TRENDS IN HYDROMETEOROLOGICAL VARIABLES WITH CONSIDERATION OF CLIMATE CHANGE IN AGUASCALIENTES, MEXICO

A Dissertation

by

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ABSTRACT

The main goals of this dissertation were to determine the trend of monthly evaporation, study the trend in extreme temperature indices, analyze trends in extreme precipitation indices, and explain the implications of trends in hydrometeorological variables in Aguascalientes' agriculture. Daily evaporation, daily maximum and minimum temperature, daily precipitation data, and bibliographic references of agricultural statistics and published works on the adaptation of the crop to the environment were used. Sixteen/eleven extreme temperature/precipitation indices were estimated, and their trends were evaluated with the Mann-Kendall test. In all cases, the rate of change was obtained with the Theil-Sen estimator. In evaporation, significant trends ($p \leq 0.05$) were obtained in 107-time series, from which 88 were negative, and 19 were positive. It decreased, in January and from March to December in the north; from January to March, August, September, November and December in the center; from February to November in the northwest; from March to August, October, and November in the east; from January to July, and from September to December in the South; and in January, March, June, July, and from September to November in the southwest. It increased in April in the north; in May, November and December in the center; in March, November, and December in the east; in February, April, May, October, and November in the south; and from February to April, November, and December in the southwest. It is perceived cooling due to the decrease in TNMean, TNx, TNn; and for the increase in FD0, TN10p, and CSDI. This increases the vulnerability of crops to damages caused by frost and germination declining

in crops, such as corn, poblano pepper, and beans; in alfalfa, the winter growth is stopped; and in guava, greater time is required to get heat requirements and maturity. Also was observed warming caused by the increase in TXMean, SU25, TXx, TXn, TX90p, TN90p, and WSDI. This causes a faster accumulation of heat requirements, increases populations of insects and their life cycle durations; agriculture turns vulnerable to damages, such as slow growth, poor development, and low yields in crops, such as corn, poblano pepper, beans, sorghum, oat, and alfalfa; in grapevine and peaches, damages caused by cold declination can occur. There existed a propensity toward more humid conditions caused by the increase in RX1day, RX5day, SDII, R10, R20, R95p, and PRCPTOT. This can provoke problems related to moisture excesses, such as poor growth and yield reduction, soil diseases, weed, and insect infestations. Also, some regions were showing drought due to the increase in CDD and SDII decrease. This pattern indicates the occurrence of agricultural drought and an increase of water volumes for irrigation. In corn and beans, late sowing should be implemented, but in the first, varieties or hybrids with better adaptation will be the precocious ones. Under insufficient cold accumulation, in addition to growth regulators, the soil moisture management in orchards during dormant avoids early bud break. Water use efficiency should be increased, either repairing the irrigation infrastructure, training farmers on water management, or through the use of soil cover to avoid losses by evaporation. Crops with high water use efficiency and high forage production may be promoted. Research in deficit irrigation should be conducted to mitigate low water availability and to balance recharge with extraction.

DEDICATION

I dedicate this work to my parents (Oscar Ruiz Rodriguez and Elia Alvarez Vazquez), and sisters and brothers (Judith, Sandra, Damariz, and Oscar-RIP). Each one has demonstrated to me how important I am for him/her.

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NOMENCLATURE

˚C	Celsius degree
BS1h	Semi-dry warm
BS1k	Semi-dry and temperate
C(w)	Temperate and subhumid
CCI	Commision for Climatology
CDD	Consecutive dry days
CLIVAR	Climate Variability and Predictability Project
CNA	Comision Nacional del Agua
CO_2	Carbon dioxide
CSDI	Cold spell duration indicator
CWD	Consecutive wet days
DPT	Dew point temperature
DTR	Diurnal thermal/temperature range
ET_0	Reference evapotranspiration
ET_C	Crop evapotranspiration
ETCCDMI	Expert Team on Climate Change Detection Monitoring and Indices
Ev	Evaporation
FD0	Frost days
GSL	Growing season length

ha	Hectare
Hm^3	Cubic hectometer
IDW	Inverse distance weighting
INEGI	Instituto Nacional de Estadistica y Geografia
INIFAP	Instituto Nacional de Investigaciones Forestales, Agricolas y Pecuarias
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile range
Km	Kilometer
m	Metter
m^3	Cubic meter
mm	Millimeter
Mm^3	Millions of cubic meters
P/PET	Ratio of mean annual precipitation and mean annual potential evapotranspiration
PRCPTOT	Annual total wet-day precipitation
Q	Theil-Sen trend estimator
QC	Quality control
R10	Number of heavy precipitation days
R20	Number of very heavy precipitation days
R50	Number of days above 50 mm
R95p	Very wet days

R99p	Extremely wet days
r_s	Spearman correlation coefficient
RX1day	Max 1-day precipitation amount
RX5day	Max 5-day precipitation amount
S	Mann-Kendall score
SDII	Simple daily intensity index
sgn	Sign of Mann-Kendall score
SIAP	Sistema de Informacion Agroalimentaria y Pesquera
SMN	Servicio Meteorologico Nacional
STD	Standard deviation
SU25	Summer days
Tmax	Maximum temperature
Tmin	Minimum temperature
TN10p	Cool nights
TN90p	Warm nights
TNMean	Annual averaged minimum temperature
TNn	Min Tmin
TNx	Max Tmin
TX10p	Cool days
TX90p	Warm days
TXMean	Annual averaged maximum temperature
TXn	Min Tmax

TXx	Max Tmax
VAR	Variance
VPD	Vapor pressure deficit
WMO	World Meteorological Organization
WSDI	Warm spell duration indicator
Z	Test statistic of the normal distribution

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1. INTRODUCTION

Global warming affects hydrometeorological patterns of the terrestrial surface. In some regions of the world, the frequency of adverse weather phenomena is increasing (Allen *et al.*, 2018). These phenomena affect drinking water supplies, reduce cultivable lands, increase food insecurity, and cause health hazard, adding pressure and competition for water resources (Allen *et al.*, 2018). They also drastically diminish the quality life.

1.1. The problem and some key definitions

Climate change and climate variability affect the society in many ways. Climate is defined as the average, or like the statistical description in terms of mean and variability of relevant quantities (temperature, precipitation, and wind), over a period of time that varies from months to thousands or millions of years (WMO, 2017). On the other hand, the climatic system is a highly complex system that is formed by four main components and their interactions: atmosphere, hydrosphere, cryosphere, and land surface. This system evolves through time under the influence of its own internal dynamics and due to external forcing, such as volcanic eruptions, solar variations, and man induced forcing, such as changing the composition of atmosphere and change of land use (WMO, 2017). Climate change is a statistically significant variation either in the mean state of climate or its variability, persisting for a prolonged period (decades or more); it can be caused by internal natural processes or external forcing, or by persisting anthropogenic changes in the composition of atmosphere or land use (WMO, 2017). Similarly, climate variability is defined as a set of variations in the mean state and other statistics (standard deviation, the occurrence of extremes) of climate, at all temporal and spatial scales, beyond individual meteorological events (WMO, 2017). An extreme meteorological event is a meteorological or climatic phenomenon which is rare at a particular place or in a season of the year, such as heat wave, cold wave, intense precipitation, droughts, floods, and severe storms, which directly affect the society (National Academies of Sciences, Engineering and Medicine, 2016). Definitions of these phenomena and their mechanisms should be understood clearly by the population to understand how hydrometeorological events are changing due to global warming.

1.1.1. Global climate change

The warming of the climatic system is largely a consequence of human activities. Different research works indicate that around 97% of climate science experts agree that global warming is caused by human activities (Doran and Zimmerman, 2009; Anderegg *et al.,* 2010; Cook *et al.,* 2013). This phenomenon is defined as the combined average increase between air temperature and the sea surface at the global level over 30 years, and is commonly compared to the period 1850-1900 (Allen *et al.,* 2018). After the start of the industrial revolution, the planet got 1.0°C warmer. During the decade 2006-2015, the mean global warming was 0.87°C; but it is reported that for that period between 20% and 40% of the world population had already experienced warming bigger than 1.5°C. Even quicker warming than the global average is occurring in many parts of the globe and specific seasons of the year, such as the case of artic where warming is two to three times faster (Allen *et al.,* 2018). Currently, in specific regions of the world, the planet is warming at 2°C per decade due to current and past emissions (Allen *et al.*, 2018). If climate change continues at the same rate as today, we would expect that the planet would get an average warmth of 1.5°C between 2030 and 2052 (Allen *et al.*, 2018). It is expected that this dynamic of warming has a direct impact on the hydrology and natural resources of the planet.

Climatic warming has considerable impacts on natural and human systems. Many lands and systems of oceans and services they provide are already changing by global warming. The warming is associated with alterations in hydrological patterns, such as an increase in the frequency and duration of marine heat waves, increase in the frequency and intensity of precipitation and drought events, and trends in the intensity and frequency of extreme meteorological events (Vincent *et al.,* 2005). Warming by about 2°C would lead to an expansion of areas with increase in runoff, and increase of areas with risk of flooding (Allen *et al.*, 2018). For the artic, simulation models suggest that warming by 2°C is expected at least a summer free of marine ice every ten years, while for a warming of 1.5°C the frequency decreases to one summer every 100 years (Allen *et al.,* 2018). Under the scenario of climate change and warming of 1.5°C, an increase of the mean sea level is observed, however, it is projected to be 0.1 m less than for a warming of 2°C. Also, the oceans absorb around 30% of anthropogenic carbon dioxide resulting in the acidification of water and changes in the carbonate chemistry, which affects a wide range of marine taxonomic groups, aquaculture, and fishing (Allen *et al.*, 2018). For global warming of 1.5°C there exists a high risk of loss of local species, for example, 6% insects, 8% plants, and 4% vertebrates. In the same way, at a rate of 1.5°C of warming there exists a risk of occurrence of forest fires and extreme meteorological events, dispersion of invasive species and appearing of pests and diseases (Raza *et al.*, 2015). According to Abatzoglou and Williams (2016) anthropogenic increases of temperature and vapor pressure deficit have increased the aridity of fuel significantly in forests of Western United States of America for several decades; during 2000-2015 these increases contributed 75% more wooded area which experienced high aridity of fuels during a season of forest fires that was lengthened by nine additional days. There has been an expansion of desert areas and vegetation modification under the warming by 1.5˚C; existing evidence shows that the increase of desert areas is related to changes in meteorological patterns, mainly evaporation changes (Roderick and Farquhar, 2004). In countries located in high latitudes, tundra is being encroached by timber bush which increases the risk of occurrence of fires. In summary, change in climate shows a great potential for destruction of natural resources of the world.

Global warming and its effect also influence agricultural productivity and human health. Extreme variations of weather have significant agricultural consequences either by extreme temperatures or extreme soil moisture levels (excess, deficit/drought). Climate change leads to a series of alterations in parameters or agroclimatic indicators, such as reduction/increase of growing season in terms of temperature or precipitation. Substantial increases of temperature promote the arrival of new plague insects, which could represent a threat for some agricultural species that in the past had been exempt of this kind of damages (Raza *et al.*, 2015). The increase of temperature is also associated with changes in growing degree days (heat units), crops, reference evapotranspiration changes (ET_0), changes in irrigation requirements, changes in the use of water by crops and pumping (Ojeda *et al.*, 2011; Ruiz *et al.*, 2018).

To date, some health damages have also been documented. According to Bell *et al.* (2018) extreme weather and climate events affect human health, cause death and diseases, and generate great socioeconomic impacts. Among the phenomena that affect humans more are heat and cold waves, droughts, fires, dust storms, urban and coastal floods, high tides, and hurricanes. The more common damages provoked by extreme events are death by freezing, hypothermia, cardiac arrhythmia, heart attack, and loss of cerebral blood flow (Bell *et al.,* 2018). Also, in 1995 heat waves associated with high humidity caused 500 deaths in Chicago and more than 800 in all the territory of the United States of America (Bell *et al.,* 2018). It can be observed that climate change effects do not exclude man either or his productive activities; understanding the magnitude of these changes will help mitigate impacts.

Warming of the climatic system has positive effects on the precipitation pattern in specific regions of the world. It is known that a warmer atmosphere can keep more moisture; globally, the water vapor increases by 7% per centigrade degree of warming. The precise way in which this is going to impact global precipitation is not known yet but is very likely that total precipitation volume increases between 1 and 2% per centigrade degree of warming (see: https://www.theguardian.com/environment/2011/dec/15/climate-change-rainfall). There is evidence that shows that humid regions could get more humid, and sub-tropical dry regions could get drier and are moved to the poles. It is expected that in a warmer weather intense precipitation increases, which could lead to a bigger risk of floods (see https://www.theguardian.com/environment/2011/dec/15/climate-change-rainfall). According to Bitanja (2018), in the artic, temperature increases between two and three times faster than the global average and influences the intensification of hydrological cycle in the northern region. One factor that contributes to the precipitation increase is the positive trend of evaporation and the moisture transport to the poles. Also, in this region, the precipitation increase is between 50 and 60% in the XXI century; of that increase, 70% is caused by local warming and 30% is owing to nonlocal dynamical processes related to precipitation (Bitanja, 2018). In the United States, annual average precipitation has increased around 4% in the period 1901-2015, and is slightly less than the increase of 5% reported in the Third National Climate Assessment (NCA3) in the period 1901-2012 (USGCRP, 2017). Seasonally, national increases are more significant in fall, while in winter changes are short. In the North, Midwest and Great Plains precipitation has increased; while in Southwest and Southeast it has decreased. The annual precipitation decrease through the United States since NCA3 seems to be the result of recent and persisting droughts in West and Southwest (USGCRP, 2017). Almazroui *et al.* (2017) mention that an increase in the frequency of wet periods for two climatological periods (2020-2049 and 2070-2099) is expected in a watershed of Saudi Arabia; moreover, it is attributed to the increase in extreme precipitation events and to the decrease of dry spells that will occur in this region at the end of the 21st century. According to Dore (2005), great precipitation variability is expected in all regions of the world. Also, it is expected that humid areas become more humid, and arid lands become more arid. Currently, precipitation increases in high latitudes (northern hemisphere), while in China, Australia, and small island states of Pacific reductions occur (Dore, 2005). In synthesis, climate change effects foresee precipitation increase in a great part of the continental surface, so it is important to study and characterize those precipitation increases in terms of magnitude, geographical location, and destructive force.

1.1.2. Climate change in Mexico

In Mexico, different social sectors are being affected by global warming. In this country, 2011 was the driest year in the previous seven decades, so that the absence of precipitation affected around 40% of the Mexican territory. In years previous to 2011, there had already been extreme and lengthy rains so that analogously 2010 was the rainiest year. During the 2011 drought, the states more affected by the absence of rain were Sonora, Chihuahua, Coahuila, Durango, Nuevo Leon, and Zacatecas, where there was a loss of around 450 thousand cows. The crops more affected were the ones in the North, mainly wheat and corn. The drought also brought with it the depletion of water reservoirs, which in turn caused that in the next year (2012) the irrigation water requirements were not met (see https://expansion.mx/nacional/2011/11/09/la-sequia-del-norte-de-mexico-es-la-peor-en-70-anos-advierten-autoridades). In Mexico, the global warming effects also are expressed at regional levels. Results from research show that for some parts of Mexico modifications of hydrological and agrometeorological patterns have been observed. In Zacatecas, changes in some meteorological variables have been reported; in an analysis of changes in temperature Brito-Castillo *et al.* (2009) found that in the South the diurnal temperature range (DTR) increased due to the increase in maximum temperature and the decrease in minimum temperature. In the North, DTR decreased owing to the decrease in maximum temperature and the increase of minimum temperature.

In the Northwest, Arriaga-Ramírez and Cavazos (2010) found positive trends in the number of very wet days and the number of days with intense precipitation. They explained that one part of these trends was attributed to natural oscillations, and other parts could be explained by global warming. Breña-Naranjo *et al.* (2017) found an evaporation decrease of -3.3 mm per year during the period 1961-2010 and showed that wind speed and net radiation had the biggest significant statistical correlation with evaporation. In Sinaloa, Ojeda *et al.* (2011) found that climate change was reflected in temperature changes which, in turn, modified the growth of crops, growing degree days, reference evapotranspiration, and irrigation requirements.

On the other hand, in Aguascalientes, important changes in some hydrometeorological variables have also been reported. Ruiz *et al.* (2016) statistically documented significant trends in monthly maximum and minimum temperatures, and commented that the distribution of trend was pretty heterogeneous. Also, statistically significant changes in evaporation time series have been reported, which also have had a heterogeneous spatial distribution in Aguascalientes state (Ruiz *et al.*, 2018). In this state, there also exist reports about the depletion of water level in wells and the pollution of their waters. This situation puts a higher risk on the future of both rainfed and irrigated agriculture (CNA-WMO, 2006). In general, for Mexico, advances in climate change are scarce and gradual, they are constrained to some regions and few meteorological variables. For this reason, a diagnostic study of hydro-meteorology would provide valuable information for the design of strategies for adaptation/mitigation of climate change in Aguascalientes, Mexico.

1.2. Objectives and hypothesis

Considering the information that exists in the Mexican Republic and Aguascalientes for making decisions that contributes to climate change detection and generation of strategies for adaptation/mitigation, this work will have the following objectives:

1.2.1. General objective:

To carry out a study of trends in hydro-meteorological variables with consideration of climate change in Aguascalientes, Mexico.

1.2.1.1. Specific objectives

i. To determine spatio-temporal trends in monthly pan evaporation in Aguascalientes, Mexico. Evaporation reduction is explained by the combined effect of reduction of wind speed, solar radiation, and maximum temperature, and due to the relative humidity increase. However, the most important reason is the reduction in the diurnal temperature range (DTR). On the other hand, evaporation increases are due to increases in solar radiation, number of sunny days, wind speed, and decrease of relative humidity. These factors cause augments in DTR, which is the main cause of evaporation increase.

ii. To study temporal trends in daily extreme temperature indices in Aguascalientes, Mexico. The cause of temperature trends is explained by the theory of changes in radiative balance caused by natural agents, such as solar irradiance and volcanic eruptions; and also, by anthropogenic agents like greenhouse gasses among which are carbon dioxide, methane, nitrous oxide, water vapor, ozone, and aerosols. Solar irradiance shows changes, and its main causes are sunspots that originate in the photosphere of sun and that in turn produce magnetic fields. Gasses present in the atmosphere can impede the passing of any kind of radiation to the earth, which can cause cooling, and can also reflect the radiation as long wave radiation and provoke a warming of the surface. Greenhouse gasses can absorb energy reflected from earth when this has an albedo relatively high and reflect it back to the terrestrial surface.

iii. To analyze trends in daily extreme precipitation indices in Aguascalientes, Mexico. The cause of changes on precipitation pattern is explained through the thermodynamics of atmosphere, and by the emission of particles and aerosol. With respect to the thermodynamics of atmosphere, it is known that changes in temperature affect the water holding capacity and vapor pressure. We incorporate the definition of Clausius-Clapeyron equation and an explanation about how precipitable available water changes in the atmosphere.

iv. To explain the implications of trends in hydrometeorological variables in Aguascalientes' agriculture. Crops have an optimum thermal range in which growth and development occur. If temperatures are within this range, the plant keeps active, carries out vital processes, and produces acceptable economic yields. However, if temperature, either diurnal or nightly, is out of the required range, stress occurs, which makes it difficult for biological processes and yield. In this chapter, the impacts of either positive or negative trends of extreme indices in Aguascalientes' crops are described. Also, a description of the physical meaning of trends in extreme indices observed is added.

1.2.2. Hypothesis:

i. Global warming is altering cumulative monthly evaporation patterns in Aguascalientes, Mexico.

ii. Extreme temperatures associated with climate variability are having trends as a consequence of climate change.

iii. The temporal patterns in daily extreme precipitation indices vary spatially over Aguascalientes state.

iv. The trends in hydrometeorological variables and extreme indices can affect crop growth and development.

This research was carried out for evaluate if hydrometeorological changes exist simultaneous to the changes that the physical context of Aguascalientes has faced in recent years. This state is located in the central plateau, in the region known as North-Central Mexico. It has a significant area of lands that harbor different types of desert vegetation, and also lands dedicated to agricultural activities and to the exploitation of natural resources. Paradoxically, in these arid lands, agriculture that produces the highest yields is practiced, and also here a big part of crops more profitable in Mexico is found. In this state, cereals, forage, vegetables, and deciduous fruit trees of cold climate and high commercial value are cultivated; also, here one part of the most important milk production and industrial region of the country is found. However, similar to the rest of arid lands, this ecosystem presents great fragility due to water limitations and the misuse of natural resources. This region is also being affected by the accelerated augment of population and by the demand of goods and services of society.

There has been the growth of industry, agriculture, and livestock, increase of urban surface/cover, and decrease of forest area (INEGI, 1990; INEGI, 2016). Lately, a series of meteorological adverse phenomena have been observed, such as the 2011 drought which affected economically and socially. In the last three years, in this state extreme precipitation events of high frequency have been registered which have provoked floods with important economic consequences. In this situation, agricultural environment has responded with floods, large runoff volumes, and erosion putting at risk the sustainability of soils and local agriculture. Also, agroclimatic changes have been detected, such as changes on temperatures of agricultural interest and growing degree days, changes in the duration of growing season and irrigation requirements (Ojeda *et al.,* 2011). In the same way, in the last three decades, this state has been showing enormous changes in the land use (INEGI, 1990; INEGI, 2016). For these reasons, we consider that the Aguascalientes hydrometeorological analysis is of vital importance for a more conscious and efficient management of natural and economic resources.

1.3. Structure of dissertation

The objectives formulated in this research are addressed through four chapters. Chapter two focusses on the study of monthly evaporation trend. First, serial database autocorrelation is eliminated. Monthly pan evaporation trend is calculated using two non-parametric techniques. The rate of change of evaporation through the time is estimated with the Theil-Sen estimator. Also, the causes of evaporation trends are discussed since the point of view of the diurnal temperature range (DTR) changes, which is a consequence of changes in a series of weather elements, such as cloudiness, solar radiation, wind speed, maximum temperature, minimum temperature, among others.

Chapter three focusses on the study of 16 extreme indices proposed by CCI/CLIVAR/ETCCDI which are estimated from daily temperature (maximum and minimum). The use of RClimdex software is proposed. First, a quality control analysis of database is carried out and after that indices are estimated. The causes of trends are explained from natural processes, such as changes in solar irradiance and volcanic eruption occurrences. On the other hand, causes are also discussed, taking into account anthropogenic activities and greenhouse effect. Similarly, discussion of the relationship between extreme temperature indices and altitude is incorporated.

Chapter four is a study of 11 extreme precipitation indices developed by CCI/CLIVAR/ETCCDI which are calculated from daily precipitation. First, a quality control database is performed and then indices are estimated. Trends causes are discussed from the point of view of changes in water vapor holding of atmosphere, which in turn, changes as a consequence of changes in temperature, that is governed by the Clausius-Clapeyron relationship. Also, causes of trends are explained, since the aerosols and pollutant particles affect the condensation process and precipitation formation. We also add a discussion about the relationship between precipitation extreme indices and elevation.

Chapter five describes Aguascalientes' agriculture. The main crops, their growing season, sowing dates, and potential yields that can be gotten are mentioned. An explanation of water resources of the state, their importance, and current problems being faced is presented. Also, the physical meaning of extreme indices trends, implications, and effects of these trends in the growing cycle of most important Aguascalientes' crops are explained.

Finally, in chapter six, main research conclusions are articulated, and also more important recommendations are stated.

2. SPATIO-TEMPORAL TRENDS IN MONTHLY PAN EVAPORATION IN AGUASCALIENTES, MEXICO[1]

2.1. Synopsis

Emission of greenhouse gases is being alleged to be causing climate change in different regions of the world. The objective of this study was to analyze the spatio-temporal trends of monthly evaporation at 52 weather stations in the state of Aguascalientes (Mexico) which have hydrometeorological records of long periods. The autocorrelation was eliminated with an auto-regressive model, and the trend was determined using the Spearman (S) and Kendall (K) tests. The statistical significance of the trend was determined with the Spearman correlation coefficient (r_s) and the Z statistic (the test statistic of the normal distribution), both indicated that there were statistically significant trends in 107 time series, of these 88 series had negative trends and 19 series had positive trends. Negative trends were present in all months of the year, while positive trends occurred from February to May and from October to December only. The reduction of evaporation from -4.10 to -20.50 mm/month/year from June to September showed a hopeful future scenario for rainfed agriculture. Irrigated agriculture during dry months could have a reduction of irrigation requirements as a consequence of the reduction in reference and crop evapotranspiration. The evaporation increase during dry months could increase irrigation requirements and pumping, mainly in March, April, and November

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[1] Part of this section is reprinted with permission from "Spatio-Temporal Trends in Monthly Pan Evaporation in Aguascalientes, Mexico" by Ruíz-Álvarez O., Singh V.P., Enciso-Medina J., Munster C., Kaiser R., Ontiveros-Capurata R.E., Diaz-Garcia L.A., and Costa Dos Santos C.A. 2018. *Theor. Appl. Climatol.*, 1–4. https://doi.org/10.1007/s00704-018-2514-5. Copyright 2019 Springer Nature.

when there are trends with increases of about 26.90, 24.60 and 23.90 mm/month/year, respectively. The spatial variability of evaporation trend means that other effects of climate change could vary in different parts of the state. Results of this study will be useful for farmers and institutions in charge of the administration of water resources for developing adaptation and mitigation strategies to climate change.

2.2. Introduction

Spatio-temporal trends of meteorological variables play a major role in identifying vulnerable regions, predicting their behavior in the future and defining adaptation strategies. Considerable attention has therefore been paid to trend analysis of temperature, solar radiation, precipitation, and droughts (Liepert, 2002; Ceballos-Barbancho *et al.,* 2004; Kothawale and Rupa Kumar, 2005; Brunet *et al.,* 2007; IPCC 2007; Ceballos-Barbancho *et al.,* 2008). Trends help explain the change of a meteorological variable and show the rate of change per unit of time during a given period. Although there is a large body of literature on analysis of climatic variables, the literature on spatio-temporal climatic trends in specific regions like Mexico is scarce (Moratiel *et al.,* 2011).

Evaporation is one of the most important components of the hydrologic cycle. It is expressed as the depth of water evaporated per unit surface area per unit of time and is a measure of the atmospheric potential for holding water (Liu *et al.,* 2010; Liu *et al.,* 2011). Changes in its pattern are associated with changes in vapor pressure deficit, solar radiation, availability of water, evapotranspiration, temperature, soil moisture, aridity index, and the modification of ecosystem structure (Kirono *et al.,* 2009).

Effects of global warming on hydrometeorological variables, natural resources, and society have been determined by time series analysis (Bayazit and Önöz, 2007; Mandal *et al.*, 2013). In a study on the spatio-temporal trends in the use, deficit and crop water requirements in Europe, Supit *et al.* (2010) found a negative trend in evaporation which was attributed to the reduction of solar radiation in winter and spring during 1976-2005. Analyzing the evaporation trend at twelve locations during 1982-2003 in Western Iran, Tabari and Marofi (2011) found significant positive trends at 67 % of the weather stations, and the rate of increase was 160 mm/month/decade. In a study of evaporation from type "A" pan over the United States, Hobbins *et al.* (2004) found a decreasing pattern in 64 % of the analyzed series. Investigating evaporation and evapotranspiration trends for 1992-2009 at nine locations in South Florida, Abtew *et al.* (2011) found that the increase was due to the rise in vapor pressure deficit.

In Zacatecas, Mexico, Blanco-Macías *et al.* (2011) analyzed the spatio-temporal trends in evaporation at 40 weather stations; the mean rates of decrease and increase were -0.9 mm/year and 1.09 mm/year, respectively, and were correlated to El Niño. In India, Chattopadhyay and Hulme (1997) found negative patterns in evaporation and evapotranspiration for two seasons of the year and two historical series (15 and 32 years) and they argued that negative trends have serious economic and environmental implications. Roderick and Farquhar (2004) found in Australia that evaporation from type "A" pan decreased at a rate of 4 mm/year at 14 of 30 weather stations, but the trend did not have a definite spatio-temporal pattern, perhaps due to the reduction in the desert. Other researchers have studied evaporation trends in several parts of the globe and have evaluated the evaporation paradox, which states that evaporation reduces while temperature increases (Roderick *et al.,* 2007; Cong *et al.,* 2009).

In Mexico, there have been few studies on the effect of climate change on evaporation and evapotranspiration and their impacts on agriculture (Breña-Naranjo *et al.*, 2017). This situation has restricted the possibility of finding alternatives for mitigating the adverse effects on the agricultural sector (Ojeda-Bustamante *et al.,* 2011). Studies on trends in climatic variables have mainly focused on temperature with emphasis on growing degree days, cold units and aridity index (Lemus and Gay, 1988; Ojeda-Bustamante *et al.*, 2011; Ruiz-Corral *et al.,* 2011; Santillán-Espinoza *et al.,* 2011; Zarazúa-Villaseñor *et al.*, 2011). However, spatio-temporal trends in evaporation have not received much emphasis, even though this is a key for developing strategies for water resources management, especially in arid lands where water is scarce, intermittent, and unpredictable (Liu *et al.*, 2004; Liu *et al.,* 2010). The objective of this chapter, therefore, was to determine the existence or absence of spatio-temporal trends in 602 time series of monthly evaporation from 52 weather stations in Aguascalientes, Mexico.

2.3. Materials and methods

2.3.1. Area of study

Aguascalientes state is located between 21° 38´and 22° 27´ north latitude and 101° 53´and 102° 52´ west longitude in the North Central region of Mexico. It has an area of 5617.8 km^2, from which 2407.7 km^2 are used for agriculture, 1406.1 km^2 for grassland, 929.8 km^2 for forests, and 325.4 km^2 are jungle (INEGI 1995) (Figure 2.1). Aguascalientes borders Zacatecas state on the north, east and west, and Jalisco state on the south (Figure

2.1). According to Garcia´s classification, the major part (68.90 %) of Aguascalientes state is semi-dry and temperate (BS1k), 17.70 % of the area is semi-dry warm (BS1h), and 13.40 % of the territory is temperate and subhumid [C(w)] with rainfall in summer (García 1973). Figure 2.2 was constructed using monthly mean precipitation, evaporation, maximum and minimum temperature [these are the variables commonly observed on the conventional weather stations of Comision Nacional del Agua, (CNA)] observed during 30 years at 52 weather stations in Aguascalientes state.

In general, the four temperatures show a similar pattern through the year, especially mean maximum/minimum temperature and their extremes. With respect to mean maximum temperature, this increases linearly from January, the month in which minimum value (21.8 °C) occurs and it reaches its maximum (30.3 °C) value on May; after this month it starts to decrease, perhaps due to the precipitation increase and its cooling effect, but also owing to radiation decrease; in Aguascalientes the annual mean maximum temperature is 25.9 °C. The upper extreme maximum temperature is the deviation that the mean maximum temperature can show as a function of location and month; this deviation can vary between 2.3 and 3.7 °C which correspond to August and May, respectively. In connection with mean minimum temperature, this increases slowly from January the month in which minimum value (3.2 °C) occurs and increases until June when the maximum value (13.1 °C) occurs; after June the mean minimum temperature decreases perhaps due also to radiation decrease; in Aguascalientes the annual mean minimum temperature is 8.6 °C. The lower extreme minimum temperature is the deviation that the mean minimum temperature can show as a function of location and month; this deviation can vary between 2.2 and 3.4 °C which correspond to December and July, respectively.

Potential evaporation of water from the earth surface to the atmosphere varies from 113.7 (December) to 235.5 mm (May); annual mean total evaporation is 1958.5 mm. For providing an idea about the spatial pattern in the atmospheric water demand, shown in Figure 2.3, a map with the annual mean evaporation in the Aguascalientes state is presented. This map was constructed with information from climatological normals (1981-2010) generated by Servicio Meteorologico Nacional of Comision Nacional del Agua.

Finally, precipitation has a unimodal regime; the month with less mean precipitation is March (3.4 mm), while the month with the higher value is July (130.4 mm); and annual mean total precipitation is 516.8 mm. Aguascalientes state has a semi-arid climate since the estimated P/PET (in this quotient, PET was calculated multiplying 0.75 by annual total evaporation) ratio is 0.35.

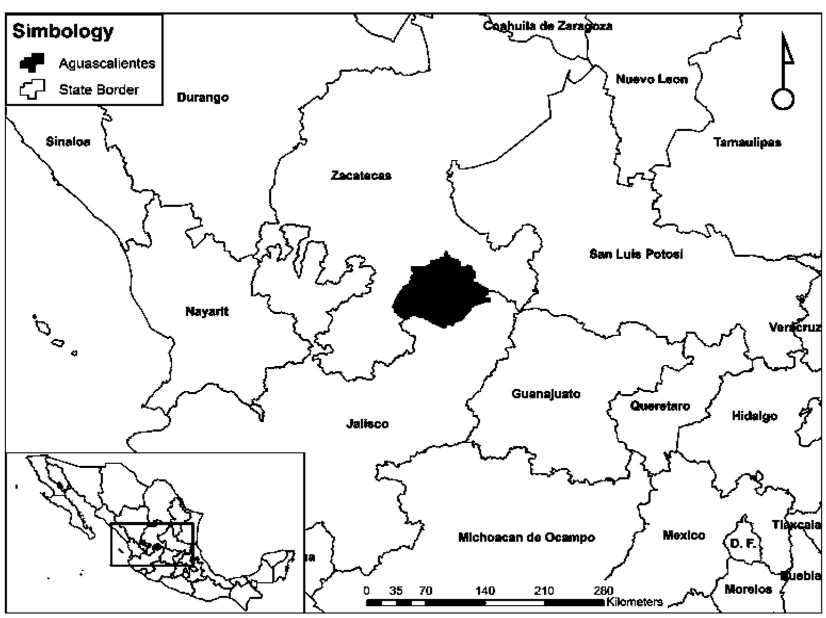


Figure 2.1. Location of Aguascalientes state in Mexico.

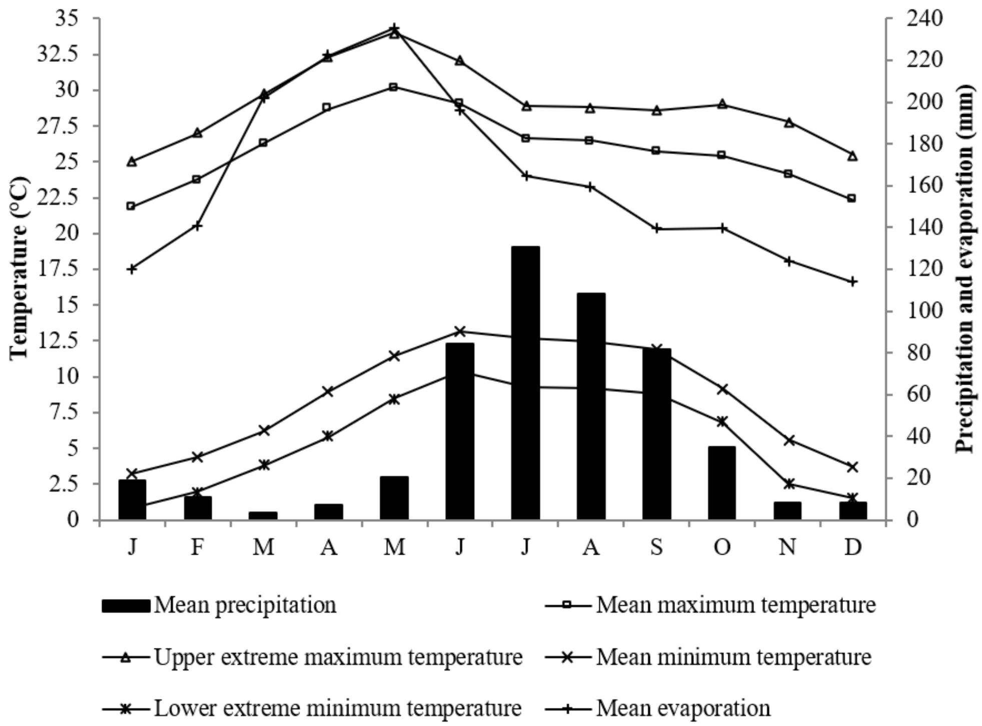


Figure 2.2. Temperature, precipitation and evaporation in Aguascalientes.

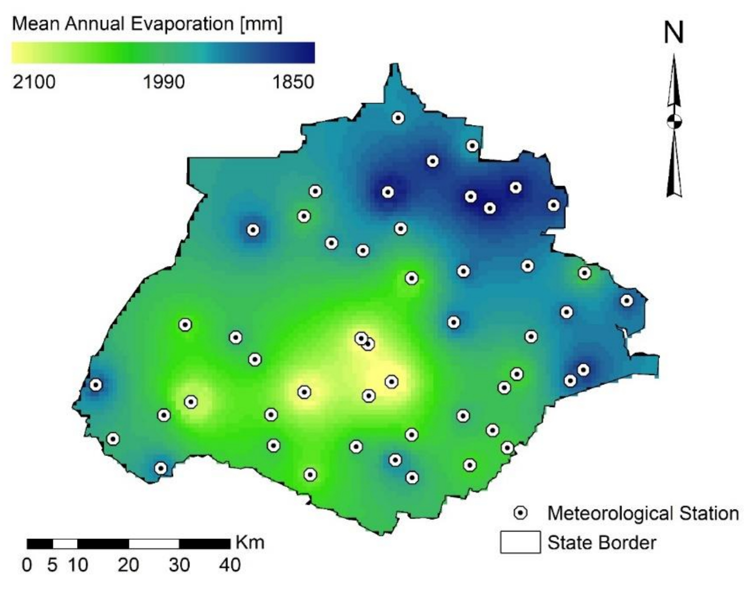


Figure 2.3. Spatial variation of mean annual evaporation in Aguascalientes (period 1981-2010).

2.3.2. Meteorological data

Daily evaporation data from type “A” pan were obtained from 52 weather stations from Aguascalientes state, managed by Servicio Meteorologico Nacional (SMN) (Table 2.1). Before starting this research, the evaporation database had already been subjected to a quality analysis by the staff of CNA, the agency in charge of managing, regulation and protection of national waters of Mexico; the analysis that this dependency carries out consists of deleting daily outliers within a month and for each weather station, that is to say, those daily evaporation measurements that were out of an interval (upper and lower limit) were deleted, this interval is defined by two allowable thresholds (maximum and minimum) (Portocarrero; personal communication), for this reason, we did not carry out another quality analysis of the data. Monthly evaporation was obtained by adding daily evaporation, and these data were used for trend analysis.

In this work one time series was defined for each month per weather station, so that at each weather station we had twelve time series. In theory, considering 52 meteorological stations we would have 624 time series, but since some stations did not have information in the twelve months, we only had 602 time series.

2.3.3. Management of meteorological data

A trend test requires independent data. When there is autocorrelation the probability to make type I error is high; type I error is the incorrect rejection of the null hypothesis when there is actually no trend, its probability is equal to the assigned significance level (Bayazit and Önöz, 2007). For avoiding this error, von Storch (1995) proposed a pre-whitening method which eliminates auto-correlation through an auto-regressive model that generates a new time series which can then be analyzed. The auto-correlation is eliminated using the model (von Storch, 1995):

$$Y_t = X_t - r_1 X_{t-1} \tag{1}$$

where Y_t is the new series data at time t, X_t is the original series data at time t, X_{t-1} is the original series data at time t-1, and r_1 is the serial correlation coefficient of the sample which is estimated as (Yue and Wang, 2002):

$$r_1 = \frac{\left(\frac{1}{(n-1)}\right)\sum_{t=1}^{n-1}[X_t - E(X_t)][X_{t+1} - E(X_t)]}{\frac{1}{n}\sum_{t=1}^{n}[X_t - E(X_t)]^2} \tag{2}$$

Furthermore,

$$E(X_t) = \frac{1}{n}\sum_{t=1}^{n} X_t \tag{3}$$

2.3.4. Trend analysis

The trend analysis was made with two non-parametric techniques:

2.3.4.1. Spearman test

According to del Río *et al.* (2005), the trend of a meteorological series can be obtained through the Spearman correlation coefficient and a linear regression of two series (i and y_i) as:

$$r_s = 1 - \frac{[6\sum(y_i - i)^2]}{[n(n^2 - 1)]} \tag{4}$$

where n is the number of years, and i is the order of elements, additionally r_s has a normal distribution with μ=0. For testing the null hypothesis (H_O) which establishes that there is no trend, one must calculate the probability (Tabari and Marofi, 2011) as:

$$\propto = P(|u| > |u(r_s)|) \tag{5}$$

$$u(r_s) = r_s(n-1)^{\frac{1}{2}} \tag{6}$$

The criterion for rejecting the hypothesis is: if $\alpha < \alpha_0$ the null hypothesis is rejected at a significance level (α_0) set at the beginning of the test. The level of significance used in this study was 0.05; there is a positive trend if $r_s > 0$ or negative if $r_s < 0$.

2.3.4.2. Kendall test

The Kendall test assesses the significance of a trend and when combined with Spearman coefficient it gives a higher confidence. This technique does not require that data be adjusted to a particular distribution and if there are missing data in the series, the results are not significantly affected (del Río *et al.*, 2005). From each value of the series the value of the following year is subtracted, if the resultant magnitude is positive it takes on +1; if it is negative, it takes on -1. At the end the total of +1 and -1 is counted which determines the S value as described below (Hamed, 2008):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(x_j - x_k\right) \tag{7}$$

$$sgn\left(x_j - x_k\right) = \begin{cases} +1 \ if \ x_j - x_k > 0 \\ 0 \ if \ x_j - x_k = 0 \\ -1 \ if \ x_j - x_k < 0 \end{cases} \tag{8}$$

where x_j and x_k represent the values in the years j and k, furthermore $j > k$.

When n is ≥ 10 S tends to the normal distribution with $E(S) = 0$ and variance:

$$VAR\ (S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \quad (9)$$

where *q* is the number of tied groups and *tp* is the number of data in the *pth* group. Then, *S* and *VAR (S)* are used for estimating the test statistic *Z* (Tabari and Marofi, 2011):

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}\ if\ S < 0 \end{cases} \quad (10)$$

A positive value of *Z* indicates an upward trend, while a negative value suggests a downward trend. H_O is rejected in favor of H_A if the absolute value of *Z* is greater than $Z_{1-\alpha/2}$ (Hamed, 2008).

2.3.4.3. Theil-Sen trend estimator

The evaporation trend was estimated using the nonparametric Theil and Sen method (Theil, 1950; Sen, 1968). The method is based on estimating *N´* slope estimate, *Q*:

$$Q = \frac{x_{i'} - x_i}{i' - i} \quad (11)$$

where $x_{i'}$ and x_i are the values at times *i´* and *i*, respectively, and *i´>i*; *N´* is the number of data pairs for which *i´>i*. The median of *N´* values of *Q* is Sen´s estimator of slope. Furthermore,

$$N' = \frac{n(n-1)}{2} \quad (12)$$

where *n* is the number of time periods. The *N´* values of *Q* are ranked from the smallest to the largest and the median of these *N´* values of *Q* is Sen´s estimate of slope computed as:

$$Sen\acute{}s\ estimator = \begin{cases} Q_{\left[\frac{(N\acute{}+1)}{2}\right]}\ if\ N\acute{}is\ odd \\ \frac{1}{2}\left[Q_{\left(\frac{N\acute{}}{2}\right)} + Q_{\left(\frac{N\acute{}+2}{2}\right)}\right]\ if\ N\acute{}is\ even \end{cases} \tag{13}$$

Then, to determine whether the median of slope is statistically different from zero, the next confidence interval is estimated:

$$C_\alpha = Z_{1-\frac{\alpha}{2}}\sqrt{VAR(S)} \tag{14}$$

where Var(S) was defined in equation (9) and $Z_{\alpha/2}$ is obtained from the normal distribution table.

2.4. Results and discussion

2.4.1. Time series and serial autocorrelation

Forty-seven of fifty two stations had evaporation data during the twelve months of the year, and five stations had data between five and eleven, so that a total of six hundred and two time series were obtained for analysis. Positive or negative auto-correlation was found in 91% (548 series) and 9% (54 series) of the series, respectively. The positive auto-correlation increases the risk of rejecting the null hypothesis when it is true, and negative autocorrelation decreases the risk of rejecting it.

2.4.2. Spatio-temporal evaporation trend

Table 2.2 presents a summary of the number of time series statistically significant/not significant obtained in this study, and also the calculated values of Theil-Sen (Q) are shown, that is to say, the value of monthly evaporation trend. Of the total number of analyzed time series, only a small proportion of stations presented statistical significance and different spatial and temporal variation. Out of six hundred and two analyzed series, just 107 (17.77%) had statistically significant ($p \leq 0.05$) trends (Table 2.2). Nineteen time series with positive significant trends were identified (Table 2.2), which constitute 17.75 % of total series with statistical significance. These trends were distributed from February to May and from October to December. It is observed that there were 88 time series with significant negative trends (Table 2.2), that is 82.24 % of total time series with statistical significance. Unlike positive trends, negative trends were during the twelve months of the year and these trends were more prevalent.

2.4.2.1. Negative trends

There are six regions where significant negative trends ($p \leq 0.05$) showed a different pattern. In the northern part of the state, Rincon de Romos and Tepezala municipalities showed significant negative trends at stations Puerto de la Concepcion, Tepezala, Presa Potrerillos and Rincon de Romos in January and from March to December. In the center of the state, Pabellon de Arteaga and Jesus Maria municipalities showed negative trends at stations Campo Experimental Pabellon, Presa Jocoque and Venaderos in January through March, August, September, November, and December. On the other hand, in the northwest part of the state, San Jose de Gracia municipality had a negative trend in La Tinaja, Presa 50 Aniversario, and Presa Plutarco Elias Calles in February through November. In the east of the state, El Llano and Asientos municipalities had negative trends at Palo Alto, San Isidro, El Novillo, Las Fraguas, La Tinaja II, Villa Juarez and Asientos in March through August, October, and November. It is important to mention that the highest value of negative trend was at El Llano municipality (weather station Palo Alto) in the month of April and was about -24.27 mm/month/year. In the south of the State, particularly in Aguascalientes municipality, negative trends were at Cañada Honda, Presa El Niagara, Sandovales, Montoro and El Ocote I in January through July and in September through December. Finally, in the southwest of the State, Calvillo had negative trends at Presa La Codorniz and Calvillo in January, March, June, July and from September to November. It is important to mention that there were places (22 weather stations) that had only significant negative trends through the year (Table 2.2), in these places there are small rural areas where rainfed and irrigated agriculture is practiced, there is shrub and mountain vegetation; bodies of water are relatively big, such as dams (the biggest dams of Aguascalientes). It is important to underline that there were two cases of stations in which, in addition to having months with negative trends, also they had months with positive trends through the year, for example Puerto de la Concepcion and San Isidro (Table 2.2), the first location is characterized by some shrubs, a rivulet and some agriculture; the second location has small rural population, irrigated agriculture is practiced and there are short bodies of water.

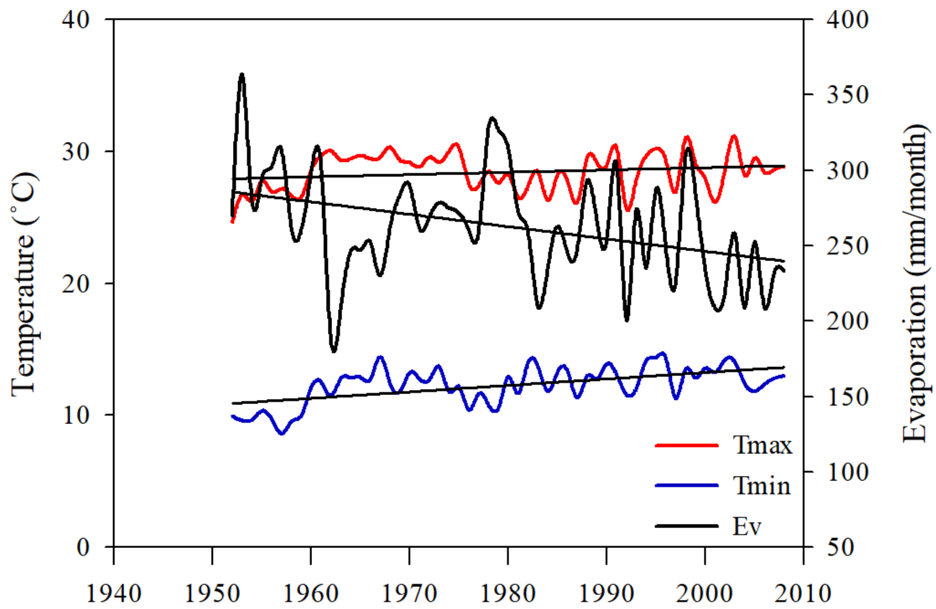
Some authors (Liu *et al.,* 2010; Liu *et al.,* 2011; Mandal *et al.,* 2013) argue that the decrease in evaporation is due to the combined effect of reduction in wind speed, solar radiation, and daily maximum temperature as well as due to the increase in relative humidity. Roderick and Farquhar (2002) explained that evaporation is reduced due to the decrease in diurnal thermal range (DTR), that is to say, even though the mean global temperature has increased, the dew point temperature (DPT) has increased as well, but at a rate higher than the maximum temperature. When DTR is reduced, the vapor pressure deficit (VPD) gets a reduction as well and makes that air gets saturated more rapidly so that the evaporation rate gets smaller (Cong *et al.*, 2009). Recent studies reveal that in different parts of the world, the increase of minimum temperature (T_{min}) is causing an important reduction of the thermal oscillation (Price *et al.*, 1999; Yan *et al.*, 2002; Santillán-Espinoza *et al.*, 2011) which could explain the evaporation reduction in regions where there is no data for DPT and making a valid estimate, as proposed by Roderick and Farquhar (2002), since with the exception of tropics T_{min} is quite similar to DPT (Allen *et al.*, 1998). The seasonal behavior of trends observed in the study is consistent with the findings of Liu *et al.* (2010) and Liu *et al.* (2011) for arid regions in China, where they found that the greater proportion with negative trends occurred in spring, summer, and autumn.

Figure 2.4 presents time series of evaporation for some months at weather station Presa Potrerillo where negative trends were significant ($p \leq 0.05$) in January (-8.55 mm/month/year), March (-15.82 mm/month/year), April (-17.30 mm/month/year), May (-12.47 mm/month/year), July (-9.92 mm/month/year), August (-7.85 mm/month/year), September (-9.12 mm/month/year), October (-8.80 mm/month/year) and November (-8.02 mm/month/year); for this weather station February (-7.01 mm/month/year), June (-12.52 mm/month/year) and December (-6.33 mm/month/year) were not statistically significant (Table 2.2). In Aguascalientes, the negative trend of evaporation is explained by the reduction of DTR which is occasioned by the statistically significant increase/decrease of T_{min}/T_{max}. This occurred, for example, at weather station of Presa Potrerillos in May (Figure 2.4a), July (Figure 2.4b), August (Figure 2.4c), September (Figure 2.4d), October (Figure 2.4e), and November (Figure 2.4f) when there was a significant positive trend in

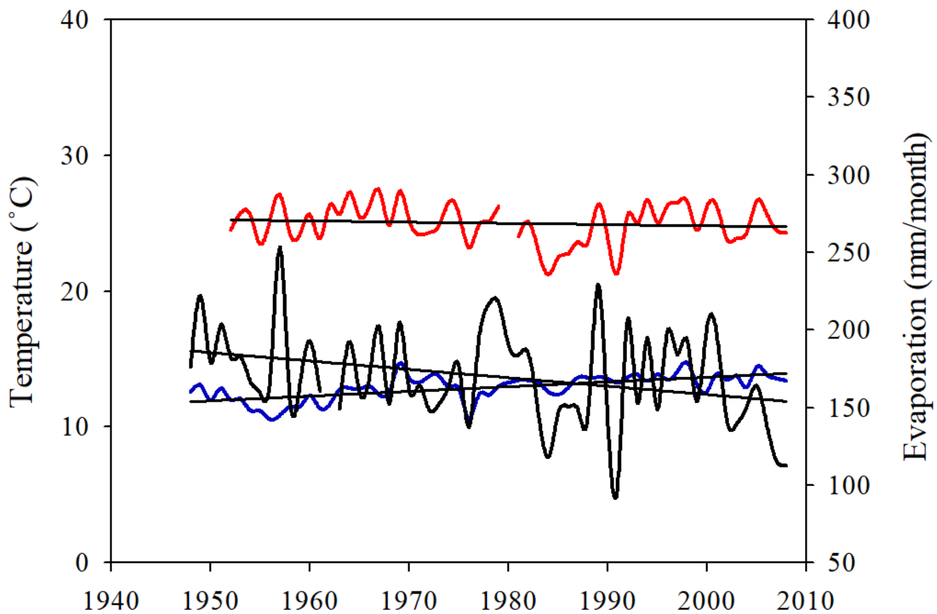
T_{min} between 0.02 and 0.04 °C/month/year and significant negative trend in T_{max} of about -0.03 °C/month/year in September (Figure 2.4d).

Responsible factors of evaporation decrease in Aguascalientes

The evaporation decrease in Aguascalientes also can be explained by the same causes of evaporation decrease in other regions of north hemisphere. According to Rebetez and Beniston (1998), the decrease in sunshine hours influences the reduction in water absorption capacity (in terms of DTR) of the environment, the sunshine decrease is due to the increase in cloud cover (Dai *et al.,* 1999). When cloud cover increases, the diurnal incoming solar radiation diminishes and nocturnal long-wave solar radiation output gets slow which reduces the maximum temperature and increases the minimum temperature (Jhajharia and Singh, 2011); so as a consequence, the DTR and evaporation are reduced (Roderick and Farquhar, 2002; Roderick *et al.,* 2007; Limjirakan and Limsakul, 2012; Xing-Jie *et al.,* 2012). On the other hand, different studies in China, Australia and Thailand show that the main cause of evaporation reduction is the reduction in wind speed which clarifies the evaporation paradox (Roderick *et al.,* 2007; Limjirakan and Limsakul, 2012; Xing-Jie *et al.,* 2012).



(a)



(b)

Figure 2. 4. Time series of evaporation and temperature for May (a), July (b), August (c), September (d), October (e) and November (f) at Presa Potrerillos weather station.

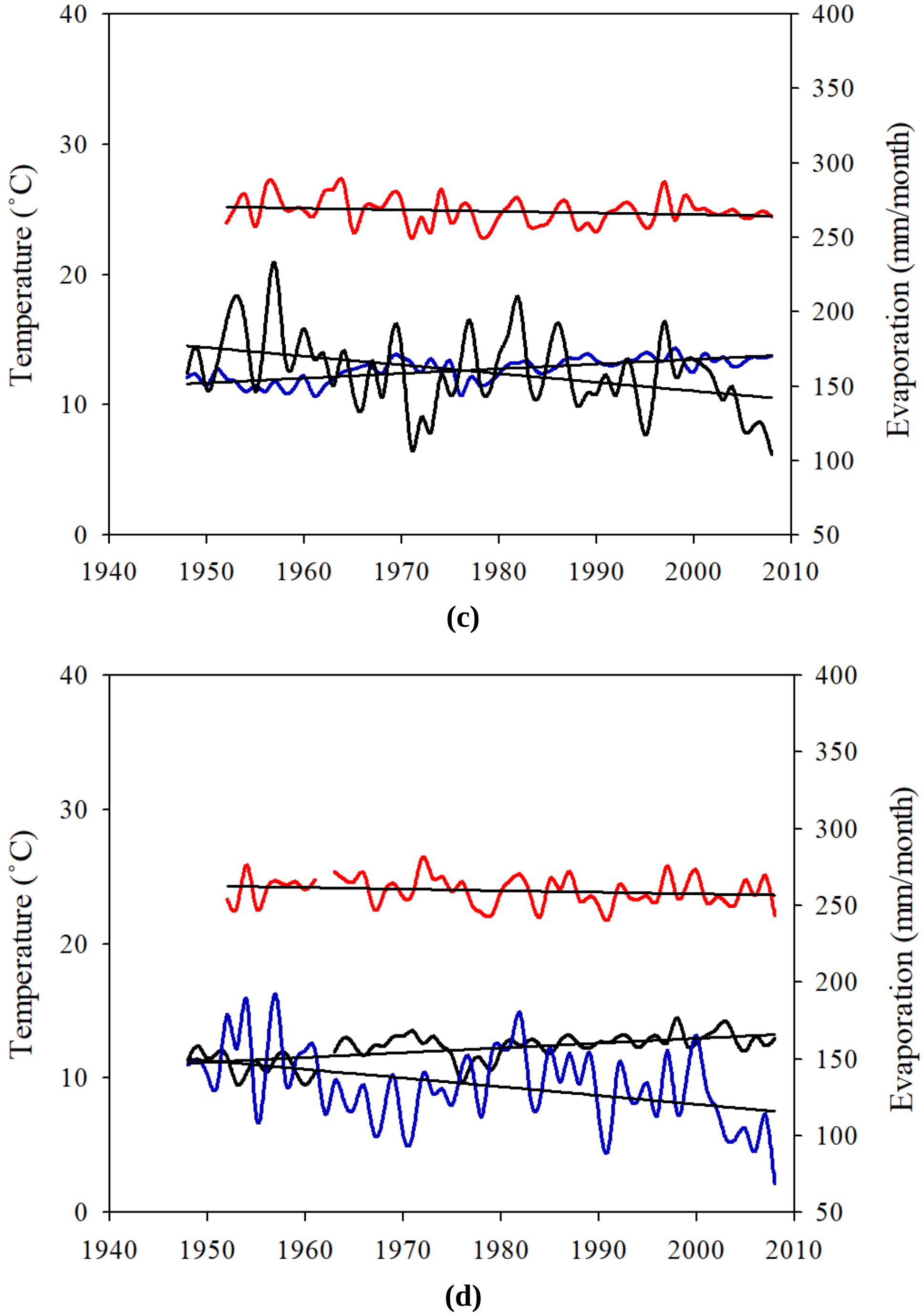
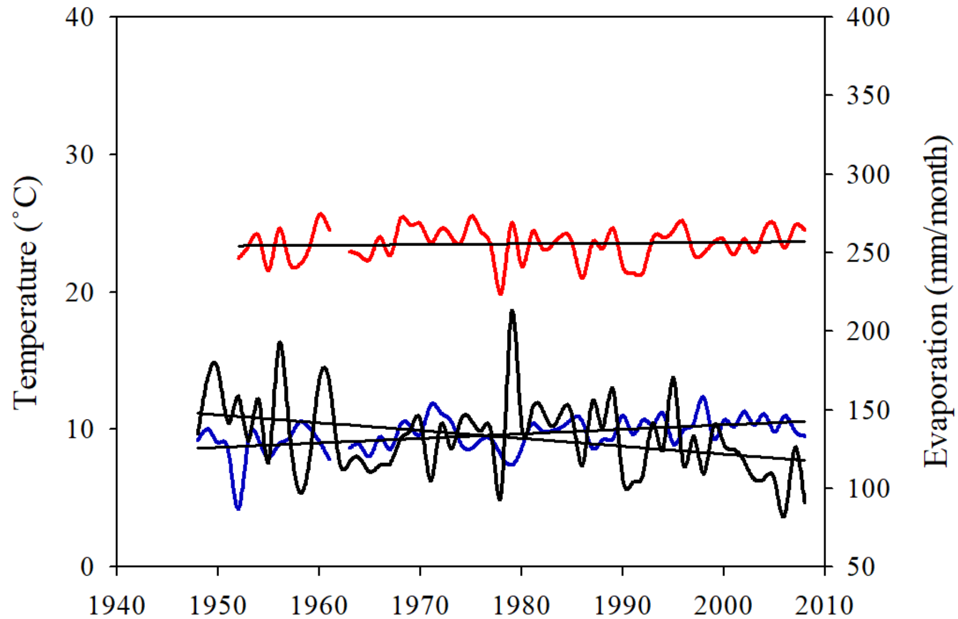


Figure 2.4 Continued.



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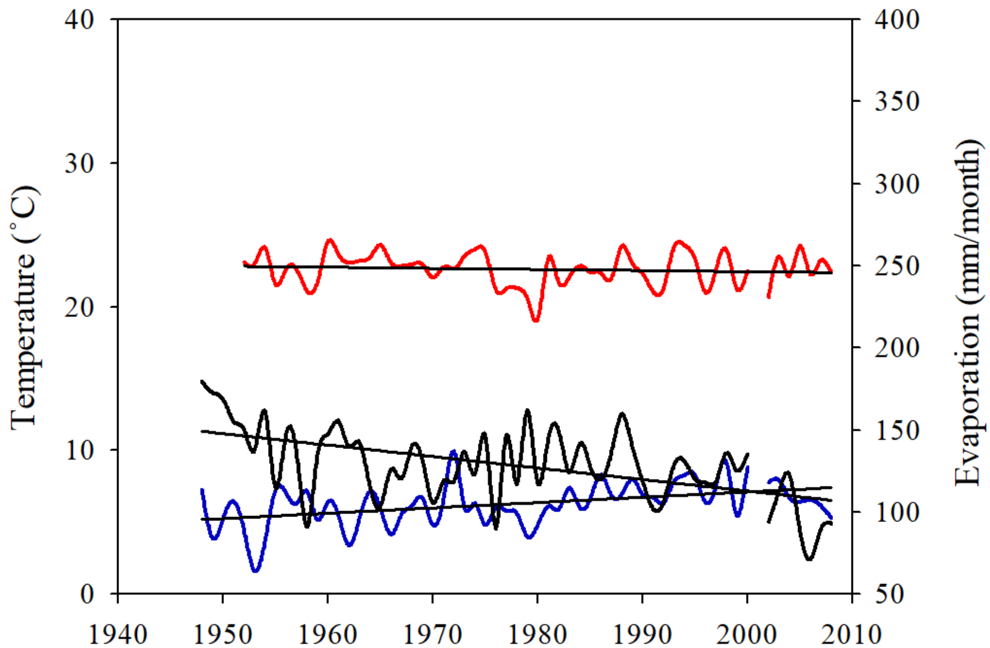


(f)

Figure 2.4 Continued.

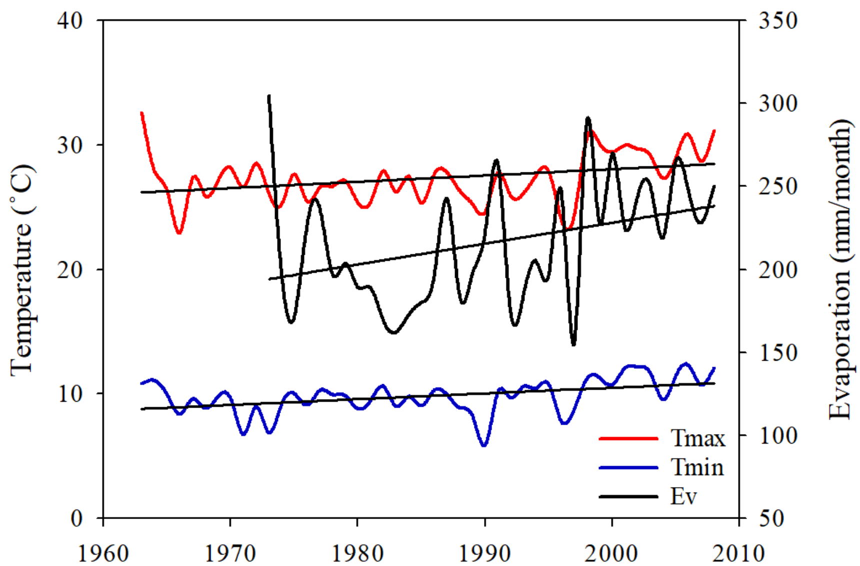
2.4.2.2. Positive trends

Significant positive trends ($p \leq 0.05$) were distributed differently in the five regions. In the north of the state, Tepezala municipality presented a significant positive trend at weather station Puerto de la Concepcion just in April. In the center of the state, Jesus Maria and San Francisco de los Romo municipalities presented positive trends at weather stations Jesus Maria and San Francisco de los Romo in May, November and December. In the east, El Llano municipality had positive trends in March, November and December at weather stations San Isidro, Jesus Teran and Rancho Seco. It is important to mention that in this late municipality the highest significant positive trend (weather station Rancho Seco) was found which was 26.91 mm/month/year in March. In the south of the state, Aguascalientes municipality presented significant positive trends in February, April, May, October and November at weather stations Arellano, Cieneguilla, and Calvillito. In the southwest of the State, Calvillo municipality had significant positive trends from February to April, November and December at weather stations Presa Media Luna and Malpaso. It is important to mention that of the 19 time series with significant positive trends, 11 are located in the south and southwest of the state (six in Aguascalientes and five in Calvillo). There were no significant positive trends in January, June, July, August and September. Nine locations (Table 2.2) only had significant positive trends through the year, they are characterized for having zones with bare soils, they are inside or close to urban areas and relatively big rural populations, they possess fallow land; in some of these locations some irrigated agriculture and a little rainfed agriculture are practiced. According to Fan and Thomas (2013), evaporation increases mainly due to increasing solar radiation, number of major sunny days, increasing wind speed, and decreasing relative humidity. In rainfed agriculture, the evaporation increase translates into a reduction of soil moisture, which is critical when crops are in reproductive stage. The area of study escapes this situation, because with exception of Jesus Maria (May) and Arellano (May), the months with significant positive trends ($p \leq 0.05$) are not in the period of crop growth, called spring-summer (May-September). In areas with natural vegetation, the evaporation increase modifies the distribution of species, affecting the aridity index and the dryness ratio (Campos, 2006). Figure 2.5 shows that at weather stations Puerto de la Concepcion (Figure 2.5a), Jesus Maria (Figure 2.5b), and Malpaso (Figure 2.5c) the time series had significant positive trends ($p \leq 0.05$) in April (20.36 mm/month/year), May (19.65 mm/month/year), and December (9.69 mm/month/year). Figure 2.5 is also used to illustrate that in Aguascalientes the origin of the evaporation positive trends lies in situations of DTR: the first situation is that both T_{max} and T_{min} have significant positive trends, but T_{max} increases faster than T_{min}; in Figure 2.5a this case is shown for weather station Puerto de la Concepcion in April where T_{max} and T_{min} increase at a rate of 0.08 and 0.05 °C/month/year, respectively.

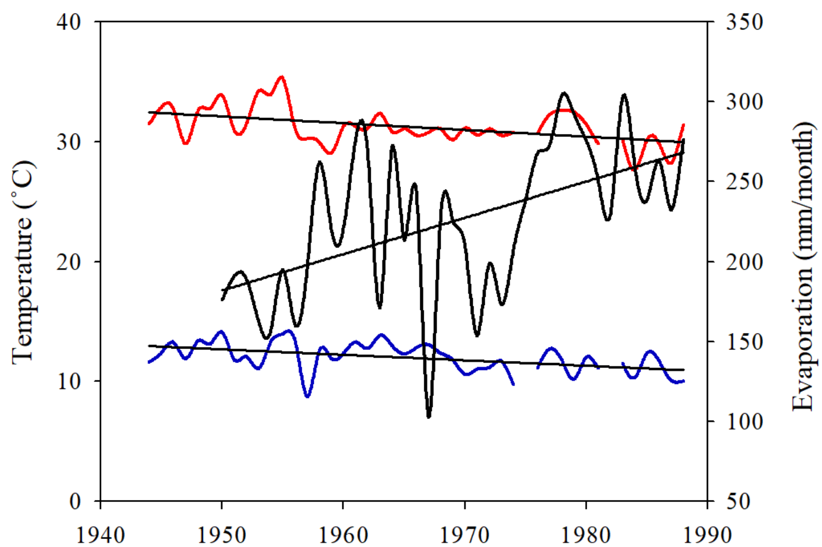
The second situation of DTR is that both T_{max} and T_{min} decrease but T_{min} decreases faster; this situation occurs at weather station Jesus Maria where T_{max} and T_{min} decrease in May at a rate of -0.048 and -0.049 °C/month/year, respectively (Figure 2.5b). Finally the last situation of DTR is that T_{max} presents significant positive trends, while T_{min} remains constant (Figure 2.5c); this occurred at weather station Malpaso in December when there was a significant positive trend in T_{max} of 0.02 °C/month/year, causing a positive trend of evaporation of 9.69 mm/month/year.

Responsible factors of evaporation increase in Aguascalientes

Similar to the evaporation decrease, the evaporation increase in Aguascalientes also can be explained by the same causes of evaporation increase in other regions of the northern hemisphere. The research carried out until today shows that the main reason for evaporation increase is the maximum temperature increase and minimum temperature decrease, this fact increases the DTR and the evaporative capacity of the environment (Jhajharia and Singh, 2011). The above is due to solar radiation increase which in turn is caused by the decrease in cloud cover (Roy and Balling, 2005). Also, Ruíz-Alvarez *et al.* (2016) found significant changes in maximum and minimum temperatures over a major surface of Aguascalientes state; these changes can be the cause of evaporation increase in this region. Other researchers mention that evaporative capacity (in terms of DTR) of the environment also increases due to the afternoon relative humidity decrease (Jhajharia and Singh, 2011).

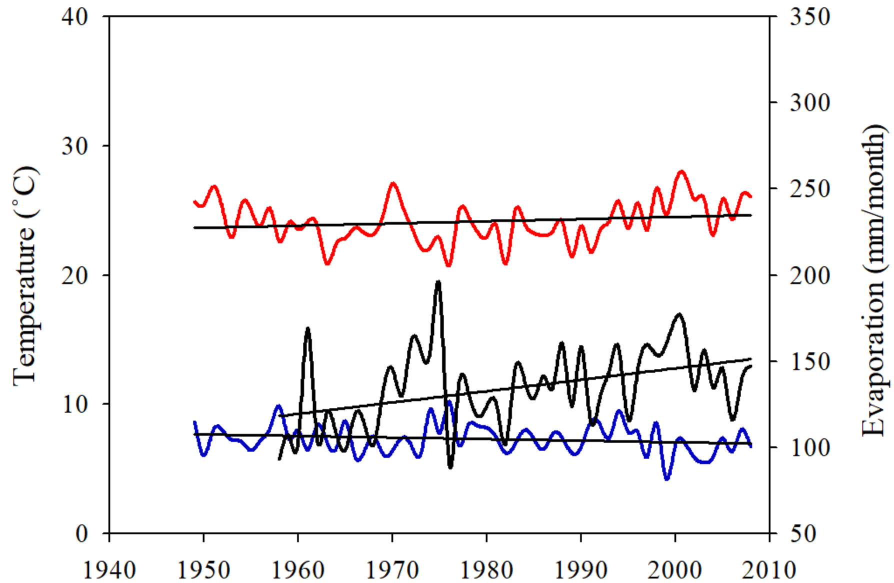


(a)



(b)

Figure 2.5. Times series of evaporation and temperature for April (a), May (b), and December (c) at weather stations Puerto de La Concepcion, Jesus Maria, and Malpaso, respectively.



(c)

Figure 2.5 Continued.

2.4.3. No significant trends

There were 19 stations that did not have significant trends in any month (Table 2.2). The zones of these stations are characterized for having rural populations, shrub and mountain vegetation, reservoirs and small impoundments, and rainfed and irrigated agriculture. The fact, that significant trends were not found, could be that some (several) other meteorological variables that affect evaporation can be experiencing no significant changes; some other research works show the evidence that rural areas are less prone to changes in meteorological variables than urban areas and this is because of the difference in land use (Arthur and Allen, 2002; Lee *et al.*, 2013). The absence of trend (mainly positive) in these places offers an optimistic scenario, since the current vegetation could endure (if man does not intervene) through time; in these places increases in water requirements of rainfed and irrigated crops are not expected; in other words, changes that represent a risk of the sustainability of natural resources and productive activities are not expected. In these places, the government and organizations should start strategies for conservation, management and use of soil, water and vegetation; so that the status (no trends) of the locations will remain constant and will not change to other situation facing positive evaporation trends.

2.4.4. Spatial influence on climatic trends

It is important to identify discrepancies at short distances. From February to May, October, and November, municipalities like Aguascalientes, El Llano, and Calvillo showed both positive and negative trends. These results coincide with the observation that the effects of climate change are localized and vary even at a level of micro-region (Fan and Thomas, 2013). The behavior of both positive and negative trends showed a pattern similar to that reported by Blanco-Macías *et al.* (2011) in the neighboring state of Zacatecas.

Figure 2.6 was constructed with the help of the values presented in Table 2.2. This figure shows the spatial distribution of trends in monthly evaporation for the state of Aguascalientes. The significant negative trend ($p \leq 0.05$) from June to September indicates a favorable future scenario for rainfed crops for the period locally known as spring-summer, since the evaporation reduction promotes a longer duration for soil moisture in the upper profile. These trends occur in the municipalities of Rincon de Romos (weather stations Presa Potrerillos and Rincon de Romos), San Jose de Gracia (weather stations La Tinaja, Presa 50 Aniversario and Presa Plutarco Elias Calles), Pabellon de Arteaga (weather stations Campo Experimental Pabellon and Presa Jocoque), Calvillo (weather stations La Codorniz and Calvillo), Tepezala (weather stations Puerto de la Concepcion and Tepezala) and Asientos (weather stations Villa Juarez and Asientos), where trends from -4.10 to -20.50 mm/month/year were registered.

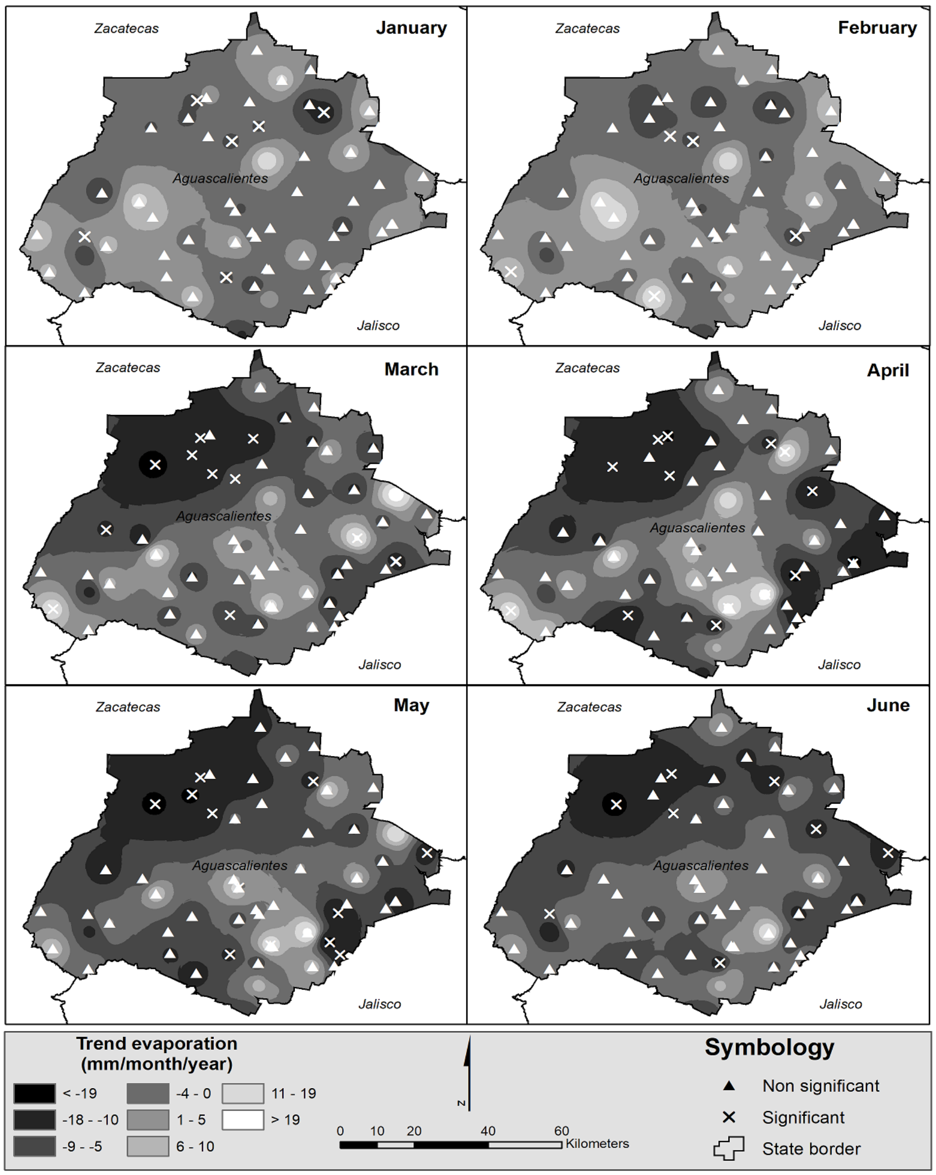


Figure 2.6. Spatial variation of evaporation trend in Aguascalientes.

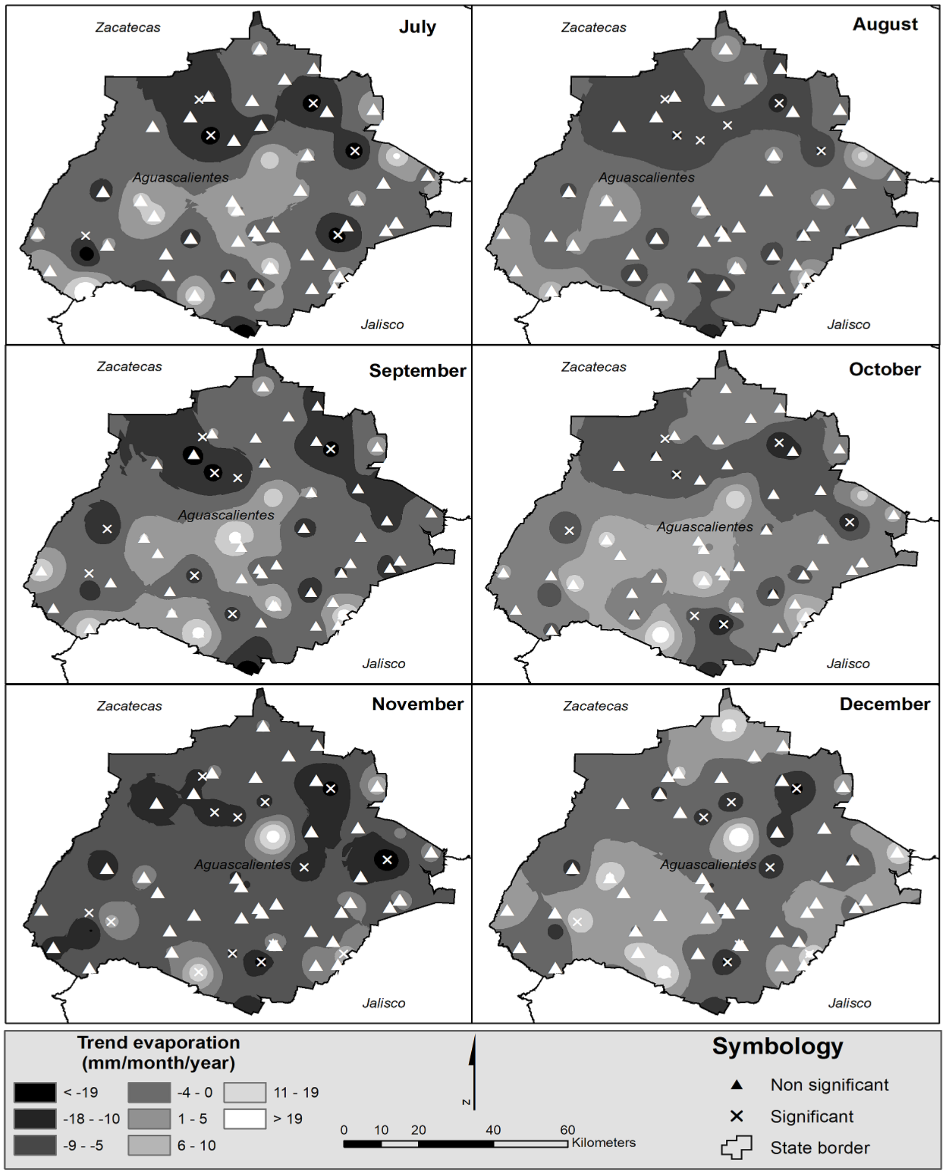


Figure 2.6 Continued.

For the remaining months (dry months, is that to say, when precipitation is not significant) the evaporation reduction could notably help irrigated agriculture, since the evaporation behavior is associated with reference evapotranspiration (ET_0), crop evapotranspiration and finally with the pumping of water for crops especially in municipalities of El Llano (weather station Palo Alto), San Jose de Gracia (weather station la Tinaja) and Aguascalientes (weather station Sandovales), where significant ($p \leq 0.05$) negative trends from -24.27, -23.16 and -23.90 mm/month/year were identified (Figure 2.6).

The regions with significant positive trends ($p \leq 0.05$) in dry months would be showing an environment with higher water demand due to ET_0 increase (Liu *et al.*, 2011). The increase of ET_0 leads to the increase of crop evapotranspiration and irrigation requirements which could increase water withdrawal from aquifers. This is particularly important in San Francisco de Los Romo (weather station San Francisco de los Romo), Aguascalientes (weather station Calvillito) and El Llano (weather station Rancho Seco) municipalities, where according to Comision Nacional del Agua and World Meteorological Organization (CNA-WMO, 2006) there are aquifers with a high level of over-exploitation. In those places significant positive trends of about 23.95, 24.63 and 26.91 mm/month/year were found for November, April and March, respectively (Figure 2.6).

2.4.5. Correlation analysis between the trend magnitude of monthly evaporation and altitude

For knowing if elevation of weather stations exerts any influence on the trend magnitude of evaporation, a correlation analysis was carried out (Ding *et al.*, 2019). This analysis was performed between the trend magnitude of evaporation and altitude, for which three elevation ranges were used 1585m-1990m, 1995m-2425m and 1585m-2425m. In Aguascalientes, elevation is not a robust factor for making inferences about the trend on monthly evaporation. For ranges 1585-1990 and 1585-2425 there was greater occurrence of negative correlation (Table 2.3); while for the range 1995-2425, there was greater occurrence of positive correlation (Table 2.3). In all cases, correlations were weak and were not statistically significant ($p \leq 0.05$) (Table 2.3). The above means that in Aguascalientes elevation is not correlated with the rate of change of evaporation, as it is for other elements of hydrological cycle (Ding *et al.*, 2019; Zhang *et al.*, 2014). Rather, given the diversity of vegetation characteristics where significant monthly evaporation trends occurred, the sign and magnitude of trend could be influenced by micro weather and by the way in which land use changes occur (Roque-Malo and Kumar, 2017).

2.4.6. Importance of evaporation trends in agriculture and water resources

Evaporation has a direct influence on water losses from dams and surface reservoirs. Different studies have highlighted the role of evaporation in water losses in reservoirs. In Turkey, evaporation from lakes and dams is bigger than the water extracted from the ground. For this country it is reported that one fifth of water used for irrigation is lost through evaporation; this volume is bigger than the ones used in domestic and industrial sectors (Gokbulak and Ozhan, 2006). In the Rio Grande (USA) watershed, the evaporation of a medium size reservoir represents 15-25% water used from Rio Grande (New Mexico) and represents the water requirements of Albuquerque during 2-4 years (Gupta *et al.*, 2002). According to Craig *et al.* (2005), in Queensland (Australia), annual evaporation in reservoirs was around $1000*10^6$ m^3 of total storage capacity of around $2500*10^6$ m^3. They commented that this volume of evaporated water would be enough to irrigate around 125,000 hectares which would help get up to US$ 375 million per year.

On the other hand, Bengoechea *et al.* (1991) calculated evaporation losses in southeastern Spain up to 5% of total water supplied for irrigation. According to Martinez-Alvarez *et al.* (2008), for the same country, most of the water lost by evaporation in reservoirs occurs in Mar Menor and Sur de Alicante with magnitudes of $15.43*10^6$ and $9.50*10^6$ m^3 $year^{-1}$, followed by Segura and Guadalentin valleys with $6.93*10^6$ and $9.17*10^6$ m^3, respectively. Also, for Spain, at the watershed scale, annual evaporation in reservoirs varies between $68.2*10^6$ and $58.1*10^6$ m^3. The above evidences the importance of the change evaporation rates can have in arid environments as Aguascalientes, which is an important area of artificial reservoirs.

Evaporation changes influence runoff volume and soil moisture. The hydrological balance is modified when changes in evaporation occur. According to Ekness and Randhir (2015) the temperature increase by one Celsius degree caused more evaporation and transpiration losses, and as a consequence a reduction of runoff by 0.15%. This same phenomenon was reported by Shang *et al.* (2019) in an analysis of climate change and land use effects in the variation of runoff in the Uppers Heihe River basin. Evaporation also modifies atmosphere moisture. It has been observed that evaporation increase increases water vapor in the lower atmosphere until the extent of influencing atmospheric circulation and precipitation patterns (Porter *et al.,* 2012). In United States, soil moisture reductions are correlated with adverse impacts on aquifers recharge, especially in Great Plains, Southwest, and Southeast (Melillo *et al.,* 2014). The more evaporating and hot a region becomes, this tends to get a per capita use of water higher and to extract greater quantities of ground water (Balling *et al.,* 2007).

Changes in the evaporating power of the atmosphere can have a direct effect on soil moisture. Evaporation of bare soil causes a significant loss of moisture and has a direct impact on the yield of rainfed crops in arid regions (Mellouli *et al.,* 2000). According to Peters (1960), in the western United States, up to 50% of corn evapotranspiration corresponds to evaporation losses during a normal growing season. In Tunisia, bare soil evaporation amounted to 75% of annual precipitation (Riou, 1977). According to Stewart and Burnett (1987), between 30 and 61% of annual precipitation is lost by evaporation in production systems of winter wheat. Even with a cover of perennial grass, losses of evaporation are around 30%, which amount to the half of available soil moisture (Floret *et al.,* 1982). In Syria, in soils with barley crops and nutritional deficiency, up to 75% of moisture content is lost by evaporation (Cooper *et al.,* 1987).

From an agricultural point of view, losses by evaporation are very important, so that their reduction and management will contribute greatly to soil moisture conservation for crop production. This is especially important in arid and semiarid regions characterized by high deficiency and variability of precipitation (Mellouli *et al.*, 2000). The Food and Agriculture Organization indicates that if evaporation increases in rainfed systems, moisture available in the root zone will be depleted rapidly, requiring either crop varieties of shorter growing cycle or to accept low yields and frequent loss of crops (Turral et al., 2001). Higher atmospheric moisture demand represented by the evaporation increase leads to fast drying of soils, increases irrigation demand and exacerbates the current stress in agricultural production (Melillo *et al.*, 2014).

2.5. CONCLUSIONS

In Aguascalientes state, the area with no noticeable evaporation change is dominant; one important area shows evaporation reduction and another minimum part shows an increase. The negative trends are present during all year and positive trends just from February to May and from October to December.

The trends in evaporation vary considerably in time and space, suggesting that the variation in evaporation trend would have variable effects over the state. If the negative pattern of evaporation continues in summer months, rainfed agriculture may have better soil moisture conditions.

On the other hand, positive trends could increase crop evapotranspiration and irrigation requirements during spring and winter; such situation could be critical in regions with over-exploited aquifers.

Results of this study provide a basis for farmers and institutions in charge of water resources management and developing adaptation/mitigation strategies for coping with the effect of climate change on agriculture.

Research in agricultural water management of the region must be intensified for creating suitable methods to deal with current and future scenarios. The deficit irrigation could be an efficient technique for optimizing the use of water in critical regions of Aguascalientes.

3. OBSERVED TRENDS IN DAILY TEMPERATURE EXTREME INDICES IN AGUASCALIENTES, MEXICO

3.1. Synopsis

Climate change is a pernicious and irrefutable reality. The objective of this work was to analyze trends in extreme temperature indices in Aguascalientes. With RClimdex 1.0 and data on daily maximum (T_{max}) and minimum temperature (T_{min}), 16 temperature indices were calculated. The trend in indices was determined with the non-parametric Mann-Kendall test ($p \leq 0.05$), while the rate of change was obtained with Theil-Sen´s trend estimator. Significant positive trends were observed in 72 time series of indices associated with T_{max} and in 39 time series of indices associated with T_{min}. Significant negative trends were observed in 22 time series of indices associated with T_{max}; and in 45 time series of indices associated with T_{min}. In some regions of Aguascalientes diurnal warming is occurring; in other regions warmer or less cold nights prevail. The changes in extreme temperature indices might have severe implications in the use of irrigation water, cause physiological stress in crops, promote respiratory and cardiac diseases, and improve the reproduction cycles and populations of insects. Also, fruit production, such as guava, could be affected under the reduction of minimum temperature, and the increase in warm days where other fruit trees are cultivated can intensify the use of chemical compensators of cold. These results are of significance for long-term economic planning and design of strategies of adaptation/mitigation to climate change. In Aguascalientes, the changes

observed in extreme temperature indices could be due to climate change of a bigger scale either regional or at the watershed level.

3.2. Introduction

Currently, climate change is an inescapable reality. According to Intergovernmental Panel on Climate Change (IPCC, 2007), during the period 1906-2005 the planet got warmer with an increase of 0.74 ± 0.18 °C as a consequence of combustion of fossil fuels which releases different greenhouse gases to the atmosphere.

Governments from different countries are trying to quantify the impacts of climate change and eradicate its effects. In recent decades, there has been much focus on studying changes in climate parameters from averages and accumulated monthly or annual values. Li *et al.* (2011) mentioned that temperature, environment, precipitation, greenhouse gases, risk, and biodiversity are important fields of research related to climate change during the first years of XXI century. The study of these fields helps explain what is happening to hydrological variables and how the patterns of their extreme values impact the society (Peterson *et al.,* 2001; Vincent *et al.,* 2005). Extreme meteorological events encompass heat waves, cold waves, droughts, heavy rainfall, and hurricanes, and pose considerable risk to the society (National Academies of Sciences, Engineering, and Medicine, 2016). According to IPCC (2007) extreme meteorological indices are widely used to evaluate climate variability and get a clearer insight into the pattern of warm spells, droughts, and heavy rainfall over terrestrial surfaces. However, IPCC also states that these kinds of studies are scarce, especially at regional and local scales. New *et al.* (2006) point out that studying trends of extreme events helps verify the results of climate models to improve the confidence in climate projections. Thus, at the end of the 1990s, the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) sponsored by the Commission for Climatology (CCI) of the World Meteorological Organization and the Climate Variability and Predictability Project (CLIVAR) developed 27 extreme meteorological indices associated with precipitation and temperature (Peterson *et al.,* 2001; ETCCDMI, see http://www.etccdi.pacificclimate.org). Nowadays, these indices constitute a methodological guide accepted globally to analyze climate change, and they have been used at regional and global levels in different investigations related to extreme meteorological events (Vincent *et al.,* 2005; Zhang *et al.,* 2005; Haylock *et al.,* 2006).

In this regard, many researchers from different parts of the world have studied extreme meteorological events following the tools developed by CCI/CLIVAR/ETCCDMI. Zhang *et al.* (2005) studied trends of 17 extreme temperature indices using daily temperature from 15 countries in the Middle East for a period of 1950-2003. They reported positive trends in annual maximum of daily maximum and minimum temperatures, the annual minimum of daily maximum and minimum temperatures, the number of summer nights, and the number of days when daily temperature had exceeded its 90th percentile, also negative trend in the number of days when daily temperature was below its 10th percentile, and diurnal temperature range. Alexander *et al.* (2006) used these indices for studying changes at the global level in extreme temperature during the XXth century, and found positive trends in those indices related to daily minimum temperature and stated that about 70% from the sampled global area had negative trends in the number of cold nights and an increase in summer nights.

New *et al.* (2006) studied trends in 16 extreme temperature indices in 14 countries from South and West Africa, and reported decreases in the number of cold nights and days, increases in the number of extremely hot days and nights. They also found that the average length of warm spells had increased, while the average length of cold spells had decreased. Similarly, Caesar *et al.* (2011) analyzed changes in nine extreme temperature indices over 13 countries from the Indo-Pacific region and identified increases in warm nights and decreases in the number of cold nights. Likewise, Santos *et al.* (2011) studied 11 extreme temperature indices in Utah, and found increases in the number of days with maximum temperature >25 °C, decreases in the number of days with maximum temperature <0 °C, increases in the number of days with minimum temperature <20 °C, and negative trends in the number of days with daily minimum temperature < 0 °C. Analougusly, there were positive trends in the number of days with at least six consecutive days when the maximum temperature > 90th percentile, decrease in the number of days with at least six consecutive days when the minimum temperature <10th percentile and in the diurnal temperature range. Shrestha *et al.* (2017) investigated trends in 11 extreme temperature indices in the Koshi River basin and found increases in daily maximum and minimum temperatures, and in the number of warm nights. They also mentioned that warm days, warm spell duration, and diurnal temperature range increased in mountainous regions only; while minimum and maximum values of daily maximum temperature, cold nights, cold spell duration indicator, and diurnal temperature range decreased in plains.

In Mexico, the majority of climatic studies are based just on the analysis of mean values (monthly or annual) of hydrological variables. Literature review shows that for

Mexico there is little research on extreme meteorological events. Lopez-Diaz *et al.* (2013) analyzed extreme temperature events in Apizaco (Tlaxcala) during 1952-2003 and reported increases in the summer days and in the number of days with temperature < 0°C, decreases in the number of cold days and increasingly extreme temperatures. On the other hand, Aguascalientes State has preponderant and competitive agriculture. The most important crops are basic grains (corn, beans), forage (corn, oats, and sorghum), and vegetables. Each year 143,654.20 hectares of land are cultivated of which 50,820.20 hectares are managed with irrigation and 92,834.00 under rainfed agriculture (SIAP, 2018). However, currently this region faces adverse environmental conditions, such as contamination and depletion of aquifers (CNA-WMO, 2006), and if that were not enough, significant changes have been unveiled in the monthly patterns of temperature and evaporation (Ruíz-Álvarez *et al.*, 2016; Ruíz-Álvarez *et al.*, 2018) which seem to put the future of agriculture at risk.

The objective of this chapter therefore is to study trends in 16 extreme temperature indices at 25 weather stations of Aguascalientes during a period of 34 years (1980-2013), using the methodology developed by ETCCDMI. Results of this work will determine which areas have been more affected by climate change, and construct a picture of the spatial distribution of extreme meteorological events, which might help decision makers to develop or adopt new technologies and production systems.

3.3. Materials and methods

3.3.1. Area of study

Aguascalientes is one of the 31 states that form the Mexican Republic. It is located in the South plateau in the region known as North-Central Mexico (Figure 3.1a) between 22°27´ and 21°38´ North latitude, and 101°53´ and 102°52´ West longitude. It adjoins the state of Zacatecas in the North, East and West; and Jalisco in the South, Southeast, and Southwest. In this state three types of climate exist: temperate and subhumid with rainfall in summer (Cw, 13.55%), semi-dry warm (BS1h, 15.44%), and semi-dry and temperate (BS1k, 71.01%), where the average annual temperature is 17.1, 20.1 and 14.5°C, respectively; and the predominant land uses are forest, jungle, scrub, pastureland, and agriculture (INEGI 2017). In Figure 3.2, the spatial distribution of mean annual temperature in the Aguascalientes state is presented. This map was created with the annual mean of observations of climatological normals of Servicio Meteorologico Nacional during 1981-2010.

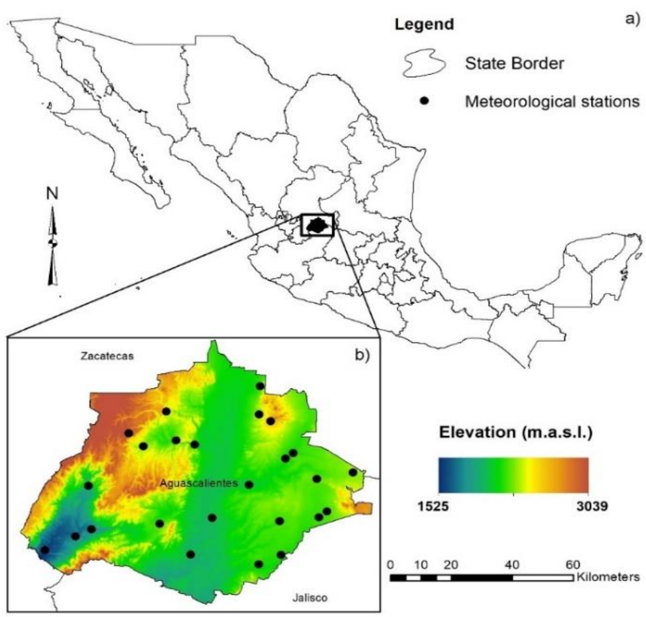


Figure 3.1. Location of Aguascalientes state in Mexico (a) and spatial distribution of 25 weather stations utilized in this study (b).

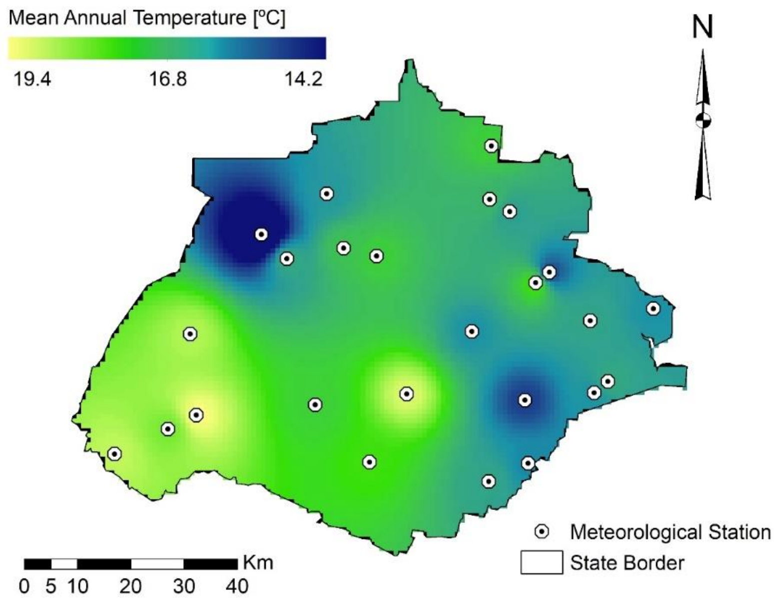


Figure 3.2. Spatial variation of mean annual temperature in Aguascalientes (period 1981-2010).

3.3.2. Database of temperature

We used daily data of temperature (maximum and minimum) from 25 conventional weather stations of National Meteorological Service (SMN) [federal organization belonging to Comision Nacional del Agua (CNA)] for a period of 34 years (Figure 3.1b) (Table 3.1). Our study is focused on the period 1980-2013, since this has uninterrupted meteorological data, which led to picking up the weather stations presented in Table 3.1. A critical characteristic of these weather stations is that they have not been moved off the site, which provides consistency to their measurements for trend detection analysis. This database was already subjected to quality control by the staff of SMN, which included deleting daily outliers within a month and for each weather station, that is, those daily measurements that were out of an interval (upper and lower limit) were deleted, and this interval was defined by two allowable thresholds (maximum and minimum) (Portocarrero; personal communication).

3.3.3. RClimdex 1.0 and preparation of temperature data

We used RClimdex 1.0 developed by the Climate Research Branch of Meteorological Service of Canada. This software provides an easy interface for computing 27 basic indices suggested by CCI/CLIVAR/ETCCDI (Zhang and Yang, 2004). Before estimating the indices, a quality control phase must be performed, which is a prerequisite of the software and consists of the following phases (Zhang *et al.*, 2015): 1) replacing all missing observations (coded as -99.9) in an internal format (NA) recognized by the software, 2) replacing all unreasonable values by NA, 3) identifying outliers of daily temperature values out of the interval defined by the user, and 4) identifying daily precipitation values higher than the upper limit defined by the user (Zhang *et al.*, 2015). It is important to point out that those unreasonable values from phase two include a) daily precipitation values less than zero millimeters, b) daily maximum temperature less than daily minimum temperature, c) daily temperature values higher than 70 degree Celsius or less than -70 degree Celsius, d) leap days (i.e. 29th February), e) all values corresponding to an impossible date (i.e., 32nd March 2013, 12th June 20AA, among others), and f) any non-numerical values (Zhang *et al.*, 2015). On the other hand, the region defined by the user that is mentioned in phase three is given by mean-*n**STD*, mean+*n**STD* (Zhang and Yang, 2004), where mean and STD are the mean and standard deviation of the sample, respectively; and the *n* value in this study was 4 (Barry *et al.*, 2018).

3.3.4. Extreme temperature indices

The extreme temperature indices were also estimated with RClimdex 1.0 software, according to the recommendations published by Zhang and Yang (2004), and Zhang *et al.,* (2015), which has also been employed in other studies (Vincent *et al.*, 2005; Zhang *et al.*, 2011; Shresta *et al.,* 2016; Ye *et al.*, 2018). In total, 16 extreme temperature indices were estimated, and we chose these indices because they are more related to the climatology of Aguascalientes (Table 3.2).

3.3.5. Statistical analysis

The resulting time series were subjected to a statistical analysis to determine the presence or absence of a trend and its sign and statistical significance ($p \leq 0.05$), using the non- parametric Mann-Kendall test (Mann 1945; Kendall 1975; Río *et al.,* 2005). This test is robust in the sense that it is not affected when missing values exist through the time series. Furthermore it does not require that observations follow a particular distribution function (Gilbert, 1987). In the same way, the rate of change of extreme indices through the time was obtained with Theil-Sen´s trend estimator (Theil, 1950; Sen, 1968). In global warming studies, it is essential to know the sign of extreme indices, which makes it possible to predict other indices intended for applications related to climate change impacts (Almazroui *et al.,* 2014). For this reason and for understanding interrelations among all indices, we obtained a correlation matrix, for which Pearson correlation coefficient was calculated among all indices and for each weather station (Lyman and Longnecker, 2001).

3.4. Results and discussion

Below we discuss the trends in 16 extreme temperature indices at 25 weather stations in Aguascalientes, Mexico. We discuss the results for those that showed statistically significant trends ($p \leq 0.05$) at least at one weather station.

3.4.1. Extreme temperature indices

3.4.1.1. TXMean, TNMean, and DTR

The trends in the annual average of maximum (TXMean) and minimum temperatures (TNMean) were different in the statistically significant number of stations, trend magnitude, spatial distribution and in the influence on the diurnal temperature range (DTR). TXMean showed statistically significant trends ($p \leq 0.05$) at 21 weather stations from which 20 stations had positive trends, and one had a negative trend (Table 3.3). The significant positive trends in TXMean varied between 0.356 and 1.057 °C decade^{-1} at Sandovales and Villa Juarez, respectively (Table 3.3); were distributed in Southeast (San Bartolo, San Isidro, Los Conos and Sandovales), Northwest (Puerto de La Concepcion, Presa Potrerillos, Presa Plutarco Elias Calles and Rancho Viejo), East (Palo Alto, El Novillo and Las Fraguas), South (El Niagara), West (Presa La Codorniz), Northeast (Mesillas and Villa Juarez), Southwest (Malpaso and Venadero), Center (Cañada Honda), North-Center (Presa Jocoque) and South-Center (Aguascalientes) of the study region (Figure 3.3a). Our findings are in agreement with reports from other parts of the northern hemisphere, both for the magnitudes and for the high prevalence of positive trends. For these trends, different researchers have reported a range that goes from 0.100 to 1.120 °C decade^{-1} (Brito-Castillo *et al.*, 2009; Jhajharia and Singh, 2011; Ghasemi, 2015), which is similar to what we found in this work. On the other hand, the magnitude of the unique negative significant trend of TXMean was -0.364 °C $decade^{-1}$ at Calvillo (Table 3.3) in Southwest (Figure 3.3a) and was higher than -2.200 °C $decade^{-1}$ for the neighboring state of Zacatecas reported by Brito-Castillo *et al.* (2009). The increase of TXMean is due to a more significant surface absorption of solar radiation, which, in turn, is due to the decrease in the cloud cover; when the opposite conditions take place, TXMean decreases (Jhajharia and Singh, 2011). In contrast, TNMean showed statistically significant trends ($p \leq 0.05$) at 16 weather stations. From these, seven stations presented positive trends, and nine had negative trends (Table 3.3). The significant positive trends oscillated between 0.181 and 1.000 °C $decade^{-1}$ at Presa Potrerillos and Puerto de La Concepcion, respectively (Table 3.3), and were distributed in Central-North (Presa Jocoque), Central-South (Aguascalientes), East (Las Fraguas), West (Presa La Codorniz), Northwest (Puerto de La Concepcion and Presa Potrerillos) and Southwest (Malpaso) of Aguascalientes (Figure 3.3b). For this index, the range of variation of positive trends was something similar to the one reported by other scientists. For instance, Jhajharia and Singh (2011) found one range that varied from 0.100 to 0.600 °C $decade^{-1}$; otherwise, Brito-Castillo *et al.* (2009) reported a range from 0.290 to 0.880 °C $decade^{-1}$ for Zacatecas. Similarly, negative significant trends were between -1.427 and -0.271 °C $decade^{-1}$ at Mesillas and Calvillo, respectively (Table 3.3) which were distributed in Northeast (Mesillas), Souht (Presa El Niagara), East (Palo Alto and El Novillo), Northwest (Rancho Viejo), Southwest (Calvillo and Venadero), and Southeast (Los Conos and Sandovales) of the State (Figure 3.3b). In the literature, similar values to ours have been reported. For example, Brito-Castillo *et al.*

(2009) found negative trends from -2.500 to -1.140 °C $decade^{-1}$ in Zacatecas. Similarly, Jhajharia and Singh (2011) informed trends of -0.500 °C $decade^{-1}$. Some studies explain that the increase in the minimum temperature is caused by the intensification in cloud cover, which reduces the incoming short-wave radiation during days and delays the outgoing longwave radiation during nights. In another way, the minimum temperature reduction is related to less nocturnal cloudiness occurrence and less incidence of solar radiation during the day (Jhajharia and Singh, 2011). From a different point of view, the changes in TXMean and TNMean have direct implications in the DTR (Easterling *et al.,* 1997; Price *et al.,* 1999; Roderick and Farquhar 2002; New *et al.,* 2006). In this way, DTR had statistically significant trends ($p \leq 0.05$) at 18 weather stations, 17 out of them were positive, and one had a negative trend (Table 3.3). In connection with positive significant trends, these fluctuated between 0.387 and 1.473 °C $decade^{-1}$ at Presa Potrerillos and El Novillo, respectively (Table 3.3) and were distributed in Southeast (San Bartolo, San Isidro, Los Conos and Sandovales), Southwest (Malpaso, Calvillo and Venadero), Northwest (Presa Potrerillos, Presa Plutarco Elias Calles and Rancho Viejo), South (El Niagara), East (Palo Alto and El Novillo), Northeast (Mesillas and Villa Juarez), Center (Cañada Honda), and Center-North (Presa Jocoque) (Figure 3.3c). For this index, some authors have reported positive trends higher than those found in this research, for example, Brito-Castillo *et al.* (2009) found 2.260 °C $decade^{-1}$ in Southeast of Zacatecas. In the same way, the only negative significant trend was about -0.425 °C $decade^{-1}$ at Puerto de La Concepcion (Table 3.3), on the Northwest of State (Figure 3.3c). The magnitude of our negative trend looks like those reported in other studies; for example, Jhajharia and Singh

(2011) published a range of negative trends from -0.800 to -0.200 °C decade^{-1}. Similarly, You *et al.* (2016) reported an average of -0.200 °C decade^{-1}; also, Price *et al.* (1999) obtained an interval from -0.350 a -0.050 °C decade^{-1}. In Aguascalientes State, the increases in DTR might be associated with more extreme weather, greater air evaporative capacity, greater environment dryness, increase of the reference evapotranspiration (ET_0) and crop evapotranspiration (ET_C), and more water for irrigation. With the help of Table 3.3 we can observe that five increases in DTR were caused by significant positive trends in TXMean that occurred at Cañada Honda, Presa Plutarco Elias Calles, San Bartolo, San Isidro and Villa Juarez (Center, Northwest and Southeast) (Figure 3.3c); eight increments were produced by the increase in TXMean and the decrease in TNMean at Presa El Niagara, Mesillas, Palo Alto, Rancho Viejo, Venadero, El Novillo, Los Conos y Sandovales (Southeast, East, South, Northeast, Northwest and Southeast) (Figure 3.3c); three increases occurred due to the increase in TXMean and TNMean (TXMean had a higher rate of change) at the Malpaso, Presa Potrerillos and Presa Jocoque weather stations (Southwest, Northwest, and North-Center) (Figure 3.3c); one increase was caused by the reduction in TXMean and TNMean (TNMean decreased at a higher rate) at the Calvillo weather station (Southwest) (Figure 3.3c). Finally, the only decrease in DTR was due to the increase in TXMean and TNMean (TNMean increased at a higher rate) at the Puerto de La Concepcion weather station (Northwest) (Figure 3.3c). In the area of influence of this weather station, the decrease in DTR could cause a reduction in the evaporative capacity and in the dryness of the environment, reduction in ET_0 and ET_C and in irrigation requirements.

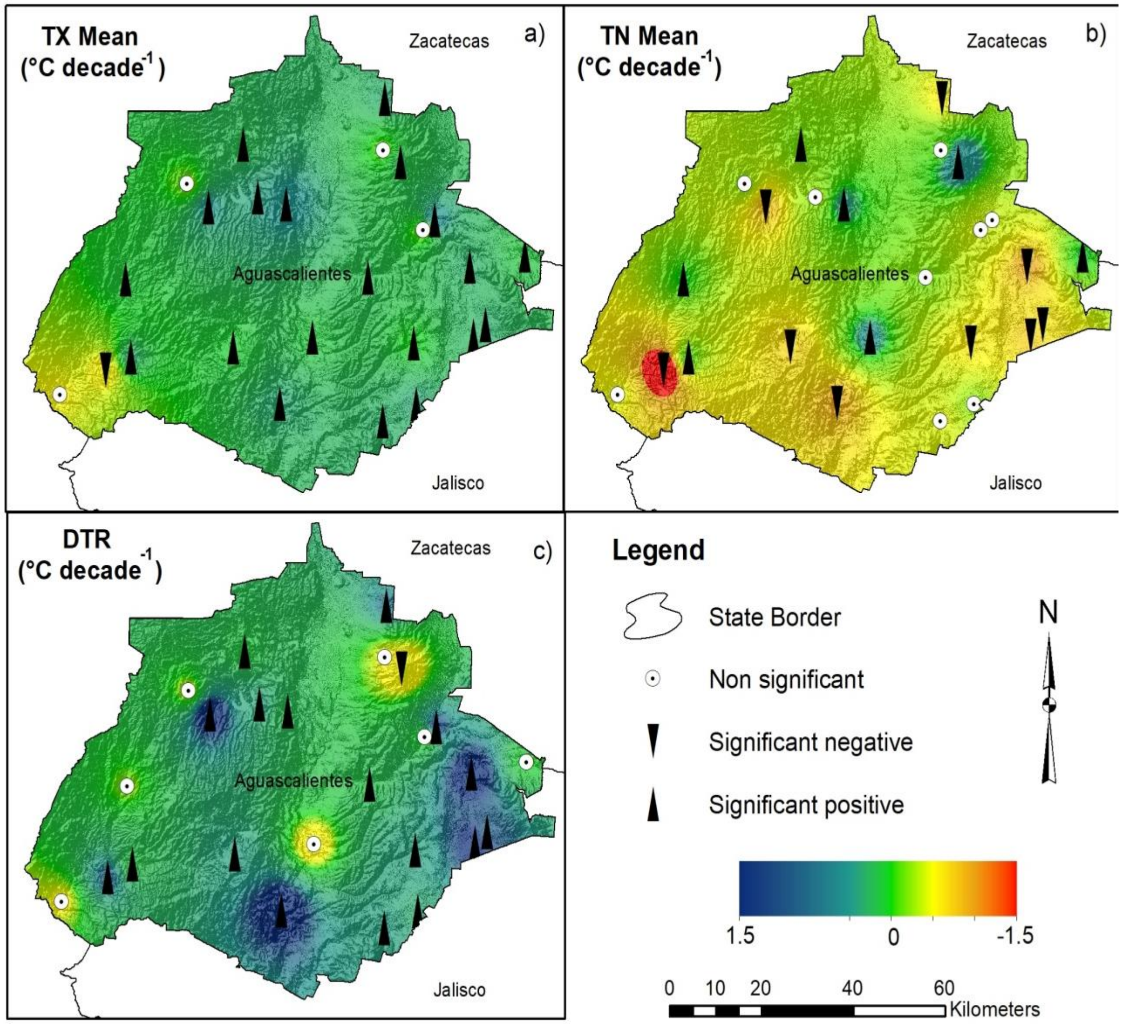


Figure 3.3. Spatial distribution of TXMean (a), TNMean (b) and DTR (c) indices in Aguascalientes, Mexico.

3.4.1.2. FD0 and SU25

Analysis of the frost days (FD0) and summer days (SU25) did not indicate absolute warming or cooling at those weather stations that were statistically significant. The FD0 index revealed statistically significant trends ($p \leq 0.05$) at 13 weather stations; out of these stations ten were positive, and three were negative (Table 3.3). The significant positive trends oscillated between 0.870 and 11.250 days decade^{-1} at Mesillas and Calvillo, respectively (Table 3.3), and were located in Northwest (La Tinaja and Rancho Viejo), Southwest (Presa Media Luna and Calvillo), East (Palo Alto and El Novillo), Center (Cañada Honda), South (El Niagara), Northeast (Mesillas) and Southeast (Los Conos) of the study area (Figure 3.4a). In connection with FD0, our results differed from those reported to other parts of the world. Frich *et al.* (2002) mentioned that it was more common to find negative trends, and in their study, just a few stations showed significant increases, and it was less usual than in other parts of North America which presented significant positive trends. However, Rahimi and Hejabi (2018) indicated that negative trends in FD0 just occurred at sites located between low and medium altitudes, whereas in lands situated at great altitudes more prevalence of positive trends existed. In this sense, for Apizaco (Mexico plateau), López-Díaz *et al.* (2013) found increases of 11.071 days decade^{-1}, a very similar magnitude to the ones we obtained at the Cañada Honda, Calvillo and Los Conos weather stations (Table 3.3) in the Center, Southwest and Southeast of the state (Figure 3.4a). In contrast, the significant negative trends varied between -10.200 and -2.143 days decade^{-1} at Villa Juarez and Las Fraguas, respectively (Table 3.3) and were distributed in the Northeast (Villa Juarez), East (Las Fraguas) and Southeast of Aguascalientes (Figure 3.4a). These trends are very similar to those reported by Ruml *et al.* (2017) who published magnitudes between -9.400 and -7.700 °C decade^{-1}. Similarly, Santos *et al.* (2011) reported a range from -7.320 to -1.040 days decade^{-1}. Our results indicated that in an important portion of Aguascalientes, the number of days in a year when temperatures <0°C were more frequent and decreased on a small surface. The increases in FD0 were directly related to the negative trends detected in TNmean, and could cause a reduction in the growing season and an increase in the risk of frost both for agricultural species (period crop growth spring-summer) and species at the ecosystem level (Snyder and Melo-Abreu, 2010). On the contrary, the FD0 reductions were associated with the increase in TNMean and lengthened the growing period and reduced the risk of agricultural damages by frosts events. Relative to SU25, 17 weather stations had statistically significant trends ($p \leq 0.05$); 16 stations had positive trends, and one had a negative trend (Table 3.3). The significant positive trends in SU25 were between 16.429 and 42.950 days decade^{-1} at Presa El Niagara and Villa Juarez, respectively (Table 3.3), and were located in the East (Palo Alto, El Novillo and Las Fraguas), Northwest (Puerto de La Concepcion, Presa Plutarco Elias Calles and Rancho Viejo), Northeast (Mesillas, Presa Potrerillos and Villa Juarez), Southeast (San Bartolo, San Isidro and Los Conos), South (El Niagara), Southwest (Malpaso), Center (Cañada Honda) and North-Center (Presa Jocoque) of this federal entity (Figure 3.4b). These results were somewhat different from those reported in the literature for other regions of the world, the range of variation of SU25 was between 0.790 and 5.740 days decade^{-1} (Zhang *et al.,* 2005; New *et al.,* 2006; Santos *et al.,* 2011; López-Díaz *et al.,* 2013; Barry *et al.,* 2018; Rahimi and Hejabi, 2018). Our trends presented differences relative to others because extreme indices have a wide range of variation throughout the globe (National Academies of Sciences, Engineering, and Medicine, 2016). In Figure 3.5, an example of time series for SU25 at the Presa El Niagara weather station is presented, where the trend was statistically significant ($p \leq 0.05$), and the rate of change was 16.429 days decade^{-1}. Contrarily, the only negative significant trend was -9.815 days decade^{-1} at Calvillo (Table 3.3) in the Southwest of the area under study (Figure 3.4b) and was within the range from -15.7 to -4.5 days decade^{-1} reported by Ruml *et al.* (2017). These findings mean that in a big area of Aguascalientes the days when temperature ≥25 °C were more frequent and that in a very small area these temperatures were occurring with less frequency (Figure 3.4b). In other words, on larger areas, the atmosphere could be presenting evidence of warming, while in the smaller area the atmosphere could be getting colder or less warm. It is important to mention that SU25 is intimately related to maximum temperature, as the weather stations with an increase in SU25 had increases in TXMean. Furthermore, the only station with a negative trend in SU25 also presented a negative trend in TXMean (Table 3.3). Those sites with increases in SU25 should receive special attention since long periods with temperature >25 °C could affect the growing and developing of some crops, particularly beans, which is very sensitive to heat (Jenni *et al.*, 2000). Also, the increase in SU25 could promote conditions for faster drying of the soil both for irrigated and rainfed crops. Similarly, the decrease in SU25 in Calvillo is particularly significant, since in this region guava (Psidium guava) is cultivated (Padilla *et al.*, 2010), which requires important quantities of heat units and in the short time, its productivity could be affected.

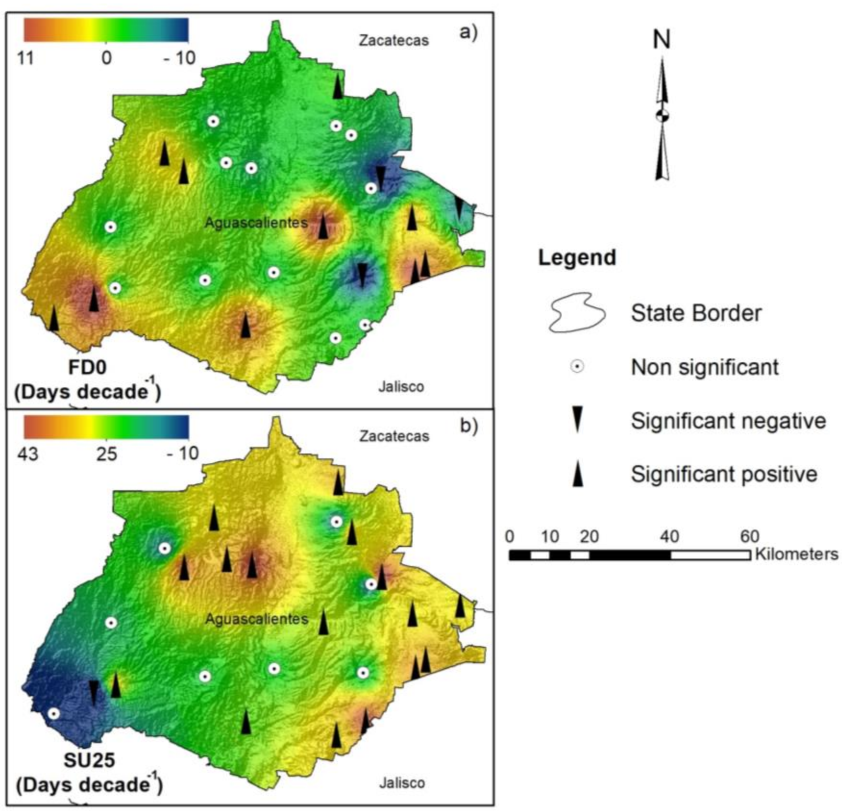


Figure 3.4. Spatial distribution of FD0 (a) and SU25 (b) indices in Aguascalientes, Mexico.

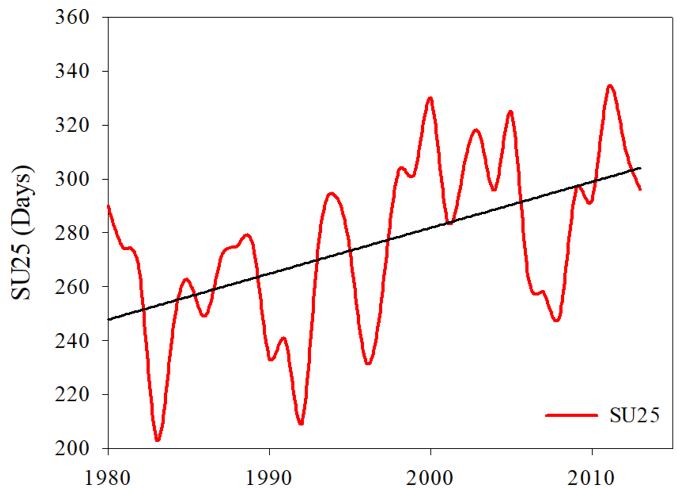


Figure 3.5. Time series example for SU25 in the Presa El Niagara weather station ($p \leq 0.05$).

3.4.1.3. TNx and TXx

The monthly maximum value of daily minimum temperature (TNx) and the monthly maximum value of daily maximum temperature (TXx) indicated that in Aguascalientes there is more predisposition to the warming than for the cooling. The TNx showed statistically significant trends ($p \leq 0.05$) at 11 weather stations out of which five had positive trends and six had negative trends (Table 3.3). The positive significant trends were between 0.435 and 1.136 °C decade^{-1} at the Las Fraguas and Puerto de La Concepcion weather stations, respectively (Table 3.3), located in the Center (Cañada Honda), Northwest (Puerto de La Concepcion), North-Central (Presa Jocoque), Southeast (San Isidro), and East (Las Fraguas) of Aguascalientes (Figure 3.6a). The positive trends in TNx around the world were quite heterogeneous. However, our results were similar to or fell within the range reported by some researchers. For instance, positive values of TNx slightly lower than ours have been reported which oscillated between 0.100 and 0.342 °C decade^{-1} (New *et al.*, 2006; Beharry *et al.*, 2015; Ruml *et al.*, 2017; Rahimi and Hejabi, 2018; Xi *et al.*, 2018). Other authors had published ranges of TNx that included totally our interval, such as Almazroui *et al.* (2014) who reported an interval from 0.300 to 1.300 °C decade^{-1} and Shresta *et al.* (2016) who showed a range from 0.200 to 1.200 °C decade^{-1}. Additionally, Caesar *et al.* (2011) obtained positive trends of 0.330, 0.540 and 0.940 °C decade^{-1} in three different regions of study. The significant negative trends fluctuated between -1.250 and -0.417 °C decade^{-1} at Villa Juarez and Rancho Viejo, respectively (Table 3.3). These trends were found in South (El Niagara), Northwest (Rancho Viejo), Southeast (San Bartolo), Southwest (Calvillo), Northeast (Villa Juarez), and in the East

(El Novillo) of the study area (Figure 3.6a). The negative trends of TNx reported by other researchers were observed in the range of -1.700 to -0.180 °C $decade^{-1}$, which included our trends (Santos *et al.,* 2011; Ruml *et al.,* 2017). These results indicated that one considerable area of Aguascalientes is experiencing changes in the monthly maximum value of daily minimum temperature, in less than half of this surface, the TNx value increased and in more than half, these values decreased. It is important to point out that out of five weather stations with positive trends in TNx, three of them showed positive trends in TNMean. In the same way, out of six stations with negative trend in TNx, four of them showed negative trends in TNMean (Table 3.3). Studies suggested that increases in TNx were related to anthropogenic releases of carbon dioxide, methane, nitrous oxide and chlorofluorocarbons to the atmosphere (Christidis and Stott, 2016); and also, to the albedo modifications caused by deforestation. In the Northern Hemisphere, the decreases in TNx were caused by a combination of atmospheric dynamics and thermodynamics, particularly by the increase in the flows coming from the north which increase winter cold extreme winds (Horton *et al.*, 2015). Some authors pointed out that the variations in these temperatures could have sever implications for human health, energy demand, transport, and food safety (DeGaetano, 1996; Easterling *et al.,* 2007). In another way, TXx experienced statistically significant positive trends ($p \leq 0.05$) at 13 weather stations (Table 3.3). These trends varied between 0.435 and 1.389 °C $decade^{-1}$ at Sandovales and El Novillo, respectively (Table 3.3), and were spatial distributed in the Northwest (Puerto de La Concepcion, Presa Potrerillos, Presa Plutarco Elias Calles and Rancho Viejo), East (Palo Alto and El Novillo), Southeast (Los Conos and Sandovales), South (El Niagara), Southwest (Malpaso), Northeast (Mesillas), West (Presa La Codorniz), and North-Central (Presa El Jocoque) of the state (Figure 3.6b). For this index, our results agree with those presented in different studies. It was observed that at the global level TXx tended more to the increase, and just in very few cases negative trends were obtained (Santos *et al.*, 2011; Ruml *et al.*, 2017). In this manner, the majority of researchers reported values similar to ours, so that a very common range of the positive trends in TXx was from 0.290 to 1.200 °C $decade^{-1}$ (Zhang *et al.*, 2005; Caesar *et al.*, 2011; Almazroui *et al.*, 2014; Beharry *et al.*, 2015). From another perspective, the results of this research indicated that in a substantial area of Aguascalientes where changes in TXx were occurring, so that the monthly maximum value of daily maximum temperature was increasing (Figure 3.6b), which indicated that the atmosphere was getting warmer (Donat *et al.*, 2013). It is important to emphasize that the weather stations with significant positive trends in this index showed significant positive trends in TXMean (Table 3.3). Furthermore, except for the Sandovales weather station, all stations with significant positive trends in TXx also presented positive trends in SU25 (Table 3.3). Some authors argued that the increase in TXx was caused by anthropogenic changes in the atmosphere composition (Easterling *et al.*, 2016; Christidis and Stott, 2016) and in its circulation, mainly that occurred during 1979-2013 (Abatzoglou and Redmond, 2007; Horton *et al.*, 2015). The implications of the increases in extreme temperatures were associated with heat waves. These have come to cause the death of people in Pennsylvania, New Hampshire, and Washington DC (Knapp *et al.*, 1993; DeGaetano, 1996). The heat waves also have caused big agricultural damages, especially in the Peninsula poultry industry, and also structural damages in roads

(DeGaetano, 1996). It is important that in the future to make an analysis of the duration time of TXx, it could offer information of interest to different agricultural species and also for other productive activities.

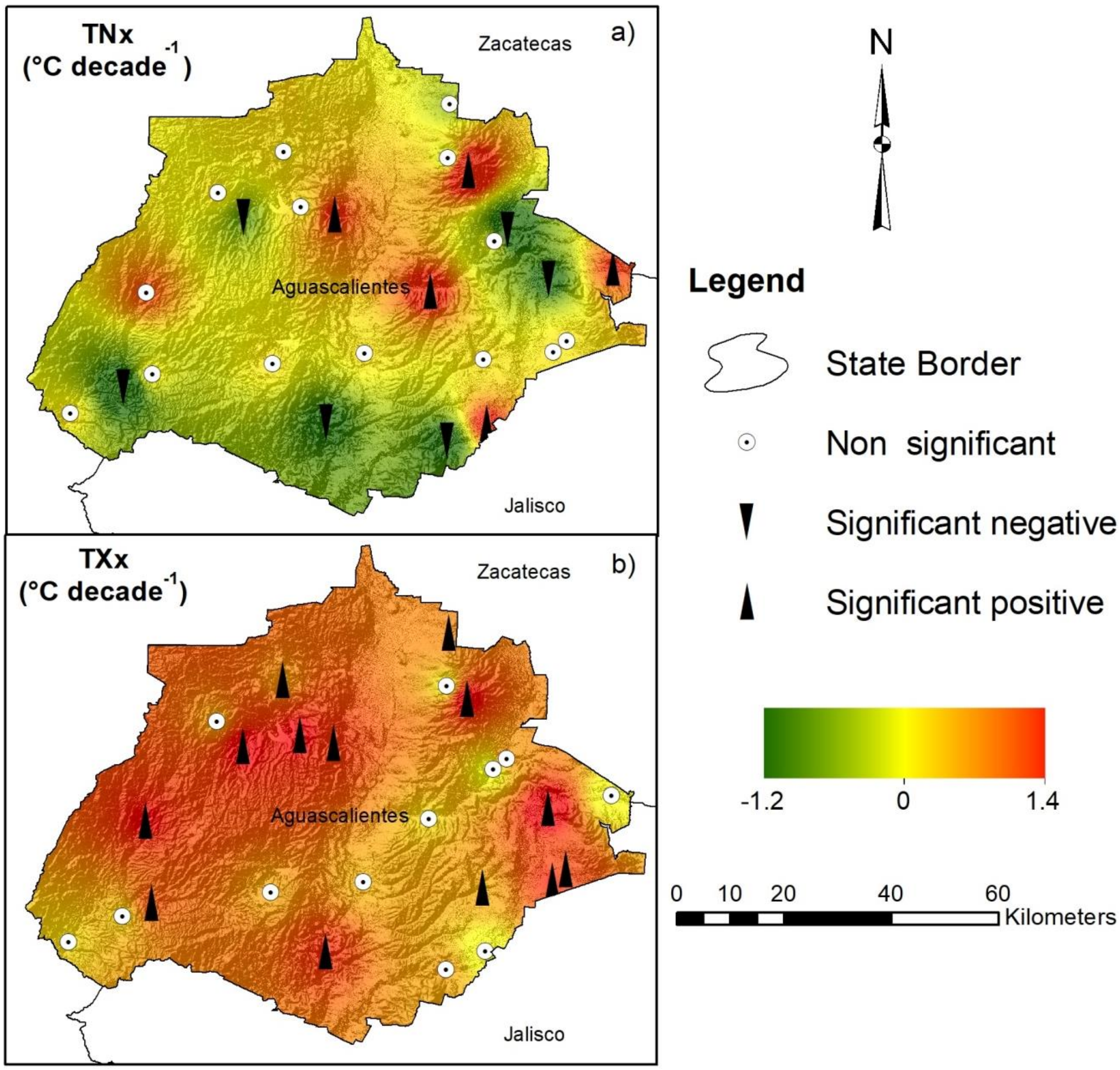


Figure 3.6. Spatial distribution of TNx (a) and TXx (b) in Aguascalientes, Mexico.

3.4.1.4. TNn and TXn

Analysis of monthly minimum value of daily minimum temperature (TNn) and monthly minimum value of daily maximum temperature (TXn) did not show a concrete pattern, but it did show a slightly greater proclivity to the cooling of the surface. The TNn index revealed statistically significant trends ($p \leq 0.05$) at 11 weather stations, two of them had positive trends, and nine had negative trends (Table 3.3). The significant positive trends were 1.064 and 1.429 °C decade^{-1} at Villa Juarez and Sandovales (Table 3.3) in the Northeast and Southeast of the State, respectively (Figure 3.7a). Our results were somewhat different from the ones found in the literature, since for this index, a generally greater occurrence of positive trends was reported. Worldwide, the magnitudes of these trends were variable, some authors reported a relatively small range from 0.050 to 0.440 °C decade^{-1} (Zhang *et al.*, 2005; New *et al.*, 2006; Shresta *et al.*, 2016; Xi *et al.*, 2018; Rahimi and Hejabi, 2018), whereas other researchers published values between 0.700 and 1.210 °C decade^{-1} (Caesar *et al.*, 2011; Santos *et al.*, 2011; Almazroui *et al.*, 2014; Beharry *et al.*, 2015), which look similar to ours. Differently, the significant negative trends were between -2.407 and -0.377 °C decade^{-1} at Calvillo and La Tinaja, respectively (Table 3.3) and were located in the Northwest (La Tinaja and Rancho Viejo), Southwest (Presa Media Luna and Calvillo), Center (Cañada Honda), South (Presa El Niagara), East (El Novillo), Northeast (Mesillas) and Southeast (Los Conos) of the study area (Figure 3.7a). The literature review showed that a big proportion of negative trends was not reported for TNn. However, the magnitude obtained by Caesar *et al.* (2011) was about -0.590 °C decade^{-1}, which is within the range obtained in this work. These results indicate that the TNn index is presenting changes on an important surface of the State (Figure 3.7a); in a small area, it is increasing, and in a greater part it is decreasing. That is to say, in the small area, the weather is less cold or warmer, whereas on the bigger surface the atmosphere is presenting colder extremes. It is presumed that external forcing and an anthropogenic component causes the increases in TNn or decreases in cold extremes, while the TNn reductions or the increases in cold extremes are produced by the increases in the intensity of advection of cold winds from polar regions to lower latitudes (National Academies of Sciences, Engineering, and Medicine, 2016). In connection with the repercussions of the decreases of these temperatures, some studies indicate that the deaths caused by low temperatures represent the greater percentage of deaths associated with temperatures changes; and the main causes are freezing, hypothermia, cardiac arrhythmia, cardiac arrest and loss of cerebral blood flow (Bell *et al.,* 2018). The TXn index showed statistically significant trends ($p \leq 0.05$) at five stations from which three had positive trends and two had negative trends (Table 3.3). The positive significant trends varied between 1.667 and 2.222 °C decade^{-1} at San Bartolo and Villa Juarez, respectively (Table 3.3). They were in the Southeast (San Bartolo and San Isidro) and Northeast (Villa Juarez) of this federal entity (Figure 3.7b). For this index, studies from different parts of the world show that the trends are pretty heterogeneous. However, the interval of all these trends include the values that we obtained in this research. Some authors have found values that range from 0.240 to 1.000 °C decade^{-1} (Almazouri *et al.,* 2014; Beharry *et al.,* 2015). Other researchers have obtained intervals of trends wider which encompass almost all of our values, such is the case of Santos *et al.* (2011) who reported trends between 0.190 and 2.010 °C decade^{-1}.

Conversely, the negative significant trends were -1.273 and -1.176 °C decade^{-1} at Calvillo and Puerto de la Concepcion (Table 3.3) in the Southwest and Northwest of Aguascalientes (Figure 3.7b). This pattern is similar to the one described by New *et al.* (2006) who state that for this index almost always less proportion of negative trends is obtained. Differently, our trends were pretty similar to those reported by Shresta *et al.* (2016) who found values between -1.300 and -0.600 °C decade^{-1}, as we can see this interval encompasses our values. In Figure 3.8, an example of a time series for TXn index at the Calvillo weather station is presented. At this station, trend analysis was statistically significant ($p \leq 0.05$), and the rate of change was -1.273 °C decade^{-1}. Our results suggest that the monthly minimum value of daily maximum temperature is experiencing changes in a litte part of the state. In more than half (three stations) of this, it is increasing, and in less than the half (two stations) it is decreasing. It is important to highlight that all the stations with a positive trend in TXn showed positive trends in TXMean. Moreover, of the two stations with negative trends in TXn, one showed a negative trend in TXMean (Table 3.3). The increases in TXn come mainly from the increase in concentrations of anthropogenic greenhouse gasses and solar forcing (National Academies of Sciences, Engineering, and Medicine 2016), whereas its decrease is associated with less absorption of incoming solar radiation, which in turn is due to the increase in cloudiness (Jhajharia and Singh, 2011). Alternatively, Baidya *et al.* (2008) suggested that the negative trend on TXn in plains could be the result of fog episodes in winter which have gotten more frequent, sometimes lasting more than a week or even a month. In the same way, Ji *et al.* (2011) explained that the negative trend on TXn in plains could be due to the emission of anthropogenic particles, such as sulfate and organic carbon, which scatter incoming solar radiation and reduce radiative forcing causing a decrease in temperature. In Australia and other parts of the world, the implications of the increase in TXn are related to heat waves and high temperatures. In the United States, these events when associated with droughts have resulted in billions of dollars of economic losses and more than 800 deaths (Bell *et al.*, 2018).

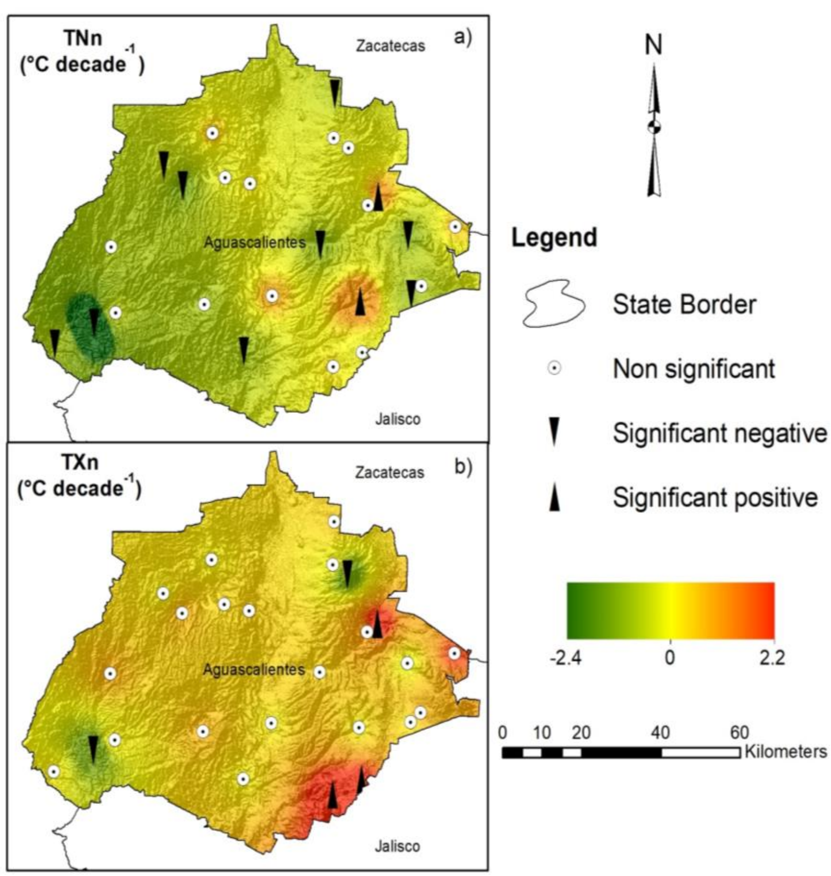


Figure 3.7. Spatial distribution of TNn (a) and TXn (b) indices in Aguascalientes, Mexico.

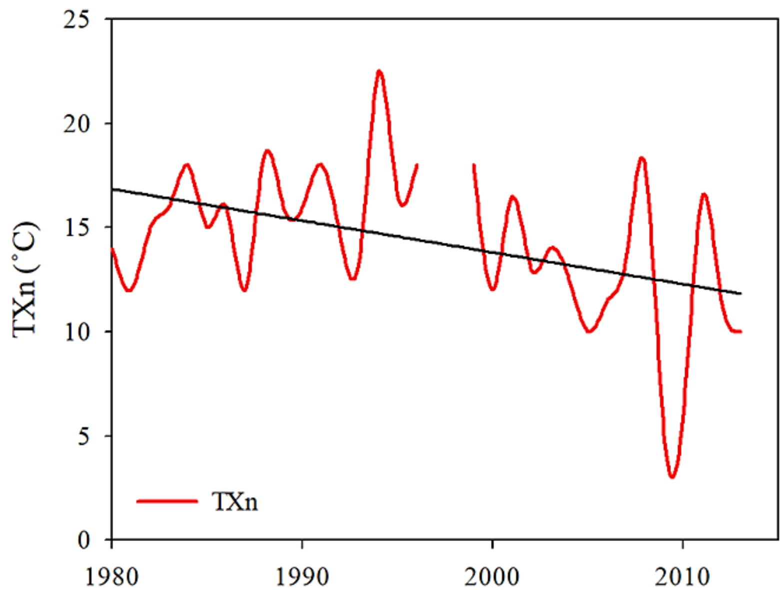


Figure 3.8. Time series example for TXn in the Calvillo weather station ($p \leq 0.05$).

3.4.1.5.TX10p and TX90p

According to the number of cold days (TX10p) and the number of warm days (TX90p), one important area of Aguascalientes experiences fewer cold extremes but another important part experiences more warm extremes. Thus, the TX10p index revealed statistically significant negative trends ($p \leq 0.05$) at 18 weather stations (Table 3.3). These trends were between -5.665 and -1.204 days decade^{-1} in Villa Juarez and El Tule, respectively (Table 3.3). They are distributed in the Northeast (Mesillas, Tepezala, Villa Juarez and El Tule), East (Palo Alto, El Novillo and Las Fraguas), Northwest (Presa Potrerillos, Presa Plutarco Elias Calles and Rancho Viejo), Southeast (San Bartolo, San Isidro and Los Conos), Center (Cañada Honda), South (Presa El Niagara), Southwest (Malpaso), North-Central (Presa Jocoque) and West (Presa La Codorniz) of the federal entity (Figure 3.9a). Our results agreed with those of other studies who presented only the occurrence of negative trends. Furthermore, our magnitudes were within the interval reported in other works, such as Xi *et al.* (2018) who obtained trends of -5.930 days decade^{-1}, and Zhang *et al*. (2005) who found trends of -0.200 days decade^{-1}.

Other authors have reported magnitudes going from -4.490 to -1.003 days decade^{-1} (New *et al.* 2006; Caesar *et al.*, 2011; Beharry *et al.*, 2015; Shresta *et al.*, 2016), which also corresponded to those obtained in this study. Our results indicate that at the sites where TX10p had negative trends, the cool days were occurring with less frequency; in other words, the number of days when TX<10th percentile was decreasing. With the exception of El Tule and Tepezala (both in the Northeast), all weather stations that showed significant negative trends in TX10p presented significant increases in TXMean (Table 3.3). According to Rusticucci and Barrucand (2004), the decrease in cool days was caused by the increase in mean temperature, especially during winter days. The negative trends in TX10p shown in Figure 3.9a are of prime importance, since some crops, such as grapevine, peach-tree, wheat, barley, alfalfa, and oats, could be affected by a decrease of cold and hence their productivity (Hatfield and Prueguer, 2015). However, under these conditions, the growing season could get slightly lengthened, permitting the cropping of other species (Christidis and Sttot, 2016).

On the other hand, the TX90p index experienced a statistically significant positive trend ($p \leq 0.05$) at 19 weather stations (Table 3.3). These trends oscillated between 1.760 and 4.811 days decade^{-1} at the Venadero and Presa El Niagara weather stations, respectively (Table 3.3), and were located in the Northwest (Puerto de La Concepcion, Presa Potrerillos, Presa Plutarco Elias Calles and Rancho Viejo), Southeast (San Bartolo, San Isidro, Los Conos and Sandovales), Southwest (Malpaso and Venadero), Northeast (Mesillas and Villa Juarez), East (Palo Alto and El Novillo), Center (Cañada Honda), South (Presa El Niagara), North-Central (Presa Jocoque), West (Presa La Codorniz) and South-Central (Aguascalientes) of the state (Figure 3.9b). Our results were in agreement with other reports that showed just positive trends. Nevertheless, the magnitudes reported until today were very diverse. Some authors reported trends that varied between 1.470 and 5.300 days decade^{-1} (Zhang *et al.*, 2005; New *et al.*, 2006; Caesar *et al.*, 2011), a range which contained the magnitudes obtained in this work.

Other scientists have reported trends oscillating between 5.790 and 33.600 days decade^{-1} (Almozroui *et al.*, 2014; Beharry *et al.*, 2015; Ruml *et al.*, 2017; Xi *et al.*, 2018) which are greater than ours. From another perspective, our findings indicated that in an important area of Aguascalientes warm days were increasing; in other words, the percentage of days when TX>90th percentile was increasing. It is important to add that the correspondence between TXMean and TX90p is distinguished, that is, the weather stations with significant positive trends in the first index had significant positive trends in the second one (Table 3.3). According to Rusticucci and Barrucand (2004), the increase in warm days is a consequence of the increase in mean temperature especially from the one that occurred in summer. On agricultural lands that presented statistically significant increase in TX90p the implications could be related to the damage to crops sensitive to heat as is the case with corn which is very sensitive during emergence, foliar development and flowering (Coligado and Brown, 1974; Cutforth and Shaykewich, 1989; Summerfield *et al.,* 1991). On these lands, beans could be another vulnerable crop, because of its susceptibility to heat during the growth of plants (Jenni *et al.,* 2000).

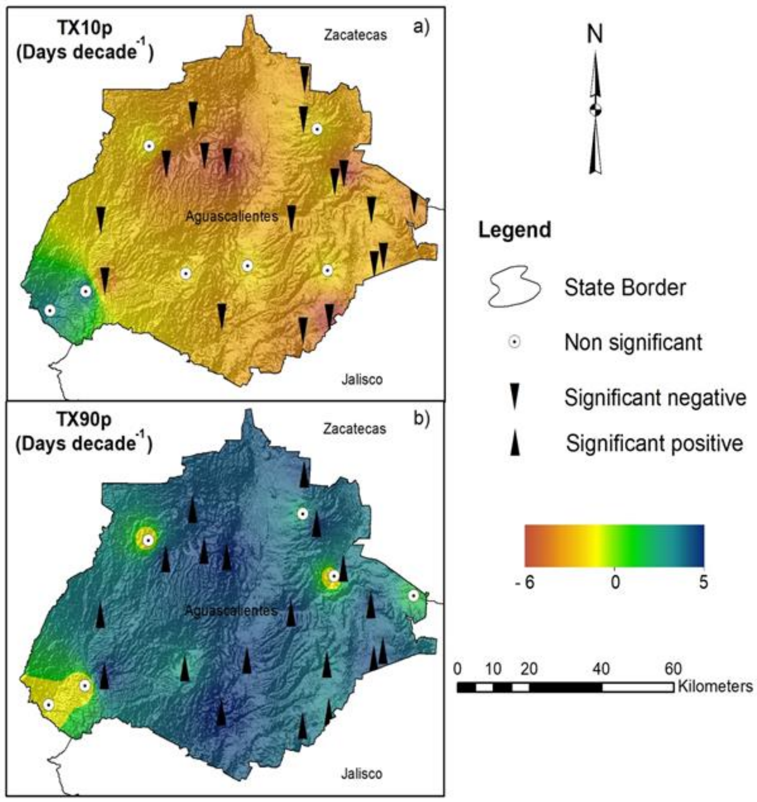


Figure 3. 9. Spatial distribution of TX10p (a) and TX90p (b) indices in Aguascalientes, Mexico**.**

3.4.1.6.TN10p and TN90p

In Aguascalientes cool nights (TN10p) and warm nights (TN90p) do not seem to indicate an absolute pattern of warming or cooling. It is observed that the nocturnal weather could be getting less warm in some zones and warmer in others. In the same way, while the cold weather increases in one region, it decreases in another. The TN10p index showed statistically significant ($p \leq 0.05$) trends at 13 weather stations, out of which six had positive trends, and seven showed negative trends (Table 3.3). The significant positive trends were between 1.707 and 6.812 days decade^{-1} at Palo Alto and Calvillo, respectively (Table 3.3), and were distributed in the East (Palo Alto and El Novillo), South (Presa El Niagara), Northwest (Rancho Viejo), Southwest (Calvillo) and Southeast (Los Conos) of the study area (Figure 3.10a). For this index, very few analyses have indicated significant positive trends (Barry *et al.,* 2018). However, the magnitudes reported by some authors are similar to the ones we found in this work. For instance, trends between 0.730 and 3.010 days decade^{-1} have been reported (Lopez-Diaz *et al.,* 2013; Shresta *et al.,* 2016; Xi *et al.,* 2018); this range encompasses ours partially. In contrast, negative significant trends oscillated between -3.736 and -1.827 days decade^{-1} at Presa Jocoque and Presa Potrerillos, respectively (Table 3.3), and were located in the Northwest (Puerto de La Concepcion and Presa Potrerillos), Southwest (Malpaso), North-Central (Presa Jocoque), Northeast (Villa Juarez), East (Las Fraguas) and South-Central (Aguascalientes) of the federal entity (Figure 3.10a). The pattern that we found is similar to those of other studies who observed a greater occurrence of negative trends (Barry *et al.,* 2018). The negative trends published for this index predominantly oscillated between -5.000 and -0.863 days decade^{-1} (Zhang *et al.,* 2005; New *et al.,* 2006; Caesar *et al.,* 2011; Beharry *et al.,* 2015; Shresta *et al.,* 2016; Rahimi and Hejabi, 2018), which encompass the trend values that were obtained in this work.

Other authors have published trends ranging from -36.500 to -6.500 days decade^{-1} (Almozroui *et al.,* 2014; Ruml *et al.,* 2017) that are considerably different from ours. In connection with TN10p, Aguascalientes can be divided into two important parts; in one this index increases, that is, the days when TN<10th percentile are more frequent (Figure

3.10a) and in another part this index decreases, that is, the days when TN<10th percentile are less frequent (Figure 3.10a). It is important to mention that except for the Mesillas, Presa La Codorniz, Venadero, Villa Juarez and Sandovales weather stations the TN10p index presented a correspondence with TNMean, that is when the first index increases the second one decreases (Table 3.3). According to Christidis and Stott (2016), the increase in cool nights (TN10p) could be due to great volcanic eruptions which decrease the conditions for the cloud formation.

On the other hand, the decrease in TN10p is produced by the increase of night temperature during winter (Rusticucci and Barrucand, 2004), probably because of the greater presence of cloudiness and the increase of greenhouse gasses. In corn, the increase on cool nights could generate slow growth rates and delay all physiological processes, reducing potential yield (Hatfield and Prueger, 2015). On the contrary, the decrease in cool nights (TN10p) is associated with the increase in minimum temperature which favors the appearance and survival of many insect species (Raza *et al.*, 2015). Thus, the increase in temperature by 2 °C could generate an increase between one and five additional life cycles per season (Yamamura and Kiritani, 1998), reinforcing populations and generating public health problems, agricultural diseases and important damages to forests (Raza *et al.*, 2015). Simultaneously, the TN90p index had statistically significant trends ($p \leq 0.05$) at 19 weather stations out of which eight had positive trends, and 11 had negative trends (Table 3.3).

The positive significant trends oscillated between 0.977 and 7.056 days decade^{-1} at Presa Potrerillos and Puerto de La Concepcion, respectively (Table 3.3), and were distributed in the Center (Cañada Honda), Northwest (Puerto de La Concepcion and Presa Potrerillos), Southwest (Malpaso), North-Central (Presa Jocoque), West (Presa La Codorniz), South-Central (Aguascalientes), and East (Las Fraguas) of the study area (Figure 3.10b). Unlike our results, the majority of studies reported a greater proportion of positive trends in TN90p (Almazroui *et al.*, 2014). For this index, the positive magnitudes reported in the literature are diverse also; some authors have reported trends between 1.200 and 6.410 days decade^{-1} (Zhang *et al.*, 2005; Caesar *et al.*, 2011; Beharry *et al.*, 2015) which are similar to ours. Other authors have reported positive trends from 8.100 to 27.000 days decade^{-1} (New *et al.*, 2006; Almazroui *et al.*, 2014; Ruml *et al.*, 2017; Xi *et al.*, 2018), which are considerably greater than those that we found. Similarly, the significant negative trends oscillated between -5.848 and -4.183 days decade^{-1} at Calvillo and Rancho Viejo, respectively (Table 3.3), and were distributed in the Southeast (San Bartolo, Los Conos and Sandovales), Northeast (Mesillas and Villa Juarez), Southwest (Calvillo and Venadero), East (Palo Alto and El Novillo), Northwest (Rancho Viejo) and South (Presa El Niagara) of the state (Figure 3.10b). Concerning this index, one difference between our results and those reported in the literature is that they almost do not report the presence of negative trends, perhaps because globally extreme indices present a wide variability (National Academies of Sciences, Engineering, and Medicine, 2016).

In our study area, the increase in TN90p denoted that warm nights were increasing in one part of the state, that is, the days when TN>90th percentile were being more frequent. In another part of the state, the decrease in this index denoted that warm nights were decreasing, that is, the days when TN>90th percentile were less frequent. It is important to mention that except for the Cañada Honda weather station, the rest of the stations with a positive significant trend in TNMean presented positive significant trends in TN90p (Table 3.3). Analogously, with the exception of the San Bartolo and Villa Juarez weather stations, all stations with significant negative trends in TNMean presented negative trends in TN90p (Table 3.3). The increase in the number of warm nights is related to the increase in the minimum temperature, especially occurring on winter (Rusticucci and Barrucand, 2004), which in turn is caused by the increase in urbanization and clouds cover (Price *et al.*, 1999). According to Frich *et al.* (2002), TN90p provides an idea about potential detrimental effects associated with the absence of nocturnal cooling, a main contributor to stress related to the heat. Thus, the nocturnal warming is expected in a climate of forced greenhouse gases, which is going to occur in part as a radiative effect of clear sky and part as a result of the increase in the layer of clouds due to additional available humidity for the nocturnal condensation. The increases in warm nights (TN90p) could favor the expansion of insects to new areas and the modifications that these temperatures provoke in the ecosystem permit that some insects get an extreme level of population and at the same time cause the extinction of other species (Raza *et al.*, 2015). In agriculture, pollination is one of the more sensitive processes to high temperatures, specifically due to the vapor pressure deficit. In the case of corn, the reproductive development phase is affected, and the potential yield is reduced to 80-90% (Hatfield and Prueger, 2015).

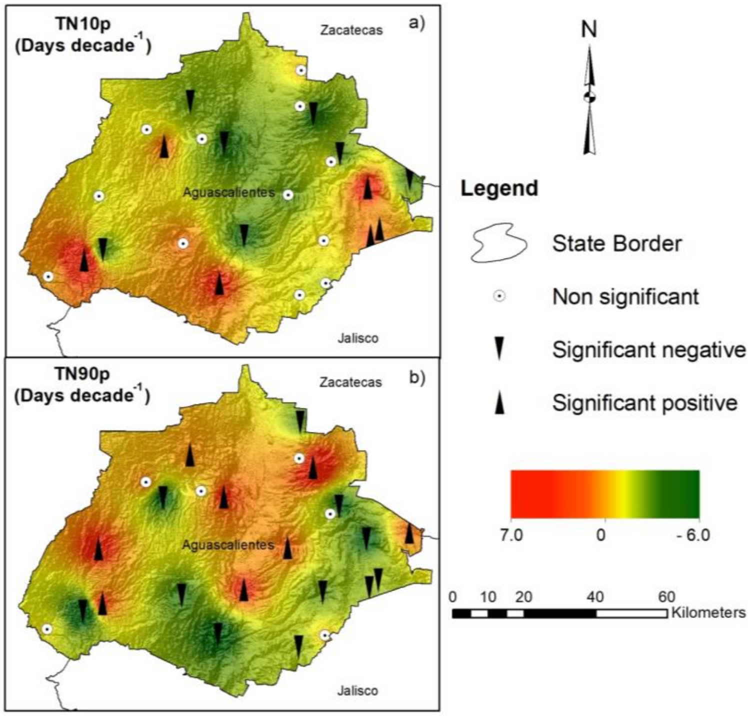


Figure 3.10. Spatial distribution of TN10p (a) and TN90p (b) in Aguascalientes, Mexico.

3.4.1.7. WSDI and CSDI

According to the warm spell duration indicator (WSDI) and cold spell duration indicator (CSDI), Aguascalientes does not seem to be experiencing relevant changes. In connection with WSDI, there was a statistically significant trend ($p \leq 0.05$) just at one weather station in the South (Presa El Niagara) of state (Figure 3.11a) and its magnitude was 2.857 days decade^{-1} (Table 3.3). For this index, previous publications indicated a greater prevalence of positive trends. Also, researches till today show that these trends present a relatively wide variation range so that a group of authors reports oscillations between 0.510 and 7.300 days decade^{-1} (Zhang *et al.*, 2005; New *et al.*, 2006; Santos *et* *al.,* 2011; Almazroui *et al.,* 2014; Rahimi and Hejabi, 2018) which encompass the magnitudes that we found in this study. Other scientists have obtained values between 5.000 and 52.100 days decade^{-1} (Shresta *et al.,* 2016; Ruml *et al.,* 2017). Our results show that the warm spell duration is increasing in one small part of the South of Aguascalientes (Figure 3.11a), in other words, this small part is presenting periods with at least six consecutive days when TX>90th percentile with more frequency. It is important to add that the weather station (Presa El Niagara) that presented an increase in WSDI also presented significant positive trends in TXMean which supports the idea that increases in the second index cause increases in the first index. Some studies indicate that the increases in WSDI in the last 20 years have been caused by external forcing (Christidis and Stott, 2016). The implications of these increases can be related to some implications of TN90p and TX90p. This is important since in the area of influence of the Presa El Niagara weather station (the only station with positive significant trend) occurs in around 1265 hectares where extensive agriculture is practiced, in which corn, sorghum, oats, rye, and alfalfa predominate which could be affected (Maciel *et al.,* 2007).

In the same way, the CSDI index showed statistically significant trends ($p \leq 0.05$) only at the Calvillo weather station in the Southwest of Aguascalientes (Figure 3.11b) and its magnitude was 2.143 days decade^{-1} (Table 3.3). For this index, our results were different from those obtained by other authors, since in their works only the presence of negative trends was reported (Rahimi and Hejabi, 2018; Ruml *et al.,* 2017). Our findings indicate that the cold spell duration indicator is increasing just in one small part of the Southwest of the study area (Figure 3.11b); in other words, this part of the state is presenting periods with at least six consecutive days when TN<10th percentile with more frequency. It is important to highlight that the CSDI behavior in this station is in agreement with TNMean, since while this latter index decreases, CSDI increases. Some regions of the world for which long periods of observations are available to have noted increases in CSDI after great volcanic eruptions and under conditions of reduction in cloudiness (Christidis and Stott, 2016). The increase in the cold period produces, as a consequence, a greater risk of early and late frosts for specific crops (Snyder and Melo-Abreu, 2010). This is of particular importance since at this location the increase of cold could affect the development of guava trees that are cultivated in this region (Padilla *et al.*, 2010).

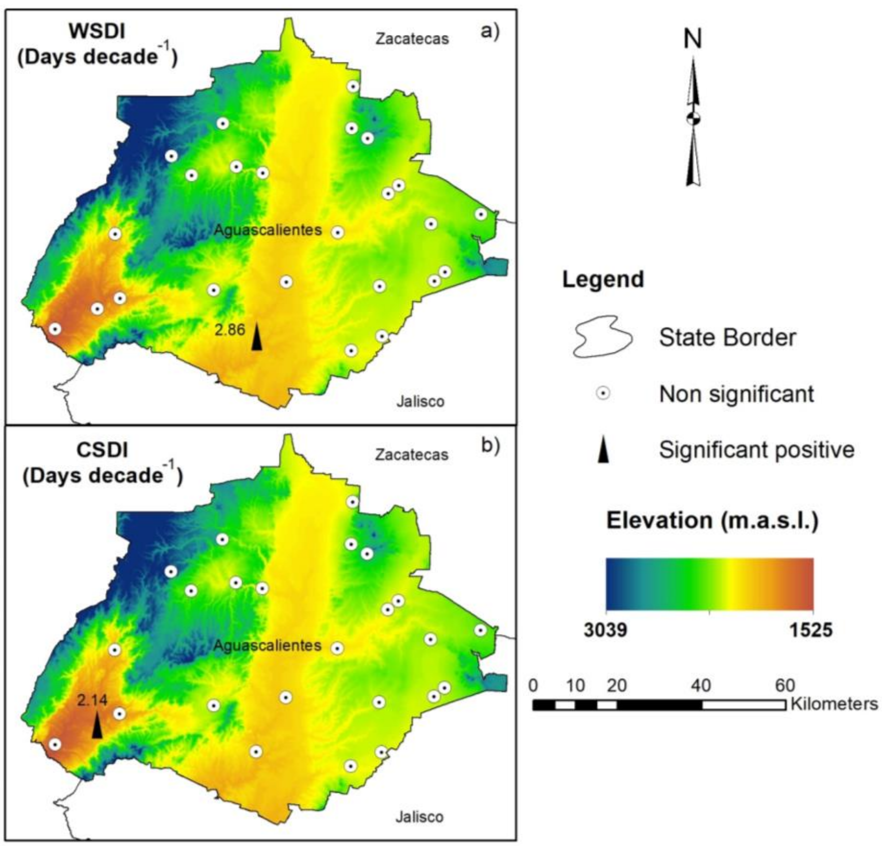


Figure 3.11. Spatial distribution of WSDI (a) and CSDI (b) in Aguascalientes, Mexico**.**

3.4.2. Correlation analysis of extreme temperature indices

Correlation is important to understand the interrelations that exist between all indices. In Table 3.4 the correlation matrix obtained for all extreme temperature indices is presented. It is observed that among most of the indices there was statistically significant ($p \leq 0.05$) correlation so that the only pairs of indices that were not correlated were GSL-TXMean, GSL-DTR, GSL-SU25, TXn-GSL, TX10p-GSL, TX90p-GSL, TN90p-GSL, and WSDI-GSL. On the other hand, the correlation range varied between -0.965 and 0.987 for the pairs SU25-TXMean and CSDI-FD0, respectively. According to Almazroui *et al.* (2014), knowing the correlation among some indices is important since from these the relations among all others can be deduced.

3.4.3. Relationship between elevation and extreme temperature indices

A correlation analysis between the magnitude of extreme temperature indices and elevation was performed. Some authors have found evidence that the trend magnitude of extreme temperature indices depend upon elevation (Li *et al.*, 2012; Ding *et al.*, 2018). The elevation range of weather stations used in this study was divided into two intervals 1580m-1990m and 1995m-2425m, the correlation analysis was carried out for both, and also for the total elevation range which was 1580m-2425m. For the interval 1580m-1990m, statistically significant ($p \leq 0.05$) correlation was found for five indices (Table 3.5). The TX10p index was negative and strong significant correlated; while TXMean, SU25, TNn, and TXn showed positive and strong significant correlation (Table 3.5). In the case of TXMean, SU25, TNn, and TXn, positive significant correlation indicates that magnitude increases as height also increases. On the other hand, negative trend on TX10p indicates that the magnitude of this index decreases when elevation increases. These results are partially different to the ones reported by Pepin and Seidel (2005), who comment that magnitudes in indices associated to warming decrease when elevation increases; under this premise, also would be expected that magnitude on TNn and TXn would decrease when height increases, which does not occur. However, the TX10p behavior is more coherent through elevation increases, that is to say, cool days stop decrease or show smaller rates of decrease when height increases. For the interval 1995m-2425m, correlation was statistically significant ($p \leq 0.05$) into two indices (Table 3.5). The DTR index showed negative and strong significant correlation; while the TN90p index had positive and significant correlation (Table 3.5). This means that as the height increases, the magnitude on the DTR trend is smaller, and the trends of the warm nights magnitude is bigger. Some authors have found negative and significant correlation for DTR (Ding *et al.*, 2018). The negative correlation on DTR, indicates that at sites located at bigger height, the difference between TXMean and TNMean is smaller. However, as the TN90p correlation is positive, it can be deduced that for this altitudinal range the magnitude on DTR trend decreases due to the increase on minimum temperature.

On the other hand, statistically significant correlation was not obtained between the magnitude of extreme temperature indices and elevation in the range 1585m-2425m. According to this analysis, in Aguascalientes, temperature extreme indices are not too sensitive to all elevation range used in this research.

3.4.4. Causes of temperature trends

To date, two factors are recognized as causes of global warming. Through laboratory research and simulation models, in the last decades has been demonstrated that the origin of warming/cooling is owing to two primordial sources: natural or anthropogenic drivers.

3.4.4.1. Natural drivers

The main natural agent that produces changes on terrestrial surface temperature is solar irradiance. Magnetic sources generated by sun, produce the big majority of fluctuations on radiation that occur in 27 days and 11 years cycles (Lean, 1997). Magnetic activity increases and decreases through solar cycle producing sunspots, faculae, changing plages and networks that trap outgoing net solar radiation altering temperature and density of solar atmosphere. On one hand, in the sun photosphere, the groups of magnetic fields form sunspots which are darker and colder than the surrounding photosphere, due to magnetic fields that somehow inhibit ascendent flow of energy from the convection zone to surface (Lean, 1997). On the other hand, dark sunspots and the brightness faculae act in opposition to module total irradiance and the spectrum at near-UV, visible and infrared radiation wavelengths; the influence of sunspots increase with respect to the influence of faculae by increasing the wavelength. Also, the plage emission by itself, controls the variability of photospheric radiation and chromospheric in the UV and EUV spectrum at wavelengths less than 300 nm (Lean, 1997).

Other natural source that causes changes on temperature are volcanic eruptions. Volcanic eruptions inject tens of teragrams of active gasses and solid aerosol particles to the atmosphere. In several weeks, volcanic cloud forms sulfate aerosol and other microphysic transformations by means of conversion of SO_2 (Pinto *et al.*, 1989; Zhao *et al.*, 1995). The resulting cloud of aerosol sulfate particles has important impacts in the long and shortwave radiation. The resulting perturbation in the earth radiative balance affects earth temperatures through direct and indirect radiative effects in the atmospheric circulation. In cold regions of stratosphere, aerosol particles also work as surface for heterogeneous chemical reactions that release chlorine and destroy ozone (Robock, 2000).

On the other hand, explosive volcanic eruptions (stronger volcanic eruptions) emit other kind of gasses, among which are H_2O, N_2 and CO_2. The more important climate effect of this type of eruptions is throughout emission of sulfur species to the stratosphere mainly in the form of SO_2 (Rampino and Self, 1984) and sometimes as H_2S (Luhr *et al.*, 1984). These sulfur species react with OH and H_2O for forming H_2SO_4 in times scales of weeks, the resulting H_2SO_4 aerosol produces the dominant radiative effect of volcanic eruptions; which is estimated to be around -0.2 W m^{-2} for the globe and -0.3 W m^{-2} for north hemisphere (Robock, 2000).

According to Robock (2000), aerosol sulfate particles are around the same size than visible light, they have a typical effective radius of 0.5 µm, a dispersion albedo of 1 and interact strongly with the solar radiation throughout dispersion. So that, some of sunlight is backscattered and reflected back to space; this increase the net planetary albedo, reduces the quantity of solar energy reaching the terrestrial surface and also it results in a net cooling. According to Robock (2000), the big individual eruptions produce hemispheric or global cooling that can last two or three years. Also, the winter following a tropical eruption is warmer over continents of north hemisphere because of nonlinear response through atmospheric dynamic. Volcanic eruptions can have a big local effect on terrestrial temperatures in regions near to the eruption until several days after the explosion.

3.4.4.2. Anthropogenic drivers

The intergovernmental panel on climate change states that anthropogenic drivers causing warming are gasses coming from combustion of fossil fuels and other productive activities; and classifies them into two groups: principal well-mixed greenhouse gasses and other well-mixed greenhouse gasses (IPCC, 2007).

Well mixed greenhouse gasses

Carbon dioxide (CO_2) increases earth temperature through absorption of outgoing terrestrial radiation. This gas is the more important of gasses causing greenhouse effect and the one of longer duration due to its abundance and permanence in the atmosphere. Its main sources in the planet are found in the atmosphere (in the form of carbon dioxide), terrestrial biosphere and oceans (Mitchell, 1989). The change in CO_2 content affects the flux of net radiation from earth surface, and the flux of latent and sensible heat from the terrestrial surface to atmosphere (Manabe and Wetherald, 1975). In a modelling experiment, Manabe and Wetherald (1975) found that the increase in the CO_2 concentration increases the greenhouse effect, and in turn produces an increase in the general warming of the troposphere.

The increase in incoming terrestrial radiation produced by the increase in the quantity of CO_2 also contributes in the decrease of area with snow cover and the increase in the quantity of absorbed solar radiation by earth surface (Manabe and Wetherald, 1975). The Manabe and Wetherald model (Manabe and Wetherald, 1975) also indicated that in the stratosphere occurs a cooling as a consequence of increase in the emission from the stratosphere to the space as a result of increase in the CO_2 concentration. The total quantity of CO2 above of a given level decreases with the increase in altitude, thus the absorption of above emissions also decreases (Manabe and Wetherald, 1975). Atmospheric methane (CH_4) is a greenhouse effect gas that is emitted by natural (wetlands, oceans, termites and clathrates) and anthropogenic sources (fossil fuel exploitation, ruminant animals, rice agriculture, waste management and biomass burning) (Dlugokencky *et al.*, 2012). It has a strong infrared radiation absorption at 7.66 µm and a direct effect in the radiative balance of troposphere and stratosphere (Dlugokencky *et al.*, 1994).

According to Dlugokencky *et al.* (2012) CH_4 contributes directly with 0.5 W m^{-2} of total radiative forcing of greenhouse gasses of long duration, although according to Hofmann *et al.* (2006) total radiative forcing for 2009 would have been around 2.77 W m^{-2}. When CH_4 is oxidized, leads to CO_2 and Ozono (O_3) under conditions where the mixing ratio of nitric oxide (NO) is bigger than 5-10 ppm (Cicerone and Oremland, 1988). Given that CO_2 and O_3 are greenhouse gases, methane oxidation produces a direct effect on climate (Lelieveld *et al.*, 1998). According to Donner and Ramanathan (1980) CH_4 has a warming effect over the earth-troposphere system, in a modelling experiment they deleted the CH_4 presence and found that the earth-troposphere system cooled at an approximate rate of 1-2 W m^{-2}, with a higher effect at low latitudes and more pronounced latitudinal variation during winter. When they doubled CH_4 concentrations, the cooling was less than that obtained without CH_4. Also, they found that removing CH_4 and N_2O from atmosphere, in winter, was produced a cooling around ~1.15 K in the Ecuador, in the lowest stratosphere. So that, the hemispheric mean annual contribution of radiative warming to earth-troposphere due to CH_4 can become around 1.7 W m^{-2} (Donner and Ramanathan, 1980).

Nitrous oxide (N_2O) is another component of the system of gasses of the atmosphere. It plays an important role in the troposphere chemistry, earth radiation balance, in the global nitrogen cycle and it is an important source of nitric oxide in the catalytic destruction of stratospheric ozone (Badr and Probert,1993). N_2O is produced and emitted to the atmosphere in natural way by microbial processes occurring in ground and waters (oceans and freshwater systems), as well as from anthropogenic sources as a result of agricultural activities (use of fertilizers, biomass burning and deforestation) and combustion of fossil fuels (Badr and Probert, 1993). N_2O is an important greenhouse gas and the main cause of stratospheric ozone depleting. Due to its long life (150 years) in the atmosphere and the high radiative capacity, nitrous oxide plays a significant role contributing to the earth atmospheric warming with a potential of global warming 298 times bigger than carbon dioxide (Badr and Probert, 1993; Skiba and Rees, 2014). The capture of thermal radiation of long wave caused by the presence of N_2O in the troposphere is proportional to the square root of its atmospheric concentration (Dickinson and Cicerone, 1986). The nitrous oxide losses around a half of its captured radiation by the overlap among its bands and those of water vapor and carbon dioxide. If all N_2O was removed from atmosphere, the earth-troposphere system would get cool at a rate between

0.9 and 1.6 W m^{-2} with the strongest effect occurring at low latitudes (Badr and Probert, 1993).

Other well mixed greenhouse gasses

Water vapor is a greenhouse gas highly variable and the most powerful in earth atmosphere; it represents approximately the half of today greenhouse effect. The emissions of this vapor come from human activities such as irrigation, cooling systems, aircraft and domestic use of water (Sherwood *et al.*, 2018). Increases of 1 K in the surface temperature generates an increase of pressure on saturated vapor around 6%. The increase in water vapor intensifies the warming by long wave (infrared), and in a less extent, by short (solar) wave of troposphere and surface, and leads to a further warming giving a positive feedback between water vapor and atmospheric temperature (Mitchell, 1989). According to Solomon *et al.* (2010) the water vapor content in the stratosphere is controlled by its transport trough the tropopause region and the methane oxidation inside the stratosphere. Also, increases of tropospheric water vapor warms the troposphere but cools stratosphere; while the stratospheric water vapor decreases, stratosphere warms and troposphere cools (Solomon *et al.*, 2010). Some simulations carried out for the period 1996-2000 indicated that average radiative forcing of water vapor including stratospheric adjust was +0.24 W m^{-2} for an increase of 1-ppmv (Solomon *et al.*, 2010). So that, the atmospheric warming due to water vapor is around 100 W m^{-2}.

Atmospheric ozone (O_3) is found in stratosphere and troposphere. Stratospheric ozone plays a benefic role absorbing the major part of harmful ultraviolet solar light, and permits that just a short quantity gets the terrestrial surface. The ultraviolet radiation absorption by the ozone creates a color source that plays a key role in the temperature structure of terrestrial atmosphere. Nonetheless, in the last decades, through measurements, important decreases in the quantity of stratospheric ozone have been detected; science has demonstrated that the responsible agents of such decreases are chemicals produced and used by human. Among the more aggressive compounds for the ozone layer are chlorine (clorofluorocarbon, CFC) and bromine (halon), which have been widely used in spray aerosols, refrigerants, pesticides, solvents and fire extintors (WMO, 1998). When these substances reach the stratosphere, sun ultraviolet radiation makes they get separated and release chlorine and bromine atoms which react with ozone unchaining chemical cycles of destruction of this protecting layer. Atmospheric ozone has two effects in the earth thermal balance, it absorbs ultraviolet solar radiation, which warms stratosphere, and absorbs infrared radiation emitted from terrestrial surface, trapping the heat in the troposphere effectively (WMO, 1998). So that, the climatic impact of change in ozone concentrations vary with the altitude to which these ozone changes occur.

On one hand, the biggest ozone losses observed in the lowest stratosphere due to gasses produced by human (chlorine and bromine) have a cooling effect in the earth surface (WMO, 1998). On the other hand, the ozone increases occurred in the troposphere due to surface contamination with gasses have a warming effect in earth surface, contributing thus to the greenhouse effect (WMO, 1998). Aerosol, also known as particulate matter, is one of the biggest contaminants and determinant of air quality. Particle size vary since few nm (10^{-9}m) to ones few hundreds of μm in diameter. Those with diameter shorter than 10μm mean a risk for health due to they can penetrate lungs;

and those shorter than 2.5μm possess further risks related to respiratory and cardiovascular diseases, and deaths (Chin *et al.,* 2007).

Within the main sources of aerosol emissions are dust storms from deserts, volcanic eruptions and industrial contamination (Wiegner, 1988). These particles help to cloud formation and determine the cloud droplets spectrum and the optic properties of clouds (Wiegner, 1988). They also influence the radiation transference into the atmosphere and so they can modify the energy cycles of earth-atmosphere system (Wiegner, 1988). The principle consists in the aerosol layer warms by the short-wave radiation absorption, if more radiation is dispersed back to the space (increase of planetary albedo), a cooling is produced; but a warming could be produced, if the reflected radiation by the surface be reversed (Wiegner, 1988). According to Lenoble *et al.* (1982), the net radiative loss in a planetary scale for average global values is around 25 W m^{-2}, which corresponds to one decrease of 1.1 K in the global temperature of surface. Aerosol can be classified as stratospheric and tropospheric.

The stratospheric aerosol consists mainly of sulfate particles and can come from anthropogenic sources or volcanic origin. Stratospheric aerosol generally fulfills pretty well with horizontal homogeneity and is very persistent through time since is dissociated from tropospheric turbulence by the tropopause (Wiegner, 1988). Harshvardhan and Cess (1976), for a normal aerosol concentration, predicted a decrease of surface temperature of 0.7 K; but in absence of stratospheric aerosol, temperature showed a considerably major decrease. On the other hand, high concentrations consistent with measurements after the Mt. Agung eruption showed an important increase of temperature owing to the longer longitude of the radiation trajectory. According to Labitzke *et al.* (1983), the unusual warming of tropical stratosphere could be nearly correlated to observations of transport of volcanic dust. Other researchers (Dyer, 1974; Harshvardhan and Cess, 1976) demonstrated that the cooling due to increase on planetary albedo is partially offset with a bigger warming of greenhouse effect due to the aerosol opacity and infrared wave longitudes.

During the first months after the volcanic eruption, when particles are pretty big, a short and net warming of the surface and an increase of the stratospheric temperature take place, sometime later, the smaller particles cause a net cooling. The integrated effect over all stages after eruption is a cooling of surface (Wiegner, 1988). On the other hand, tropospheric aerosol is concentrated principally in the lowest atmospheric layers, thus, the difference of temperature between surface and the aerosol layer is pretty small and so the effect of infrared aerosol is less significant than for stratospheric aerosols (Ackerman *et al.,* 1976). They also can produce either a cooling or warming in the limit of the layer depending on induced changes in the planetary albedo.

According to Wiegner (1988), for low albedos, the cooling and warming is possible depending on the albedo of simple dispersion, for one surface albedo$\geq$ 40% the warming is more likely due to the reduction of planetary albedo. In the troposphere, reduction of solar radiation dominates, and under those conditions a net cooling is expected. Some studies suggest a warming of troposphere surface system because of high albedo of surface (Wiegner, 1988). Also, due to its persistence for several months, the impact of dust particles coming from soil of arid lands is important, some studies have concluded that an increment of 10% in the cooling rates of infrared radiation is presented with respect to cases with no dust emissions (Wiegner, 1988).

3.4.5. Implications of temperature trends

Impacts of temperature changes are complex, some of them interact among themselves and generate implications with an impact even higher than the original one. Just in agricultural and livestock sectors, damages caused by climate increase significantly. Many regions already experiment decreases of production because of the stress caused by physiological disorders, weeds, diseases, pests, and other environmental agents related to climate change. It is presumed that this phenomenon also threatens the stability of food supply and will create new challenges for food safety (Melillo *et al.*, 2014; FAO, 2015). Table 3.6 shows the most important implications that changes in maximum and minimum temperature can cause in agriculture and natural resources of the state of Aguascalientes. These implications were obtained from the literature; so that, for a more complete consulting of ramifications of the phenomenon, it is recommended to review Melillo *et al.,* (2014) who present in a complete and classified way all impacts of climate change in 13 vulnerable sectors of the society.

3.5. Conclusions

Trends in 16 extreme temperature indices at 25 weather stations of Aguascalientes State were investigated. In Aguascalientes, Mexico, the vast majority of extreme temperature indices show a temporal trend; however, these trends occur in one part of the state only, while other parts keep without evident changes. Within the region that exhibits trends, there is one area that presents an evidence of diurnal warming, another area shows colder nights, and other parts show warmer/less cold nights.

According to this work's findings, different social sectors of Aguascalientes require actions to face climate change. In agriculture, research on irrigation water must be carried out for producing more food with less impact on natural resources; crop varieties with high potential yield, resistant to extreme temperatures, mainly cold temperatures, with efficient production in reduced growing season must be introduced. Measures have to be taken for the rescue of fruticulture in small zones where an increase of frost is observed. In an important area of Aguascalientes, the increase on extreme temperatures can be faced with the introduction of corn and bean varieties resistant to extreme heat, in those areas the use of soil covers can provide complementary help for avoiding exaggerated losses of water by evaporation. Also, in some regions of Aguascalientes, given the increase in heat, technology and qualified personnel should be updated for managing plagues, mostly insects associated with health and agriculture.

It is recommended to start campaigns or research to ensure the suitability of guava production under a scenario of extreme cold since in the zone of guava production of Aguascalientes was found that cold temperature occurs with higher frequency. The health programs associated with climate variability/climate change should strengthen those lines related to respiratory and cardiac diseases caused by cold temperatures, and for proceeding in eventualities of heat waves. In some regions, and in fruit trees, it is already the time to start or intensify the use of synthetic products to compensate for the cold decreases.

It is recommended that this research continues with the analysis of extreme temperature indices using the outputs of climate models both for the present climate and future climate. Results will be very valuable at the moment of long-term socioeconomic planning. Also, it is suggested to carry out an analysis about the duration of extreme temperatures which will permit to obtain important information related to the magnitude of the impact on different agricultural species and other productive activities.

In Aguascalientes, the changes found in extreme temperature indices could belong to a climate change of a bigger scale either regional or at the watershed level.

4. OBSERVED TRENDS IN DAILY PRECIPITATION EXTREME INDICES IN AGUASCALIENTES, MEXICO[2]

4.1. Synopsis

Precipitation and its distribution greatly influence the evolution of ecosystems and development of society. The objective was to analyze trends in extreme precipitation indices at 25 weather stations of Aguascalientes State. Eleven extreme precipitation indices were obtained. The time series of these indices were analyzed with the non-parametric Mann-Kendall test. The number of days above 50 mm, consecutive wet days, and extremely wet days indices did not have significant trends at any of the weather stations. Each of the indices, max 1-day precipitation amount, max 5-day precipitation amount, and number of very heavy precipitation days, showed significant positive trend at 12% of weather stations; both the number of heavy precipitation days and very wet days had significant positive trends at 8% of weather stations; simple daily intensity index, consecutive dry days, and annual total wet-day precipitation showed significant positive trends at 20%, 36%, and 4% of weather stations, respectively. The intensity index was the only one that showed a significant negative trend which happened at 4% of the weather stations. In a small part of Aguascalientes, precipitation intensity, the number of rainy days and accumulated total precipitation increased in short periods. Also, in a reduced

[2] Part of this section is reprinted with permission from "Observed trends in daily extreme precipitation indices in Aguascalientes, Mexico" by Ruíz-Álvarez O., Singh V.P., Enciso-Medina J., Ontiveros-Capurata R.E., and Costa Dos Santos C.A. 2019. *Meteorol. Appl.* 1–20. DOI: 10.1002/met.1838. Copyright 2020 John Wiley and Sons.

region, daily precipitation intensity decreased; and in another considerably small area, the number of dry days increased. For mitigating the effects of these phenomena, it is suggested to use water more efficiently for sustained agricultural production systems and ecosystem management. Results of this study will be of great importance in future economic planning in the Aguascalientes state.

4.2. Introduction

Currently, one of the most significant challenges is to understand climate change and mitigate its adverse effects. It is believed that during the period 1880-2012 the global average of warming was 0.85 °C, and its leading causes were attributed to the anthropogenic activities, especially those related to the excessive burning of fossil fuel (IPCC, 2014; Allen *et al.*, 2018). However, it is also estimated that today between 20 and 40% of the world population lives in regions with warming even higher than the average mentioned above (Allen *et al.*, 2018).

Climate change, climate variability, and extreme events are of great interest to the society. Climate change is a statistically significant variation either in the mean state of climate or its variability, persisting for an extended period (decades or more). It can be caused by internal natural processes or external forcing, or by persistent anthropogenic changes in the composition of the atmosphere or land use (WMO, 2017). In the last decades, important advances have been made in the field of climatology and studies have been focused predominantly on the variables of hydrological cycle (for example, precipitation, temperature, and evaporation) either monthly or annual average (Ceballos-Barbancho *et al.*, 2004; Kothawale and Rupa Kumar, 2005; Mandal *et al.*, 2013).

However, extreme events have received relatively limited attention. An extreme meteorological event is a climatic or meteorological phenomenon that is rare at a particular place or time of the year, for instance, heat waves, cold waves, heavy rain, droughts, floods, and severe storms (National Academies of Sciences, Engineering and Medicine, 2016). These events are produced by climatic variability, which is defined as the variation in the mean state and other statistics (standard deviation, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events (WMO, 2017). Differently, an extreme precipitation event is an event in which precipitation in a specific period exceeds some threshold either at a point (that is to say, measured just by one rain indicator) or in an average over some spatial region (National Academies of Sciences, Engineering and Medicine, 2016). Extreme precipitation is associated with a series of meteorological processes, such as tropical cyclones, extratropical cyclones, monsoons, atmospheric rivers, or localized convection (Kunkel *et al.*, 2013a).

In the past two decades, extreme indices received great attention. Although rain is beneficial for humanity and environmental and hydrological processes; its frequent extremes are associated with adverse effects, such as high runoff, floods, and erosion. Nevertheless, low and erratic precipitation events lead to droughts and significant agricultural damages. For the study of extremes, the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) sponsored by the Commission for Climatology (CCI) of the World Meteorological Organization and the Climate Variability and Predictability Project (CLIVAR) developed 27 extreme meteorological indices associated with precipitation and temperature (Peterson *et al.*, 2001; ETCCDMI, see http://www.etccdi.pacificclimate.org). Currently, these indices constitute a methodological guide accepted globally to analyze climate change, and they have been used at regional and global levels in different studies related to extreme meteorological events (Vincent *et al.*, 2005; Zhang *et al.*, 2005; Haylock *et al.*, 2006).

Worldwide a great variety of studies focusing on extreme precipitation events have been carried out. Zhang *et al.* (2005) considered ten extreme precipitation indices in a survey carried out in 15 countries of the Middle East. They found significant positive trends in the number of days with precipitation and on the average precipitation intensity. In a study of trends in ten extreme precipitation events in 14 countries from South and West Africa; New *et al.* (2006) found significant increases in daily rainfall intensity, dry spell duration, and 1-day rainfall. Similarly, Santos *et al.* (2011) studied nine extreme precipitation indices in Utah and found that the precipitation trend was diverse over the state; they found increases in one-day precipitation, total precipitation in five consecutive days, and accumulated annual precipitation.

Likewise, Shrestha *et al.* (2016) investigated trends and changes in 11 extreme precipitation indices over the Koshi River basin, India, and reported an increase in accumulated annual precipitation and the number of consecutive dry days. Similarly, in a study of changes in precipitation extremes in Central America and northern South America, including south and southeast of Mexico, Aguilar *et al.* (2005) analyzed ten precipitation indices developed by ETCCDMI and did not find a significant increase in total precipitation. However, they reported significant positive trends in daily precipitation amount, and the number of wet days confirming the idea of a trend towards more humid conditions in that area of study. Moreover, Alexander *et al.* (2006) studied global changes in daily climatic extremes of precipitation during the period 1901-2003. They found a significant increase in the majority of precipitation indices, except dry days and consecutive wet days, so that they suggested there exist more tendency to more humid conditions.

Similarly, Arriaga-Ramirez and Cavazos (2010) investigated the seasonal and annual trend in ten precipitation indices in six regions of Northwest Mexico and Southwest of the United States. At the annual scale, they found significant negative trends in rainy days, but significant positive trends in the annual amount of precipitation. Differently, at the seasonal scale, summer showed significant positive trends in total precipitation and simple daily intensity index; instead, in winter, total precipitation, number of heavy precipitation days and very wet days showed significant positive trends, and just max 5-day precipitation amount had a significant negative trend.

In the same way, Brown *et al.* (2010) studied ten precipitation indices at 40 weather stations in Northeastern United States. In general, they found significant positive trends in intensity and amount of precipitation. Because of the major prevalence of significant positive trends associated with precipitation indices, these authors emphasized that the region showed a tendency toward wetter conditions. Similarly, Boot *et al.* (2012) considered four precipitation indices in a study of climate change for Western North America during 1950-2005. In many parts of the territory, they found a moderate increase in both amount and intensity of precipitation, and commented that stronger precipitation trends occurred in regions with climate controlled by air masses coming from the Gulf of Mexico. Also, Insaf *et al.* (2013) examined trends in 11 precipitation indices in New York state in the period 1948-2008 and indicated that the number of days with heavy precipitation, consecutive wet days, total wet days precipitation and the simple daily intensity index were the indices that showed the highest significant positive trends. Moreover, total wet days precipitation and simple daily intensity index revealed a significant increase at most of the stations.

For North America, Peterson *et al.* (2008) evaluated changes in extreme events derived from daily precipitation for 1950-2000. They found that heavy precipitation and total precipitation increased in the second half of the last century; they also indicated that these increases were consistent with the warming that the planet is experiencing. Likewise, Powell and Keim (2015) investigated the trend in extreme precipitation in the Southeast United States during 1948-2012. They found a significant increase in both intensity and magnitude of extreme precipitation except at those locations located further east. Also, they showed that autumn was getting significant wetter, while spring and summer were getting drier. Moreover, Skansi *et al.* (2013) investigated the signal in the degree of wetting through an analysis of nine extreme precipitation indices in South America during the period 1950-2010. They observed significant trends in max 1-day precipitation amount, max 5-day precipitation amount, number of very heavy precipitation days, consecutive dry days, very wet days, extremely wet days, simple daily intensity index, and annual total wet-day precipitation. In the same way, Stephenson *et al.* (2014) analyzed changes in extreme precipitation in the Caribbean during 1961-2010. They suggested that changes in rainfall were little consistent and that in general trends were weak. They also reported short significant positive trends in annual total precipitation, daily intensity index, maximum number of consecutive dry days, and heavy rainfall events; and related precipitation extremes with Atlantic Multidecadal Oscillation (AMO). Also, Zandonadi *et al.* (2015) used the 11 extreme precipitation indices of ETCCDI in a study of precipitation variation in Brazil during 1986-2011. They observed an increase in total precipitation at almost all weather stations and attributed it to extreme precipitation.

In the north center of the country, the increase in total annual rainfall was related to high rates of heavy precipitation, and also to the highest precipitation event which was above 10 mm. Instead, in the north, they reported a decrease in extreme precipitation, which was caused mainly by the reduction in precipitation greater than the 95th percentile. Also, they added that positive precipitation trend could cause floods which suggest the necessity of implementing urban planning more efficiently for the future.

In Mexico, the majority of climatic studies have been focused on the analysis of average trends in some variables of the hydrological cycle. However, studies on the pattern of extreme precipitation events are required to provide information for different sectors of society (Nowreen *et al.,* 2015), such as the agricultural sector. For example, the Aguascalientes State has preponderant and competitive agriculture, where the main crops are corn (grain and forage), bean, oats, sorghum, and vegetables both in irrigated conditions and rainfed (INIFAP, 1998). This state is already facing adverse environmental problems, such as contamination and depletion of aquifers (CNA-WMO, 2006), and essential changes in the patterns of temperature and evaporation (Ruíz *et al.*, 2016; Ruíz *et al.*, 2018), which increase even more the risk of productive activities.

The objective of this research, therefore, was to analyze trends in 11 extreme precipitation indices at 25 weather stations of Aguascalientes State using the methodology suggested by ETCCDMI for a period of 34 (1980-2013) years. Results of this work will help determine the areas of Aguascalientes that are affected by climate change and construct a picture of the spatial distribution of extreme precipitation events which will help generate or adapt technology and production systems according to current conditions.

4.3. Materials and methods

4.3.1. Area of study

Aguascalientes State is located between 22° 27´ and 21° 38´ north latitudes and 101° 53´ and 102° 52´ west longitudes in the north-central region of Mexico (Figure 4.1a). It has a territorial area of 5617.8 km^2 and adjoins Zacatecas on the north, northeast, and west; with Jalisco on the south and east. According to García´s classification, this state has three different climates: semi-dry temperate (BS1k), semi-dry warm (BS1h), and temperate sub-humid (Cw); in these climates, the average annual temperature is 17.1, 20.1 and 14.5 °C, respectively (García, 1973). Previous studies indicate that average annual precipitation has a unimodal regime and varies from 3.4 mm in March to 130.4 mm in July (Ruiz *et al.,* 2018). The total annual precipitation is around 516.8 mm, and average monthly evaporation oscillates between 113.7 mm in December and 235.5 mm in May, summing up an annual total of 1958.5 mm approximately (Ruiz *et al.,* 2018). The lands of this state are semiarid, and the P/PET quotient is equal to 0.35 (Ruíz *et al.*, 2018). Figure

4.2 shows the variation of mean annual precipitation in Aguascalientes; the map was constructed with information of climatological normals corresponding to 1981-2010.

4.3.2. Meteorological data

Uninterrupted daily precipitation data from 25 weather stations of the National Meteorological Service (SMN) belonging to the Comision Nacional del Agua (CNA) for 34 years (1980-2013) were utilized (Table 4.1) (Figure 4.1b). Before starting the study, this database was subjected to quality control (QC) analysis which was carried out by the staff of SMN, consisting of identifying daily outliers, i.e., those daily measurements that were out of an interval (upper and lower limit) were deleted. This interval was defined by two allowable thresholds (maximum and minimum) (Portocarrero; personal communication).

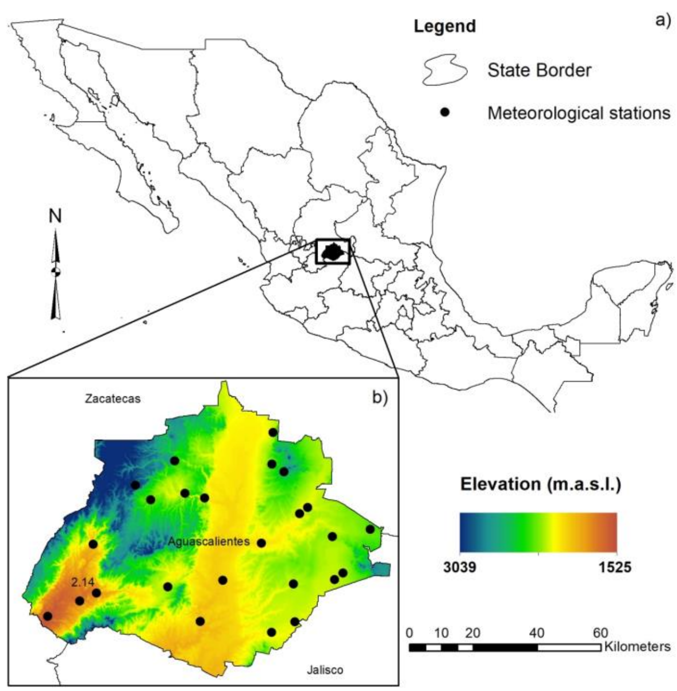


Figure 4.1. Location of Aguascalientes state in Mexico (a) and spatial distribution of 25 weather stations utilized in this study (b).

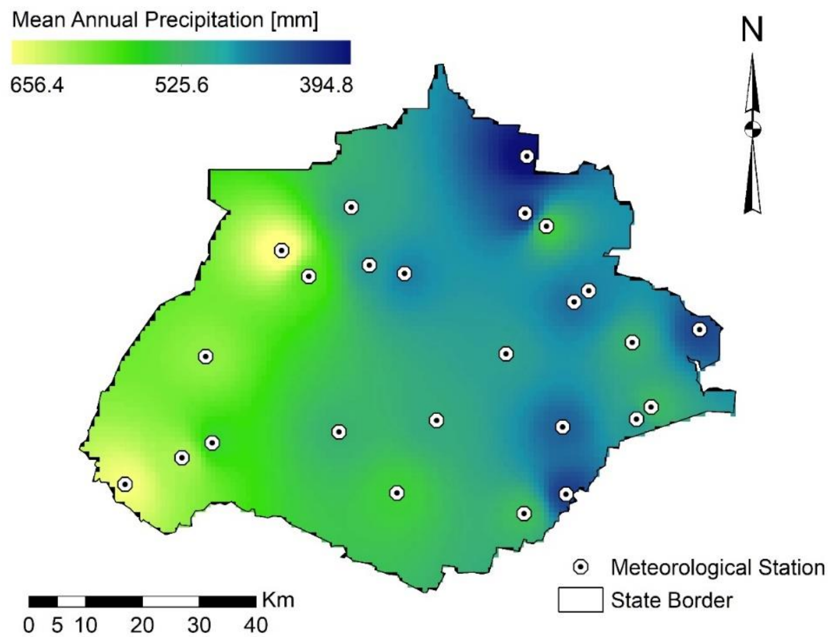


Figure 4.2. Spatial variation of annual mean precipitation in Aguascalientes (period 1981-2010).

4.3.3. Software and data quality analysis

The RClimdex 1.0 software, which was developed by the Climate Research Branch of Meteorological Service of Canada, was used. This software provides an easy interface for computing 27 primary indices suggested by CCI/CLIVAR/ETCCDMI expert team for detection and monitoring of climate change (ETCCDI) as well as calculating other temperature and precipitation indices with thresholds defined by the user (Zhang and Yang, 2004). A second QC phase was performed before estimating the indices, which is a prerequisite of the software and consists of the following phases (Zhang *et al.*, 2015): 1) replacing all missing observations (coded as -99.9) in an internal format (NA) recognized by the software, 2) replacing all unreasonable values by NA, and 3) identifying daily precipitation values higher than the upper limit defined by the user (Zhang *et al.*, 2015). It is important to point out that those unreasonable values from phase two included: a) daily precipitation values less than zero millimeters, b) all values corresponding to an impossible date (i.e., 32nd March 2013, 12th June 20AA, etc.), and c) any non-numerical values (Zhang *et al.*, 2015). Therefore, the region defined by the user is given by mean-*n*STD*, mean+*n*STD* (Zhang and Yang, 2004); where mean and STD are the mean and standard deviation of the sample, respectively; and the n value in this study was 4 (Barry *et al.*, 2018).

4.3.4. Calculation of extreme precipitation indices and their statistical analysis

The estimation of extreme precipitation indices was carried out with the RClimdex 1.0 software according to recommendations published by Zhang and Yang (2004), and Zhang *et al.,* (2015). This study also considered a wide variety of publications where the use of this software has been reported (Vincent *et al.*, 2005; Zhang *et al.*, 2011; Shresta *et al.,* 2017; Ye *et al.*, 2018). In total, 11 extreme precipitation indices were estimated. We chose these indices because they are more related to the climatology of our study area (Table 4.2). Also, for knowing the behavior of precipitation variation, the interquartile range (IQR) of daily precipitation for each month was estimated (Trenary *et al*., 2015).

After obtaining the extreme indices and the IQR for each weather station, the resulting time series were subjected to a statistical analysis to determine the presence or absence of trends, and determine their statistical significance ($p \leq 0.05$). This analysis was carried out with the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975; Río *et al.*, 2005). This test is robust and is not affected when missing values exist in the time series. Furthermore, it does not require that observations follow a distribution function (Gilbert, 1987).

In the same way, the rate of change of the extreme indices and IQR through time was obtained with Theil-Sen´s trend estimator (Theil, 1950; Sen, 1968). In global warming studies, it is essential to know the sign of extreme indices; this makes it possible to predict other indices intended for applications related to climate change impacts (Almazroui *et al.*, 2014). For this reason and for understanding interrelations among all precipitation indices, we obtained a correlation matrix. The Pearson correlation coefficient was calculated among all indices and for each weather station (Lyman and Longnecker, 2001).

4.3.5. Graphical illustration of trends

Once all trends of precipitation indices were estimated, spatial distribution maps were generated for graphical illustration purposes using Inverse Distance Weighting (IDW) interpolation method (Shepard, 1968). This method assumes that the nearby values contribute more to the interpolated values than distant observations. The advantage of IDW over other geostatistical methods is that it is intuitive, efficient, and does not require an a priori investigation of spatial variability (Berndt and Haberlamdt, 2018).

4.3.6. Relationship between elevation and extreme precipitation indices

Topography plays a vital role in the distribution of precipitation indices. Several studies indicate that a relationship exists between elevation and extreme precipitation indices (Zhang *et al*., 2014; Yao *et al*., 2016; Ding *et al*., 2019). For measuring this relationship, the Pearson correlation coefficient is used. This statistic measures the degree of compactness of the relationship between two variables (Ding *et al*., 2019). When the correlation coefficient is greater than 0, the two variables are positively correlated and are negatively correlated when the coefficient is less than 0 (Ding *et al*., 2019). An absolute value of the correlation coefficient that is nearer 1 indicates a stronger correlation between the two variables, whereas a correlation coefficient value nearer zero shows a weak correlation (Ding *et al*., 2019). A correlation coefficient equal to zero indicates that no linear relationship exists (Lyman and Longnecker, 2001; Ding *et al*., 2019). For Aguascalientes, we carried out a correlation analysis between the magnitude of precipitation extreme indices trends and altitude. This analysis was made, as suggested by Ding *et al.* (2019) and Yao *et al.* (2016), by establishing different ranges of elevation: 1585-1990 m, 1995-2425 m, and 1585-2425 m.

4.4. Results and discussion

This section presents trends of 11 extreme precipitation indices at 25 weather stations of Aguascalientes, Mexico. From the total of studied indices, the results for those that showed statistically significant trends ($p \leq 0.05$) at least at one weather station are discussed.

4.4.1. Extreme precipitation indices

4.4.1.1. RX1day and RX5day

The Max 1-day precipitation amount (RX1day) and Max 5-day precipitation amount (RX5day) seemed to be increasing just in a small part of Aguascalientes. The RX1day index showed statistically significant ($p \leq 0.05$) trends only at three weather stations. The magnitudes of these trends were 5.340, 5.607, and 5.861 mm decade^{-1} in Mesillas, Palo Alto, and Los Conos (Table 4.3) in the north, east, and southeast of the study area, respectively (Figure 4.3a). For this index, the trends fell within the interval reported in previous studies. For instance, some authors showed a range of 2.410 to 8.900 mm decade^{-1} (Beharry *et al.,* 2015; Croitoru *et al.,* 2016). Others described magnitudes different from ours, such as the case of Santos *et al.* (2011) who reported a range that was from 1.140 to 1.640 mm decade^{-1}. Also, Shresta *et al.* (2017) informed trends with a value of 34.600 mm decade^{-1}. In figure 4.4, we present an example of a time series for the RX1day index at the Los Conos weather station, where the analysis was statistically significant ($p \leq 0.05$), and the rate of change was 5.861 mm decade^{-1}. The positive trend in RX1day in the north, east, and southeast of the state (Figure 4.3a) indicated that at these locations, the monthly maximum 1-day precipitation was increasing. The augments for RX1day may be linked to global warming, changes in the moisture close to the terrestrial surface and the coincidental circulation (O'Gorman and Schneider, 2009), as well as the increase in the interannual variability of monsoon in response to the duplication of carbon dioxide (Meehl and Washington, 1993). These increases in precipitation are of great environmental importance, since they improve runoff and recharge of the aquifers (Nowreen *et al.,* 2015). Also, at these three locations and their nearby regions, the increases in RX1day can improve soil moisture conditions and favor rainfed agriculture particularly during the crop growth period known as spring-summer in which corn, bean, and alfalfa are cultivated. In addition, a detrimental effect associated with the increases in RX1day is the increase in the frequency of massive floods (Nowreen *et al.,* 2015).

In the same way, RX5day had statistically significant ($p \leq 0.05$) trend only at the same three weather stations whose magnitudes were 10.428, 12.887 and 15.568 mm decade^{-1} at Palo Alto, Los Conos, and Mesillas (Table 4.3) in the east, southeast, and north of the state, respectively (Figure 4.3b). The magnitudes of our trends were higher than those reported by other studies, such as the case of Beharry *et al.* (2015) who found values between 7.760 and 8.600 mm decade^{-1}. Studies, such as Santos *et al. (*2011) and Croitoru *et al. (*2016), had found trends substantially smaller whose magnitudes were between 1.150 and 5.420 mm decade^{-1}. Also, Shresta *et al.* (2017) reported trends considerably higher than ours; these were between 55.300 and 61.000 mm decade^{-1}.

It is important to highlight that the weather stations with a significant positive trend in RX5day are the same that showed a significant positive trend in RX1day (Table 4.3), ratifying that at these locations, the maximum precipitation of short periods is increasing. According to Frich *et al.* (2002), the increase in RX5day is caused by the forcing of greenhouse gasses; thus, the greater quantity of water vapor available for condensation leading to an increase in the maximum quantity of total precipitation with a hydrological cycle notably improved. In this way, the increase in RX5day confirmed the idea set before by RX1day about one optimistic scenario for the environment and rainfed agriculture at these three locations; however, these increases also could bring with them flash floods (Frich *et al.*, 2002; Nowreen *et al.* 2015). In summary, relative to these indices the perceived scenario for the nearby zones of these three locations shows that the climate tends to offer a greater availability of moisture coming from the rains.

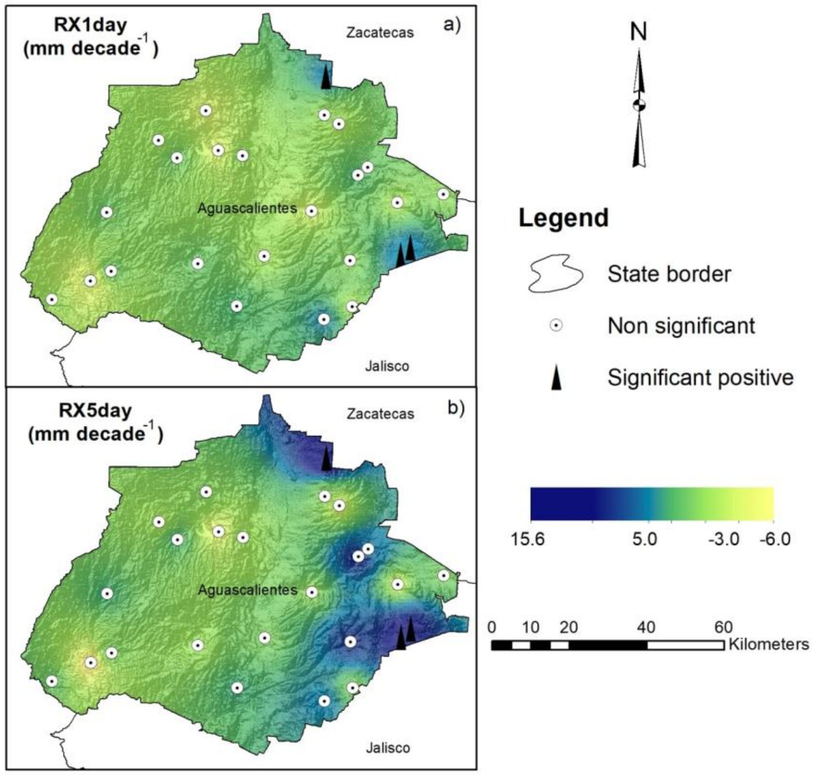


Figure 4.3. Spatial distribution of RX1day (a) and RX5day (b) in Aguascalientes, Mexico.

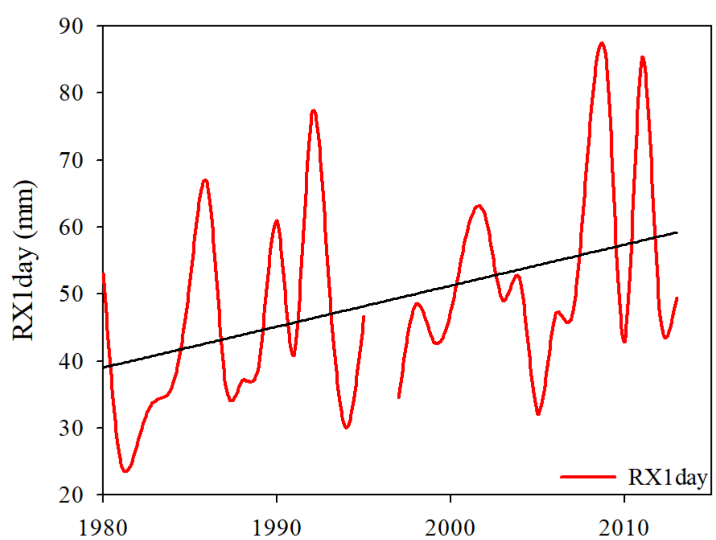


Figure 4.4. Time series example for RX1day at the Los Conos weather station ($p \leq 0.05$).

4.4.1.2. SDII

Analysis of simple daily intensity index (SDII) also manifested changes in one small part of the study area. This index showed a statistically significant trend ($p \leq 0.05$) at six weather stations from which five had a positive trend, and one had a negative trend (Table 4.3). The positive significant trends varied between 0.824 and 1.592 mm/day decade^{-1} in Sandovales and Palo Alto, respectively (Table 4.3), and were distributed in the south (Presa El Niagara), east (Palo Alto), northeast (Villa Juarez and El Tule), and southeast (Sandovales) of the state (Figure 4.5). Our positive trends were within the values reported by Shresta *et al.* (2017), who obtained a range from 0.600 to 2.400 mm/day decade^{-1}; however, our magnitudes were higher than the ones obtained by Croitoru *et al.* (2016) and Santos *et al.* (2011) who had obtained trends between 0.110 and 0.320 mm/day decade^{-1}. On the other hand, the only negative significant trend occurred at the Puerto de La Concepcion weather station in the northeast of Aguascalientes (Figure 4.5) and had a magnitude of -1.200 mm/day decade^{-1} (Table 4.3). This negative trend was slightly higher than the values of Shresta *et al.* (2017), who found an interval that was from -2.100 to -1.700 mm/day decade^{-1}.

In Figure 4.6, we present a time series example for the SDII index at the Puerto de La Concepcion weather station where the analysis was statistically significant ($p \leq 0.05$), and the rate of change was -1.200 mm/day decade^{-1}. Our results showed that in Aguascalientes the simple daily intensity index just affected a relatively small area; for the most part it increased, and in a very little area it decreased; in other words, in most of the area the annual total precipitation divided by the number of wet days increased, and in a small area it decreased. The increase in SDII in the majority of climate models was due directly related to the greenhouse gasses forcing (Frich *et al.*, 2002). The implications of the increase in this index relate to the positive effects of RX1day and RX5day, particularly the intensification of the hydrological cycle.

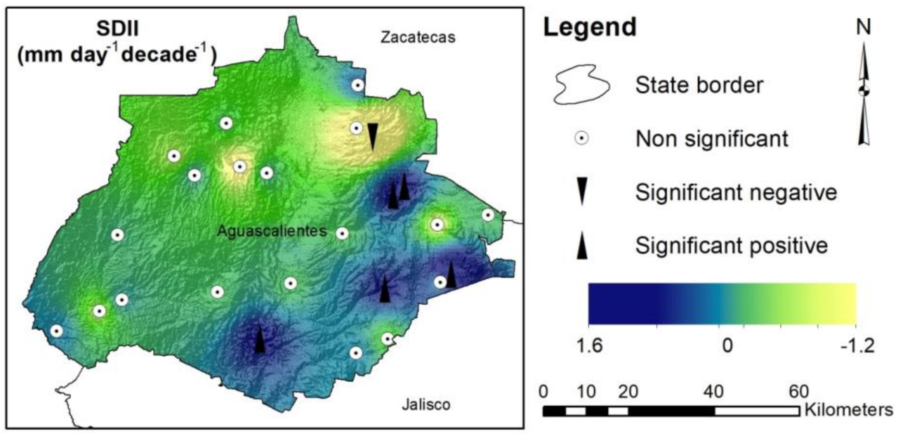


Figure 4.5. Spatial distribution of SDII in Aguascalientes, Mexico.

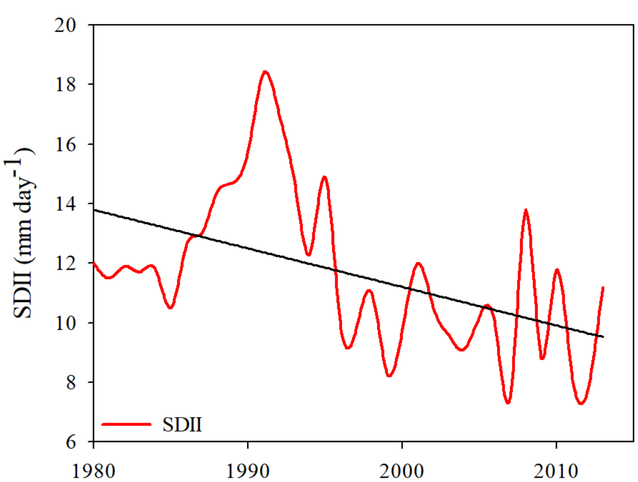


Figure 4.6. Time series example for SDII in the Puerto de La Concepcion weather station ($p \leq 0.05$).

4.4.1.3. R10 and R20

The number of heavy precipitation days (R10 and R20) only showed changes in a small part of the study area. The R10 index showed a statistically significant ($p \leq 0.05$) trends solely at two weather stations (Table 4.3), with magnitudes of 2.174 and 2.414 days decade^{-1} at El Tule and Sandovales (Table 4.3) in the northeast and southeast of Aguascalientes (Figure 4.7a), respectively. For this index, previous studies reported pretty heterogeneous magnitudes. Nevertheless, our trends were within these ranges; for example, for this index, trends oscillated between 0.420 and 5.900 days decade^{-1} (Arriaga-Ramirez and Cavazos, 2010; Santos *et al.*, 2011; Croitoru *et al.*, 2016; Shresta *et al.*, 2017).

Our results indicated that the number of days in the year with precipitation ≥10 mm was increasing just in a small part of the state. According to Frich *et al.* (2002), this indicator is a direct measure of the number of very wet days, and it is highly correlated with annual total precipitation in almost all types of climates. The R10 increase is produced by climatic perturbations caused by the forcing of greenhouse gasses, which provoke a greater availability of water vapor for condensation and, in turn, permit a clear increase in the number of days with heavy precipitation (Frich *et al.*, 2002).

In soils with slope and low hydraulic conductivity, the increase in R10 could bring with it an increase in the erosion risk, mostly at the beginning of the growing season when the crops do not provide enough cover (Haan *et al.*, 1994). It is important to mention that Sandovales and El Tule (sites with an increase on R10) are locations with high tradition in bean and corn production. In these crops, farmers have started to adopt inexpensive technologies for conserving soil and harvesting water from rain. This avoids the loss of water by runoff and reduces erosion of plots. At the same time, this practice permits to increase water infiltration, improving the soil agronomic properties, and increasing crop productivity (Jones and Clark, 1987). Nevertheless, R20 showed a statistically significant ($p \leq 0.05$) trend just at three weather stations (Table 4.3) and their magnitudes were 1.111, 1.538, and 1.579 days decade^{-1} at Sandovales, Presa El Niagara, and El Tule (Table 4.3) in the southeast, south, and northeast of Aguascalientes, respectively (Figure 4.7b). For this index, the reported trends for other parts of the world varied importantly; however, the magnitudes of our trends were within that interval. Some authors comment that globally, these trends are between 0.270 and 10.910 days decade^{-1} (Croitoru *et al.*, 2016; Shresta *et al.*, 2017; Barry *et al.*, 2018). Our findings indicate that the number of days with precipitation ≥20 mm is increasing just in a small area of the state. The increase in R20 is associated with the forcing of greenhouses gasses (Frich *et al.*, 2002). The problems related to the increase in this index are linked to the erosion of both agricultural and non-agricultural soils, so that at Sandovales, Presa El Niagara and El Tule some strategies to prevent damages associated with this type of rain might be the same recommended for R10, besides the establishment of contours, terraces, runoff control works, and reforestation of the lower lands for lessening the destructive force of runoff.

4.4.1.4. CDD

Analysis of the number of consecutive dry days (CDD) indicated notable changes in the moisture regime in one part of the state. The CDD index had statistically significant ($p \leq 0.05$) trends at nine weather stations (Table 4.3). These trends varied between 12.727 and 22.308 days decade^{-1} at Presa Potrerillos and Calvillo (Table 4.3), respectively. Thus, the increases in CDD were distributed in the southwest (Presa Media Luna and Calvillo), northwest (Presa Potrerillos and Rancho Viejo), west (Presa La Codorniz), southeast (San Bartolo), Northeast (Tepezala and Villa Juarez), and south-central (Aguascalientes) of Aguascalientes (Figure 4.8).

The trends obtained in this study were quite similar to those reported in other studies. Croitoru *et al.* (2016) observed a range from 0.490 to 1.330 days decade^{-1}, other researchers reported trends between 10.200 and 18.700 days decade^{-1} (Shresta *et al.*, 2017; Nkemelang *et al.*, 2018) which are more similar to ours. These results indicated that in an important part of Aguascalientes the maximum number of consecutive days with precipitation <1 mm occurred with more frequency. In other words, at these locations, the number of dry days increased.

According to the National Academies of Sciences, Engineering, and Medicine (2016), an increase in drought occurrences is caused by the influence of anthropogenic activities. Similarly, Rosenfeld *et al.* (2001) indicated that dust has an inhibitive effect of precipitation on the properties of clouds. This effect is less compared to the combustion of vegetation or anthropogenic gasses, but what it makes important is the abundance of dust that deserts release to the atmosphere. The precipitation reduction in clouds affected by desert dust causes soil dryness, which in turn increases the dust forming a feedback loop that decreases precipitation even more (Rosenfeld *et al.*, 2001). The implications of this phenomena could be moisture deficit in the first soil horizon, reduction of crop yield, and reduction of natural vegetation. When this phenomenon is combined with an evaporation increase, it can lead to the desertification increase (Frich *et al.*, 2002).

On the other hand, Nkemelang *et al.* (2018) indicated that the increase in CDD implicated a longer dry season, and late-onset of rains and its early end. This is particularly important at the Presa Media Luna weather station for which significant evaporation increases have been reported (Ruíz *et al.*, 2018), which could increase even more pressure on water resources of the region.

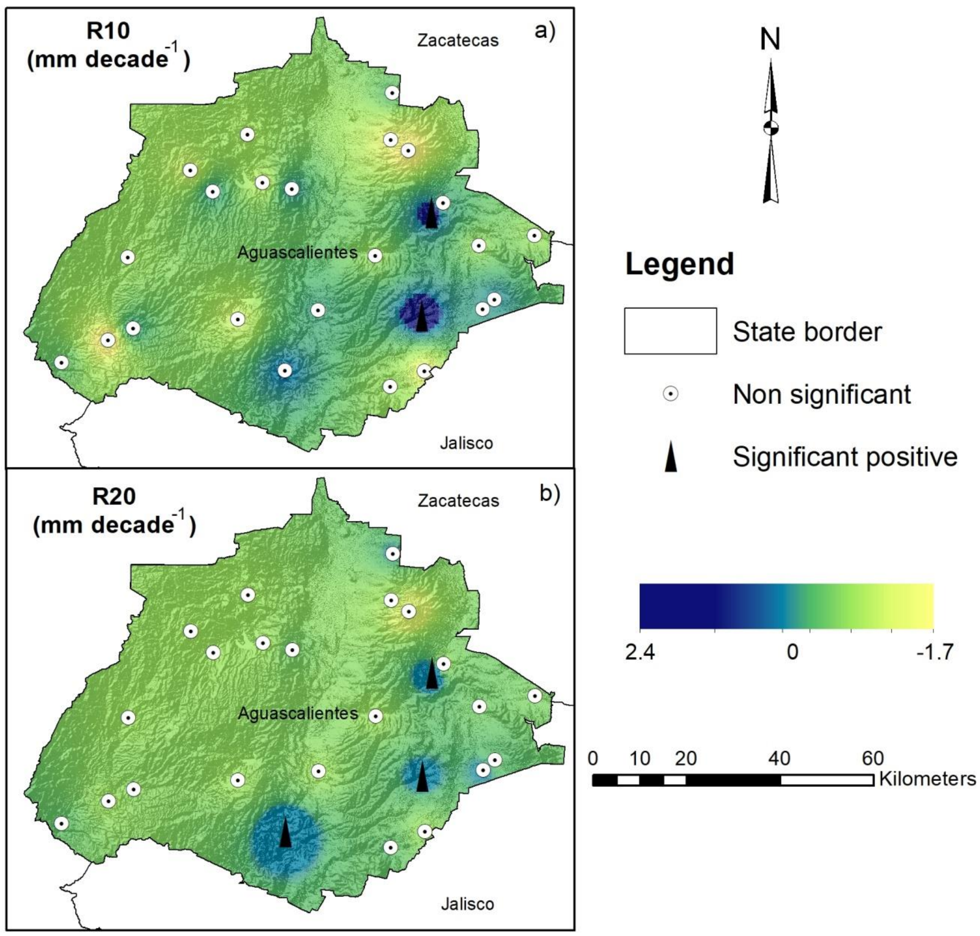


Figure 4.7. Spatial distribution of R10 (a) and R20 (b) in Aguascalientes, Mexico.

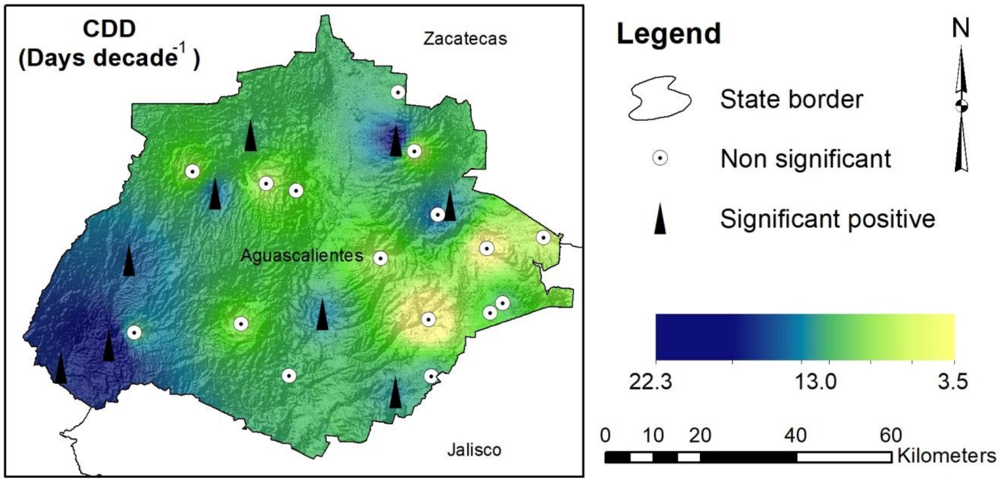


Figure 4.8. Spatial distribution of CDD in Aguascalientes, Mexico.

4.4.1.5.R95p

The number of very wet days (R95p) is changing in a very little surface area of the state. The R95p index had statistically significant ($p \leq 0.05$) trends, only positive at two weather stations (Table 4.3). These magnitudes were 33.493 and 37.143 mm decade^{-1} at Los Conos and Palo Alto (Table 4.3) in the southeast and east of the study area, respectively (Figure 4.9). In connection with this index, our trend values were within the range reported for other parts of the world. Some authors have found magnitudes lower than ours, such as the case of Arriaga-Ramirez and Cavazos (2010) who obtained trends between 7.300 and 10.000 mm decade^{-1}. Similarly, Croitoru *et al.* (2016) reported a range from 11.720 to 17.510 mm decade^{-1}.

In other studies, trends relatively higher than ours were reported; for example, Shresta *et al.* (2017) found trends between 65.300 and 152.900 mm decade^{-1}. Also, Barry *et al.* (2018) reported a regional average trend of about 28.070 mm decade^{-1}, which is quite close to the one we found. Our results indicated that the very wet days, that is to say, annual total precipitation when RR>95th, increased in a small part of the state (Figure 4.9). According to climate models, increases in R95p are also a consequence of the forcing of greenhouses gasses (Frich *et al.,* 2002). The increases in R95 in this area of Aguascalientes could have significant environmental and economic effects, such as greater moisture availability to maintain the dynamism of the ecosystem and hydrological cycle, and higher soil moisture availability during the growing season. The scenario for the region of influence of the Palo Alto weather station improves even more when considering the evaporation decreases that have been reported for this place (Ruíz *et al.,* 2018). Another important benefit of the increase in R95 is that in regions where irrigation is practiced, pumping and the pressure in the use of water could decrease.

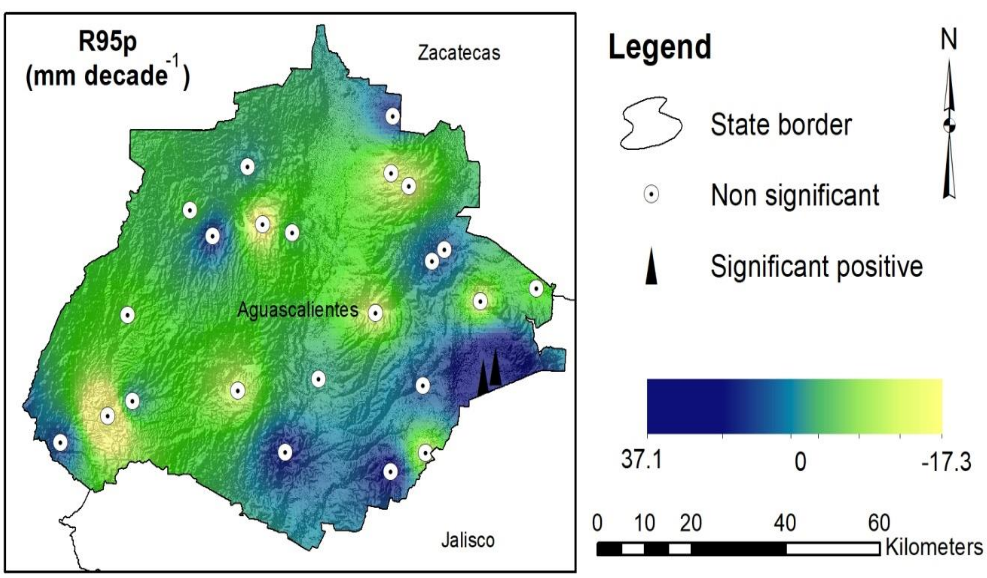


Figure 4.9. Spatial distribution of R95p in Aguascalientes Mexico.

4.4.1.6. PRCPTOT

The annual total wet-day precipitation (PRCPTOT) also indicated changes in a small area of Aguascalientes. The PRCPTOT index showed a statistically significant ($p \leq 0.05$) trend only at one weather station (Table 4.3), and its value was 67.500 mm decade^{-1} at Sandovales in the southeast of State (Figure 4.10). For this index, previous studies have reported very heterogeneous magnitudes, but the range of these encompassed the trend values we obtained. For example, Croitoru *et al.* (2016) reported trends between 14.470 and 28.560 mm decade^{-1} and Santos *et al.* (2011) reported positive trends from 8.320 to 26.690 mm decade^{-1}.

On the other hand, Shresta *et al.* (2017) found considerably higher positive trends which were between 131.800 and 261.500 mm decade^{-1}. Nevertheless, Barry *et al.* (2018) reported a regional average trend of about 61.430 mm decade^{-1}, which is quite close to ours. According to the National Academies of Sciences, Engineering, and Medicine (2016), the previous heterogeneity in the positive trends of PRCPTOT is because of the extreme indices present high variability among the different sites of meteorological monitoring. Our results indicated annual total wet-day precipitation increases in a small area of the state, while the more significant part did not show changes; in other words, the Sandovales weather station (Southeast) is the only site where annual total PRCP in wet days was increasing. The increases in precipitation are related to the forcing associated with the strong vertical movement and the significant increase of water vapor derived from warming (Hartmann *et al.*, 2013; Westra *et al.*, 2014). As a consequence, the increases in PRCPTOT in Sandovales could bring with them an increase of runoff and recharge, increase in vegetation, improving the hydrological cycle, aridity index reduction, and higher soil moisture availability.

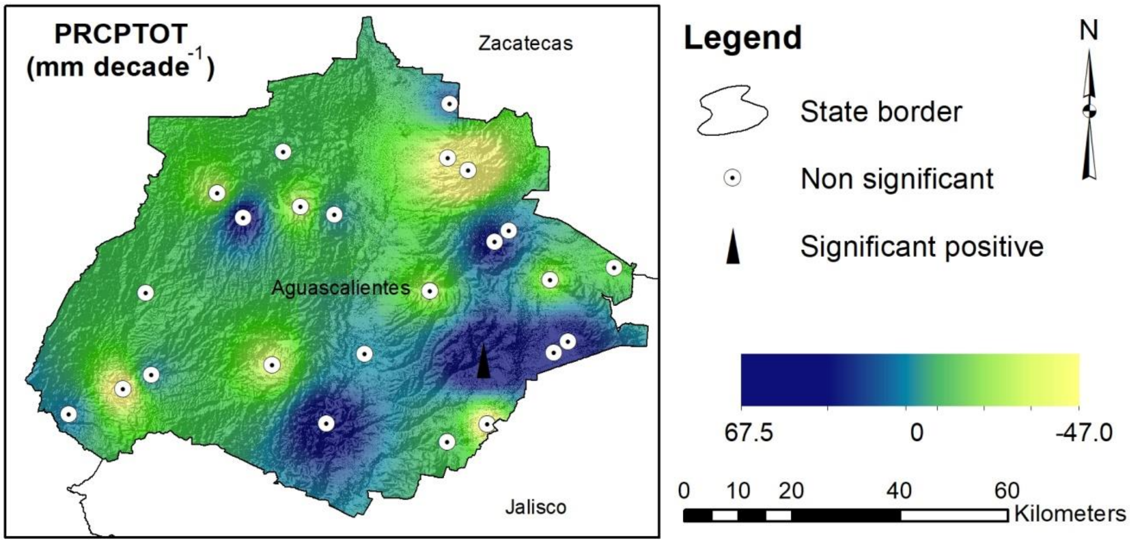


Figure 4.10. Spatial distribution of PRCPTOT in Aguascalientes, Mexico.

4.4.2. Summary of significant vs. No significant trends of extreme precipitation indices

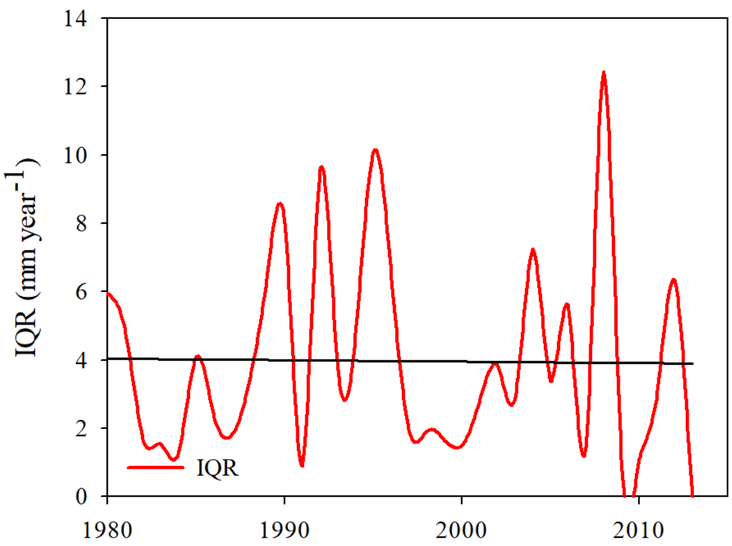
The R50, CWD, and R99p indices did not show statistically significant trends ($p \leq 0.05$) at none of the weather stations considered in the study. On the bottom of Table 4.3, a resume of the number of weather stations with no significant trends, the number of weather stations with significant positive trends, and the number of weather stations with significant negative trends is presented. For all indices, most of the weather stations did not show significant trends; as indicated above R50, CWD and R99p did not experience significant trends at any weather station. A small number of weather stations had significant positive trends in most indices, and SDII was the only index with significant negative trend in only one weather station. This information is presented in Table 4.4 also, but in this case information is shown as a percentage of weather stations.

4.4.3. Correlation analysis of extreme precipitation indices

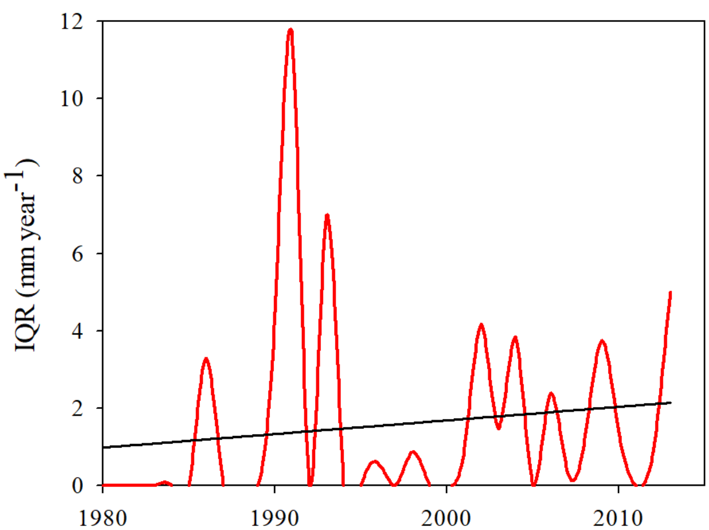
The correlation is essential to understand the existing interrelation among all extreme indices. Except for the pairs CDD-RX1day, CDD-R50, R95-CDD, and R99p-CDD, all pairs of extreme precipitation indices showed a statistically significant correlation ($p \leq 0.05$) at the weather stations considered (Table 4.5). All statistically significant correlations had a negative sign (Table 4.5), except for the pairs CDD-R5day, CDD-R10, CDD-R20, CWD-CDD and PRCPTOT-CDD (Table 4.5). Finally, the range of variation of all correlations was -0.5301+0.9830 and was given by the pairs R10-CDD and R50-R99p, respectively (Table 4.5).

4.4.4. Trend of the interquartile range of monthly daily precipitation

No important changes were noted in IQR of daily monthly precipitation. The IQR was estimated in 300 time series, i.e., 12 months and 25 weather stations. However, for this statistic, values greater than zero were obtained only in wet months (June, July, August and September). Out of 300 time series, only a significant trend was obtained in September at Puerto de La Concepcion weather station, the magnitude was 0.196 mm decade^{-1}. Thus, in the majority of weather stations and months, the variability of monthly precipitation is quite stable through the years, i.e., no trends of IQR exist through time. In Figure 4.11, two examples of IQR time series are shown, Figure 4.11a corresponds to August at Presa El Niagara weather station (no significant trend), and Figure 4.11b corresponds to September at Puerto de La Concepcion weather station (significant trend).



(a)



(b)

Figure 4.11. Time series example of IQR for August at Presa El Niagara (a) and September at Puerto de la Concepcion (b) weather stations.

4.4.5. Microclimate effect in the spatial distribution of precipitation indices

The spatial distribution of sign and magnitude of trends in precipitation indices is related to differences in local climate and vegetation characteristics. According to Chattopadhyay *et al.* (2017), the spatial variation of extreme precipitation indices, among other things, is caused by microclimate and characteristics of local vegetation. They commented that significant trends were distributed mainly in lands covered by pasture/hay and in urban zones. In Aguascalientes, the three significant positive trends in RX1day and RX5day occurred at sites (Mesillas, Palo Alto, and Los Conos) where irrigated agriculture is practiced. One of these sites (Los Conos) is located near to secondary bushy vegetation.

On the other hand, four (Presa El Niagara, Palo Alto, Villa Juarez, and El Tule) out of five significant positive trends of SDII occurred in irrigated lands, and one (Sandovales) occurred in lands with rainfed agriculture and near to secondary bushy vegetation. The only (Puerto de La Concepcion) significant negative trend in SDII was located in an area with scrub. Similarly, both significant positive trends in R10 were located near lands with secondary bushy vegetation (El Tule and Sandovales); one of them (El Tule) encompassed irrigated lands, and another one (Sandovales) was in lands dedicated to rainfed agriculture. Analogously, out of three significant positive trends in R20, one (Presa El Niagara) occurred in irrigated soils, another R20 positive trend (El Tule) also occurred in irrigated soils but near lands with secondary bushy vegetation, and another (Sandovales) in lands with secondary bushy vegetation and close to soils where rainfed agriculture is practiced. Out of nine significant positive trends in CDD, four (Presa Media Luna, Presa La Codorniz, Calvillo, and Villa Juarez) were at sites of irrigated agriculture, two of these (Presa Media Luna and Presa La Codorniz) also were located very close to secondary bushy vegetation, and another weather station (Calvillo) was close to the limit of Calvillo city which is showing an accelerated growth in the last decades. Another (Rancho Viejo) trend took place in soils with rainfed agriculture near soils covered by grassland. Three more (Presa Potrerillos, San Bartolo, and Tepezala) occurred in grasslands, but of these, one (San Bartolo) was close to the limits of irrigated lands, and another (Tepezala) was close to limit of scrub. Finally, another significant positive trend was located in the urban zone of Aguascalientes city. This is the only index with more magnitude variability in those stations with a significant positive trend (Table 4.3). The magnitudes of significant positive trends for this index increased in the following order: grassland, grassland, and close to irrigated soils, irrigated lands, urban area, rainfed agriculture, and close to limits of grassland, secondary bushy vegetation near to irrigated soils, irrigated crops, and close to secondary bushy vegetation, grassland, and near to the limit of scrub, irrigated agriculture, and on the limits of urban growth.

In the same way, both (Palo Alto and Los Conos) significant positive trends in R95p occurred in regions with irrigated agriculture, but one of them (Los Conos) also was close to secondary bushy vegetation. Similarly, the only significant positive trend in PRCPTOT was at a site (Sandovales) with secondary bushy vegetation, very close to the limits with rainfed agriculture. In Aguascalientes, for all indices, the existence/absence of uniformity, both sign and magnitude of significant trends could be related to the similarity/difference of microclimate and characteristics of vegetation. Roque-Malo and Kumar (2017) investigated the potential microclimate role as an explanatory variable of changes in precipitation indices pattern; they found that the climate diversity or microclimate was responsible for the lack of uniformity in the trends found in their study area. They added that the extent of uniformity of trends also was influenced by how the changes and rotation in the vegetation covered and land use occurred (Roque-Malo and Kumar, 2017). In this regard, it is important to highlight that between 1985 and 2014, important changes in land use occurred in Aguascalientes.

The total surface covered by bodies of water increased 180.62%, i.e., there was an increment of 30.03 km^2; the forest area was reduced by 64.19%, which is equivalent to a loss of 686.74 km^2; the area covered by grassland grew up 9.72%, which equals an increase of 135.97 km^2; urban area increased 983.25%, i.e., it had a growth of 190.24 km^2; the surface of scrub grew up 19.37%, which equals 162.60 km^2; also the agricultural area augmented 7.31%, that is 166.63 km^2 (INEGI, 1990; INEGI, 2016). In Aguascalientes, local microclimate and characteristics of vegetation at each weather station could be significant contributors in the spatial pattern of extreme index trends.

4.4.6. Relationship between elevation and extreme precipitation indices

It is considered that there exists a relation between elevation and extreme precipitation indices. Extreme rainfall indices trends are much less consistent spatially than other meteorological factors due to the complexity of topography and geomorphology in the mountain region (Alexander *et al.*, 2006); which impacts cloud thickness and water content, as a result of which the amount of precipitation is affected (Ding *et al.*, 2019). There exist studies that show an evidence of correlation between elevation and precipitation extreme indices. In a study that encompassed an altitudinal range of 1245-

4200 m, Zhang *et al.* (2014) found a significant correlation ($p \leq 0.05$) between elevation and the magnitude of six extreme indices (NW, CDD, CWD, R20, R25 and SDII). Ding *et al.* (2019) analyzed the relationship between topography and extreme precipitation through correlation analysis at different gradients of height, they found that RX1day was significantly correlated with the height of weather stations at less than 500 m. On the other hand, RX1day, RX5day, R5, and PRCPTOT trends were significant and positively correlated above 3500 meters; there was no significant correlation at stations located between 500 and 3500 meters.

According to correlation analysis, in Aguascalientes the relationship between precipitation extreme indices and elevation was not obvious, since for each range of elevation only one significant ($p \leq 0.05$) correlation was obtained (Table 4.6). For the range 1585-1990, most of the correlations were positive and oscillated between moderate and weak; only CWD and CDD were negative, the first one was weakly correlated, and the last one between moderate and strong; however, CDD was the unique index with a significant correlation in this range of altitude (Table 4.6). The significant negative correlation between CDD and elevation indicates that the number of consecutive dry days decreases while height increases. This reduction in the number of consecutive dry days is coherent with the precipitation increase that occurs when elevation increases (Yao *et al.*, 2016). Other studies also have found a significant correlation between CDD and elevation (Zhang *et al.*, 2014; Gao and Wang, 2017).

In the same way, for the range 1995-2425, the majority of correlations were negative and varied from moderate to weak; the unique index with positive correlation was CDD, which was weak (Table 4.6). In this range, R20 was the unique index with significant correlation and oscillated between moderate and strong, furthermore, it was negative (Table 4.6). This means that as the height increases, the negative trend in R20 is smaller, in other words, when increasing the height R20 stops decreasing, which also is coherent with the positive pattern of rainfall through elevation (Yao *et al.,* 2016). Also, a significant negative correlation for R20 has been reported by Gao and Wang (2017). In the range 1585-2425, RX5day, SDII, R10, R20, CDD, and PRCPTOT had a negative correlation between moderate and weak (Table 4.6). Similarly, RX1day, CWD, and R95p were positive and weakly correlated with elevation (Table 4.6). Thus, for this range, also CDD was the only index with significant correlation, that means that the number of consecutive dry days decreases as elevation increases. Also, other studies have shown the sensitivity of CDD with respect to elevation (Gao and Wang, 2017; Zhang *et al.,* 2014).

The fact, that correlations in all ranges were not significant in the majority of indices, could be because our ranges of elevation were not too wide; for the complete elevation range (1585m-2425m), the difference in elevation between the weather station located at highest elevation and the one located at lowest elevation was just 840 meters. Some works where more correlation was reported between extreme indices and elevation considered greater differences in elevation (Zhang *et al.,* 2014; Ding *et al.,* 2019). So, in this study, indices that showed greater sensitivity to elevation were CDD and R20.

4.4.7. Causes of precipitation trends

In a general way, changes on precipitation patterns are attributed to climate change caused by anthropogenic global warming, which has shown its greater acceleration in the last decades. In this section, two explanations that could be the root of the problem of precipitation trends are addressed.

4.4.7.1. Thermodynamic drivers and atmospheric particles

Productive human activities are partially responsible for the changes in extreme precipitation events. The greenhouse gasses produced by man have contributed to the intensification of extreme precipitation events observed in terrestrial surface (Min *et al.*, 2011; Zhang *et al.*, 2013). Research indicates that one of the causes of precipitation increase is the increase of atmospheric moisture, which, in turn, is a consequence of changes on temperature. According to Trenberth (1999) atmospheric moisture increase also leads to the increase in relative humidity and cloud increase, which can reduce solar radiation and available energy for evaporation in surface; while the increase in atmospheric moisture content favors harder precipitation events. According to Lehmann *et al.* (2015), the increase in global extreme precipitation during the period 1980-2010 was owing to the increase of humidity produced by changes in temperature. Also, Zhang *et al.* (2013) reported an increase of 4% in RX1day and 4.7% in RX5day during 1951-2005, and indicated that was due to atmospheric warming. During these periods the increase in the number of extreme precipitation events was produced by the high humidity content in the atmosphere (Donat *et al.*, 2016). According to Trenberth *et al.* (2003) atmospheric moisture levels are increasing after 1973. In several parts of north hemisphere (EEUU, Caribbean, and Hawaii), average available precipitable water increased significantly at a rate of 5% decade^{-1} during 1973-1995; and produced a significant increase of 2-3% of relative humidity in Southeast, Caribbean, and Subtropical Pacific. However, the precipitation increases are related to temperature increases and increase of atmospheric water holding capacity (Trenberth *et al.*, 2003). These changes in the atmospheric moisture content in response to temperature increase are governed by the Clausius-Clapeyron equation (Trenberth *et al.*, 2003; O'Gorman and Muller, 2010; Donat *et al.*, 2016). According to Kininmonth (2010) the Clausius-Clapeyron relationship is the rate of increase of saturated vapor pressure with the temperature, this means that while atmospheric temperature increases, its water holding capacity also increases. This equation estimates the vapor pressure as a function of temperature or finds the heat of the transition phase of vapor pressures for two temperatures and it is written as $de_s/e_s = LdT/RT^2$ where e_s is the saturated vapor pressure at the temperature *T*, *L* is the latent heat of vaporization, and *R* is the constant of gas. Changes in specific humidity of saturation also implies the relationship between the gas constant of dry air and the water vapor (0.622) and a rank of 6.0% K^{-1} at 300 K at 7.4% K^{-1} at 270 K (Trenberth *et al.*, 2003). In this way, some modeling studies indicate that if relative humidity keeps constant, the water holding capacity of atmosphere will increase 7% per degree of increase on temperature (Lehmann *et al.*, 2015). On the other hand, chemical particles released through anthropogenic activities affect the process of formation of precipitation. There exists evidence of aerosols and air contaminant particles affect not just the radiative balance, but also cloudiness and process of formation of precipitation. So that, one cloud precipitates due to dissociation of water droplets, a basic requirement is that, above of the base of the cloud, a great number of big droplets with radius of 15-50 μ should form continuously

(Gunn, 1956). Condensation nuclei of clouds are small particles typically of 0.2 µm in which water vapor condensates.

However it has been documented that air contamination by great concentrations of submicron particles deletes the precipitation formation processes, since they act as nuclei condensation of droplets/clouds that form clouds with very short droplets that are slow for get together in raindrops and precipitate which is reflected in less precipitation reaching the ground (Gunn and Phillips, 1957; Rosenfeld, 1999; Rosenfeld, 2000; Andreae *et al.*, 2004). The presence of big numbers of contaminant particles in the lower atmosphere promotes the formation of clouds that do not precipitate but persist in the atmosphere until re-evaporate. Thus, instead of precipitation, a big cloudiness take place which is characteristic of air masses highly contaminated and saturated (Gunn, 1956).

According to Rosenfeld (1999), the smoke coming from biomass burning provokes that the effective radius of droplets that form be smaller, this causes that the precipitation formation process inhibits. Such precipitation inhibition can be an important contributor of the negative trend of precipitation in many parts of the world. Nonetheless, in some places, the knowledge of this physical mechanism can help make decisions, as is the fact of injecting clouds with aerosols designed for accelerating the conversion of precipitation droplets into water (Rosenfeld *et al.*, 2007).

4.4.8. Implications of precipitation trends

Implications of changes in precipitation patterns generally are associated with natural disasters and high economic costs. In agriculture, there exist records that the rain has produced large losses due to droughts and floods (Nowreen *et al.*, 2015, Bell *et al.*, 2018). Unfortunately, in the short, medium and long term, climate projections predict changes on precipitation regime which can imply important risks for society. In Table 4.7 are the most important implications that changes in precipitation can cause in the agriculture and natural resources of the state of Aguascalientes. For knowing in a complete way all impacts that changes on precipitation patterns can have, it is recommended to read Melillo *et al.* (2014) who classify climate change impacts in different sectors of society.

4.5. Conclusions

Analysis of trends in 11 extreme precipitation indices at 25 weather stations of Aguascalientes State was carried out. In small zones in east and north of the state, precipitation in one and five-days increases; in east and south, both rainfall intensity and the number of days with heavy precipitation increase, in a very small zone of the east annual total precipitation also shows an evidence of increase. This is an indicator that in these parts of the state, more proclivity to wetter conditions exists. On the other hand, at a specific site of northeast precipitation intensity decreases; in north, west, central, and southeast regions dry days show evidence of an increase. This suggests in these places traits of drier conditions prevail.

In those regions where precipitation increased both in intensity and annual accumulated total to lower the erosion risk, it is recommended to intensify the use of soil management technology both in agricultural lands and in lands with natural vegetation. On the other hand, at sites with increases in the number of dry days, production systems that use water more efficiently should be adopted. The harvest of water using furrow dikes could be a useful technique whose use should be intensified. Also, the deficit irrigation could constitute a potential strategy for producing more foods under the scenario of water deficit.

This line of research should continue with the analysis of extreme precipitation events using data from the climate model outputs both for the present climate and future; these results will benefit society in the long-term socioeconomic planning.

The changes found in extreme precipitation indices in this study also could be part of climate change effects that face other parts of the watershed to which Aguascalientes belongs.

5. STRATEGIES FOR ADAPTING AGUASCALIENTES' AGRICULTURE TO CLIMATE CHANGE

5.1. Synopsis

Although important advances exist in agricultural meteorology, the impact of extreme weather on crops is not known precisely. This section describes basic statistics of the main Aguascalientes crops, water bodies, and impacts of extreme indices in agricultural productivity; and connects the findings of previous chapters with Aguascalientes state agriculture. Agricultural statistics were obtained from Servicio de Informacion Agroalimentaria y Pesquera (SIAP) of the Mexican government, technical guide of the Campo Experimental Pabellon of Instituto Nacional de Investigaciones Forestales Agricolas y Pecuarias (INIFAP), agricultural and technical agenda of Aguascalientes, and published research results. Hydrological information was obtained from outreach books and official websites of state government. The influence of trends of indices and meteorological variables was taken from published works in the field of applied agricultural meteorology; several works, based on the response of crops to extreme temperatures considering cardinal temperatures of each crop, were revised. Aguascalientes belongs to hydrological regions Lerma-Santiago-Pacifico and 37 El Salado and poses two major rivers, Aguascalientes and Calvillo Rivers. It accounts for a network of seven important dams whose main use is irrigation and urban water supply. It has five aquifers which, to date, are overexploited. This region does not have any study of drought characterization, but some works demonstrate that surrounding states always have been vulnerable to severe droughts, which have caused significant agricultural losses.

Corn is one of the most important crops of the state, but it is too susceptible to certain minimum temperature thresholds and frosts, so that the increase of their frequency can force sowing dates be modified. Beans is another important crop in the local diet, but also is sensitive to minimum temperatures and frosts which sometimes occur at the beginning of growing cycle, also it is sensitive to diurnal and nightly high temperatures that take place in summer, which can retard the growth, decrease the photosynthetic efficiency, cause abortion of flowers, among others. Indices related to extreme, heavy, and total annual precipitation indicate that better conditions of soil moisture conditions could exist, so that the total area cultivated with corn and beans could be raised, mainly in the east. On the other hand, the CDD index indicates that in irrigated crops, water requirements can increase to compensate for moisture deficit caused by dry days within the growing season. In regions showing an increase in the number of frosts, the use of varieties or hybrids of corn with a shorter growing cycle is suggested. The fluctuations in the minimum temperature of winter cause early bud break and the depletion of grapevine and peache tree reservations, so that reductions in the potential yield occur; adaptation to these thermal oscillations in the cold period could be required to increase the use of synthetic products compensating for chilling hours or through crop breeding and establishing varieties adapted to these conditions. The efficiency of irrigation systems should be increased through the repair of conveyance and supply systems, and also, through farmers training in the management and operation of irrigation systems. The use of materials for covering the soil to reduce evaporation losses and as a consequence, irrigation water volume should be promoted. Also, the reduction of cultivated area with crops of high-water demand, such as alfalfa, should be promoted; instead, the use of crops with high forage potential and biofuel production should be intensified in order to reduce the high dependence of fossil fuels and so reduce the CO_2 emissions. It is crucial to investigate the effect of extreme temperature duration on the crop performance, and the duration and severity of droughts. The length of period free of frost at different levels of probability for each crop should be defined accurately. Also, research on deficit irrigation should be intensified.

5.2. Agriculture in the state of Aguascalientes

In spite of arid lands, the North of Mexico is characterized for having a significant part of the most fertile lands of the country; in this region, a wide variety of profitable crops are produced from which the best yields are obtained. Aguascalientes has an important variety of soils with high agricultural potential, so that, out of a total area of the state (5617.8 km^2), 90000 hectares are used in rainfed agriculture, and 35246 in irrigated agriculture (INIFAP, 2017). Regarding irrigated agriculture, the most important crops are corn, poblano pepper (Capsicum annuum var annuum Poblano), garlic, beans, oat, alfalfa, guava, grapevine, and peaches (Table 5.1) (INIFAP, 2017). In rainfed agriculture, the most outstanding crops are corn, beans, sorghum, oat, and nopal tunero (Table 5.1) (INIFAP, 2017). In Table 5.1, the most important crops of Aguascalientes are shown, both under rainfed conditions and irrigation, also cultivated area, sowing dates, harvest dates, yields, among others, are shown; some other crops were not added to this table, since they are cultivated in small areas.

5.3. Hydrology of Aguascalientes

Most of the Aguascalientes state is located within the hydrologic region Lerma-Santiago-Pacific; and another small part in the region number 37 El Salado. This state basically accounts for two important rivers: Rio Aguascalientes (San Pedro) and Calvillo River (CONABIO-IMAE-UAA, 2008).

5.3.1. Aguascalientes river (San Pedro)

The main river of the state is the Aguascalientes River (San Pedro River). It starts at 40 km south of Zacatecas city, in the sierra of Piedra Gorda. It enters the Aguascalientes state, and in its travel, joins Pabellon, Santiago, Morcinique, Chicalote, and San Francisco rivers and other less important channels. It crosses abrupt and difficult lands for agriculture, but also crosses flatlands where it is used almost in total (CONABIO-IMAE-UAA, 2008). Its annual discharge is around 208 million cubic meters (Avelar-Gonzalez *et al.*, 2011). It flows through the state from north-south in a straight line of around 90 km and drains an area of 2820.6 km^2 (Avelar-Gonzalez *et al.*, 2011). It is the primary rainfall collector, sewage waters and treated waters. The river has no base flow, and close to 96% of treated or no treated sewage waters flows directly to the river (Avelar-Gonzalez *et al.*, 2011). Currently, it is contaminated and is a threat for public health of neighboring communities; it also constitutes a potential source of contamination of the valley of Aguascalientes aquifer (Avelar-Gonzalez *et al.*, 2011).

5.3.2. Calvillo river

It starts at 15 km at the west of Aguascalientes city and continues until joining the Juchipila River at Jalpa in the state of Zacatecas. It has a tributary river called La Labor, over which La Codorniz dam is located (CONABIO-IMAE-UAA, 2008). The topography of the region is abrupt, but at its banks it permits that waters be used for agricultural purposes. It is the second river of importance in Aguascalientes and covers an approximate area of 1100 km^2, and runoff is around 50 million of annual cubic meters (Gobierno del Estado de Aguascalientes, 2019).

5.3.3. Minor rivers

There exist other rivers that are considered of less importance given their travel length and discharge; these rivers join Aguascalientes River. These rivers are Pabellon, Santiago, Chicalote, Morcinique, and arroyo El Cedazo.

5.3.4. Dams

The Aguascalientes state accounts for an extensive network of dams and ponds. Most of these dams are for agricultural purposes (Table 5.2). In Table 5.2 main dams, from the point of view of their storage capacity, are presented; also information about the municipality of location, current stored volume, primary use, and the irrigated area is shown. In the state, there exist other dams and ponds, but given that their size or storage capacity is considerably small are not included in Table 5.2; furthermore, they are used only for providing water to cattle.

5.3.5. Aquifers

Aguascalientes state has five aquifers. Currently, these are overexploited; and their source of natural recharge is runoff generated by variable rainfall from one year to another that occurs in the valleys (CONABIO-IMAE-UAA, 2008).

5.3.5.1. Valle de Aguascalientes Aquifer

This aquifer is located in the center of Aguascalientes, between 21˚37' and 22˚ 28' north latitude and 102˚ 07' and 102˚ 41' west longitude in an area of 3129 km^2 (CONAGUA, 2015a). It compasses completely Cosio, Rincon de Romos, and Pabellon de Arteaga municipalities, almost entirely Aguascalientes, Tepezala, San Jose de Gracia, and Jesus Maria; and one part of Calvillo, San Francisco de Los Romo, and Asientos. It occupies the central belt of the state, and it has a length of 90 km in a north-south straight line and 13 km wide. The main land uses of the aquifer are livestock and agriculture (63%), grassland (16%), shrubbery (15%), oak forest (3.9%), mesquite (0.2%), and the rest corresponds to an urban area where more than 85% of the state population resides (CONABIO-IMAE-UAA, 2008). According to observations of the level of wells, groundwater flows from north to south, it is an unconfined aquifer but with a thick vadose zone; it is heterogeneous and anisotropic, constituted in the upper profile by alluvial and fluvial sediments of varied granulometry and conglomerates (CONAGUA, 2015a). The static level varies between 80 and 150 meters, the shallow levels (80 to 100 meters) are located in north of the aquifer where the irrigation district number 001 Pabellon is located (CONAGUA, 2015a); while deeper levels (130-150) are in the north of the urban region of the aquifer (CONAGUA, 2015a). The static elevation level varies between 1725 and

1920 above sea level (CONAGUA, 2015a). It has a deficit of recharge of 91,242,520 annual cubic meters that are extracted from the non-renewable storage of the aquifer (CONAGUA, 2015a). In a study, it was determined that the highest value of recharge is located mainly in the north and central valley, with a maximum value recharge of 525.67 mm per year (Guerrero *et al.*, 2018). On the north and south limits of the study area, and metropolitan area of Aguascalientes, the lowest value of recharge is 0.086 mm per year (Guerrero *et al.*, 2018). The aquifer is classified as a zone of availability 1, the primary user of its waters is agriculture, and in the north portion, the irrigation district 001 Pabellon is located (CONAGUA, 2015a). Currently, over whole Aguascalientes, there exists a prohibition that does not permit to extract additional water. This prohibition is type III, which permits only limited extraction for domestic, industrial, and irrigation uses (CONAGUA, 2015a).

5.3.5.2. Valle de Chicalote Aquifer

This aquifer is located in the northwest of the state, at 45 km to the northwest of Aguascalientes city, in an approximate area of 657 km^2. It has an extended form and northeast-northwest orientation; the maximum length is 45 km and the width 5 km (CONAGUA, 2015b). The Valle de Chicalote aquifer encompasses completely Asientos municipality, and a small portion of San Francisco de Los Romo and Aguascalientes municipalities, expands its boundaries until the borders of Zacatecas state. According to measurements carried out in a study in 1998, out of total extractions (48 000 000 cubic meters per year), 70% is for agricultural use, 20.42% for multiple uses and, 9.58% for urban and public uses (CONAGUA, 2015b). The static level varies between 20 and 80 m;

the shallowest levels are located in Villa Juarez, while the deepest ones are located in Asientos. The elevation of the statistic level varies between 1970 and 1880 meters above sea level, the highest elevations have been registered on the limits of Zacatecas state, close to the location of Asientos, Northeast of the valley; while the lowest values have been registered in the location Jose Maria Morelos. The underground flow of these waters occurs in the same direction as that of Chicalote Rivers which also crosses the Aguascalientes valley, and another part flows in south direction to El Llano. This aquifer presents a total recharge of 35 000 000 cubic meters per year, an extraction of 48 000 000 cubic meters per year, so that the deficit is around 13 000 000 cubic meters per year. Currently, the aquifer does not have available volumes for new concessions (CONAGUA, 2015b).

5.3.5.3. Valle de Calvillo Aquifer

The Valle de Calvillo aquifer is located in the southwest portion of Aguascalientes state, covers a belt with orientation north-southwest. It compasses partially Jesus Maria and San Jose de Gracia municipalities; completely the Calvillo municipality; and a portion of Jalpa municipality, in Zacatecas state (CONAGUA, 2015c). Its total extraction is around 40 000 000 cubic meters per year, from which 82.5% is for agricultural purposes, 16% for public-urban use, and the rest for multiple uses (domestic and livestock) (CONAGUA, 2015c). In this zone, irrigation districts do not exist, but there exist irrigation units, the use is for agriculture and urban-public. Currently, it shows a deficit of recharge of around 14716988 cubic meters per year, which indicates that in the aquifer, no available volumes for new concessions exist (CONAGUA, 2015c). The deficit in recharge is attributed to the rising influence of dam construction and the great number of ponds that have altered the natural runoff of surface waters, decreasing the infiltration through the channels. Due to the aquifer overexploitation, this region was declared a prohibited zone, so that only limited extractions for domestic, industrial, and irrigation uses are permitted (CONAGUA, 2015c). In this aquifer, the depth of the static level varies between 50m and 130m.

5.3.5.4. Venadero Aquifer

It is located in the south of Aguascalientes and encompasses an area of 111 km^2. In the north, east, and south adjoins Valle de Aguascalientes aquifer, and in the west with Valle de Calvillo aquifer. The estimated total extraction volume is around 2 000 000 cubic meters per year, mainly due to horizontal output to the arroyo Gil's canyon, Valle de Calvillo aquifer, and artificial pumping. The granted volume of groundwaters for this aquifer on March 31, 2010, was 996 847 cubic meters per year. There exists a deficit of recharge of around 96 847 cubic meters per year extracted from the non-renewable storage of the aquifer (CONAGUA, 2015d). Out of total use of water, 920 000 cubic meters are intended for agriculture, 710 000 cubic meters (35.5%) for multiple uses, 300 000 (15%) for urban-public use, 50 000 cubic meters (2.5%) for domestic use, and 20000 cubic meters per year (1%) for industrial use. It is an aquifer of free type, heterogeneous and anisotropic; in the shallow profile, it is constituted by alluvial and fluvial sediments, conglomerates and sandstones, and in the deepest layers it is formed by fractured volcanic rocks. In 2010, the static level varied from 10 to 130 meters (CONAGUA, 2015d); the shallowest (10 to 20 m) values were located close to the Tapias Viejas dam, where the Arroyo Gil canyon is formed to continue its travel to the neighboring Valle de Calvillo aquifer (CONAGUA, 2015d); the deepest values were located in the central portion of the aquifer, where the pumping is concentrated. In 2010, the static level elevation varied from 1910 to 1870 meters above sea level.

5.3.5.5. Zone of el Llano aquifer

The Valle del Llano aquifer is located in the southeast portion of Aguascalientes. It covers an approximate area of 487 km^2, which is a surface with irregular form and soft slope in southwest direction (CONAGUA, 2015e). It encompasses El Llano municipality completely, and small portions of Asientos and Aguascalientes municipalities, and extends its domains until Jalisco state (CONAGUA, 2015e). It is within the central plateau; adjoins the Sierra Madre Oriental in north and east; the Sierra Madre Occidental in the west; and the neovolcanic axis province in south. The composition of the aquifer is based on fractured igneous rocks in a complex system of tectonic blocks that integrate an intricate structural-geologic frame (CONAGUA, 2015e). The most important source of recharge is the rainfall infiltration, lateral inputs from the reolithic sequence located on the high parts, and by irrigation returns. The primary discharge is from the pumping of wells and norias as well as horizontal outputs to the south and southeast of the valley (CONAGUA, 2015e). At the end of the 1990s, the depth of static level varied between 100 and 160 m, while the elevation of static level varied between 1880 and 1900 meters above sea level. Currently, there are no available volumes for new concessions; on the contrary, there is a recharge deficit of 5 007 256 cubic meters (CONAGUA, 2015e).

5.3.6. Droughts

The location of Aguascalientes and the characteristics of its environment make it vulnerable to droughts and the spatial variation of precipitation. Given the location of the study area and its arid lands, this and surrounding areas have been impacted by extreme meteorological droughts. In a study that included the period 1922-1993, and under two methodologies (Foley, and Gibs and Maher), Flores and Campos (1998) state that during 1960-1989, San Luis Potosi state showed severe droughts of different duration. In that period of study, there were several periods of droughts, but the most important were in 1969-1989. These droughts are characterized by a considerable decrease in precipitation below the mean. For the Zacatecas state, Castorena *et al.* (1980) comment that there have been droughts from 1900. From 1900 to 1950, there were droughts in five non-consecutive years, while during 1950-1970, there were droughts in two years; however, despite the short duration of these events, the economic and social effects were the death of cattle due to grass scarcity and lodd of maize forage. More recently, for this state, Corvera *et al.* (2006) studied the occurrence of droughts through the standardized precipitation index in the period 1974-2005. They found that Gonzalez Ortega location had 23 years in which precipitation was significantly less than the annual mean; the driest year was 1989 with precipitation being less than the mean by 66.6%. In Juan Aldama location, there were 18 years with precipitation being less than the mean, and 1982 was the driest year with precipitation being less than the mean by 42.3%. As can be observed, years with drought in Zacatecas coincide pretty well with those reported by Flores and Campos (1998) for San Luis Potosi. Corvera *et al.* (2006), comment that for the droughts recorded between

1990 and 2005, the Zacatecas' agricultural affected area was between 2 and 48% of total rainfed agriculture, the mean was 20%. Although for Aguascalientes, there is missing research on droughts, and given the closeness and similar lands, it is expected that at the San Luis Potosi and Zacatecas scarce precipitation has followed a similar pattern in Aguascalientes.

5.3.7. Effect of hydrometeorological trends in agriculture

In Table 5.3, the physical meaning shows a significant positive/negative trends of those extreme indices. Klein-Tank *et al.* (2009) and Zhang *et al.* (2015) present a definition and general interpretation of each index, however, when trends occur, these bring with them implicit additional physical impacts either on the atmosphere or environment, so that in Table 5.3 some of the most essential physical impacts are mentioned.

5.3.8. Impacts of extreme indices trends in crops

Most of the crops show similar responses to the stimulus of weather. Most crops suffer from temperature stress (maximum or minimum) and when it reaches the limits of growth range, the development can stop, or physical damage can be caused. In Table 5.4, the effects of TXMean and TNMean for each crop are not included, since, in general, the effects are the same for each of them. An increase in TXMean creates conditions for the increase of crop water requirements (Ojeda *et al.,* 2011). If the mean, maximum, and minimum temperatures increase, that means that heat crop requirements are met faster and plants mature earlier (Ojeda *et al.,* 2011). If the mean maximum and minimum temperature decrease, that means that heat crop requirements are met in more time, and maturity gets late (Ojeda *et al.*, 2011). The increase of average maximum temperature in cold seasons favors the length of the period of life of insects and diseases of economic importance and health of both animals and man (Raza *et al.*, 2015). On the other hand, changes in DTR cause changes in the irrigation demands of crops. Increases in DTR are associated with an increase in crop water requirements due to the increase in the evaporative capacity of the air.

Also, not all extreme indices influence agriculture; for that reason, in Table 5.4, not all indices are included. In the case of nopal tunero, abrupt changes on temperature do not mean risk for decreasing yields or to sinister the crop. This species has a very wide thermal adaptation range for survival; it can survive until 65 ˚C, and can die if it is exposed to 5 ˚C for a long time, as indicated by Nobel (1995) and Ruiz *et al.*, (2013). On the other hand, extreme precipitation indices express only some few categories of moisture, that is to say, they express just excess or deficit, so that in Table 5.4, moisture indices are organized into two groups, one related with drought and the other to enough or excess moisture. The impact of each index over each crop is described for the trend type that was registered in the study. That is, if an index just showed a positive trend in analysis, then just the effect of the positive trend of that index is explained in connection of its effect on the crop; in some cases, the trends in some indices are not related to the crop because they do not exert any influence on it. It should be noted that in agronomy, the effect of trends of extreme indices has not been investigated still in detail. The information presented in Table 5.4 was obtained from research works carried out for characterizing the response of crops to the environment.

5.3.9. Adaptation strategies

The positive trend of frosts in east, center, and south of state indicates that sowing dates could be required to be modified; that is, sowing dates could be delayed for avoiding damages by late frosts. Varieties or hybrids that can be used in late dates are those with precocious growing cycle. The Instituto Nacional de Investigaciones Forestales Agricolas y Pecuarias has generated different precocious genotypes, such as SZ6018 and AGMA1014Y varieties, which produce until 14 tons per hectare and mature at 170 days (INIFAP, 2017); also, the H-383 hybrid maturates in 150-160 days, and has a potential yield until 12 (rainfed) or 15 (irrigation) tons per hectare (Peña *et al.*, 2017). According to precipitation indices, the greater moisture availability in the east of state can be used to increase the area cultivated under rainfed agriculture and so attenuates the problem of overexploitation of aquifers in this region.

On the other hand, the poblano pepper and beans are crops that can be benefited considerably when changing sowing dates to late ones for avoiding damages by frost. The beans is a crop that also can gain area of cultivation under rainfed conditions in the east of state where moisture conditions are increasing.

In the grapevine and peaches case, in winter, when minimum temperature increases after a period with some cold nights, the buds of trees start the bud break which is a negative factor, since when very low cold temperatures occurs again, buds are damaged by frost which significantly affects yield (Godoy *et al.*, 2003). One way of preventing early bud break, even when minimum temperature rises within the cold period (winter), is keeping the orchard soil under a moisture restriction regime that is irrigation should be suspended after pruning and during winter (Godoy *et al.*, 2003). On the other hand, when minimum temperature in winter shows a positive trend (less cold on winter), one way of compensate for the loss of cold in grapevine and peaches is by supplying hormones that regulate the bud break, so that the uniform bud break is promoted on the buds once temperature starts to increase, and there are no nights with extreme cold. Also, in these cases, grafts can be used to graft scions of varieties with low cold requirements over rootstock that already are in production.

The increase in the water use efficiency and farmers training on the irrigation systems management could impact the conservation of resources. The increase in irrigation systems efficiency can be another choice for improving the water resources use. In Aguascalientes, one important part of conveyance systems shows deterioration that causes too low efficiencies in both conveyance system and irrigation system. The fixing of the systems that present leaks or that have already used up their useful life are suggested. Financing politics should be designed in order for farmers to change their irrigation systems; that is, they should migrate from furrow irrigation to pressurized irrigation systems. Crop production using soil cover can be another technique useful for saving water and increase water efficiency in agriculture. It has been demonstrated that in some fruit trees, the use of organic matter, plastic, and gravel for protecting soil led to significant water saving in grapevine and peaches (Galindo and Ruiz, 2016). Scientific research is a powerful key that can contribute to finding adaptation strategies of high impact, deficit irrigation should be evaluated, the use of restriction on irrigation also promotes the reduction of water volumes supplied on irrigation. On the other hand, farmers face the problem they do not know how to operate irrigation systems. When irrigation machines work on prolonged times, they use excessive irrigation depths that are not appropriately used by the crop. Training farmers through specialists and technicians provided by the administrative office of irrigation waters would lead to more efficient use and saving of water. These strategies are going to help alleviate the depletion of aquifers caused by the increase in water requirements produced by the positive trend of temperature, diurnal temperature range, evaporation, consecutive dry days, among others.

The water volumes permitted for irrigation of crops with high water demands such as alfalfa should be reduced. Several regions of Mexico already face risks of irrigation sustainability due to this species has high requirements, and provoke depletion of aquifers. Instead, other crops with high potential for producing forage and also for generating biofuels, such as higuerilla, sorghum, and corn, could be introduced; and so, alleviate the pressure and dependency on fossil fuels that contribute to CO_2 emissions and increase the sustainability of water resources.

6. CONCLUSIONS

This research focused on hydrometeorological analyses of Aguascalientes, Mexico. We analyzed the trend of three meteorological variables and a set of extreme meteorological events. In the first objective, an analysis of monthly evaporation trend at 52 weather stations was carried out. The second one involved trend analysis on 16 extreme events based on daily temperature at 25 weather stations. The third objective focused on studying trends in 11 extreme events based on daily precipitation at 25 weather stations.

In Aguascalientes, a decrease of evaporation occurs during the whole year; this decrease is distributed in different ways in six different regions. In the north (Rincon de Romos and Tepezala), evaporation decreases in January and from March to December. In the center (Pabellon de Arteaga and Jesus Maria), it decreases from January to March, August, September, November and December. In the northwest (San Jose de Gracia), it decreases from February to November. In the east (El Llano and Asientos), it decreases from March to August, October and November. In the south (Aguascalientes municipality), it decreases from January to July, and from September to December. In the southwest (Calvillo), it decreases in January, March, June, July, and from September to November.

In the north (Rincon de Romos and Tepezala), northwest (San Jose de Gracia), center (Pabellon de Arteaga), southwest (Calvillo) and east (Asientos), the evaporation decreases during June-September could yield a longer duration of soil moisture in rainfed crops.

The evaporation decrease in dry months could be an indicator that irrigated agriculture can benefit from reference evapotranspiration and crop evapotranspiration decrease, especially in the east (El Llano), northwest (San Jose de Gracia) and south (Aguascalientes).

In Aguascalientes, evaporation increases in seven months of the year, from February to May, and from October to December; and the augments are distributed differently in the five regions. Evaporation increases in April in the north (Tepezala), in May, November, and December in the center (Jesus Maria and San Francisco de Los Romo). Also, evaporation increases in March, November, and December in the east (El Llano), and in February, April, May, October and November in the south (Aguascalientes municipality). In the southwest (Calvillo), evaporation increases from February to April, November and December. In addition, south and southwest Aguascalientes are the regions more prone to face evaporation increases, since out of 19 sites with increases, 11 are in these parts of the state.

In places where irrigated agriculture is practiced, the evaporation increase in dry months could be an indication that the environment is more demanding of humidity and that the number of consecutive dry days is increasing. The evaporation increase also could show increases of reference evapotranspiration, crop evapotranspiration, and irrigation requirements. This can enhance the pressure of water resources, meanly in the center (San Francisco de Los Romo), south (Aguascalientes), and east (El Llano) where overexploited aquifers already exist.

For those regions where evaporation increases do not occur in June, July, August, and September, it is assumed that rainfed agriculture does not face increases in humidity demand during critical stages of growing crop.

It is perceived clearly that some parts of Aguascalientes State are showing a remarkable cooling. In this state, indices related to minimum temperature indicate a tendency toward cooling. At nine sites which are located in north, south, east, and southwest mean minimum temperature decreases. Frost days augment at ten sites located in south, east, southwest and in a small part of the north. Similarly, the monthly maximum value of daily minimum temperature decreases at six sites located in south, southwest, east, and northwest. On the other hand, the monthly minimum value of daily minimum temperature decreases at nine sites located in south, southeast, east, north, and northwest. Likewise, cool nights increase at six sites in south, southeast, southwest, and northwest. In the same way, cold spell duration indicator increases just at a site (Calvillo) of southwest. The above indicates that nights/early mornings are cooler, greater occurrence of meteorological frosts, days with more intense cools, greater occurrence of six periods with more intense cools, frost-free period reduction for specific crops, among others.

As a result of the cooling, Aguascalientes state can suffer from implications for human health, and high energy consume for producing heat in homes during winter and early spring. Also, food production can be affected; this cooling, mainly that one caused by frosts, means an increase in the risk of losses by freezing and low efficiency in corn, poblano pepper, and beans germination. In alfalfa, in these zones, higher frequency in the growth inhibition is expected.

The Aguascalientes cooling is confirmed by the negative trend in some indices of maximum temperature which is an indicator of lower degree of heat. Average maximum temperature decreases at a site of southwest (Calvillo). Similarly, summer days decrease at a site of southwest (Calvillo). The monthly minimum value of daily maximum temperature decreases at two sites, one of them is located in the southwest (Calvillo) and another one in the northeast. In the same way, warm nights decrease at eleven sites distributed in south, east, southeast, southwest (Calvillo), north, and northwest. In these places, negative trends in these indices indicate the occurrence of lower degree of heat.

In the southwest, the zone of guava production, cooling can promote that heat requirement or growing degree days of crops be satisfied for more time, so that more time to get maturity can be required.

Analogously, in Aguascalientes also heating occurs. In this state, indices related to maximum temperature indicate tendency toward warming. Average maximum temperature increases in most of the surface (20 sites). This causes an increase in summer days at sixteen sites located in east, northeast, and southeast. Similarly, monthly maximum value of daily maximum temperature increases at thirteen sites located in east, south, southwest, and north. On the other hand, monthly minimum value of daily maximum temperature increases at three sites located in east and southeast. In the same way, warm days increase in most part of the state (19 sites). Likewise, warm nights increase at eight sites distributed in the center, north, east, and west. Also, the warm spell duration indicator increases at a site at south of entity. The above produce increase on the number of days with temperature greater than 25 ˚C, a warmer weather, more intense heats, warmer nights, increase on the duration of warm spell, among others. The warming of these zones foresees a faster accumulation of growing degree days and shortening of the growing cycle, so that for rescuing the viability of these crops, varieties/hybrids with a shorter growing cycle should be utilized. These locations should be prepared for eradicating insects with a longer cycle of life and new species of agricultural and forest plagues.

In Aguascalientes, warming increases the risk of heat waves. In some places where indices associated with maximum temperature increase, the heat can damage sensitive crops. The increase in the frequency of warm weather adds vulnerability to Aguascalientes' agriculture, which means more frequent damages in the growth and development, and hence in the yield and quality of corn, poblano pepper, beans, sorghum, oat, alfalfa, grapevine, and peaches.

In some regions of Aguascalientes, heating is confirmed by positive trends of some indices related to minimum temperature, which indicates traits of the occurrence of lower degree of cold. Average minimum temperature increases at seven sites located in center, east, west, southwest, north, and northeast. Frost days decrease at three locations in east. On the other hand, the monthly maximum value of daily minimum temperature increases at five sites distributed in east, north-center, northeast, and southeast. In the same way, monthly minimum value of daily minimum temperature increases at two locations in southeast and northeast. Cool days decrease in most parts of the state, except near center, in the most southwest part (Calvillo), at one site in northeast and another at northwest. Cool nights decrease at seven sites located in north, north-center, northeast, and southwest.

This shows that in places mentioned above, nights/early mornings are less cold, the cold is less intense, less meteorological frost, fewer cold nights, among others.

In Aguascalientes, the decrease of cold can have an agricultural importance. This pattern indicates problems in the grapevine and peaches production due to the occurrence of less cold or intermittent cold that reduces the potential yield by the freezing of premature bud and flowers. This suggests greater use of synthetic substances that regulate the growth through the compensation for chilling hours. Also, farmers can use varieties or hybrids with low cold requirements; they can either plant new orchards or use the graft on trees that are already on production.

In Aguascalientes, there exist changes in the pattern of precipitation indices, however, these affect less areas with respect to temperature indices. This shows that the Aguascalientes region is less sensitive to changes in precipitation indices than to changes caused by temperature indices.

In the north, south, east, and southeast there exists an evidence of tendency toward more humid conditions. Thus, max 1 and 5-day precipitation amount increased at three sites located in east and north. Also, daily intensity index increased at five sites distributed in east and south. Similarly, the number of heavy precipitation days just increased at two sites in east. On the other hand, the number of very heavy precipitation days increased at three sites located in south and east. Annual total wet-day precipitation increased at a site in southeast. The above means that in these places, the quantity of rain in one and five days is increasing, rains are more intense and heavier; these together create conditions tending to higher humidity.

In north, south, east, and southeast Aguascalientes, this type of precipitation increase could have environmental and agricultural implications. It is expected that precipitation increases enhance runoff and recharge of aquifers. Also, due to these trends, it is expected that in these locations, crops have better soil moisture conditions that help reduce irrigation water volumes. However, another kind of agronomic problems can emerge, for example, rachitic growth and lodging risks can occur in corn; in poblano pepper growth gets difficult; in beans, growth of plants gets difficult, grains weight decreases, and flowers abortion occurs; in alfalfa, damages in the root system and low efficiency of transpiration occur; in grapevine photosynthesis decreases; and in peaches, diseases, weed, and insects could be promoted, also there could be increase in the risk of damages by salinity.

When considering precipitation increases and evaporation decrease, it is expected that in irrigated lands pumping of and pressure on water resources be reduced. Also it is expected to enhance vegetation and reduce aridity index.

Also, there is evidence that in some parts of Aguascalientes conditions more tending to drought are occurring; however, this is just evidenced by two indices. The number of consecutive dry days increases at nine sites located in the center, southeast, northeast, west, southwest, and northwest. Furthermore, the simple daily intensity index decreased just at a site in northeast. This means that at these sites the number of days with no significant precipitation increases, and that precipitation events are less intense.

In these places, the decrease of rainy days could bring an increase in the dry season duration or a decrease in the rainy season duration. In southwest (Presa Media Luna), where evaporation and drought increases exist, the pressure on water resources could increase.

Calvillo is a municipality with an obvious cooling. In this region, the specific changes with respect to temperature indices are the decrease in average maximum temperature and average minimum temperature, increase of cool days, decrease of warm days, decrease of monthly maximum value of daily minimum temperature, decrease of monthly minimum value of daily minimum temperature, decrease of monthly minimum value of daily maximum temperature, increase of cool nights, decrease of warm nights, and increase of cold spells duration. Under these conditions, in this municipality, the guava crop could present problems of meeting heat requirements.

It is suggested that this research continues for Aguascalientes and in other parts of the watershed. The impact of these meteorological variables/extreme events trends should be evaluated through modelling on the more important productivity crops, considering the role of soil, water supply, and weather. Also, outputs of prediction and simulation models should be considered for knowing the pattern of extreme indices and their agricultural effects either in the near, middle or distant future.

It is required for the authorities and government participation for promoting a more efficient use of water. In regions with evaporation increase, warming, and precipitation decrease, authorities in charge of water management should promote the repair and maintenance of irrigation infrastructure and systems for increasing the efficiency in the use of water and attenuating the impacts of climate change/variability captured in this work.

In east of Aguascalientes, particularly in Sandovales and El Tule, it is recommended to use technologies for conserving soil and harvesting water from rain. This will help avoid water lost by runoff and reduce soil erosion. At the same time, this practice will improve agronomic properties of soils and crop productivity. Also, one can introduce contour lines, terraces, control runoff work, and reforestation for reducing the destructive water force.

In regions where rainy season and growing season duration decrease precocious varieties/hybrids capable of maturing earlier and require less time to the harvest can be adopted. These varieties/hybrids should be adapted to abrupt temperature oscillations or extreme temperatures.

Research on agricultural use of water should be intensified in Aguascalientes and in nearby zones of the watershed. Deficit/limited irrigation is a technique that can contribute significantly to saving water for food production under conditions of climate change, and in regions with overexploited aquifers.

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APPENDIX A

Table 2. 1. Characteristics of 52 weather stations used in the study.

Weather station	Latitude (N)	Longitude (W)	AMSL	Duration of data
Cañada Honda	22°00´0´´	102°11´56´´	1702	1970-2008
Presa El Niagara	21°46´44´´	102°22´19´´	1828	1957-2008
Jesus Maria	21°57´0´´	102°21´0´´	1800	1949-1988
P. De La Concepcion	22°12´7´´	102°08´6´´	2300	1973-2008
La Tinaja	22°09´50´´	102°33´14´´	2425	1971-2008
Malpaso	21°51´36´´	102°39´50´´	1775	1958-2008
Presa Media Luna	21°47´38´´	102°48´7´´	1585	1970-2008
Mesillas	22°18´47´´	102°09´58´´	1990	1963-2008
Campo Exp. Pabellon	22°10´1´´	102°17´35´´	1909	1946-2006
Palo Alto	21°54´58´´	101°58´8´´	2015	1970-2008
Ganaderia Peñuelas	21°42´0´´	102°18´0´´	1878	1945-1970
Presa Potrerillos	22°13´59´´	102°26´38´´	2090	1947-2008
Presa P. E. Calles	22°08´28´´	102°24´54´´	2020	1937-2008
Presa Jocoque	22°07´41´´	102°21´32´´	1970	1942-2008
Presa La Codorniz	21°59´49´´	102°40´26´´	1783	1963-2008
San Bartolo	21°44´53´´	102°10´12´´	1965	1949-2000
Calvillo	21°50´13´´	102°42´43´´	1665	1959-2008
San Isidro	21°46´40.80´´	102°5´14.40´´	1895	1970-2008
Tepezala	22°13´23´´	102°10´8´´	2110	1962-2008
Venadero	21°52´37´´	102°27´47´´	1995	1951-2008
Villa Juarez	22°06´4´´	102°04´5´´	1970	1958-2003
Asientos	22°14´31´´	102°25´12´´	2155	1963-2008
Aguascalientes	21°53´42´´	102°18´29´´	1865	1947-2008
El Novillo	22°01´8´´	101°59´56´´	2010	1972-2008
Las Fraguas	22°02´20´´	101°53´31´´	2020	1972-2008
Los Conos	21°53´49´´	101°59´31´´	2015	1972-2008
Sandovales	21°53´6´´	102°06´32´´	2000	1972-2008
Agua Zarca	21°58´26´´	102°35´2´´	2300	1976-2008
Arellano	21°48´7´´	102°16´23´´	1890	1979-2008
La Tinaja II	21°48´36´´	102°07´44´´	2010	1977-2008
Cieneguilla	21°43´52´´	102°27´11´´	1780	1979-2008
Montoro	21°45´25´´	102°18´7´´	1855	1979-2008

Table 2.1 Continued.

Weather station	Latitude (N)	Longitude (W)	AMSL	Duration of data
Los Negritos	21°52´12´´	102°20´56´´	1845	1980-2008
El Ocote I	21°46´55´´	102°31´1´´	2005	1979-2008
El Ocote II	21°53´24´´	102°49´55´´	2275	1980-2008
Peñuelas	21°43´34´´	102°16´19´´	1860	1979-2008
Presa Canutillo	21°50´13´´	102°31´19´´	1930	1979-2008
Rancho Seco	22°05´17´´	101°58´1´´	2055	1979-2008
Rincon De Romos	22°13´52´´	102°18´54´´	1947	1979-2008
San Fco. de Los Romo	22°04´44´´	102°16´23´´	1885	1979-2008
San Gil	22°12´29´´	102°01´19´´	2010	1979-2008
Tepetatillo	22°05´28´´	102°10´52´´	2020	1979-2008
Cosio	22°21´47´´	102°17´49´´	1885	1978-2008
Presa 50 aniversario	22°11´20´´	102°27´50´´	2050	1980-2004
Jesus Maria	21°57´11´´	102°20´31´´	1907	1979-2008
Los Alisos	21°44´31´´	102°42´58´´	2040	1981-2008
El Chayote	22°17´10´´	102°14´10´´	1930	1983-2008
Milpillas De Arriba	21°56´6´´	102°33´4´´	2140	1982-2008
Calvillito	21°50´6´´	102°10´55´´	1950	1983-2008
La Posta UAA	21°58´19.20´´	102°21´43.20´´	1905	1986-2008
Jesus Teran	21°58´34´´	102°03´43´´	2040	1985-2008
Las Presas, El Llano	21°54´32.40´´	102°5´13.20´´	2025	1986-2008

Table 2.2. Monthly evaporation trend [Theil-Sen (Q) value] at 52 weather stations of Aguascalientes.

Weather Station	J	F	M	A	M	J	J	A	S	O	N	D
Cañada Honda	-4.17	-1.27	-2.68	-0.37	0.32	-2.50	0.71	-2.07	-7.23	-5.35	-9.36*	-8.01*
Presa El Niagara	-6.07*	-6.19	-10.04*	-11.58	-11.92*	-9.08	-6.64	-5.53	-6.87*	-6.77*	-5.40*	-3.15
Jesus Maria	2.75	6.27	9.87	15.94	19.65*	6.82	10.87	5.96	7.04	10.51	4.82	4.86
P. De La Concepcion	-14.71*	-6.56	7.49	20.36*	12.90	3.78	-6.53	-6.48	-12.15*	-11.10	-11.85*	-11.70*
La Tinaja	-5.23	-1.98	-23.16*	-17.52*	-21.48*	-23.09*	-4.60	-10.05	-4.81	-8.40	-6.69	-3.57
Malpaso	7.65	3.78	6.54	5.38	0.50	2.82	0.92	0.62	-2.72	8.40	7.12*	9.69*
Presa Media Luna	5.80	9.41*	13.76*	13.04*	8.23	4.01	2.95	2.79	-3.45	-4.64	-5.68	-4.15
Mesillas	-0.23	5.05	-0.55	-0.06	-5.11	-4.24	-4.49	-9.84	-7.46	-0.60	-0.46	1.17
Campo Exp. Pabellon	-5.82*	-4.84	-9.81	-7.54	-7.35	-3.12	-6.21	-6.40*	-5.10	-8.44	-6.07*	-8.37*
Palo Alto	5.10	-5.41	-13.53*	-24.27*	-14.93	-11.70	-2.14	-2.86	-4.38	0.09	2.33	3.87
Ganaderia Peñuelas	-0.62	-2.61	-3.32	6.43	8.40	7.61	0.42	-3.25	-7.55	-6.88	-4.11	-3.72
Presa Potrerillos	-8.55*	-7.01	-15.82*	-17.30*	-12.47*	-12.52	-9.92*	-7.85*	-9.12*	-8.80*	-8.02*	-6.33
Presa P. E. Calles	-4.45	-4.72*	-11.35*	-16.53*	-14.92*	-10.10*	-12.81*	-10.65*	-12.49*	-10.72*	-6.95*	-5.02
Presa Jocoque	-6.27*	-5.79*	-8.64*	-8.18	-3.81	-4.58	-8.43	-8.43*	-8.10*	-6.35	-6.74*	-6.25*
Presa La Codorniz	-9.08	-4.43	-10.78*	-12.66	-14.44	-11.12	-7.01	-6.01	-9.47*	-8.67*	-6.87	-6.65
San Bartolo	-5.40	4.06	0.81	-1.87	8.25	-5.66	-4.84	-5.59	-1.23	-0.64	2.28	4.11
Calvillo	-9.58*	-7.55	-11.99	-8.66	-11.52	-14.89*	-13.15*	-4.08	-7.85*	-9.27	-10.08*	-7.47
San Isidro	8.52	3.46	-9.77	-15.00	-13.88*	-3.76	4.78	10.58	13.28	9.71	9.72*	11.18*
Tepezala	-11.50	-11.57	-12.23	-16.16*	-16.29*	-20.52*	-13.41*	-13.51*	-7.94	-14.34*	-9.71	-5.25
Venadero	-1.99	-2.48	-11.19	-8.06	-9.43	-6.06	-7.63	-7.30	-7.45*	-0.79	-1.31	4.11
Villa Juarez	6.89	3.28	-11.56	-20.11*	-11.17	-12.05*	-13.10*	-10.69*	-5.44	-5.31	-4.50	-0.04
Asientos	4.49	-2.23	-13.04	-20.58*	-10.73	-14.77*	-4.40	-8.18	2.38	-2.03	3.09	8.73
Aguascalientes	-3.64	-1.90	0.98	-0.56	-0.83	-3.72	-3.04	-5.65	-5.34	-0.23	-2.29	-1.97
El Novillo	-3.18	-3.43	-7.78	-9.24	-6.50	-6.34	-2.62	-3.71	-5.98	-14.60*	-16.27*	-6.17
Las Fraguas	4.94	4.99	-3.87	-11.11	-16.33*	-14.81*	-0.65	-0.11	-0.35	1.77	2.43	7.91

Table 2.2. Continued.

Weather Station	J	F	M	A	M	J	J	A	S	O	N	D
Los Conos	1.97	0.21	-7.98	-2.25	-8.01	-6.69	-1.96	-6.19	-6.76	-2.50	-1.87	-2.63
Sandovales	-4.85	-11.79*	-12.24	-23.90*	-20.87*	-13.69	-14.39*	-6.14	-5.78	-8.29	-2.10	2.01
Agua Zarca	12.36	12.40	-15.50	-12.43	-7.24	-2.72	6.29	5.84	5.38	6.61	1.87	10.92
Arellano	-0.16	11.51	14.16	22.29*	17.11*	4.27	10.06	4.14	9.21	2.90	3.01	-2.88
La Tinaja II	-4.78	2.05	-12.73	-13.83	-23.02*	-9.89	-3.53	-0.95	0.77	3.22	-2.78	-3.58
Cieneguilla	8.42	17.18*	2.50	-5.17	-12.76	-3.49	8.97	4.54	11.79	14.25*	14.94*	12.01
Montoro	-10.43	-7.45	-11.28	-19.36*	-9.42	-15.72*	-9.39	-9.54	-5.23	-22.31*	-12.69*	-11.48*
Los Negritos	7.79	2.38	-1.09	8.90	-7.97	-7.90	2.96	-3.96	2.98	9.61	-0.23	5.03
El Ocote I	4.21	-2.49	-8.27	-19.44*	-10.72	-8.00	-1.80	-9.41	5.49	-5.83	0.09	9.59
El Ocote II	8.89	3.08	=	=	=	=	0.38	3.26	8.58	0.63	-1.55	3.05
Peñuelas	3.06	6.94	-3.90	2.82	-2.46	2.56	3.06	-4.23	-1.19	-1.85	-3.29	-3.86
Presa Canutillo	0.35	4.04	4.02	0.51	-6.58	-3.07	-4.86	-3.47	-2.56	-2.41	-1.42	-0.62
Rancho Seco	=	=	26.91*	=	17.35	=	10.86	11.74	=	7.21	1.55	4.33
Rincon De Romos	-0.38	-8.62	-16.21*	-12.01	-17.95	-12.13	-1.98	-3.49	-3.47	-3.76	-3.27	-1.23
San Fco. de Los Romo	14.97	15.55	7.82	14.73	-9.72	-6.59	8.16	-1.82	8.47	9.37	23.95*	16.91*
San Gil	8.86	9.99	-10.90	-4.97	-3.09	-4.24	5.24	-1.01	2.60	-2.38	9.29	1.39
Tepetatillo	=	-6.44	-8.82	-1.87	-7.05	-2.10	0.64	1.56	0.57	-9.08	-7.73	-8.30
Cosio	3.70	5.04	0.96	5.34	-10.98	3.35	1.15	3.77	2.08	-0.70	0.50	11.80
Presa 50 aniversario	-6.04	-10.12	-16.10*	-18.59	-22.48*	-10.93	-5.41	-4.69	-13.25	-10.57	-5.37	-6.33
Jesus Maria	-9.91	-11.38	-5.09	-7.20	-4.60	3.93	-1.53	-5.66	3.44	-4.53	-9.21	-7.84
Los Alisos	=	2.05	3.99	9.22	-3.88	-1.43	14.80	7.11	8.84	-5.58	=	=
El Chayote	11.63	1.05	-10.79	-0.12	-2.42	-11.66	-4.75	1.19	-1.15	-0.20	-3.48	0.48
Milpillas De Arriba	7.99	15.68	14.18	14.46	9.46	-3.40	7.98	5.12	5.09	3.82	-1.39	-0.26
Calvillito	5.05	5.63	9.00	24.63*	22.85	18.39	-2.87	-8.10	-10.83	-11.56	-0.49	-0.66
La Posta UAA	=	=	=	=	=	=	=	=	13.76	1.42	-6.75	=

Table 2.2. Continued.

Weather Station	J	F	M	A	M	J	J	A	S	O	N	D
Jesus Teran	-4.64	7.89	20.20*	7.36	7.99	7.99	1.75	2.36	-2.68	0.61	-7.12	-0.84
Las Presas, El Llano	-7.52	1.17	-8.34	-10.16	-9.50	-7.72	-6.41	-3.06	-3.85	-2.02	4.66	3.79
Summary												
Not significant	42	45	38	35	38	41	45	45	43	44	37	42
Significant positive	0	2	3	4	2	0	0	0	0	1	4	3
Significant negative	6	3	9	10	10	8	6	6	8	7	10	5
Total	48	50	50	49	50	49	51	51	51	52	51	50

Table 2.3. Pearson correlation coefficient for the correlation between the trend magnitude of monthly evaporation and elevation.

Mes	Altitude (m)		
	1585-1990	1995-2425	1585-2425
January	0.054	0.030	-0.045
February	-0.076	0.154	-0.087
March	-0.223	-0.111	-0.243
April	-0.119	0.153	-0.234
May	-0.038	0.107	-0.152
June	-0.005	-0.144	-0.279
July	-0.196	0.056	-0.078
August	-0.360	-0.012	-0.110
September	0.040	0.110	-0.025
October	-0.030	0.024	-0.120
November	0.096	-0.161	-0.091
December	0.122	-0.054	0.028

All correlation coefficients were not significant ($p \leq 0.05$).

Table 3.1. Characteristics of 25 weather stations used in the study.

Weather station	Latitude (N)	Longitude (W)	Elevation (m)	Duration of data
Cañada Honda	22°00´0"	102°11´56"	1925	1980-2013
Presa El Niagara	21°46´44"	102°22´19"	1828	1980-2013
P. De La Concepcion	22°12´7"	102°08´6"	2300	1980-2013
La Tinaja	22°09´50"	102°33´14"	2425	1980-2013
Malpaso	21°51´36"	102°39´50"	1775	1980-2013
Presa Media Luna	21°47´38"	102°48´7"	1585	1980-2013
Mesillas	22°18´47"	102°09´58"	1990	1980-2013
Palo Alto	21°54´58"	101°58´8"	2015	1980-2013
Presa Potrerillos	22°13´59"	102°26´38"	2090	1980-2013
Presa P. E. Calles	22°08´28"	102°24´54"	2020	1980-2013
Presa Jocoque	22°07´41"	102°21´32"	1970	1980-2013
Presa La Codorniz	21°59´49"	102°40´26"	1783	1980-2013
Rancho Viejo	22°07´23"	102°30´40"	2090	1980-2013
San Bartolo	21°44´53"	102°10´12"	1965	1980-2013
Calvillo	21°50´13"	102°42´43"	1665	1980-2013
San Isidro	21°46´41"	102°6´14"	1895	1980-2013
Tepezala	22°13´23"	102°10´8"	2110	1980-2013
Venadero	21°52´37"	102°27´47"	1995	1980-2013
Villa Juarez	22°06´4"	102°04´5"	1970	1980-2013
Aguascalientes	21°53´42"	102°18´29"	1865	1980-2013
El Novillo	22°01´8"	101°59´56"	2010	1980-2013
Las Fraguas	22°02´20"	101°53´31"	2020	1980-2013
Los Conos	21°53´49"	101°59´31"	2015	1980-2013
Sandovales	21°53´6"	102°06´32"	2000	1980-2013
El Tule	22°04´59"	102°05´28"	1960	1980-2013

Table 3.2. Extreme temperature indices suggested by ETCCDI and used in this study.

Index	Indicator name	Definitions	Units
TXMean	Annual averaged maximum temperature	Annual mean of TX	°C
TNMean	Annual averaged minimum temperature	Annual mean of TN	°C
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
FD0	Frost days	Annual count when TN (daily minimum) <0°C	Days
SU25	Summer days	Annual count when TX (daily maximum) >25°C	Days
GSL	Growing season length	Annual count between first span of at least 6 days with TG >5°C after winter and first span after summer of 6 days with TG <5°C	Days
TNx	Max Tmin	Monthly maximum value of daily minimum temp	°C
TXx	Max Tmax	Montly maximum value of daily maximum temp	°C
TNn	Min Tmin	Monthly minimum value of daily minimum temp	°C
TXn	Min Tmax	Monthly minimum value of daily maximum temp	°C
TX10p	Cool days	Percentage of days when TX<10th percentile	Days
TX90p	Warm days	Percentage of days when TX>90th percentile	Days
TN10p	Cool nights	Percentage of days when TN<10th percentile	Days
TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	Days

Table 3.3. Decadal trends of extreme temperature indices in Aguascalientes, Mexico.

Station name	TXMean	TNMean	DTR	FD0	SU25	TNx	TXx	TNn	TXn	TX10p	TX90p	TN10p	TN90p	WSDI	CSDI
Cañada Honda	0.550*	0.161	0.450*	8.153*	19.552*	0.588*	0.286	-0.984*	0.379	-2.821*	3.751*	-2.005	1.801*	0.000	0.000
Presa El Niagara	0.725*	-0.695*	1.433*	6.250*	16.429*	-0.667*	0.909*	-0.769*	0.000	-2.611*	4.811*	3.682*	-4.506*	2.857*	0.000
P. De La Concepcion	0.566*	1.000*	-0.425*	0.000	23.448*	1.136*	1.190*	0.000	-1.176*	-1.317	3.955*	-3.736*	7.056*	0.000	0.000
La Tinaja	0.177	0.104	0.026	3.333*	4.143	0.000	0.445	-0.377*	0.000	-0.845	-0.138	0.070	1.231	0.000	0.000
Malpaso	0.693*	0.300*	0.406*	0.000	22.129*	0.000	0.714*	-0.278	0.096	-3.387*	4.392*	-2.536*	2.710*	0.000	0.000
Presa Media Luna	-0.215	-0.143	-0.043	3.957*	-9.258	0.000	0.278	-0.667*	0.000	1.488	0.292	1.425	-0.440	0.000	0.000
Mesillas	0.698*	-0.271*	0.956*	0.870*	26.667*	-0.257	0.541*	-0.477*	0.426	-3.008*	3.891*	0.902	-2.575*	0.000	0.000
Palo Alto	0.693*	-0.303*	0.977*	5.205*	26.667*	0.000	0.785*	-0.526	0.870	-2.964*	3.175*	1.707*	-1.441*	0.000	0.000
Presa Potrerillos	0.560*	0.181*	0.387*	-0.351	22.000*	0.000	0.500*	0.400	0.000	-2.690*	3.537*	-1.827*	0.977*	0.000	0.000
P. E. Calles	0.794*	0.079	0.721*	0.000	26.667*	0.000	1.071*	0.000	0.278	-4.264*	3.961*	-0.750	-0.300	0.000	0.000
Presa Jocoque	1.005*	0.567*	0.476*	-0.667	38.261*	0.455*	0.870*	0.250	0.417	-5.119*	4.550*	-3.736*	2.754*	0.000	0.000
Presa La Codorniz	0.475*	0.414*	0.119	0.000	10.417	0.357	1.000*	-0.590	0.817	-1.670*	2.643*	-0.108	3.390*	0.000	0.000
Rancho Viejo	0.886*	-0.600*	1.441*	3.077*	33.333*	-0.417*	1.111*	-1.176*	0.769	-4.489*	3.838*	2.353*	-4.183*	0.000	0.000
San Bartolo	0.667*	-0.132	0.767*	0.667	23.125*	-0.741*	0.469	0.250	2.174*	-3.390*	2.845*	-0.008	-1.632*	0.000	0.000
Calvillo	-0.364*	-1.427*	1.027*	11.250*	-9.815*	-1.000*	0.313	-2.407*	-1.273*	1.809	-0.438	6.812*	-5.848*	0.000	2.143*
San Isidro	0.747*	0.129	0.632*	0.000	36.250*	0.556*	0.000	0.000	1.667*	-5.525*	2.046*	-0.600	-0.028	0.000	0.000
Tepezala	0.240	0.243	0.019	0.000	5.000	-0.200	0.161	0.000	0.000	-2.143*	1.280	-0.840	0.260	0.000	0.000
Venadero	0.435*	-0.433*	0.755*	0.000	12.500	0.000	0.435	-0.690	0.690	-1.745	1.760*	2.300	-3.257*	0.000	0.000
Villa Juarez	1.057*	-0.048	1.160*	-10.200*	42.950*	-1.250*	0.556	1.064*	2.222*	-5.665*	3.293*	-2.745*	-4.618*	0.000	0.000
Aguascalientes	0.477*	0.631*	-0.210	0.000	12.857	0.000	0.400	0.588	0.000	-1.520	4.005*	-3.236*	2.900*	0.000	0.000
El Novillo	0.692*	-0.780*	1.473*	4.211*	21.818*	-0.741*	1.389*	-1.000*	-0.313	-2.096*	3.669*	4.856*	-4.338*	0.000	0.000
Las Fraguas	0.480*	0.436*	0.263	-2.143*	21.667*	0.435*	0.000	0.400	1.538	-3.508*	1.025	-2.564*	1.708*	0.000	0.000
Los Conos	0.628*	-0.541*	1.315*	8.431*	29.773*	0.000	0.952*	-0.952*	0.000	-2.115*	4.122*	2.821*	-2.108*	0.000	0.000
Sandovales	0.356*	-0.288*	0.725*	-5.455*	10.833	0.000	0.435*	1.429*	0.000	-1.400	2.367*	0.374	-2.500*	0.000	0.000
El Tule	0.144	-0.092	0.181	1.034	0.385	0.000	0.000	-0.357	0.870	-1.204*	-0.861	0.393	-0.836	0.000	0.000
Summary															
Not significant	4	9	7	12	8	14	12	14	20	7	6	12	6	24	24
Significant positive	20	7	17	10	16	5	13	2	3	0	19	6	8	1	1
Significant negative	1	9	1	3	1	6	0	9	2	18	0	7	11	0	0
Total	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

*Statistically significant at 95% level ($p \leq 0.05$).
GSL index does not appear in any column by virtue of this was not statistically significant ($p \leq 0.05$) in none of the considered weather stations.

Table 3.4. Correlation matrix among the extreme temperature indices in Aguascalientes, Mexico during the period 1980-2013.

	TXMean	TNMean	DTR	FD0	SU25	GSL	TNx	TXx	TNn	TXn	TX10p	TX90p	TN10p	TN90p	WSDI	CSDI
TXMean	1															
TNMean	-0.638+0.791[a] 44[b]	1														
DTR	+0.418+0.954 88	-0.869-0.380 68	1													
FD0	-0.478+0.478 28	-0.874-0.361 64	+0.375+0.944 52	1												
SU25	+0.830+0.975 100	-0.666+0.808 52	+0.692+0.930 80	-0.515+0.441 36	1											
GSL	= =	+0.434 4	= =	-0.511 4	= =	1										
TNx	-0.448+0.727 40	+0.373+0.799 72	-0.755+0.630 52	-0.732+0.581 28	-0.556+0.694 40	-0.391-0.362 8	1									
TXx	+0.361+0.801 92	-0.470+0.689 24	+0.371+0.762 84	+0.388+0.531 28	+0.350+0.670 80	-0.413 4	+0.368+0.545 16	1								
TNn	-0.472+0.390 20	+0.395+0.884 52	-0.627+0.425 48	-0.836-0.416 96	-0.442+0.387 24	+0.358+0.642 16	-0.515+0.615 16	-0.417+0.427 8	1							
TXn	+0.370+0.739 44	-0.495+0.477 24	+0.358+0.685 24	-0.482-0.460 8	+0.372+0.727 28	= =	-0.522+0.404 8	-0.365+0.480 16	+0.344+0.445 12	1						
TX10p	-0.965-0.728 100	-0.810+0.615 36	-0.914-0.368 92	-0.515+0.463 32	-0.962-0.484 100	= =	-0.636+0.409 32	-0.721-0.374 76	-0.492+0.411 20	-0.756-0.368 68	1					
TX90p	+0.508+0.914 100	-0.509+0.648 36	+0.508+0.877 88	+0.435+0.535 16	+0.455+0.930 100	= =	-0.448+0.591 28	+0.374+0.766 88	-0.530+0.405 28	+0.430+0.645 16	-0.745-0.402 96	1				
TN10p	-0.814+0.400 36	-0.940-0.615 100	-0.415+0.856 60	+0.346+0.937 76	-0.831+0.427 32	-0.521 4	-0.756+0.443 52	-0.582+0.433 28	-0.832-0.348 52	-0.509+0.394 16	-0.367+0.801 36	-0.644+0.448 28	1			
TN90p	-0.702+0.673 44	+0.547+0.926 100	-0.860-0.397 60	-0.703+0.477 36	-0.723+0.670 52	= =	+0.349+0.794 96	-0.428+0.703 28	-0.442+0.792 36	-0.504+0.427 12	-0.667+0.709 36	-0.531+0.752 44	-0.772-0.371 80	1		
WSDI	+0.356+0.828 100	-0.413+0.546 16	+0.347+0.798 92	+0.415+0.694 8	+0.369+0.898 88	= =	-0.489+482 20	+0.341+0.666 56	-0.366+0.388 8	+0.387+0.529 28	-0.579-0.345 68	+0.371+0.950 100	-0.386+0.535 16	-0.398+0.749 24	1	
CSDI	-0.362+0.474 20	-0.905-0.340 80	+0.353+0.917 32	+0.433+0.987 56	-0.392+0.474 24	-0.529+0.389 12	-0.743+0.376 36	-0.384+0.615 16	-0.692-0.363 20	-0.513+0.457 16	-0.391+0.384 16	+0.480+0.490 12	+0.410+0.975 100	-0.563-0.348 24	+0.406+0.657 12	1

[a] These numbers represent the correlation range for those weather stations where the correlation analysis was statistically significant ($p \leq 0.05$).
[b] These numbers indicate the percentage of weather stations that was statistically significant ($p \leq 0.05$) in the correlation analysis for this pair of indices.
[=] Correlation was not statically significant ($p \leq 0.05$).

Table 3.5. Spearman correlation coefficients for correlation between extreme temperature indices and elevation.

Index	1585m-1990m	1995m-2425m	1585m-2425m
TXMean	0.7371*	-0.4353	0.2741
TNMean	0.3549	0.5371	0.3054
DTR	0.2365	-0.6460*	-0.1322
FD0	-0.4877	0.0702	-0.2094
SU25	0.7291*	-0.3742	0.2912
GSL	=	=	=
TNx	0.0515	0.3921	0.2496
TXx	-0.0107	-0.0026	0.1888
TNn	0.5804*	-0.0222	0.2791
TXn	0.6208*	-0.4730	-0.0292
TX10p	-0.7558*	0.4692	-0.2399
TX90p	0.4094	-0.3723	0.0603
TN10p	-0.5152	-0.4116	-0.2737
TN90p	0.0511	0.6248*	0.2417
WSDI	-0.0746	=	-0.1704
CSDI	-0.4584	=	-0.3651

*Statistically significant at 95% level ($p \leq 0.05$).

Table 3.6. Some impacts of temperatures change over agricultural, livestock and natural resources sectors.

Author	Variable	Sector	Impact
Walthall *et al.*, 2012	Minimum temperature (increase)	Agriculture	Damages in pollination stage provokes deficiencies in the development of fruits/grains/fiber, also yield reduction
Melillo *et al.*, 2014	Maximum temperature (increase)	Livestock	Animal stress, reduction on the rates of production of meat, milk and eggs, and reduction of the conception rates
Luedeling, 2012; Walthall *et al.*, 2012	Minimum temperature (increase)	Agriculture	Dissatisfaction in the number of chilling hours, low bloom viability, and yield reduction
Melillo *et al.*, 2014	Mean temperature (increase)	Agriculture	Increase on crop water requirements
Garrett et al., 2006; Walthall *et al.*, 2012	Wintry maximum (increase) and minimum (increase) temperature and precipitation (increase)	Agriculture	New conditions for enhancing insect populations and its distribution, incidence of pathogens, and enhanced geographical distribution of diseases
Ziska, 2003; Koleva and Schneider, 2009; Ziska, 2010	Maximum temperature (increase), minimum temperature (increase) and CO_2 (increase)	Agriculture	Increase in weeds incidence, increase in the use and costs of herbicides, and yield reduction
Ziska *et al;* 1999	Maximum temperature (increase), minimum temperature (increase) and CO_2 (increase)	Agriculture	Loss of efficacy of herbicides based on glyphosate, and bigger crop stress due to competition with weeds
Doney *et al.*, 2014; Ziska *et al.*, 2016	Oceanic temperature (increase)	Natural resources	Appearance of diseases in corals, eelgrass and abalone

Table 3.6. Continued.

Author	Variable	Sector	Impact
Parmesan *et al.*, 1999	Maximum (increase) and minimum temperature (increase)	Natural resources	Migration of butterflies and appearance of new insects
Gaughan *et al.*, 2009	Maximum (increase) and minimum (increase) temperature, and precipitation (increase)	Livestock	Change on the distribution of diseases such as anthrax, blackleg and hemorrhagic septicemia, which leads to ketosis, mastitis and lameness in milky cows
Pan *et al.*, 2010	Temperature (increase) and precipitation (increase)	Agriculture and Natural resources	Loss of soil, change on soil carbon content, change on soil temperature, change on available soil water, and changes on organic matter content
Melillo *et al.*, 2014	Temperature (increase), CO_2 (increase) and precipitation (decrease)	Agriculture and natural resources	Changes on crop water requirements, changes on available water for agriculture, increases in water costs
Melillo *et al.*, 2014	Maximum (increase) and minimum (increase) temperature	Agriculture and natural resources	Increase in evaporation and transpiration rates, reduction on runoff and baseflow
Alexander *et al.*, 2006; Karl *et al.*, 2012	Temperature (increase) and precipitation (decrease)	Agriculture and natural resources	Severe droughts
Schmidhuber and Tubiello, 2007	Temperature (increase) and extreme meteorological events	Agriculture	Distribution of diseases through trade and transport of water and food
Ziska *et al.*, 2016	High aquatic temperature and salinity	Natural resources	Incidence and distribution of parasites in oysters in the Atlantic Ocean
Milner *et al.*, 2017	Maximum temperature (increase)	Natural resources	Melting glaciers and sea level increase

Table 3.6. Continued.

Author	Variable	Sector	Impact
Doney *et al.*, 2014; Ziska *et al.*, 2016	Wintry maximum (increase) and minimum (increase) temperature in the arctic	Natural resources	Proliferation of salmon diseases in the Bering sea, and reduction of Yukon Chinook Salmon populations
Moller *et al.*, 2008	Wintry and spring minimum temperature (increase)	Agriculture and natural resources	Early winter retreat, changes on dates of occurrence of biological habits such as migration, flowering and reproduction
Hahn and Mader, 1997	Maximum (increase) temperature and increase on the frequency of heat waves	Livestock	Death of cattle not accustomed to extreme thermal changes
Christidis and Sttot 2016	Minimum temperature (increase/decrease)	Agriculture and natural resources	Change on growing season length (minimum temperature greater than zero Celsius degrees)
Ruiz *et al.*, 2018	Maximum temperature (increase) and evaporation (increase)	Agriculture and natural resources	Increase on groundwater extraction and reduction of its availability
Kaushal *et al.*, 2010	Temperature (increase) and precipitation (increase on intensity)	Agriculture and natural resources	Decrease on rivers water quality, and increase of sediments, nitrogen, etc.

Table 4.1. Characteristics of 25 weather stations used in the study.

Weather station	Latitude (N)	Longitude (W)	Elevation (m)	Duration of data
Cañada Honda	22°00´0"	102°11´56"	1925	1980-2013
Presa El Niagara	21°46´44"	102°22´19"	1828	1980-2013
P. De La Concepcion	22°12´7"	102°08´6"	2300	1980-2013
La Tinaja	22°09´50"	102°33´14"	2425	1980-2013
Malpaso	21°51´36"	102°39´50"	1775	1980-2013
Presa Media Luna	21°47´38"	102°48´7"	1585	1980-2013
Mesillas	22°18´47"	102°09´58"	1990	1980-2013
Palo Alto	21°54´58"	101°58´8"	2015	1980-2013
Presa Potrerillos	22°13´59"	102°26´38"	2090	1980-2013
Presa P. E. Calles	22°08´28"	102°24´54"	2020	1980-2013
Presa Jocoque	22°07´41"	102°21´32"	1970	1980-2013
Presa La Codorniz	21°59´49"	102°40´26"	1783	1980-2013
Rancho Viejo	22°07´23"	102°30´40"	2090	1980-2013
San Bartolo	21°44´53"	102°10´12"	1965	1980-2013
Calvillo	21°50´13"	102°42´43"	1665	1980-2013
San Isidro	21°46´41"	102°6´14"	1895	1980-2013
Tepezala	22°13´23"	102°10´8"	2110	1980-2013
Venadero	21°52´37"	102°27´47"	1995	1980-2013
Villa Juarez	22°06´4"	102°04´5"	1970	1980-2013
Aguascalientes	21°53´42"	102°18´29"	1865	1980-2013
El Novillo	22°01´8"	101°59´56"	2010	1980-2013
Las Fraguas	22°02´20"	101°53´31"	2020	1980-2013
Los Conos	21°53´49"	101°59´31"	2015	1980-2013
Sandovales	21°53´6"	102°06´32"	2000	1980-2013
El Tule	22°04´59"	102°05´28"	1960	1980-2013

Table 4.2. Extreme precipitation indices, suggested by ETCCDI, used in this study.

Index	Indicator name	Definition	Units
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP>=1.0 mm) in the year	mm/day
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10 mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20 mm	Days
R50	Number of days above 50 mm	Annual count of days when PRCP>=50 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1 mm	Days
R95p	Very wet days	Annual total PRCP when RR>95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm

Table 4.3. Decadal trend of extreme precipitation indices in Aguascalientes, Mexico.

Station name	RX1day	RX5day	SDII	R10	R20	R50	CDD	CWD	R95p	R99p	PRCPTOT
Cañada Honda	-0.948	0.255	0.204	0.000	0.000	0.000	9.167	0.000	0.000	0.000	-8.411
Presa El Niagara	3.043	3.571	0.867*	1.667	1.538*	0.000	12.500	0.000	22.750	0.000	44.933
P. De La Concepcion	-0.115	-3.300	-1.200*	-1.667	-0.769	0.000	7.857	0.000	-0.087	0.000	-47.034
La Tinaja	0.705	-0.689	-0.125	-0.690	0.000	0.000	9.438	0.000	8.258	0.000	-12.194
Malpaso	2.065	1.540	0.400	1.111	0.167	0.000	12.639	0.000	14.900	0.000	17.711
Presa Media Luna	0.517	1.919	0.500	0.556	0.607	0.000	16.754*	0.000	20.300	0.000	20.104
Mesillas	5.340*	15.568*	0.625	0.607	0.923	0.000	12.487	0.000	21.906	0.000	25.086
Palo Alto	5.607*	10.428*	1.592*	1.429	0.627	0.000	12.427	0.000	37.143*	0.000	37.969
Presa Potrerillos	-1.429	0.688	0.151	-0.185	0.000	0.000	12.727*	-0.370	14.316	0.000	7.371
Presa P. E. Calles	-1.648	-4.149	-0.538	-0.435	0.000	0.000	8.621	0.000	-3.875	0.000	-11.933
Presa Jocoque	0.857	-0.267	0.286	1.250	0.417	0.000	10.690	0.000	9.667	0.000	16.435
Presa La Codorniz	1.948	3.378	0.277	0.000	0.000	0.000	15.486*	0.000	6.796	0.000	6.108
Rancho Viejo	2.000	3.125	0.348	1.111	0.000	0.000	15.000*	0.000	22.500	0.000	40.769
San Bartolo	5.000	5.513	0.467	0.000	0.625	0.000	14.000*	0.000	25.050	0.000	6.625
Calvillo	-3.442	-6.073	-0.111	-1.667	0.000	0.000	22.308*	0.000	-17.320	0.000	-25.261
San Isidro	0.261	0.942	0.071	-1.176	0.000	0.000	13.333	0.000	1.077	0.000	-21.200
Tepezala	0.885	0.559	-0.529	-1.000	0.000	0.000	19.000*	0.455	0.000	0.000	-15.238
Venadero	2.158	-0.317	0.218	-0.625	0.000	0.000	10.000	0.000	1.270	0.000	-12.914
Villa Juarez	2.053	5.196	0.857*	0.833	0.000	0.000	14.000*	-0.476	19.333	0.000	20.588
Aguascalientes	0.357	0.903	0.208	1.000	0.000	0.000	14.400*	0.000	13.250	0.000	17.267
El Novillo	0.000	-1.933	-0.286	0.000	0.417	0.000	6.000	0.357	0.000	0.000	-8.417
Las Fraguas	0.938	1.000	0.222	0.000	0.313	0.000	8.462	0.000	6.842	0.000	1.778
Los Conos	5.861*	12.887*	0.413	1.144	1.000	0.000	10.945	0.000	33.493*	0.000	44.000
Sandovales	1.176	8.640	0.824*	2.414*	1.111*	0.000	3.462	0.000	18.889	0.000	67.500*
El Tule	3.000	10.000	0.875*	2.174*	1.579*	0.000	15.833	0.000	18.750	0.000	42.500

Table 4.3 Continued.

Station name	RX1day	RX5day	SDII	R10	R20	R50	CDD	CWD	R95p	R99p	PRCPTOT
Summary											
Not significant	22	22	19	23	22	25	16	25	23	25	24
Significant positive	3	3	5	2	3	0	9	0	2	0	1
Significant negative	0	0	1	0	0	0	0	0	0	0	0
Total	25	25	25	25	25	25	25	25	25	25	25

Table 4.4. Percentage of no significant, significant positive and negative weather stations for each extreme precipitation index.

Index	Non-significant	Significant positive	Significant negative
RX1day	88	12	0
RX5day	88	12	0
SDII	76	20	4
R10	92	8	0
R20	88	12	0
R50	100	0	0
CDD	64	36	0
CWD	100	0	0
R95p	92	8	0
R99p	100	0	0
PRCPTOT	96	4	0

Table 4.5. Correlation matrix among the precipitation extreme indices in Aguascalientes, Mexico during the period 1980-2013.

	RX1day	RX5day	SDII	R10	R20	R50	CDD	CWD	R95p	R99p	PRCPTOT
RX1day	1										
RX5day	+0.4115+0.907[a] 100[b]	1									
SDII	+0.3559+0.7495 96	+0.3912+0.8091 100	1								
R10	+0.3486+0.4950 24	+0.3752+0.7898 92	+0.3503+0.7823 92	1							
R20	+0.3446+0.6474 56	+0.4254+0.8140 100	+0.4631+0.8731 100	+0.5455+0.8793 100	1						
R50	+0.4497+0.8395 100	+0.3479+0.7305 92	+0.3634+0.7298 84	+0.3500+0.4474 28	+0.3505+0.5962 56	1					
CDD	= =	-0.3484 4	+0.3931+0.4924 8	-0.5301-0.3430 28	-0.3839-0.3470 12	= =	1				
CWD	+0.3788+0.4487 8	+0.3430+0.6446 72	+0.3703+0.6183 20	+0.3947+0.7617 92	+0.3625+0.6091 56	+0.4436+0.5826 12	-0.4308-0.3967 8	1			
R95p	+0.4457+0.8743 96	+0.4032+0.8635 100	+0.5164+0.8510 100	+0.4471+0.6837 88	+0.4637+0.8801 100	+0.4578+0.8289 100	= =	+0.3489+0.5347 52	1		
R99p	+0.4517+0.8941 100	+0.3484+0.7664 92	+0.3934+0.7159 88	+0.3921+0.4644 16	+0.3616+0.5786 44	+0.7717+0.9830 100	= =	+0.3687+0.4535 16	+0.4731+0.7954 100	1	
PRCPTOT	+0.3585+0.7469 80	+0.4399+0.8080 100	+0.3669+0.8177 100	+0.3505+0.5962 56	+0.6842+0.9060 100	+0.3506+0.6124 84	-0.5047-0.3549 60	+0.4079+0.6607 96	+0.5519+0.8379 100	+0.3664+0.6405 80	1

[a] These numbers represent the correlation range for those weather stations where the correlation analysis was statistically significant (p≤0.05).
[b] These numbers indicate the percentage of weather stations that was statistically significant (p≤0.05) in the correlation analysis for this pair of indices.
[=]Correlation was not statically significant (p≤0.05).

Table 4.6. Pearson correlation coefficient obtained between altitude and extreme precipitation indices.

Indices	Altitude (m)		
	1585-1990	1995-2425	1585-2425
RX1day	0.5251	-0.2581	0.0734
RX5day	0.5432	-0.3733	-0.0074
SDII	0.3393	-0.4748	-0.3521
R10	0.3148	-0.5294	-0.2004
R20	0.1812	-0.5789*	-0.2635
R50	0	0	0
CDD	-0.6195*	0.0649	-0.4749*
CWD	-0.2597	-0.0655	0.0471
R95p	0.326	-0.2285	0.0113
R99p	0	0	0
PRCPTOT	0.2194	-0.4889	-0.2114

*Significant at 95% level ($p \leq 0.05$).

Table 4.7. Impacts of precipitation change over agricultural, livestock and natural resources sectors.

Author	Variable	Sector	Impact
Garrett *et al.*, 2006; Walthall *et al.*, 2012	Precipitation (increase), maximum (increase) and minimum (increase) temperature	Agriculture	New conditions for improving insects populations and its distribution, incidence of pathogens, and enhanced geographical distribution of diseases
Gaughan *et al.*, 2009	Precipitation (increase), maximum (increase) and minimum (increase) temperature	Livestock	Change on the distribution of diseases such as anthrax, blackleg and hemorrhagic septicemia, which lead to ketosis, mastitis and lameness in milky cows
Delgado *et al.*, 2011; Mass *et al.*, 2011; Kunkel *et al.*, 2013b	Precipitation (increase on intensity)	Natural resources	Increase of erosive power of the precipitation, soil erosion, increase on off-site and non-point pollution
Pan *et al.*, 2010	Precipitation (increase) and temperature (increase)	Agriculture and Natural resources	Loss of soil, change on soil carbon content, change on soil temperature, change on available soil water, and changes on organic matter content
Melillo *et al.*, 2014	Precipitation (increase in intensity)	Agriculture and Natural resources	Increase in runoff
Melillo *et al.*, 2014	Precipitation (decrease), temperature (increase) and CO_2 (increase)	Agriculture and Natural resources	Changes on crops water requirements and available water for crops, increase in costs of water

Table 4.7. Continued.

Author	Variable	Sector	Impact
Alexander *et al.*, 2006; Karl *et al.*, 2012	Precipitation (decrease) and temperature (increase)	Agriculture and Natural resources	Severe droughts
Zeppel *et al.*, 2014	Precipitation (increase on intensity and migration to another month)	Natural resources	Changes on the time of occurrence of certain physiological processes such as bloom, ripening of fruits, maturation of leaves, etc.
Donat *et al.*, (2016)	Precipitation (increase in intensity and total)	Agriculture and Natural resources	Increase in the risk of floods
Hatfield *et al.*, 2008	Precipitation (increase in total, and temporal lag)	Agriculture	Excessive precipitation out of the usual date obligates to delay sowing and other activities. Flooded fields produce economic losses related to anoxia. Increase on compaction, runoff and nutrient leaching. During the harvest it generates conditions for losses by rot and deterioration of quality
Coakley *et al.*, 1999	Precipitation (increase in intensity and total)	Agriculture	Increase in incidence on root pathogens
Hatfield and Prueger, 2004	Precipitation (increase in total and intensity)	Agriculture and natural resources	Risk of soil moisture deficiencies in other seasons due to migration of precipitation to other months
Hatfield *et al.*, 2008	Precipitation (increase in intensity) and wind (increase in speed)	Agriculture	Storms accompanied of strong winds cause crops lodging
Young, 1991	Precipitation (decrease)	Natural resources	Greater incidence of fires

Table 4.7. Continued.

Author	Variable	Sector	Impact
Neilson 1986	Precipitation (seasonal changes and increase in total)	Natural resources	Increase on precipitation favors the invasion of woody shrubs over herbaceous vegetation
Samson and Knopf, 1994; Briggs *et al.*, 2005	Wintry precipitation (increase)	Natural resources	Invasion of woody shrubs on grassland
Polley *et al.*, 2000	Precipitation (decrease) and CO_2 (increase)	Livestock	C3 pastures, herbs and some legumes could improve the use of water and available soil moisture
Hanzon and Weltzin, 2000	Precipitation (decrease)	Natural resources	Occurrence of droughts and decrease of forest productivity
Dunning *et al.*, 2018	Precipitation (increase or decrease of total, and seasonal change)	Agriculture and natural resources	Change on rainy season length
Luce and Holden, 2009	Precipitation (increase on intensity)	Natural resources	Increase on runoff and decrease on baseflow of rivers
Kaushal *et al.*, 2010	Precipitation (increase on intensity)	Agriculture and natural resources	Decrease on rivers water quality, increase of sediments, nitrogen, etc.

Table 5.1. More important crops of Aguascalientes and their main characteristics.

Crop	Type	Season	Area (ha)	Sowing/transplant	Harvest*	Yield**
Corn (forage)	Annual	S-S	14600	April/15-June/5	120-150	28-33
Corn (grain)	Annual	S-S	6416	April/15-May/20	170-184	7
Poblano pepper	Annual	S-S	922	April/1-20	90-110	35
Garlic	Annual	W-S	159	October/1-20	210	12.7
Beans	Annual	S-S	944	April/15-30	85	3-3.5
Oat	Annual	F-W	3423	September/15-October/30	75	3.120
Alfalfa	Perennial	J-D	5600	October/15-December/15. February	144, 174, 206, 236, 271 and 312	13
Guava	Perennial	J-D	6594	June/1-July/30	December	16
Grapevine	Perennial	J-D	639	February/1-April/30	August	8.35
Peaches	Perennial	J-D	495	January/15-March/15	June/15-September/15	9.8
Corn (forage)	Annual	S-S	42400	June/15-July/15	70-85	3.2
Corn (grain)	Annual	S-S	33500	June/15-July/15	102	0.7-1.3
Beans	Annual	S-S	9028	June/15-July/25	85-100	0.310
Sorghum (forage)	Annual	S-S	1131	June/15-July/15	97	4-6
Oat	Annual	S-S	2234	July/15-August/15	75	7
Nopal tunero	Perennial	J-D	1550	February/1-April/30	October	3.8

*These can be days after sowing/plating, month or period.
**Tons per hectare.
S-S: Spring-Summer, W-S: Winter-Spring, F-W: Fall-Winter, J-D: January-December.
This table was constructed with information from: Godoy *et al.*, 2003; Rosales *et al.*, 2004; Ramirez *et al.*, 2013; SIAP, 2019.

Table 5.2. Most important dams in Aguascalientes state and their main characteristics.

Dam	Municipality	Storage capacity (hm^3)	Current storage (hm^3)	Use	Area (ha)
Abelardo Rodríguez	Jesus Maria	16.04	6.59	Irrigation	700
San Jose de Gracia	San Jose de Gracia	4.10	4.13	Irrigation	380
El Niagara	Aguascalientes	16.19	16.50	Irrigation	1,750
Jocoque	San Jose de Gracia	10.98	10.48	Irrigation	11,874
La Codorniz	Calvillo	5.37	3.96	Irrigation	672
Media Luna	Calvillo	15.00	10.21	Irrigation	2,100
Plutarco E. Calles	San Jose de Gracia	358.12	171.12	Irrigation and urban	4,000

This table was constructed with information from: IMTA, 2005; INEGI, 2017; INAGUA, 2019; SINA, 2019.

Table 5.3. The physical meaning of positive or negative trend of extreme indices.

Index	Positive trend	Negative trend
Extreme temperature indices		
TXMean	Greater absorption of solar radiation in the terrestrial surface, and less cloud cover on the day. Increase of average maximum temperature on the warm season.	Less absorption of solar radiation in the terrestrial surface, and bigger cloud cover on the day. Decrease in average maximum temperature on the warm season.
TNMean	Increase on cloud cover on nights. Increase of average minimum temperature on the cold season.	Less incidence of solar radiation on the day and less cover of nightly cloud. A decrease in average minimum temperature on the cold season.
DTR	More extreme climate and weather, greater evaporative capacity of the environment. More dryness on the environment.	A decrease in the evaporative capacity of the atmosphere. Declining on the extent of dryness on the environment. Climate and weather are less extreme.
FD0	Increase the number of days with frosts. Decrease of mean minimum temperature on fall, winter, and early spring, and reduction of free frost period.	Decrease in the number of days with frosts; increase on the average minimum temperature in fall, winter, and early spring; and increase in the free period of frosts.
SU25	Increase on the number of days with a maximum temperature higher than 25 ˚C, mainly in late summer; fall and early spring.	Decrease in the number of days with a maximum temperature higher than 25 ˚C, mainly in late winter, early spring, summer, and early fall.
TNx	Increase of temperature in summer nights. Summer nights are warmer.	Decrease of temperatures in summer nights. Summer nights are less warm.
TXx	Increase of daytime temperature in summer days. Summer days are warmer.	A decrease in daytime temperature in summer days. Summer days are less warm.
TNn	Increase of night temperature in winter. Winter nights are less cold.	Decrease of night temperature in winter. Winter nights are colder.

Table 5.3. Continued.

Index	Positive trend	Negative trend
TXn	Increase of daytime temperature in winter. Winter days are less cold.	A decrease in daytime temperature in winter. Winter days are colder.
TX10p	Increase in the number of days less hot or with less extreme heat (cold days) in summer.	Decrease in the number of days less hot or with less extreme heat (cold days) in summer.
TX90p	Increase in the number of warm or hot days or days with extreme heat in summer.	A decrease in the number of warm or hot days or days with extreme heat in summer.
TN10p	Increase on the number of nights with more intense cold or extreme in winter.	A decrease in the number of nights with more intense cold or extreme in winter.
TN90p	Increase in the number of warm nights in summer.	A decrease in the number of warm nights in summer.
WSDI	Increase in the number of periods with at least six warm consecutive days or with more extreme heats during summer.	Increase in the number of periods with at least six warm days or with more extreme heats during summer.
CSDI	Increase in the number of periods of at least six consecutive nights with more intense cold or extreme in winter.	A decrease in the number of periods of at least six consecutive nights with more intense cold or extreme in winter.
Extreme precipitation indices		
RX1day	Higher content of atmospheric moisture, increase on surface runoff, increase on the frequency of massive floods, and greater availability of environmental moisture.	=

Table 5.3. Continued.

Index	Positive trend	Negative trend
RX5day	Higher content of atmospheric moisture, increase in surface runoff, flash floods, and higher availability of environmental moisture.	=
SDII	Increase in the annual precipitation, decrease in the number of days with precipitation.	Increase in the number of days with precipitation, a decrease in the annual precipitation.
R10	Higher moisture content on the atmosphere available for condensation, increase in the frequency of massive floods, greater availability of environmental moisture, higher potential runoff, greater erosion risk, and increase in annual precipitation.	=
R20	Higher moisture content on the atmosphere available for condensation, increase in surface runoff, an increase of floods, higher availability of environmental moisture, and greater risk of erosion.	=
CDD	Decrease on the number of days with available precipitation, increase in the dust emissions of deserts, increase in the dryness of soils, an increase of desertification, higher duration of the dry season, late onset of the rainy season, and less duration of the rainy season.	=

Table 5.3. Continued.

Index	Positive trend	Negative trend
R95p	Increase of extreme and heavy precipitation, an increase of surface runoff, floods occurrence, greater availability of soil moisture.	=
PRCPTOT	Greater number of days with precipitation, higher atmospheric vapor available for condensation, an increase of extreme and heavy precipitation, and a higher volume of water available for runoff.	=

=These indices did not show any negative trend.

Table 5.4. Impact of the extreme indices trends on crops.

Index	Crop
Extreme temperature indices	
	Corn
FD0	Positive trends of early (fall) and late (spring) frosts reduce the growing period of corn more frequently. They destroy the crop by tissue freezing.
SU25	Positive trends of this index produce that the upper threshold of temperature for growing is exceeded, particularly during blooming-maturity; the growing is stopped, and the photosynthetic efficiency is reduced (Ruiz *et al.,* 2002).
TNx	Positive trends in this index provoke more occurrence of warm nights. This favors corn accelerates its growing rate (Duncan, 1975). Negative trends cause nights relatively colder and delay the growing and development of this crop (Duncan, 1975); photosynthesis, growing, leave extension, and water and minerals uptaking are reduced (Miedema, 1982).
TXx	The positive trend indicates that a higher degree of heat is available, which helps to accumulate growing degree days and mature faster (FAO, 2000; Ojeda *et al.,* 2011).
TX10p	Negative trends enhance the conditions for the growing and development of crops; photosynthesis is enhanced considerably (Duncan, 1975).
TX90p	Positive trends can difficult growing and development due to low photosynthesis efficiency (Duncan, 1975). If 35 ˚C periods with eight days duration during the reproductive stage occur, the yield is reduced until 74% (Rincon *et al.,* 2006); due to the miss of fecundation and grain development, resulted from desiccation of stigmas and pollen grains.
TN90p	Positive trends difficult the growing and development more frequently, also pollen formation and pollination can be affected (Warrington and Kanemasu, 1983). Negative trends create better conditions for this crop.
WSDI	A positive trend increases the number of days or periods with difficulty for growing and development due to decreasing photosynthesis efficiency (Duncan, 1975).
CSDI	A positive trend reduces the growing period of this crop due to the increase of early (fall) and late (spring) frosts.

Table 5.4. Continued.

Index	Crop
	Poblano pepper
FD0	The positive trend of this index, produces with greater frequency, a low percentage of germination; by freezing, it destroys tissues of young crops recently transplanted (Ibar and Juscafresa, 1987).
SU25	Positive trend promotes that maximum daily temperature tends to exceed the optimum range for photosynthesis, which decreases the photosynthetic efficiency (Benacchio, 1982); also, the optimum temperature for fruit development is exceeded (Yuste, 1997).
TNx	The positive trend tends to promote that nighty optimum temperature be exceeded (Yuste, 1997), which decreases efficiency on the fruit clamping (Rylski and Spiegelman, 1982). A negative trend offers better night conditions for the development of tissues and reproductive organs.
TXx	The positive trend tends to cause that the upper threshold of optimum temperature for growing and photosynthesis be exceeded, so that, the efficiency of these processes decreases (Benacchio, 1982). It also decreases the efficiency of the clamping and development of fruit (Baradas, 1994; Yuste, 1997). Above 35 ˚C, the fertility and pollen viability are affected which provokes high percentages of floral abortion and a significant negative effect on the fruits growing (Prasad *et al.,* 2000; Porch and Jahn, 2001; Suzuki *et al.,* 2001; Prasad *et al.,* 2002; Vallejo and Estrada, 2004).
TX10p	The negative trend in this index indicates that more warm days exist, so that floral abortion can occur more frequently. If the crop is in the first growing stages, a decrease in this index can cause the upper optimum temperature threshold for growing to be exceeded more frequently (Sims and Smith, 1976).
TX90p	The positive trend indicates that photosynthetic efficiency declines more frequently (Benacchio, 1982). It is produced more floral abortions, and inhibition of fruit formation (Sims and Smith, 1976; De Vilmorin, 1977; Yuste, 1997).
TN90p	Positive trends increase the poor development of flowers and fruits (Rylski, 1985; Baradas, 1994); above 20 ˚C the pollen viability and fertility are affected, which provokes high percentages of floral abortion and low efficiency in the fruit development. Negative trends promote better conditions for this crop.

Table 5.4. Continued.

Index	Crop
WSDI	A positive trend promotes the increase of periods with a reduction of photosynthetic efficiency (Benacchio, 1982), a higher frequency of floral abortion, and poor fruit development (De Vilmorin, 1977; Yuste, 1997).
CSDI	A positive trend increases the probability of late frosts occurrence, which causes damages in this crop by freezing and a low percentage of germination.
	Garlic
FD0	In late sowing dates, positive trends cause low percentages of germination (Santibáñez, 1994).
TNn	The negative trend indicates a higher risk of damages by frosts in the germination stage (Benacchio, 1982), while positive trend offers more comfortable temperatures for the winter growing (Ruiz *et al.*, 2013).
TXn	The positive trend indicates that temperature during cold months is getting closer to the optimum interval for the growing and developing of this crop. The negative trend indicates that there exist more risks of delaying germination.
TN10p	A positive trend on this index can cause more significant cooling and lead to inhibition of growth; mainly, it causes delays in the germination on late sowing dates. A negative trend promotes better conditions for crop growing and development.
CSDI	A positive trend in this index increases the risk of damages caused by frosts, which delay germination (Ruiz *et al.*, 2013).
	Beans
FD0	A positive trend favors the occurrence of late frosts (Debouck and Hidalgo, 1985).
SU25	A positive trend, to a certain extent, helps photosynthesis; but if the temperature gets closer to 30 ˚C, the growing is stopped, and floral abortion is produced (Duke, 1983).
TNx	High rates of positive trends can inhibit development and flower formation (Benacchio, 1982). Negative trends favor growth and development (Benacchio, 1982).

Table 5.4. Continued.

Index	Crop
TXx	Positive trends favor that the upper threshold of optimum temperature for growing is exceeded. During blooming, these trends provoke flower abortion (Duke, 1983).
TX10p	Negative trends promote the upper threshold of range temperature for growing to be exceeded, and that photosynthesis efficiency decrease (Benacchio, 1982).
TX90p	Positive trends of this index make it difficult growing and development; they promote abortion of flowers (Duke, 1983).
WSDI	Positive trend increases periods with a higher risk of floral abortion (Duke, 1983), and low photosynthesis efficiency (Ortiz, 1982).
	Sorghum
FD0	A positive trend increases the number and risk of frosts and damages by freezing in the early stages of the crop (Anda and Pinter, 1994).
SU25	A positive trend on this index can provoke that optimum growing temperature be exceeded, so that, the growth can be slowed (Baradas, 1994).
TNx	The positive trend could favor the growth in summer (Santacruz and Santacruz, 2007). A negative trend on this index does not mean high risk for this crop since, in this region, varieties adapted to temperate climates are cultivated (Santacruz and Santacruz, 2007).
TXx	Some genotypes stop their growing when 30 ˚C is exceeded, so a positive trend on this index can reduce the growth and yields (Acuña *et al.*, 2002).
TX90p	A positive trend on this index can reduce the growing efficiency (Baradas, 1994; Acuña *et al.*, 2002) since some genotypes have as the limit of adaptation 30 ˚C (Acuña *et al.*, 2002).
WSDI	A positive trend in this index indicates more periods with low growing efficiency (Baradas, 1994; Acuña *et al.*, 2002).
CSDI	A positive trend in this index can provoke more periods with frosts damages (Anda and Pinter, 1994).
	Oat
FD0	Positive trends favor the occurrence of damages by frosts; they stop the growing and development (FAO, 1994).

Table 5.4. Continued.

Index	Crop
SU25	Positive trends inhibit flower formation; plants tend to form panicles poorly developed (Shands and Cisar, 1985).
TNx	Positive trends on this index induce more yields reduction due to the maturity acceleration (Shands and Cisar, 1985). Negative trends indicate that colder conditions exist during the growing season, which is better for optimum growing (Shands and Cisar, 1985).
TXx	Positive trends indicate that through time, oat can be reducing its growing cycle, mainly an anticipated panicle formation, which reduces yield (Shands and Cisar, 1985).
TX10p	The negative trend indicates that day are less cold, which accelerates crop maturity and produce less dry matter (Ruiz *et al.,* 2013).
TX90p	Positive trends promote plants to form small panicles (Shands and Cisar, 1985).
WSDI	The positive trend of warm periods reduces yield due to maturity acceleration (Ruiz *et al.,* 2013).
	Alfalfa
FD0	Positive trends in this index indicate more reduction in growth due to frosts (Quiroga, 2013).
SU25	Positive trends indicate that growing and development get slower (Sharrat *et al.,* 1986, 1987), which is due to the reduction in carbohydrates translocation (Al-Hamdani and Todd, 1990).
TNx	The positive trend indicates that in specific summer periods, growing is reduced since temperature gets closer to the upper night limit (Sharrat *et al.,* 1986, 1987). A decrease in this index indicates better nightly conditions for growth (Quiroga, 2013).
TXx	A positive trend reduces growing because the temperature gets closer to the upper threshold of the growing range (Quiroga, 2013).
TNn	The positive trend keeps the crop active and growing in winter (Quiroga, 2013), while the negative trend obligates the crop to keep on dormant (Quiroga, 2013).
TXn	The positive trend indicates crop growing during the colder season of the year (Quiroga, 2013), while a negative trend indicates more days of dormant (Quiroga, 2013).

Table 5.4. Continued.

Index	Crop
TX10p	The negative trend of this index indicates that days with reductions in crop growth can increase (Quiroga, 2013).
TX90p	The positive trend indicates that daytime temperature gets closer to the upper threshold for growing; also, the growth rate is lower (Sharrat *et al.*, 1986, 1987).
TN10p	A positive trend in this index increases the frequency of growing inhibition during winter (Quiroga, 2013). The negative trend on this index promotes less restrictive conditions; that is, there are more nights with better conditions for winter growing (Quiroga, 2013).
TN90p	Positive trends can increase the number of nights with temperatures within the range for growing (Quiroga, 2013). Negative trends can increase the number of nights with temperatures that decrease or inhibit the growth of the crop (Quiroga, 2013).
WSDI	The positive trend indicates a higher occurrence of days or periods with less rate of growth due to temperature gets closer to the upper threshold of growing range (Sharrat *et al.*, 1986, 1987).
CSDI	A positive trend on this index indicates more days or periods with inhibition of growing during winter (Quiroga, 2013).
	Guava
FD0	A positive trend in this index increases the frequency of damage in young and adult trees (Ruehle, 1959). Frost also damage plant and fruit tissues (Orduz and Rangel, 2002).
SU25	A positive trend in this index indicates better conditions for crop growing and development (Benacchio, 1982).
TNx	The positive trend indicates a higher number of nights with temperatures within the optimum range for growing and development (Benacchio, 1982). While negative trends indicate that temperatures decrease below the optimum range, causing slow-growing and development (Ruiz *et al.*, 1992).
TXx	A positive trend of this index indicates more days with maximum temperature within the optimum ones for this crop growing.

Table 5.4. Continued.

Index	Crop
TNn	A positive trend of this index indicates less damage to fruits during the season previous to harvest (Orduz and Rangel, 2002). The negative trend indicates more favorable conditions for plants and fruits in winter (Orduz and Rangel, 2002).
TXn	A positive trend of this index indicates less damage to fruits during the previous season to harvest (Orduz and Rangel, 2002). The negative trend of this index indicates more adverse conditions for plants and fruits in winter (Orduz and Rangel, 2002).
TX10p	The negative trend of this index indicates that cold is decreasing, so that, temperatures get closer to optimum ones required by the crop (Benacchio, 1982).
TX90p	A positive trend in this index provokes that temperatures keep in the optimum range for growing and development (Benacchio, 1982).
TN10p	Positive trends decrease the crop growing, can destroy the plants by frosts. In winter, the frequency of damage in plants and fruits increases. The negative trend indicates better conditions for plants and fruits in winter (Ruiz *et al.*, 1992).
TN90p	The positive trend in this index promotes better conditions for the comfort of plants, while negative trends promote adverse conditions (Ruiz *et al.*, 1992).
WSDI	The positive trend indicates better conditions for this crop growing, mainly in summer. With this trend, temperatures closer to optimum ones are expected.
CSDI	The positive trend indicates more periods with damaging temperatures for plants and fruit during winter (Ruiz *et al.*, 1992).
	Grapevine
FD0	Positive trends in this index lengthen the dormant period of this crop (Benacchio, 1982).
SU25	A positive trend in this crop promotes poor blooming and clamping of fruits (Benacchio, 1982, Santibañez *et al.*, 1994). If the trend is relatively high, this can cause difficulty in the anthocyanin synthesis, which influences the juice and wine quality.
TNx	A positive trend increases the risk of damages on blooming (Dalmasso and Eynard, 1979). If the trend is too high, blooming efficiency and quality on veraison and maturation can be reduced (Dalmasso and Eynard, 1979).

Table 5.4. Continued.

Index	Crop
TXx	The positive trend in this index promotes inefficient blooming and deficiencies on the fruit clamping (Benacchio, 1982, Santibañez *et al.*, 1994). Also, it can cause difficulties in anthocyanin synthesis, which influences juice and wine quality.
TNn	The positive trend indicates decreases in cold available in winter, which generates early bud break and losses of buds by frosts (Ruiz *et al.*, 2013). The negative trend indicates greater cold availability, which helps to induce /promote a better and timely bud break (Dalmasso and Eynard, 1979).
TXn	A positive trend of this index indicates less cold accumulation. It can promote early bud break of buds and its lost by late frosts. The negative trend indicates a higher accumulation of cold and can promote a better and timely bud break.
TX10p	Negative trend promotes the occurrence of warmer days that increase the damage on blooming, veraison, maturity, and harvest (Dalmasso and Eynard, 1979).
TX90p	A positive trend in this index can cause damages or a reduction in the blooming, veraison, maturation, and harvest efficiency (Benacchio, 1982; Dalmasso and Eynard, 1979). Also, it can cause difficulty in the anthocyanin synthesis, which influences on juice and wine quality.
TN10p	The positive trend indicates a greater occurrence of chill hours. If these temperatures are stable, a good and timely bud break occurs. Negative trend provokes fewer chilling hours, early bursting, and loss of shoots by frosts.
TN90p	A positive trend increases the risk of damages on blooming (Dalmasso and Eynard, 1979). A negative trend promotes better night temperatures for the crop growing.
WSDI	The positive trend in this index indicates an enhancing of those temperatures that reduce photosynthesis, blooming, and maturity efficiency (Benacchio, 1982). Also, they can cause difficulty in the anthocyanin synthesis, which influences on the juice and wine quality.
CSDI	The increase of this index favors the chilling hours accumulation in winter.
	Peaches
FD0	A positive trend in this index promotes a higher accumulation of chilling hours (Ruiz *et al.*, 2013). Although its intermittence promotes that plants to bloom and bud break early, which decreases the yield.

Table 5.4. Continued.

Index	Crop
TNn	A positive trend of this index indicates less cold accumulation and can produce early blooming and bud break (Santibañez, 1994). Negative trend promotes higher cold accumulation, however, if cold events are intermittent, and then minimum temperature increases again within the cold period, early blooming and bud break can be promoted, which wears down plants reservations and led to yield reduction.
TXn	A positive trend of this index indicates less cold accumulation, and it can produce early blooming and bud break (Santibañez, 1994). A negative trend promotes better cold accumulation.
TN10p	The positive trend in this index helps to accumulate colder; however, if the minimum temperature is not stable, and increases again within the cold period, it can cause early blooming and bud break, exposing flowers and buds to damages by frosts. Negative trends promote fewer chilling hours accumulation.
CSDI	A positive trend in this index indicates more periods with extreme cold in nights that help to get a higher accumulation of chilling hours, but if these cold periods are not stable, also promote early blooming and bud break, which reduces yields (Ruiz *et al.*, 2013).
Precipitation extreme indices	
	Corn
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. However, in soils without a slope or proper leveling, they can cause problems related to moisture saturation, which reduces ATP formation; this, in turn, reduces the metabolic process efficiency (Drew, 1997). Also, flooding increases the risk of lodging when high genotypes are cultivated. The volume of water applied by irrigation can decrease.
SDII	The positive trend in poor soils increases the risk of erosion. Also, it increases the risk of lodging.
CDD	The positive trend can reduce available soil moisture. It can contribute with more significant droughts occurrence, which reduces meristematic activity, root lengthening, and increases root suberization, causing a detrimental effect in water and nutrients uptakes (De Santa Olalla and De Juan Valero, 1993). Increases water volumes applied by irrigation.

Table 5.4. Continued.

Index	Crop
	Poblano pepper
RX1day, RX5day, R10, R20, R95 and PRCPTOT	The positive trend in this index indicates better soil moisture conditions for the crop. In soils with few slopes or with no leveling, it can cause waterlogging problems, so that, plants close stomata, inhibits photosynthesis, water and, minerals uptake decreases, occur changes on hormonal equilibrium (Bradford and Yang, 1981; Bradford and Hsiao, 1982; Kozlowski, 1984). Water volumes supplied through irrigation can decrease.
SDII	The positive trend can cause flower abortion.
CDD	The positive trend can cause a decrease in the chlorophyll content, provoke photosynthesis inactivation, and decrease the stomatal conductance (Li *et al.*, 2017; Okunlola *et al.*, 2017). Increase in the water volumes applied in irrigation.
	Garlic
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend on these indices enhances the available moisture for the crop. However, on late genotypes, high water availability can cause secondary growing (germination, pseudobulbs) (Burba, 2003). Irrigation requirements decrease as a consequence of an increase in effective precipitation increase.
CDD	A positive trend increases water requirements that should be supplied on irrigation.
	Beans
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. However, waterlogging on blooming affects plant development, yield, number of plants, and weight of grains (Thuang and Cunha, 1992). According to Burin *et al.* (1991), heavy precipitations after blooming cause a high percentage of floral abortion. When roots are in a saturated environment of water, the oxygen absence is a conditioning factor, and roots suffer notably (Write, 1985). Also, water volumes supplied through irrigation decrease.
SDII	The positive trend can cause flower abortion.
CDD	A positive trend promotes less soil moisture and can promote droughts. Soil moisture deficit can cause loss of starch reservations (Zinselmeier *et al.*, 1999) and no structural sugars that support the growing and development due to a decrease in the activity of galactinol synthase enzyme (Pattanagul and Madore, 1999). Increase in irrigation requirements.

Table 5.4. Continued.

Index	Crop
	Sorghum
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. However, moisture excess does not permit the proline accumulation, and the hydrocyanic acid decreases (Franzke, 1945).
CDD	A positive trend in this index can cause droughts. It is vulnerable to droughts on the panicle formation stage, which reduces the number of grains (Manjarrez, 1986) and grain growing (Fisher and Turner, 1978). Irrigation requirements increase.
	Oat
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend on these indices improves soil moisture conditions for the crop. Although it tolerates water excess well, in humid years, when precipitation exceeds 400 mm, the yield can be reduced significantly (Teran *et al.* 2012). Also, lodging of the crop can occur. Water volumes supplied though irrigation decrease.
SDII	A positive trend on this index can cause lodging of the crop.
CDD	A positive trend on this index can provoke droughts. On grain filling, water deficit accelerates leaf senescence and reduces conversion efficiency of intercepted radiation decreasing grain weight (Abbate *et al.*, 1994). Irrigation requirements increase.
	Alfalfa
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. Irrigation decreases. Soil waterlogging stop the root elongation and cause deterioration on the root system, plant transpiration declines due to soil saturation and inactivation of the plant by the lower concentration of oxygen in roots (Fick *et al.,* 1988).
CDD	The positive trend of this index can cause drought. Moisture deficit reduces dry matter formation from aerial organs until 43%, and around 23% in underground organs (Erice *et al.,* 2006). In long periods with dry days, a specific area of leaves is modified (Erice *et al.,* 2010), causing less leaf area exposed to solar radiation (Álvarez *et al.*, 2009). The increase in the number of dry days increases irrigation requirements.

Table 5.4. Continued.

Index	Crop
	Guava
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. Water volumes required through irrigation decreases.
SDII	Positive trends can produce flower abortion.
CDD	A positive trend in this index can cause drought conditions. In this crop, drought induces abundant blooming (Rathore, 1976; Chadha and Pandey, 1986). Irrigation requirements increase.
	Grapevine
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. However, oxygen deficit inhibits or decreases photosynthesis, transport of carbon; it causes stomata closure and slow-growing of roots (Kozlowski, 1997). Irrigation requirements decrease.
SDII	Positive trends can cause soil erosion in the grapevine furrows.
CDD	Positive trends in this index can cause droughts. Drought, on this crop, improves the chemical composition of grapes (Jackson and Lombard, 1993; Reynolds and Naylor, 1994), and wine quality (Dry *et al.*, 2001). Water volumes supplied through irrigation increase.
	Peaches
RX1day, RX5day, R10, R20, R95 and PRCPTOT	A positive trend in these indices improves soil moisture conditions. However, soil moisture excess restricts crop productivity significantly due to factors as diseases, weed, insects, or high salinity (Irrifrut, 2007). Irrigation requirements decrease.
CDD	A positive trend in this index can cause drought conditions. Due to drought, this crop modifies the leaf area in which transpiration occurs (Valladares, 2004). Irrigation requirements increase.