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Articles

Rainfall and temperature trends in the Altiplano Potosino Region, Mexico (1975-2015)

Tendencias de precipitación y temperatura en el altiplano potosino, México (1975-2015)

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Abstract

The observed changes in the climate systems during the last decades have generated a growing popular concern, especially in the scientific world, which has led to a series of research on the causes and possible consequences of climate change. This is a topic of great interest worldwide, including in Mexico. The Altiplano Potosino Region, Mexico, is located in the northwestern part of the state of San Luis Potosi, Mexico, with an approximate area of 29 119 km^2, with an annual rainfall lower than 400 mm and an annual average temperature of 17.5 °C. Groundwater is the main source of supply because surface runoff is limited. The objective of this study was to perform a time series analysis of the historical records of rainfall and temperature, at the meteorological stations located in the study region from the period 1975 to 2015, to identify spatial and temporal trends and patterns. For this, the non-parametric Mann-Kendall test was used. The results indicate both increased and decreasing trends in the annual and monthly periods for the variables analyzed. Trends suggest local behaviors. Monthly precipitation trends show increases in spring and summer, while they tend to decrease in autumn. Annual and monthly temperature trends show a greater variability spatial and temporal, where there are important annual variations because of the monthly changes; or there are monthly variations that are not yet reflected in an annual trend.

Keywords: Rainfall, temperature, Altiplano Potosino Region, time series, trend analysis, climate change, rate of increase or decrease.

Resumen

Los cambios observados en el clima durante las últimas décadas han generado una creciente inquietud popular, especialmente en el mundo científico, lo que ha propiciado una serie de investigaciones sobre las causas y posibles consecuencias del cambio climático. Éste es un tema de gran interés a nivel mundial, incluyendo México. La región denominada altiplano potosino se localiza en la parte noroccidental del estado de San Luis Potosí, México, con un área de 29 119.80 km²; tiene una precipitación anual inferior a los 400 mm y temperatura media anual de 17.5 °C. El agua subterránea es la principal fuente de abastecimiento, ya que las escorrentías superficiales son limitadas. El objetivo de este trabajo fue realizar un análisis de series de tiempo de los registros históricos de la precipitación y la temperatura en las estaciones meteorológicas ubicadas en la región de estudio en el periodo 1975-2015, para identificar tendencias y patrones espaciales y temporales. Para ello, se utilizó la prueba estadística no-paramétrica de Mann-Kendall. Los resultados indican tanto incrementos como decrementos en las tendencias anuales y mensuales para las variables analizadas. Dichas tendencias sugieren comportamientos locales. Con respecto a la precipitación, se presentan incrementos en primavera y verano mientras que tienden a disminuir en otoño. Con respecto a la temperatura, se detectó una mayor variabilidad en las tendencias (anuales y mensuales); hay un mayor reflejo en la variabilidad anual, sustentada por los cambios mensuales; o en su caso, existen variaciones mensuales que aún no se ven reflejadas en una tendencia anual.

Palabras clave: precipitación, temperatura, altiplano potosino, series de tiempo, análisis de tendencias, tasa de incremento o decremento, cambio climático.

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Introduction

The changes observed in the climate during the last decades have generated a growing popular concern, especially in the scientific world, which has led to a series of investigations into the causes and possible consequences of climate change. The Earth's climate has not always been the same; we must remember the glaciations of the Upper Cenozoic and the interglacial eras through which the planet has passed, which in some periods led the seas to a level three meters higher than the present and temperatures greater than 2 to 3 ° C of the current average. These climatic changes can be attributed to natural causes and the most recent as a consequence of human activities (Allyón, 2003).

There is strong evidence of climate change on a global scale, so this is a topic of great interest worldwide, including in Mexico (Méndez, Návar, & González, 2008). In this sense, from the late nineteenth century to the date, studies have been carried out to detect climate change in various parts of the world through an analysis of rainfall trends. Some of these studies include those carried out by Bradley *et al*. (1987) in the Northern Hemisphere; Hurrel (1995) in the North Atlantic; Brunetti, Buffoni, Maugeri, and Nanni (2000) in Italy; Haylock and Nicholls (2000) in

Australia; Kruger (2006) in South Africa; Reiter, Weidinger, and Mauser (2012) in the upper basin of the Danube River (Austria, Germany and Czech Republic); and Carlón and Mendoza (2007), Méndez *et al*. (2008), Montero and Pérez (2008), Algara (2009), Campos (2015), and Tello (2019) recently in Mexico. Regardless of geographical location, the results show the presence of significant changes in rainfall and temperature trends, which could have an impact on vulnerability effects to changes in meteorological phenomena in various regions.

Global climate change is one of the most severe environmental problems facing this century due to the increase in greenhouse gases, attributed to human activities, without ruling out natural variability, above historical levels (Magaña, 2004; IPCC, 2001). Global climate change has the enormous potential to produce significant changes in the average state of the land-ocean-atmosphere system, which would result in changes in the circulation patterns of the atmosphere and ocean which will produce an increase in global average temperature, and strongly affect current rainfall patterns (IPCC, 2001).

Experts in the field have pointed out that to evidence the existence of climate change, it is necessary to analyze the trends of climatic variables considering different scales of time and space (Méndez *et al*., 2008).

Among many other factors, updated information on climate change is key for Mexico to integrate a strategy that combines its own, regional and multilateral actions, to locate them around the security and well-being of its inhabitants. The current interest in understanding the causes of climate variability imposes the need to analyze trends of a series of meteorological variables (Miklos, 2018).

If it is clear that Mexico is highly vulnerable to extreme weather and climate conditions, it would be desirable to have better information and forecasting capacity at regional and local scales, as well as accurate diagnoses of vulnerability. These diagnoses would allow for the construction of dynamic risk assessments to design preventive strategies for the forecast of extreme hydrometeorological conditions, as well as action schemes that provide an efficient and effective response to possible disasters (Magaña, Landa, & Neri, 2008).

The state of San Luis Potosí, due to its unique geographical conditions, is a complex scenario, of national importance, which allows us to understand the processes, present throughout the territory, associated with climate change. An interesting feature of the Potosi territory is its extraordinary physical, climatic, ecological, and cultural diversity, which is manifested in a wide variety of ecosystems, agricultural and livestock production systems, biodiversity, and technologies. This great diversity is a natural result of the geographical and climatic variability of the state and is considered one of the most important in the world (Blanco, Vázquez, Reyes, & Guzmán, 2015).

The region called Altiplano Potosino Region (AP) is located in the northwestern part of the state of San Luis Potosi, Mexico, with an approximate area of 29 119.80 km² (Figure 1), has an annual rainfall of less than 400 mm and an average annual temperature of 17.5 °C; it is an arid and semi-arid region (Sedeco, 2013). Its hydrography is formed by a set of endorheic basins, storm currents, underground mantles, and some springs (INEGI, 2007). Due to its geographical location, it fuses desert landscapes with woodland and combines xerophilous vegetation with tropical deciduous, coniferous and broadleaf forests, which provides it with a great natural diversity (Inafed, 2010).

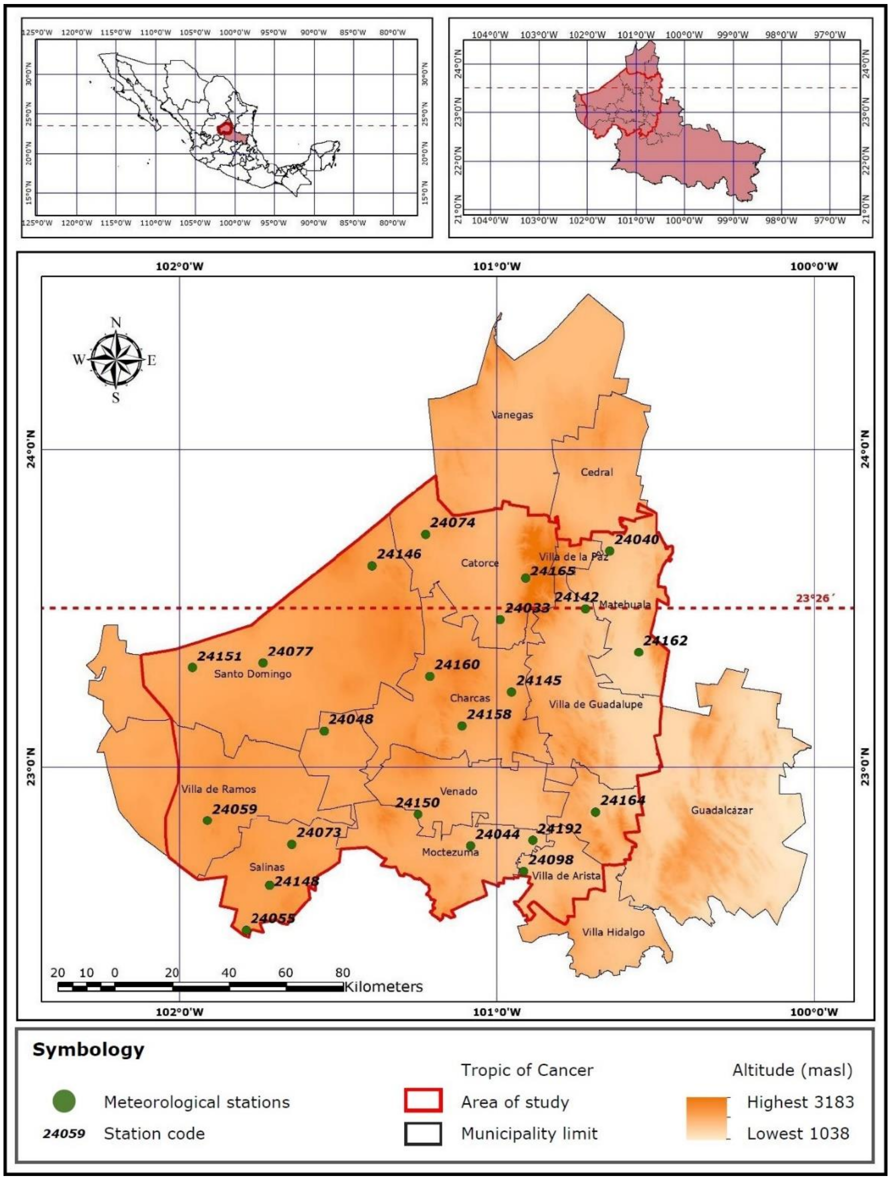

Figure 1. Location of the Altiplano Potosino Region and delimitation of the study area.

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Recent evidence indicates that the climate in Mexico exhibits fluctuations different from those recorded historically. The evaluation of a possible change in the rainfall regime is of great importance since this entails the management and control of agricultural, livestock, forestry, economic and social activities (Méndez *et al*., 2008; Corte-Real, Qian, & Xu, 1998). Studying the variability of the regional climate is of fundamental importance to planning for the management of the natural resources of a country; however, assessing climate variability and the mechanisms that produce the changes is complicated. One of the ways to analyze and interpret the average climate of a region is through annual or seasonal averages of temperature and/or rainfall (Ayllón, 2003).

Based on the above, the objective of this work was to perform an analysis of the time series of historical records of rainfall and temperature in the meteorological stations located in AP, Mexico, in the period between 1975 and 2015, to identify trends and spatial and temporal patterns.

Area of study

Location

The region called AP is located (Figure 1) in the northwestern part of the state of San Luis Potosi, Mexico, located between 22°16' and 23°08' north latitude and between 100°05' and 101°10' west longitude; it comprises 15 of the 58 municipalities of the entity and an approximate area of 29 119.80 km²; it is an arid and semi-arid region that is part of the Chihuahuan Desert (Sedeco, 2013). Most of its territory is located at the height of the Tropic of Cancer. In the AP is the most important orographic group in the state after the Sierra Madre Oriental: to the north, the mountains of Charcas, Catorce, Guadalcazar, Coro and Ypoa and San Pedro Naola; in the south, the mountains of Peñón Blanco, Ahualulco and San Miguelito. In the western part are the Sabino and Ballena mountain ranges, the latter on the borders with the state of Zacatecas (INEGI, 2007).

Weather

According to Conabio (1998), the climate of the AP is classified in most of the territory as dry semi-arid with rains distributed throughout the year (BSok(x')), with temperatures between 12°C and 18°C, the temperature of the coldest month between -3°C and 18°C and temperature of the hottest month less than 22°C and with a percentage of winter rain greater than 18% of the annual total. there is an extension of land to the north with an arid dry climate with rains in summer (BWkw) and a small extension to the east with a temperate climate, subhumid with less than 40 mm of rainfall in the driest month C(wo); both climates with the percentage of winter rainfall between 5 and 10.2% of the annual total. The shape of the country's territory together with the alignment of the Sierra Madre Oriental, the Sierra Madre Occidental, and the Transverse Volcanic Axis decisively influence the distribution of humidity and temperature, being important factors of the aridity of the AP and other parts of Mexico (García, 1986).

Hydrology

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The AP hydrography is located in the hydrological region called "El Salado". It is formed by a set of endorheic basins, storm currents, underground mantles, and some springs (INEGI, 2007). It almost completely lacks significant elevations which together with the climatic conditions of the region, means that there are no large surface currents.

Groundwater is the main source of supply, despite its relative potential, because surface currents are generally limited and transient. In the northern part of the state, there are wide valleys filled with tertiary and recent sediments, finding isolated structures of limestone mines. The quality of floodwaters is good, both for irrigation and for domestic use. Alluvial fillers are shallow and have a good chance of aquifer production. There are other conglomeratic and sandy tertiary sediments, and their water is abundant and of good quality.

Materials and methods

For the development of this research, an analysis of trends of the time series of monthly and annual averages of rainfall and temperature in the

AP region was carried out. To do this, in the first stage, the monthly historical records of 53 meteorological stations that are located within the AP were obtained. However, when analyzing and verifying the information of each of the stations, it was decided to work with 22 of them, because they had the largest number of records in common in the 41 years of analysis that comprised the study period (1975-2015). In addition, they complied with the homogeneity analyses through the application of the Helmert test, which is a non-parametric test that is based on sequences and changes from the mean (Mather, 1977; Campos, 1998). Some stations had missing data in some months, so various methods were applied: such as the deductive rationale, for the missing rainfall, and the arithmetic average of neighboring stations (same month and year), for temperature (Campos, 1998). The historical records were obtained by direct request to the State Directorate of the National Water Commission in the State of San Luis Potosi, Mexico.

For each of the meteorological stations, the total monthly rainfall (PrTM), total annual rainfall (PrTA), monthly average temperature (MMR), and the average annual temperature (TMA) of each of the 41 years of the study period (1975-2015) were obtained, to have the complete series for the analysis of time series.

In the second stage of the research, the temporal and spatial trends of rainfall and temperatures were evaluated on an annual and monthly

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basis, first by the entire study region as a whole and, subsequently, by each of the meteorological stations. For this, the non-parametric statistical test of Mann-Kendall (Mann (1945) was used; Hoeffding (1948); Kendall (1975); Dietz and Killen (1981) with a significance level of $p \leq 0.05$; this test has been used in environmental sciences since it can analyze records regardless of distribution, lost or seasonal data (Méndez *et al*., 2008). In addition, this test has been widely recommended and used worldwide to identify trends in climate parameters (IPCC, 2001) due to the consistency and rigidity it presents (Méndez *et al*., 2008). As part of the evaluation of the trend, the magnitude of the trend was determined, which was called "rate of increase" or "rate of decrease" and was obtained by determining the slope of the trend line. Through the use of a Geographic Information System (GIS), interpolations of the annual and monthly increase and/or decrease rates of rainfall and temperature were carried out to determine the temporality and spatiality of the phenomena analyzed; stations that did not show a statistically significant trend were assigned a value of "0" (zero). The interpolation of the annual increase and decrease rates was performed using the inverse distanced weighted method (IDW), which assumes that each point has a local influence, which decreases with distance (Juárez, 2015).

The nonparametric Mann-Kendall test (Kendall, 1938) has been widely used to test randomness against trends in climate data from time series (Zhang, Harvey, Hogg, & Yuzyk, 2001). This is an especially convenient linear procedure for data with non-normal distribution, for data containing extreme values and nonlinear trends. The null hypothesis H_0 of the nonparametric Mann-Kendall test consists of the data (x_1, x_2,..., X_n) being an independent and identically distributed sample of random variables. The alternate hypothesis H_1 consists of the distribution of x_k and x_j not being identical for all k, $j \leq n$ with $k = j$. Statistical analysis of the S trend is defined as (Hirsch, Hesel, Cohn, & Gilroy, 1993):

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

where $sgn()$ is the sample function.

According to H_0, the distribution S is normal at the limit when $n \rightarrow \infty$. The mean of the variance of S, considering that there may be nodes in the x-series, is:

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$$E[S] = 0 \quad (2)$$

$$Var[S] = \left[n(n-1)(2n+5) - \sum_{p} t_p(t_p - 1)(2t_p + 5) \right] \div 18 \quad (3)$$

where t_p is the number of identical data values in the observed values, and n is the number of values in the analyzed data series. The values of S and Var[S] are used to calculate the Z test statistic, which is a measure of the degree of significance of the trends to test the hypothesis (Mann, 1945; Kendall, 1975):

$$Z = \frac{[S-1]}{\sqrt{Var(S)}} \cdots\cdots\cdots\cdots\ if\ S > 0 \quad (4)$$

$$Z = 0 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\ if\ S = 0 \quad (5)$$

$$Z = \frac{[S+1]}{\sqrt{Var(S)}} \cdots\cdots\cdots\cdots\ if\ S < 0 \quad (6)$$

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In a two-sided test for trends, the null hypothesis is rejected at a significance level of α if $|Z|>Z_{(1-\infty/2)}$, where $Z_{(1-\infty/2)}$ is the value of the normal distribution exceeding $\alpha/2$. A positive value of Z indicates an upward trend; a negative value indicates a downward trend in the time series evaluated. In this paper, the trends are identified at a significance level of $\alpha=0.05$, with a critical value of 1.96. The Z trend statistical test is used to indicate the significant trend, but it is not a quantification of the magnitude of the trend (Molnár & Ramírez, 2001; Carlón & Mendoza, 2007).

With the identification of the variations of the meteorological trends, the data of the identified stations were graphed using the years on the *X* axis, and the values of temperature and rainfall on the *Y* axis. Subsequently, the equation of the line was obtained, in which the slope (m) is considered as the rate of change, which indicates a decrease as negative values and an increase as positive values (Nieto, Martínez, Regalado, & Hernández, 2002).

For the analysis of the results, a spatial and temporal interpretation was carried out. This was carried out annually, monthly, and grouped by seasons of the year: winter (January, February, and March), spring (April, May, and June), summer (July, August, and September), and autumn (October, November, and December).

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Results and discussion

Table 1 presents the complete results of the homogeneity analysis using the Helmert Test performed at the 53 meteorological stations in the region of study; nevertheless, only 22 stations, labeled as used stations (US), complied with the homogeneity test in conjunction with the analysis period 1975-2015. The other 31 stations are labeled as non-used stations (NS), and their data is included for reference. In addition, the result of the homogeneity test is presented as "homogeneous" (H) or "non-homogeneous" (NH).

Table 1. Results of the test of homogeneity and periods with the registration of the meteorological stations in the Altiplano Potosino Region.

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Meteorological station		Number of years recorded	Period	Helmert test	Type of station analyzed
Code	Name				
24007	Cedral	41	1975-2015	NH	NS
24010	Charcas (DGE)	23	1975-1997	H	NS
24019	El Estribo	41	1975-2015	NH	NS
24021	El Grito	39	1975-2013	H	NS
24022	El Huizache	15	2001-2015	NH	NS
24033	La Maroma	41	1975-2015	H	US
24038	Los Pilares	34	1975-2008	H	NS
24040	Matehuala (SMN)	41	1975-2015	H	US
24041	Matehuala (DGE)	26	1975-2000	NH	NS
24044	Moctezuma (DGE)	41	1975-2015	H	US
24048	Vallejo	41	1975-2015	H	US
24055	Peñón Blanco	41	1975-2015	H	US
24057	Presa de Guadalupe	39	1975-2013	NH	NS
24059	Villa de Ramos	41	1975-2015	H	US
24062	Rincón del Porvenir	26	1990-2015	H	NS
24073	Reforma	41	1975-2015	H	US
24074	Sta. María del Refugio	41	1975-2015	H	US
24077	Santo Domingo	41	1975-2015	H	US

Meteorological station		Number of years recorded	Period	Helmert test	Type of station analyzed
Code	**Name**				
24078	Santiago	38	1975-2012	H	NS
24094	Vanegas	34	1975-2008	H	NS
24096	Venado	38	1975-2012	NH	NS
24097	El Tule	19	1979-1997	H	NS
24098	El Mezquite	41	1975-2015	H	US
24099	Arista	32	1975-2007	H	NS
24102	Villa Hidalgo	12	1975-1986	NH	NS
24142	La Presa	41	1975-2015	H	US
24144	La Cardoncita	41	1975-2015	NH	NS
24145	Laguna Seca	41	1975-2015	H	US
24146	La Victoria	41	1975-2015	H	US
24148	Salinas	41	1975-2015	H	US
24150	Guanamé	41	1975-2015	H	US
24151	San Juan del Salado	41	1975-2015	H	US
24152	Sauz de la Calera	30	1977-2006	H	NS
24154	San Francisco	41	1975-2015	NH	NS
24157	Ojo de Agua	15	2001-2015	H	NS
24158	Charcas	41	1975-2015	H	US

Meteorological station		Number of years recorded	Period	Helmert test	Type of station analyzed
Code	Name				
24159	El Barril	37	1975-2011	H	NS
24160	Coyotillos	41	1975-2015	H	US
24161	La Herradura	37	1979-2015	NH	NS
24162	El Carmen	41	1975-2015	H	US
24164	Llanos del Carmen	41	1975-2015	H	US
24165	San José de Coronado	41	1975-2015	H	US
24169	Buena Vista	35	1981-2015	NH	NS
24175	El Salado	36	1980-2015	NH	NS
24176	San Juan del Tuzal	36	1980-2015	H	NS
24180	Cañada Verde	32	1979-2010	H	NS
24188	Coronado	31	1982-2012	H	NS
24189	El Hospital	33	1982-2015	H	NS
24191	San Antonio del Mezquite	33	1982-2015	NH	NS
24192	San Francisco	41	1975-2015	H	US
24194	San Rafael	33	1982-2015	H	NS
24196	El Toro	15	2001-2015	NH	NS
24197	El Terrero	33	1983-2015	H	NS

Rainfall

The trend analysis of the time series of the annual rainfall data for the period 1975-2015 presents increases and decreases in different regions of the AP. For instance, there is an increase in the southeast (municipality of Villa de Arista) and north (municipality of Catorce, north of the Tropic of Cancer), where the rates of change go from 2 to 8 mm·year^{-1}; the trend of decrease in the southeast (municipality of Moctezuma) shows rates of up to -2 mm·year^{-1} (Figure 2). These increases and decreases resulting in the total amount of annual rainfall are not yet reflected in regional effects and could lead to higher and lower rainfall than those historically recorded for each of the areas.

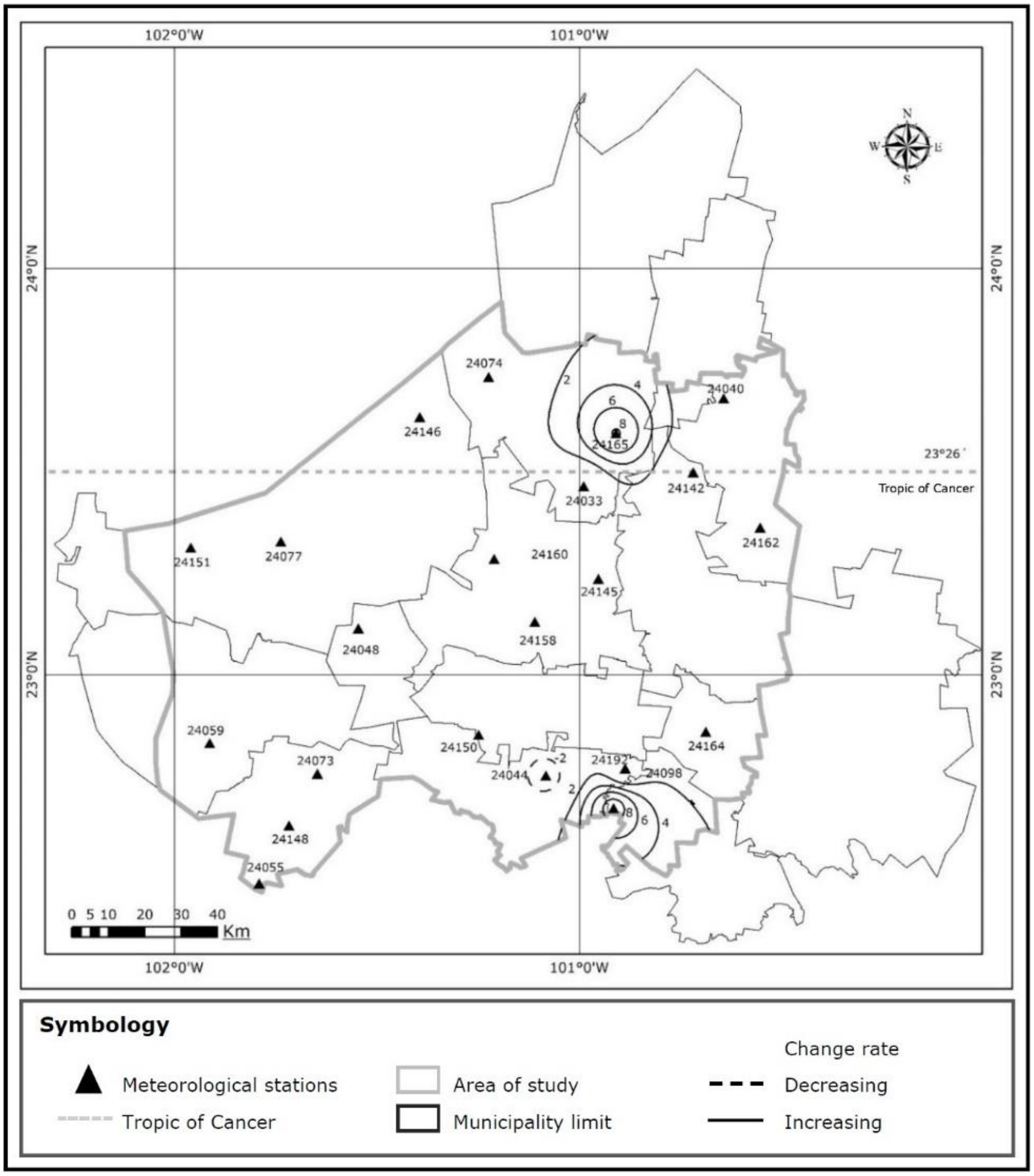

Figure 2. Result of the annual trend analysis for rainfall (1975-2015).

The analysis of trends of the time series of the monthly rainfall data for the period 1975-2015 presents that there are increases and decreases mainly in spring, summer, and autumn. The changes of greater magnitude, in space and time, occur in September (summer) and December (autumn).

For September (1975-2015), as shown in Figure 3, there is an increasing trend in the southeast (municipalities of Villa de Arista and Moctezuma) and north (municipalities of Catorce, Villa de Guadalupe, and Charcas), with rates of change from 0.5 to 2 mm·year^{-1}, with greater magnitudes of increase north of the Tropic of Cancer, compared to the southern part of the same area. Also, there is an increasing trend in the southwest of the AP, mainly in the municipality of Salinas de Hidalgo, with a change rate of between 0.5 and 1 mm·year^{-1}. As in the result of trends of total annual rainfall, the results for September indicate trends, in this case only increasing, with a local behavior, which is not yet reflected in regional effects and that coincides spatially with the results obtained in the annual analysis.

From December (1975-to 2015), there are decreasing trends in a large area of the AP, including municipalities in the north (Catorce, Charcas, and Villa de Guadalupe), south (Venado and Moctezuma), southeast (Villa de Arista and Villa Hidalgo) and southwest (Salinas de

Hidalgo and Villa de Ramos), with rates of changing ranging from -0.1 to -0.5 mm·year^{-1}; being the highest (-0.5 mm·year^{-1}), at the center of the AP region in the municipalities of Catorce, Charcas, and Moctezuma (Figure 4). This result already suggests a regional trend. It can be observed that the areas with a tendency to decrease in the north (municipalities of Catorce, Charcas, and Villa de Guadalupe) and in the southeast (municipality of Villa de Arista) also show an increasing trend as shown in Figure 3, which indicates a variation in the temporality of rainfall, increasing in summer and decreasing in autumn.

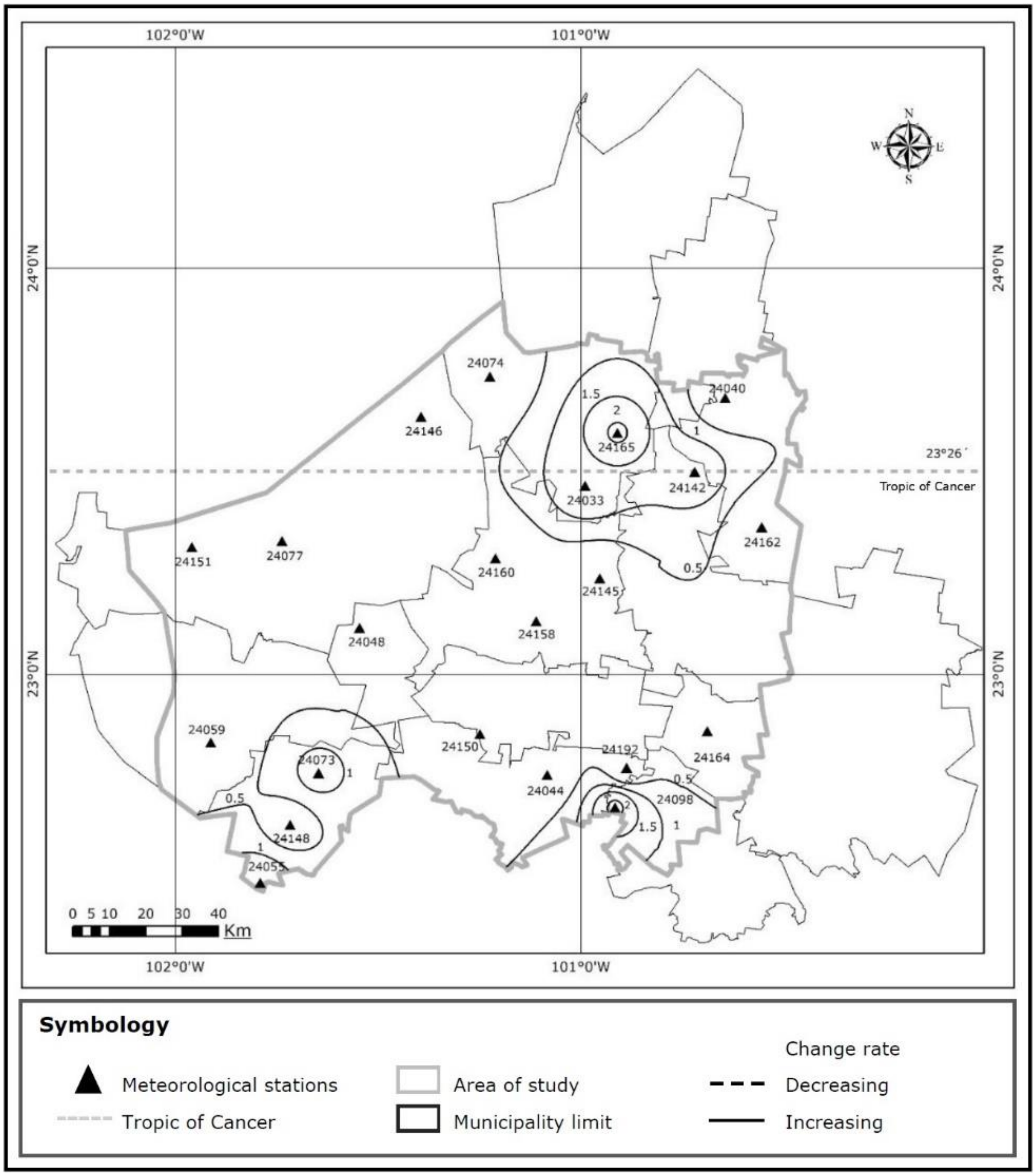

Figure 3. Result of the monthly trend analysis for rainfall (September 1975-2015).

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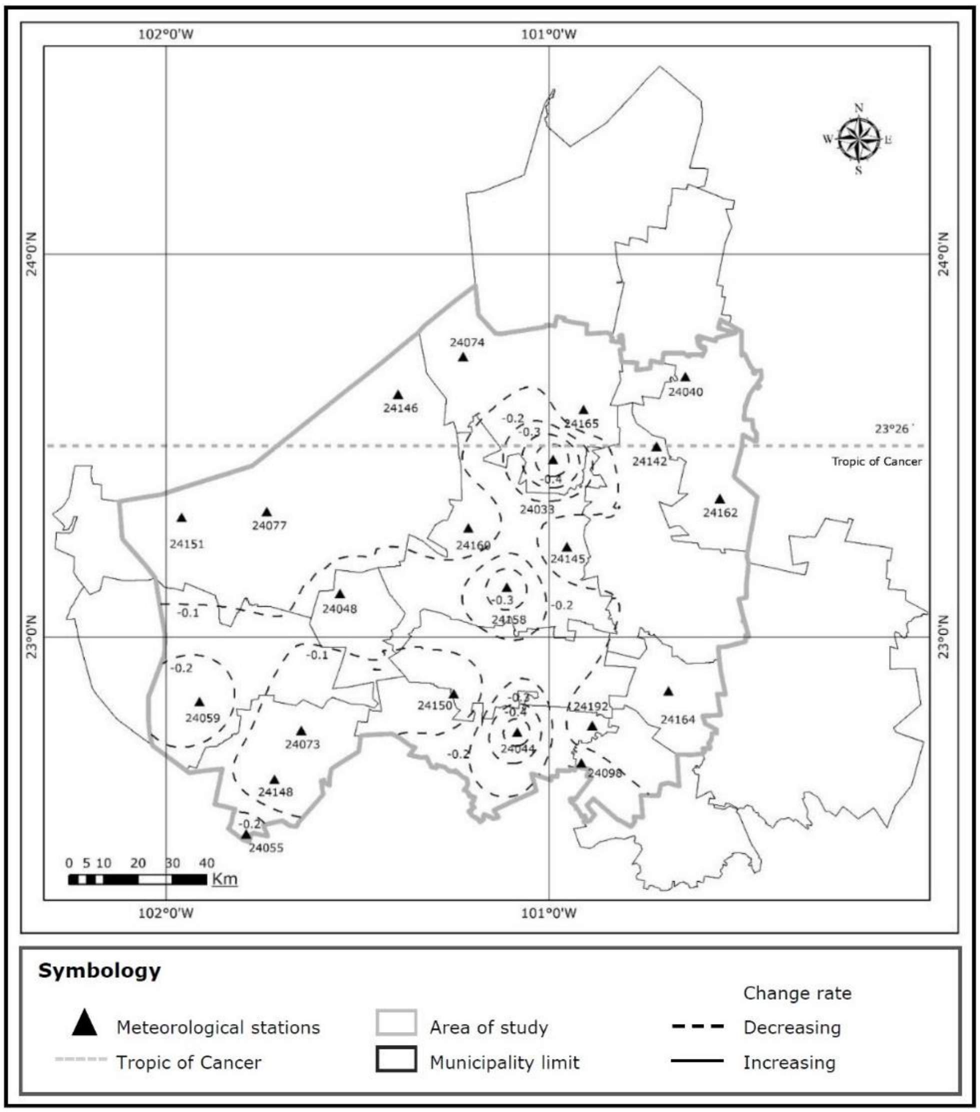

Figure 4. Result of the monthly trend analysis for rainfall (December 1975-2015).

Based on the increases detected in summer and the decreases in autumn, and that there are practically no trends in total annual rainfall, it is suggested that there is a temporary change in the behavior of rainfall, presenting a "temporary compensation" that maintains the total annual rainfall without a tendency to increase or decrease.

Table 2 presents the complete results of the trend analysis for total annual rainfall and total monthly rainfall. As mentioned above, three stations presented a change in the analysis of total annual rainfall. For example, station 24044, located in the municipality of Moctezuma, in the southern part of the AP, presents an annual decreasing rate of -2.75 $mm \cdot year^{-1}$, with decreases, in the monthly analysis, in spring (June) and autumn (December) of -0.07 and -0.45 $mm \cdot year^{-1}$, respectively, in the analyzed period. Station 24098, located southeast of the AP in the municipality of Villa de Arista, has an annual increase rate of 8.92 $mm \cdot year^{-1}$, with monthly increase rates in June (spring) and July and September (summer) of 0.99, 2.23, and 2.12 $mm \cdot year^{-1}$ respectively; there is also a decrease rate in December (autumn) of -0.13 $mm \cdot year^{-1}$. A temporal component of change is observed, in addition to the spatial component, because the increasing rates exceed the decreasing ones; therefore, it is suggested that when rainfall increases in spring and summer, there should be another area where there is a decrease in rainfall that compensates for the total annual rainfall, which, has no trend in the study period. For station 24165 located in the municipality of Catorce, north of the AP, an annual change rate of 8.10 mm·year^{-1} is observed, with increasing trends in monthly rainfall in the summer months. In some seasons (e.g., 24040), there were no changes in the total annual and total monthly rainfall trends; while for other seasons (e.g., 25055), temporary changes in total monthly rainfall are observed, which are not reflected in annual change rates. Although in general terms in spatial terms, there are few cases of changes in rainfall trends in the AP seasons, increases in rainfall in spring and summer predominate; while, in autumn there is a tendency to decrease it. The blank cells indicate that there is no increasing or decreasing tendency of rainfall.

Table 2. Results of the analysis of rainfall trends in the Altiplano Potosino Region (1975-2015).

Station	Annual	Winter			Spring			Summer			Fall		
		J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
24040													
24044	-2.75						-0.07						-0.45
24048				0.78			0.73						-0.12
24055										1.47			-0.25

24059													-0.30
24073										1.22			
24074													
24077													
24098	8.92						0.99	2.23		2.12			-0.13
24142										1.41			
24145													
24146													
24148							0.41	1.22		0.18			
24150													
24158							1.52						-0.37
24160					-0.55								
24033										1.49			-0.49
24151													
24162													
24164													
24165	8.10							2.14	1.29	2.08			
24192													

Temperature

The trend analysis of the time series of the annual data of average temperature presents that there are increases in the center (municipality of Charcas) with rates of 0.2 to 0.8 °C·year^{-1}; to the southeast (municipalities of Moctezuma, Venado, Villa de Arista, and Villa Hidalgo) and northwest (Municipality of Catorce) of the AP, with increasing rates from 0.2 to 0.6 °C·year^{-1} and 0.2 to 0.4 °C·year^{-1}, respectively. Meanwhile, decreases are presented in the center (municipality of Charcas) and west (municipality of Santo Domingo) of the AP with rates of -0.2 to -0.4 °C·year^{-1} (Figure 5). This indicates increasing trends in a wide extension to the center and southeast (which could be considered an effect at the regional level) and increasing and decreasing trends for the north and center of the PA, respectively.

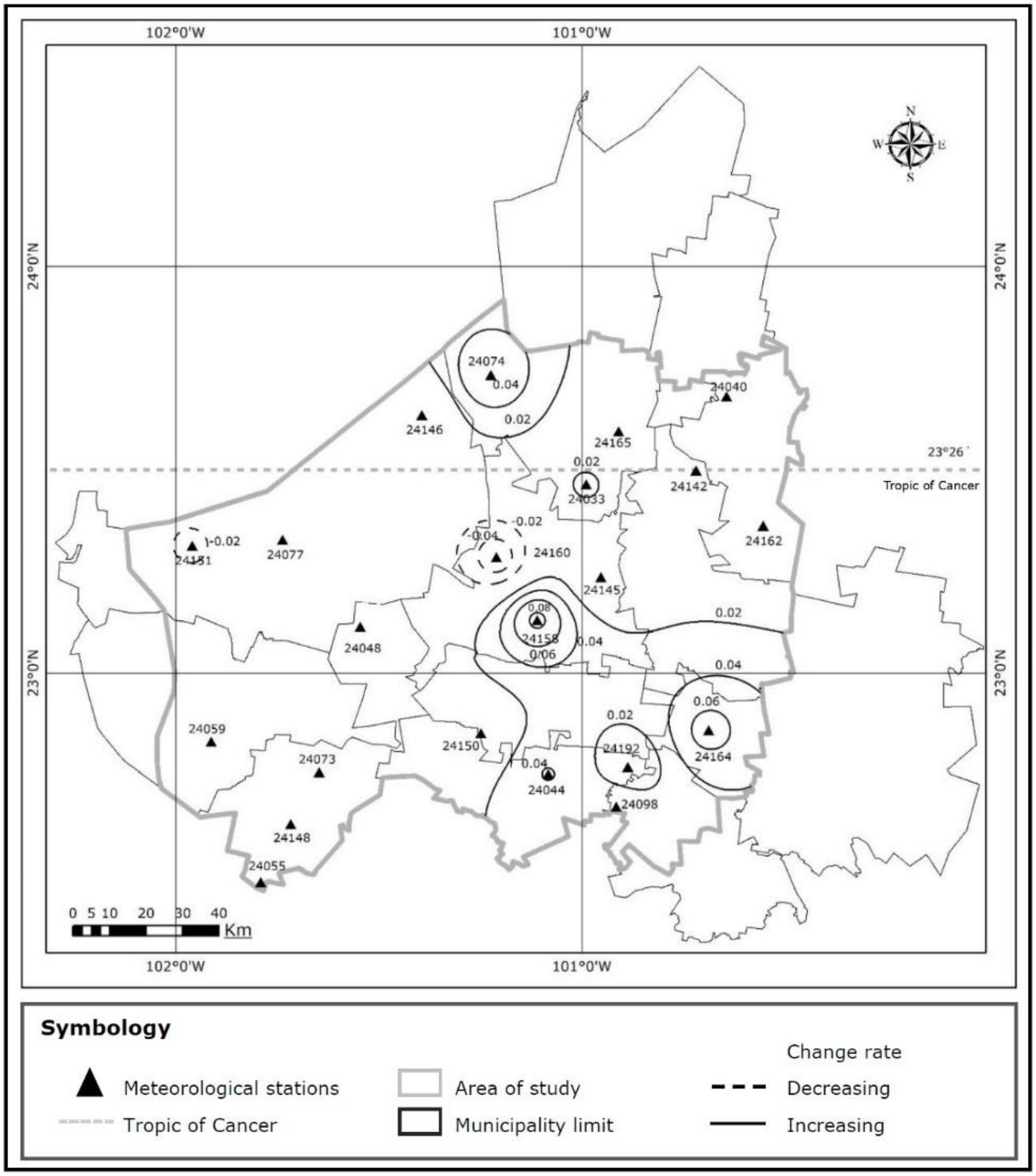

Figure 5. Result of the annual trend analysis for temperature (1975-2015).

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The analysis of trends for June (1975-2015) presents that there are increases in the northeast (Matehuala and Villa de la Paz) and northwest (Catorce) with change rates of 0.02 to 0.04 °C·year^{-1}; center (Charcas, Villa de Guadalupe and Venado) and southeast (Villa de Arista and Villa Hidalgo) with change rates of 0.02 to 0.10 °C·year^{-1} and, west (Santo Domingo) and southwest (Villa de Ramos) of the AP, with change rates of 0.02 to 0.08 °C·year^{-1}. Also, there is a decreasing trend in the center of the AP, mainly north of the municipality of Salinas de Hidalgo and west of the municipality of Charcas, with a change rate of between -0.02 and -0.04 °C·year^{-1} (Figure 6). Based on these results, the increase trends presented in the northeast and northwest can be identified as precise, while, in the center and southeast, it seems to indicate a trend with a regional behavior.

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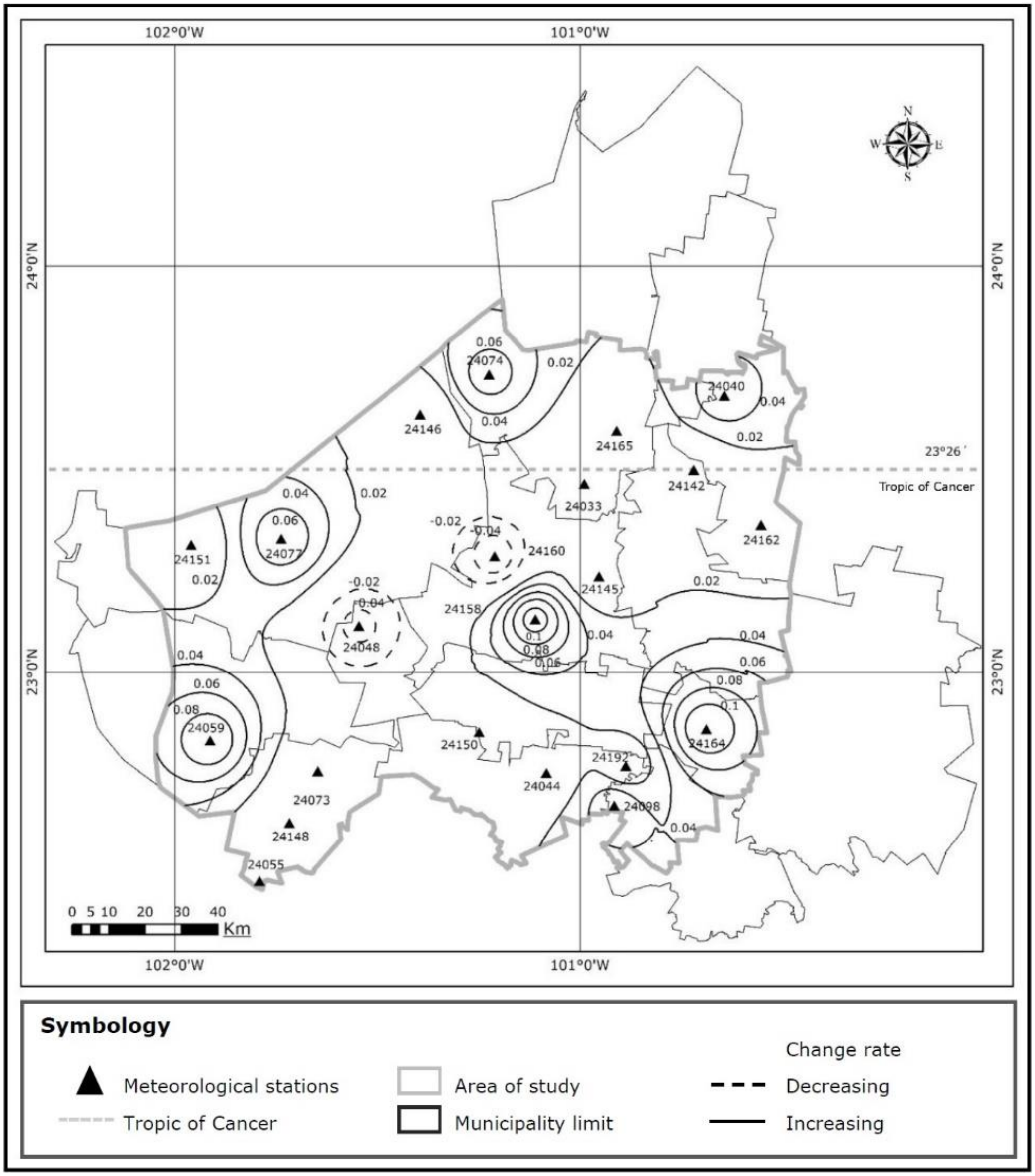

Figure 6. Result of the monthly trend analysis for average temperature (June 1975-2015).

The decreasing trends located in the central area of the AP (Charcas) suggest local effects that are related to the downward trend in the annual analysis, which would indicate that the monthly changes are being reflected on an annual basis.

The analysis of trends for December (1975-2015) shows there are specific increases to the south (Moctezuma) and southwest (Salinas de Hidalgo) with change rates of 0.02 to 0.04 °C·year^{-1}. Also, there are trends of precise decreases in the center (Charcas) and west (Santo Domingo) of the AP, with a change rate of between -0.02 and -0.04 °C·year^{-1} (Figure 7). These precise behaviors suggest that changes in monthly temperature trends may be due to local effects. The result of this month is the most representative in terms of the trend of temperature decrease. As mentioned above, the decreasing trends in the central area of the AP (Charcas) suggest local effects that are being reflected on an annual basis.

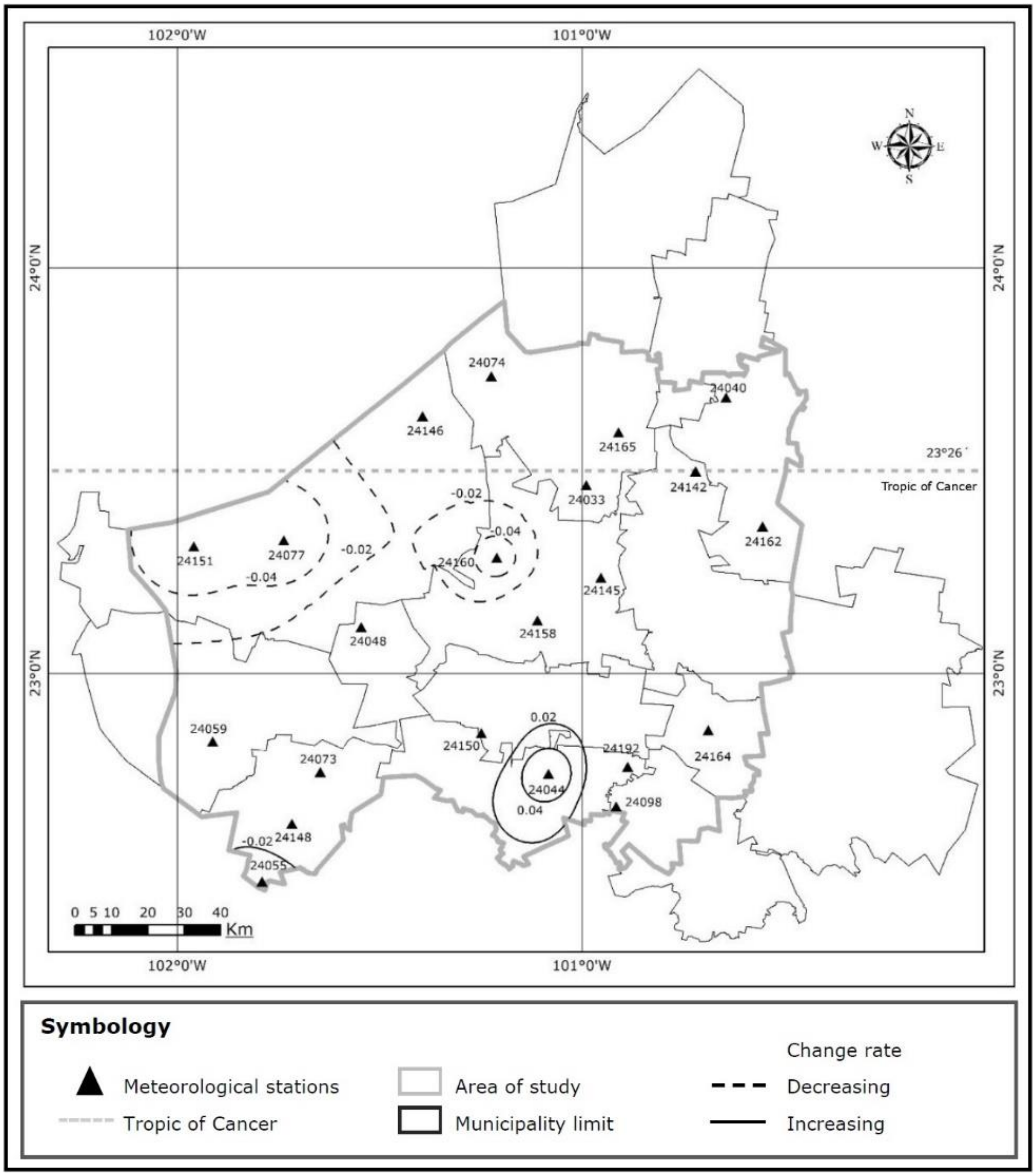

Figure 7. Result of the monthly trend analysis for average temperature (December 1975-2015).

Unlike the behavior observed in the monthly rainfall, trends in the analyzed seasons, changes in the trends of average annual, and monthly temperatures were more common. Table 3 presents the complete results of the trend analysis for average annual temperatures and monthly averages. It is important to point out that in 8 of the 22 stations analyzed there are changes in the average annual temperature trends: 6 of them with an increasing trend (from 0.02 to 0.08 °C·year^{-1}) and two decreasing ones (from -0.02 to -0.05 °C·year^{-1}), both cases without a spatial trend. In all months of the year, there are increasing and decreasing tendencies in most meteorological stations. Only two stations, 24142, located northeast of the AP in the municipality of Villa de Guadalupe, and 24150, located to the south in the municipality of Venado, do not have any temporal trends. Most meteorological stations tend to have an increase in average monthly temperatures, which supports the evidence of changes in average annual temperatures reported in Figure 5. The blank cells indicate that there was no increasing or decreasing tendency in the temperature.

Table 3. Results of the analysis of temperature trends in the Altiplano Potosino Region (1975-2015).

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Station	Annual	Winter			Spring			Summer			Fall		
		J	F	M	A	M	J	J	A	S	O	N	D
24040						0.06	0.05				0.05		
24044	0.04	0.06	0.07						0.04				0.06
24048						-0.06	-0.05						
24055		0.08	0.05										0.04
24059							0.10	0.09	0.08		0.10		
24073									0.03	0.03			
24074	0.06		0.09			0.08	0.07	0.11	0.09	0.05			
24077		-0.07			0.08	0.08	0.08	0.00	0.08	0.06		-0.06	-0.06
24098	0.04					0.02	0.06	0.06	0.06	0.03			
24142													
24145									0.04				
24146									0.03				
24148		-0.04		-0.06									
24150													
24158	0.08				0.10	0.10	0.11	0.11	0.11	0.08	0.10	0.08	
24160	-0.05			-0.05	-0.06	-0.08	-0.06	-0.06	-0.07	-0.06	-0.06	-0.05	-0.05
24033	0.02		0.04						0.03	0.02			
24151	-0.02					-0.02		-0.03			-0.04	-0.06	-0.05

Station	Annual	Winter			Spring			Summer			Fall		
		J	F	M	A	M	J	J	A	S	O	N	D
24162		-0.07	0.08	-0.08								-0.08	
24164	0.07				0.12		0.12		0.09				
24165			0.09		0.11								
24192						0.07				0.04			

Rainfall and temperature

When observing the results of the trends of the two variables analyzed, only two stations in which there were increasing and decreasing trends in annual rainfall presented a changing trend in temperature. In the case of meteorological station 24044, it presented a decreasing trend in annual rainfall of -2.75 mm·year^{-1} and for average annual temperature, an increase of 0.04 °C·year^{-1}. In meteorological station 24098, there was a trend of increase in annual rainfall of 8.92 mm·year^{-1} and for average annual temperature, an increase of 0.04 °C·year^{-1}.

All the meteorological stations presented a changing trend for any of the variables analyzed, either annually or monthly, except for the meteorological station 24150, located in the municipality of Venado, which does not present any change in the trends analyzed.

The results show that in January, February (winter), May (spring), October, and November (autumn) there are increasing and decreasing tendencies in temperature in some stations while no trends were identified in the rainfall variable for any meteorological station analyzed, which indicates that temperature changes have not had an influence on the behavior of rainfall for the aforementioned months. In March (winter) and August (summer) there are increasing and decreasing changes in the trends of temperature and increasing changes in the tendency of rainfall in one single station for each of the months mentioned; but this does not coincide with the station where there are changes in the trend of temperature. Thus, one can infer that there is no spatial relationship in the behavior of the trends of both variables. For April, June (spring), July, September (summer), and December (autumn) there are increasing and decreasing changes in the variables of rainfall and temperature coinciding in at least one same station in their different combinations of trends. For example, in April, station 24160 presents a decreasing tendency of temperature and rainfall with -0.06 °C·year^{-1} and -0.55 mm·year^{-1}, respectively; while for December, there are temperature increases of 0.06

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and 0.04 °C·year^{-1} and rainfall decreases of -0.55 and -0.25 mm·year^{-1} for stations 24044 and 25055, respectively, among other cases.

For trend changes in monthly rainfall, it is observed that there is no spatial pattern. In terms of temporality, the increasing trends are mainly present in spring and summer, specifically in June and September, respectively; the decreasing trends are present in autumn, exclusively in December.

In the results of the analysis of trends in monthly temperatures, it is observed that there is no spatial pattern, in all months there are significant increases and/or decreases in at least 3 meteorological stations. In terms of temporality, the increasing trends occur mainly in spring and summer; decreasing trends occur mainly in the autumn and winter months. It should be noted that particularly in station 24160, located in Charcas, there is a very marked decreasing trend (in all seasons of the year, except in January and February), which can be interpreted as a local effect. The trends of temperature increase predominate in the AP which agrees with what was reported by Martínez (2007), who mentions that, based on the results of climate change models, significant temperature increases are expected in Mexico during the present century.

Conclusions

After statistically evaluating 41 years of information corresponding to annual and monthly rainfall and temperatures in the meteorological stations located in the AP region, changes in annual rainfall trends were detected locally in three stations (24044, 24098, and 24165); while, in the analysis of monthly rainfall, there was greater variability in trends, without any spatial pattern having been detected. Temporarily, it was detected that, in the spring and summer months, there is an increasing tendency in the monthly rainfall, while in autumn, specifically in December, there is a clear decreasing trend of rainfall. It is suggested that, between the periods of increase and decrease, there is compensation, in such a way that it is not yet reflected and, therefore, an increase and/or decrease in the annual temporality is detected significantly, except for the aforementioned stations.

About temperature assessment, either annually or monthly, greater variability in the trends was detected. There is a greater reflection in the annual variability, supported by monthly changes; or where appropriate, there are monthly variations that are not yet reflected in the annual trends. This variable suggests greater sensitivity concerning the rainfall variable and future repercussions on rainfall behavior should be evaluated. Concerning the results obtained, there is a trend of increase in the average annual temperature in the southeast area of the AP, and that is also a consequence of the same behavior observed in increasing trends of the average monthly temperatures, in the same region for June and September. Concerning the decreases detected in the annual and monthly analyses, the results suggest specific behaviors.

On the other hand, the historical information available is a great limitation for this type of analysis, because, if there were a greater quantity and quality of historical information continuously, an analysis with a greater degree of spatial and temporal resolution could be carried out.

The analysis of trends of rainfall and temperature time series is a first step to identifying the causes that are involved in the changes of temporality and spatiality in the meteorological phenomena analyzed.

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