LETTER

Multiscale trends and precipitation extremes in the Central American Midsummer Drought

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Abstract

Anecdotal evidence suggests that the timing and intensity of the Central American Midsummer Drought (MSD) may be changing, while observations from limited meteorological station data and paleoclimate reconstructions show neither significant nor consistent trends in seasonal rainfall. Climate model simulations project robust future drying across the region, but internal variability is expected to dominate until the end of the century. Here we use a high-resolution gridded precipitation dataset to investigate these apparent discrepancies and to quantify the spatiotemporal complexities of the MSD. We detect spatially variable trends in MSD timing, the amount of rainy season precipitation, the number of consecutive and total dry days, and extreme wet events at the local scale. At the regional scale, we find a positive trend in the duration, but not the magnitude of the MSD, which is dominated by spatially heterogeneous trends and interannual variability linked to large-scale modes of ocean-atmosphere circulation. Although the current climate still reflects predominantly internal variability, some Central American communities are already experiencing significant changes in local characteristics of the MSD. A detailed spatiotemporal understanding of MSD trends and variability can contribute to evidence-based adaptation planning and help reduce the vulnerability of Central American communities to both natural rainfall variability and anthropogenic change.

1. Introduction

Highly variable precipitation is among the many challenges faced by the millions of families who rely directly on smallholder farming in Central America (PRESANCA-FAO 2011, Van der Zee Arias et al 2012) and is linked to both food insecurity and migration (Lobell et al 2008, Nawrotzki et al 2016). Recently, smallholder farmers have reported changes in the distribution and intensity of rainfall across Central America, resulting in crop losses and reductions in yields for those already contending with pervasive social and economic inequalities (Eakin et al 2014, Pons et al 2016, Hellin et al 2017, de Sousa et al 2018, Harvey et al 2018, Rice 2018, Bellante 2019). Farmers in the western highlands of Guatemala and the Chiapas lowlands of Mexico have specifically reported that the Central American Midsummer Drought (MSD) (Magaña et al 1999) is becoming more prolonged, increasingly variable, and harder to predict (Hellin et al 2017, Bellante 2019). The MSD, locally known as the canícula or veranillo, affects much of Central America during the May to October rainy season and is defined by a reduction in rainfall, typically occurring between early July and late August (Magaña et al 1999) (figure 1). During the MSD period, precipitation may decline by up to 40% from the maximum summer rainfall (Magaña et al 1999) and its variable characteristics, including the timing, duration, and magnitude have significant influences on planting dates and crop yields (Hastenrath 1966, Magaña et al 1999, Van der Zee Arias et al 2012, Pons...
Rainfall during the MSD is particularly tenuous throughout the Dry Corridor region, which is marked by lower rainfall and relatively frequent dry spells in comparison to the rest of Central America (Van der Zee Arias et al 2012, FAO 2016, Gotlieb et al 2019) (figure 1(a)). Identifying changes in characteristics of the MSD and in the timing and quantity of rainfall throughout the region is crucial, because it is bound to the livelihoods and food security of many rural communities and is expected to significantly shift by the end of the 21st century in response to anthropogenic modification of the climate system (Rauscher et al 2008, Maurer et al 2017).

Despite local reports of changes in rainfall, regional analyzes of instrumental meteorological station data and paleoclimatic reconstructions for Central America and the Caribbean do not reveal significant, broad-scale trends in annual or seasonal precipitation totals (Aguilar et al 2005, Anchukaitis et al 2015, Jones et al 2016, Pons et al 2016, Hidalgo et al 2017). One possible origin of this discrepancy is that most anecdotal reports refer to lengthening dry periods and rainfall extremes (Hellin et al 2017, Rice 2018, de Sousa et al 2018), rather than annual or seasonal precipitation totals (Aguilar et al 2005, Neelin et al 2006, Hidalgo et al 2017). In addition to this difference in temporal scale, another complication is that the lack of meteorological station data and the spatial heterogeneity in rainfall due to complex topography impedes robust characterization of precipitation variability and trends over much of Central America and the Caribbean (Giannini et al 2000, Jones et al 2016). Here, we use daily and pentadal 0.05° rainfall data from the CHIRPS gridded precipitation products (Climate Hazards Infrared Precipitation with Stations, Funk et al 2015) to overcome these challenges and to analyze the spatiotemporal trends and variability in precipitation across Central America. Our study considers the Central American domain provided by CHIRPS, which provides previously unavailable spatiotemporal coverage and resolution to characterize the multiscale variability of the MSD.

2. Methods

We use the daily and pentadal 0.05° CHIRPS (Funk et al 2015) gridded precipitation datasets from 1981 to 2018 to characterize and quantify spatial and temporal variability in the MSD. CHIRPS blends satellite and meteorological station information when available to account for regions where data are scarce, resulting in more favorable validation results than other gridded products in a number of countries (Funk et al 2015). In Mexico, the monthly CHIRPS product was previously found to be suitable for analyzing the MSD, reproducing important local seasonal features in precipitation, although overestimating total annual precipitation by up to 30% in mountain regions (Perdigón-Morales 2016).
The daily CHIRPS data has also been used to evaluate shifts in certain extreme event indices in Guatemala, but specifically focused on two relatively small ecoregions (de Sousa et al. 2018). Although CHIRPS provides robust rainfall estimates in sparsely-gauged areas, difficulty in capturing exact precipitation amounts from satellite observations and the inverse-distance weighting algorithm used to blend the satellite and station data are sources of uncertainty in the dataset (Funk et al. 2015) and our analyses.

Here, we subset the CHIRPS data from 11 to 18°N and −93 to −83°W, which encompasses the primary Dry Corridor countries that experience an MSD as part of their normal rainfall distribution and face increased risk related to future drying (Hidalgo et al. 2017, Maurer et al. 2017). We smoothed the pentadal CHIRPS data using a running triangular mean with a 6-pentad window (30 d) (Alfaro 2014, Maldonado et al. 2016). To prevent the false detection of the MSD due to single rainfall events, a double-pass of the smoothing filter was necessary. Our yearly MSD classification procedure searches for the minimum rainfall between June 1 and August 31 and bounds it by the highest peaks in rainfall—the start and end dates—between the May 1 and October 31 rainy season. Using a defined minimum rainfall period from June 1 to August 31 prevents false discovery of the MSD during onset and end of the rainy season (Maldonado et al. 2016) and does not affect local or regional trend analysis in the core MSD region (Maurer et al. 2017). We did not assume the presence of an MSD in each year and we only include gridpoints with an MSD lasting at least three pentads (15 d). We calculated MSD characteristics for those gridpoints with at least 33 years of defined summer drought. By limiting the number of allowable missing MSD years to a maximum of five, our spatial domain is similar to that used by Maurer et al. (2017).

We calculate indices that capture unique features of the MSD, drawing on previously established metrics for the gridpoints and years in which we identify its presence to evaluate trends and large-scale climate relationships (figure 1(b)) (Karnauskas et al. 2013, Alfaro 2014, Maldonado et al. 2016). We define MSD duration as the difference between the start and end day peaks (in units of days) (Alfaro 2014). To quantify the depth of the MSD (strength), we calculate the difference between the June 1 and August 31 minimum and the mean of the two peaks (Karnauskas et al. 2013). We also assess the magnitude of the MSD by summing the total amount of precipitation between the two rainy season peaks and dividing it by the duration (in units of mm/day) (Maldonado et al. 2016). The magnitude index therefore combines and integrates components of both the strength and duration and effectively provides a measure of the mean daily rainfall during the MSD period.

We used the daily CHIRPS data to calculate total precipitation from May 1 to October 31, the total amount of precipitation falling in events ≥95th percentile (R95p), consecutive dry days with precipitation less than 1 mm (CDD), and total number of dry days (TDD) for individual gridpoints. R95p and CDD are part of a standardized set of extreme event metrics and are designed to be flexible across global regions (Zhang et al. 2007). As above, we limited the calculation of these indices to gridpoints with no more than five years of an absent MSD. The temporal range used to evaluate the R95p, CDD, and TDD indices shifts each year for every gridpoint in order to match the start and end dates of the MSD at that location. This is to ensure we are evaluating changes within the MSD period, rather than detecting for changes in other seasons or across the whole year.

We use empirical orthogonal function (EOF) analysis to isolate and evaluate region-wide spatiotemporal patterns from the individual gridpoints. Consistent with the calculations described above, gridpoints that recorded an MSD for at least 33 of the 38 year study period were used in the EOF analysis. Limiting the number of missing values provides a better estimate of the spatiotemporal covariance. To check the robustness of our regional calculations using the CHIRPS data, we also repeated this analysis using the shorter and lower spatial resolution (0.25°) PERSIANN-CDR dataset (1983–present; Ashouri et al. 2015), another product developed for tracking trends in precipitation and extremes with high temporal resolution. Daily PERSIANN measurements were summed in order to be comparable to the pentadal rainfall defined in Funk et al. (2015).

We composite gridded sea surface temperature (SST) and atmospheric Reanalysis data for years in which the leading EOFs of the CHIRPS duration, strength, and magnitude MSD time series, each with one annual value, are above and below their 75th and the 25th percentiles. For SST comparisons, we used the National Oceanic Atmospheric Administration (NOAA) 0.25° Optimum Interpolation Sea Surface Temperature (OISST) dataset, which combines observations from satellites, buoys, and ships from 1981 to present and has a high spatial resolution covering the time span of our analysis (Reynolds et al. 2007, Banzon et al. 2016). We also verified these analyses using the SST data from ERA-Interim Reanalysis (Dee et al. 2011), which gives nearly identical results. We used wind and atmospheric pressure data extracted from the ERA Interim Reanalysis (Dee et al. 2011) from 1981 to present in order to evaluate the influence of the Caribbean Low Level Jet (CLLJ) and the North Atlantic Subtropical High (NASH) on MSD variability. To specifically assess changes related to the spatial extent and position of the NASH, we follow Li et al. (2011) and use the location of the 850 mb geopotential height in order to avoid the effects of topography and because the NASH is known to have barotropic structure below 600 mb.
Trends in local (individual gridpoints) and region-wide (EOFs) MSD metrics were evaluated using the non-parametric Mann–Kendall test with the Theil–Sen estimate of the slope to account for non-normal distributions and outliers (Yue et al 2002, Burkey 2006). Our inferences are robust to the method of trend calculation, as the results from ordinary least squares (OLS) accounting for autocorrelation (Trenberth 1984) give very similar results. We estimate field significance using a Monte Carlo method by randomizing \( n = 1000 \) the order of the annual index fields, disrupting their temporal order but retaining their spatial autocorrelation structure, re-calculating trends on the randomized data, counting the number of significant gridpoints, and then comparing this distribution with the observed number of significant gridpoints (Livezey and Chen 1983). We interpret the exact spatial extent of significant correlations shown here cautiously, as the precise boundaries may be influenced by the spatial autocorrelation of the gridded data (Livezey and Chen 1983, Wilks 2011).

3. Results and discussion

In agreement with previous studies, our classification identifies a consistent MSD along the Pacific coastal region but not the Caribbean, where locations experience a single maximum in precipitation or an autumn reduction in rainfall driven by different mechanisms (Magaña et al 1999, Amador et al 2006, Curtis and Gamble 2007, Karnauskas et al 2013, Maurer et al 2017). The long-term averages for duration and magnitude highlight the high spatial variability of the MSD (figures 1(c)–(d)). The average duration of the MSD increases from approximately 50 d in southern Mexico and Guatemala to nearly 125 d towards the southern extent of our study area along the Pacific coast of Nicaragua. The smaller average magnitude values (lower average daily precipitation) occur in the Dry Corridor and can be as small as 3 mm/day, in contrast to an average of up to 25 mm/day along coastal southern Mexico and Guatemala. These wide-ranging differences in the MSD duration and magnitude place constraints on viable agricultural strategies and the availability of water during the rainy season, emphasizing the importance of the local scale and spatial perspective.

We find that MSD onset dates are relatively stable through time across most of the region, in contrast to the end date and duration (figure 2(a)). However, the majority of locations that exhibit a shift in the start date of the MSD show an earlier onset over the last four decades, whether or not this change is statistically significant. Statistically significant changes in the start date are found primarily in Guatemala, where the slope of the trend indicates the drought begins between 1 and 1.5 day/decade earlier \( (p < 0.05) \), or approximately 4–6 d over the 38 year study period. The sign of this trend is consistent with modeling work that projects that the MSD will start earlier in the summer season by the end of the 21st century (Rauscher et al 2008, Maurer et al 2017), but does not pass a test for field significance \( (p = 0.36) \). Increasing trends in the MSD end date (indicating a later end date and a delayed return of wetter conditions) are observed across a greater portion of the region and are statistically significant throughout the Dry Corridor regions of Nicaragua and Honduras, as well as along sections of the Pacific coast in Guatemala (figure 2(b)), and pass a field significance test \( (p = 0.04) \). Combined changes in the onset and end dates of the MSD result in an increase in the duration of the drought (figure 2(c)). Duration increases by up to \( \sim 20 \) days/decade and is locally significant \( (p < 0.05) \) along substantial regions of the Pacific slope of Guatemala and Nicaragua. The duration field is marginally field significant \( (p = 0.05) \).

By the end of the 21st century, model simulations project decreases in the minimum MSD rainfall and a lengthening of the drought by a week on average when considering the entirety of Central America, with some locations experiencing more than a 15 d increase (Maurer et al 2017). Our analysis suggests that local changes could significantly surpass the regional average increase and that the shift in the end date is thus far larger than the onset. The later season end date would itself have considerable impacts on the planting and success of the destacada crops (including maize, beans, and sorghum), which depend on precipitation that falls in the second half of the rainy season (Van der Zee Arias et al 2012). An abundant destacada harvest is particularly important for agriculturalists because it is generally more reliable and less risky than the first crop (primera) cycle of the rainy season (Van der Zee Arias et al 2012). Although the majority of the local (individual gridpoint) trends in MSD duration are not statistically significant at an arbitrary \( (p < 0.05) \) threshold, it is unclear if this formal significance level reflects the ways in which smallholder agriculturalists may perceive or recall changes in their local environment (Metz 2006, Hellin et al 2017). The sign of the observed change and areas of significantly longer MSDs in Guatemala and Mexico in particular may provide support for local anecdotal reports of shifting precipitation patterns and a prolonged MSD (Hellin et al 2017, Beltante 2019, de Sousa et al 2018), but more research is necessary to understand how formal measurements and local perceptions of the MSD may be aligned.

In addition to the timing and duration of the MSD, the distribution and quantity of rainfall affect planting strategies and crop yields. The largest increases in total precipitation are along the Pacific coast in southern Mexico and Guatemala and are contrasted by significant drying in south central Mexico and central Honduras (figure 3(a)). Differences between our estimates of these seasonal precipitation trends and previous analyses (Aguilar et al 2005, Neelin et al 2006,
Hidalgo et al. (2017) are likely due to some combination of the underlying data composition, the spatial scale, and the temporal extent (1981 to present) of the CHIRPS data. Southern Mexico and Guatemala experience the most significant increase in R95p in our analysis (figure 3(b)). Trends in R95p are mostly locally insignificant ($p > 0.05$), and overall would only pass a weaker threshold of field significance ($p = 0.08$), but patterns of extreme rainfall events generally mimic the trends in total May–October precipitation—that is, where May–October total rainfall increases, R95p also tends to increase. Trends in CDD and TDD are also generally non-significant ($p > 0.05$, figures 3(c)–(d)) and do not pass a test of field significance ($p = 0.15$ and $p = 0.23$, respectively). While CDD appears to show no sign change for the majority of our study area, the sign of TDD increases across most of the region. Despite increasing total rainy season precipitation in some of these locations, R95p and TDD reveal that some of these places are may be experiencing short, high-intensity events interspersed with an overall increase in the number of dry days. This could be particularly detrimental to agriculturalists, because crops such as maize and beans, food staples throughout the Dry Corridor, are highly sensitive to extreme events and are not resilient to climate shocks (Tucker et al. 2010, Conde et al. 2008).

Although some individual gridpoint locations in Central America do experience statistically significant changes in MSD characteristics and rainfall extremes, it is still interannual variability that dominates over secular trends across much of the region. Nevertheless,
the sign of increasing MSD duration across most of the domain (figures 2, 4(a)) results in a leading mode (EOF) of variability that accounts for 30% of total variance and has a significant positive trend \((slope = 1.31)\) at the \(p \leq 0.1\) level, evidence of a weak regional-scale trend toward longer MSD events (figures 4(b), (c)). The leading EOF time series for MSD strength is significantly correlated with duration \((r = 0.65, p \leq 0.01)\), indicating that longer MSDs are associated with lower rainfall minima (more intense drought) and that shorter MSDs correspond to higher rainfall minima (less intense drought). Approximately 41% of the variance in the MSD magnitude index is explained by the leading EOF mode with positive loadings across the region, demonstrating significant regional coherence (figures 4(d)–(f)). However, we do not observe any significant trends in the leading EOF of the magnitude index \((slope = −0.91, p = 0.38)\), which is consistent with a lack of broad-scale significant seasonal and annual precipitation signals (Aguilar et al 2005, Jones et al 2016, Hidalgo et al 2017). The lack of a trend in the regional magnitude
signal and the dominance of interannual variability in this metric reflects its spatial complexities (figure 4(d)). Repeating the regional EOF analysis with the PERSIANN-CDR data gives similar results as CHIRPS for duration, but the positive trend in MSD duration is statistically significant at $p = 0.02$. The direction of change in the regional magnitude index remains insignificant using the PERSIANN-CDR data ($p = 0.86$). The PERSIANN-CDR data analyses indicate that our assessment of regional MSD duration and magnitude is consistent across these two different data products, but the exact significance level of these trends can be sensitive to the dataset. We emphasize the importance of our multiple scales and sources of analysis here, as the sign, intensity, and statistical significance of local trends that are important for specific communities of agriculturalists can be subsumed in the calculation and evaluation of large-scale regional averages (Libertino et al. 2019).

Regional averages remain useful in assessing the large-scale drivers of MSD variability. We find that our analysis of the CHIRPS data confirms previously described patterns (Magaña et al. 1999, Mestas-Nuñez et al. 2007, Small et al. 2007, Muñoz et al. 2008, Herrera et al. 2014, Maldonado et al. 2016) and that the MSD is clearly linked to large-scale ocean-atmosphere variability over the last four decades. The smallest magnitude (driest) years correspond to warmer eastern tropical Pacific SSTs, a stronger Caribbean Low Level Jet (CLLJ), and a westward expansion of the North Atlantic Subtropical High (NASH) (figure 5). These relationships are important for sub-seasonal forecasting of the MSD and trends in these modes of ocean-atmosphere variability are likely to play an important role in the evolution of the MSD magnitude and timing in the future. Warm ENSO (El Niño) events have previously resulted in decreased coffee production in Mexico (Conde et al. 2008) and weather disasters associated with these events between 1972 and 2010 caused around $2.9$ billion in damages and $1.1$ billion in agriculture and forestry sector losses in Latin America (Bello et al. 2014). While 21st century changes in ENSO variability remain uncertain (Kim et al. 2014, Chen et al. 2017), El Niño events will likely continue to result in decreased precipitation and the concomitant agricultural consequences across parts of Central America. Future projections also support a more intense sea level pressure gradient between the NASH and the Eastern Equatorial Pacific and a stronger CLLJ (Rauscher et al. 2008). Assuming the stability of these relationships, the combination of these projections suggests enhanced surface divergence in the MSD region, indicating a strengthening of the drought in the future (Rauscher et al. 2008, Maurer et al. 2017).

Although we observe trends in several MSD and daily rainfall indices, it would be difficult to unambiguously attribute these tendencies to either natural variability or anthropogenic climate change. Substantial natural decadal variability in Central American rainfall (Hastenrath and Polzin 2012, Anchukaitis et al. 2015, Jones et al. 2016) makes it a challenge to distinguish the cause of trends over the limited 38 year period of CHIRPS alone. Rising temperatures are known to increase the severity and extent of drought in some regions (Griffin and Anchukaitis 2014, Herrera et al. 2018), which could further exacerbate soil moisture deficits during normal MSD conditions and enhance the negative effects of a longer and more irregular MSD, particularly in the Dry Corridor. Whether any of the trends we have identified and quantified here are associated with the emergent consequences of anthropogenic climate change or are linked to internal multidecadal variability in the ocean-atmosphere system is beyond the time span of these data and the scope of this study and requires additional regional modeling experiments. Nevertheless, the direction of the change we detect in the timing of the MSD and extreme rainfall events for the majority of the domain is consistent with expectations from climate model projections and in some locations complements informal reports from smallholder agriculturalists that altered and more variable MSD patterns have contributed to crop losses and food insecurity (Rauscher et al. 2008, Hellín et al. 2017, Maurer et al. 2017, Rice 2018, Bellante 2019). These findings emphasize the importance of reducing the vulnerability of agriculturalists in Central America to both current climate variability and future anthropogenic change.

4. Conclusions

Our multiscale results are a step toward resolving some of the apparent discrepancies between local reports of changing precipitation patterns and regional instrumental trends in seasonal precipitation. We find that the MSD has increased in duration over the past four decades across most of the domain with some of these changes reaching statistical significance locally. Because the regional average subsumes the magnitude and spatial pattern of local changes, assessments of the potential agricultural consequences of these changes need to be evaluated at the community level—for instance, the largest statistically significant changes in MSD duration occur in the wet regions of coastal Guatemala and Mexico as well as the Dry Corridor of Nicaragua (figures 1(a), 2(c)). In addition to these local climate complexities, the impacts of climate change are variable and influenced by the specific environmental conditions and the resilience, adaptive capacity, and strategies of individuals and communities (Mimura et al. 2014). Changes in MSD magnitude are variable in sign, there is no significant regional trend, and interannual variability over the last four decades in this metric continues to be the dominant signal. Although increasing trends in the TDD and R95p metrics across much of the region could support
anecdotal perceptions of a more intense, variable, and longer MSD, these trends do not yet meet formal thresholds of statistical significance in most locations and neither pass field significance tests at $p < 0.05$. While agriculturalists in Central America have dealt with high variability in the timing and quantity of rainfall for centuries (Metz 2006), and will continue to do so, increasing drying over the region due to human modification to the climate system will exacerbate the vulnerability of many rural communities in Central America in the future (Rauscher et al 2008, Maurer et al 2017, Herrera et al 2018). Integrating local knowledge and informal observation of climate variability with high-resolution datasets is therefore critical in addressing some of the uncertainties in data, trends, and future impacts, and in developing relevant, equitable, and evidence-based climate adaptation plans.

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Data availability statement

The data that support the findings of this study are openly available: CHIRPS (doi:10.15780/G2RP4Q), PERSIANN-CDR (doi:10.1038/sdata.2018.296), ERA Interim (https://apps.ecmwf.int/datasets/data/interim-full-mnth), and OISST (https://ncdc.noaa.gov/oisst).

References

Aguilar E et al 2005 Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003 J. Geophys. Res.: Atmos. 110 D23107
Alfaro E 2014 Caracterización del ‘veranillo’ en dos cuencas de la vertiente del Pacífico de Costa Rica, América Central Rev. Biol. Tropical 16 1–15
Amador J A, Alfaro E J, Lizano O G and Magaña V O 2006 Atmospheric forcing of the eastern tropical Pacific: a review Prog. Oceanogr. 69 101–42
Anchukaitis K J, Taylor M J, Leland C, Pons D, Martin-Fernandez J and Castellanos E 2015 Tree-ring reconstructed dry season rainfall in Guatemala Clim. Dyn. 45 1537–46
Ashouri H, Hsu K L, Sorooshian S, Braithwaite D K, Knapp K R, Cecil I D, Nelson B R and Prat O P 2015 PERSIANN-CDR: daily precipitation climate data record from multisatellite observations for hydrological and climate studies Bull. Am. Meteorol. Soc. 96 69–83
Banzon V, Smith T M, Chiu T M, Liu C and Hankins W 2016 A long-term record of blended satellite and in situ sea-surface

Figure 5. (a) Composite NOAA OISST (Reynolds et al 2007) JJA SST differences between the smallest (driest) and the largest (wettest) MSD years. Positive SST anomalies represent higher (lower) SSTs during MSD years with less (more) rainfall. (b) the ERA Interim (Dee et al 2011) JJA 1560 gpm contour line at the 850 mb geopotential height and 925 mb wind vector differences between the smallest (less rain) and the largest (more rain) EOF1 scores for the magnitude index. The red (blue) contour represents the locations of 850 mb pressure during years with less (more) rainfall. Easterly wind anomalies concentrated over the Central American isthmus represent a stronger (weaker) CLLJ in years with less (more) rainfall. Using SST data from ERA Interim instead of NOAA OISST gives nearly identical results.
Small R J O, de Szoeke S P and Xie S P 2007 The Central American midsummer drought: regional aspects and large-scale forcing J. Clim. 20 4853–73
Trenberth K E 1984 Some effects of finite sample size and persistence on meteorological statistics: I: autocorrelations Mon. Weather Rev. 112 2359–68
Tucker C M, Eakin H and Castellanos E J 2010 Perceptions of risk and adaptation: coffee producers, market shocks, and extreme weather in Central America and Mexico Glob. Environ. Change 20 23–32
Van der Zee Arias A, Meyrat A, Picado L, Poveda C and Van der Zee J 2012 Estudio de caracterización del corredor seco centroamericano Technical Report 630.2515/V217e Food and Agriculture Organisation of the United Nations (FAO)
Wilks D S 2011 Statistical Methods in the Atmospheric Sciences (New York: Academic)
Yue S, Pilon P and Cavadias G 2002 Power of the Mann–Kendall and Spearman’s rho tests for detecting monotonic trends in hydrological series J. Hydrol. 259 254–71
Zhang X, Zwiers F W, Hegerl G C, Lambert F H, Gillett N P, Solomon S, Stott P A and Nozawa T 2007 Detection of human influence on twentieth-century precipitation trends Nature 448 661–5