Meteorological droughts are projected to worsen in Central America’s dry corridor throughout the 21st century

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Abstract
Understanding past and projected drought patterns across Central America’s ‘Dry Corridor’ (CADC) is crucial for adaptation planning and impact mitigation, especially in small-scale agricultural communities. We analyzed historical and predicted drought patterns in the CADC by calculating Standardized Precipitation Index (SPI) values from local rain gauge records, reanalysis data and a 20-member ensemble of bias-corrected, downscaled CMIP-5 GCMs at both seasonal (3 month) and annual (12 month) scales. Trends in drought frequency, duration, intensity were assessed for three, 30 year future periods compared to historical values. Our results suggest a decrease in mean annual rainfall of 8%–14% in the CADC under moderate to high emissions scenarios, respectively, by end-of-century (2071–2100) relative to a historical baseline (1950–2005). However, projected changes to drought characteristics under these scenarios are more pronounced, with seasonal-scale droughts projected to lengthen by 12%–30%, intensify by 17%–42% and increase in frequency by 21%–24% by end-of-century. Annual-scale, longer-term droughts are projected to lengthen by 68% under moderate emissions, potentially triple in length under high emissions and to intensify by 27%–74%. These results were similar yet slightly more pronounced for some drought metrics when just considering rainy/cropping season months (May–Oct).

End-of-century changes to rainfall reliability and drought occurrence such as these would severely impact millions of vulnerable inhabitants in the CADC and should be considered in adaptation policymaking efforts.

1. Introduction

Central America’s dry corridor (CADC) routinely experiences periods of drought that impact the livelihoods of millions of people, especially those living in rainfed agricultural communities. This has been true in recent years throughout the CADC, which spans Guatemala, El Salvador, Honduras and Nicaragua (figure 1) (Van der Zee Arias et al 2012).

The CADC is home to 10.5 million people, nearly two-thirds of whom live in poverty, primarily in small farming communities (Van der Zee Arias et al 2012, Hidalgo et al 2019). In early 2019, the region was entering its fifth consecutive drought year, with 2.2 million people having suffered severe crop losses and 1.4 million people in urgent need of food aid (Vaqué 2017, FAO 2018, WFP 2019, 2020). Rural, small-holder farming communities dependent on timely and sufficient rainfall from May to October for the production of both staple grains and cash crops, like coffee, were most impacted by the ongoing drought (Anderson et al 2019, Rauscher et al 2008, Van der Zee Arias et al 2012, Hannah et al 2017, Marroquín and Gómez 2019).

Droughts have impacted these communities’ crop yields, income and food security and have been linked to internal displacement and migration in the region (Lobell et al 2008, Nawrotzki et al 2016, Rivera et al 2019, IDB 2017, The World Food Program USA (WFP) 2020). The World Food Program estimated that emigration from the CADC increased nearly five-fold between 2010 and 2015, with nearly a third of
emigrants citing extreme weather as their primary reason for leaving (The World Food Program USA (WFP) 2020). In economic terms, Central America has suffered roughly $5 billion USD in losses due to drought impacts on agriculture in the past 30 years (GWP 2016).

The CADC receives approximately 1500 mm of rainfall each year, with some regions receiving just 800 mm year$^{-1}$. The annual pattern of precipitation is characterized by a dry season from November to April, followed by a rainy season from May to October with an intermediate period of decreased rainfall from July to August known as the mid-summer drought (MSD), or colloquially as the canícula or veranillo period (supplemental figure 1 (available online at stacks.iop.org/ERL/16/014001/mmedia)) (Anderson et al 2019, Inoue et al 2002, Wang and Lee 2007, Rauscher et al 2008, Hannah et al 2017, Marroquín and Gómez 2019). It should be noted that the colloquial definition of this mid-summer decline in rainfall as a ‘drought’ is not equivalent to the meteorological definition of drought employed in this study, which only defines a period as being a drought if it anomalously dry compared to average historical values. Since the MSD is an annual lull in July–August rainfall, its occurrence would only be classified as a meteorological drought if it was particularly dry compared to the average MSD.

Numerous studies have predicted decreases in mean annual precipitation (MAP) in Central America by ~10%–50% by 2100 for CADC countries (Campbell et al 2011, Karmalkar et al 2011, Kitoh et al 2013, Nakaegawa et al 2014, Pons et al 2018). There have also been a growing number of studies of droughts in the region, particularly with respect to future projections of MSD characteristics. Rauscher et al (2008) and Maurer et al (2017) employed multi-model GCM ensembles to show that CADC MSDs are predicted to increase in variability, duration and intensity in coming decades in concert with the expansion of the North Atlantic subtropical high (NASH) and strengthening of low-level easterly winds.

![Figure 1. CADC study region with estimated boundaries and corresponding 0.25 degree pixels used from the climate datasets used for CADC-averaged calculations. Spatial extent approximated from Van der Zee Arias et al (2012) and FAO (2016).](image-url)
of the Caribbean low-level jet (CLJJ). Anderson et al (2019) showed that MSD durations have increased over the past 40 years in the CADC as well. These findings are important, as variability, extension and intensification of MSDs can delay or disrupt crop- ping practices (Rauscher et al 2008, Van der Zee Arias et al 2012, Maurer et al 2017, Marroquín and Gómez 2019). Hidalgo et al (2013) also found statistically significant decreases in projected precipitation and hydrologic runoff throughout much of Central America by 2100 and other studies of largescale climate dynamics project drying trends due to a southward migrating Eastern Pacific inter-tropical convergence zone (ITCZ) as temperatures warm and a potential increased frequency of El Niño (ENSO) events (Rauscher et al 2008, Taylor et al 2013, Steinhoff et al 2015).

However, there is a lack of research on future drought predictions in the CADC that takes a broader focus than trends of MSDs. While the MSD is one of the most important climate features for CADC communities, there is also a need to understand how rainfall and the occurrence of seasonal and longer-term droughts are projected to change. Lack of rainfall throughout the year can impact water supply and soil moisture leading up to cropping seasons and longer-term droughts can have crippling impacts on the region as a whole. This study complements the growing body of CADC-drought literature by providing the following contributions: (i) an analysis of past and projected drought characteristics throughout the CADC using a bias-corrected, statistically downscaled, 20-member GCM ensemble for both short-term and long-term droughts, (ii) assessment of projected changes to drought patterns both during the rainy/cropping season (May–Oct), which encompasses MSD trends, as well as the entire calendar year, (iii) application of a suite of drought metrics, including a novel metric that integrates duration, intensity, frequency into one variable, and (iv) uses observed station data to validate the GCM ensemble and a relatively new reanalysis dataset (ERA-5) for drought assessments in the CADC.

The analysis was done in two stages, the first being an evaluation of historical droughts through a comparison observational station records, reanalysis and historical climate model data to evaluate the ability of the GCM ensemble to reproduce precipitation and droughts observed over the CADC in the past (1981–2018) and identify model bias. We then assessed projected changes to precipitation and droughts across the GCM ensemble for three, 30 year future periods extending to 2100 compared to reference period (1950–2005) values.

2. Data

Observational records from 101 rainfall stations maintained by Guatemala’s national meteorological agency INSIVUMEH were obtained for the 1981–2018 period throughout Guatemala. These stations span a range of climate regions both within and outside the Guatemalan portion of the CADC and were used to assess the ability of historical reanalysis and GCM data to capture historical rainfall and drought patterns. For such comparison purposes, all 101 available station were utilized—not just those located within the CADC—due to the limited number of station-records available in the study area and the desire to validate gridded reanalysis and climate model data along both the Pacific and Caribbean coasts.

Historical reanalysis estimates of monthly precipitation were obtained from the European Centre for Medium-Range Weather Forecasts’ ERA-5 reanalysis dataset—a global, 0.25° × 0.25° product with data available from 1979 to 2018. Its total precipitation values are estimated from remotely-sensed (satellite) and ground-based radar station estimates (C3S 2017). The ERA-5 values were compared against both Tropical Rainfall Measurement Mission (TRMM—Version 7) and the Global Precipitation Climatology Centre’s (GPCC Version 2018) monthly precipitation values during the period of overlap (01/1998–12/2016) for the three datasets at grid cells corresponding to observed station locations. Monthly averages of all three datasets were compared to observed values for this 19 year period and it was found that ERA-5 performed the best in capturing the seasonal pattern of rainfall observed in the Guatemalan station data, with both TRMM and GPCC over-estimating rainfall, especially during July–August MSD periods (supplemental figure 2).

Data from 20 global climate model implementations (GCMs), included in the Coupled Model Intercomparison Project Phase 5 (CMIP-5) (Taylor et al 2012), were used to evaluate projected changes in rainfall and drought patterns across the CADC (table 1). These data are from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP), which provides an ensemble of different GCMs, all bias-corrected and statistically downscaled (BCSD) to a uniform 0.25° × 0.25° grid via a quantile mapping approach between historical forcing data and model outputs as detailed by Thrasher et al (2012), Wood et al (2002, 2004), and Maurer and Hidalgo (2008). The historical forcing dataset used in this BCSD process was the Global Meteorological Forcing Dataset from Princeton’s Terrestrial Hydrology Research Group (Sheffield et al 2006). The ensemble consists of three scenarios for each model—a historical reference baseline from 1950 to 2005, and moderate (RCP 4.5) and high-emissions (RCP 8.5) ‘future’ scenarios from 2006 to 2100, which roughly correspond to increases in mean global temperatures by 2.4°C and 4.9°C by 2100, respectively (Moss et al 2010, Meinshausen et al 2011, Rogelj et al 2012). We did not perform any additional bias
correction on these GCM models for use in the CADC region.

3. Methods

We used a simple, meteorological drought definition solely based on accumulated precipitation (Mishra and Singh 2010) due to the high prevalence of rainfed agriculture throughout the CADC (as opposed to highly managed systems with storage and conveyance) and also due to the CADC’s location in the tropics, making fluctuations in monthly temperatures and, by partial extension evaporative demand, relatively minimal compared to those in more temperate climes. Monthly station and ERA-5 precipitation data were used to assess both the GCM ensemble’s agreement with historical data across the study region and its projected rainfall and drought trends in the future. Drought periods were defined using the Standardized Precipitation Index (SPI), a measure of normalized, accumulated rainfall anomalies. Calculating SPI only requires precipitation data and can be defined for various time-scales (e.g. 3, 6, 12 month), which allows for analysis of both short and long-term periods of accumulated rainfall deficits (McKee et al 1993, Edwards 1997, Guttman 1999). A 2-parameter gamma (2PG) distribution was utilized with maximum-likelihood estimation for shape and scale parameters (Naresh Kumar et al 2009, Strzepek et al 2010, Vicente-Serrano et al 2010, Blain 2011, Penalba and Rivera 2013, Zarch et al 2015, Ukkola et al 2018). Nearly all CADC rainfall values (station, reanalysis and GCMs) fit the 2PG distribution, as determined from application of Kolmogorov–Smirnov tests (p-value < 0.05) (supplemental Table 1).

Drought periods were defined as any span of continuously negative SPI values with at least one value of −1 or lower (Guttman 1999, McKee et al 1993, Kallis 2008, Svoboda et al 2012). This study assesses both 3 month SPI values (SPI3) to assess short-term droughts as well as 12 month SPI (SPI12), similar to the approach taken by Penalba and Rivera (2013) (figure 2). SPI3 time-series show more-frequent, shorter droughts and higher variability while the SPI12 series are smoother with less-frequent, longer droughts.

SPI3 and SPI12 values were derived from station, ERA-5 and GCM data for historical and future periods. These values were used to characterize drought patterns at each station or grid-cell location by calculating the following metrics: (i) mean duration (DUR), in months, of each drought period (ii) mean intensity (INT) of each drought, with intensity for a given drought equal to that period’s average SPI-value (iii) mean 10 year drought frequency (FREQ10), or the number of droughts per decade, and (iv) mean annual, intensity-weighted total drought duration (AIWD), which is defined as the absolute sum of all SPI-values during droughts over a given period divided by that period’s length, in years. AIWD is

| Model          | Developing institution                                      |
|----------------|------------------------------------------------------------|
| 1  bcc-csm1-1- | Beijing Climate Center, China Meteorological Administration|
| 2  BNU-ESM    | Beijing Normal University                                  |
| 3  CanESM2    | Canadian Centre for Climate Modelling & Analysis           |
| 4  CCSM4       | National Center for Atmospheric Research                   |
| 5  CESM1-BGC   | National Center for Atmospheric Research                   |
| 6  CNRM-CM5    | National Centre for Meteorological Research                |
| 7  CSIRO-Mk3-6-0 | Commonwealth Scientific and Industrial Research Organisation|
| 8  GFDL-CM3    | Geophysical Fluid Dynamics Laboratory, NOAA                 |
| 9  GFDL-ESM2G  | Geophysical Fluid Dynamics Laboratory, NOAA                 |
| 10 GFDL-ESM2M  | Geophysical Fluid Dynamics Laboratory, NOAA                 |
| 11 inmcm4      | Russian Institute for Numerical Mathematics                |
| 12 IPSL-CM5A-LR | Institute Pierre Simon Laplace                             |
| 13 IPSL-CM5A-MR | Institute Pierre Simon Laplace                             |
| 14 MIROC-ESM-CHEM | Japan Agency for Marine-Earth Science and Technology     |
| 15 MIROC-ESM   | Japan Agency for Marine-Earth Science and Technology       |
| 16 MIROC5      | Japan Agency for Marine-Earth Science and Technology       |
| 17 MPI-ESM-LR  | Max Planck Institute                                       |
| 18 MPI-ESM-MR  | Max Planck Institute                                       |
| 19 MRI-CGCM3   | Meteorological Research Institute, Japan Meteorological Agency|
| 20 NorESM1-M   | Norwegian Climate Center                                   |
equivalent to the average number of drought months each year, weighted by intensity (a drought month with an SPI value of \(-2\) would receive twice the weight of a drought month with a value of \(-1\)) (equation 1).

\[
AIWD = \frac{\left| \sum_{d}^D \sum_{m}^M \text{SPI}_{d,m} \right|}{Y}
\]  

(eq. 1)

\(D\) represents the set of all drought periods \((d)\) in the SPI time-series, \(M\) is set of each month \(m\) in a given drought \(d\) and \(Y\) is the record length in years. This metric embeds the duration, intensity and frequency of drought events and can be thought of as an aggregate of DUR, INT and FREQ10. It is equal to the integrated area of the shaded periods in figure 2 divided by \(Y\).

ERA-5 and GCM ensemble data were compared to the station values from 1981 to 2018 to evaluate their agreement with ground observations. This analysis was split into two periods, one from 1981 to 2005 using the ensemble’s historical reference runs, and a second from 2006 to 2018 using the ‘future’ RCP 4.5 and 8.5 ensemble runs, which span from 2006 to 2100. The second analysis period allowed for a crude assessment of the ability of GCM models to broadly emulate observed rainfall and droughts in their ‘future’ configurations for 13 years outside of their historical reference period, already subject to bias-correction.

Future changes in drought patterns were assessed by calculating SPI from GCM ensemble rainfall during three, 30 year ‘future’ periods: 2011–2040, 2041–2070 and 2071–2100. In order to evaluate how future rainfall and droughts differ relative to a historical baseline, SPI values in these three periods were calculated using the same shape and scale parameters that were derived from fitting the corresponding historical rainfall from 1950 to 2005 to a 2PG distribution (Touma et al 2015). Future SPI values therefore represent how many standard deviations each accumulated rainfall value is from the historical mean in that location. Changes from historical averages were evaluated for mean annual rainfall and all drought metrics for SPI3 and SPI12, for the entire year (Jan–Dec) and solely rainy season months (May–Oct). Historical and future rainfall and drought trends were assessed for statistical significance using the non-parametric Mann–Kendall trend test (Mann 1945, Kendall 1975).

We should note that we also considered using the Standardized Precipitation Evapotranspiration Index (SPEI) as our drought metric, which incorporates potential evapotranspiration (PET) in its calculation. However, reliable calculation of PET can vary depending on the estimation method, the most accurate of which requires additional meteorological variables that were not directly available in our observational records or downscaled GCM ensemble outputs (Da Silva Junior et al 2017, Quesada-Montano et al 2019). Additionally, Quesada-Montano et al (2019) conducted a side-by-side comparison of SPI and SPEI for use in characterizing historical droughts across Central America and found them to produce largely similar results, though they do acknowledge the benefits of accounting for PET when feasible. Given the relative stability of annual PET between months, SPI was deemed sufficient for estimating changes in meteorological drought in the region.

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**Figure 2.** Example of 3 & 12 month historical SPI time-series for Chiquimula Department, Guatemala from 1979 to 2018 using the department-average ERA-5 precipitation. Droughts shaded orange. Drought duration, intensity and decadal frequencies are demonstrated for the SPI3 series.
4. Results and discussion

4.1. Historical comparisons

Historical mean monthly rainfall patterns for station and ERA-5 data in Guatemala were found to be very similar in both magnitude and seasonality from 1981 to 2018 (figure 3). The downscaled, bias-corrected GCM ensemble at station locations also captures observed seasonality but consistently overestimates rainfall throughout the year, roughly by +45% during the rainy season (May–Oct) over this historical period and shows a slightly delayed MSD peak, modeled as being most severe in August as opposed to July. However, given that our analysis considers precipitation smoothed across 3 and 12 month periods (SPI3, SPI12), our results are likely less sensitive to this July–August discrepancy than if we had focused on individual monthly values (SPI1). The duration of the MSD and timing of the bimodal precipitation maxima are very consistent between the station, reanalysis and ensemble data.

The ensemble was found to produce similar monthly mean rainfall values at the gauge locations during both the 1981–2005 and 2006–2018 periods, which provides crude validation of their ability to capture local rainfall pattern outside of the bias-correction period, though there is slightly higher model variance in the 2006–2018 period (supplementary figure 3). Additionally, there is some spatial heterogeneity in the bias of the ensemble mean’s average annual rainfall across the study region as compared to ERA-5 (figure 4(a)). The ensemble is biased-high compared to ERA-5 in most regions, especially along the northern slope of Guatemala’s Pacific Coast range. Overall, mean annual rainfall bias between the GCM data and ERA-5 throughout the CADC from 1979 to 2018 was +18% for the historical/RCP4.5 ensemble and +21% for the historical/RCP8.5 ensemble for that period, and are assumed to be generally unvarying during future modeling periods. Mean monthly rainfall patterns are well-represented by the ensemble (figure 4(b)).

The rainfall bias produced by the GCMs from 1979 to 2018 in the eastern regions of Guatemala, Nicaragua, and Honduras suggests the ensemble may be modeling a slightly more intense CLLJ than observed in reality. This is potentially due to overrepresentation of the westward move of the NASH (Wang and Lee 2007) or to an overactive convective precipitation parameterization, causing some incorrect moisture fluxes over the region. This pattern has been observed before in GCMs assessments of CLLJ historical representations (Martin and Schumacher 2011). Enhanced divergence of moisture in the Caribbean by the CLLJ could result in enhanced rainfall via orographic lifting, which may explain the overestimation of rainfall observed along the eastern slope of the Pacific coastal range, especially in southeastern Guatemala. However, these observed biases may also be partly due to an under-representation of the region’s orographic rainfall more generally in the ensemble compared to ERA-5, potentially due to a low density of observational data used in the original BCSD process.

Both the GCM ensemble and ERA-5 reanalysis data also reflect historical DUR, INT, FREQ10, AIWD compared to station values from 1981 to 2018 at the SPI3 and SPI12 scales fairly well (figure 5). ERA-5 drought metrics diverge from station values more than the ensemble, though still in general agreement for AIWD. The most notable differences are ERA-5’s overestimate of DUR and, therefore, its underestimate of FREQ10 for SPI3 and SPI12 droughts during the 1981–2005 period (fewer, longer events than observed in station data). It should be noted that the low frequency of SPI12 droughts means that its metrics are calculated from smaller sample
Figure 4. (a) Percent difference in annual mean rainfall between the GCM ensemble mean (average of both RCP scenarios) and ERA-5 from 1979 to 2018. (b) Dry Corridor (CADC) mean monthly rainfall for the GCM ensemble and ERA-5 reanalysis data from 1979 to 2018.

Figure 5. Comparison of average drought metrics across all calendar months observed across the gauging station network and at the ERA-5 and GCM ensemble datasets at these station locations. Results provided for both SPI-scales (3, 12 month) and for each sub-period of the historical analysis. DUR = mean drought duration in months, INT = mean drought intensity in SPI values, FREQ10 = mean number of droughts per decade, AIWD = mean number of intensity-weighted drought months each year.

sizes than SPI3 metrics, making values between datasets prone to higher variability. This comparison was also done for solely rainy season months (May–Oct), for which there is similarly high accuracy of ensemble drought metrics relative to observed values (Supplemental figure 4), which provides validation for its use in analyzing future drought patterns.
4.2. Projected rainfall and drought patterns

For each GCM ensemble-member, non-parametric Mann–Kendall tests were performed to assess the statistical significance of trends in CADC-averaged mean annual precipitation (MAP) and mean annual DUR, INT, and AIWD values during the historical (1950–2005) and full ‘future’ (2011–2100) periods (Anderson et al. 2019, Hidalgo et al. 2019). Since FREQ10 is a decadal measure, it was not assessed due to its low sample size (<6 decades in historical period), but is partially represented in AIWD. Statistically significant (p < 0.05) MAP trends from 1950 to 2005 were found in only 4 of 20 ensemble members, each of which was negative. CADC-mean ERA-5 MAP values from 1979 to 2018 also showed no significant trend. These findings corroborate Hidalgo et al. (2017)’s study, which similarly found no significant trends in MAP in the CADC from 1970 to 1999, and gives some credence to our implicit assumption of rainfall stationarity during the reference period. For historical drought metrics, very few significant trends were found—just 2–3 members exhibiting (increasing) significant trends for each SPI3 and SPI12 metric.

From 2011 to 2100, 6 and 13 ensemble members displayed significant trends in MAP under moderate (RCP 4.5) and high (RCP 8.5) emissions, respectively. However, the direction of these trends was more mixed under RCP 4.5 as compared to RCP 8.5, the former with 4 of 6 of its significant members showing declining rainfalls by end-of-century and the latter with 11 of 13. For drought metrics, the total number of significant trends amongst ensemble-members was similar to the number of significant MAP trends under each emissions scenario, and there was strong agreement regarding the direction (increasing) of these metrics, especially with respect to drought intensity and all SPI3 metrics. This is likely partly due to the fact that a number of GCMs (e.g. MIROC-5) projected no appreciable change in mean precipitation, but showed a higher frequency of extreme rainfall events, including droughts and intense storms (supplemental figure 5).

In terms of magnitudes of change, the projected decrease in ensemble-mean MAP throughout the CADC is −8.1% (−155 mm yr$^{-1}$) and −14.1% (−270 mm yr$^{-1}$) by end-of-century (2071–2100) compared to 1950–2005 under RCP 4.5 and RCP 8.5 emissions scenarios, respectively. Declines in solely rainy season precipitation changes by end-of-century were slightly higher at −8.5% (−165 mm yr$^{-1}$) and −15.5% (−300 mm yr$^{-1}$) (figure 6). These results are in general agreement with other multi-model climate change assessments conducted in the region focused on projected changes in annual average rainfall (Giorgi and Diffenbaugh 2008, Karmalkar et al. 2011, Hidalgo et al. 2013). Reductions are fairly uniform across the study region, though with higher reductions projected in inland regions compared to coastal zones (supplemental figure 6).

Changes in mean monthly rainfall are most pronounced during the rainy season, especially during midsummer months (figure 7). Slight increases in October and November rainfall are observed by 2071–2100 primarily under the high emissions scenario, possibly from extension and intensification of the CLLJ from July to November (Rauscher et al. 2008, Steinhoff et al. 2015, Taylor et al. 2013, Maurer et al. 2017). However, the mean monthly rainfall pattern emerging by 2071–2100 is distributionally more similar to observed values in terms of July currently experiencing the midsummer rainfall minimum followed by a slight increase in August. Therefore, projected changes in the distribution of rainfall for certain individual months may be more difficult to decipher than annual or rainy season totals due to ensemble bias of monthly distributions.
Figure 7. GCM ensemble-mean, monthly rainfall over the historical reference period and end-of-century 30 year period for both moderate and high emissions scenarios.

Figure 8. Projected changes in drought metrics throughout the study period. All values are CADC averages, with point values representing ensemble means and shading represents 95% confidence intervals derived from the 20-member population standard deviations.
Changes in annual drought metric averages, however, are more substantial than those predicted for MAP (figures 8 and 9). By end-of-century, short-term droughts across all months are projected to lengthen by roughly 12%–30% (0.7–1.8 months) under moderate to high emissions and by 11%–23% (0.5–1.1 months) during the rainy season. They are projected to intensify by 17%–42% across all months and by 21%–51% during the rainy season. Increased frequencies are also projected, with models showing 21%–24% (+1.3–1.5 per decade) more events throughout the year and 42%–52% more often (+1.7–2.1 per decade) during the rainy season.

Long-term droughts are projected to intensify by 27%–73% across all months and by 27%–75% during the rainy season by end-of-century. These droughts are shown to lengthen as well, with some models showing a more than tripling (>300%) in average duration during both the rainy season and entire calendar year (from 2.2 years to >6.6 years per SPI12 drought). Frequencies of SPI12 droughts are shown as decreasing by end-of-century, though this is primarily due to the fact that many GCMs project substantial drying by this time, some projecting much of the 2071–2100 period to be in semi-continuous, SPI12 drought conditions. Therefore, the predicted decrease in frequency of SPI12 droughts corresponds to a dramatic increase in projected duration per drought. It should also be noted that SPI12 drought metrics are generally more variable between different ensemble-members compared to SPI3 metrics due to the relatively small sample size of long-term droughts compared to short-term ones—the GCM ensemble averaged just 3.9 SPI12 droughts during 2071–2100 under high emissions compared to 22.6 for SPI3 (supplemental figure 7). Therefore, end-of-century results
for longer drought events are more difficult to interpret than results for earlier future periods or for short-term droughts.

The AIWD metric, which incorporates DUR, INT and FREQ10, offers more comprehensive insight into overall drought conditions, and we can see from this metric that droughts are predicted to worsen over time, particularly in rainy season months, and more so under high emissions relative to moderate. End-of-century changes to AIWD are on the order of 69%–150% for short-term droughts across all months and (100%–230% during the rainy season), and 110%–240% for long-term events over all months (120%–250% during the rainy season).

For all metrics, near-term (2011–2040) changes are comparable between both emissions scenarios. Gridded, end-of-century changes for the entire study region reveal fairly homogenous spatial trends in drought metrics across the CADC (figure 10). Changes in the cumulative distribution functions (CDFs) of SPI3 and SPI12 values over time under each emissions scenario show the extent to which low SPI-values are projected to increase in frequency (supplemental figure 8).

From a physical mechanism perspective, the projected increase in duration, intensity, and frequency of droughts are potentially due to the intensification of the CLLJ in the future (Rauscher et al. 2008 and Maurer et al. 2017) and also potentially to a shifting ENSO regime (Taylor et al. 2013, Steinhoff et al. 2015). Aside from the annual cycle, ENSO is the main forcing mechanism of climate variability in Central America (Karmalkar et al. 2011). Though the future frequency and intensity of El Niño events overall remains uncertain in climate models (Achutarao and Sperber 2006, Wang et al. 2019, Lim et al. 2019), there is broad model agreement regarding the mean-state trend of warming sea-surface temperatures (SSTs) over the eastern Pacific (Rojo Hernández et al. 2020). This increase in SSTs corresponds to robust model predictions of increasingly frequent extreme El Niño events under future periods, though overall trends remain less clear (Cai et al. 2014). It is possible that this increase in the sea-surface temperature anomaly (SSTA) amplitude in the equatorial Pacific condition could contribute to a drier mean-state under conditions of higher radiative forcing in the future (Cai et al. 2014). However, the additional influence
of amplitude, frequency, and location of the maximum SST anomalies needs to be better understood as well as the non-linearity of the ENSO system and the consistency of its teleconnections with rainfall in Central America (Steinhoff et al 2015; Lim et al 2019).

5. Conclusions

Central America’s CADC has been prone to droughts of varying length and severity in the past, which have impacted the livelihoods and food security of the region’s large, subsistence farming population. According to this analysis, both short and long-term droughts are projected to worsen substantially across the region under both moderate and high emissions scenarios by end-of-century. Despite somewhat modest projected reductions in mean annual rainfall by 2071–2100 compared to historical (1950–2005) conditions, relative changes in drought characteristics (duration, intensity, frequency, intensity-weighted drought months per year) are projected to be more pronounced.

Throughout the rainy season, during which farmers are most dependent upon stable rainfall patterns, short-term droughts are slated to lengthen, intensify and become more frequent, with the majority of these changes being proportionately higher than predicted changes to mean annual precipitation. Long-term droughts, which can have severe regional impacts, are also projected to worsen by 2100. Across all months, they are projected to potentially more-than-triple in length, making for longer but fewer individual events, and to intensify. This entails that though annual, total rainfall may decline modestly by the end of the century, droughts (and their impacts) will likely be disproportionately more severe.

Insufficient water supply, particularly those projected during the midsummer months, could have severe impacts on crops like maize and beans in the CADC, whose first planting season or Primera determines the agricultural calendar for the season. Both staple crops and cash crops, like coffee, are affected by diminished rainfall and worsening drought patterns, which could result in not only a shortage of staples for subsistence farmers but also reduced incomes and potential food insecurity for cash crop farm workers (Tucker et al 2010).

Better understanding of projected, worsening drought conditions information can assist policymaking throughout the CADC. Adaptation-oriented policies could proactively increase resilience of agricultural systems throughout the coming decades. Such programs could help farmers gradually shift from one crop to another, or to more drought-resistant varieties. However, expected near-term worsening of droughts could have more immediate impacts on vulnerable agricultural communities and may require more urgent resiliency planning efforts.

Further research should be done to better understanding the specific atmospheric dynamics underlying each of these projected changes in rainfall and drought metrics in this ensemble. It is important to note that meteorological drought projections such as those derived from SPI do not account for likely some future climatic changes, such as warming temperatures and subsequent increases in evapotranspiration. Exploring such factors with more comprehensive drought metrics (e.g. SPEI) would also be a good topic of complementary research and would potentially produce even more dire drought projections for rainfed agricultural systems in the CADC, as rising temperatures would serve to reduce soil moisture in conjunction with the worsening rainfall deficits displayed in this study.

Similar analysis should also be done both using large ensemble (LENS) GCM datasets to better understand the role of internal variability. Conducting similar analysis for the CADC using new, CMIP-6 GCM model outputs is also needed, although an assessment by Cook et al (2020) found remarkable consistency between CMIP-5 and CMIP-6 drought predictions for various drought ‘hotspots’ across the globe, including Central America. Analysis of socioeconomic impacts of projected drought trends would also help to further inform important adaptation policymaking in the region and should be pursued as well.

Data Availability Statement

The data that support the findings of this study are available upon request from the authors.

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