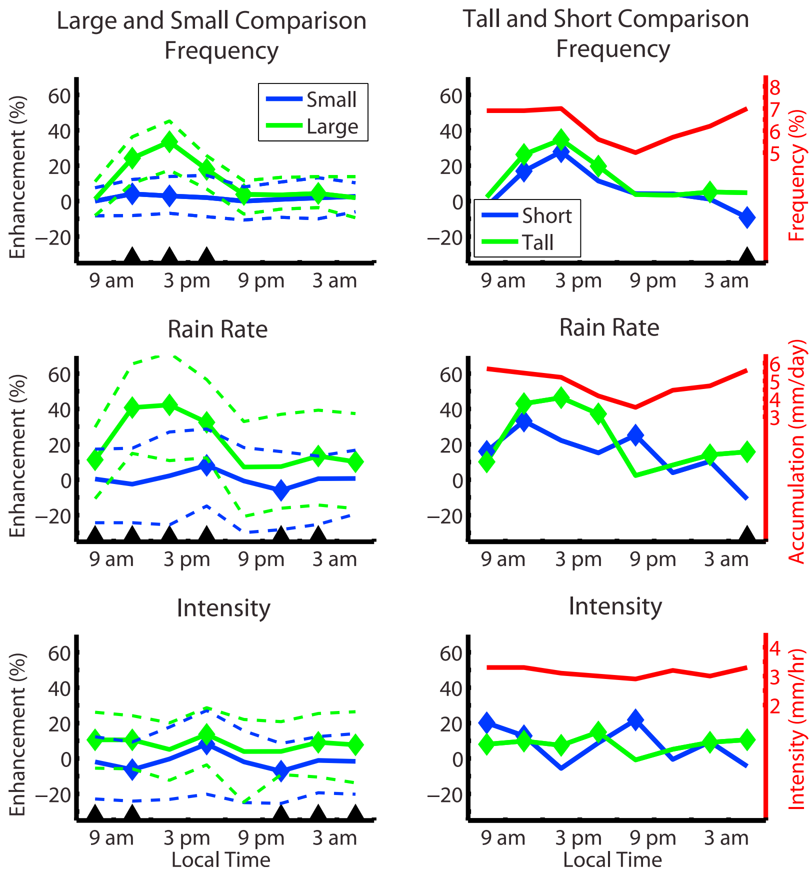

Figure 9. Diurnal variation of the mean enhancement is plotted as a function of local time in the Indo-Pacific region. On the left are the 3-hourly mean enhancements for islands greater than (green line) and less than (blue line) 315 km^2. Dashed lines plot the 25th and 75th percentiles of the distribution of enhancements. (right) Mean enhancements are plotted for islands with a 75th percentile elevation value greater than (green line) and less than (blue line) 50 m, with only islands with area greater than 315 km^2 used in the calculation. A solid diamond symbol is used to indicate when a particular value is significantly different than zero. A solid black triangle on the *x* axis is indicative of a significant positive difference between the large and small or tall and short islands. (right) A red line is used to plot the mean value of each variable averaged over all oceanic points surrounding the islands, used as a reference to the relative enhancements given.

Interestingly, small Caribbean islands have a noticeable (~19%) positive and significant enhancement in daytime rainfall intensity. Small Caribbean islands show substantial negative enhancements in total rain rate and frequency.

[35] For small islands in the Indo-Pacific, there is no statistically significant difference between the day and night means in any variable. The lack of a strong diurnal signal is true for all islands in the Caribbean, save for small islands in the case of intensity. For large islands in the Indo-Pacific, the day-night differences in frequency and total rain rate are significant, while that in intensity is not.

[36] Table 2 shows statistics stratified by elevation. In this case, only islands with areas greater than 315 km^2 are shown. Islands are grouped into those whose 75th percentile of elevation is greater than or less than 50 m, labeled “tall” and “short” respectively, and averages computed over these two sets, for a very crude measure of the effects of topography. For all variables, and both halves of the diurnal cycle, the enhancements are greater for tall than short islands, indicating a clear effect of orography in enhancing rainfall. The magnitude and statistical significance of this effect, measured by the tall minus short difference for each row of Table 2, varies.

[37] For total rain rate and frequency, the orographic effect is statistically significant for the Caribbean during the day, night, and daily mean. For tall islands, enhancements in total rainfall are on the order of 45–50% versus values for short islands in the range 5–15%, while for frequency the enhancements are ~30% for tall islands versus 0–10% for short islands. In the daily mean, the orographic effect on intensity is significant for tall islands. The difference between day versus night is not statistically significant for tall islands in the Caribbean, though the values are different enough (13–14% for tall islands versus 5–6% for short) to suggest that the signal is still present.

[38] In the Indo-Pacific, the orographic enhancement measured for tall versus small islands is statistically significant only for frequency, and only in the daily mean. Again, though, the fact that the values for frequency and rain rate are consistently larger (by 5–10%) for tall versus short islands,

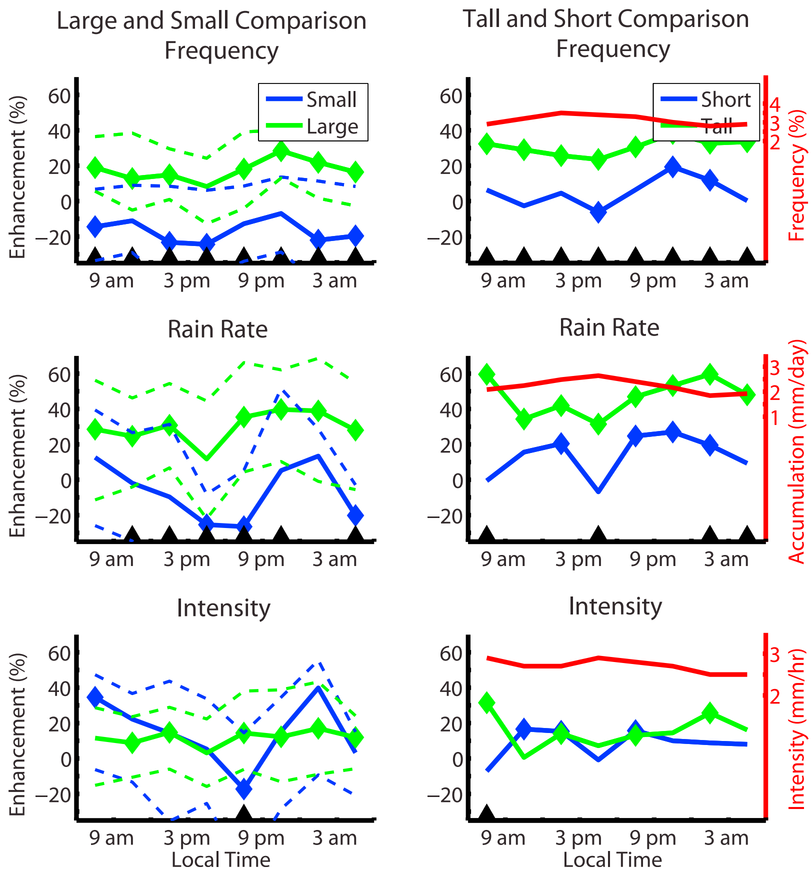

Figure 10. Same as Figure 9 but for the Caribbean.

together with the visual impression gained from Figures 2 and 6, suggest that there is an orographic enhancement in rain rate and frequency during both day and night, though small sample size prevents it from rising to 95% significance; for intensity the results are less clear (and the tall-short difference again statistically insignificant).

[39] The third column in Table 2 contains results only for islands that are both large and tall, according to our classifications. We can get a measure of the influence of diurnal heating in this sample by taking the differences between the day and night values. For the Indo-Pacific, this difference is significant for rain rate and frequency, but not intensity; for the Caribbean, it is not significant for any of the three variables.

3.6. Island Rainfall Enhancements in Absolute Units

[40] The above results were expressed as percentages, normalizing all island-ocean rainfall differences by the mean rainfall of the island and ocean region combined. In this section, we briefly present a subset of the results without

Table 1. Mean Percentage Island Enhancement: Small, Large[a]

Region (Time UTC)	Total Rain Rate	Frequency	Intensity
Pacific (all)	0.7, **24.9**	**2.3**, **13.2**	−1.6, **9.9**
Pacific (0000–1200)	0.2, **36.2**	**2.4**, **22.0**	−2.4, **11.1**
Pacific (1200–2400)	1.0, **11.4**	**2.1**, **3.6**	−1.4, **7.2**
Caribbean (all)	−9.7, **31.2**	−16.6, **17.5**	12.8, **12.6**
Caribbean (0000–1200)	−15.1, **24.3**	−18.1, **13.6**	6.9, **8.8**
Caribbean (1200–2400)	−1.9, **30.8**	−14.7, **21.1**	**19.1**, 9.2

[a]Summary of statistics computed from the data in Figures 2–7, focusing on the role of island size, for the total rain rate, frequency, and intensity, the averaged percentage island enhancement is shown for the Indo-Pacific Maritime Continent and Caribbean regions, for the total daily mean and both phases of the diurnal cycle (hours shown in parentheses). Results are shown for both islands with areas less ("small," left entry in each column) and greater ("large," right entry in each column) than 315 km^2. Boldface indicates values that are both positive and significantly different from zero at the 95% confidence level.

Table 2. Mean Percentage Island Enhancement: Short, Tall[a]

Region (Time UTC)	Total Rain Rate	Frequency	Intensity
Pacific (all)	**15.3**, **25.8**	**8.5**, **13.5**	5.9, **10.3**
Pacific (0000–1200)	**30.2**, **37.7**	**17.2**, **23.4**	10.3, **11.2**
Pacific (1200–2400)	−0.8, **12.0**	−0.3, 3.1	−0.4, **8.1**
Caribbean (all)	12.2, **51.6**	**5.6**, **30.1**	5.6, **20.0**
Caribbean (0000–1200)	5.9, **43.8**	1.0, **27.0**	4.2, **13.8**
Caribbean (1200–2400)	16.2, **46.3**	9.4, **33.6**	5.6, **13.2**

[a]Summary of statistics computed from the data in Figures 2–7, focusing on the role of orography, for the total rain rate, frequency, and intensity, the averaged percentage island enhancement is shown for the Indo-Pacific Maritime Continent and Caribbean regions, for the total daily mean and both phases of the diurnal cycle (hours shown in parentheses). Results are shown for both islands whose 75th percentile of surface elevation is less ("tall," left entry in each column) and greater ("short," right entry in each column) than 50 m. Bold typeface indicates values that are both positive and significantly different from zero at the 95% confidence level.

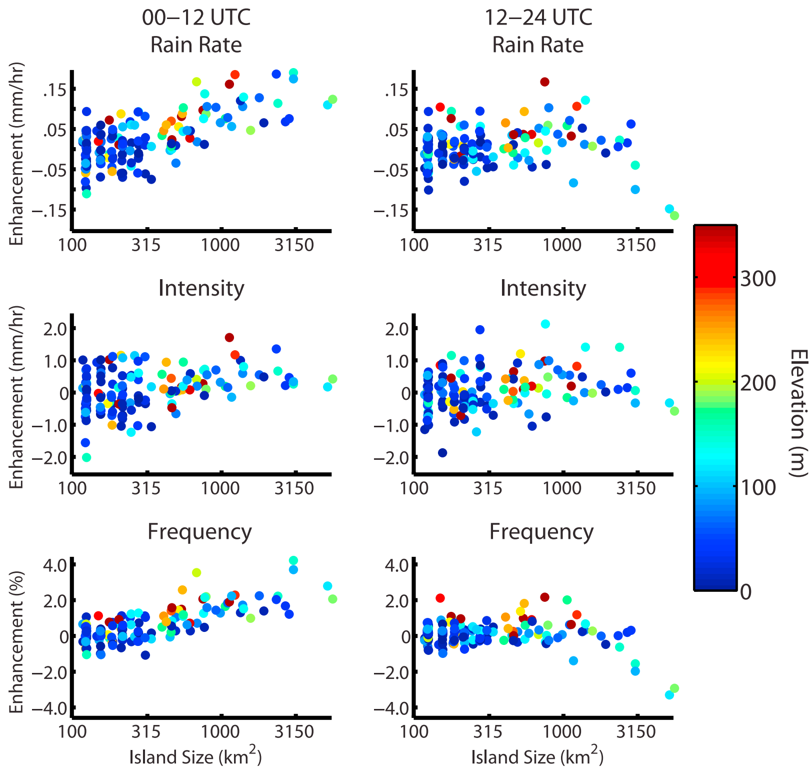

Figure 11. Same as Figure 5 but without normalizing the values on the *y* axis by the mean rainfall of the island and surrounding ocean region. Thus the values on the *y* axis are in mm h^{-1} for rain rate and intensity, and percent for frequency. The frequency values in this case are differences in absolute frequency of rain occurrence, not normalized by the land-ocean mean frequency.

the normalization, so that the island-ocean differences are in the physical units of each rainfall quantity—mm h^{-1} for total rainfall and intensity, and percent for frequency—though in this case the frequency values are differences in rainfall frequency for island versus ocean, rather than those values normalized by the average frequency of the two combined as above. These results without normalization are presented in Figures 11 and 12. Figures 11 and 12 show results for the two phases of the diurnal cycle. They are thus exactly analogous to Figures 5 and 6, and comparison of Figures 11 and 12 with Figures 5 and 6 reveals the effect of the normalization.

[41] Qualitatively, in most respects the results in Figures 11 and 12 are very similar to those in Figures 5 and 6. One difference is the relative magnitude of the island enhancements in the two regions. In absolute units, the rainfall enhancements in the Indo-Pacific are somewhat larger than those in the Caribbean. This is particularly true for islands without high orography. For such flat islands, there is essentially no enhancement at larger island areas in the Caribbean in absolute units. In the Indo-Pacific the enhancements approach 0.2 mm h^{-1}, and do not show an orographic influence nearly as large as that in the Caribbean. As a climatological value, this Indo-Pacific enhancement is quite substantial; it is equivalent to 2.4 mm d^{-1}, which is not much smaller than the global mean rain rate. When both are put in percentage units (sections 3.1–3.4), the Indo-Pacific island enhancements do not exceed the Caribbean ones as much because climatological rainfall rates are higher in the Indo-Pacific than in the Caribbean.

4. Discussion

[42] An initial motivation for our work was to understand the scale dependence of convective forcing—how large must a surface inhomogeneity (such as an island) be in order to produce a measurable response in deep convection? In this respect our results confirm those of *Williams et al.* [2004]. As they did in lightning, we find in rainfall a significant response for islands with areas greater than a few hundred km^2. For smaller islands, there is no significant diurnal mean response (though the sampling noise also becomes greater for smaller islands, in both our analysis and theirs); there are significant intensity enhancements in the Caribbean, though these are compensated by large (but still not significant) negative enhancements in frequency.

[43] As lightning tends to be associated with more vigorous convection, presumably enhanced over islands due to surface heating, the results of *Williams et al.* [2004] might lead us to expect the enhanced island rainfall to result primarily from increased rainfall intensity during the day. Our results are only partly consistent with this picture. While rain intensity is significantly enhanced over larger islands, there is not a significant diurnal cycle in this enhancement. The weak diurnal cycle in rainfall intensity is also shown in the 3-hourly composite diurnal cycle. It is possible that convection initially

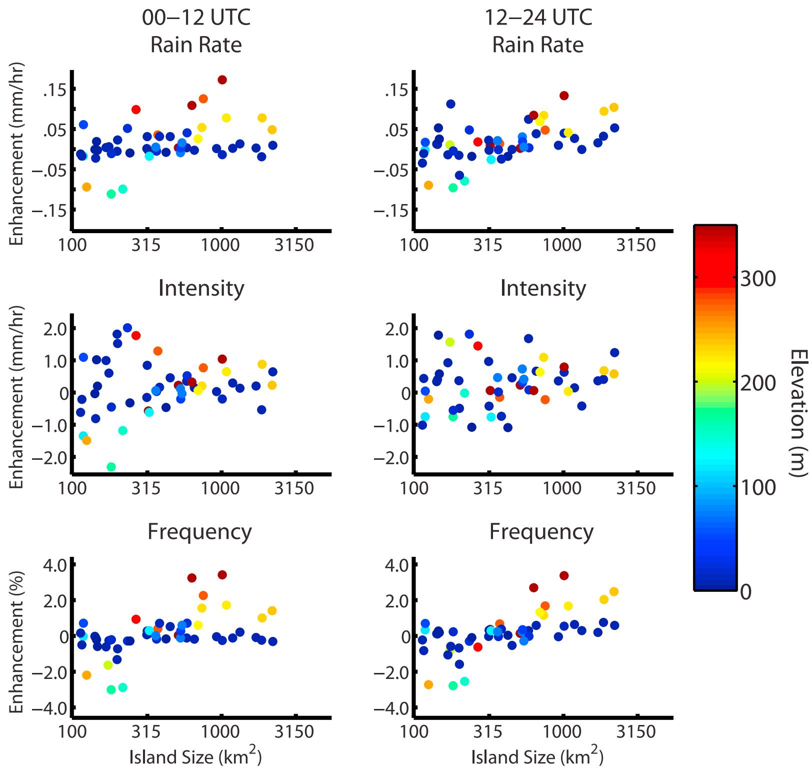

Figure 12. Same as Figure 6 but without normalizing the values on the *y* axis by the mean rainfall of the island and surrounding ocean region. Thus the values on the *y* axis are in mm h^{-1} for rate and intensity, and percent for frequency. The frequency values in this case are differences in absolute frequency of rain occurrence, not normalized by the land-ocean mean frequency.

forced by daytime heating does not fully mature until after sundown. *Qian* [2008] finds that rainfall maximizes at night over Borneo, but not over smaller islands; most islands in our sample are smaller than any of those on which Qian focuses, so a long delay between daytime storm initiation to storm maturity seems unlikely. Many authors [e.g., *Houze et al.*, 1981; *Qian*, 2008] have noted the importance of land breezes in triggering nighttime convection of the coasts of Borneo and Java. Smaller islands would have weaker land breezes but there may still be an effect especially for our subset of larger islands. Another possibility is that island heating forces convection which then can move offshore, so that the largest conditional rain rates sometimes occur over ocean despite being island-forced. In this case, however, we might expect the island enhancements in rain frequency and total rain rate also to be eliminated, which does not occur.

[44] Another interesting question is whether the dependence of rainfall (or any other measure of convection) on island size is best described as monotonic, as suggested by *Williams et al.* [2004] as well as by a casual perusal of our results, or whether there is an optimal island size at which the response is maximum, as in the modeling results of *Robinson et al.* [2008]. This question is most appropriately addressed by the daytime results, shown in the left column of Figure 5 and the right one of Figure 6. The scatter is probably too large to determine conclusively whether there is a peak in the response, but it appears to us that they are consistent with a weak one at most, or about equally well with none at all.

[45] Taken together, our results on the role of topography and the diurnal cycle suggest a more nuanced picture on the roles of different physical mechanisms in influencing island rainfall in different regions.

[46] The more apparent diurnal cycle in the Indo-Pacific compared to the Caribbean suggests that thermal forcing plays a greater role in the Indo-Pacific. The Indo-Pacific has higher sea surface temperature, greater free tropospheric relative humidity, weaker winds, and greater rainfall in the large-scale mean than does the Caribbean (Figure 1). Perhaps this explains the difference in island enhancements: in a moister large-scale environment, already closer to the threshold for deep convection, it is easier for sea breezes driven by localized surface heating to induce a deep convective response [e.g., *Burpee*, 1974].

[47] The role of orography is qualitatively similar in both regions, but more important quantitatively (at least in the percentagewise measures used here) in the Caribbean. In both regions, the larger islands with high orography tend to have greater rainfall enhancements than islands of similar areas with lower orography. In the Caribbean, this is particularly so when the results are shown in terms of absolute rainfall rather than percentage. These results indicate, unsurprisingly, that orography enhances rainfall in the island average. Perhaps more interestingly, our results also shed light on the relative roles of upslope flow and elevated heat source effects. In both regions, the orographic enhancement of rainfall is significant during both day and night, not dramatically larger in the

daytime, and more apparent in frequency than intensity. This suggests that much of the orographic enhancement in rainfall on small tropical islands occurs by mechanical forcing of upslope flow, rather than elevated surface heating. This does not isolate the mechanism precisely, since upslope flow can enhance rainfall by a number of distinct physical mechanisms [*Roe*, 2005]. It will require more detailed investigation to determine whether the most important effect over the islands in our sample is forced shallow convection as in the case of Dominica [*Smith et al.*, 2009; *Kirshbaum and Smith*, 2009], triggering of deep convection, or simple forced ascent with large-scale condensation.

[48] The above discussion focuses on the influences of island size and orography that are captured by the simple measures of these quantities that we have used. Much variation between islands in island mean rainfall (not to mention spatial rainfall variations within single islands) is not explained by these simple measures. Our analysis cannot determine to what extent these additional variations result from sampling error, large- or regional-scale climatic variations resulting from islands' different locations, or different individual island characteristics that do not correspond to island area or our simple measure of elevation. The orientation of island orography to the mean wind is likely to be an important variable; a measure of aspect ratio (long narrow islands compared to others) could be another. To what extent more detailed characterization of different islands along these lines or others would allow more of the variability to be explained is an interesting question for future work.

5. Conclusions

[49] We have used rainfall retrievals from the TRMM PR instrument to determine the climatological differences in total rainfall, rain frequency, and rain intensity between small tropical islands (defined as those with areas less than 6150 km^2) and their oceanic surroundings, in the Indo-Pacific Maritime Continent and Caribbean regions. The results have been stratified by island area, a measure of island orography, and the diurnal cycle. Our primary findings are the following.

[50] 1. There is a significant enhancement of rainfall for islands with areas larger than 315 km^2 compared to the surrounding ocean. In the daily mean, averaged over all of the islands in the larger size category, the enhancement is close to 30% (Table 1). This number is very similar in the Indo-Pacific and Caribbean, although the scatter is much larger in the Caribbean. The enhancements in the Pacific are larger than those in the Caribbean when expressed in terms of absolute rainfall rather than percentage.

[51] 2. Islands smaller than 315 km^2 show no significant enhancement in intensity or total rain rate. Small islands in the Caribbean show a small negative enhancements in total rain rate and frequency, that is, less rainfall over the island than over the ocean.

[52] 3. In the daily mean, island enhancements in rain frequency and intensity are of comparable amplitude, and both contribute to the enhancement in total mean rainfall. In the Caribbean, the difference in enhancement in rain intensity between day and night is small (~10%) and approximately equal for islands smaller and larger than 315 km^2.

[53] 4. The diurnal cycle is significant in rain frequency (and consequently in total rain rate) for larger islands in the Indo-Pacific, but not in the Caribbean.

[54] 5. Rainfall is more greatly enhanced for larger islands with higher orography compared to those with similar areas but lower orography. The difference in orographic enhancement is to a large extent independent of the diurnal cycle, suggesting that mechanically forced upslope flow plays a greater role than elevated surface heating.

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