Atmósfera
ISSN: 0187-6236
Universidad Nacional Autónoma de México, Centro de Ciencias de la Atmósfera

Murray-Tortarolo, Guillermo N.
Seven decades of climate change across Mexico
Atmósfera, vol. 34, no. 2, 2021, pp. 217-226
Universidad Nacional Autónoma de México, Centro de Ciencias de la Atmósfera

DOI: https://doi.org/10.20937/ATM.52803

Atmósfera 34(2), 217-226 (2021)
https://doi.org/10.20937/ATM.52803

SHORT CONTRIBUTIONS

Seven decades of climate change across Mexico

Guillermo N. MURRAY-TORTAROLO

Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Campus Morelia, Antigua Carretera a Pátzcuaro 8701, 58190 Morelia, Michoacán, México.
E-mail: gmurray@iies.unam.mx

Received: November 28, 2019; accepted: April 11, 2020

RESUMEN

Debido a su localización geográfica, México es uno de los países más vulnerables frente al cambio climático. No obstante, ignoramos la magnitud exacta y las particularidades del cambio climático ya sucedido, y no contamos con un análisis espacialmente explícito basado en datos observacionales. Para completar dicho conocimiento, analicé los cambios en la temperatura, precipitación y el balance hídrico del país entre 1951 y 2017 a escala anual y estacional. Mis resultados muestran un claro incremento en la temperatura media nacional (+0.71 °C) y no muestran cambios en la precipitación promedio anual. Estacionalmente, la precipitación en la época de lluvias (junio-noviembre) ha tenido un aumento constante (+31 mm), mientras que la de la época de sequía (diciembre-mayo) permanece sin cambios. No obstante, cuando calculé el balance hídrico completo (precipitación menos evapotranspiración potencial), el resultado es una tendencia al aumento en humedad en la estación de lluvias y una estación de sequía mucho más seca, en todo el país. Regionalmente, los cambios estacionales son evidentes en la región circundante al Golfo de México e inversos a la tendencia general en la península de Yucatán y el altiplano mexicano. Mis resultados explican el incremento reciente en sequías, tormentas e inundaciones en México a consecuencia del cambio climático, y sugieren que la presencia de climas extremos se exacerbará en el futuro.

ABSTRACT

Due to its geographical location, Mexico is one of the most vulnerable countries to climate change. However, we currently ignore the exact magnitude and particularities of past climate change in the Mexican territory and are missing a country-level spatially explicit analysis based on observed data. To fill this gap, I analyzed how temperature, precipitation and the water balance of Mexico changed over 1951-2017 at interannual and seasonal scales. My results show a clear national increment in temperature (+0.71 ºC) but no modification in annual mean precipitation. At the seasonal scale, the wet season (June-November) had higher rainfall (+31 mm) and no change was detectable on the dry season (December-May). However, when the full water balance was seasonally accounted for (precipitation minus potential evapotranspiration), the trend resulted in a wetter wet season and a much drier dry season across the country. Regionally, seasonal changes in water balance were larger in the area surrounding the Gulf of Mexico and positive in the Yucatan Peninsula and the central highlands. My results help explaining the recent increase in drought, storms and intense rainfall across Mexico and suggest even more extreme seasonal weather in the future if climate change exacerbates.

Keywords: drought, flooding, extreme weather events, regional climate change.

1. Introduction

Planetary climate will continue to change as a consequence of human greenhouse gas emissions (IPCC, 2013). This includes a surge in global temperatures, a redistribution of hydrological patterns and an increment of extreme events (Collins et al., 2013). Just from 1950 until today the mean global temperature has increased by 0.7 ºC, with some regions (such as the high latitudes of the Northern Hemisphere) already experiencing as much as an additional 3 ºC (Hartman et al., 2013). Similarly, over the past two decades we have seen changes in precipitation seasonality (Chou et al., 2013; Feng et al., 2013), in hurricane intensity (Knutson et al., 2013) and on the strength of droughts (Trenberth et al., 2014). Thus, we are living under a new global climatic regime, completely different from the whole of the Holocene and likely in the history of life on Earth (Steffen et al., 2018).

As a result of climate change, several components of the Earth system that provide key contributions to humanity are or will be impacted. From a reduction in food producing systems to rising sea levels, more intense droughts, vector-borne diseases spread, and increasing wildfire frequency to mention just a few (IPCC, 2014). These negative impacts are and will be widespread globally. However, the true magnitude of the impact is dependent on the particularities of each region and the vulnerabilities of each country (Wootten et al., 2017). Thus, there is a pressing need to understand local and regional particularities of climate change.

Mexico is one of the most vulnerable countries to climate change due to its geographical location. Precipitation in the country is highly variable and depends on multiple global factors such as El Niño Southern Oscillation, the North Atlantic Oscillation (Lachinet et al., 2012), the North Atlantic and Pacific hurricane season length and strength (Krishnamurti et al., 1990), and precedent soil moisture and vegetation altering the intensity of the Mexican monsoon (Xiang et al., 2018). As a result, the country's precipitation pattern is highly variable on the interannual scale (with annual national means varying from 620 to 1025 mm according to my calculation, and similar values estimated by Livneh et al., 2015) leading to recurrent extreme precipitation events across most of the territory; a pattern likely to strengthen in future climate change scenarios (Magaña et al., 1997).

Worrisome climate change has already strengthened climate variability and extremes in Mexico (e.g., Gay et al., 2015). This has resulted in increasing drought and water scarcity, as well as the opposite, namely increased storms, intense rainfall and flooding across the country (Mora et al., 2018). A large increment in potential evapotranspiration has also been observed, as a result of higher temperatures, which lead to increasingly drier conditions due to a reduction of soil moisture and water availability (Livertman and O'Brien, 1991). Both the continuous increment in dryness and extreme droughts have strong negative impacts on grain production (Arce et al., 2020), crop yields (Murray-Tortarolo et al., 2018) and livestock populations (Murray-Tortarolo and Jaramillo, 2019), ultimately impacting the society and causing increase migration to the USA (Feng et al., 2013).

Despite the above mentioned conditions, we currently ignore the exact magnitude and particularities of past climate change in Mexico. In particular, we are missing a country-level spatially explicit analysis, based on observed data. Thus, the main objective of this work is to fill this gap by showing how climate has changed in Mexico over the last 70 years (from 1950) in terms of precipitation, temperature and the full hydrological budget. Specifically, I seek to understand changes at the national level and regionally within the country.

2. Methodology

2.1 Datasets

I used mean monthly temperature, precipitation, potential evapotranspiration (based on the Penman-Monteith formula) and number of rainy days (defined as a day with precipitation values above 0.1mm) for the period 1950-2017, extracted from CRUv4.02 datasets (for a full explanation on how the variables are computed please see Harris et al., 2014). These global databases have estimated monthly values at a 0.5º × 0.5º resolution from 1901-2017. I selected the period 1950-2017 due to inherent limitations of the dataset, as 63% of the weather stations do not present measurements prior to the selected period. Due to the low resolution of the pixels for a national-level analysis, I re-scaled the grid to 0.1º × 0.1º using a bilinear interpolation that accounted from topographic patterns for better presentation of the results; however, nation-level statistics were done on the original half degree resolution.

2.2 Advantages and limitations of employed data

I selected the CRUv4.02 database based on several important advantages for this particular analysis;

however, it also has some important limitations that need to be considered when interpreting and using my results. In the next paragraph I detail both.

Probably the most important benefit is the regularity of the grid. The database uses a regular 0.5º grid, which allows for quick computation of statistics and trends, and simplifies plotting (for a total of 2442 grid points for the whole territory). In the particular case of Mexico, the climate information for each grid-point is based on an average of 7.6 weather stations, which translates in a total of 104 to 348 stations used across the whole territory, depending on the year. But, importantly, one station can provide information for several grid points, as mean climate is interpolated from all available datapoints, thus providing a large extent of information. The dataset also benefits from providing a full spatiotemporal cover that has been shown to correctly replicate coarse-resolution observations (Livneh et al., 2015). However, it has some important limitations. The output data itself is not homogenized; thus, linear temporal trends should be analyzed carefully. In addition, a 0.5º grid is too coarse to capture the full extent of local micro-climates derived from the largely heterogeneous Mexican topography. As a result, spatially explicit trends should be interpreted carefully and, if used for local-scale studies, they should be regarded as a general guideline and not as observations. Despite the previous, decadal patterns and national-level trends can be considered to be reliable (Harris et al., 2013). In the future, a comparison with other observation-based datasets could provide further insights on how climate changed in Mexico, particularly at the regional scale within the country.

2.3 Data analysis

National level statistics (mean, deviation and trends) were calculated at two different temporal scales, seasonal and annual, for the whole time period. I split the year into the usual four seasons (spring, summer, autumn and winter), but also into two precipitation seasons (with an equal number of six months): wet (June-November, which accounted for 79-87% of the total annual rainfall based on my calculation) and dry (December-May). For the whole time series (based on annual means) I calculated the net change in the variables, as the slope of a 10-year running mean and from decadal averages. The monthly national scale means for precipitation minus potential evapotranspiration were calculated for each decade, but only the first and last are presented to simplify the results. I also calculated the standard error for each month ($n = 10$ based on each year of the decade) and perform a repeated measure analysis of variance (RMANOVA) using both decades. Similarly, I calculated the average number of rainy days per season for the same decades.

For the spatial analysis I calculated the gridded mean (0.5º × 0.5º grid) and linear trend (I presented the gridded slope to show general spatial patterns, and the significance of the trends as stipple) for temperature, precipitation and precipitation minus potential evapotranspiration for the full time period. I further re-calculated the later at a seasonal scale. Regional-level statistics (mean and trends for all variables) were calculated for three regions within the country which were determined a posteriori, based on distinctive spatial patterns: the surrounding area to the Gulf of Baja California, the Central Highlands and the Yucatan Peninsula.

3. Results

3.1 Changes in mean national-scale temperature and precipitation

Mean climate in Mexico has changed over the last 70 years. In particular, the mean national-scale temperature has increased by +0.71 ºC from 1951 to 2017 (10-year running mean, $p < 0.001$) or by +0.96 ºC if calculated using decadal means ($p < 0.001$) (Fig. 1, left panel). Interestingly, there was a –0.36 ºC decline during the period 1951-1980 ($p = 0.01$), also seen globally and likely driven by the global increment in atmospheric aerosols (Tegen et al., 2000); thus, the warming trend over the last 40 years was even stronger, gaining almost 2 ºC (+1.93 ºC, $p < 0.001$). As a result of the warming, the five hottest years in this record occured in the last 10 years (2017, 2016, 2015, 2012 and 2009, in that order) all of which had an exceeding temperature of at least +0.9 ºC compared to the mean of the whole period or an additional +1.3 ºC if compared to the 1951-1960 average. However, the change was not homogeneous within the year, with spring temperatures (March-

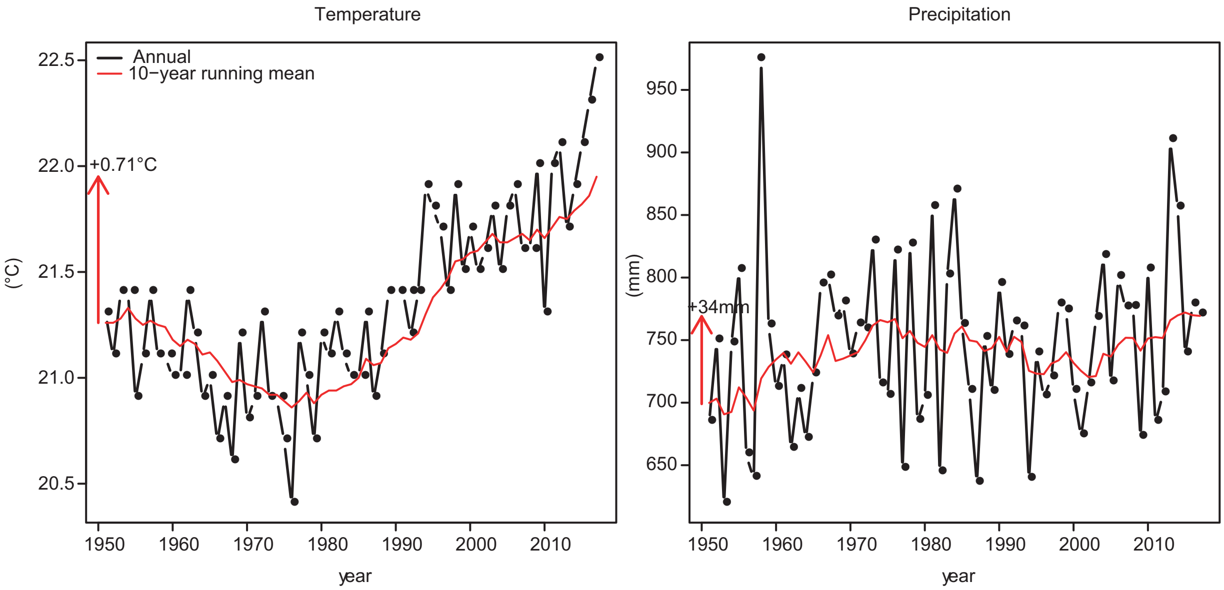

Fig. 1. Temporal evolution of mean annual temperature (left) and precipitation (right) across the whole of Mexico from 1951-2017. Dots represent the annual mean and the red line a 10-year running mean. The red arrow indicates the net decadal change from the 1950s to the 2010s in both variables.

May) increasing the most with +0.93 ºC and summer-autumn (July to November) the least with +0.57 ºC. Thus, representing a higher temperature increment in the dry season (December-May: +0.82 ºC) than during the rainfall season (July-November: +0.58 ºC) (Table I).

Contrary to temperature, precipitation did not show a clear annual trend over the last 70 years. On average, there was a +34 mm increment in mean annual precipitation, but it was not significant ($p = 0.08$) (Fig. 1, right panel). The five wettest years on record were distributed across the whole time series (2013, 1958, 1984, 1981, 1973), just like the five driest years (1953, 1994, 1987, 1977, 1982), which are potentially related to variation in El Niño Southern Oscillation as suggested by previous studies (Magaña et al., 2003). Nonetheless, there were statistically significant changes in the seasonal precipitation. In particular, the wet season precipitation (June-November) had an increment of +32 mm ($p = 0.02$), which accounts for 94% of the whole annual trend. In contrast, dry season precipitation (December-May) showed no changed (+1.95 mm) with even a small decline in winter (December-February) precipitation (Table I).

Table I. Seasonal (based on four thermal and two rainfall seasons) changes in mean annual temperature (ºC) and precipitation (mm and percentage of the seasonal or annual mean) across Mexico, for the period 1951-2017.

Season	Temperature change (ºC)	Precipitation change (mm and %)
Spring (MAM)	0.93	2.29 (3.18%)
Summer (JJA)	0.58	18.37 (5.06%)
Autumn (SON)	0.57	13.51 (5.42%)
Winter (DJF)	0.69	–0.34 (–0.7%)
Dry season (DJFMAM)	0.81	1.95 (1.66%)
Wet Season (JJASON)	0.575	31.88 (5.20%)
Annual	0.71	34.41 (4.51%)

3.2 Seasonal changes in the water balance

My results show a clear seasonal change over the last 70 years: the wet season has become wetter and the dry season drier (Fig. 2). In that sense, the July-November (wet season) water balance shows an excess of +54 mm of available water (not evaporated) for soil moisture recharge and runoff, when comparing 2008-2017 against 1951-1960. In contrast, December-March precipitation (dry season) had an average decrement of –39mm.

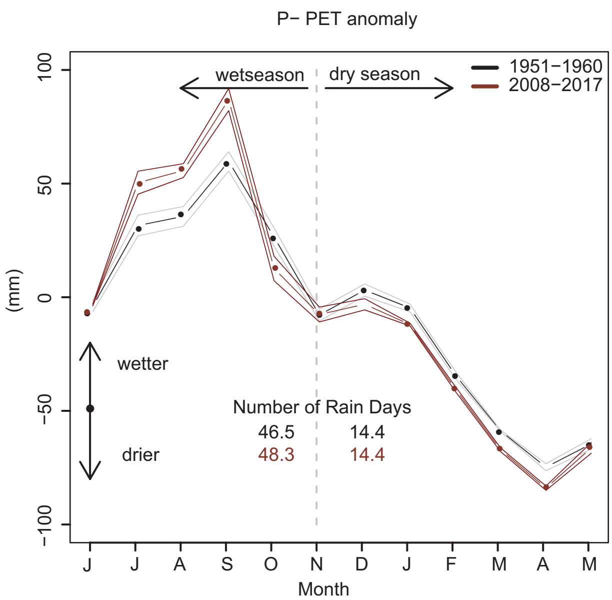

Fig. 2. Monthly precipitation minus potential evapotranspiration as the mean of two decades: the start of the period (1951-1960; black dotted line) and the end (2008-2017; red dotted line). Solid lines indicate one standard error from the mean (n = 10).

Two key seasonal aspects are also evident: the consistent monthly differences across decades and the unchanged number of wet days in each season. In this sense, the increment/decrement in wet season/dry season water balance is consistent across all months (except for October-November). Thus, we see an increase in excess available water throughout the wet season (statistically significant for July, August and September) and a decrease across all the dry months (statistically significant throughout the whole season). In contrast, the number of wet days in each season did not change (from 46.5 ± 2.2 to 48.3 ± 2.3 rainy days in the wet season from 1951-1960 to 2008-2017, and from 14.4 ± 0.6 to 14.4 ± 0.6 in the dry season). This means that the seasonal changes in water availability, particularly in the wet season, are driven by changes in the amount and not the seasonality of precipitation.

3.3 Spatial distribution of trends

Spatially, the climate trends were largely heterogeneous across the country, but more so for precipitation than for temperature. In the case of temperature, there was a consistent increase all over the country over this seven decades, that ranged from +0.01 to +0.029 ºC per year (or an increment of +0.1 to +2.7 ºC across the whole time series), with three marked regional patterns. The region surrounding the Gulf of Baja California had the highest increment, gaining as much as +2.7 ºC over the last 67 years. The Yucatan Peninsula also displayed a thermal increment, although much smaller (+0.7 ºC). Finally, the mid and mid-west regions had only a minor increment of +0.1 ºC (Fig. 3).

Precipitation shows both increments and decrements across the nation, which consistently lead to the zero-sum national trend. In that sense, the mountainous regions in the east, middle and particularly the west, display a decrease in precipitation between –40 and –70 mm yr^{-1}. The pattern is particularly strong across the region surrounding the Gulf of Baja California, where the decline represented as much as 20% less annual rainfall. In contrast, precipitation increased in the central highlands (+32 mm yr^{-1}) and the Yucatan Peninsula (+53 mm yr^{-1}); nevertheless, the percentage increment in the first region represented an order of magnitude higher (+18% and 0.2%, respectively) (Fig. 3).

The spatial integration of precipitation minus the potential evapotranspiration reveals the arrangement of changes in water availability across the country. In this sense, the pattern is remarkably similar to the changes in precipitation and is also spatially consistent across seasons. Thus, there has been a general decline in the hydrological balance across the country that extends throughout the year, and an increment in the Central Highlands and the Yucatan Peninsula. In addition, there is a positive trend in the wet season water balance in the south (centered around the state of Guerrero), which is also seen in the total precipitation. Importantly, a key region with strong negative trends is the one surrounding the Gulf of Baja California (Fig. 4).

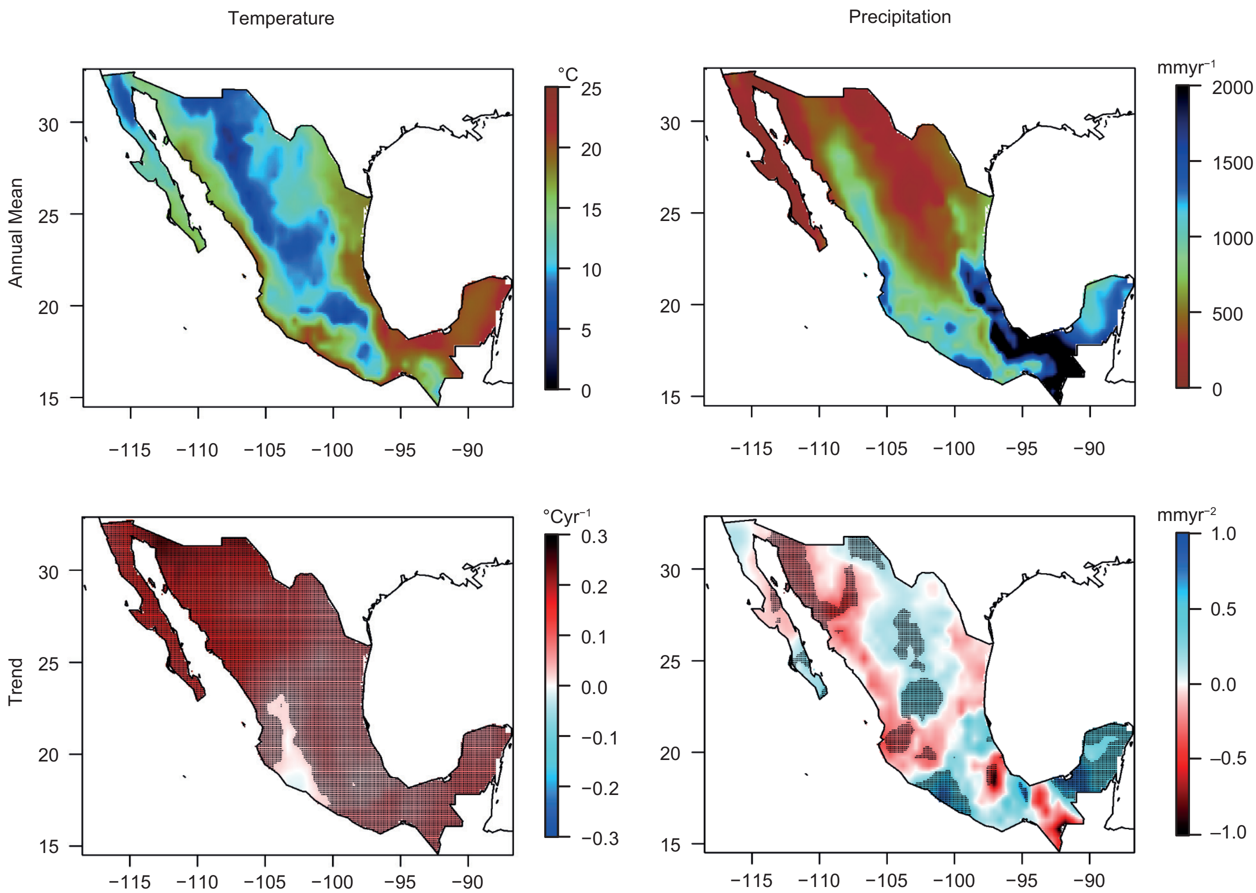

Fig. 3. Mean (top) and linear trend (bottom) for temperature (left) and precipitation (right) for the period 1951-2017. Stippling indicates regions with statistically significant trends ($p < 0.05$).

4. Discussion

My results show a change in climate across Mexico over the last 70 years, consistent with global patterns (see Harris et al., 2013). Firstly, the net country-scale temperature increment (+0.71 ºC from 1950 to 2017) coincides with a global increment of land temperature (+0.67 ºC) for the same time period, with a higher gain since the 1980s (IPCC, 2013). Interestingly, the interannual variation is similar across global and national scales; e.g., extremely hot years, such as 2017, coincide in magnitude with +1.3 ºC above the mean (Thompson, 2017). Thus, it is possible that the surge in temperature across the nation is the result of global climate change and not the natural variability of Mexican climate, as also supported by local studies (e.g., Martínez-Austria et al., 2016). However, a formal attribution is needed to support such statement. Hence, it is very likely that temperature will keep rising in the future, at a rate determined by the global pathway (Magaña et al., 2000).

However, important regional differences occur within the country in the thermal trends. In that sense, the Northwest warmed much faster than the rest of the country. At least two potential mechanisms may be responsible for such regional pattern. Firstly, the extremely fast warming of the northern Pacific Ocean, which has led to increasing temperatures along western North America (Barnett et al., 2005; Karmalkar and Bradley, 2017) and impacted extreme heatwave frequency in northern Mexico (Martínez-Austria et al., 2016). Secondly, a link to precipitation trends: a reduction in available water can increase atmospheric temperature through a reduction in latent heat fluxes. Globally, a reduction in precipitation has

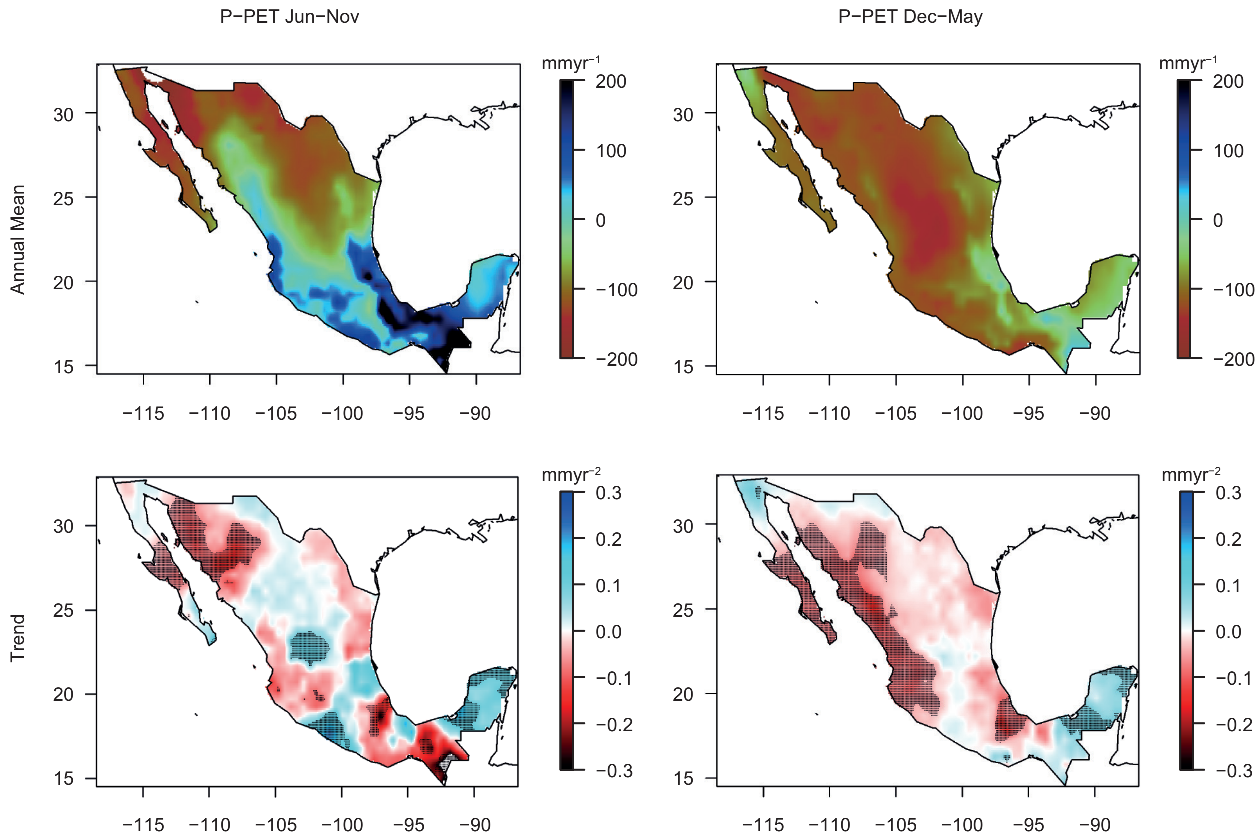

Fig. 4. Water balance for the wet (left) and dry (right) seasons (precipitation minus potential evapotranspiration), represented as mean (top) and linear trend (bottom), over the period 1951-2017. Stipple indicates regions where the trend is statistically significative ($p < 0.05$).

been shown to increase the consecutive number of hot days (Mueller et al., 2012), which could be the case of the high temperature increment in the areas where precipitation decreased (e.g., Sonora). In contrast, the additional rain and positive water balance in the central highlands means lower sensible heat fluxes and a smaller temperature gain. Thus, it is very likely that future regional temperature trends will be closely linked to changes in available water and oceanic heat fluxes.

Precipitation did not change at a national scale, in line with global patterns (Harris et al., 2013); however, there was an increment in the seasonality of water availability. In that sense, the dry season got drier and the wet season wetter throughout the country, similar to what has been observed globally for recent decades (Chou et al., 2013) and particularly over the tropics (Feng et al., 2015). The analysis shows a stable number of wet days across the years, which means that the increment in water availability during the wet season is the result of higher precipitation rates (based on the data employed, mean national-level wet season rainfall rate changed significantly from 12.05 to 12.27 mm day^{-1} or a 2% change) and must be a consequence of more intense rainfall over the same number of days. One potential explanation is an increase in intense precipitation pulses, such as hurricanes or tropical storms that induced precipitation or a stronger monsoon season. On the opposite hand, the deficit in the dry season is likely the result of increased vapor pressure deficit as a consequence of a higher increase in temperature during the season. Interestingly, these results are consistent with a recent global analysis by Mora et al. (2018), who identified an increase in drought and storm events across Mexico, both presently and in the future. This also helps explain the contrasting trend of excess and lack of available water as a result of marked seasonal changes, but further research is needed to attribute its causes.

Finally, regional precipitation patterns present an interesting feature: a general reduction following a U-shape across the limits of the country and an increase in the central plains and the Yucatan Peninsula, leading to mirrored spatial changes in water availability. One potential explanation across the northern and central West Pacific region is the observed reduction in westerlies velocity, which has led to lower winter precipitation rates across western US and potentially Mexico, and may explain the decreasing dry-season water balance (Luce et al., 2013); but it can also be related to seasonal changes in the North American Monsoon (Cook and Seager, 2003; Demaria et al., 2019). In the Yucatan Peninsula, local studies have also shown this increase in rainfall, likely a result of changes in meridional trade winds, which have been shown to shift from shallow (low precipitation) to deep (high precipitation) convection (Díaz-Esteban and Raga, 2019), with a strong increase in seasonality probably modulated by ENSO (Díaz-Esteban and Raga, 2018). For the central highlands, precipitation has been shown to be controlled by the Mexican monsoon (Douglas et al., 1993), likely strengthening as a consequence of higher temperatures. Finally, though spatially explicit trends should be interpreted carefully, the patterns of changes in water availability are almost mimicked by the corresponding trends in river discharge over a similar time period (Milliam et al., 2008), which improves the reliability of the regional hydrological patterns presented.

5. Conclusion

My analysis shows a clear change in Mexican climate over the last 70 years. In particular, the country is getting warmer and the seasonal water balance more extreme. These results are in line with global patterns and current observations, showing the nation to be facing stronger droughts and more intense rainfall. The patterns are very likely the consequence of early climate change, although a formal attribution is needed; thus, it seems likely – and worrisome – that the national-scale climate will become even more seasonally extreme in the future, at a magnitude defined by the global pathway.

Acknowledgments

This work was funded by the Universidad Nacional Autónoma de Mexico, project PAPIIT IA-200420. The author also thanks two anonymous reviewers for their helpful insights.

References

Arce Romero A, Monterroso Rivas AI, Gómez Díaz JD, Palacios Mendoza MÁ, Navarro Salas EN, López Blanco J, Conde Álvarez AC. 2020. Crop yield simulations in Mexican agriculture for climate change adaptation. Atmósfera 33: 215-231. https://doi.org/10.20937/ATM.52430

Barnett TP, Pierce DW, AchutaRao KM, Gleckler PJ, Santer BD, Gregory JM, Washington WM. 2005. Penetration of human-induced warming into the world's oceans. Science 309: 284-287. https://doi.org/10.1126/science.1112418

Chou C, Chiang JC, Lan CW, Chung CH, Liao YC, Lee CJ. 2013. Increase in the range between wet and dry season precipitation. Nature Geoscience 6: 263-267. https://doi.org/https://doi.org/10.1038/ngeo1744

Collins M, Knutti R, Arblaster J, Dufresne JL, Fichefet T, Friedlingstein P, Gao WJ, Gutowski X, Johns J, Krinner G, Shongwe M, Tebaldi C, Weaver AJ, Wehner M. 2013. Long-term climate change: Projections, commitments and irreversibility. In: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029-1136.

Cook BI, Seager R. 2013. The response of the North American Monsoon to increased greenhouse gas forcing. Journal of Geophysical Research: Atmospheres 118: 1690-1699. https://doi.org/10.1002/jgrd.50111

Demaria EM, Hazenberg P, Scott RL, Meles MB, Nichols M, Goodrich D. 2019. Intensification of the North American Monsoon rainfall as observed from a long-term high-density gauge network. Geophysical Research Letters 46: 6839-6847. https://doi.org/https://doi.org/10.1029/2019GL082461

Díaz-Esteban Y, Raga GB. 2018. Weather regimes associated with summer rainfall variability over southern

Mexico. International Journal of Climatology 38: 169-186. https://doi.org/https://doi.org/10.1002/joc.5168

Díaz-Esteban Y, Raga GB. 2019. Observational evidence of the transition from shallow to deep convection in the Western Caribbean Trade Winds. Atmosphere 10: 700-712. https://doi.org/10.3390/atmos10110700

Douglas MW, Maddox RA, Howard K, Reyes S. 1993. The Mexican Monsoon. Journal of Climate 6: 1665-1677. https://doi.org/https://doi.org/10.1175/1520-0442(1993)006<1665:TMM>2.0.CO;2

Feng X, Porporato A, Rodríguez-Iturbe I. 2013. Changes in rainfall seasonality in the tropics. Nature Climate Change 3: 811:815. https://doi.org/https://doi.org/10.1038/nclimate190

Gay C, Cos A, Peña CT. 2015. Reporte mexicano de cambio climatico. Vol 1. Available at: http://www.pincc.unam.mx/libro_reportemex/RMCC_vol1.pdf

Harris IPDJ, Jones PD, Osborn TJ, Lister DH. 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS310 dataset. International Journal of Climatology 34: 623-642. https://doi.org/https://doi.org/10.1002/joc.3711

Hartmann DL, Klein AMG, Tank, Rusticucci M, Alexander LV, Brönnimann S, Charabi Y, Dentener FJ, Dlugokencky EJ, Easterling DR, Kaplan A, Soden BJ, Thorne PW, Wild M, Zhai PM. 2013. Observations: Atmosphere and surface. In: Climate Change 2013: The Physical Science BasisContribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159-254.

IPCC. 2013. Summary for policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 28 pp.

IPCC. 2014. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp. 1-32.

Karmalkar AV, Bradley RS. 2017. Consequences of global warming of 1.5 ºC and 2 ºC for regional temperature and precipitation changes in the contiguous United States. PloS One 12:e0168697. https://doi.org/https://doi.org/10.1371/journal.pone.0168697

Krishnnamurti TN, Bedi HS, Oosterhof DK. 1990. Precipitation prediction over the tropics from a global spectral model. Atmósfera 3: 255-280.

Knutson TR, Sirutis JJ, Vecchi GA, Garner S, Zhao M, Kim HS, Bender M, Tuleya RE, Held I, Villarini G. 2013. Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. Journal of Climate 26: 6591-6617. https://doi.org/https://doi.org/10.1175/JCLI-D-12-00539.1

Lachniet MS, Bernal JP, Asmerom Y, Polyak V, Piperno D. 2012. A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. Geology 40: 259-262. https://doi.org/10.1130/g32471.1

Liverman DM, O'Brien KL. 1991. Global warming and climate change in Mexico. Global Environmental Change 1: 351-364. https://doi.org/10.1016/0959-3780(91)90002-B

Livneh B, Bohn TJ, Pierce DW, Munoz-Arriola F, Nijssen B, Vose R, Brekke L. 2015. A spatially comprehensive, hydrometeorological data set for Mexico, the US, and Southern Canada 1950–2013. Scientific Data 2: 1-12. https://doi.org/https://doi.org/10.1038/sdata.2015.42

Luce CH, Abatzoglou JT, Holden ZA. 2013. The missing mountain water: Slower westerlies decrease orographic enhancement in the Pacific Northwest USA. Science 342: 1360-1364. https://doi.org/10.1126/science.1242335

Magaña V, Conde C, Sánchez O, Gay C. 1997. Assessment of current and future regional climate scenarios for Mexico. Climate Research 9: 107-114.

Magaña V, Conde C, Sánchez O, Gay C. 2000. Evaluación de escenarios regionales de clima actual y de cambio climático futuro para México. In: México: una visión hacia el siglo XXI. El cambio climático en México (Gay C, Ed.). UNAM-INE-U.S. Country Studies Program, 1-25.

Magaña V, Vázquez JL, Pérez JL, Pérez JB. 2003. Impact of El Niño on precipitation in Mexico. Geofisica Internacional 42: 313:330.

Martínez-Austria PF, Bandala ER, Patiño-Gómez C. 2016. Temperature and heat wave trends in northwest Mexico. Physics and Chemistry of the Earth, Parts A/B/C 91: 20-26. https://doi.org/https://doi.org/10.1016/j.pce.2015.07.005

Milliman JD, Farnsworth KL, Jones PD, Xu KH, Smith LC. 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951-2000. Global and Planetary Change 62: 187-194. https://doi.org/10.1016/j.gloplacha.2008.03.001

Mora C, Spirandelli D, Franklin EC, Lynham J, Kantar MB, Miles W, Barba EW. 2018. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. Nature Climate Change 8: 1062-1068. https://doi.org/https://doi.org/10.1038/s41558-018-0315-6

Mueller B, Seneviratne SI. 2012. Hot days induced by precipitation deficits at the global scale. Proceedings of the National Academy of Sciences 109: 12398-12403. https://doi.org/https://doi.org/10.1073/pnas.1204330109

Murray-Tortarolo GN, Jaramillo VJ, Larsen J. 2018. Food security and climate change: The case of rainfed maize production in Mexico. Agricultural and Forest Meteorology 253: 124-131. https://doi.org/10.1016/j.agrformet.2018.02.011

Murray-Tortarolo G., Jaramillo VJ. 2019. The impact of extreme weather events on livestock populations: the case of the 2011 drought in Mexico. Climatic Change 153: 79-89. https://doi.org/10.1007/s10584-019-02373-1

Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, Donges JF. 2018. Trajectories of the Earth system in the Anthropocene. Proceedings of the National Academy of Sciences 115: 8252-8259. https://doi.org/https://doi.org/10.1073/pnas.1810141115

Tegen I, Koch D, Lacis AA, Sato M. 2000. Trends in tropospheric aerosol loads and corresponding impact on direct radiative forcing between 1950 and 1990: A model study. Journal of Geophysical Research: Atmospheres 105: 26971-26989. https://doi.org/https://doi.org/10.1029/2000JD900280

Trenberth KE, Dai A, van Der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J. 2014. Global warming and changes in drought. Nature Climate Change 4: 17-22. https://doi.org/https://doi.org/10.1038/nclimate2067

Thompson A. 2017. At midway point, 2017 is 2nd-hottest year on record. Climate Central. Available at: https://www.climatecentral.org/news/midway-point-2017-2nd-hottest-year-21625

Wootten A, Terando A, Reich BJ, Boyles RP, Semazzi F. 2017. Characterizing sources of uncertainty from global climate models and downscaling techniques. Journal of Applied Meteorology and Climatology 56: 3245-3262. https://doi.org/https://doi.org/10.1175/JAMC-D-17-0087.1

Xiang T, Vivoni ER, Gochis DJ. 2018. Influence of initial soil moisture and vegetation conditions on monsoon precipitation events in northwest Mexico. Atmósfera 31: 25-45. https://doi.org/10.20937/ATM.2018.31.01.03