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A 42 year inference of cloud base height trends in the Luquillo Mountains of northeastern Puerto Rico

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ABSTRACT: The Luquillo Mountains of eastern Puerto Rico are home to the only tropical rainforest managed by the United States Forest Service, with cloud-immersed forests historically occupying the highest elevations. However, within the past 50 yr, studies of the Luquillo cloud forest have suggested an increase in cloud base heights (CBH), although the CBH in the area was not quantified until recently. The present work uses radiosonde observations from nearby San Juan, Puerto Rico, to contextualize the present-day CBH within a 42 yr (1975–2016) proxy record and determine evidence for rising cloud base. Two key questions are addressed: (1) Can theoretical CBH calculations from San Juan provide a reasonable proxy for CBHs in the Luquillo Mountains? (2) Does a significant trend accompany the CBH lifting inferred from recent work in the region? The mean-layer lifted condensation level (MLLCL), a thermodynamic parameter expressing the altitude at which a rising air parcel reaches 100% relative humidity, serves as the proxy. The 42 yr MLLCL time series corroborates both the low CBHs claimed in the 1980s and the higher CBHs documented by recent work. When considering all available radiosonde data, statistically significant increasing CBH trends are detected for all seasons. However, when the record is standardized to correct for progressive vertical resolution improvements to radiosonde observations, recent CBH increases are more modest than initially indicated, and statistically significant increases are only apparent in the late rainfall season.

KEY WORDS: Cloud base height · Luquillo Mountains · Cloud forest · Lifted condensation level · Tropical rainforest · Caribbean

1. INTRODUCTION

The Luquillo Mountains of eastern Puerto Rico (18.3° N, 65.8° W) are an ecologically unique setting in the United States and home to the El Yunque National Forest (also known as the Luquillo Experimental Forest). This Caribbean landscape lies directly in the easterly trade-wind regime, providing a constant source of warm, humid air. The transition from coastline to 1075 m elevation occurs across a horizontal distance of only 10 km, creating a steep topographic gradient for the incoming maritime flow (González et al. 2013). In the process of surmounting the mountain barrier, the easterly trades are forced to ascend Luquillo's slopes, leading to adiabatic cooling and condensation. Direct deposition of moisture from the enveloping clouds, as well as regular orographic rainfall, create an environment that ecologists consider an elfin cloud forest at elevations >750 m, according to Odum (1970a, p. B-5).

Given the low variability of the annual cycle in tropical regions, even minor changes in microclimate are theorized to disturb the delicate biomes existing in the world's cloud forest belts (Foster 2001). Cur-

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rent climate model projections suggest a decreasing precipitation trend for the eastern Caribbean (Karmalkar et al. 2013), including Puerto Rico (Khalyani et al. 2016), which may affect the region's wet tropical rain forests, whose organisms rely on abundant precipitation for survival. Additionally, changes in climatic and disturbance regimes can influence forest nutrient cycling and the structure and productivity of tropical montane cloud forests (Dalling et al. 2016). Even in the absence of the projected precipitation decreases, changes in the cloud base height (CBH), a function of near-surface temperature and humidity, could be problematic for the cloud-immersed forest of the Luquillo Mountains (Foster 2001, Holwerda et al. 2006, Scholl & Murphy 2014, Van Beusekom et al. 2017). Beyond northeastern Puerto Rico, ecological concerns have prompted studies of CBH and orographic rainfall variability in the vicinity of other montane forests, including the Canary Islands (Sperling et al. 2004), Hawaii (Diaz et al. 2011, Zhang et al. 2012), and the eastern United States (Richardson et al. 2003).

Recognizing the strong dependence of these unique ecosystems on requisite cloud cover, Van Beusekom et al. (2017) established the contemporary Luquillo CBH for the purpose of confidently diagnosing any future changes. As such, they identified average CBHs of 702 and 915 m using 2 different CBH definitions (Van Beusekom et al. 2017). Both of these values represent increases from the 'usual' 500–600 m CBH suggested by Scatena & Larsen (1991), the 600 m 'average cloud-condensation level' reported by Odum (1970a, p. B-3), and other historical work reporting qualitatively lower CBHs (Baynton 1968, Weaver 1995). This sequence of findings anecdotally implies that cloud base lifting may already have occurred, as suggested by Van Beusekom et al. (2017).

However, with no long-term record of direct CBH measurements, studies of interannual cloud base variability in the Luquillo Mountains (and elsewhere) are difficult. In their absence, the present study employs a meteorological thermodynamic parameter called the lifted condensation level (LCL; AMS 2018) as a CBH proxy. The LCL has been previously applied to orographic cloud forest research (Still et al. 1999, Nair et al. 2003), including prior work in the Luquillo Mountains (Odum 1970b, p. H-43; Van Beusekom et al. 2017). Changes in the near-surface thermodynamic environment, captured by the LCL, are often theorized as the physical mechanism associated with orographic cloud lifting (e.g. Pounds et al. 1999, Still et al. 1999, Lawton et al. 2001). Though fewer studies have directly calculated the LCL from radiosonde observations, Nair et al. (2003) and Van Beusekom et al. (2017) both computed LCLs from *in situ* measurements that corresponded well to observed CBHs in nearby cloud forests.

The purpose of this research is to situate the present-day CBH of the Luquillo Mountains within a longer record based on thermodynamic calculations of CBH. In doing so, we address 2 key questions: (1) Can theoretical CBH calculations provide a reasonable proxy for CBHs in the Luquillo Mountains? (2) Does a statistically significant trend accompany the potential CBH increase inferred from the studies above? It is beyond the scope of this study to address the climatological controls governing the CBH.

2. DATA AND METHODS

Though meteorologists have developed several variations of the LCL calculation, this study uses the mean-layer LCL (MLLCL). The MLLCL is a thermodynamic parameter that represents the altitude at which a mixture of air from the sub-cloud layer would first begin to condense cloud droplets, assuming a mechanism for lifting the air is present (Craven et al. 2002). In the present study, the MLLCL computation is performed using observations of the atmosphere's lowest 100 hPa (roughly 1 km) as recorded by the 12:00 h UTC (08:00 h local time) radiosonde (i.e. weather balloon) released in San Juan, Puerto Rico. Radiosonde records were retrieved from the publicly accessible Integrated Global Radiosonde Archive (IGRA; Durre et al. 2006), version 2. For each sounding, the mean potential temperature and mixing ratio is determined for the lowest 100 hPa, and the temperature at which this air parcel would achieve 100% relative humidity is calculated. The MLLCL is then designated as the altitude where this temperature would occur if cooled at the dry adiabatic lapse rate (°C km^{-1}), with all computations carried out using the SHARPpy software package (Blumberg et al. 2017). Whereas the present section will describe the conceptual suitability of the MLLCL as a CBH proxy, Section 3.1 will quantitatively assess its representativeness by comparing the San Juan MLLCL to ceilometer observations from the Luquillo Mountains.

This form of the LCL represents a desirable middle ground between the 2 types of condensation level used by Odum et al. (1970, p. B-348) to characterize cloud base altitude in the Luquillo Mountains: the orographic condensation level and the convective condensation level. The former is calculated in a similar manner to the MLLCL; however, by ignoring the role of near-surface mixing, it only incorporates the temperature and mixing ratio observation at ground level. The latter acknowledges turbulent mixing processes during the daytime; however, it assumes that parcel buoyancy arising from diurnal heating is the only mechanism available for parcel ascent, resulting in a higher condensation level prediction than when forcing is present. Odum et al. (1970, p. B-349) calculated the orographic condensation level to be approximately 360 m and the convective condensation level to be 1500 m, suggesting that these values presented a lower and upper bound for CBH in the Luquillo Mountains. The MLLCL bridges this conceptual and computational gap by calculating the LCL for a mixture of near-surface air that would form via orographically forced ascent. According to Odum et al. (1970, p. B-349), when both processes were active around mid-day, the cloud base was approximately 750 m.

The San Juan sounding site (Luis Muñoz Marín International Airport, TJSJ; Fig. 1) is roughly 25 km northwest of the Luquillo Mountains; however, the MLLCL's incorporation of all observations in the lowest 100 hPa means that it is more spatially representative than other LCL calculations. Though the immediate surface measurement might possess an urban microclimate signal (Velazquez-Lozada et al. 2006), the remainder of the boundary layer observations are believed to be representative of the atmosphere surrounding the Luquillo Mountains in northeastern Puerto Rico. Further, the MLLCL, though a theoretical value rather than a direct observation, possesses several strengths that support its application here, as in previous work in the region (Odum 1970b). (1) Radiosondes have been launched from San Juan since 1945. Although data-quality inhomogeneities preclude the use of this entire period, the remaining archive exceeds that of any publicly accessible ceilometers on the island, the earliest of which date to the mid-1990s. (2) Previous research has confirmed that the MLLCL is an accurate reflection of collocated CBH in other geographic settings. A comparison study from the continental USA found that the MLLCL only slightly underestimated ceilometer-measured CBHs at the launch site with a mean absolute error of 46 m (Craven et al. 2002). Additionally, the MLLCL was superior to the manually reported CBHs that prevailed prior to ceilometers (Stull & Eloranta 1985, Craven et al. 2002). (3) Lastly, the steep terrain of the Luquillo Mountains is a permanent lifting mechanism that forces the 100 hPa near-surface layer to ascend and cool. The strong mechanical forcing leads to cloud formation even in the absence of thermodynamic modification from surface heating, lowering cloud bases below the convective condensation level.

Changes in radiosonde reporting practices, data processing, and instrumentation led to a data-quality discontinuity in 1973 (Elliott & Gaffen 1991), and in addition, the TJSJ launch site moved to its current location in 1975. Given these confounding factors, the results presented below represent MLLCL statistics between 1975 and 2016. Though other instrumentation changes have also taken place after 1975 (Elliott et al. 2002), they are reported to be more subtle than the pre-1975 shifts, and less apparent in the tropics and near-surface layers (Elliott & Gaffen 1991), both of which are the focus of the present work. Such instrument transitions at TJSJ are known

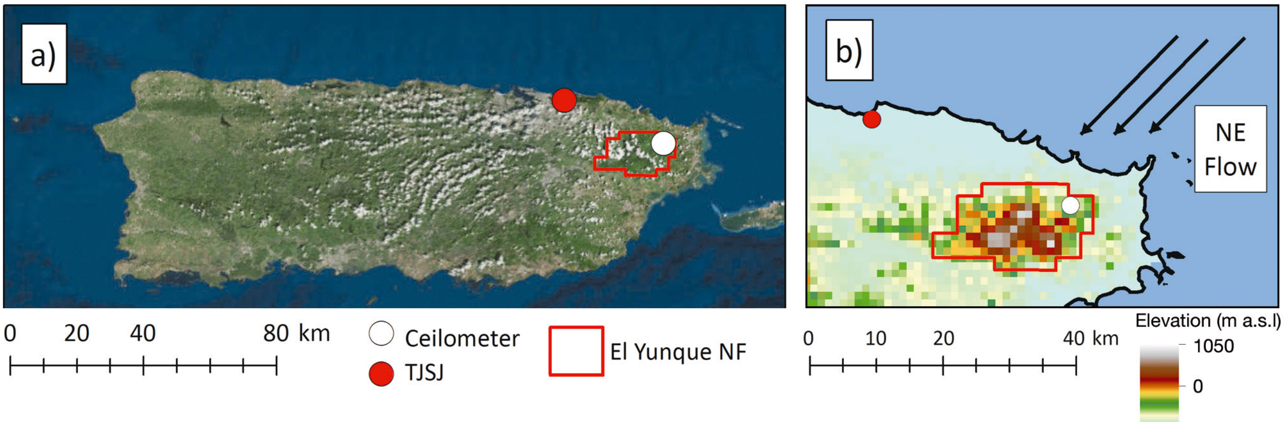

Fig. 1. (a) Data collection sites and (b) topography within the study area shown in 0.01° × 0.01° resolution. El Yunque National Forest (NF) (also known as the Luquillo Experimental Forest) generally outlines the Luquillo Mountains. Due to its orientation relative to the Luquillo Mountains, the ceilometer (elevation: 100 m) detects the strongest orographic forcing when low-level winds arrive from the northeast (NE). TJSJ: Luis Muñoz Marín International Airport. Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User community

to have occurred in 1980, 1988, 1997, and 1998, but this study does not attempt to correct for any possible biases.

In addition to instrument changes, the near-surface vertical resolution of the radiosonde observations nearly doubled during the period of record. Because the MLLCL is typically greater than the surface-based LCL (Craven et al. 2002), higher near-surface vertical resolution more accurately characterizes the near-surface layer and increasingly differentiates it from the lower, surface-based LCL. Consequently, the progressive increase in vertical resolution will drive increases in the MLLCL irrespective of the physical evolution of the local climate. A similar problem was identified by Seidel et al. (2010) during the construction of a global climatology of planetary boundary layer heights. The consequence of this secular influence will be discussed in the next section.

In the following section, results will be presented for 2 MLLCL records: (1) an unstandardized record incorporating all available near-surface observations, and (2) a standardized version that maintains the same vertical resolution apparent in the late 1970s across the entire 42 yr record. The standardization procedure limits the number of mean-layer observations to 3, the typical number of mean-layer observations prior to 1990. Two of the 3 observations are always collected at the surface and 1000 hPa level, whereas the third observation is selected as close as possible to 30 hPa below the top of the mean layer. The 30 hPa criterion is designed to replicate the pre-1990 altitude of the third mean-layer observation. MLLCLs will also be presented on a sub-annual basis, with seasons defined as follows: early rainfall season (April, May, June, and July; AMJJ), late rainfall season (August, September, October, and November; ASON), and the dry season (December, January, February, and March; DJFM).

3. RESULTS AND DISCUSSION

3.1. MLLCL as a representative Luquillo CBH proxy

Though Craven et al. (2002) determined a strong correlation between the MLLCL and measured CBHs, their research was conducted using collocated radiosonde and ceilometer measurements in much different climates and topography than northeastern Puerto Rico. Thus, the first task was to assess the reliability of the sounding-calculated MLLCL as a proxy for CBHs in the Luquillo Mountains. A Vaisala CL31 laser ceilometer in the Luquillo Experimental Forest (Fig. 1) has been recording CBH at 30 s intervals since April 2013 (González 2017). During technical testing, the CL31 detected the distance to hard targets with an accuracy of ±1 % or ±5 m, whichever is greater (Vaisala 2018). After filtering months with >15 % missing data, a 46 mo period of overlap (September 2013 to July 2017) with TJSJ radiosonde observations is available for comparison. The mean CBH altitude, determined as the bottom of a 100 m layer of no vertical visibility (5 % contrast threshold), is averaged for each cloud-detecting observation recorded between 12:00 and 12:59 h UTC each month. A scatterplot of the monthly mean ceilometer CBH and monthly mean 12:00 h UTC MLLCL is shown in Fig. 2a. The regression analysis finds little evidence of a relationship between the San Juan MLLCLs and measured CBHs at Luquillo. The mean absolute error is 240 m, much larger than the 46 m found by Craven et al. (2002) for collocated radiosonde-ceilometer sites.

As mentioned in the previous section, the MLLCL is most accurate when support for ascent is present. Though the Luquillo Mountains are an effective orographic lifting mechanism, this will only be reflected in the ceilometer observations if the instrument is oriented on the windward face of the mountain relative to the low-level flow (Fig. 1b shows that the windward direction at the location of the ceilometer is northeast). Otherwise, the ceilometer will be measuring cloud bases that were forced above the MLLCL in order to surmount the highest terrain from a different direction. Recognizing the errors inherent to this situation, Craven et al. (2002) were careful to remove such instances from their analysis. In our Fig. 2b, the monthly percentage of TJSJ surface wind observations originating from the northeast quadrant (defined as 0–90° from due north) is compared to the MLLCL error (i.e. MLLCL minus ceilometer CBH). The association is clear ($R = 0.55$; $p < 0.01$), and indicates that when windward flow dominates (>60 % of hourly observations during the month), the mean absolute error decreases to 25.0 m. Additionally, the range of mean MLLCLs for 2014–2016 (845–875 m) compares well to a recent time-lapse photography analysis by Bassiouni et al. (2017) that placed the typical CBH for the Luquillo Mountains between 794 and 904 m for the same period.

This result addresses Question (1) (Section 1): the MLLCL, computed from the TJSJ sounding, is an accurate CBH proxy for the Luquillo Mountains under the prevailing northeast trade-wind conditions. Further, the relationships in Fig. 2 also show that the CBH is generally greater than or equal to the

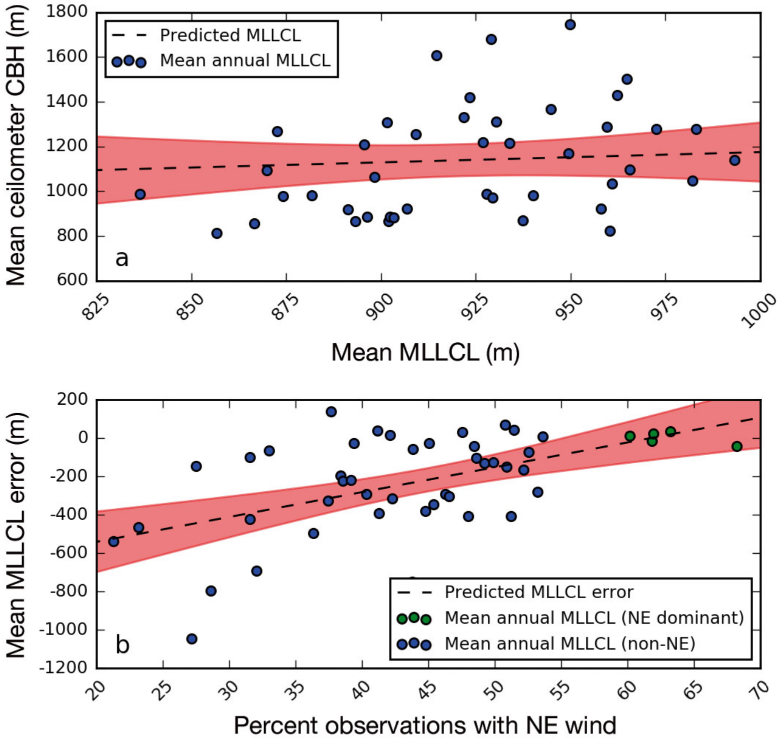

Fig. 2. (a) Monthly mean comparisons of mean-layer lifted condensation level (MLLCL) and the ceilometer-observed cloud base height (CBH). The fitted regression relationship (dashed line, both panels; R = 0.10) shows a positive, yet statistically insignificant (p = 0.48) slope. (b) However, the MLLCL's accuracy is closely tied to wind direction, with smaller errors (MLLCL minus ceilometer) arising when windward flow dominates. The regression relationship (R = 0.55) and its 95% confidence interval (shaded area, both panes) indicate that when northeast (NE) flow prevails, the MLLCL and ceilometer agree closely (green circles). Surface wind observations retrieved from the National Centers for Environmental Information's (NCEI) Integrated Surface Global Hourly Data

altitude of the MLLCL, and that any elevations lying below the MLLCL are typically cloud-free.

3.2. Temporal trends in the MLLCL

Fig. 3a depicts the 42 yr time series of annual MLLCLs, calculated by averaging all available MLLCL observations in a calendar year, and reveals considerable variability about the long-term mean (746 m). An immediately apparent feature of the time series is the roughly 350 m increase in mean MLLCL between the late 1980s and the end of the record. However, before this feature is described further, its authenticity is evaluated by correcting for the progressively increasing vertical radiosonde resolution referenced in Section 2. Fig. 3a also displays the mean number of near-surface observations that contribute to the MLLCL calculation. Increases of roughly 1 observation are evident in 1990 and 2010, which are roughly paralleled by increases in the MLLCL. For clarity, the non-standardized MLLCL is more accurate as a representation of the CBH for the reasons given above (see Section 2); however, it is a less accurate representation of cloud base evolution during the 42 yr study period. Thus, the standardized record is used to infer any changes in CBH evolution, but no references are made to its actual value.

The resulting vertically standardized record is also shown in Fig. 3a. MLLCLs decrease steadily from 1975 to the late 1980s before beginning an oscillating increasing pattern until 2000. The MLLCL remains relatively constant through 2010 before once again increasing from 2010 to 2015. Though it is beyond the scope of this paper to identify the mechanisms controlling interannual MLLCL variability, previous climate research in Puerto Rico has employed the North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO), and Atlantic Multidecadal Oscillation (AMO) to explain regional climate (e.g. Klotzbach 2011, Mote et al. 2017). An exploratory analysis of this dataset found no statistically significant MLLCL differences between Niño 3.4 warm/cool phases (Rayner et al. 2003) nor NAO positive/negative phases (Climate Prediction Center 2018) on an annual scale. On a multidecadal scale, the 42 yr period of record is too short to permit a confident comparison with the AMO. The intra-annual CBH pattern (calculated from the nonstandard MLLCLs; Fig. 3b) roughly mimics a sine curve, with the highest MLLCLs during the dry season (DJFM) and the lowest MLLCLs during the late rainfall season (ASON). The early rainfall season (AMJJ) represents a transition between the two. CBHs are highest in February (761 m) and lowest in August (666 m).

Addressing the second key question (Question (2), see Section 1) of this study, when the entire record is considered, there is no statistically significant trend in the mean annual MLLCL. Though an ordinary least-squares regression analysis does detect an increasing trend in the annual CBH means, the slope of the trend line is statistically indistinguishable from zero at the 0.05 significance level. Table 1 shows the

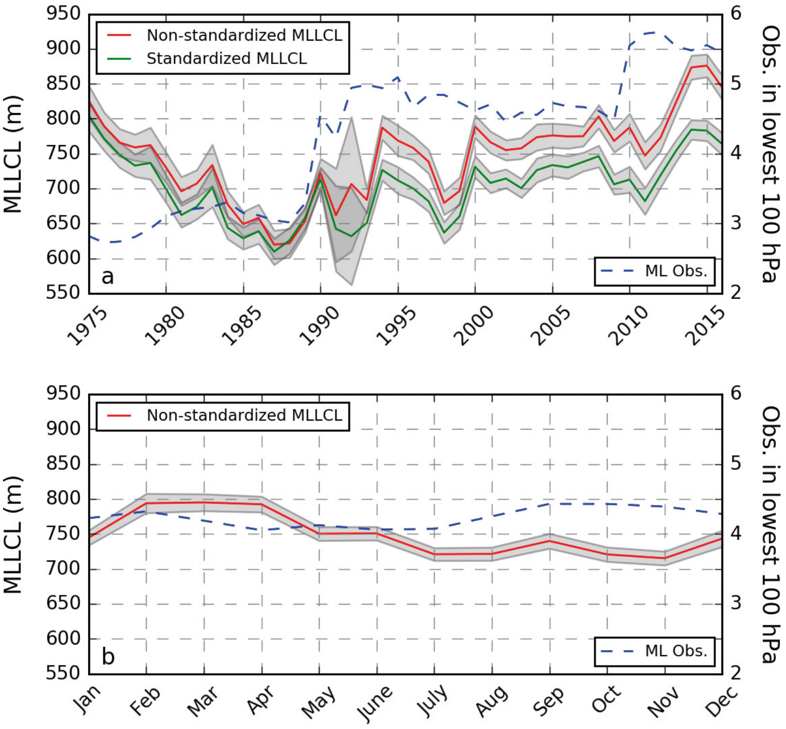

Fig. 3. (a) TJSJ 42 yr time series for the annual mean of mean-layer lifted condensation level (MLLCL) (solid red), mean number of mean-layer observations (ML obs.) recorded in the lowest 100 hPa (dashed blue), and vertically standardized MLLCL (green) records. (b) The intra-annual MLLCL cycle is also shown for the unstandardized MLLCLs (red) with the near-surface vertical resolution (dashed blue) for reference. The wider 95% confidence intervals (shaded gray) for 1991 and 1992 result from Integrated Global Radiosonde Archive (IGRA) data available on only 22 and 15 d, respectively, as opposed to >300 d for all other years

average change in the annual and seasonal MLLCLs according to the regression equations. Similarly, no long-term changes are observed during the dry season or early rainfall season; however, the MLLCL has increased 73 m on average during the late rainfall season (ASON), which is generally characterized by the lowest MLLCLs of the year (Fig. 3b). Though climate simulations predict hydrological changes to Puerto Rico's late rainfall season, its projected rainfall decreases are less severe than for other seasons (Campbell et al. 2011, Karmalkar et al. 2013). Thus, the MLLCL increase observed only during the late rainfall season deserves further study, specifically related to its origin and ecological implications.

Scatena & Larsen's (1991) estimate of a 500–600 m cloud base in Luquillo, though lower than the MLLCL calculations, was formed during the MLLCL minimum in the mid-1980s (our Fig. 3a). Their study, aimed at assessing the ecological impact of Hurricane Hugo in 1989, would have likely compared post-Hugo conditions to the 'usual' state informed by the immediately preceding years, when the present analysis shows that the MLLCL was sub-700 m. Thus, the CBH increase inferred by contrasting Scatena & Larsen (1991) with Van Beusekom et al. (2017) and Bassiouni et al. (2017) is supported by the radiosonde record. However, when the annual mean MLLCLs are extended to the late 1970s, modern MLLCLs are shown to reside within the historical range.

Table 1 also contains the hypothetical regression parameters that would be computed from the non-standardized MLLCL record. Without accounting for the vertical resolution, statistical significance is detected for most CBH trends, with mean increases >100 m detected for all but the dry season (DJFM). This scenario offers a cautionary case for the time series analyses of meteorological derived quantities. Though it is possible to calculate the MLLCL from any sounding, regardless of the vertical resolution, great attention should be given to ensure the resulting values maintain comparable quality.

Table 1. Comparison of regression parameters for the non-standardized versus standardized mean-layer lifted condensation level (MLLCL)–time relationship. Each 'Mean 1975–2016 change' column is the product of the corresponding 'Change' column and the 42 yr time span

Parameter	Non-standardized			Standardized		
	Change (m decade^{-1})	p	Mean 1975–2016 change (m)	Change (m decade^{-1})	p	Mean 1975–2016 change (m)
Annual mean	25.8	<0.01	108.3	11.1	0.07	46.6
AMJJ only	30.6	<0.01	128.5	11.6	0.08	48.7
ASON only	32.1	<0.01	134.8	17.3	0.01	72.7
DJFM only	13.0	0.11	54.6	2.7	0.70	11.3

4. CONCLUSION

This study establishes a 42 yr record of the MLLCL calculated from radiosonde observations to serve as a CBH proxy for northeastern Puerto Rico's Luquillo Mountains. The goal of this research was to investigate the multi-decadal CBH variability in the Luquillo Mountains, including possible ascension speculated from cloud-forest-related studies during the last 50 yr. If authentic, such a lifting trend could prompt significant ecological change within one of the United States' most biodiverse regions.

However, when considering the entire period of record, there has been no significant CBH change. The low CBHs anecdotally reported by Scatena & Larsen (1991) that contribute to the qualitative increase described in our Section 1 reflected a period of lower-than-average MLLCLs. Meanwhile, the higher, modern CBHs documented by Van Beusekom et al. (2017) and Bassiouni et al. (2017) coincided with comparable MLLCLs to those during the mid-1970s. This result is important for foresters, biologists, and ecologists studying this unique environment. Future research might investigate the potential ecological impact of the CBH lifting documented in the late rainfall season. For instance, do higher CBHs during this hydrologically important period lead to a reduction in ASON orographic rainfall? Additionally, the MLLCL represents the thermodynamic control on CBH, but as our analysis revealed, the low-level wind field is critical to realizing the MLLCL. Subsequent work may further investigate the kinematic component of the CBH by considering near-surface flow.

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LITERATURE CITED

AMS (American Meteorological Society) (2018) Glossary of meteorology. AMS, Boston, MA

Bassiouni M, Scholl MA, Torres-Sanchez AJ, Murphy SF (2017) A method for quantifying cloud immersion in a tropical mountain forest using time-lapse photography. Agric For Meteorol 243:100–112

Baynton HW (1968) The ecology of an elfin forest in Puerto Rico: the microclimate of Pico del Oeste. J Arnold Arbor 49:419–430

Blumberg WG, Halbert KT, Supinie TA, Marsh PT, Thompson RL, Hart JA (2017) SHARPpy: an open source sounding analysis toolkit for the atmospheric sciences. Bull Am Meteorol Soc 98:1625–1636

Campbell JD, Taylor MA, Stephenson TS, Watson RA, Whyte FS (2011) Future climate of the Caribbean from a regional climate model. Int J Climatol 31:1866–1878

Climate Prediction Center (2018) North Atlantic Oscillation (NAO). www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml (accessed 9 May 2018)

Craven JP, Jewell RE, Brooks HE (2002) Comparison between observed convective cloud-base heights and lifting condensation level for two different lifted parcels. Weather Forecast 17:885–890

Dalling JW, Heineman K, González G, Ostertag R (2016) Geographic, environmental and biotic sources of variation in the nutrient relations of tropical montane forests. J Trop Ecol 32:368–383

Diaz HF, Giambelluca TW, Eischeid JK (2011) Changes in the vertical profiles of mean temperature and humidity in the Hawaiian Islands. Global Planet Change 77:21–25

Durre I, Vose RS, Wuertz DB (2006) Overview of the Integrated Global Radiosonde Archive. J Clim 19:53–68

Elliott WP, Gaffen DJ (1991) On the utility of radiosonde humidity archives for climate studies. Bull Am Meteorol Soc 72:1507–1520

Elliott WP, Ross RJ, Blackmore WH (2002) Recent changes in NWS upper-air observations with emphasis on changes from VIZ to Vaisala radiosondes. Bull Am Meteorol Soc 83:1003–1017

Foster P (2001) The potential negative impacts of global climate change on tropical montane cloud forests. Earth Sci Rev 55:73–106

González G (2017) Luquillo Mountains meteorological and ceilometer archive. In: Forest Service Research Data Archive (ed), Fort Collins, CO. www.fs.usda.gov/rds/archive/Product/RDS-2017-0023

González G, Willig MR, Waide RB (2013) Ecological gradient analyses in a tropical landscape: multiples perspectives and emerging themes. Ecol Bull 54:245–250

Holwerda F, Burkard R, Eugster W, Scatena FN, Meesters AGCA, Bruijnzeel LA (2006) Estimating fog deposition at a Puerto Rican elfin cloud forest site: comparison of the water budget and eddy covariance methods. Hydrol Processes 20:2669–2692

Karmalkar AV, Taylor MA, Campbell J, Stephenson T and others (2013) A review of observed and projected changes in climate for the islands in the Caribbean. Atmosfera 26:283–309

Khalyani AH, Gould WA, Harmsen E, Terando A, Quinones M, Collazo JA (2016) Climate change implications for tropical islands: interpolating and interpreting statistically downscaled GCM projections for management and planning. J Appl Meteorol Climatol 55:265–282

Klotzbach PJ (2011) The influence of El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean tropical cyclone activity. J Clim 24:721–731

Lawton RO, Nair US, Pielke RA, Welch RM (2001) Climatic impact of tropical lowland deforestation on nearby montane cloud forests. Science 294:584–587

Mote TL, Ramseyer CA, Miller PW (2017) The Saharan air layer as an early rainfall season suppressant in the Eastern Caribbean: the 2015 Puerto Rico drought. J Geophys Res Atmos 122:10966–10982

Nair US, Lawton RO, Welch RM, Pielke RA (2003) Impact of land use on Costa Rican tropical montane cloud forests: sensitivity of cumulus cloud field characteristics to lowland deforestation. J Geophys Res Atmos 108:4206

Odum H (1970a) The El Verde study area and the rain forest systems of Puerto Rico. In: Odum H, Pigeon R (eds) A tropical rain forest: a study of irradiation and ecology at El Verde, Puerto Rico. US Atomic Energy Commission, Oak Ridge, TN, p B-3–B-32

Odum H (1970b) Rain forest structure and mineral-cycling homeostasis. In: Odum H, Pigeon R (eds) A tropical rain forest: a study of irradiation and ecology at El Verde, Puerto Rico. US Atomic Energy Commission, Oak Ridge, TN, p H-3–H-52

Odum H, Drewry G, Kline JR (1970) Climate at El Verde, 1963-1966. In: Odum H, Pigeon R (eds) A tropical rain forest: a study of irradiation and ecology at El Verde, Puerto Rico. US Atomic Energy Commission, Oak Ridge, TN, p B-347–B-418

Pounds JA, Fogden MPL, Campbell JH (1999) Biological response to climate change on a tropical mountain. Nature 398:611–615

Rayner NA, Parker DE, Horton EB, Folland CK and others (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res Atmos 108:4407

Richardson AD, Denny EG, Siccama TG, Lee X (2003) Evidence for a rising cloud ceiling in eastern North America. J Clim 16:2093–2098

Scatena FN, Larsen MC (1991) Physical aspects of Hurricane Hugo in Puerto Rico. Biotropica 23:317–323

Scholl MA, Murphy SF (2014) Precipitation isotopes link regional climate patterns to water supply in a tropical mountain forest, eastern Puerto Rico. Water Resour Res 50:4305–4322

Seidel DJ, Ao CO, Li K (2010) Estimating climatological planetary boundary layer heights from radiosonde observations: comparison of methods and uncertainty analysis. J Geophys Res Atmos 115:D16113

Sperling FN, Washington R, Whittaker RJ (2004) Future climate change of the subtropical North Atlantic: implications for the cloud forests of Tenerife. Clim Change 65: 103–123

Still CJ, Foster PN, Schneider SH (1999) Simulating the effects of climate change on tropical montane cloud forests. Nature 398:608–610

Stull R, Eloranta E (1985) A case study of the accuracy of routine, fair-weather cloud-base reports. Natl Weather Dig 10:19–24

Vaisala (2018) CL31 technical data. www.vaisala.com/sites/default/files/documents/CL31-Datasheet-B210415EN_0.pdf

Van Beusekom AE, González G, Scholl MA (2017) Analyzing cloud base at local and regional scales to understand tropical montane cloud forest vulnerability to climate change. Atmos Chem Phys 17:7245–7259

Velazquez-Lozada A, Gonzalez JE, Winter A (2006) Urban heat island effect analysis for San Juan, Puerto Rico. Atmos Environ 40:1731–1741

Weaver PL (1995) The colorado and dwarf forests of Puerto Rico's Luquillo Mountains. In: Lugo AE, Lowe C (eds) Tropical forests: management and ecology. Springer, New York, NY, p 109–141

Zhang C, Wang Y, Lauer A, Hamilton K, Xie F (2012) Cloud base and top heights in the Hawaiian region determined with satellite and ground-based measurements. Geophys Res Lett 39:L15706

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