

Spatial variation of climate change indices in the state of Chiapas, Mexico

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RESUMEN

Aunque el cambio climático es evidenciado por el aumento constante de la temperatura en el planeta, se han definido una serie de indicadores que se representan mediante expresiones matemáticas llamados índices. Éstos se identifican, registran y comparan para demostrar variaciones en el cambio climático. Sin embargo, para su uso es necesario: 1) evaluar de forma puntual estos índices y 2) determinar su variación espacial a lo largo de una región determinada. No obstante, existen pocos estudios sobre la tendencia espacial de estos índices, lo cual es importante teniendo en cuenta que los impactos del cambio climático, así como los factores que los determinan, no son espacialmente homogéneos. De acuerdo con lo anterior, el objetivo de este estudio fue determinar la variación espacial de un grupo de índices climáticos a partir de las variables de mayor disponibilidad. Para ello se usó información de las series históricas (1969-2009) de 16 estaciones meteorológicas distribuidas en el estado de Chiapas, México. Para determinar la variación espacial de los índices climáticos, cada índice se asoció con 25 variables ambientales a través de una serie de regresiones lineales múltiples definidas mediante el procedimiento de regresión paso a paso (*stepwise*). De acuerdo con los resultados, las variables ambientales con mayor influencia significativa ($p < 0.001$) fueron la temperatura media anual, la escorrentía media anual, la evapotranspiración real, la temperatura mínima media y las isotermas medias anuales. Por otro lado, las variables que no se utilizaron en los modelos fueron: mayor insolación de mayo, regímenes de humedad del suelo, hidrogeología, provincias bióticas y provincias fisiográficas. Los modelos de regresión lineal múltiple resultantes definieron valores elevados de R^2 (de 0.72 a 0.97). La cartografía resultante muestra que cada índice definió una variación espacial particular. Finalmente, concluimos que, con el propósito de evidenciar el cambio climático, el proceso seguido en este trabajo puede usarse para determinar la variación de este tipo de índices en otras regiones.

ABSTRACT

Although climate change is evidenced by a steady increase in global temperature, several indicators have been defined and are represented by mathematical expressions called indices, which are identified, recorded, and compared to demonstrate variations in climate change. However, using these indices requires: (1) timely evaluation, and (2) determining their spatial variation over a given region. However, there are only a few studies on the spatial trend of these indices, which is important considering that the impacts of climate change, as well as the factors that determine them, are not spatially homogeneous. Therefore, information from the historical series (1969-2009) of 16 meteorological stations, distributed in Chiapas, Mexico, was used. To determine the spatial variation of the climatic indices, each index was associated with 25 environmental variables through multiple linear regressions defined by the stepwise procedure. According to the results, the environmental variables with the greatest significant influence ($p < 0.001$) were mean annual temperature, mean annual runoff, real evapotranspiration, mean minimum temperature, and mean annual isotherms. On the other hand, the variables not used in the models were: highest insolation in May, soil moisture regimes, hydrogeology,

biotic provinces, and physiographic provinces. The results of multiple linear regression models defined high R^2 values (from 0.72 to 0.97), and the resulting mapping shows that each index defined a particular spatial variation. We conclude that, for the purpose of evidencing climate change, the process followed in this work can be used to determine the variation of this type of index in other regions.

Keywords: climate impacts, climate policy performance, systematic climate comparison.

1. Introduction

One evidence of the trend towards climate change is the constant temperature increase on the planet, where, in the last 100 years, the global temperature has increased by approximately 0.74 °C (IPCC, 2007a; Chen et al., 2021). Furthermore, the frequency and intensity of this trend has increased noticeably in the last 30 years, manifesting itself in periods of heat above the average in northeastern China (Yu and Li, 2015), which have been a consequence of the increase in gas emissions (greenhouse effect) derived from human activities (IPCC, 2007b; Chen et al., 2021). This has produced warmth of the oceans, an increase in continental temperature, extreme temperature and extreme wind behavior patterns (IPCC, 2013; Lata-Beharry et al., 2015; Chen et al., 2021), which define extreme weather conditions, causing natural disasters, directly and indirectly (Degefie et al., 2014), such as floods (Pineda-Martínez et al., 2014), heat waves, and forest fires. In this regard, Mexico is a vulnerable country to climate change (Wang et al., 2014; Chen et al., 2021) specifically in the northeast and northwest regions (Magaña et al., 2012), where the problem of water scarcity can be exacerbated due to the increase in temperature and the reduction of precipitation (García-Cueto et al., 2009; Ríos, 2011; Cavazos and Arriaga-Ramírez, 2012). Furthermore, various studies in Mexico conclude that, after 1970, there was a significant increase in maximum temperature, compared to minimum temperatures, especially in the northwest and central regions, showing contrasting trends with respect to the rest of the country (Englehart and Douglas 2005; Pavía et al., 2008; Gutiérrez-Ruacho et al., 2010). However, trends have also been detected in the increase of maximum temperatures in the southeast region (Peralta-Hernández et al., 2009; de la Mora-Orozco et al., 2016; Pineda-Martínez et al., 2020), such as the frequency of warm days.

To better understand the above, the increase in warm waves should be considered (Griffiths and

Bradley, 2007; Cutter et al., 2012) because they can influence biogeochemical processes related to global warming, such as the carbon or nitrogen cycle (Degefie et al., 2014). The increased frequency of warm years may decrease the CO₂ uptake by terrestrial ecosystems (Arnone et al., 2008). To assess this, simulation models related to climatological events have been developed, based on which the future trend of more frequent and severe extreme weather events has been confirmed (Schär et al., 2004; Meehl et al., 2005; Tebaldi et al., 2006; Koutroulis et al., 2013). This has been manifested in the decreased frequency of cold extremes and the increase in both daytime and nighttime temperatures (Acquaotta et al., 2014; Wang et al., 2012), based on which a decrease in number of cold nights and increase in warm nights during the last 50 years has been detected in 70% of the planet (Alexander et al., 2006; Herrera-Salcedo, 2011). In accordance with the above, indicators have been defined, when presented as mathematical expressions (indices), whose advantage lies in their identification, evaluation, and comparison, allowing climate change demonstration (IPCC, 2007a, 2013). However, the use of these indices may represent a disadvantage (Pandey and Jha, 2012; Rising et al., 2022; Sinnarong et al., 2022) if: (a) there is no adequate assessment of spatial and temporal variations; (b) there is a lack of reliable and actionable data; (c) apparent climate changes may be due to inhomogeneities, and (d) there is an uneven distribution of observations. In general, these indicators are grouped in relation to extreme behaviors of (Easterling et al., 2000; Vázquez-Aguirre, 2010): (a) temperature, exemplified by indices on consecutive dry days, icy days, duration of cold periods, etc., and (b) pluvial precipitation, where indices are evaluated for maximum 5-day rainfall, consecutive wet days, total annual rainfall, etc.

According to the above, to demonstrate global warming, it is necessary to address two aspects related to the indicators (indices) of climate change:

(1) the punctual evaluation of these indices, and (2) determining the variation of these indices throughout a given region. In this regard, few studies in Mexico focus mainly on evaluating these indices (Colorado-Ruiz and Cavazos, 2021) and their potential trends (Villa-Falfán et al., 2023), and even less on the spatial trend of these indices (Ruiz-Álvarez et al., 2019). Moreover, it should be considered that the impacts of climate change are not spatially homogeneous (Mendoza-Uribe, 2022; Montero-Martínez et al., 2022), as well as the factors that determine them (Vázquez-Aguirre et al., 2008; Gay-García et al., 2010). For example, because global warming increases water vapor in the atmosphere, there is an increase in precipitation, meaning that precipitation is an indicator of global warming (García-Herrera et al., 2010).

In this way, the objective of this study was to determine the variation of the spatial distribution of climatic indices, based on variables of higher availability, such as maximum temperatures, minimum temperatures, and precipitation. The data used were generated by de la Mora-Orozco et al. (2016), who determined the trend of climate indices (1960–2009) based on maximum and minimum temperatures and precipitation recorded in 16 meteorological stations in Chiapas. Due to the distribution of environmental variables, the scope of the results of this work is at the state level. However, its spatial resolution is limited to the scale of these variables (CONABIO, 2012). Climate change in Chiapas could impact water security, land degradation, mangrove degradation, increased risk for subsistence farmers, reduced crop yields, etc. (de la Mora-Orozco et al., 2016).

2. Methodology

2.1 Study area

The state of Chiapas is located between 14° 39'–17° 57' N, and 90° 22'–94° 08' W. Its geography is variable; it has high mountain ranges, plateaus, mountains, hills, valleys, and coasts (Bollo-Manet and Hernández-Santana, 2008). Its altitude ranges from 0 m in the limits with the sea, to a little more than 4000 masl in the Tacaná Volcano (Barrios-Calderón et al., 2024). The climatic types of greater territorial extension are the warm humid tropical and the warm sub-humid tropical. However, other climatic variants such as the temperate sub-humid subtropical and the semi-warm humid subtropical, among others, are also represented (Medina-García et al., 1998; de la Mora-Orozco et al., 2016).

We used the averages of eight indices estimated by de la Mora-Orozco et al. (2016) (Table I), which were based on the historical series (1969–2009) of 16 weather stations, distributed in the state of Chiapas (Fig. 1). The criteria for data analysis were (de la Mora-Orozco et al., 2016): (a) 30 years or more of information, (b) 95% or more of data, (c) elimination of years with three months or more without data, and (d) elimination of stations with several consecutive years without data.

2.2 Auxiliary variables

To determine the spatial variation of the climatic indices, each was associated with 25 environmental variables (Table II), derived from digital mapping of the National Biodiversity Information System of the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2012). This information, which covers all of Chiapas state, was used because

Table I. Climatic indices related to maximum and minimum temperatures and precipitation (de la Mora-Orozco et al., 2016).

Index	Code	Description	Units
Summer days	SU25	Number of days with Tmax >25 °C	Days
Tropical nights	TR20	Number of days with Tmin >20 °C	Days
Extreme maximum temperature	TXx	Highest monthly and yearly maximum temperature	°C
Lowest maximum temperature	TXn	Lowest monthly and yearly maximum temperature	°C
Highest minimum temperature	TNx	Highest monthly and yearly minimum temperature	°C
Extreme minimum temperature	TNn	Lowest monthly and yearly minimum temperature	°C
Daytime temperature range	DTR	Average differences between monthly and yearly Tx and Ti	°C
Consecutive days without rain	CDD	Number of consecutive days without rain or rain < 1mm	Days

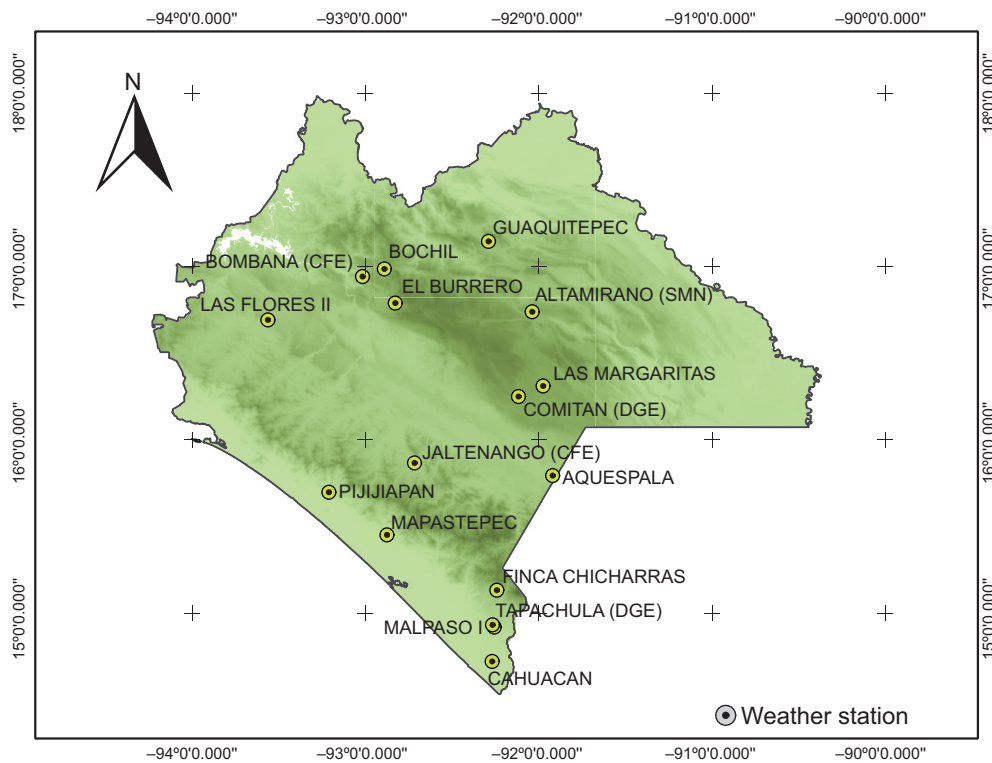


Fig. 1. Location of the weather stations in the state of Chiapas, Mexico.

Table II. Independent variables used to estimate climate indices, derived from the digital mapping of the National Biodiversity Information System (CONABIO, 2012).

Variable	Source	Information
Edaphology	Union of 32 covers	Soil type, texture, physical phase, chemical phase
Dominant soils	Dominant soils (INEGI, FAO/UNESCO/ISRIC)	At the level of soil units and subunits
Mean annual runoff	Average total surface natural runoff by administrative hydrological region	Medium surface natural runoff in hm^3
Real evapotranspiration	Turc method (precipitation and average annual temperature)	Five ranges and isolines have values from >100 mm to >1200 mm
Hypsometry	The cartographic data was obtained from digitization	Hypsometric ranges that oscillate between 200 to > 5000 masl
Annual insolation	Intervals of annual sunshine hours	With values from <1800 to > 3400
Minimum January insolation	Intervals of hours of sunshine in January, the month of minimum sunshine	With values from <140 to > 220
Distribution of precipitation	Information from 382 stations, over a period from 1921 to 1980	Rainfall regimes: winter ($\text{PI} > 36\%$), intermediate ($\text{PI} < 36\%$), and summer (PI between 5 and 10.2%)

Table II. Independent variables used to estimate climate indices, derived from the digital mapping of the National Biodiversity Information System (CONABIO, 2012).

Variable	Source	Information
Mean annual precipitation	Precipitation ranges	Scale from 0 to more than 4000 mm
Total annual precipitation	It considers relief, wind direction, and mountain barrier effects	50, 100, 200, 400, 600, 1000, 1500, 2000, 3000, and 4000 mm
Climate	National Meteorological Service, Federal Electricity Commission, and National Water Commission	Climate types (Koppen classification modified by García)
Maximum average temperature	Average maximum temperature of the hottest month, equidistance of the isotherms by two degrees	Thermal zones: very warm, warm, semi-warm, temperate, semi-cold, cold, and very cold.
Average annual temperature	Statistical information from 1800 stations of the Climatological Observation System (1921-1980)	Thermal zones: very warm, warm, semi-warm, temperate, semi-cold, and cold -very cold
Minimum temperature average	Average minimum isotherms of the coldest month	Thermal zones: warm, semi-warm, temperate, semi-cold, cold, and very cold
Annual mean isotherms	Thermal gradients according to the slopes of the mountains and altitudes at which the isotherms pass	Thermal zones: very warm, semi-warm, temperate, semi-cold, and very cold
Land use and vegetation	Photointerpretation of Landsat 2018 images and field work	Plant communities and anthropic uses
Biogeographic provinces	Based on ecoregions and climatic, geological, and biotic factors	14 biogeographic provinces of Mexico
Humidity ranges according to climates	It considers climate, temperature, and humidity	Classifications: humid, subhumid, semiarid, arid, and very arid
Natural regions	It includes maps of vegetation, climate, soil, geology, and topography	Seven ecoregions
Height above sea level	Extracted from INEGI's Digital Terrain Model (1:250 000)	Presents contour lines every 200 m
Higher May insolation	Maximum sunshine recorded in May	In conical projection
Soil humidity regimes	US Department of Agriculture	Regimes: Arid, Xeric, Ustic and Aqueous
Hydrogeology	Characterizing the porosity and permeability of the soil in order to describe the subsoil	12 units are recognized
Biotic provinces	Biotic provinces and subprovinces based on morphotectonic criteria	20 provinces
Physiographic provinces	Limit of the physiographic provinces that corresponds to the subprovinces and physiographic discontinuities of INEGI	88 physiographic provinces

of its spatial context, and the variables used are related to various climatic aspects, which, at the same time, are related to climate change (García-Cueto and Santillán-Soto, 2012).

2.3 Multiple linear regression

To determine the spatial variability of each climate change index, a series of multiple linear regressions was performed to predict the behavior of each index (dependent variable). These models allow for capturing the complexity associated with each index as a dependent variable by considering multiple factors (independent variables), which tends to reduce the error and bias of the estimates. Moreover, this technique allows us to know the variables that most influence the determination of climate indices. Although there are other alternatives to define the spatial variation of climate indices (Wang and Feng, 2010), such as geostatistics strategies, specifically kriging (Wang, 2008; Gimesi, 2009; Wang et al., 2010; Guo and Li, 2023), these have limitations, such as: (a) they require a larger number of data points (meteorological stations), and (b) the data points must be distributed throughout the area of interest. In this way, the environmental variables of CONABIO (2012) were used as regression variables. To avoid the redundancy of some variables, or irrelevant variables (that do not contribute substantially to the model), the models did not consider all the specified variables simultaneously. According to this, the following stepwise procedure was used (Fig. 2): (1) the process started with an empty model, that is, without any independent variable; (2) additional models were adjusted by adding the independent variable that most influences the model (linear regression), based on the probability value (p) and the adjusted coefficient of determination (adjusted R^2); (3) this process is followed until all the variables have been added; and (4) the modeling of each variable, concerning each climate index, made it possible to determine which variables have a significant influence (p value), and only the variables that most significantly influence the model were maintained.

The adjusted coefficient of determination (R_a^2) was used to define the degree of correlation between the climate change indices and the environmental variables. However, to measure the percentage of variation in climate change indices that is collectively

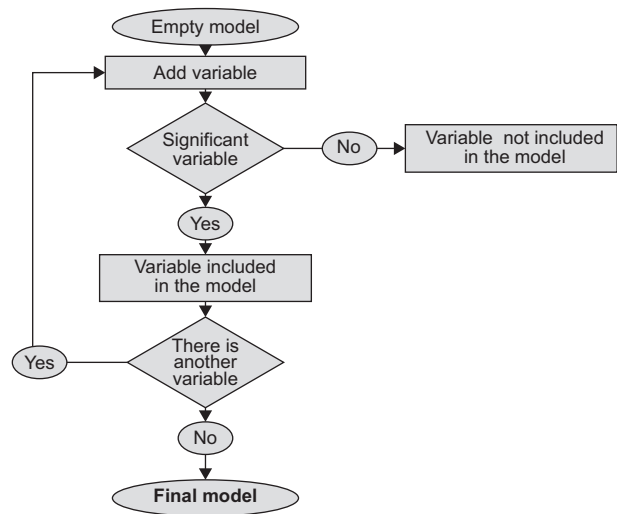


Fig. 2. Sequence of the stepwise regression algorithm.

explained by all environmental variables, the adjusted R^2 value was also defined (Martínez-Rodríguez, 2005). This avoids overestimating the generated model, meaning that when variables are added in a regression, the value of R^2 may tend to increase, even when the contribution of some variables is statistically irrelevant. In this way, the determination coefficient of each of the generated models was adjusted through the following equation (Martínez-Rodríguez, 2005):

$$R_a^2 = 1 - \left(\frac{n-1}{n-k-1} \right) * (1 - R^2) \quad (1)$$

where R_a^2 is the adjusted coefficient of determination, R^2 is coefficient of determination, n is the number of observations in the sample, and k is the number of independent variables.

2.4 Thematic mapping

Once the models were defined for each climate change index, they were implemented in a geographic information system (ArcGis) through the map algebra procedure to generate the thematic cartography corresponding to the spatial distribution of these indices in the state of Chiapas.

3. Results and discussion

The averages of the eight climate change indices are presented in Table III, where it can be observed that almost all of them present high homogeneity

Table III. Statistics of the climate change indices derived from the historical series (1969-2009) of 16 weather stations, distributed in the state of Chiapas.

Variable	SU25	TR20	TXx	TXn	TNx	TNn	DTR	CDD
Minimum	346	115	31.2	14.18	17.28	1.41	10.25	21.77
1st Quantile	356.75	268.75	34.455	15.84	19.16	4.29	12.22	47.49
Mean	357.3	299.6	36.6	20.7	21.8	9.2	12.9	63.9
Median	357.5	343.5	36.9	21.0	22.4	8.2	13.0	61.4
3rd Quantile	359	359	38.82	26.51	24.12	13.73	14.20	83.54
Maximum	363	359	41.12	27.58	26.33	16.55	15.03	6.87
N	16	16	16	16	16	16	16	16
SD	3.50	80.93	3.03	5.13	3.07	5.24	1.49	27.36

SU25: summer days; TR20: tropical nights; TXx: extreme maximum temperature; TXn: lowest maximum temperature; TNx: highest minimum temperature; TNn: extreme minimum temperature; DTR: daytime temperature range; CCD: consecutive days without rain; SD: standard deviation.

(low standard deviation), while tropical nights (TR20) correspond to the index with the greatest variation, which implies that their influence on climate change is highly variable (Ha and Yun, 2012). On the other hand, the correlation between these indices was analyzed (Table IV), finding that the maximum correlation was defined between TXn and TNn and TNx. At the same time, TNx was also acceptably correlated with TXx, as well as CDD with TNx. Accordingly, it would be expected that these correlated variables would present a similar spatial distribution.

The stepwise procedure showed that not all climate change indices required the same environmental variables to determine the corresponding models (Table V).

Specifically, the most widely used environmental variables were mean annual temperature, mean annual runoff, actual evapotranspiration, minimum mean temperature, and mean annual isotherms. This is consistent with the results of similar works (Gruza et al., 1999). Variables such as dominant soils, minimum insolation in January, and mean annual precipitation were only used by one model, contrary to the results obtained in other regions of the world (Rahmani and Harrington, 2019). On the other hand, the following variables were not used to determine any of the climate change index models: greater May insolation, soil moisture regimes, hydrogeology, biotic provinces, and physiographic provinces. In the first instance, it could be thought that the reason for this is that these variables did not

Table IV. Coefficient of determination between the climate change indices evaluated for the state of Chiapas.

	SU25	TR20	TXx	TXn	TNx	TNn	DTR	CDD
SU25	1.00	0.21	0.05	0.32	0.10	0.50	0.52	0.09
TR20	0.33	1.00	0.21	0.54	0.88	0.15	0.04	0.83
TXx	-0.50	-0.33	1.00	0.01	1.8E-05	0.07	0.02	9.5E-04
TXn	-0.27	0.17	0.64	1.00	1.3E-05	4.6E-07	0.40	8.5E-04
TNx	-0.43	-0.04	0.86	0.87	1.00	1.3E-04	0.45	1.5E-04
TNn	-0.18	0.38	0.47	0.92	0.81	1.00	0.62	0.02
DTR	-0.17	-0.52	0.58	0.23	0.20	-0.13	1.00	0.16
CDD	-0.44	-0.06	0.74	0.75	0.81	0.58	0.37	1.00

SU25: summer days; TR20: tropical nights; TXx: extreme maximum temperature; TXn: lowest maximum temperature; TNx: highest minimum temperature; TNn: extreme minimum temperature; DTR: daytime temperature range; CCD: consecutive days without rain.

Numbers in bold represent the coefficients of indices with the best prediction.

Table V. Environmental variables used to determine the models corresponding to each climate change index. The figures correspond to the p-value for each term (< 0.05).

Code	Description	SU25	TR20	TXx	TXn	TNx	TNn	DTR	CDD
eda25 lmg	Edaphology						0.0021		0.0030
edafo4mg	Dominant soils				0.0353				
esmea4mg	Annual mean runoff			0.1456				0.1181	
evapr4mg	Actual evapotranspiration					0.0384			
hipso4mg	Hipsometry	0.0025	0.0092						
insa8mg	Annual insolation						0.1112	0.0046	
insmi8mg	Minimum Sunshine JANUARY	0.0739							
regllgeo	Precipitation distribution	0.1052							
prec14mg	Average annual rainfall								0.0072
isoyt lmg	Annual total precipitation		0.0108			0.0399			
clima lmg	Climate	0.0091							
tmaxp lmg	Average maximum temperature								
temgeo	Average annual temperature			< 0.0001	< 0.0001	< 0.0001	0.0011		0.0458
tmnplmg	Average minimum temperature		0.0001	0.0105		0.0069			
isotm lmg	Annual mean isotherms		< 0.0001				0.0604		0.0060
usvea lmg	Land use-vegetation (INEGI)		0.0005						
biogeo	Biogeographic provinces							0.0001	< 0.0001
humegeo	Humidity ranges according to climates		0.0315	0.0045					
renat4mg	Natural regions				0.0151				
altitude	Height above sea level				0.0054	0.0025		0.0099	

SU25: summer days; TR20: tropical nights; TXx: extreme maximum temperature; TXn: lowest maximum temperature; TNx: highest minimum temperature; TNn: extreme minimum temperature; DTR: daytime temperature range; CCD: consecutive days without rain.

present a high spatial variation. However, in the case of insolation, it has been found that this variable has a significant influence on climate change (Leuschner and Sirocko, 2003), while the influence of soil moisture on factors related to climate change has also been demonstrated (Nouri and Homaei, 2021). The resulting multiple linear regression models for each index are presented in Table VI, where, in general, high values of R^2 were defined, which were not modified considerably when determining the adjustment of this coefficient. However, if the correlation between indices SU25 and DTR fell substantially when determining the adjusted R^2 , it would imply that the adjustment of these models was penalized with the inclusion of some environmental variables of low relevance (Table V) (Martínez-Rodríguez, 2005).

The implementation of correlation models to generate the cartography of the climate change indices is presented in Figures 3 and 4, where, in general, each index defined a particular variation. Although some similarities were found, as in the case of the TXx and TXn indices, which showed an increase

in the higher zones, coinciding with similar works (Beniston et al., 1994; Shi and Ye, 2021). On the other hand, it is important to note that there is no generalized trend regarding the spatial distribution of these indices throughout the state of Chiapas. However, considering the physiographic regions of Chiapas (Müllerried, 1957), the values of the indices concerning the altitudinal gradient are variable, since indices such as TNx, TNn, and Txn tend to present their lowest values in the central highlands of the state, which coincides with those reported for other regions (Lalic et al., 2013). While other indices, such as TR20, TNx, TNn, CDD and TXn, show low values along the Pacific coastal plain. In the case of SU25, the low values are located in several regions, such as the northern mountains, the coastal plain of the Gulf, and the eastern mountains, which is similar to the distribution of the low values of the CDD index.

In general, information on climate change indices is reported about the location of meteorological stations, from which the data that generate them are obtained. However, this implies gaps (between

Table VI. Simple regression models determined for each climate change index based on its correlation with Chiapas' environmental variables.

Index	Equation	R^2	Adjusted R^2
SU25	$= 360.79 + (\text{hipso4mg} * 0.0037) - (\text{insmi8mg} * 0.04) - (\text{clima1mg} * 0.54) - (\text{regllgeo} * 0.09)$	0.72	0.61
TR20	$= -2504.79 + (\text{isotm1mg} * 0.57) - (\text{tminp1mg} * 0.4) + (0.32 * \text{usvea1mg}) - (0.9 * \text{isoyt1mg}) - (0.05 * \text{hipso4mg}) - (2.06 * \text{humegeo})$	0.93	0.88
TXx	$= 53.98 - (0.03 * \text{temgeo}) - (0.07 * \text{humegeo}) + (0.01 * \text{tminp1mg}) - (0.01 * \text{esmea4mg})$	0.94	0.92
TXn	$= -51.22 - (0.05 * \text{biogeo}) + (0.37 * \text{renat4mg}) + (0.06 * \text{esmea4mg}) + (0.00094 * \text{hipso4mg}) + (0.04 * \text{regllgeo})$	0.99	0.99
TNx	$= 25.89 - (0.03 * \text{temgeo}) + (0.01 * \text{evapr4mg}) - (0.01 * \text{isoyt1mg}) + (0.0043 * \text{tminp1mg}) - (0.0033 * \text{ALTITUD})$	0.97	0.95
TNn	$= -7.58 + (0.07 * \text{esmea4mg}) + (0.0032 * \text{eda251mg}) + (0.04 * \text{evapr4mg}) - (0.02 * \text{temgeo}) + (0.0041 * \text{isotm1mg}) - (0.01 * \text{insa8mg})$	0.97	0.96
DTR	$= 66.71 - (0.03 * \text{biogeo}) - (0.01 * \text{esmea4mg}) + (0.02 * \text{insa8mg}) - (0.29 * \text{renat4mg})$	0.79	0.72
CDD	$= 2.33 - (0.46 * \text{biogeo}) + (0.28 * \text{preci4mg}) - (0.02 * \text{eda251mg}) + (0.05 * \text{isotm1mg}) + (0.02 * \text{tmaxp1mg})$	0.93	0.90

SU25: summer days; TR20: tropical nights; TXx: extreme maximum temperature; TXn: lowest maximum temperature; TNx: highest minimum temperature; TNn: extreme minimum temperature; DTR: daytime temperature range; CCD: consecutive days without rain.

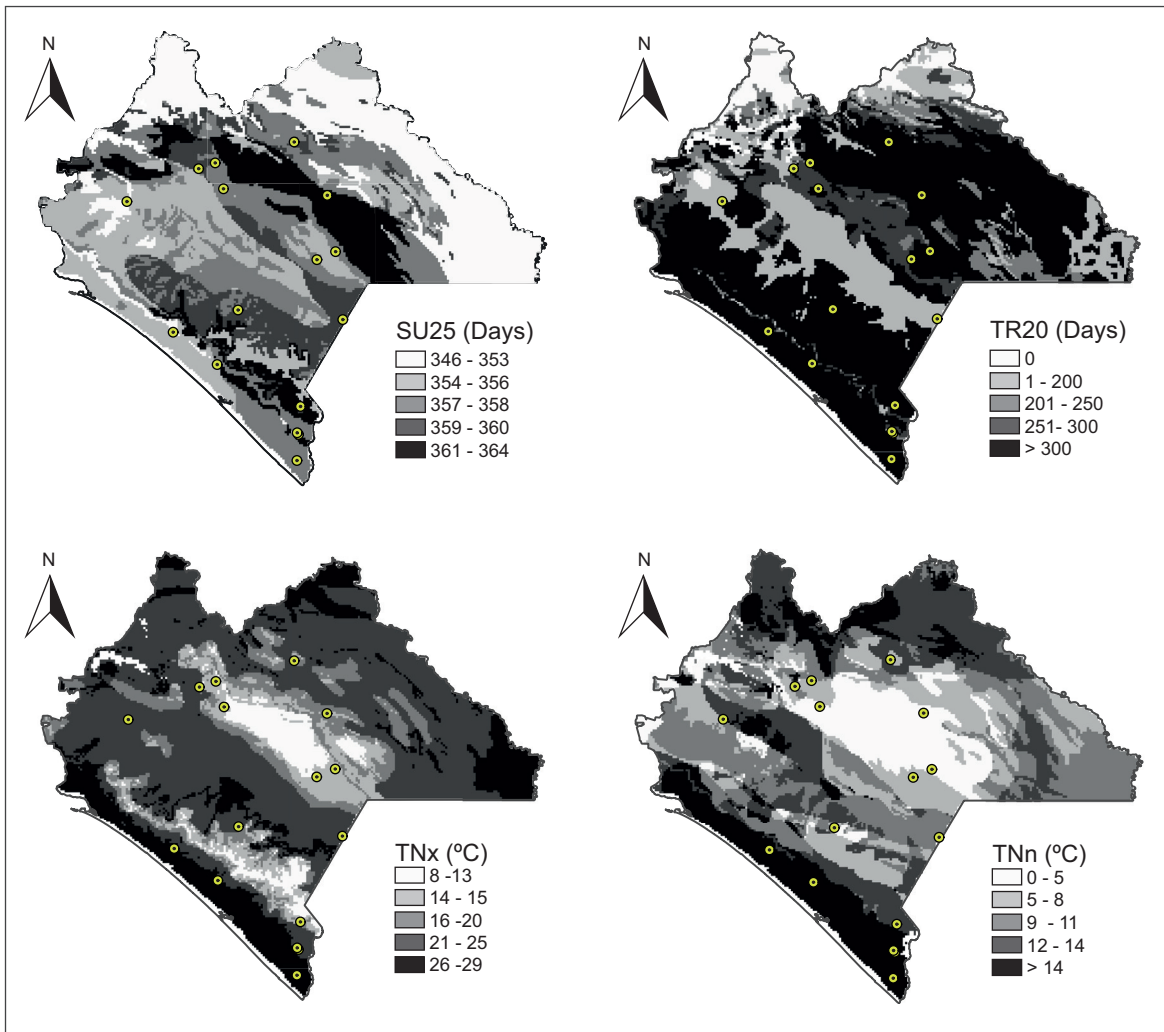


Fig. 3. Spatial distribution of climate change indices, generated from correlation models with environmental variables in the state of Chiapas. SU25: summer days; TR20: tropical nights; TNx: highest minimum temperature; TNn: extreme minimum temperature.

meteorological stations) without information, which represent a great challenge to understanding the impacts of climate change on ecosystems (Zarazúa-Villaseñor et al., 2014; Arowolo et al., 2017). To cover these gaps, strategies have been defined aimed at calculating the missing information with the smallest possible error, seeking a downscaling that allows better detection of their spatial variability (Bootsma et al., 2005; Weiss and Overpeck, 2005). However, little has been studied in this regard, and, in most cases, there is a small number of meteorological stations, together with their limited distribu-

tion (Zhang et al., 2011; Pérez-Bello and Mailhot, 2020). This limits interpolation strategies, such as spline, inverse distance weighted, or kriging (Escalante-Sandoval and Amores-Rovelo, 2014; Luo et al., 2018; Kouman et al., 2022). Because of this, the World Meteorological Organization suggests that missing data be estimated based on statistical correlations (Aragón-Moreno et al., 2019), as was done in the present work, where environmental variables were correlated with climate change indices. Under this same perspective, geostatistical strategies of spatial cross-correlation can also be

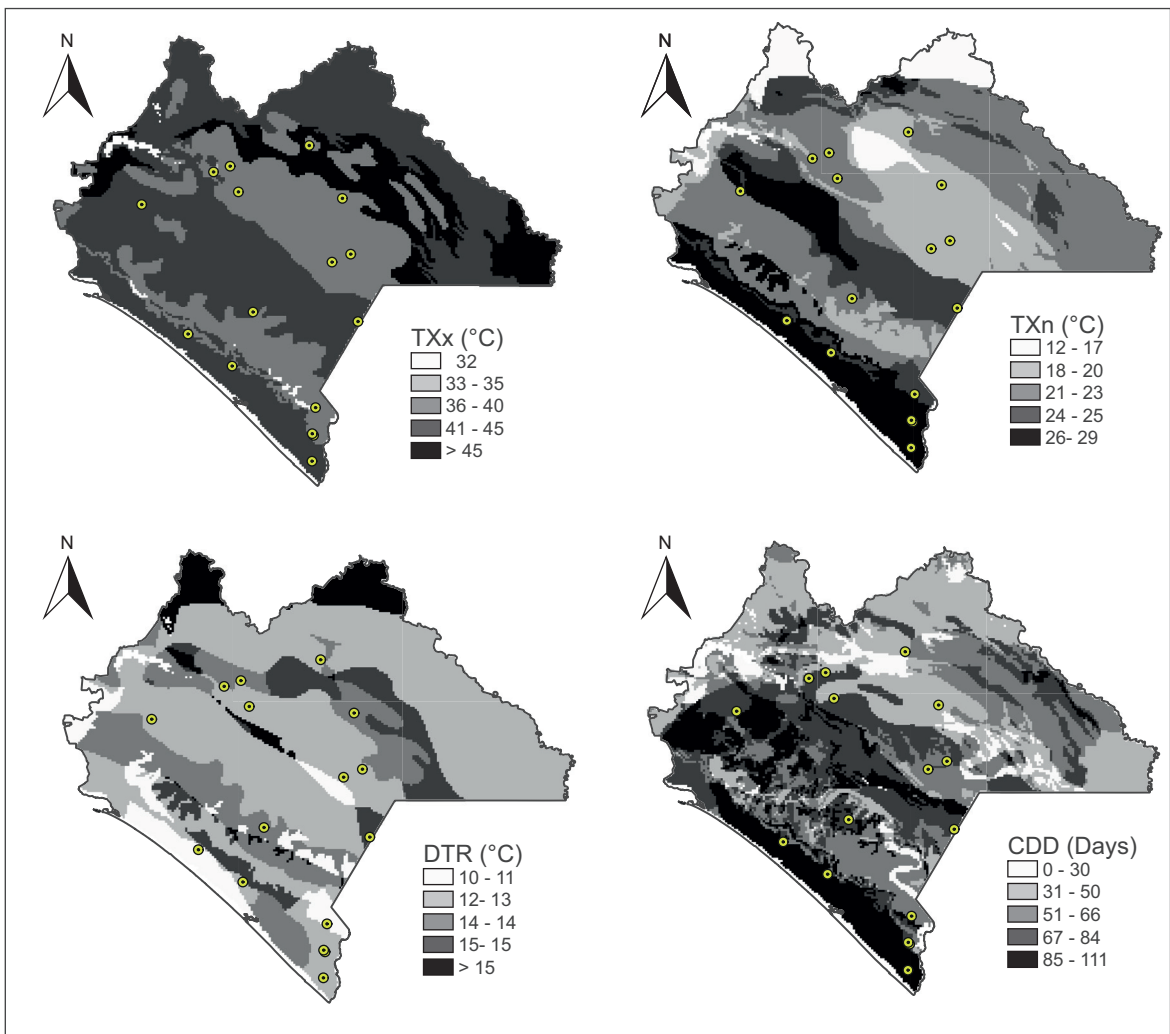


Fig. 4. Spatial distribution of climate change indices generated from correlation models with environmental variables in the state of Chiapas. TXx: extreme maximum temperature; TXn: lowest maximum temperature; DTR: daytime temperature range; CCD: consecutive days without rain.

implemented, such as co-kriging (Luo et al., 2018) or hybrid interpolation (Alsafadi et al., 2023).

4. Conclusions

The information from weather stations distributed throughout the state of Chiapas made it possible to determine the spatial variation of the studied climate change indices, which resulted from the high correlation of environmental variables, used as regression variables, with these indices. However, there were no variables to be used in all the

correlation models generated. Furthermore, each model required a specific set of environmental variables. However, some models presented environmental variables in common. On the other hand, the SU25 and DTR indices required the inclusion of variables with low correlation, which was penalized through the definition of the adjusted R^2 value. So, it is suggested that the spatial variation defined for these variables be taken with reserve. Regarding the distribution of the indices throughout Chiapas, it was possible to appreciate trends in the variation of high and low values closely related to the

physiographic regions. Nevertheless, these trends were not widespread.

Finally, the main purpose of this work was to present a methodology to define the spatial distribution of climate change indices, which can be used to support new evaluations in the state of Chiapas, as well as in other regions. Likewise, it is important to point out that monitoring climate change implies making periodic evaluations that allow comparative temporal analysis between past and current evaluations, on the basis of which it is possible to define trends in climate change. However, it is often difficult to find evaluations from past years, which highlights the importance of the results presented in this study, since they can be used as baseline data that, when compared with recent evaluations, will help to demonstrate the trend of the climate change process. Furthermore, the proposed methodology will make it possible to locate and measure temporal and spatial changes in the spatial distribution of the different indices used to quantify climate change. Therefore, in subsequent studies, it is suggested, if possible, to contemplate a greater number and a wider distribution of meteorological stations.

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