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How important is tropospheric humidity for coastal rainfall in the tropics?

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Key Points:
- The presence of the coast influences the humidity to rainfall relationship in the tropics
- Coastally influenced rainfall can occur in drier atmospheres than over the open ocean or over continental land
- There is no discernible critical humidity value for the pickup of coastal rainfall

Supporting Information:
- Supporting Information S1

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Abstract Climate models show considerable rainfall biases in coastal tropical areas, where approximately 33% of the overall rainfall received is associated with coastal land-sea interaction. Building on an algorithm to objectively identify rainfall that is associated with land-sea interaction we investigate whether the relationship between rainfall in coastal regions and atmospheric humidity differs from that over the open ocean or over inland areas. We combine 3-hourly satellite estimates of rainfall with humidity estimates from reanalyses and investigate if coastal rainfall reveals the well-known relationship between area-averaged precipitation and column-integrated moisture. We find that rainfall that is associated with coastal land-sea effects occurs under much drier midtropospheric conditions than that over the ocean and does not exhibit a pronounced critical value of humidity. In addition, the dependence of the amount of rainfall on midtropospheric moisture is significantly weaker when the rainfall is coastally influenced.

1. Introduction

Rainfall in coastal regions of the tropics is well known to show a complex behavior that is strongly shaped by dynamical features that act on mesoscales in response to the topography, thermal heating contrast between land and adjacent ocean, and orographically induced wind systems [*Pearce*, 1982; *Crosman and Horel*, 2010]. Several studies showed that coastal convection and rainfall are strongly modulated by the coastlines [*Pielke*, 1974; *Holland and Keenan*, 1980; *Simpson et al.*, 1980, 1993; *Baker et al.*, 2001]. These modulations are land-sea breeze circulations that tend to interact with mountain-valley-breeze systems [*Qian*, 2008] or gravity waves [*Mapes et al.*, 2003a]. The details of any land-sea breeze circulation are dependent on several factors, including details of the coastal arrangement, orography, and variations due to the Coriolis effect [*Haurwitz*, 1947; *Rotunno*, 1983]. However, in an overall sense tropical coastal precipitation reveals a distinct pattern when it is dominated by land-sea interaction. The rainfall usually develops in the afternoon over the coastal land areas, peaks in the early-to-late evening, and then propagates offshore over night producing an early-morning peak over the adjacent ocean [e.g., *Kousky*, 1980; *Geotis and Houze*, 1985; *Mori et al.*, 2004; *Yang and Slingo*, 2001; *Rauniyar and Walsh*, 2010]. Using an objective pattern recognition technique *Bergemann et al.* [2015] showed that in coastal regions of the tropics, in particular over the many islands of the Maritime Continent, coastally influenced rainfall constitutes more than a third of the overall annual rainfall received, indicating its importance for the region and its likely strong effect on the large-scale circulation through convective heating effects [*Neale and Slingo*, 2002]. Several recent studies [*Rauniyar and Walsh*, 2010, 2012; *Peatman et al.*, 2014; *Bergemann et al.*, 2015] have presented evidence that the rainfall characteristics of large-scale tropical circulations, such as the Madden-Julian Oscillation (MJO) [*Madden and Julian*, 1971, 1972, 1994], are strongly modified by the presence of coasts. They showed that in the coastal regions of the Maritime Continent, rainfall is strongly modulated by coastline effects leading to enhanced precipitation in the suppressed MJO phase and therefore very small differences in rainfall between active and suppressed MJO conditions over the land regions of the Maritime Continent. This is in stark contrast to the very large differences over the open ocean. This indicates that coastal tropical convection might occur under significantly different large-scale conditions than its open-ocean counterpart. It is the purpose of this study to investigate and quantify relationships of the atmospheric state and rainfall over tropical coastal areas.

Global weather and climate models show an overall poor representation of precipitation [*Stephens et al.*, 2010], with particularly large errors in coastal regions such as the Maritime Continent [*Yang and Slingo*, 2001; *Neale and Slingo*, 2002; *Qian*, 2008; *Nguyen et al.*, 2015]. Here rainfall is frequently underestimated over land and overestimated over the ocean indicating that the complex processes associated with coastal rainfall are poorly captured [e.g., *Mapes et al.*, 2003b; *Slingo et al.*, 2004; *Gianotti et al.*, 2011]. One reason for the lack of accuracy in the representation of coastal tropical rainfall can be seen in the need to parameterize the processes associated with rainfall in global climate models, in particular that of atmospheric convection [*Arakawa*, 2004]. At their most fundamental level, cumulus parameterizations relate the explicitly resolved state of the atmosphere to convective processes. Most existing parameterizations implement ideas based on observations over the open ocean [*Xu and Emanuel*, 1989; *Arakawa*, 2004].

Several past studies have documented that atmospheric moisture plays a key role in the inhibition and generation of moist atmospheric convection over the tropical oceans [e.g., *Bretherton et al.*, 2004; *Derbyshire et al.*, 2004; *Holloway and Neelin*, 2009; *Ahmed and Schumacher*, 2015]. As a consequence, recent efforts by the climate modeling community suggest that making cumulus parameterizations more moisture sensitive can improve the representation of tropical convection in climate models [*Del Genio et al.*, 2015; *Klingaman et al.*, 2015]. One immediate question then is, does the documented atmospheric moisture to rainfall relationship in coastal regions differ from those over the open ocean? The aim of this paper is to investigate if the rainfall to humidity relationship over the open ocean that has driven the recent parameterization developments is applicable in coastal regions. We hypothesize that the occurrence of rainfall near coasts in the suppressed phases of the MJO indicates that convection is strongly modulated by coastal effects and can therefore occur in an atmosphere that is much drier than over the open ocean. If true, this would have implications for the design of parameterizations if they are to represent this important type of convection. We use the coastal rainfall data set derived by *Bergemann et al.* [2015] to investigate the rainfall to humidity relationship for coastal and noncoastal rainfall.

Section 2 describes the data used in this study and the methodology that is applied to combine rainfall observation with atmospheric moisture observations to compare the convective behavior. Section 3 presents the main results and shows the uniqueness of coastal convection when compared to noncoastal convection. This is followed by a summary and conclusion in section 4.

2. Data and Methodology

2.1. Humidity

Bretherton et al. [2004] were one of the first to establish an empirical relationship between vertically integrated moisture saturation fraction r and rainfall over the tropical oceans. The measure r is defined by the vertically integrated specific humidity normalized by the vertically integrated saturation specific humidity.

$$r = \frac{\int_{\mathrm{toa}}^{\mathrm{sfc}} q(p)\mathrm{d}p}{\int_{\mathrm{toa}}^{\mathrm{sfc}} q_s(p)\mathrm{d}p}$$

The main variability in space and time of the saturation fraction is a result of humidity variations in the midtroposphere, making r a good measure to assess the influence of the latter on moist tropical convection. The use of an integrated measure is useful because in ERA-Interim the vertically integrated humidity information is assimilated. Additionally, we test the midtropospheric moisture to rainfall relationship by analyzing the relative humidity (RH) at 600, 700, and 800 hPa.

The above measures r and RH are derived from the ERA-Interim reanalysis project [*Dee et al.*, 2011]. The data has a spatial resolution of $0.75^\circ \times 0.75^\circ$, the temporal resolution is 6 h. The considered time period is January 1998 to September 2015.

2.2. Rainfall

The goal of this study is to investigate if the relationship of atmospheric moisture on scales typical for global climate models with rainfall is significantly different for coastally influenced rainfall events from that over the open ocean. To investigate this, we first require a definition of what constitutes coastal rainfall. The simplest way of defining coastal rainfall is to just use all rainfall near the coasts. However, as shown in *Bergemann et al.* [2015], a considerable fraction of this rainfall is not likely related to coastal processes, but simply the result of synoptic-scale features traversing coastal regions. To identify rainfall that is actually related to coastal land-sea interaction, we use a pattern recognition technique recently developed by *Bergemann et al.* [2015]. The method considers only geometrical aspects of satellite rainfall estimates and finds mesoscale precipitation

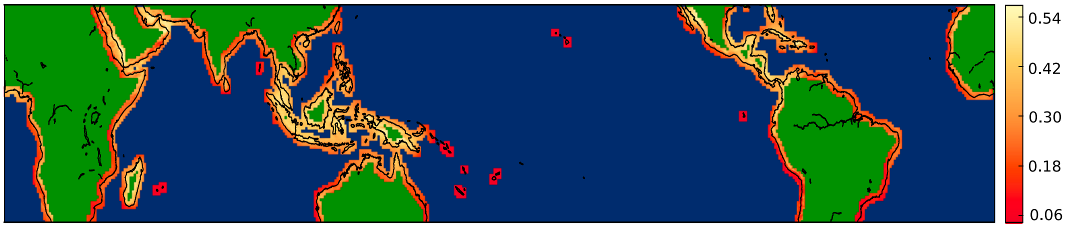

Figure 1. The different regions considered in the study. The tropical ocean region is marked in blue. The tropical land is marked in green. The shaded area spans ≈150 km onshore and offshore. The shading indicates the average fraction of rainfall that can be attributed as associated with coastal processes (see text for details on the definition of rainfall due to land-sea interaction).

pattern in coastal areas that are aligned with the coastline. The pattern recognition applies four heuristics to find precipitation that is associated with land-sea interaction. These can be summarized as follows:

1. the recognized rainfall has a higher intensity compared to the surrounding;
2. the precipitation is not synoptic scale;
3. rainfall due to land-sea interaction occurs in a coastal area; and
4. the precipitation pattern is aligned with the coastline.

The interested reader might refer to *Bergemann et al.* [2015] for a detailed description and results. The algorithm yields robust results when applied to various satellite-based rainfall products. In this study we use the estimates of Climate Prediction Center Morphing Method (CMORPH) [*Joyce et al.*, 2004] at a spatial resolution of 0.25°. The time period used is 1998 to 2015. The above described method separates rainfall in coastal areas into two parts: (i) rainfall events that are associated with land-sea interaction and (ii) events that while they occur in coastal regions are unlikely to be the result of coastline effects.

For our investigation we consider rainfall occurring over tropical oceans (*oceanic*), rainfall over continental land (*land*), total rainfall in coastal areas (here referred as *total near coasts*), rainfall associated with land-sea interaction (*coastal*), and rainfall that is not associated with coastal effects but occurs in coastal areas (*noncoastal*). Based on previous studies [*Keenan and Carbone*, 2008; *Muppa et al.*, 2012; *Li and Carbone*, 2015, among others] investigating the area that is affected by coastal phenomena like land-sea breeze circulation systems, we define the region of ≈150 km onshore and offshore as coastal area (shaded area in Figure 1). Increasing this distance to 250 km does not affect the conclusions of the study.

3. Results

3.1. The *P*-*r* Relationship for Coastal Rainfall

We first investigate if the well-known exponential precipitation (P) to saturation fraction (r) relationship is reproduced by the CMORPH data set. Here we follow the approach of *Bretherton et al.* [2004] and bin the atmospheric humidity in 1% steps and calculate the mean rain-rate in each bin. We define a reasonable threshold for the "pickup" of rainfall at a rain-rate of 1 mm/d. The solid blue line marked in Figure 2a shows the exponential increase of mean precipitation rate with increasing saturation fraction for the tropical oceans. The pickup threshold where the rain-rate starts to increase quickly is exceeded earlier than in *Bretherton et al.* [2004] or *Ahmed and Schumacher* [2015]. This can be explained by the need to exclude nonprecipitating cases in our study. This need arises from the fact that we can separate rain events near coasts into those affected and not affected by the presence of the coastline, but we cannot achieve such a separation for no rain cases (0 mm/3h). The *P*-*r* relationship for the total rainfall in coastal areas is very similar when compared to the ocean regions. For very moist conditions the oceanic rain-rates are higher than those near coasts. Nevertheless, the cumulative percentage of rainfall, as shown by the dashed lines, indicates that only 10% of the total rainfall is associated with humidity values $>= 0.85$ where the average precipitation over the ocean exceeds that near coasts. This also reflects the area-weighted rainfall sum, shown in the brackets in the legend of Figure 2. The ocean regions receive ≈89% of the precipitation falling in coastal areas. This is explained by the fact that most of the oceanic rainfall is associated with humidity values of ≈0.5–0.75 where the rain-rate is still relatively small (see also Figure S1 in the supporting information). It might be tempting to conclude from this comparison that the *P*-*r* relationships in coastal areas are consistent with those over the tropical ocean, and only the lack of moisture

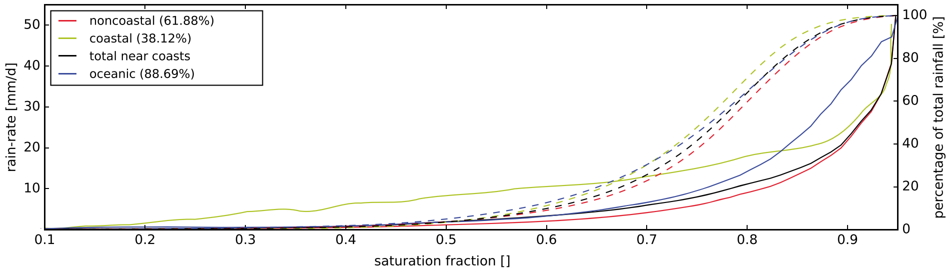

Figure 2. The *P-r* relationship for tropical ocean areas (solid blue line), coastal tropics (solid black), rainfall that is associated with coastal processes (solid yellow line) and rainfall while occurring near coast that cannot be attributed as coastline associated (solid red line). The dashed lines show the cumulative percentage of the total rainfall that is associated with the according humidity value. (the color code is the same as for the solid lines). The percentages given in brackets in the box shows the area-weighted rainfall as a percentage of the total rainfall in coastal areas.

supply over the coastal land prevents the curve from attaining rain-rates observed over the ocean. Therefore, we now split the rainfall occurring in coastal areas into events that are associated with coastal effects (*coastal*) and those that are not (*noncoastal*). The *P-r* relationship of the *coastal* rainfall, indicated by the solid yellow line in Figure 2a, is strikingly different from both the oceanic rainfall and the noncoastal rainfall. It can be seen that a considerable amount of rainfall seems to occur in drier atmospheres. For the defined 1 mm/d pickup threshold the coastally affected rainfall does not exhibit the well-documented pickup of precipitation at a critical value r_c where the rain-rate starts to increase very rapidly. The threshold is exceeded when the saturation fraction is ≈0.17. This is in stark contrast to the rainfall that cannot be associated with any coastal effects but occurs in coastal areas. Here the rain-rate increases very slowly until the threshold is exceeded for humidity values of $r_c = 0.55$. The graph converges for highest humidity rates compared with that for the *P-r* relationship in coastal areas. From the above discussion it is clear that the relationship of coastally affected rainfall to atmospheric humidity varies from that for other rainfall types and regions. Given that about one third or more of the rain near coasts is associated with coastal effects [*Bergemann et al.*, 2015], it is important to understand this relationship better.

3.2. The Moisture to Rainfall Relationship Near Coasts

The comparison of *P-r* relationships for different locations can be misleading if the distributions of rainfall amounts are very different between them. Therefore, we now group rainfall events across locations by their strength as defined by quintiles of the rainfall when present over the entire study domain and compare the distribution of the atmospheric humidity as a function for rainfall quintile across locations. This way we ensure that the atmospheric conditions in different areas are compared for rainfall events of similar strength and therefore truly represent location differences. Although the column-integrated saturated fraction has its main variability in the midtroposphere, we complement the vertically integrated *P-r* view by including relative humidity at 600 hPa (RH). A comparison for the lower free troposphere (700 and 800 hPa) can be found in Figure S2 of the supporting information. Figure 3a compares the distributions of *r* and RH, for all rainfall events over coastal regions (black) to those over the open ocean (blue). The *r* and RH distributions for the oceanic rainfall tend to display slightly longer tails toward drier conditions, especially those for RH. As a result the median values for the oceanic regions are slightly lower than those for the total rainfall in coastal regions.

Figure 3b compares the distributions of rainfall at coastal locations for events that are *not* (red) and are (yellow) affected by the coastlines (see section 2). The shape of the distributions for events not affected by the coastlines is similar to the distributions for the total rainfall in coastal locations in Figure 3a. However, this is not the case for the distributions of rainfall that is associated with *coastal* land-sea interaction. The differences between all distributions shown in Figure 3 are tested by applying a two-sided Kolmogorov-Smirnov test (KS test). Unless otherwise indicated, the statements made in the text about distribution differences are found to be significant at the 99% confidence level.

Figure 3b also shows that for all but the no-rain cases, coastally influenced rainfall categories show lower medians of the two atmospheric humidity measures used. Moreover, the distributions are heavily tailed toward lower values especially for the small and moderate rain cases (0.2–2.1 mm/3h). When coastal influences are

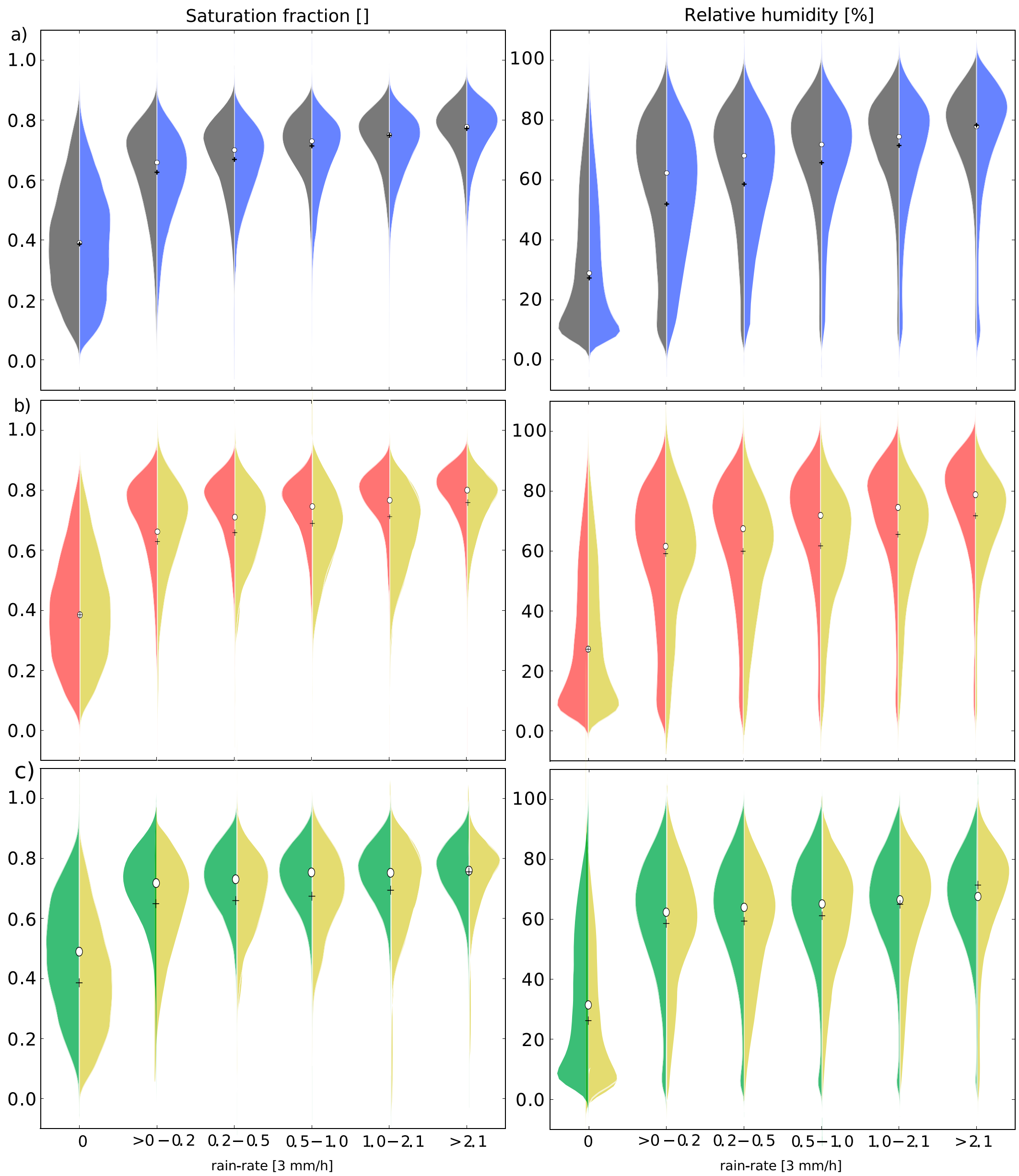

Figure 3. Distributions of the column-integrated saturative fraction *r* and the relative humidity at 600 hPa for nonrainy cases and the 5 quintiles of rainfall intensity (in mm/3h). (a) The rainfall distributions of the total rain cases in coastal areas (black) and the rainfall events over the ocean (blue). (b) The comparison for coastal rainfall that is not related to land-sea interaction (red) and coastal precipitation that can be associated with land-sea interaction (yellow). (c) Comparison of the distributions for continental land with coastally affected rainfall. Medians are indicated by white dots for the left distributions and black crosses for the right distributions.

present these rain cases are roughly 3 times more likely to occur in relatively dry atmospheres at saturation fractions of 0.5–0.6. The median values change little with rain category until the highest category is reached, where the difference between coastally influenced and other events is again small.

For scales that are typical for global climate models (≈75 – 150 km) the above results show that coastally influenced precipitation can occur under significantly drier conditions than rainfall in the same location when it is not directly influenced by the coast. An immediate question is whether this result is truly related to coastally driven rainfall or is merely a reflection of drier atmospheric conditions over land than over the ocean. We investigate this by comparing the distributions for rainfall over land with those for *coastally* affected rainfall in Figure 3c.

It is evident that the evolution of the humidity distributions with rainfall over land areas is quite different from those of the coastally affected rainfall. The land distributions are less long tailed and more symmetric with higher medians and weaker dependence on rainfall. While stronger in saturation fraction, this signal also exists for the midtropospheric relative humidity. Comparing the distributions over land to those over the ocean (see Figure S3 in the supporting information) shows that the atmosphere over land is moister for moderate rain-rates. We therefore conclude that the behavior of coastally affected rainfall is not merely the result of the presence of land, and it is not a simple feature of rainfall over land, but that it is the coastal processes themselves that create this behavior.

4. Conclusions

The purpose of this study was to determine if the humidity to coastal tropical rainfall relationships on scales that are typical for global climate model resolutions are different fromthat over the open ocean and over inland areas. The study was motivated by the recent trend to increase the sensitivity of cumulus parameterization schemes to midtropospheric humidity in those models. We investigated the rainfall relationships to column-integrated saturation fraction and midtropospheric relative humidity that are known to be relevant to the presence and strength of moist cumulus convection. Using an objective algorithm developed in an earlier study, we divided the rainfall at the coastal locations into two categories: that influenced by coastal effects and that, while falling near coasts, not directly associated with the coast.

We first investigated the rainfall to atmospheric humidity relationship (*P-r*) for coastal and oceanic rainfall. Oceanic rainfall shows the exponential dependence on atmospheric humidity that has been postulated by *Raymond* [2000] and documented by *Bretherton et al.* [2004], *Holloway and Neelin* [2009], and *Ahmed and Schumacher* [2015, among others]. When considering all coastal rainfall, i.e., paying no regard if the rainfall is associated with the presence of the coastline, a similar relationship emerges. However, when the rainfall is affected by coastal effects, its relationship to atmospheric humidity changes dramatically. The pickup of rainfall with increasing humidity for *coastal* rainfall happens in drier atmospheres compared to both oceanic and coastal rainfall not associated with the coastline.

To ensure that our findings are not just the result of rainfall intensity differences across regions, we subdivided the rainfall data into quintiles of its distribution at all considered areas. We found that the coastally influenced precipitation shows a distinctly different relationship to humidity than rainfall over land, oceans, and that falling near coasts without their direct influence. For weak and moderate cases coastally affected rainfall occurs in drier conditions than any other type. A comparison to midtropospheric humidity, considered as particularly relevant to the development of deep moist convection, reveals similar properties. By comparing the rainfall behavior to that over land (Figure 3c and Figure S3 in the supporting information), it became evident that the described characteristic is not simply due to the presence of land. A possible explanation must therefore include the presence of the coastline.

We conclude this study by hypothesizing possible mechanisms of why rainfall that is directly affected by coastlines can become less sensitive to midtropospheric humidity on scales that are explicitly resolved by a global climate model (Figure 4). We see three possible effects at work: (a) a cloud size effect, (b) a humidity-halo effect, and (c) a vertical velocity effect. All of them are directly related to the presence of a land-sea breeze system. During days when the coastal effects are strong the land exhibits a strong thermal heating contrast to the adjacent ocean. The turbulent mixing over land is deeper than over the ocean which initiates the onshore propagation of the sea breeze front and advection of moist air from the sea (I in Figure 4). The sea breeze front organizes shallow cumuli that mix vigorously with the environment along the associated convergence line of moist air (II in Figure 4). At this stage there might be three different mechanisms that can contribute to the growth of deep convective clouds (Figure 4):

1. *The cloud size effect*. The sea breeze convergence zone focuses convection to take place in a rather small area. As a result, the likelihood of clouds merging and biasing the cloud spectrum to larger cloud sizes increases. As larger clouds experience a reduced rate of entrainment, their growth becomes less affected by the drier midtroposphere, enabling them to rise deeper than their oceanic counterparts given the same atmospheric humidity profile [*Hill*, 1974; *Simpson et al.*, 1980].
2. *The humidity-halo effect*. As the sea breeze convergence focuses convection in a particular line, consecutive generations of clouds grow in roughly the same area. As a result, later generations grow into the

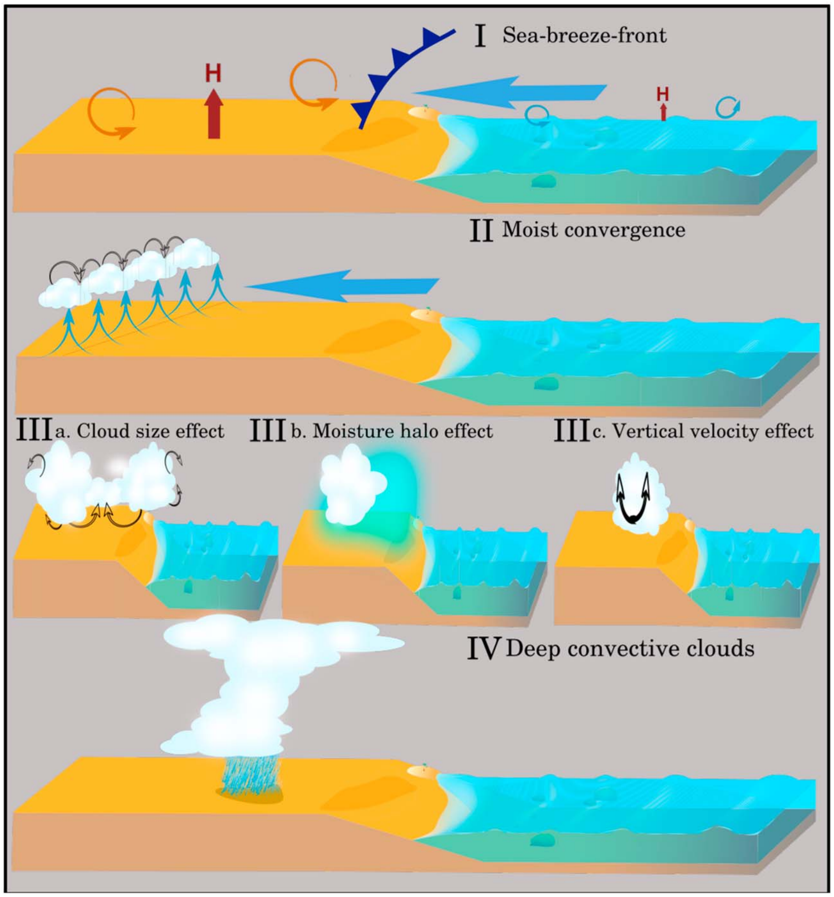

Figure 4. Sketch of a possible mesoscale dynamic mechanism that can cause rainfall in direr midtropospheric conditions: I: the thermal heating contrast (indicated by the different sizes of sensible heat flux *H*) between land and ocean initiates an onshore propagation of the sea breeze front II: The sea breeze front organizes convection along a convergence line where moist air is advected from the sea III: There mechanisms are possible: (a) Clouds that are close together merge and grow. (b) Steady humidity advection by the sea breeze convergence slowly moistens the midtroposphere until deep convection can occur. (c) The mesoscale sea breeze circulation causes enhanced updrafts in the clouds. IV) All three mechanisms can lead to deep precipitating convection.

debris of previous clouds, which will have a higher humidity than the larger-scale average. As a result, the entrained air reduces the cloud buoyancy less even though the entrainment rates are similar to oceanic clouds, thereby promoting more rapid cloud growth [*Wilson et al.*, 1992; *de Rooy et al.*, 2013].

3. *The vertical velocity effect*. In this mechanism we allow for the possibility that in-cloud vertical velocities at cloud base are enhanced by a mesoscale component due to the sea breeze [*Chen and Orville*, 1980]. The additional inertia provided by this enhancement may be sufficient to carry cloud parcels through the dry midtropospheric layers to the freezing level, after which the enhanced buoyancy due to hydrometeor freezing allows them to grow deep (Figure 4, IV).

Future studies should combine high-resolution modeling [e.g., *Wapler and Lane*, 2012; *Hassim et al.*, 2016] with high-quality satellite and ground-based radar observations [e.g., *Kumar et al.*, 2012; *Houze et al.*, 2015; *Powell and Houze*, 2015] to investigate which of the three hypothesized mechanisms has the largest influence on the generation of coastal rainfall.

Our study was motivated by the observed behavior of rainfall to occur in suppressed MJO conditions over the Maritime Continent as well as the recent push to make convection representations in climate models more sensitive to midtropospheric humidity. Our results indicate that the presence of coastal effects can likely explain the rainfall behavior with MJO phase, even though the exact mechanisms require further study. Our results also have some consequences for the representation of convection in weather and climate models, which at its heart consists of a set of rules that translate the large-scale environment into rainfall (amongst other effects). Commonly, these rules are either the same globally or contain a land-ocean difference. To our knowledge, there is no existing cumulus parameterization that allows for a different behavior near coastlines. The issue is complicated by the inability of most global models to resolve the coastlines. Yet it is evident from our results that it is necessary to enhance current cumulus parameterizations to be able to represent the globally important tropical rainfall associated with coastlines.

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