Anonymous Referee #2
Received and published: 7 February 2017

Interactive comment on acp-2016-1166: "Analyzing cloud base at local and regional scales to understand tropical montane cloud forest vulnerability to climate change"

This paper describes results of an extensive cloud and meteorological monitoring campaign in the Caribbean in order to better understand the distribution of low boundary layer marine clouds in time and space. Monitoring was uniquely carried out in mountain regions to gain insights about cloud immersion of tropical montane cloud forests and establish baseline conditions against which future changes may be measured. There are many results that I believe most readers (including me) will find cumbersome to wade through, but that is the nature of such a paper that reports on an extensive field campaign and important general conclusions were still clear. Low clouds are frequent in the year round, with the highest frequency occurring in the dry seasons. Spatial distributions of cloud frequency and base height were quite spatially heterogeneous, however, likely due to topographic effects. Although it is commonly believed that tropical montane cloud forests would be most sensitive to changes in the frequency and elevation of dry-season clouds, authors interpret their detection of a common presence of wet season clouds to indicate that changes to these clouds could also be ecologically impactful. This paper describes critical ground-work and initial results necessary for long-term monitoring of cloud variations and changes in a unique and ecologically important zone. The complicated nature of the results is just the nature of the beast for exploratory studies such as this one that include multiple sites, multiple metrics for measuring mean cloud height, and multiple monitoring tools test for corroboration. I therefore believe this paper is appropriate for publication in ACP.

Specific comments:

P1 L29: It is not explicitly clear what "higher" is relative to.

We changed "higher rainfall" to "more rainfall".

P2 L2: I would also imagine fog water input varies greatly throughout a forest depending on they types of surfaces available for collection and micro-climatic wind patterns.

We agree and hope to explore this in future work. We added "this value varies greatly from forest to forest and within the forest."

P2 L20-22: It is worth mentioning a couple other relevant studies that have used longterm cloud-base observations to investigate spatiotemporal variations and trends in cloud frequency and cloud-base height. Williams et al. (2015, GRL) used records from 24 airfields in southern California to show that substantial warming-induced increases in cloud base have corresponded to local land-cover change via nighttime urban warming. Richardson et al. (2003, J Climate) analyzed cloud heights at 24 airfields in the Appalachian Mountain region of the eastern US and documented multi-decade (1973-

1999) increases (decreases) in cloud-base height north (south) of 37.5_N. Causes of the changes are not rigorously investigated in that study but the ecological implications are stressed as important. Further, Rastogi et al. (2015, Earth Interactions) presented a relevant study that combined cloud-base observations with satellite and radiosonde observations to estimate how marine-layer stratus clouds intersect with topography.

Rastogi, B., A. P. Williams, D. T. Fischer, S. Iacobellis, K. McEachern, L. M. V. Carvalho, C. Jones, S. A. Baguskas, C. J. Still (2015), Spatial and temporal patterns of cloud cover and fog inundation in coastal California: ecological implications, Earth Interactions, In Review.

Richardson, A. D., E. G. Denny, T. G. Siccama, X. Lee (2003), Evidence for a rising cloud ceiling in eastern North America, Journal of Climate, 16(12), 2093-2098, doi:10.1175/1520-0442(2003)016<2093:EFARCC>2.0.CO;2.

Williams, A. P., R. E. Schwartz, S. Iacobellis, R. Seager, B. I. Cook, C. J. Still, G. Husak, J. Michaelsen (2015), Urbanization causes increased cloud-base height and decreased fog in coastal southern California, Geophysical Research Letters, 42(5),1527-1536, doi:10.1002/2015GL063266.

We had cited Rastogi et al. 2015 (see pg 17, line 30), in the Methods, because some of the ways they used data sets were similar to ours. We added another citation of Rastogi et al. to the Discussion where we hypothesized the trade wind inversion is limiting the clouds; Rastogi noted that too; thank you for pointing that out. We added a citation of Richardson in the Discussion (pg 21 line 16) discussing possible ecological implications. We added a citation of Williams in the Introduction, saying that future urbanization may affect cloud height (pg 13 line 19).

There are many non-traditional abbreviations that I find distracting. For example: ERS, LRS, DS, MSD, TWI. By the half-way point of page 3 I'm fearing that at some point the entire paper may be abbreviated. I recommend unabbreviating some or all of the abbreviations that I list above and I believe doing so will enhance the interpretability
and impact of the paper.

Other reviewers had this comment as well. We removed the seasonal abbreviations but left in the "trade wind inversion" with a TWI abbreviation; it is used in numerous publications and is better known than the rest of the abbreviations that had been used.

P4 L2-3: I think there is a word missing from this sentence.

The sentence now reads "Ceilometer data used in this study were the altitudes of the lowest cloud layer at a point above the instrument; the cloud layer base is the bottom of a vertically continuous layer at least 100 m thick with no vertical visibility (defined according to a 5% contrast threshold; http://www.vaisala.com)."

P4 L28-30: It is not indicated what the time-step is for the values considered in this correlation analysis. Daily or annual cycles would cause correlation even if variability that is independent of the cycles is not correlated.

We added the word “hourly”. The hourly data was used to correlate with clouds on a 5-day and monthly basis.

Interactive comment from D. Baumgardner

Received and published: 24 February 2017

Interactive comment on acp-2016-1166: "Analyzing cloud base at local and regional scales to understand tropical montane cloud forest vulnerability to climate change"

This manuscript is a revision of a submission that I reviewed prior to its publication as a discussion. I am pleased that the authors acted on some of my recommendations with respect to expanding its scope and supplementing the ceilometer measurements with satellite and radiosonde data. In my opinion the current submission is much improved and I recommend publication. The results are compelling and provide useful information about clouds that impact Tropical Montane Forests.

The only recommendation that I have is to add more explanation about the metrics that are used in defining the cloud bases. I would suggest making this part of the Appendix. A representative frequency histogram of cloud bases, such referred in the text, could be used to mark the various quartiles and tertiles that are being used to define cloud base minimums. In this same appendix it would be useful to further explain to the reader why these particular metrics are optimum, as there are no references to other studies that might have used them. If this is a first time such metrics have been used, then future studies by other investigators would have a cite-able reference if they use the same metrics.

We have added a supplement that outlines the workflow of the calculations of metrics on two random days in different seasons. A text section explains why and how we chose the metrics, and how another study could design similar metrics. The histograms of the raw data per day are shown, with the values of the metrics derived from them. The histograms of the hourly metrics used to make the daily metrics are also shown.

Anonymous Referee #3

Received and published: March 1, 2017

Interactive comment on acp-2016-1166: "Analyzing cloud base at local and regional scales to understand tropical montane cloud forest vulnerability to climate change"

This paper describes measurements of cloud base altitude using ground-based remote sensing at a site in close proximity to the Luquillo Mountains, Puerto Rico. The authors stress the importance of cloud immersion to the current ecosystem of the tropical montane cloud forest, while also advising the reader that the various mechanisms by which these ecosystems exchange water with the atmosphere are still not fully understood.

The authors suggest that rising cloud base altitude as a result of climate change would stress vulnerable species even if rainfall rates in these regions were to remain high. In addition, they hypothesize that the lack of cloud water deposition and increased evapotranspiration, resulting from elevating cloud base, could affect the watershed dynamics in the mountains. The authors also project that their study site may also be vulnerable to changes in the wet season, especially during wet season drought periods.

While the manuscript documents an important baseline for assessing future changes at this site, the reporting of the data is quite laborious to follow, and by trying to broaden the scope to assess conditions across the wider region, I think the discussion loses a lot of focus. I am not against the idea of using the other data products to bolster the understanding of the regional context, but I think the authors could make a clearer connection with the main study site. The extensive use of acronyms coupled with quite intricate data reduction methods makes the paper hard to read. My recommendation is that the manuscript needs major revisions to address the substantive points listed below, but I would also encourage the authors to consider ways to improve readability, perhaps by reducing the acronyms and perhaps by focusing the description of the results a bit more to the aspects that they wish to stress during the discussion/conclusions section.

We felt that the regional context was very important to the understanding of precipitation sources for this TMCF (as well as others at similar latitudes). Because the trade winds are a major factor in the climate, changes in climate that affect the forest may be driven more by regional than by local processes. Recognizing the spatial variability, lifting and possible additional cloud formation due to the mountain terrain, we did not assume that the cloud base altitudes measured above the ceilometer were exactly the same as at the forest location. We are currently working on the temporal correlation between the ceilometer observations (from foothills about 7 km upwind of the forest) with simultaneous observations of cloud immersion within the forest. The purpose of the present paper was to develop a method and baseline for long-term measurements and to focus on the regional system of clouds and how it may relate to TMCFs in the trade-wind latitudes. We have made an effort to bring the regional and local aspects of the research together in the discussion, but given the complexity of the subject it will take more than one paper to address the entire set of research questions. To address the readability of this paper, subsection headers were added to the methods and results to discuss each data-type in turn, and clarify the connections between the data-types. We have removed the seasonal abbreviations except in the figures, and added an illustrated supplement to explain the data reduction (as discussed in comment #2). Numerous revisions and clarifications were added (as recommended by this review and others). We hope these changes make the paper much more readable.

Substantive comments:

1) Study Area section: much of this section reads as an extension of the Introduction, in its detailed description of literature focused on tropical dynamics together with references to previous observational work in the region. However there is no actual description of the local terrain nor mention of other geographical features pertinent to the study. Many readers will not be familiar with Puerto Rico and/or the wider region and so a detailed map or at least a text description documenting the location of the ceilometer and other relevant locations such as the ASOS sites (you give coordinates for the TMCF, but in reality it is not a point. I had to wait for the Methods section to get a brief description of the ceilometer site). If you choose to do a map, you could also indicate the terrain contours in detail and show the proximity to the coast, both of which are very important to the discussion. I would recommend that the current content of this section be worked into the Introduction.

We have added material on the study area location and terrain to the Study Area section. The specific details of the ceilometer location are given in the methods section for the ceilometer, similarly, information on specific details of all the other data types are in the newly added subsections on each data-type. The "study-area" section is meant to provide a broader description of the region and how the data-types fit together. This sentence was added to the end of the study area section "Cloud base height data have been collected in the region by satellites and airport stations in addition to the newer data collected by this study nearer to the TMCF. These data types will be discussed extensively in the next section and a map of locations can be seen in Fig. 4a."

2) Cloud base statistics methods: In Page 3 lines 14-21 there is a thorough description of the method the authors used to generate various statistics for cloud base. While I understand that broken cloud, multiple layers and/or rapidly changing conditions may justify a more detailed algorithm for identifying cloud base characteristics, I think the current method involving quartiles, tertiles and octiles to produce a set of four cloud base metrics is really confusing. This becomes more confusing when these metrics are then displayed in a histogram type format, because it is hard to tell which of these metrics is most relevant to the ecosystem health. Could the histogram not display the raw 30-second resolution data and that way the frequency counts could be related to a physical diagnostic (i.e. time-in-cloud)? Unless there is an ecosystem relevance to the various statistical quantities, (do they capture/differentiate the intermittency or variability of the cloud within hourly or daily timescales?) the authors should reconsider a more readily interpretable set of metrics. If there are specific reasons, concerning the ecosystem and/or hydrology, for the specific choice of quartiles, tertiles and octiles, then a description of this is certainly warranted. Such a description would be useful for future work, if the same metrics were carried over.

We have added a supplement to show how calculation of the frequency-distribution based metrics works out in practice. For low cloud characterization, we wanted to know the cloud base values that occur consistently. We agree that the question could be stated as how often do we see cloud base at a certain altitude range but we concluded that presenting the entire frequency distribution of observations offers the most information about the atmospheric profile to 8 km, and may allow comparison to other forests, as discussed in the section and now extensively in the new supplement. We will address time-in-cloud in a future publication, as explained above, when we have a good understanding of how the ceilometer observations correlate with immersion within the forest. We have rewritten this section extensively to explain the quantiles. For example, before introducing the specific metric quantiles, we say "The specific quantiles used for metrics were chosen such that hourly metric values were between 600-1077 m a majority of the hours in each season and daily metric values were between 600-1077 m a majority of the days in each season. In this way, the metrics can be applied to help quantify the ecosystem characteristic of low-elevation cloud amount needed to sustain the forest throughout the hour, day, and season." Direct frequency histograms by season were made, but did not sufficiently answer the questions of frequency and elevation of low clouds. We hope that by rewriting this section and including the supplement these intentions are clearer.

3) CALIPSO: The authors should be careful in their usage of the CALIPSO cloud mask for the purposes they report. Lidar signal attenuates within optically thick clouds and so it is not possible to determine cloud thickness in that case. Winker et al. (2009) report a cloud optical depth of 5 as the threshold below which thickness can be determined and for optically thicker clouds, only the cloud top altitude is possible. Trade cumuli would typically be classified as optically thick using this threshold. On p5 L32, Winker et al. (2009) could be a more appropriate reference than Hunt et al. (2009), since that reference makes no mention of the cloud data products. When using the vertical feature mask, if there is "no signal" data below "cloud" data it is not possible to determine thickness.

D.M. Winker, M.A. Vaughan, A. Omar, et al. Overview of the CALIPSO mission and CALIOP data processing algorithms J. Atmos. Ocean. Technol., 26 (11) (2009), pp. 2310-2323

Thank you for the suggested reference. The attenuation issue is a very good point—the original calculation removed the attenuated measurements but after more consideration of the systematic error this would introduce we have decided to include all the measurements and use bounds. This is now explained in the methods under subsection 3.4: "Aproximately 10% of the vertical profiles had uncertainty in the cloud base as the lidar was completely attenuated below a cell of cloud (because the cloud was too thick optically; Winker et al., 2009). For these profiles, low cloud base altitude was set as minimally the altitude of land/water surface, and maximally as the lowest cell vertically that cloud is observed, before complete lidar attenuation." We put these ranges into the results subsection (4.4).

4) LCL calculation (described in Appendix A): the authors provide a brief description of calculations, which were

done to determine the LCL. The LCL is a parcel property (i.e. given the temperature, pressure and a humidity variable – RH, dew point, mixing ratio: : : - the LCL altitude, LCL pressure and LCL temperature can be uniquely defined). The authors state that surface observations are used, which is an acceptable choice, and they calculate LCL temperature with appropriate citation of the method. However at that point they also have the LCL altitude, by definition. Instead they describe an interpolation of the LCL temperature to determine a corresponding altitude on a radiosonde sounding. It is not clear to me what that altitude means, but it is not the LCL. This should be addressed before the paper is published.

Correct—thank you for pointing this out; we incorrectly used the actual lapse rate to calculate the LCL instead of using the dry adiabatic rate as it should be by definition. We have redone this calculation completely as a mean layer (ML) LCL as the MLLCL was recommended to us as a better representation of the atmospheric profile. We have corrected the description in the Appendix. Subsection 4.3 (results of radiosonde) and figure 4 are redone with the new numbers.

Minor comments:

P1 L30: "Smaller mountains have lower temperatures and steeper adiabatic lapse rates". Please consider rewording this. It is at odds with Line 27-28, and also do you mean pseudo-adiabatic lapse rates? The word steeper is generally confusing when describing lapse rates because of the conventional way of plotting them.

We changed these two sentences to: "Around 500 TMCFs have been identified world-wide on mountains with frequent cloud cover; these can be at higher elevation (on larger mountains) which have lower temperatures, or lower elevation (on smaller mountains) which have more rainfall (Jarvis and Mulligan, 2011). The global set of TMCFs are almost all within 350 km of a coast and topographically exposed to higher-humidity air (Jarvis and Mulligan, 2011). Smaller mountains are likely to have clouds at lower elevations due to slightly higher adiabatic lapse rates (more temperature loss with the same elevation gain) than larger mountains, which undergo greater heating of the land mass (the mass-elevation effect: Foster, 2001; Jarvis and Mulligan, 2011). This effect and the higher humidity near the ocean support TMCFs on small coastal mountains." This statement follows Jarvis and Mulligan who use the term "adiabatic lapse rate" as a general term.

P3 L16 "more diurnal effect of convection" Suggest rewording to make this statement less vague

Changed sentence to: "A pattern of lower clouds (bases and tops) over the ocean and higher clouds over the land with a stronger diurnal effect of convection above land has been observed in the tropics with Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (Medeiros et al., 2010)."

P3 L24 "originate with strong winds . . ." is this relevant to your site? Later you provide another reference suggesting that winds are 3-5m/s, which is quite light.

Changed to "originate with consistent winds" – which is more appropriate wording as you say. The reference here is from work in the same area where they are talking about the winds in our study region.

P3 L25 suggest "lifting" instead of "forcing"

Changed.

P4 L3-4 "Raw ceilometer: : :" what you describe is not really raw data, it is a processed product.

Good point, we've removed all the "raw" words in the paper.

P4 L9 How is temporal and spatial variability separated with a ceilometer? This whole sentence is vague, consider rewording.

We have made our intentions more clear, now saying "we developed metrics to summarize the cloud base altitude data in ways that could express differences and changes temporally (as well as spatially if the same metrics where calculated elsewhere) . . . .."

P4 L13-14 " . . . more complete picture of the climate of the entire atmosphere above the site." Consider replacing "atmosphere" with "troposphere" since you measure <8.2 km.Consider also replacing "climate" with something more specific to the measurement like "cloud patterns" or "cloud variability"

Changed to "troposphere" and "cloud patterns"

P4 L28-31 Ceiba is only a few km from the site. MSLP is certainly going to be very similar. If this is an example to support the claim that "weather immediately around the TMCF was homogeneous in pattern . . ." it is quite weak. Consider removing it. Also the statement "the weather immediately around the TMCF was homogeneous in pattern, but clearly not in magnitude" is vague but also confusing. Later, you go on to show various heterogeneities (associated with the topography and other features) that appears to be in direct contradiction with this statement. Please clarify what you mean and consider using another term instead of "weather".

The stations we were referring to are the ones in the forest, albeit at different locations, and not Ceiba. We've reworded these sentences to avoid misunderstanding: “were collected at several weather stations around the TMCF within an 8 km^2 area of the forest for differing periods of record (PORs) (Table 1). High hourly correlations were observed between these parameters across the forest stations for periods of overlap, giving confidence that patterns between the set of weather variables at each station in the immediate vicinity of the ceilometer measurements were homogeneous, although of differing magnitude at the different stations (Van Beusekom et al., 2015). Thus we used the weather data from the one station with the most complete and longest POR (Bisley at 361 m; Table 1). Mean sea level pressure (MSLP) was only collected near the TMCF at 100 m. Its relatively short record was highly correlated with the MSLP at the ASOS station TJNR, Ceiba (correlation coefficient ρ = 0.98), so the record was filled with data from Ceiba.”

P4 L34 “climate oscillations” – I think you should be more specific. Also, I think you should provide a bit more clarity on why you removed all the various segments. Was it because you could not clearly define the break between seasons? If so, do you think there is another way of classifying your seasonal groups rather than calendar months?

Changed to “However, interannual variability in the timing of seasons from climate oscillations (North Atlantic, Pacifica Decadal, and El Niño-Southern Oscillations) was observed in averages made over the shorter record (Gouirand et al., 2012).” We’ve changed the next sentence to “Because we have a short period of record for the ceilometer data (~3 years) and we focused on average seasonal behavior in this initial study, we chose to omit the unrepresentative time periods noted above and only used the time periods representative of the longer-term seasonal average (~17 years). As the ceilometer record gets longer, we will be better able to investigate effects of the large-scale climate oscillations on clouds at the site.” We could have done a more sophisticated analysis to break the seasons—but past work has shown efforts to be complicated and we feel that with three years of data that analysis would just add confusion. (See Van Beusekom, A.E., González, G., Rivera, M.M., 2015. Short-Term Precipitation and Temperature Trends along an Elevation Gradient in Northeastern Puerto Rico. Earth Interact. 19, 1–33.).

P7 L29 “within 100 m the LCL” missing “of”?

Yes, changed.

P8 L3 Suggest stating which stations you are referring to instead of “Caribbean ASOS stations windward of Luquillo” or else, perhaps substitute “windward” for “east”

Changed to “Caribbean ASOS stations east (windward) of Puerto Rico”

P8 L3-4 “stable” do you mean that the marine boundary layer is thermodynamically stable?

Changed to “thermodynamically stable marine boundary layer TWI”

P8 L5 “remnants of this weather pattern may be carrying on to land: : :” this is an awkward statement, consider rewording. Also in reference to the previous point about homogeneous “weather” this statement also seems at odds.

We changed it to “remnants of this weather pattern may be persisting on to the land in eastern Puerto Rico”.
This statement shouldn’t be at odds with the previous statement about the weather immediately around the forest—hopefully with the clarifications in the earlier statement this now appears un-contradictory.

P8 L27-29 Please consider rewording this whole sentence. In its present state the meaning is unclear and the wording may need adjusted (e.g. “. . . evidence that consistently as low, or lower, clouds exist: : :”)

Reworded sentence “This study presents evidence that cloud levels in the dry season are consistently as low, or lower, than in the wet seasons at a low-elevation TMCF under the current climate regime, indicating that the TMCF ecosystem may be more vulnerable to wet-season drought periods than was previously assumed.”

Analyzing cloud base at local and regional scales to understand tropical montane cloud forest vulnerability to climate change

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Abstract. The degree to which cloud immersion provides water in addition to rainfall, suppresses transpiration, and sustains tropical montane cloud forests (TMCFs) during rainless periods is not well understood. Climate and land use changes represent a threat to these forests if cloud base altitude rises as a result of regional warming or deforestation. To establish a baseline for quantifying future changes in cloud base, we installed a ceilometer at 100 m altitude in the forest upwind of the TMCF that occupies an altitude range from ~600 m to the peaks at 1100 m in the Luquillo Mountains of Eastern Puerto Rico. Airport ASOS ceilometer data, radiosonde data, and CALIPSO satellite data were obtained to investigate seasonal cloud base dynamics, altitude of the trade-wind inversion and typical cloud thickness for the surrounding Caribbean region. Cloud base is rarely quantified near mountains, so these results represent a first look at seasonal and diurnal cloud base dynamics for the TMCF. From May 2013 – August 2016, cloud base was lowest during the mid-summer dry season, and cloud bases were lower than the mountaintops as often in the winter dry season as in the wet seasons. The Luquillo forest low cloud base altitudes were higher than six other sites in the Caribbean by ~200-600 m, highlighting the importance of site selection to measure topographic influence on cloud height. Proximity to the oceanic cloud system where shallow cumulus clouds are seasonally invariant in altitude and cover; along with local trade-wind orographic lifting and cloud formation, may explain the dry season low clouds. The results indicate climate change threats to low-elevation TMCFs are not limited to the dry season; changes in synoptic-scale weather patterns that increase frequency of drought periods during the wet seasons (periods of higher cloud base) may also impact ecosystem health.

1 Introduction

Mountains play a key role in collecting atmospheric moisture in tropical regions (Wohl et al., 2012). Around 500 TMCFs have been identified world-wide on mountains with frequent cloud cover; these can be at higher elevation (on larger mountains) which have lower temperatures, or lower elevation (on smaller mountains) which have more rainfall (Jarvis and Mulligan, 2011). The global set of TMCFs are almost all within 350 km of a coast and topographically exposed to higher-humidity air (Jarvis and Mulligan, 2011). Smaller mountains are likely to have clouds at lower elevations due to slightly higher adiabatic lapse rates (more temperature loss with the same elevation gain) than larger mountains, which undergo

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greater heating of the land mass (the mass-elevation effect: Foster, 2001; Jarvis and Mulligan, 2011). This effect and the higher humidity near the ocean support TMCFs on small coastal mountains.

Up to 60% of the moisture input to TMCFs is derived from cloud water interception from low clouds (Bruijnzeel et al., 2011), but this value varies greatly from forest to forest and within an individual forest. Cloud water has been deemed critical for the health of TMCFs, specifically for the abundant epiphytes which require consistent moisture input from the atmosphere (Gotsch et al., 2015). Cloud water interception (including fog) adds moisture directly to the soil through the process of canopy interception and fog drip (Giambelluca et al., 2011), and indirectly alters the moisture budget through foliar uptake (Eller et al., 2013), lowering the saturation deficit of the atmosphere, and suppressing transpiration (Alvarado-Barrientos et al., 2014). For the low-elevation TMCF of this study, it might be expected that, given a relatively constant seasonal temperature lapse rate (within 0.1°C/1000 m for each season using previous study data (Van Beusekom et al., 2015)), wet seasons would have higher relative humidity caused by the larger amounts and spatial extent of rain events, and therefore lower clouds. Yet, previous field-based studies at four different low-elevation TMCFs found that similar or higher absolute amounts of fog precipitation were deposited during dry season measurements than during wet season measurements (Cavelier and Goldstein, 1989).

With their large energy inputs and fast rates of spatial and temporal change, tropical regions are some of the most dynamic atmospheric and hydrologic systems on Earth and thus may be significantly affected by climate change (Perez et al., 2016; Wohl et al., 2012). Regional cloud mass has been projected to decline with continued deforestation in maritime climates (van der Molen et al., 2006), and warming temperatures and urbanization could raise cloud base in the global set of TMCFs (Foster, 2001; Still et al., 1999; Williams et al., 2015), which could lead to some low-elevation TMCFs losing cloud immersion. In the Caribbean, the wet seasons are projected to be less wet by the end of the century (Karmalkar et al., 2013). Specifically, 1) shallow convection over Caribbean mountains in the early rain season may decrease if the trade winds continue to strengthen and shift direction, changing sea breeze dynamics and weakening orographic lift (Comarazamy and González, 2011); and 2) the regional late rain season may shorten due to strengthening of the Caribbean Low Level Jet (CLLJ) (Taylor et al., 2013).

The goal of this study was to determine cloud-base altitude and frequency of occurrence of low clouds during dry and wet seasons at a low-elevation tropical forest in the Luquillo Mountains, Puerto Rico, to establish a baseline against which to quantify future change. In addition, ceilometer, radiosonde, and satellite data for the northern Caribbean were analyzed to determine how the surrounding region influences the cloud patterns over ocean and land. Ceilometer data that are available to the research community are usually collected at airports, not in mountainous areas, and furthermore do not specifically quantify cloud frequency (Schulz et al., 2016). A dedicated ceilometer was installed to measure cloud base altitudes on the windward side of the mountains, at 100 m elevation and 7 km distance from the ridgeline at ~1000 m, and metrics were developed to quantify seasonal changes in base altitude and frequency of low, mountain-associated clouds. These metrics can also be used in the future to analyze temporal trends.

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Ashley Van Beuse..., 4/25/2017 11:55 PM
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2 Study Area

The Luquillo Experimental Forest (LEF) is located in the northern tropics at 18.3° N, 65.7° W. The LEF area is in the Luquillo Mountains on the eastern end of the island of Puerto Rico; these mountains are no more than about 13 km from the coastline (the Atlantic Ocean to the north and east and the Caribbean Sea to the south). Maximum elevation is 1077 m. High rainfall causes steep, dissected slopes and the ridges and stream valleys are covered by undeveloped tropical forest. Weather and clouds in the Luquillo Mountains follow patterns typical of the Caribbean region, which is dominated by the easterly trade-winds (Malkus, 1955; Odum and Pigeon, 1970; Taylor and Alfaro, 2005). Annual trade-winds are driven by an interplay of the North Atlantic Subtropical High (NASH) sea level pressure system and the Inter-Tropical Convergence Zone (ITCZ) position (Giannini et al., 2000). In the northern hemisphere summer, the ITCZ moves to its northern position in the southwest Caribbean, weakening the trade-winds and giving way to the progression of tropical easterly low-pressure waves, which help to create a Caribbean wet season April/May through November (Gouirand et al., 2012). During winter the NASH extends westward, strengthening the trade-winds and suppressing convection to create a cooler dry season December through March (Gouirand et al., 2012). The CLLJ is a strengthening of the trade-winds in June and July, separating the rain season into early and late with a warm drier season called the mid-summer drought (Taylor et al., 2013). Trade-wind cumulus over the ocean are found within the trade-wind moist layer, limited above by the trade-wind inversion (TWI) and below by the lifting condensation level (LCL) (Stevens, 2005). Intra-annual variation in oceanic cloud cover is dampened as an estimated two-thirds of the cloud cover comes from annually-consistent clouds near the LCL; the other third is seasonally-changing clouds higher aloft (Nuijens et al., 2014). A pattern of lower clouds (bases and tops) over the ocean and higher clouds over the land, with a stronger diurnal effect of convection above land has been observed in the tropics with Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (Medeiros et al., 2010). However, with overpasses every 16 days, satellite data do not provide the level of temporal and spatial resolution required to effectively study the clouds at a TMCF (Costa-Surós et al., 2013). Satellite data in this study are used to generalize the ceilometer findings and quantify patterns of cloud top height and cloud thickness in the region.

Experiments and long-term monitoring in the Luquillo Mountains showed that orographic precipitation events occur consistently throughout the year (from the trade-winds and thermal lifting over the mountains), providing 25% of the rainfall by volume (Scholl and Murphy, 2014) as well as additional, unmeasured cloud water. Low clouds at the mountains have been hypothesized to originate with consistent winds carrying oceanic clouds to the mountains too rapidly for dissipation (Raga et al., 2016), and additional condensation may occur with topographic lifting of moist air up the slopes. The cloud forest in the Luquillo Mountains has been reported from near 600 m where epiphytes first occur in abundance and trees are noticeably smaller (Bruijnzeel et al., 2011; Weaver and Gould, 2013); however this elevation will vary with interactions between the topography and wind direction (e.g. the TMCF elevation range is almost certainly higher on the leeward slopes). It is possible the Luquillo Mountains may have already undergone cloud base lifting since the first field studies in 1963; when cloud immersion was observed at 500 m (Odum and Pigeon, 1970) and at 600 m as noted in Weaver (1995), but the evidence is anecdotal, and there were no cloud base measurements recorded over time. Seasonal patterns of clouds in the

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Luquillo TMCF were studied with synoptic weather observations (Malkus, 1955; Odum and Pigeon, 1970) and more recently there have been summer cloud water deposition measurements (Eugster et al., 2006; Holwerda et al., 2011). Cloud base height data have been collected in the region by satellites and airport stations in addition to the newer data collected by this study nearer to the TMCF. These data types will be discussed extensively in the next section and a map of locations can be seen in Fig. 4a.

3 Methods

3.1 Ceilometer and Weather Station Data in the Luquillo Experimental Forest

A Vaisala CL31 laser ceilometer installed at 100 m elevation 7 km northeast of the northwest-trending ridgeline that connects two of the higher peaks of the Luquillo Mountains. The ceilometer collected data at 30-second intervals from April 29, 2013 through August 1, 2016. Ceilometer data used in this study were the altitudes of the lowest cloud layer at a point above the instrument; the cloud layer base is the bottom of a vertically continuous layer at least 100 m thick with no vertical visibility (defined according to a 5% contrast threshold; http://www.vaisala.com). The mean and median cloud base values that are usually calculated from ceilometer data are not sufficient to answer our questions about the frequency of clouds immersing the relatively low-elevation forested mountains, because data from a point source include numerous clear-sky and high cloud base observations. Therefore we developed metrics to summarize the cloud base altitude data in ways that could express differences and changes temporally (as well as spatially if the same metrics were calculated elsewhere) in cloud base for altitude range of interest in the TMCF; the forest is affected by clouds in the elevations from ~600-1077 m (Weaver, 1995). The metrics were derived from the frequency distributions of all cloud base measurements, where clear-sky was considered an infinite cloud altitude in the computations and clouds that may have been present below the elevation of the ceilometer (100 m) were not recorded. The more traditional metric of 'average' would not be able to account for clear-sky observations. For example, if a day had one cloud in the 24-hour period, and it had a base of 200 m, the daily average would be 200 m. However, a day with half the cloud bases at 200 m and half at 2000 m would have a daily average cloud base of 1100 m, higher than the first day even though the second day had more clouds that would affect the TMCF. We did not trim the data to the altitude of interest; using all data gave a more complete picture of the cloud patterns of the troposphere above the site.

The specific quantiles used for cloud-base metrics were chosen such that hourly metric values were between 600-1077 m a majority of the hours in each season and daily metric values were between 600-1077 m a majority of the days in each season. In this way, the metrics can be applied to help quantify the ecosystem characteristic low-elevation cloud amount needed to sustain the forest throughout the hour, day, and season. The metric 'hourly low cloud base' was defined as the altitude marking the first quartile (Q_1) of the frequency distribution of the 120 measurements in each hour. The metric 'daily low cloud base' was defined at the daily first tertile (T_1) of the distribution of Q_1 altitudes from each hour, meaning the low cloud base metric was at or below that altitude for 8 (not necessarily consecutive) hours in the 24-hour day. The metric 'hourly minimum cloud base' was defined as the single-value altitude of the lowest cloud base detected during each hour. The metric

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'daily minimum cloud base' was defined as the daily seventh octile (O_7) of the distribution of minimum values for each hour, meaning the minimum cloud base was at or below that altitude for 21 hours in the day. The daily low metric represents a cloud base altitude that is often observed in the portion of the day with the lowest clouds; whereas the daily minimum metric represents an altitude that lowest cloud base is found at throughout most of the day. For comparison with regional Automated Surface Observation System (ASOS) data, the standard hourly average cloud bases and average cloud bases (omitting clear-sky data points) were also calculated at our Luquillo Experimental Forest site (LEF). Hourly cloud cover was computed as the fraction of positive cloud base detections, at any altitude, that occurred in the 120 instrument measurements per hour. An example of these calculations in practice and more information on the design of the metrics for this study and for other potential studies is given in the Supplement.

Hourly rainfall, relative humidity (RH), temperature, wind speed, and wind direction data were collected at several weather stations around the TMCF within an 8 km^2 area of the forest for differing periods of record (PORs) (Table 1). High hourly correlations were observed between these parameters across the forest stations for periods of overlap, giving confidence that patterns between the set of weather variables at each station in the immediate vicinity of the ceilometer measurements were homogeneous, although of differing magnitude at the different stations (Van Beusekom et al., 2015). Thus we used the weather data from the one station with the most complete and longest POR (Bisley at 361 m; Table 1). Mean sea level pressure (MSLP) was only collected near the TMCF at 100 m. Its relatively short record was highly correlated with the MSLP at the ASOS station TJNR, Ceiba (correlation coefficient ρ = 0.98), so the record was filled with data from Ceiba. The rainfall and RH data at 361 m and the MSLP at 100 m (missing values filled with data from Ceiba) were representative of seasonal patterns in the Luquillo Mountains and were used to interpret the ceilometer data by season locally and regionally.

The 2000-2016 MSLP showed higher pressure in the dry seasons and lower pressure in the wet seasons (Fig. 1c), exemplifying the regional seasonal patterns that originate with the NASH and CLLJ (Brueck et al., 2014; Taylor et al., 2013). However, interannual variability in the timing of seasons from climate oscillations (North Atlantic, Pacific Decadal, and El Niño-Southern Oscillations) was observed in averages made over the shorter record (Gouirand et al., 2012). Rainfall, RH, and MSLP months April 1-15 (M4.5), October (M10), and December (M12) in the LEF ceilometer period of record (LEF POR, May 2013 through August 2016) were not representative of the longer period 2000-2016 (Fig. 1). Because we have a short period of record for the ceilometer data (~3 years) and we focused on average seasonal behavior in this initial study, we chose to omit the unrepresentative time periods noted above and only used the time periods representative of the longer-term seasonal average (~17 years). As the ceilometer record gets longer, we will be better able to investigate effects of the large-scale climate oscillations on clouds at the site.

All correlations between variables were computed as Pearson product-moment correlations with coefficient ρ measuring linear correlation. Strengths of correlations were based on the relationships between weather parameters and clouds found in this study and another Caribbean cloud and weather study (Brueck et al., 2014); correlation was assumed fair if 0.3 < $|\rho|$ < 0.4, good if 0.4 < $|\rho|$ < 0.6, and very good if $|\rho|$ > 0.6.

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3.2 Ceilometer and Weather Station Data at Airports

The ASOS data for six airport stations in the Northern Caribbean from 2000-2016 were accessed from the Iowa Environmental Mesonet (Table 1), which include average hourly cloud base when clouds exist, cloud cover as percentage of the sky, and observed weather variables. No 30-second data were available and all data have been summarized to the mean-hour before reporting, thus not specifically quantifying cloud frequency. The ASOS network reports by a range of oktas (okta = 1/8 of the sky) covered by cloud (Nadolski, 1998): "clear" for 0, "few" for 1/8-2/8, "scattered" for 3/8-4/8, "broken" for 5/8-7/8, and "overcast" for 8/8. These numbers are automatically calculated by the instrument from 30-second detections similar to our calculations for the LEF site (Nadolski, 1998). For calculation of average POR cloud cover in this study, the cover categories were converted to sky cover fraction using the middle of the range or 0 for "clear", 0.125 for "few", 0.375 for "scattered", 0.75 for "broken", and 1 for "overcast".

To characterize variations in the cloud-system of the region, metrics were again developed to summarize the hourly average cloud base data at the ASOS and LEF stations in ways that expressed the changes in seasonal altitudes of clouds at altitudes meaningful for heights in the TMCF. The metric 'daily minimum mean-hour cloud base' was defined as the minimum value each day of the hourly averages and similarly the metric 'daily maximum mean-hour cloud base' was defined as the maximum of the hourly averages. The metric 'daily low mean-hour cloud base' was defined as the daily Q_1 of the hourly averages. To characterize the cloud-system at large, mean hourly cloud cover (in fraction of sky) was also calculated.

In order to represent usual atmospheric conditions, bearing in mind the data were mean-hours of existing cloud bases and not representing clear conditions that may have been present during the hour, hourly average cloud base was considered clear sky (in calculation of the daily metrics) if the cloud cover fraction was less than 50% of a station's POR mean cloud cover. POR mean cloud cover was 0.6 fraction of the sky at the LEF station (foothills) but 0.2-0.3 fraction of the sky at the ASOS stations (airports). Under this condition, ~2% of the data at each station were removed before calculation of 'usual' conditions.

3.3 Radiosonde Data at Airports

Two to three times daily, radiosonde profiles were available for 2000-2016 at Santo Domingo, San Juan, and Sint Maarten from the Integrated Global Radiosonde Archive (Durre et al., 2009). We expected to find cloud base altitudes above the LCL and cloud tops at or below the TWI for trade-wind conditions (Brueck et al., 2014; Malkus, 1955), thus we used the radiosonde profiles to compute values of minimum LCL and maximum TWI base over each day to quantify frequency of stable marine boundary layers and trade-wind cloud conditions at the site (Rastogi et al., 2016; Zhang et al., 2012). The LCL calculation we used involves an air parcel representing the mean potential energy in the lowest 50 hPa of the atmosphere for a mean-layer LCL; this accounts for the fact that the thermodynamic profile of the boundary layer may not be well-represented by that of the surface layer (Craven et al., 2002; for details see Appendix A). The TWI calculation used the

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3.4 Satellite Data

CALIPSO satellite vertical feature mask data (Winker et al., 2009) 2006-2016 were analyzed for information on cloud tops and cloud thickness in the region. There are ten tracks in the region considered (Fig. 4a, Table 1); the northwest/southeast trending tracks are on the daytime orbit, and the other direction the nighttime orbit. Tracks are repeated at a 16 day interval and each satellite overpass records whether cloud was detected in 300 m horizontal by 30 m vertical cells up to 8.2 km altitude (data extend up to 30 km but we do not discuss those here). Data were summarized by fraction of measurements with cloud detections in larger cells of 0.05° latitude (approximately 6 km) with 30 m vertical resolution, as well as mean and Q_1 altitudes of the top and base of the lowest cloud layer over land and water, considering all regional tracks. None of the tracks went directly over the study site. As with the ceilometer metrics, the Q_1 altitudes summarize the low cloud frequency behavior in a way that can express differences and changes temporally as well as spatially. Aproximately 10% of the vertical profiles had uncertainty in the cloud base as the lidar was completely attenuated below a cell of cloud (because the cloud was too thick optically; Winker et al., 2009). For these profiles, low cloud base altitude was set as minimally the altitude of land/water surface, and maximally as the lowest cell vertically that cloud is observed, before complete lidar attenuation; this results in a range reported for the low cloud base altitude and layer thickness.

4 Results

4.1 Ceilometer and Weather Station Results in the Luquillo Experimental Forest

The data suggest that the TMCF has a greater probability of cloud interaction during the mid-summer dry season (MSD) throughout the elevation range of the forest between 600-1000 m, and during the winter dry season at the upper elevational reaches (<1000 m), than it does in the wet seasons (Figs 2, 3a). Of all the seasons, the mid-summer dry season (Fig. 2c) had low and minimum cloud bases at 600-750 m most consistently. The cloud base levels in the winter dry season (Fig. 2a) were not below 750 m as often as in the wet seasons, but were also absent above 3000 m, so on an hourly and daily basis, the low and minimum cloud bases were below 1000 m more consistently in the dry than in the wet seasons (summing the bars in Fig. 2). During the daytime hours (09:00-18:00) the median hourly low and minimum cloud bases were as low or lower in altitude in the dry seasons as the wet seasons (Fig. 3a); this was also the time of day when rainfall was the least frequent in the dry seasons (Fig. 3b). The means of median-hourly low and minimum cloud bases over the entire POR (the data shown in Fig. 3a) were 915 m and 702 m, respectively.

Of all available weather variables, the daily low and minimum cloud bases correlated best with RH and MSLP (negative correlations, Table 2, Figs 1a, c). Interestingly, RH did not correlate well with rainfall (Table 2) or with pressure indicators of wet and dry seasons (visually confirmed in Fig. 1b).

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4.2 Ceilometer and Weather Station Data at Airports

In the northern Caribbean region, the mean low cloud base was lower during the mid-summer dry season than during the other seasons at all of the stations, indicating seasonal variation (Fig. 4c). However, the longer winter dry season had a higher low cloud base than the wet seasons (Fig. 4b) except at the LEF station (the station in the Luquillo foothills; note at this station in Fig. 4b, less frequent winter dry season high clouds (see Fig. 1) lowers the mean-hour cloud base). Cloud cover percentage was highest in the mid-summer dry season relative to the other seasons at all the stations to the east (windward) and including the LEF station, and winter dry season cloud cover was similar to or higher than the wet seasons (Fig. 4d). The low and minimum cloud bases for stations near the Luquillo Mountains correlated much better with cloud cover than at the stations as a whole, with very good negative correlation at the LEF station itself (Table 2, S3).

In contrast to the LEF area (Fig. 1b) the regional pattern of RH for 2000-2016 was as expected, with lower RH during the dry seasons than the wet seasons (Fig. 5) and the low and minimum cloud bases all had fair correlation with the RH measurements (Table 3). Regionally, no metrics of daily clouds correlated with MSLP except at the LEF site, where the low and maximum cloud bases had good and very good correlation with MSLP, respectively (Table 3). The regional means and correlations were also computed over the shorter LEF POR with exclusion of the non-representative months. These were not substantially different than the 2000-2016 results presented here (in Fig. 4, and Fig. 5, Table 3), but the mathematical strength of the resulting means and significance of the correlations necessarily decreased with less data.

4.3 Radiosonde Data at Airports

Over the North Caribbean regional ceilometers excluding the LEF site, the maximum cloud base altitudes were below the TWI and the lowest near the mean-layer lifting condensation level (MLLCL) (both calculated from 2000-2016 radiosonde profiles, Fig. 4b). The TWI was distinguishable 86% of the time in the winter dry season, 74% in the mid-summer dry season, 71% in the early rain season, and 65% in the late rain season. The averages of maximum daily TWI values were 1921 m for Santo Domingo, 2141 m for San Juan, and 1851 m for Sint Maarten, with average seasonal standard deviation of ±48 m and the lowest TWI altitudes in the mid-summer dry season. This agrees with other research on global distribution and seasonal variance (Guo et al., 2011), and the influence of local topography (Carrillo et al., 2015), on the TWI. The averages of minimum daily MLLCL values were 538 m for Santo Domingo and 557 m for San Juan, with average seasonal standard deviation of ±27 m and the lowest values in the mid-summer dry season. At Sint Maarten, the POR-ceilometer-observed mean daily minimum cloud base was 202 m lower than the calculated minimum daily average MLLCL of 705 m, whereas at Santo Domingo and San Juan the difference was 37 m lower and 34 m higher, respectively. Consequently, we assumed the radiosonde measurements were not representative of conditions above the ceilometer location at Sint Maarten, and these data were not used in the regional comparison.

4.4 Satellite Data

CALIPSO data from ten tracks over the northern Caribbean (Fig. 4a) showed that land with high topography increased the likelihood of clouds in a layer from land surface elevation up to 2 km. The 2 km altitude is approximately the level of the

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TWI, which under most conditions caps the trade-wind cumuli (Fig. 6). Oceanic clouds were most likely to be found in a layer from 400 m to 1 km. Lidar attenuation causes uncertainty in the cloud base identification for the thickest 10% of clouds, as discussed earlier. For the lowest cloud layer below 8.2 km on all ten tracks, only considering when clouds are present, the mean altitude of the base of the layer ranged from 659-1385 m over ocean and 796-1155 m over land, and the mean altitude of the top of the layer was 2167 m over ocean and 2034 m over land. This indicated a similar cloud layer altitude over ocean and land; most land in the tracks was low topography so this is not unexpected. However, considering all data (i.e. clear-sky has infinite cloud base and top altitude), the Q_1 altitude range (from uncertainty due to lidar attenuation) of the base of the layer was 235-475 m over ocean and 25-355 m over land, and the Q_1 altitude of the top was 1165 m over ocean and 1315 m over land. Thus, there were possibly more low-altitude cloud base observations over land, depending on where in the range the cloud base actually existed. Highest topography land (Fig. 6c) exhibited an upper limit of the cloud layer around 2 km, however lower topography land had thicker clouds than over ocean. The mean layer thickness was 442-853 m over ocean and 582-818 m over land. Thicker clouds with more low bases occurring over land has also been found in previous studies looking at ocean and low topography land at different locations and in larger regions (Medeiros et al., 2010; Rauber et al., 2007).

5 Discussion and Conclusions

Caribbean trade-wind cumulus clouds have been observed in other studies to be relatively shallow and originating with bases near the LCL (Malkus, 1955; Nuijens et al., 2014; Rauber et al., 2007; Zhang et al., 2012). The regional ASOS and CALIPSO data in this study support the previous findings, with most oceanic cloud bases at or within 100 m of the LCL (Figs 4 and 6). Both 5-day and monthly correlations between low clouds and RH were observed region-wide (Table 3). It has been theorized that a stronger TWI increases oceanic cloud cover and lowers the cloud base, and cloud amounts reflect the upstream boundary-layer atmospheric conditions (Myers and Norris, 2013; Stevens, 2005). The Luquillo Mountains are ~10 km from the coast, and trade-wind velocity in the region is typically 3-5 m/s (Lawton et al., 2001). Existing clouds are over land for about 30 minutes before reaching the TMCF, and orographic lifting may generate additional condensation during parts of the daily cycle. We postulate that proximity of the TMCF to the coast is an ecological advantage in that the forest has adapted to the oceanic atmosphere (relatively invariant humidity, temperature profile, and cloud cover). The Caribbean ASOS stations east (windward) of Puerto Rico on small, low-relief islands may be influenced by the thermodynamically stable marine boundary layer TWI and reflect conditions closer to those over the ocean surface than to those on land. These stations have higher cloud cover in the dry seasons (Fig 3d) and lower clouds correlating with increasing cloud cover (Table 3); remnants of this weather pattern may be persisting on to the land in eastern Puerto Rico (Raga et al., 2016). However, our results clearly show the changes that occur when the clouds interact with land that extends above the LCL in a trade-wind regime: cloud base altitude and cloud cover over the mountains was increased compared to that over small low-relief islands or open ocean (Figs 4 and 6). In addition, the cloud base over land rises high enough that a TWI limit to vertical extent of the clouds may result in shallower (thinner) cloud layers at the highest land elevations (Fig. 6) (Rastogi et

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al., 2016). When topography is close to the ocean this effect is especially pronounced, as seen in the CALIPSO data with the disproportionate effect on the clouds by the lower peak elevation but closer oceanic proximity of the northernmost peninsula of the Dominican Republic Fig 6a, b). The local ceilometer data showed that the correlation of daily low and minimum cloud base metrics with RH was primarily driven by cloud bases lower than 1000 m in the calculations, and correlation of these metrics with MSLP was primarily driven by cloud bases higher than 1500 m in the calculations (Table 2). In addition, the relatively high RH during the dry seasons in the mountains is a pattern that is not seen over the low-relief sites (Figs 1b, 5) highlighting the importance of site-specific measurements of parameters that influence cloud base for TMCFs, rather than relying on data from regional stations at airports.

The Caribbean region is projected to undergo drying in the future, with various mechanisms that will suppress deep convection and affect the frequency of high rainfall (Karmalkar et al., 2013). Low peak-elevation TMCFs are especially vulnerable in a changing climate, because slight increases in cloud base altitude could end cloud immersion for the entire forest (Foster, 2001; Lawton et al., 2001; Ray et al., 2006). With our results, we question the likelihood of frequent cloud base at 600 m at the Luquillo Mountains (Figs 2, 3), the published TMCF lowest elevation based on older observations of cloud immersion (Odum and Pigeon, 1970; Weaver, 1995) and observed changes to smaller trees which dominate cloud forests (Weaver and Gould, 2013). It is possible that such characteristic vegetation may persist for some time after changing climatic conditions have lifted the cloud base (Oliveira et al., 2014; Richardson et al., 2003). Rainfall and relative humidity in the forest are currently quite high so that some species, once established, may be able to survive if rainfall remains high (Martin et al., 2011), but the diversity and numbers of epiphytes and other species that depend on cloud immersion might decline over time. During a past wet-season drought at Luquillo, trade-wind precipitation became very important in the absence of deep convection (Clark et al., 2017). If trade-wind cloud layers become thinner and shallow convection weakens, drought effects on the TMCF could be even more significant.

This study presents evidence that cloud levels in the dry season are consistently as low, or lower, than in the wet seasons at a low-elevation TMCF under the current climate regime, indicating that the TMCF ecosystem may be more vulnerable to wet-season drought periods than was previously assumed. We calculated the mean MLLCL at 557 m and mean TWI of 2141 m from San Juan airport radiosonde data, identifying the local trade-wind cloud layer near Puerto Rico. While previous studies report the forest clouds to start at 600 m, our ceilometer observations over the forest about 7 km windward of the TMCF showed the lowest cloud bases most frequently occurred at higher elevation, from 702 m to 915 m. Continued long-term measurements at the Luquillo Mountains, and comparisons to other low-elevation TMCFs, are needed to expand the low cloud pattern temporally and geographically with full confidence, and to determine how projected changes in regional temperature and atmospheric circulation patterns will affect these cloud-water-dependent ecosystems.

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6 Data Availability

The Luquillo Experimental Forest ceilometer and weather station data is hosted on the Critical Zone Observatory Data Portal http://criticalzone.org/luquillo/data.

Appendix A

This Appendix includes further detail on the calculation of the lifting condensation level (LCL) and the trade-wind inversion (TWI).

The LCL is the altitude at which a parcel of air lifts adiabatically and cools to the temperature that its relative humidity is 100%. Assuming the presence of cloud condensation nuclei, condensation of water vapor into liquid water cloud droplets is possible at and above this altitude. If the boundary layer is well-mixed, the layer will have a constant potential temperature and a constant mixing ratio and air parcel parameters at any altitude can be used to calculate the LCL; these weather parameters are most often measured at the land surface. However, the mean-layer (ML)LCL has been shown to be a more accurate descriptor of the lower boundary of cloud development than the surface-parcel based LCL (Craven et al., 2002). An MLLCL was determined from each radiosonde profile by first splining the temperature, dewpoint temperature, and pressure measurements into 5 hPa levels and calculating potential temperature and water vapour mixing ratio at each level (following Bolton, 1980). Then the mean potential temperature and water vapour mixing ratio in the lowest 50 hPa of the atmosphere was computed to define the mean-layer parcel. The pressure-temperature intersection of the mean-layer parcel potential temperature isopleth with the mixing ratio isopleth defined the MLLCL. The difference between the mean-layer parcel surface temperature and MLLCL temperature was used with the dry adiabatic lapse rate to calculate the LCL altitude.

The TWI is a layer often present in the atmosphere in the trade-wind latitudes characterized by a reversal of the usual negative temperature gradient to a positive gradient of warming with increasing altitude. A TWI base was determined from each radiosonde profile following published methods (Cao et al., 2007). The ascending radiosonde instruments recorded measurements at uneven intervals of roughly 50-300 m at the altitudes and time periods of interest to this study. The bounding altitudes containing the TWI base were determined by setting the upper bound as the lowest altitude observation with positive temperature gradient dT_p/dz between itself and the next highest observation, greater than 0 °C temperature and 0% RH, with pressure between 70 and 95 kPa. The pressure bounds are for the Atlantic Ocean TWI (Augstein et al., 1974). The lower bounding altitude was set as the observation one below the upper bounding altitude, which necessarily had a negative temperature gradient dT_n/dz below it. Inside the bounding altitude layer, the temperature gradients were then assumed to equal the positive gradient dT_p/dz above the TWI base and the negative gradient dT_n/dz below the TWI base. The intersection of these two lines of constant positive and negative gradient inside the bounding layer was set as the TWI base altitude.

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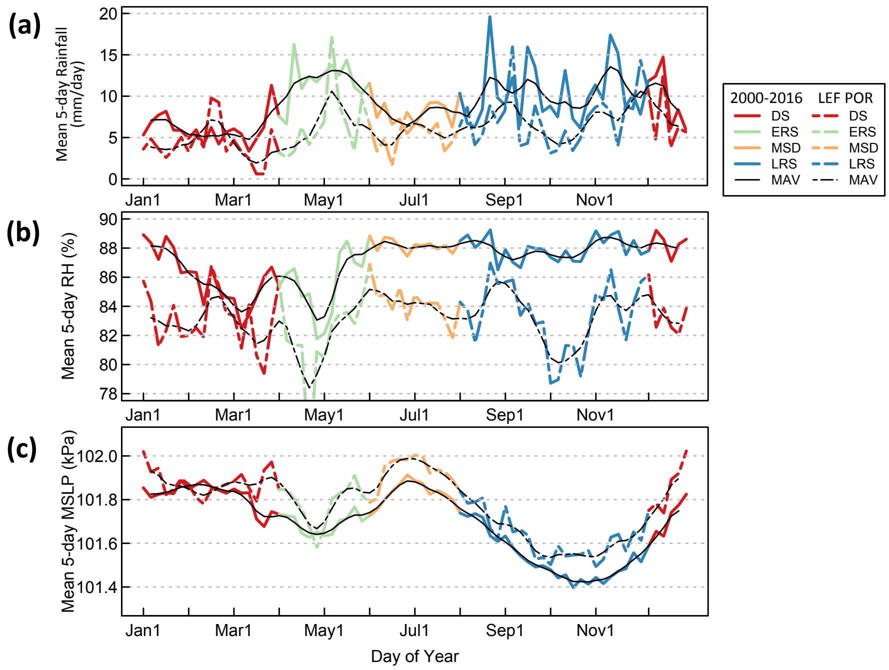

Figure 1: Day of year mean values for: a) precipitation at 361 m; b) relative humidity (RH) at 361 m; and c) mean sea level pressure (MSLP) at 100 m in the Luquillo Experimental Forest (LEF) sites. The colors show the 5-day means during the winter dry season (DS), early rain season (ERS), mid-summer dry season (MSD), and late rain season (LRS). The black line is the 15-day moving average (MAV), with the 2000-2016 period as solid lines and the LEF ceilometer period of record (LEF POR) of May 2013 through August 2016 as dashed lines.

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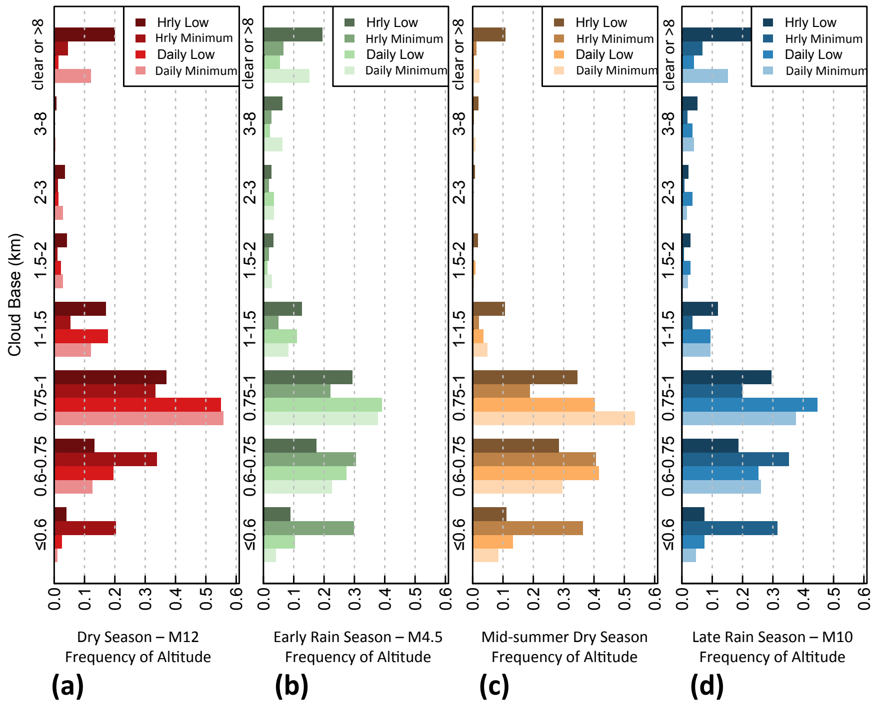

Figure 2: Frequency of low cloud base by season excluding non-representative months in each year from the Luquillo Experimental Forest ceilometer, May 2013 through August 2016: a) dry season without month December (M12); b) early rain season without April 1-15 (M4.5); c) mid-summer dry season; d) late rain season without October (M10). The metrics are hourly low cloud base (first quartile (Q_1) of each hour of 30-second cloud base altitudes), hourly minimum value, daily low value (first tertile (T_1) of the hourly low set), and daily minimum value (seventh octile (O_7) of the hourly minimum set).

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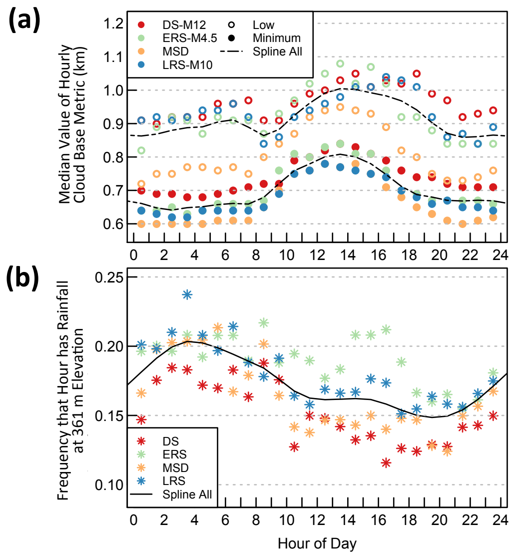

Figure 3: Summaries by hour of day for each season: a) median altitude of hourly low cloud bases and median altitude of hourly minimum cloud bases from the Luquillo Experimental Forest ceilometer, May 2013 through August 2016, for the winter dry season without month December (DS – M12), the early rain season without April 1-15 (ERS – M4.5), the mid-summer dry season (MSD), and the late rain season without October (LRS – M10); b) frequency measureable rainfall occurred in each hour of the day for 2000-2016 for the Bisley station at 361 m elevation during the seasons without excluded months. Colored symbols are seasonal values and black lines are the cubic smoothing splines of all data in the ceilometer period of record.

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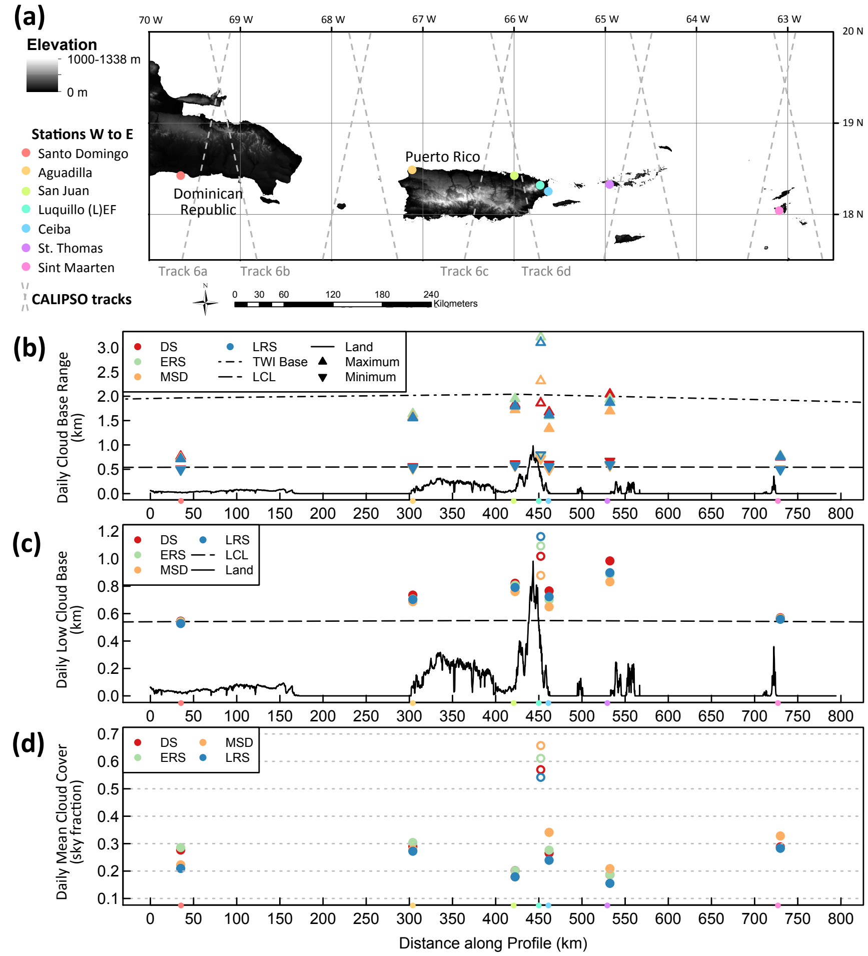

Figure 4. Daily 'usual' mean clouds averaged over the winter dry season (DS), early rain season (ERS), mid-summer dry season (MSD), and late rain season (LRS) for the period of record (POR) across the region: a) locations of airport (ASOS) stations, Luquillo Experimental Forest (LEF) station, and CALIPSO satellite tracks, along with topography; b) daily minimum and maximum cloud bases (of hourly means), splined lines of trade wind inversion (TWI) base and lifting condensation level (LCL) based on three geographical calculations, and land surface elevation along profile; c) daily low cloud base (first quartile (Q_1) of hourly means), estimated LCL, and land surface elevation along profile; d) daily mean cloud cover as fraction of sky. The land surface profile trends due east and west (shifting north and south to be near the stations). Station locations are marked with circles on the x-axis in the same colors as plot a. Dashed colored lines between San Juan and Ceiba are used to indicate that the LEF station measurements are only based on the available LEF POR, May 2013-August 2016 excluding non-representative months the entire 2000-2016. 'Usual' defined as hours with cloud cover at least 50% of mean-POR cloud cover for station.

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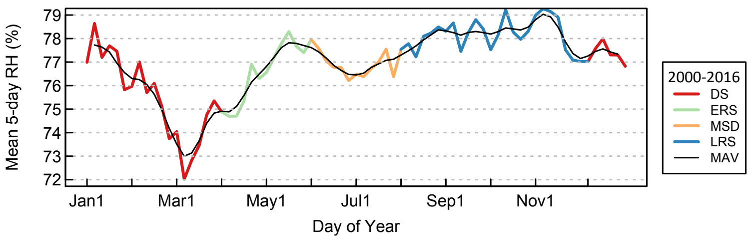

Figure 5. Day of year mean values for relative humidity (RH) averaged over all 6 regional airport stations (ASOS, does not include Luquillo Experimental Forest data). The colors show the 5-day means during the winter dry season (DS), early rain season (ERS), mid-summer dry season (MSD), and late rain season (LRS). The black line is the 15-day moving average (MAV) for the 2000-2016.

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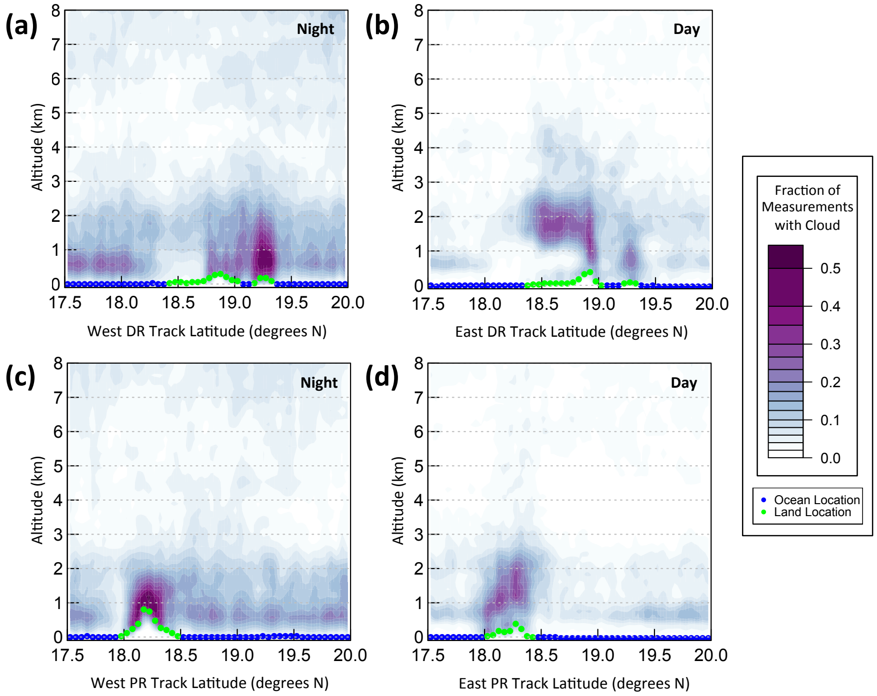

Figure 6. CALIPSO satellite data fraction of measurements with cloud recorded in cell, for years 2006-2016 with cell as 0.05° latitude along track and 30 m altitude for: a) West Dominican Republic (DR) track (night orbit); b) East DR track (day orbit); c) West Puerto Rico (PR) track (night orbit); and d) East PR track (day orbit). Since track measurement location varies slightly, surface point (land or ocean) is plotted as the mean location. Cell fractions are spline-smoothed into a surface. Tracks are marked on Figure 4a.

Station	Lat (° N)	Long (° W)	Elev (m)	Land Cover	Variables[‡]	Period Used	Data Missing	Data Reference
Sabana LEF[*,†]	18.32	65.73	100	Forest	RF, RH, MSLP, T, WD, WS	5/2013 – 8/2016	5%	http://criticalzone.org/luquillo/data/
Bisley LEF[*]	18.30	65.75	361	Forest	RF, RH, T, WD, WS	1/2000 – 8/2016	3%	http://criticalzone.org/luquillo/data/
Icacos LEF[*]	18.28	65.79	645	TMCF	RF	1/2000 – 1/2016	7%	50075000 http://waterdata.usgs.gov/nwis
Santo Domingo[†]	18.43	69.67	18	Airport	RH, T, WD, WS, S	1/2000 – 8/2016	28%	MDSD http://mesonet.agron.iastate.edu
Aquadilla[†]	18.49	67.13	72	Airport	RH, T, WD, WS	1/2000 – 8/2016	35%	TJBQ http://mesonet.agron.iastate.edu
San Juan[†]	18.43	66.01	3	Airport	RF, RH, MSLP, T, WD, WS, S	1/2000 – 8/2016	1%	TJSJ http://mesonet.agron.iastate.edu
Ceiba[†]	18.26	65.64	12	Airport	RF, RH, MSLP, T, WD, WS	1/2000 – 8/2016	37%	TJNR http://mesonet.agron.iastate.edu
St. Thomas[†]	18.34	64.97	7	Airport	RF, RH, MSLP, T, WD, WS	1/2000 – 8/2016	6%	TIST http://mesonet.agron.iastate.edu
Sint Maarten[†]	18.04	63.11	4	Airport	RH, T, WD, WS, S	1/2000 – 8/2016	7%	TISM http://mesonet.agron.iastate.edu
CALIPSO tracks[†]	17.5-20	62.5-70	vary	Various	Cloud vertical profiles	6/2006 – 8/2016	0.05%	http://www-calipso.larc.nasa.gov

[*] In Luquillo Experimental Forest (LEF)

[†] Cloud data collected at these stations

[‡] Key to abbreviations: RF = rainfall, RH = relative humidity, MSLP = mean sea level pressure, T = temperature, WD = wind direction, WS = wind speed, S = radiosonde

Table 1. Data Record Information.

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Variable	Cloud Base Altitude				Rainfall	
	Daily Low (Daily T_1 of Q_1 of each hour)		Daily Minimum (Daily O_7 of min of each hour)			
	5-day ρ	Month ρ	5-day ρ	Month ρ	5-day ρ	Month ρ
RH	**-0.34**	-0.31	**-0.36**	-0.28	**0.13**	*0.05*
MSLP	**-0.45**	**-0.58**	**-0.52**	**-0.54**	**-0.30**	**-0.46**
Cloud Cover	**-0.69**	**-0.76**	**-0.72**	**-0.75**	**0.26**	*0.21*

Significant relationships indicated by typeface: p-value < 0.1, p-value < 0.05, **p-value < 0.01**

Insignificant relationships *italicized*.

Table 2. Correlations Coefficients ρ of Relative Humidity (RH), Mean Sea Level Pressure (MSLP), and Cloud Cover with Cloud Base Altitude Metrics and Rainfall in the Luquillo Experimental Forest.

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Variable	Station	Cloud Base Altitude						Rainfall	
		Daily Low Mean-Hour (Q_1 of usual hrly means)		Daily Minimum Mean-Hour (min of usual hrly means)		Daily Maximum Mean-Hour (max of usual hrly means)			
		5-day ρ	Month ρ	5-day ρ	Month ρ	5-day ρ	Month ρ	5-day ρ	Month ρ
RH	ASOS all*	**-0.35**	**-0.30**	-0.36	*-0.26*	*-0.06*	*-0.17*	NA	NA
	ASOS near†	**-0.36**	**-0.29**	**-0.47**	*-0.33*	*-0.01*	*-0.08*	**0.22**	0.17
	LEF‡	**-0.22**	*-0.19*	**-0.37**	-0.36	*0.04*	*-0.01*	**0.13**	*0.05*
MSLP	ASOS all*	NA	NA	NA	NA	NA	NA	NA	NA
	ASOS near†	*0.04*	*0.01*	**0.17**	**0.14**	**-0.10**	*-0.08*	**-0.27**	**-0.42**
	LEF‡	**-0.40**	**-0.64**	-0.16	**-0.30**	**-0.46**	**-0.57**	**-0.30**	**-0.46**
Cloud Cover	ASOS all*	-0.21	*-0.18*	**-0.18**	*-0.08*	*0.02*	*0.01*	NA	NA
	ASOS near†	**-0.30**	**-0.42**	**-0.27**	**-0.28**	**-0.03**	*-0.14*	*-0.01*	*-0.10*
	LEF‡	**-0.46**	**-0.76**	**-0.47**	**-0.82**	*-0.02*	-0.37	**0.26**	*0.21*

Significant relationships indicated by typeface: **p-value < 0.1**, p-value < 0.05, **p-value <0.01**

Insignificant relationships *italicized*.

* Mean of ρ from all six airport (ASOS) stations 2000-2015

† Mean of ρ from three airport (ASOS) stations nearest to Luquillo 2000-2015: San Juan, Ceiba, St. Thomas

‡ ρ from Luquillo Experimental Forest (LEF) stations 5/2013 – 12/2015

'Usual' defined as hours with cloud cover at least 50% of mean-POR cloud cover for station.

Table 3. Correlation Coefficients ρ of Relative Humidity (RH), Mean Sea Level Pressure (MSLP), and Cloud Cover with Cloud Base Altitude Metrics and Rainfall Region-Wide.

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All correlations between variables were computed as Pearson product-moment correlations with coefficient ρ measuring linear correlation. Strengths of correlations were based on the relationships between weather parameters and clouds found in this study and another Caribbean cloud and weather study (Brueck et al., 2014); correlation was assumed fair if $0.3 < |\rho| < 0.4$, good if $0.4 < |\rho| < 0.6$, and very good if $|\rho| > 0.6$. The regional means and correlations were also computed over the shorter LQ POR with exclusion of the non-representative months. These were not substantially different than the 2000-2016 results presented here (in Fig. 4, and Fig. 5, Table 3), but the mathematical strength of the resulting means and significance of the correlations necessarily decreased with less data.

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In the northern Carbbean region, Regionally, the mean low cloud base from the mean-hours was lower during the MSD than during the other seasons at all of the stations, indicating seasonal variation in mean low cloud base altitude (Fig. 4c). However, the longer winter dry season, DS, had a higher low cloud base than the wet seasons except at Luquillo (note that at Luquillo in Fig. 4b, less frequent DS high clouds (see Fig. 1) lowers the mean-hour cloud base). Cloud cover percentage was highest in the MSD relative to the other seasons at all the stations to the east (windward) and including Luquillo, and DS cloud cover was similar to or higher than the wet seasons (Fig. 4d). The low and minimum cloud bases for stations near to Luquillo correlated much better with cloud cover than at the stations as a whole, with very good negative correlation at Luquillo itself (Table 2, S3).

In contrast to Luquillo (Fig. 1b) the regional pattern of RH for 2000-2016 was as expected, with lower RH during the dry seasons than the wet seasons (Fig. 5) and the low and minimum cloud bases all had fair correlation with the RH measurements (Table 3). Regionally, no metrics of daily clouds correlated with MSLP except at Luquillo, where the low and maximum cloud bases had good and very good correlation with MSLP, respectively (Table 3).

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land with high topography increased the likelihood of clouds in a layer from land surface elevation up to 2 km, approximately the altitude of the TWI which under most conditions caps the trade-wind cumuli (Fig. 6)

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land with high topography increased the likelihood of clouds in a layer from land surface elevation up to 2 km, approximately the altitude of the TWI which under most conditions caps the trade-wind cumuli (Fig. 6)

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The Caribbean region is projected to undergo drying in the future, with various mechanisms that will suppress deep convection and frequent high rainfall (Karmalkar et al., 2013). If trade-wind clouds were thinner and shallow convection was weak during those periods, drought effects on the TMCF could be significant.