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Original Research

Hydroclimatic Trends in Areas with High Agricultural Productivity in Northern Mexico

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Abstract

Global climate change affects not only temperature but also the hydrologic cycle and therefore the aridity index, with variations at the local level. A non-parametric analysis was carried out on time series data collected from temperature and precipitation records (1970 to 2011) from 38 CONAGUA (National Water Commission) weather stations located in the Mexican states of Sinaloa, Baja California Sur, Durango, Sonora, and Chihuahua. The magnitude of change trends of average, maximum, and minimum temperature and precipitation, potential evapotranspiration, and the aridity index were calculated. The data were aggregated, and the Mann-Kendall statistic calculated using the MOCLIC 1.0 program, to determine whether there was continuity in the data from each station and to define the magnitude of the statistically significant trend under the threshold α=0.05. The magnitude of the change trend was determined for significant trends using Sen's method of slopes. Potential evapotranspiration and the aridity index were calculated by the Hargreaves and UNEP methods. The results show that the climate variables displayed positive and negative trends; mainly temperature, with a range of -0.13 to 0.16ºC·yr^{-1}, which is above world averages. The values obtained for RMSE, bias, the Pearson correlation coefficient (r) and the coefficient of determination (R^2) do not show significant differences between the control values and the calculated values. It was concluded that aggregating significant trends can provide information on the direction of local climate change in this environment in northern Mexico, and its important consequences and repercussions, as well as impacts on social and environmental systems.

Keywords: aridity index, significant, non-parametric analysis

Introduction

Significant trends (ST) in factors that define climate change indicate modifications in average air temperature ($\overline{T}_{avg}$), which in turn are related to global warming and may trigger a change in global climate patterns. Projections made by the Intergovernmental Panel on Climate Change (IPCC) estimate that by 2100, $\overline{T}_{avg}$ could increase by 1.8 to 4ºC, which may affect the variability of the global climate and, in turn, the ST of maximum temperature ($\overline{T}_{max}$), $\overline{T}_{avg}$, and minimum temperature ($\overline{T}_{min}$) [1]. These shifts could cause further changes, which are usually reflected in aver-

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age annual rainfall ($\overline{P}$), altering the hydrologic cycle and thereby changing local climates. Related to this, in the last three decades of the previous century, an increase in $\overline{T}_{avg}$ of about 0.15ºC decade^{-1} has been documented [2]. To analyze environmental temperature changes more thoroughly, an *ST* can be divided into a positive trend (*PT*) and a negative trend (*NT*); where a *PT* means an increase in the parameter of interest and *NT* a decrease [3]. For example, a *PT* in $\overline{T}_{max}$, $\overline{T}_{avg}$, and $\overline{T}_{min}$ indicate warming in some particular region; an *NT* of the same three parameters indicates cooling (*T*). According to [4], *PT* in the frequency of extreme events associated with $\overline{P}$ have been detected in various regions of the World. These variables are indicators of the absence or presence of different types of rainfall, heat waves and droughts, which can cause flooding, soil erosion, tornadoes, major hurricanes, and other extreme weather events that have been causing both natural and human disasters in various parts of the World, especially in coastal areas [5].

According to [6], the effects of climate change are more pronounced in developing countries such as Mexico, where atypical and extraordinary climate events have been occurring in recent years, such as freezes, drought, increased river flooding, extreme siltation, severe hurricanes, landslides, and more – climate events that trigger starvation, poverty, and unemployment. These phenomena have been reported by the agricultural industry in the states of Sinaloa (SIN), Baja California Sur (BCS), Durango (DGO), Chihuahua (CHI), and Sonora (SON) in northwest Mexico. In spite of the availability of global and regional climate models, which may provide important input for decision makers working to counteract the effects of climate change, this information is not very representative of climate change effects on a local scale that could be used for timely decision-making. Motivated by the importance of the issue, the aim of this study was to determine the current state of the local climate, primarily by identifying climate change indicators and then conducting a statistical analysis to quantify *ST* of climate change. A time series of data from 38 CONAGUA weather stations in the five states of the region under study was used. In order to detect *ST* in average monthly *T* data and cumulative monthly $\overline{P}$ for the study period, average annual T_{max}, T_{avg}, T_{min}, and precipitation (*P*) were calculated for each station, in addition to average potential evapotranspiration (*PET*) and aridity index (*AI*). *PET* was calculated by the method of [7] and *AI* by the method of the United Nations Environment Program [8].

All variables were evaluated with a 95% confidence level, following the nonparametric methodology of Mann-Kendall to find in which zones significant changes or *ST* in the climate variables occurred and to generate hypotheses about threats to agricultural production associated with climate change in the study area. Thus, by estimating the magnitude of changes in the climate variables studied, a spatial map of changes in recent decades could be constructed. It should be noted that there are various methods for spatial interpolation of climate variables. These methods construct continuous equipotential climate surfaces based on recorded data [9]. In this study, the inverse distance weighting (IDW) interpolation method was used. The justification for choice of the study region is that the state of SIN is where the Guasave Valley is located. This is the most important agricultural region of Mexico, commonly called the "agricultural heart of Mexico" and it must be protected to preserve Mexico's food sovereignty [10, 11]. Moreover, the states of SIN and BCS contain numerous World-renowned tourist areas including Mazatlán, La Paz, Cabo San Lucas, and San Jose del Cabo, among others [12] – sources of foreign revenue and employment. Due to its climate and environmental richness, BCS is the Mexican state with the greatest number of wetlands – an important habitat to conserve. For the state of DGO, it was considered important to apply the methodology for several sound reasons, including the state's 12 wetlands, which are important for Mexico, and the fact that DGO has weather stations at the highest elevations (*E*) of the states analyzed, resulting in different climate zones. Moreover, it has numerous agricultural, forestry, and drought problems. CHI was chosen because of its rich forest resources and because it has the highest (*E*) of all the states analyzed here. SON is included in the study region for its large number of species of flora and fauna and, like SIN, for its agricultural production [13].

Materials and Methods

Thirty-eight CONAGUA (National Water Commission) weather stations in northern Mexico were analyzed for the period 1970-2011. Thirteen are located in SIN (population 2,767,761), 16 in BCS (population 637,026), six in DGO (population 1,632,934), two in CHI (population 3,406,465), and one in SON (population 2,662,480) [14]. The E ranges (m a.s.l.) of weather stations in each state were: SIN 5 to 2,050, BCS 10 to 502, DGO 15 to 2,300, CHI 780 to 2,435, and SON 50. Except for DGO, the states are all connected to mountain regions (Sierra Madre Occidental) and the Gulf of California [15] (Fig. 1). Most of the time series had continuity problems such as missing data and outliers, so time series tools were used to fill in the data gaps. The methodologies used were Mann-Kendall statistics and Sen's slope estimation method, which are appropriate for data with outliers or highly skewed values, as was the case for $\overline{P}$ and $\overline{T}$, and have also been used to detect, estimate and quantify annual averages of trends in time series of atmospheric variables, and quality of water for human consumption, agricultural irrigation, and concentrations of atmospheric pollutants, among others [16, 17]. To meet the goals of this study, $\overline{P}$ was taken at all weather stations to be a variable that decreases with *E*, from dry zones with values <100 mm to humid zones with magnitudes >1000 (Table 1). According to [18], to analyze data from a thermopluviographic series for possible *ST*, the series must be the result of at least 30 years of monitoring. The CONAGUA data was therefore suitable for detecting the presence of *ST*. Annual time series were constructed for T_{max}, T_{avg}, T_{min}, *PET*, and *AI*; to calculate the averages of $\overline{T}_{max}$, $\overline{T}_{avg}$, $\overline{T}_{min}$, $\overline{PET}$, and $\overline{AI}$ and average annual cumulative $\overline{P}$ ($\overline{P}_a$).

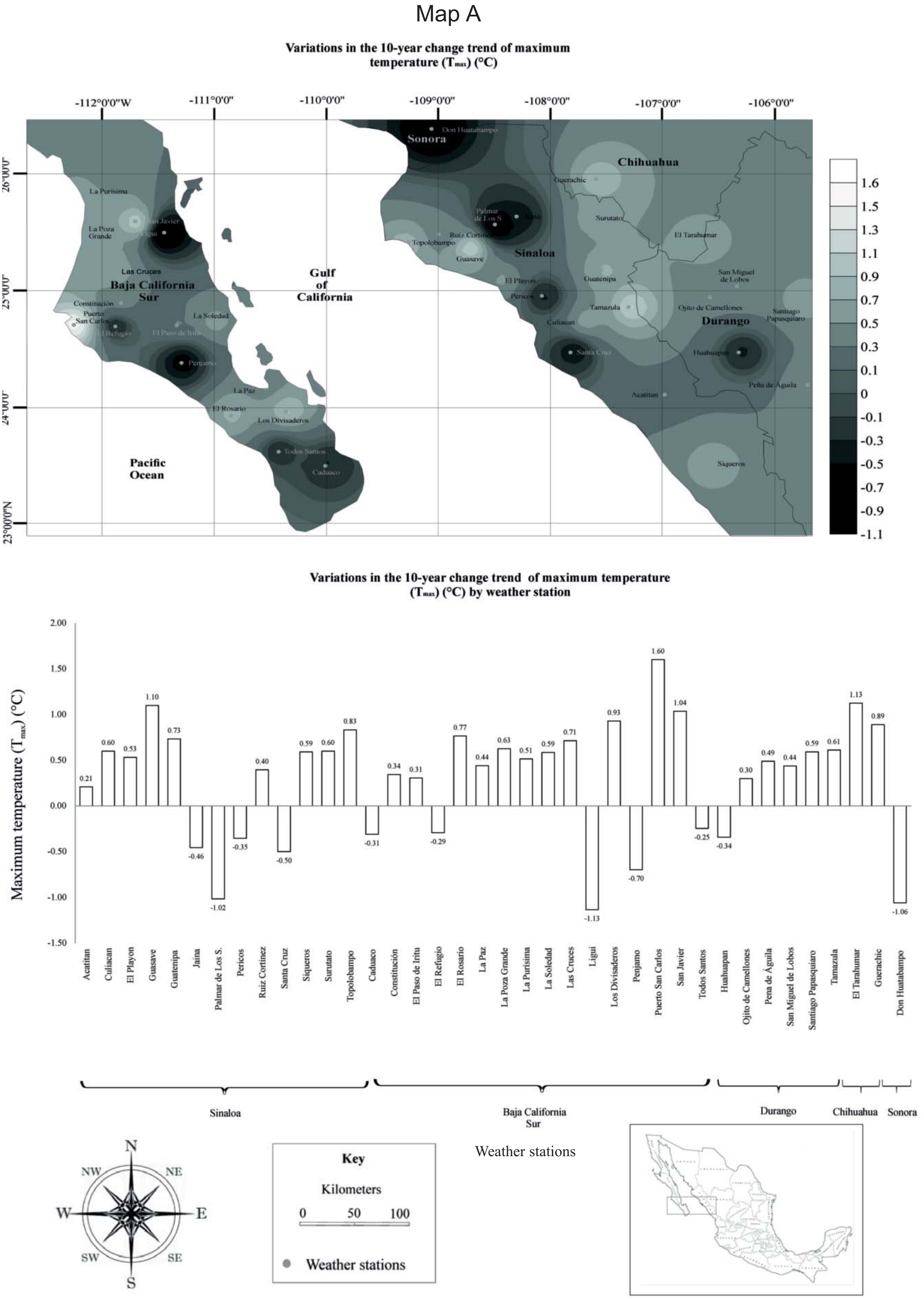

Fig. 1. Magnitude of the change trend in T_{max} (Map A), T_{min} (Map B), and T_{avg} (Map C) in states in northern Mexico with high agricultural productivity.

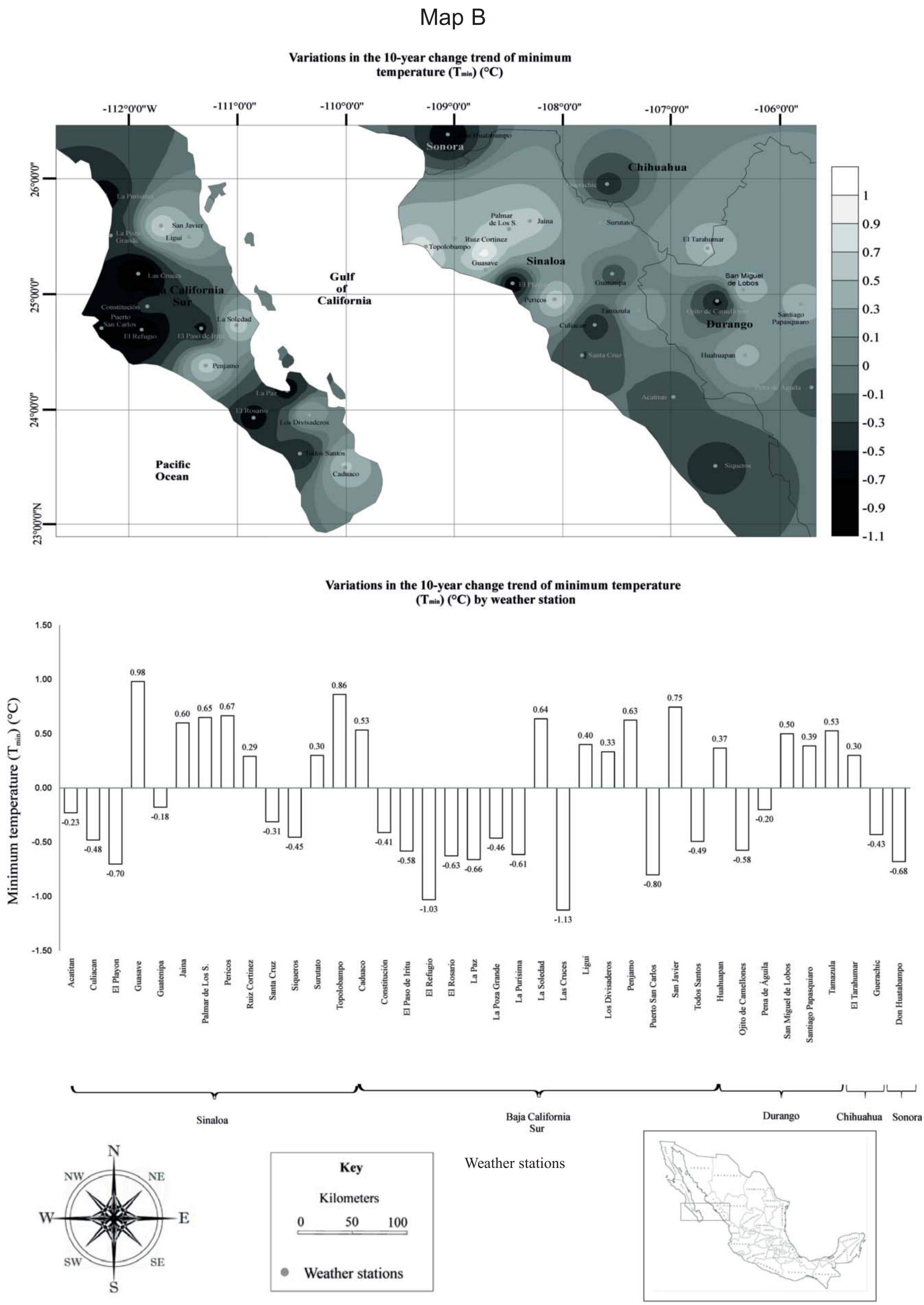

Fig. 1. Continued.

Map C

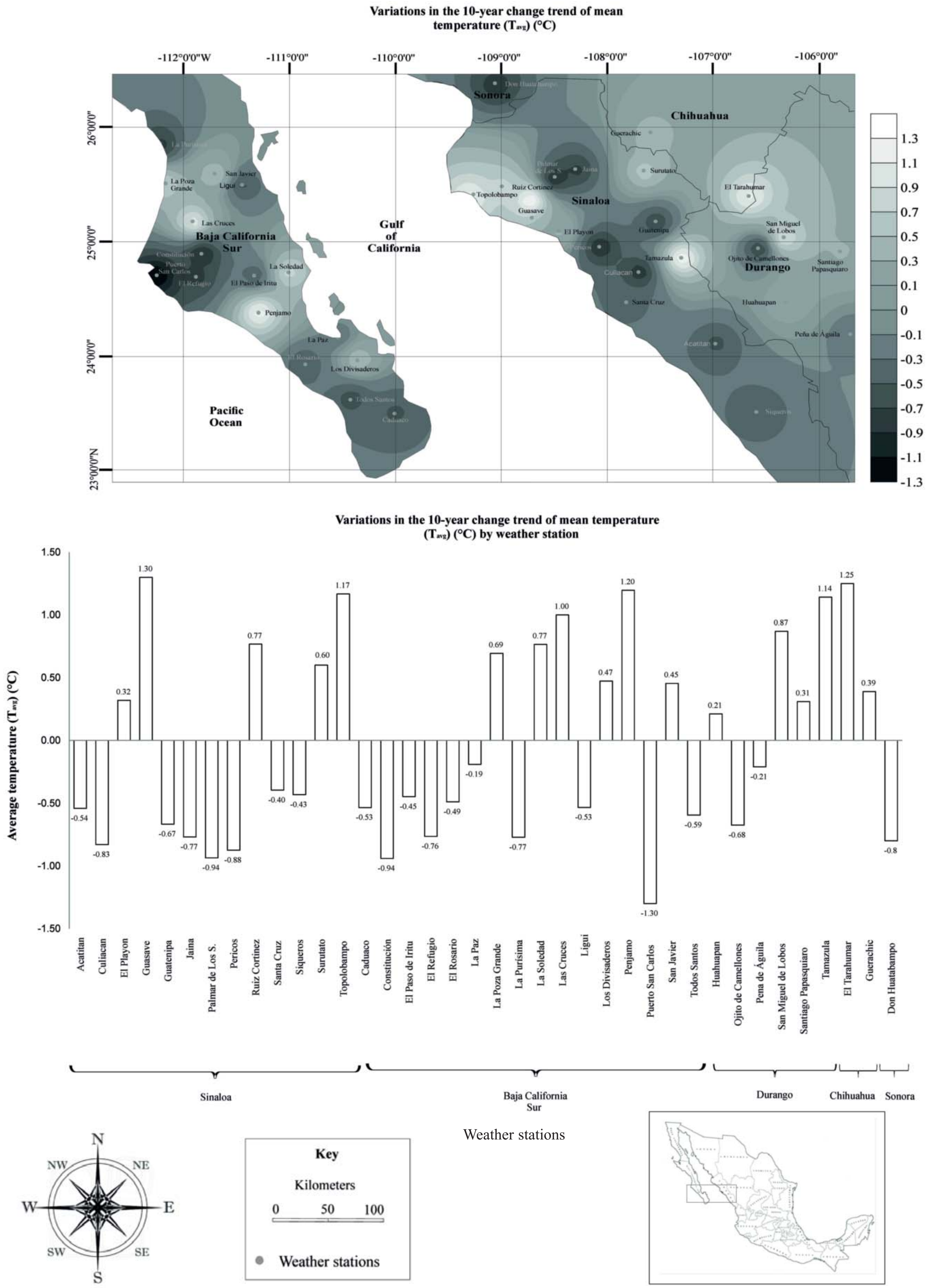

Fig. 1. Continued.

Table 1. Trend indicators using the Mann-Kendall statistic.

Location				Standarized Z (Z_{std}) with α = 0.05. threshold, Z = /1.96/ (Dimensionless)					
State	Weather station	E (masl)	$\overline{P}_a$ (mm·yr^{-1})	$\overline{T}_{max}$	$\overline{T}_{avg}$	$\overline{T}_{min}$	$\overline{P}$	$\overline{PET}$	$\overline{AI}$
Sinaloa	Acatitan	130	806	0.58	**-6.33**	-0.78	0.63	**-5.22**	-0.38
	Culiacan	40	712	**2.82**	-1.75	-0.59	-0.93	0.04	0.21
	El Playon	5	483	**3.87**	1.76	**-4.86**	**-3.61**	**3.83**	**2.59**
	Guasave	40	461	**2.83**	**2.01**	**3.35**	0.97	1.51	-1.2
	Guatenipa	18	1017	**3.01**	**-6.3**	**-4.47**	-0.6	-0.3	0.86
	Jaina	200	884	**-4.15**	**-5.39**	**4.8**	-0.04	**-8.65**	0.92
	Palmar de Los S.	21	609	-1.82	-0.28	**3.49**	-1.38	**-2.97**	**2.66**
	Pericos	11	685	-0.56	**-2.24**	0.49	1.56	**-3.32**	-0.41
	Ruiz Cortinez	15	378	**5.91**	**2.18**	**5.31**	0.33	-1.102	-1.2
	Santa Cruz	2050	763	-0.39	**-6.18**	**-2.58**	0	**-4.94**	0.1
	Siqueros	12	709	1.8	**-3.82**	-1.52	-0.303	-1.63	1.67
	Surutato	1400	1029	**3.25**	**4.92**	**3.34**	0.11	**3.39**	-0.45
	Topolobampo	34	310	0.42	1.24	**4.34**	1.19	-0.96	1.05
Baja California Sur	Caduaco	206	443	-0.2	-1.17	1.4	**3.64**	**-2.37**	-1.22
	Constitución	47	168	**5.28**	**-3.81**	-1.04	-0.31	1.22	0.88
	El Paso de Iritu	135	199	**3.38**	**-2.27**	**-7.42**	1.84	**5.21**	-0.33
	El Refugio	23	91	-0.68	**-3.35**	**-3.27**	**3.75**	1.23	**-4.5**
	El Rosario	45	109	**3.88**	-1.32	-1.13	-0.86	**2.71**	0.42
	La Paz	16	176	**5.63**	**-3.64**	**-2.73**	-0.18	**6.21**	1.47
	La Poza Grande	25	64	**4.06**	**3.73**	**-3.34**	1.33	**6.68**	0.93
	La Purísima	95	115	**2.35**	**-3.89**	**-3.05**	0.64	0.1	0.06
	La Soledad	412	272	**2.06**	0	0.42	1.86	-0.28	-0.62
	Las Cruces	40	125	0.26	0.24	**-2.35**	0.86	**3.75**	0.01
	Ligui	10	218	**-2.5**	**-2.74**	1.87	0.95	**-2.28**	1.11
	Los Divisaderos	502	403	1.74	**2.13**	**4.66**	1.11	-0.15	0.67
	Penjamo	24	137	**-2.49**	1.65	1.25	-0.95	-0.81	1.85
	Puerto San Carlos	10	91	0.65	**-4.84**	-0.37	0.11	-0.78	0.24
	San Javier	440	301	**4.65**	1.18	**3.42**	0.79	**3.58**	**2.69**
	Todos Santos	75	170	-1.65	**-5.37**	**-5.6**	1.02	-1.46	1.02
Durango	Huahuapan	1150	823	-0.05	0.83	1.15	0.29	0.61	**-3.51**
	Ojito de Camellones	15	1530	0.95	**-3.44**	-1.73	1.72	**-2.35**	**-2.3**
	Pena de Águila	1896	534	**2.21**	**-6.06**	**-2.55**	0.57	**-4.15**	0.89
	San Miguel de Lobos	2300	847	**5.02**	**5.32**	**5.14**	-1.84	**5.42**	-0.31
	Santiago Papasquiaro	1716	505	0.68	**3.74**	**1.96**	**4.25**	**2.82**	-0.07
	Tamazula	1580	996	0.06	0.11	0.05	-1.58	0.65	**2.02**
Chihuahua	El Tarahumar	2435	916	0.11	0.31	0.31	0.60	-0.08	0.7
	Guerachic	780	627	**2.33**	-1.24	-1.56	**2.46**	**2.35**	-1.11
Sonora	Don Huatabampo	50	356	-1.94	**-2.36**	-1.3	**-2.07**	0.11	**2.47**

E – elevation, $\overline{P}_a$ – average cumulative annual precipitation, $\overline{T}_{max}$ – maximum temperature, $\overline{T}_{avg}$ – average temperature, $\overline{T}_{min}$ – minimum temperature, $\overline{P}$ – cumulative annual precipitation, $\overline{PET}$ – potential evapotranspiration, $\overline{AI}$ – aridity index
Bold – significant trend indicators

To identify the existence of *ST*, the Mann-Kendall test [19, 20] was performed. If the result of the standardized value of Z (Z_{std}) is > /1.96/, there is 95% confidence of an *ST* in the time series; that is, the null hypothesis is rejected at significance level $\alpha = 0.05$. Thus a positive value of Z_{std} indicates a *PT*, and a negative value indicates an *NT* in the data series [21]. Z_{std} was calculated using the MOCLIC 1.0 program developed at the University of Mexico (UNAM). The inputs were monthly average temperature and rainfall data ($\overline{T}_{max}$, $\overline{T}_{avg}$, $\overline{T}_{min}$, and $\overline{P}$) from the period 1970-2011. The goal of the study was to determine whether there were significant trends in any of these indicators. The magnitude of each trend was estimated using the method of Sen's slopes [3], in which the median is used as the estimated value of the trend after the data (all possible slopes that can be calculated for the series) have been ranked in ascending order [18, 22]. The Hargreaves ratio was used to calculate $\overline{PET}$, which depends on $\overline{T}_{max}$, $\overline{T}_{avg}$, $\overline{T}_{min}$; and *AI* was calculated by the method proposed by [8] – which published the *World Atlas of Desertification* – to quantify the relationship between $\overline{P}_a$ and $\overline{PET}$. To classify *AI*, the UNEP criteria were used: > 0.65 humid, 0.65 to 0.5 dry sub-humid, 0.5 to 0.2 semi-arid, 0.2 to 0.05 arid, and < 0.05 hyper-arid. The inverse distance weighting (*IDW*) method, calculated using the Surfer 10.0 program, was used to interpolate average annual trends. This deterministic interpolation method is one of the most commonly used methods to construct spatial data maps [9]. However, *IDW* has the disadvantage that it tends to generate closed surfaces around the data when the power coefficient (p) is small. Therefore we took into account the criteria of [3] using a greater power coefficient (p) to produce smoother, more continuous surfaces. Thus, for the equipotential surfaces of the trend maps in this study, a power coefficient $p = 2$ was used. The results of the *IDW* interpolation were layered on urban outlines drawn using Corel Draw X6.

Validation Maps

To evaluate the variance between the observed and calculated results of the model, the variability of the parameters from each map (T_{max}, T_{avg}, T_{min} and P) was used. To validate the model, conventional statistical algorithms such as root mean squared error (*RMSE*), bias, and the Pearson correlation coefficients (r) and coefficient of determination (R^2) were used. The results were validated by comparing them with data from a government agency [23]. Validation of the model by comparing observed mean values (control) and calculated values did not result in large differences except in the case of rainfall precipitation at some weather stations, which was attributed to local climate change [24].

Results and Discussion

The *ST* of each parameter varied geographically and are shown in Table 1 for the Mann-Kendall statistic (confidence level = 95%). An *ST* was identified in $\overline{T}_{max}$ at 20 weather stations (17 *PT* and 3 *TN*). The stations with the highest magnitude of *PT* were Puerto San Carlos in BCS (0.160ºC·yr^{-1}), El Tarahumar in CHI (0.113ºC·yr^{-1}), and San Javier in BCS (0.104ºC·yr^{-1}). The stations with the highest magnitude of *NT* were Ligui in BCS (-0.113ºC·yr^{-1}), Don Huatabampo in SON (-0.106ºC·yr^{-1}), and Palmar de los Sepulveda in SIN (-0.102ºC·yr^{-1}). The average of the *NT* are similar to those calculated by [23] for the Palmar de los Sepulveda and Ligui stations. Average *PT* showed a change of 0.030ºC·yr^{-1} (0.30ºC·decade^{-1}), which is similar to the values obtained by [23] for the increase in maximum average annual air temperature ($\overline{T}_{max}$) for the period 1979-2008 (Table 2) (Fig. 1; Map A). This overall increase in air temperature, as shown by the PT of $\overline{T}_{max}$, could cause future negative impacts on climate, with repercussions in turn on agricultural and environmental systems in the region. Some examples of these effects are increased consumption of water by plants and animals, and altered biological cycles of some living organisms. Map A in Fig. 1 shows where weather stations with *PT* and *NT* are clustered, and shows that some zones display abrupt changes within short distances, such as in the western part of BCS (Ligui and San Javier stations), which are attributed to homogeneous climate changes and trends with high variability. The analysis of $\overline{T}_{avg}$ showed *ST* at 24 stations (7 *PT* and 17 *NT*). The station with the highest magnitude of *PT* was Guasave in SIN (0.013ºC·yr^{-1}). The stations with the greatest magnitude of *NT* were Puerto San Carlos in SON (-0.130ºC·yr^{-1}) and Constitucion in BCS (-0.094ºC·yr^{-1}). The average for stations with *NT* was -0.060ºC·yr^{-1}, and the average for stations with *PT* was 0.072ºC·yr^{-1} (Table 2 and Fig. 1, Map C). Without taking the *ST* of the *PT* into account, the average was -0.002ºC·yr^{-1}, which differs from the result obtained by the [1] for the 100 year linear trend (1906-2005) of the *PT* of average annual $\overline{T}_{avg}$, which was 0.74ºC (between 0.56ºC and 0.92ºC). The analysis of $\overline{T}_{min}$ showed trends at 21 stations (10 *PT* and 11 *NT*). The station with *PT* and the highest values was Guasave in SIN (0.098ºC·yr^{-1}) and the stations with the highest values of *NT* were Las Cruces in BCS (-0.113ºC·yr^{-1}) and El Refugio in BCS (-0.103ºC·yr^{-1}). The cumulative average T_{min} ($\overline{T}_{min}$) was -0.004ºC·yr^{-1} (Fig. 1).

The stations with *NT* in $\overline{T}_{min}$ are associated with increases in the frequency and intensity of freezes, affecting the yield and profitability of crops and livestock, and causing considerable losses to crops of vegetables, fruits, flowers, potatoes, corn, fodder, and other produce [4] that support the local economy. The spatial variation of $\overline{T}_{min}$ is shown in Fig. 1, Map B, with the highest values in the western and central part of the study area. In the same figure, the similarity between $\overline{T}_{min}$ and $\overline{T}_{max}$ can be seen. Of the 21 stations with *ST* in $\overline{T}_{min}$, 13 showed changes in $\overline{T}_{max}$ (Tables 1 and 2), supporting the hypothesis that climate changes are more prominent in some areas than in others where the trends have not been significant.

On a Worldwide scale, the nighttime increase in temperature has been almost twice the daytime increase, a pattern which has not been identified until now [1]. This behavior is an indicator that there has been a reduction in

Table 2. Magnitude of trends of indicators estimated by Sen's slope method.

Location		Magnitude of change trend indicator					
State	Weather station	$\overline{T}_{max}$ (ºC·yr^{-1})	$\overline{T}_{avg}$ (ºC·yr^{-1})	$\overline{T}_{min}$ (ºC·yr^{-1})	$\overline{P}$ (mm·yr^{-1})	$\overline{PET}$ (mm·yr^{-1})	$\overline{AI}$ (Dimensionless)
Sinaloa	Acatitan	0.021	**-0.054**	-0.023	9	**-58**	-1.125
	Culiacan	**0.060**	-0.083	-0.048	-28	62	1.010
	El Playon	**0.053**	0.032	**-0.070**	**-9**	**53**	**0.692**
	Guasave	**0.110**	**0.130**	**0.098**	18	56	-0.660
	Guatenipa	**0.073**	**-0.067**	**-0.018**	-15	-56	1.477
	Jaina	**-0.046**	**-0.077**	**0.060**	-15	**-56**	1.264
	Palmar de Los S.	-0.102	-0.094	**0.065**	-20	**-57**	**0.886**
	Pericos	-0.035	**-0.088**	0.067	8	**-57**	-0.965
	Ruiz Cortinez	**0.040**	**0.077**	**0.029**	10	-55	-0.567
	Santa Cruz	-0.050	**-0.040**	**-0.031**	13	**-55**	1.123
	Siqueros	0.059	**-0.043**	-0.045	-11	-57	1.021
	Surutato	**0.060**	**0.060**	**0.030**	25	**56**	-1.510
	Topolobampo	0.083	0.117	**0.086**	18	-49	0.492
Baja California Sur	Caduaco	-0.031	-0.053	0.053	**11**	**-64**	-0.550
	Constitución	**0.034**	**-0.094**	-0.041	-8	55	0.199
	El Paso de Iritu	**0.031**	**-0.045**	**-0.058**	10	**56**	-0.243
	El Refugio	-0.029	**-0.076**	**-0.103**	**4**	54	**-0.114**
	El Rosario	**0.077**	-0.049	-0.063	-12	**58**	0.147
	La Paz	**0.044**	**-0.019**	**-0.066**	-5	**54**	0.253
	La Poza Grande	**0.063**	**0.069**	**-0.046**	3	**50**	0.086
	La Purísima	**0.051**	**-0.077**	**-0.061**	3	56	0.142
	La Soledad	**0.059**	0.077	0.064	15	-58	-0.316
	Las Cruces	0.071	0.100	**-0.113**	6	**54**	0.158
	Ligui	**-0.113**	**-0.053**	0.040	17	**-54**	0.253
	Los Divisaderos	0.093	**0.047**	**0.033**	7	-51	0.688
	Penjamo	**-0.070**	0.120	0.063	-5	-58	0.173
	Puerto San Carlos	0.160	**-0.130**	-0.080	5	-42	0.140
	San Javier	**0.104**	0.045	**0.075**	10	**53**	**0.414**
	Todos Santos	-0.025	**-0.059**	**-0.049**	5	-48	0.267
Durango	Huahuapan	-0.034	0.021	0.037	9	49	**-1.408**
	Ojito de Camellones	0.030	**-0.068**	-0.058	29	**-36**	**-3.563**
	Pena de Águila	**0.049**	**-0.021**	**-0.020**	6	**-44**	1.033
	San Miguel de Lobos	**0.044**	**0.087**	**0.050**	-11	**35**	-2.020
	Santiago Papasquiaro	0.059	**0.031**	**0.039**	**7**	**47**	-0.910
	Tamazula	0.061	0.114	0.053	21	53	**1.592**
Chihuahua	El Tarahumar	0.113	0.125	0.030	14	-34	2.231
	Guerachic	**0.089**	0.039	-0.043	**15**	**53**	-1.081
Sonora	Don Huatabampo	-0.106	**-0.080**	-0.068	**-8**	59	**0.594**

$\overline{P}_a$ – average cumulative annual precipitation, $\overline{T}_{max}$ – maximum temperature, $\overline{T}_{avg}$ – average temperature, $\overline{T}_{min}$ – minimum temperature, $\overline{P}$ – cumulative annual precipitation, $\overline{PET}$ – potential evapotranspiration, $\overline{AI}$ – aridity index
Bold – significant trend indicators

Table 3. Trend observed and calculated of the temperature (ºC·yr^{-1}) and precipitation (mm·yr^{-1}) in northern Mexico.

	Trends							
	$\overline{T}_{max}$		$\overline{T}_{avg}$		$\overline{T}_{min}$		$\overline{P}$	
Weather station	Obs	Calc	Obs	Calc	Obs	Calc	Obs	Calc
Acatitan	0.024	0.021	-0.041	**-0.054**	-0.020	-0.023	6	9
Culiacan	0.022	**0.060**	-0.072	-0.083	-0.014	-0.048	-10	-28
El Playon	0.099	**0.053**	0.026	0.032	-0.062	**-0.070**	-7	**-9**
Guasave	0.110	**0.110**	0.098	**0.130**	0.093	**0.098**	10	18
Guatenipa	0.099	**0.073**	-0.048	**-0.067**	-0.015	**-0.018**	-5	-15
Jaina	-0.036	**-0.046**	-0.066	**-0.077**	0.099	**0.060**	-8	-15
Palmar de Los S.	-0.044	-0.102	-0.085	-0.094	0.038	**0.065**	-13	-20
Pericos	-0.042	-0.035	-0.074	**-0.088**	0.040	0.067	7	8
Ruiz Cortinez	0.048	**0.040**	0.040	**0.077**	0.061	**0.029**	5	10
Santa Cruz	-0.043	-0.050	-0.035	**-0.040**	-0.015	**-0.031**	10	13
Siqueros	0.066	0.059	-0.037	**-0.043**	-0.030	-0.045	-8	-11
Surutato	0.050	**0.060**	0.035	**0.060**	0.006	**0.030**	8	25
Topolobampo	0.080	0.083	0.098	0.117	0.030	**0.086**	10	18
Caduaco	-0.030	-0.031	-0.036	-0.053	0.063	0.053	8	**11**
Constitución	0.095	**0.034**	-0.124	**-0.094**	-0.043	-0.041	-6	-8
El Paso de Iritu	0.028	**0.031**	-0.025	**-0.045**	-0.051	**-0.058**	4	10
El Refugio	-0.027	-0.029	-0.038	**-0.077**	-0.101	**-0.103**	2	**4**
El Rosario	0.096	**0.077**	-0.042	-0.049	-0.043	-0.063	-8	-12
La Paz	0.044	**0.044**	-0.022	**-0.019**	-0.034	**-0.066**	-4	-5
La Poza Grande	0.060	**0.063**	0.042	**0.069**	-0.022	**-0.046**	2	3
La Purísima	0.023	**0.051**	-0.067	**-0.077**	-0.070	**-0.061**	3	3
La Soledad	0.032	**0.059**	0.058	0.077	0.081	0.064	8	15
Las Cruces	0.056	0.071	0.085	0.100	-0.105	**-0.113**	6	6
Ligui	-0.105	**-0.113**	-0.035	**-0.053**	0.035	0.040	12	17
Los Divisaderos	0.101	0.093	0.028	**0.047**	0.038	**0.033**	5	7
Penjamo	-0.065	**-0.070**	0.010	0.120	0.055	0.063	-4	-5
Puerto San Carlos	0.096	0.160	-0.025	**-0.130**	-0.043	-0.080	3	5
San Javier	0.071	**0.104**	0.026	0.045	0.041	**0.075**	8	10
Todos Santos	-0.030	-0.025	-0.050	**-0.059**	-0.041	**-0.049**	2	5
Huahuapan	-0.035	-0.034	0.023	0.021	0.035	0.037	7	9
Ojito de Camellones	0.034	0.030	-0.057	**-0.068**	-0.042	-0.058	12	29
Peña de Águila	0.040	**0.049**	-0.020	**-0.021**	-0.025	**-0.020**	5	6
San Miguel de Lobos	0.037	**0.044**	0.074	**0.087**	0.045	**0.050**	-9	-11
Santiago Papasquiaro	0.040	0.059	0.027	**0.031**	0.035	**0.039**	5	**7**
Tamazula	0.049	0.061	0.093	0.114	0.042	0.053	15	21
El Tarahumar	0.095	0.113	0.034	0.125	0.026	0.030	10	14
Guerachic	0.071	**0.089**	0.041	0.039	-0.040	-0.043	10	**15**
Don Huatabampo	-0.102	-0.106	-0.070	**-0.080**	-0.061	-0.068	-6	**-8**

$\overline{T}_{max}$ – maximum temperature, $\overline{T}_{avg}$ – average temperature, $\overline{T}_{min}$ – minimum temperature, $\overline{P}$ – cumulative annual precipitation, Obs – observed trend, Calc – calculed trend, Bold – significant trend indicators freezes and colder-than-normal days, and an increase in hot days over the previous century [1]. This behavior is partly valid; although there is an increase in daytime temperature overall, the *NT* of $\overline{T}_{min}$ show high *ST*, which implies cold nights and an increase in the probability of freeze events.

ST results for $\overline{P}_a$ were found at only 6 stations (4 *PT* and 2 *NT*), with an average of 4 mm·yr^{-1} (Table 2 and Fig. 2, Map A). For this reason, the results involving *ST* of local climate change are less significant for *P* than *T* (Table 1 and Fig. 2, Map A). The stations with the greatest magnitudes and *PT* were Guerachic in CHI (15 mm·yr^{-1}) and Caduaco in BCS (11 mm·yr^{-1}), and those with high values and *NT* were El Playón in SIN (-9 mm·yr^{-1}). The *ST* for $\overline{P}$ are similar to the [1] results, and do not indicate any evident trends in $\overline{P}_a$. *PET* showed *ST* at 20 stations (9 *NT* and 11 *PT*), and an overall average of 1 mm·yr^{-1}. The total at stations with *NT* was -53 mm·yr^{-1} and of stations with *PT* it was 52 mm·yr^{-1}. The stations with the greatest variation in *PT* were El Rosario (58 mm·yr^{-1}) and El Paso de Iritu (56 mm·yr^{-1}), both in BCS. The stations with the greatest magnitude of *NT* were Caduaco in BCS (-64 mm·yr^{-1}) and Acatitan in SIN (-58 mm·yr^{-1}).

For the analysis of *AI*, there were ST at 7 stations (2 *NT* and 5 *PT*), the greatest magnitudes being *PT* at Tamazula in DGO (1.592) and Palmar de Los Sepúlveda in SIN (0.886), and NT at Huahuapan in DGO (-1.408). When statistical significance was taken into account, the average *NT* of *AI* ($\overline{AI}$) was -0.761 and of *PT* the *AI* was 0.836. When the level of statistical significance was not taken into account, *AI* was 0.034 (Tables 1 and 2 and Fig. 3). It is vitally important to know where *AI* shows *ST*, because adaptation and mitigation measures can be taken; such as designing construction for extreme temperatures, designing and constructing coastal infrastructure to reduce the impact of storms, identifying highly vulnerable areas, and designing plans to reduce risk, and decreasing greenhouse gas emissions [23]. The $\overline{T}_{max}$, $\overline{T}_{avg}$, *and* $\overline{T}_{min}$ results specifically in the zone of Guasave in SIN suggest that these adaptation and mitigation measures should be intensified, since the natural variability, given the *ST* shown by *P* and *T* could be the main factor explaining hysteresis in the variability of agricultural production, which has suffered repeated freezes in recent years, with repercussions on food security [25].

Another important zone in SIN is the region near the El Playón station, since it showed *ST* in $\overline{T}_{max}$, $\overline{T}_{min}$, $\overline{P}$, $\overline{PET}$, and $\overline{AI}$ and it is close to the Ensenada de Pabellones wetlands, Ramsar 13 and 14 of the San Ignacio Navachiste-Macapule lagoon complex. Similar actions to minimize climate change should be undertaken to decrease climate effects in the area of the San Javier and La Purisima stations in BCS, as they showed *ST* in $\overline{T}_{max}$, $\overline{T}_{avg}$, $\overline{T}_{min}$, $\overline{P}$, $\overline{PET}$, and $\overline{AI}$, and are located close to Ramsar wetlands numbers 2, 3, 4, 5, and 6 (Laguna San Ignacio, Sierra de Guadalupe, Los Comondú, Oasis Sierra de La Giganta, and Bahía de Loreto National Park), which are among the ecosystems under threat at the World level (Fig. 3) [26]. In SIN, $\overline{AI}$ ranged from semiarid to humid with values of -1.510 (Surutato) to 1.477 (Guatenipa). The variation in BCS was arid to dry sub-humid with values from -0.550 (Caduaco) to 0.688 (Los Divisaderos).

In DGO all stations were humid, ranging from -3.563 (Ojito of Camellones) to 1.592 (Tamazula). The same pattern was seen in Chihuahua as in DGO, with extreme values of -1.081 (Guerachic) and 2.231 (El Tarahumar). With a value of 0.594, the one station located in SON was classified as dry sub-humid (Don Huatabampo) (Fig. 3). Although some stations showed NT, the overall trend in this variable from 1970 to 2011 has been increasing, with significant increases at the Puerto San Carlos station in the western part of BCS, where the increase was 1.6ºC·decade^{-1}.

One of the notable results was the *NT* in $\overline{T}_{min}$ in SIN, which reflected climate changes in the Guasave station zone. The cooling that has taken place in the local area around this agricultural region should be the subject of further detailed study. This is because agriculture plays a key role in local and national economic development; climate change requires modern society to work together to adapt food systems to achieve food security, alleviation of poverty, sustainable management, and conservation of natural resources. Some climate change adaptation measures that could be integrated into the economy of the region would be development of seed varieties resistant to climate change, emerging plans to deal with water scarcity and droughts, training human resources about climate change, and research tools that reinforce the adoption of practices that reduce disasters and the risk of food insecurity. Another event of interest is the behavior of $\overline{T}_{avg}$,where there is a *NT* at the tourist port of San Carlos. This is a result which should also be taken into account to promote adaptation in tourism and the local population, because of the effects of cold air on human health. It is important to give tourists and local residents information about these climate trends to avoid potential respiratory illness.

Overall, P did not show an *ST* at a large number of stations, but the *STs* that were found indicate annual increases in rainwater volumes. Excess rainfall affects soil and crops and promotes natural enemies such as pests and diseases to balance the environmental system [26]. Given the important role of wetlands in the capture and storage of atmospheric carbon, it is recommended to replant and care for wetlands [1] to mitigate effects of *AI*.

Some actions that can be taken, among others, are to develop plans and programs for the management of each wetland according to its needs and/or characteristics, and to identify its areas of influence and its flora and fauna. Meeting the stated objectives would help to avoid effects such as increased water consumption by plants and animals, altered hydrologic and biological cycles in living organisms, and damage to agriculture, tourism, and industry, among others. These are consequences that could be prevented with a better understanding and knowledge of climate change. In contrast to atmospheric circulation models that have low spatial resolution and are not able to distinguish local features of systems [26], this methodology

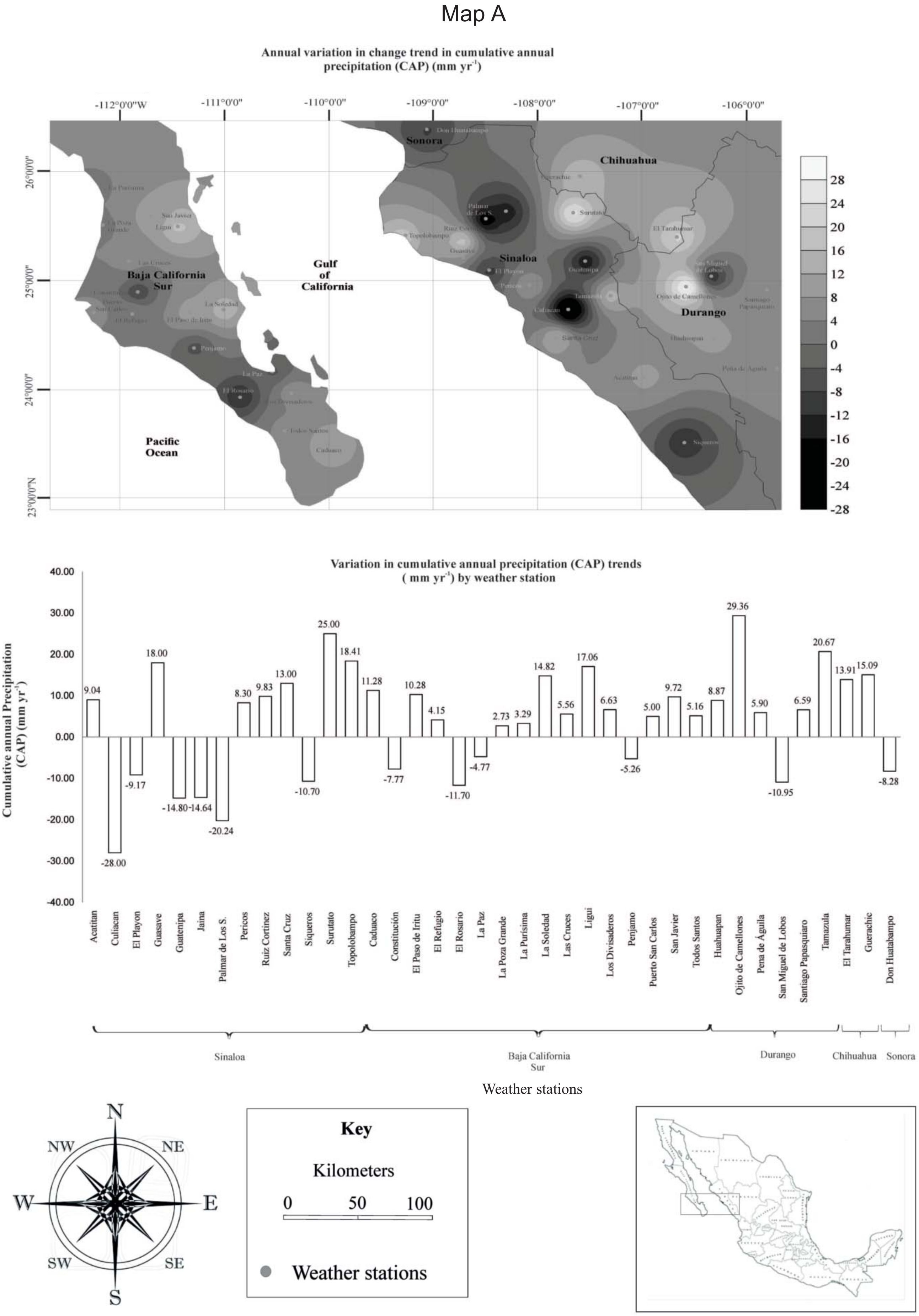

Fig. 2. Magnitude of change trends in P (Map A) and PET (Map B) in states in northern Mexico with high agricultural productivity.

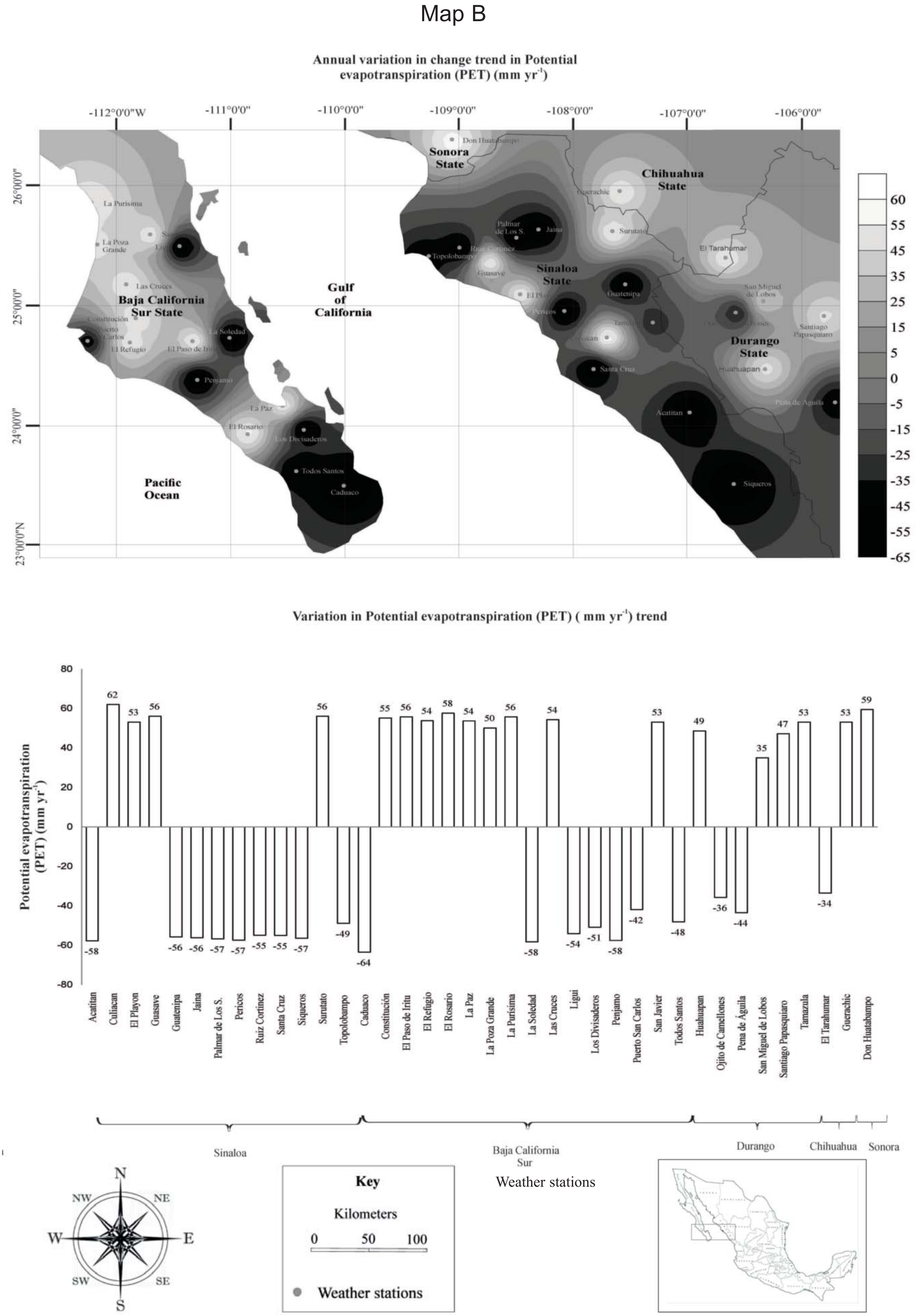

Fig. 2. Continued

provides information about climate change and the impact on *PET* and *AI* at the local scale, which is invaluable for guiding future research. Local results have shown that research on atmosphere flows cannot be framed only in terms of general circulation models [1]. Table 3 shows the observed and calculated trend of $\overline{T}_{max}$, $\overline{T}_{avg}$, and $\overline{T}_{min}$, and $\overline{P}$. The average *RMSE* of T_{max} = 0.02, of T_{avg} = 0.03, of T_{min} = 0.02, and of P = 6.39. The *NMAE* for these variables was, respectively, 0.18, 0.25, 0.03, and 0.24, and the bias was 0.0004, 0.0006, 0.0004, and 0.1203. Note that the comparison between trends in *T* did not show significant changes, but *P* showed the greatest variability among the precisions of the differences measured in the trends between in the values obtained in this study and the reference values.

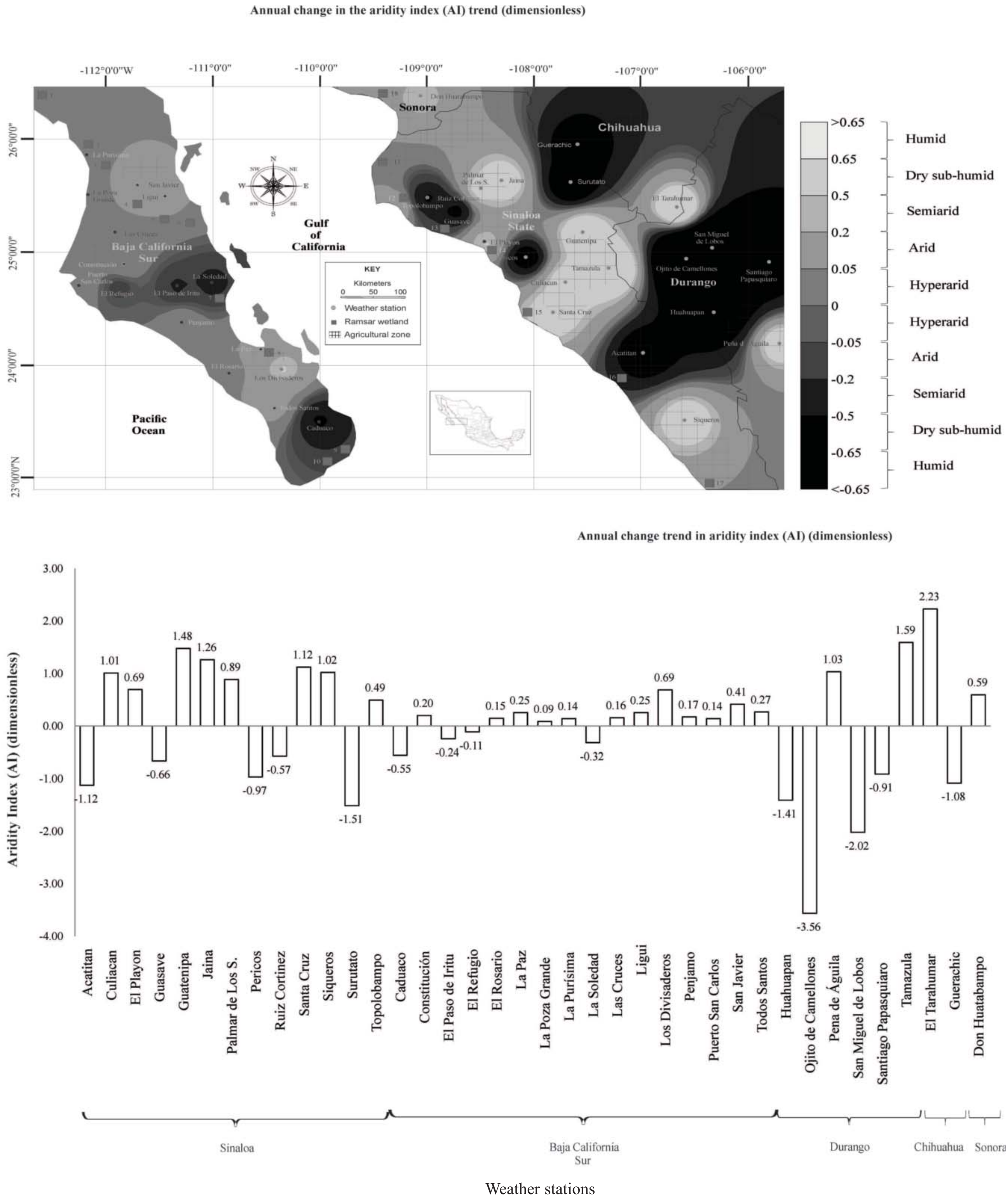

Fig. 3. Magnitude of change trends in *AI* in states in northern Mexico with high agricultural productivity.

Ramsar wetlands

State	Name	Number on map	Ramsar number
Baja California Sur	Laguna Ojo de Liebre	1	1339
	Laguna of San Ignacio	2	1341
	La sierra de Guadalupe	3	1815
	Los Comondú	4	1761
	Oasis Sierra de la Giganta	5	1793
	Parque nacional bahía de Loreto	6	1358
	Oasis de la sierra El Pilar	7	1794
	Humedales El Mogote-Ensenada La Paz	8	1816
	Parque nacional Cabo Pulmo	9	1778
	Sistema ripario de la cuenca y estuario de San José del Cabo	10	1827
Sinaloa	Sistema lagunar Agiabampo - Bacorehuis - río Fuerte	11	1797
	Lagunas de Santa María Topolobampo-Ohuira	12	2025
	Sistema Lagunar San Ignacio Navachiste-Macapule	13	1826
	Ensenada de Pabellones	14	1760
	Laguna Huizache-Caimanero	15	1689
	Laguna Playa Colorada - Santa María La Reforma	16	1327
	Sistema lagunar Ceuta	17	1824
Sonora	Complejo lagunar bahía Guásimas - Estuario Lobos	18	1790

Fig. 3. Continued.

This was attributed to the fact that 8 of the 38 stations analyzed for *P* showed high values. These were the Culiacan, Guasave, Guatenipa, Surutato, El Paso de Iritu, La Soledad, and Ojito de Camellones stations, located in different states but in very similar environmental systems. The values of the Pearson correlation for the variables are $\overline{T}_{max}$ = 0.93, $\overline{T}_{avg}$ = 0.92, $\overline{T}_{min}$ = 0.94, and P = 0.95, and their respective coefficients of determination are $\overline{T}_{max}$ = 0.87, $\overline{T}_{avg}$ = 0.84, $\overline{T}_{min}$ = 0.89, and P = 0.90.

These statistics (Fig. 4; Map A-D) show that there is little variation between the values obtained in the study and the reference values. Variation in the trends between the observed and calculated values of *P* are also attributed to the fact that the controls were measured in 2000 and calculated in 2011; a considerable time span. The values obtained for *RMSE*, bias, the Pearson correlation coefficient (r) and the coefficient of determination (R^2) do not show significant differences between the control values and the calculated values.

Conclusion

The *ST* for *T* are more pronounced than those for *P*. This suggests future changes in optimal conditions of the Ramsar wetlands and agricultural regions in the states of northern Mexico. No significant correlations were found in *T* between daytime *ST* and nighttime *ST*. The results of this study can be used for land management or to suggest changes in land use in agricultural systems. Studies of this nature should be prioritized to direct the course of future research in climate change and accurately understand its local impact. It is vital to characterize climate change in northern Mexico, since environmental conservation and adaptation of economic activities are necessary. Wetlands, tourist areas, agriculture, livestock, forestry, fisheries, and aquaculture are some of the many activities that support the regional economy.

The methodology presented here to draw continuous surfaces from point data (*IDW* method) can be extended and adapted to other parts of the country. In future studies, the limitations of the method for the spatial distribution of the variables should be taken into consideration, since it depends only on the distance between points. A suggestion for improving *ST* maps, such as $\overline{P}_a$ and $\overline{PET}$ maps, in future work is to try other methods for interpolation of climate trend variables. These methods should be validated on the basis of their usefulness in providing greater certainty to the spatial distribution maps, and also, if possible, to include other variables such as elevation and the slope of the terrain, ground cover, and geographical characteristics that influence the spatial distribution of climate variables and their change trends over time where weather stations are closer together. Thus, the methodology provides an effi-

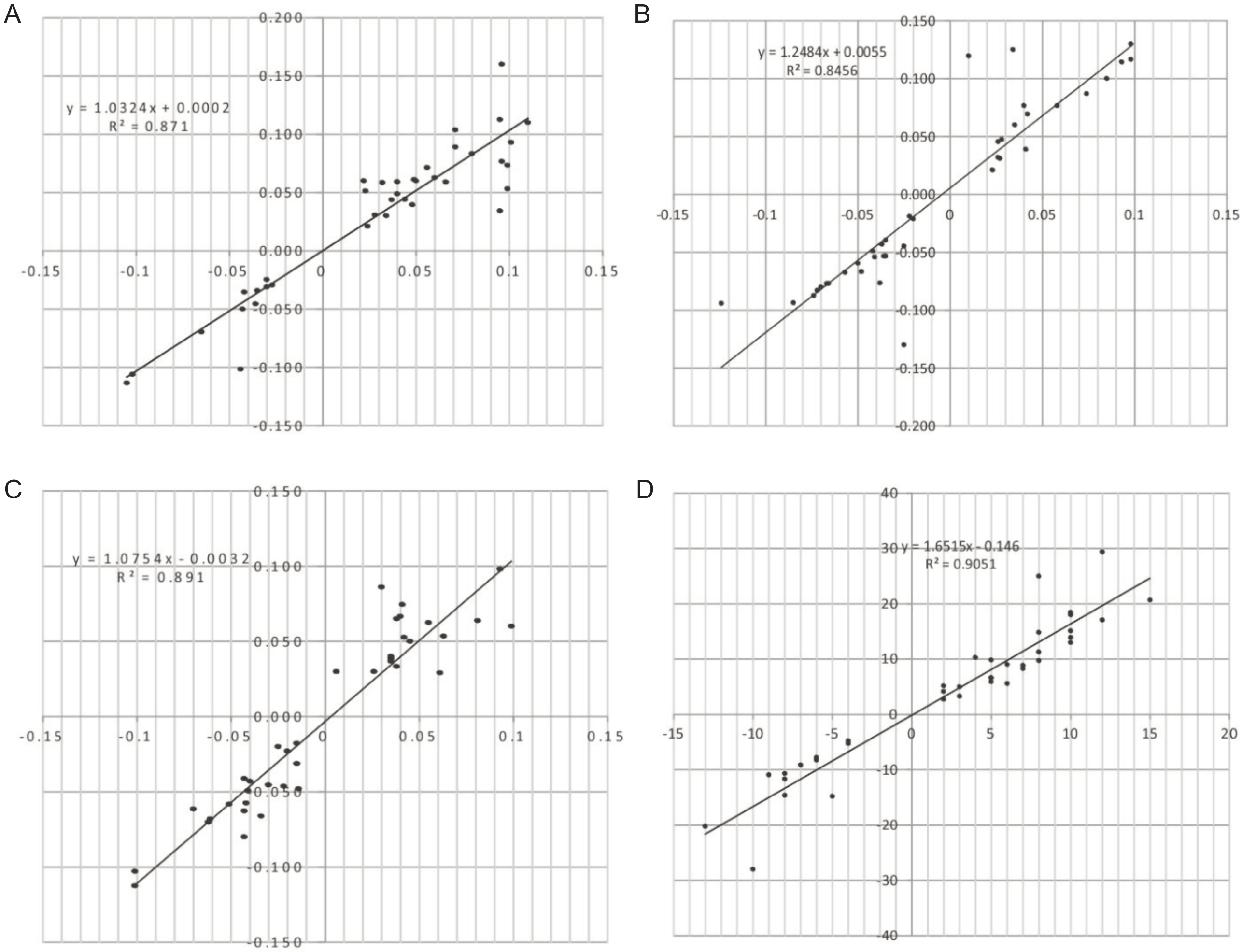

Fig. 4. Linear regressions between the observed and calculated values of temperature (ºC·yr⁻¹) and cumulative annual precipitation (mm·yr⁻¹).

cient way to detect and quantify the impacts of climate change at the local level, even when neither longterm climate time series (> 50 years) nor powerful computing resources are available.

No prior publications that give *ST* for $\overline{AI}$ were found. Given the environmental damage caused by extreme values of this variable, it should be prioritized in subsequent research agendas. Until then, this methodology and the resulting maps show the areas at risk of potential impacts of $\overline{AI}$ due to past trends of $\overline{T}$ and $\overline{P}$. The trends calculated in this study were compared to results from [23]. Correlation coefficients of 0.93, 0.92, 0.94, and 0.95 were obtained for $\overline{T}_{max}$, $\overline{T}_{avg}$, and $\overline{T}_{min}$, and $\overline{P}$, respectively, supporting the validity of this study.

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