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The influence of the regional climate in a lagoon in northeastern Mexico

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RESUMEN

El clima se manifiesta sobre la Tierra a tres niveles: aquel que se ejerce por el intercambio energético Sol-Tierra, el regional por la relación: Troposfera-Tierra (cuencas) y el local: que incluye los gradientes climáticos de las cuencas endo y exorreicas. La información de estos dos últimos sobre las lagunas costeras es escasa y sólo ha sido aplicada para definir el marco descriptivo local del área de estudio. En consecuencia el presente trabajo se enfoca a determinar a nivel del clima regional la influencia cualitativa y cuantitativa sobre los tres climas locales acotados en una cuenca exorreica ubicada al NW del Golfo de México, en uno de éstos se localiza la Laguna Costera de Tampamachoco. El clima regional influye sobre el clima local delimitando temporalmente las estaciones en latitudes tropicales como el Golfo de México, de acuerdo al origen y volumen de la precipitación; utilizando los límites de los regímenes de precipitación, propuestos en la clasificación de Kõppen modificada por García (1964), corroborados con la frecuencia e intensidad de los vientos dominantes; durante un período secular que abarca de: 1922 a 1994: 1) *Nortes*: de noviembre a febrero con 222 mm en promedio, 2) *Secas*: en marzo y abril 92 mm en promedio y 3) *Lluvias*: de mayo a octubre con 1071 mm en promedio. Se acotan espacialmente tres climas locales como respuesta al factor, básicamente orográfico, que corresponden al tipo BS_1, Aw_1 y Aw_2. El tipo Aw_1 abarca el 35% de la cuenca y se localiza en toda la planicie costera, el Aw_2 constituye el 55% y se ubica en toda la porción de sotavento de la Sierra Madre Oriental y la Sierra de Tantima y el BS_1 en la porción de barlovento de la Sierra de Tantima con el 10%. Las diferencias espaciales y temporales de la precipitación en toda la cuenca, conforman, dos escurrimientos originados en diversas partes de la misma, como consecuencia del clima regional sobre el clima local, de los cuales influyen de manera decisiva tanto en la morfología como en el comportamiento hidrológico de la laguna. El Río Tuxpam constituye un afluente permanente a la laguna con fluctuaciones en los gastos derivados de las temporadas (marzo: 695 m^3/s; julio: 965 m^3/s y septiembre: 1825 m^3/s) y tienen su origen en áreas climáticas más húmedas y el Río Santiago, cuyo aporte sólo se registra en la temporada de lluvias, se origina en el área de clima seco.

ABSTRACT

The climate affects the Earth at three levels: the relationships between the Sun-Earth energy interaction, the regional climate by the troposphere-Earth relationship (basins) and the local climate by the climatic gradients in endo and exorreic basins. The information on coastal lagoons provided by the last two is scarce and has only been used to define local descriptive frameworks for particular study areas. As a result of this, this paper aims to determine the qualitative and quantitative influence of regional climate on the three local climates defined in an exorreic basin in the northwestern Gulf of Mexico at the level of regional climate. The coastal lagoon of Tampamachoco is located in one of these local climates. The regional climate affects the local climate and defines the seasons in tropical latitudes (the Gulf of Mexico), in accordance with the origin and amount of the rain. The seasons are defined with respect to the rainfall regimes presented in Köppen's classification, later modified by García (1964), and corroborated with the frequency and intensity of the prevailing winds from 1922 to 1994. These are: 1) *the season of northers*: from November to February with an average of 222 mm, 2) *the dry season*: in March and April with an average of 92 mm and 3) *the rainy season*: from May to October with an average of 1071 mm. Three local climates are defined in response to an orographical factor, as BS_1, Aw_1 and Aw_2. Type Aw_1 corresponds to 35% of the basin and is located over the whole coastal plain, type Aw_2 makes up 55% over the leeward portion of the Sierra Madre Oriental and the Sierra de Tantima mountain ranges and type BS_1 makes up 10% over the windward portion of the Sierra de Tantima. The spatial and temporal differences in the rainfall over the whole basin produce two waterways with multiple sources as a result of the regional climate over the local climate, that affect the shape and hydrological behaviour of the lagoon. The Tuxpam River originates in the most humid climatic area and is a permanent supply to the lagoon with changes in discharge related to the seasons (March 695 m^3/s, July 965 m^3/s and September 1825 m^3/s). The Santiago River, of which the supply is registered only in the rainy season, has its origin in a dry climatic area.

1. Introduction

One of the main problems to be considered when dealing with the influence of climatic factors on ecosystems is that of scales, as the relationships between Sun-Earth, regional, or and local climates have not been defined to date. This results in authors establishing their own spatial and temporal limits.

Time scales vary, among others, from days, months, seasons and years to the secular time scale. However, in no case does one count with a spatial and temporal climatic definition that is useful to establish the spatial-temporal limits of the climate.

The Sun-Earth relationships, regional and local climates are defined in this paper with respect to latitude, altitude, topography, and land and water distribution. Marine currents and the climatic parameters of temperature, rainfall, humidity, wind direction and strength, and atmospheric pressure, which directly affect ecosystems, were not considered as they change in response to atmospheric variations depending on the inertia with which energy is transferred between the Sun-Earth relationships, regional and local climates. The first globalizes the behaviour between the Sun and the Earth, as a source of heat that changes with regard to geographical position and the size and intensity of anticyclonic cells. The high pressure cells of the Bermuda-Azores in the Northern Atlantic and the Northern Pacific give rise to the Trade Winds and the Westerly Winds which, together with masses of modified polar air, affect Mexico and its coastal ecosystems (Mosiño, 1964b, 1966; García, 1967; Herman and Goldberg, 1978). The seasonality of the winds is reflected in the annual and secular scales (Herman and Goldberg, 1978).

The regional climate directly affects the local climate on a temporal scale, and is related to the behaviour of the climatic variables of circulation of local winds, environmental temperature, evaporation and rainfall. The volume of the rivers that travel through the coastal plains, where the coastal lagoons are located, depends on this last variable. The temporality of the local climate is reflected in monthly, seasonal, annual and secular scales (Sánchez-Santillán and de la Lanza, 1994; Sánchez-Santillán, 1994).

The local climate defines geographical areas with respect to factors such as latitude, orography, land and sea distribution, marine currents and the paths of storms.

Mexican coastal lagoons systems are shallow bodies of water that are affected by the contribution of epicontinental waters from permanent and temporary flows originated in the watersheds of exorreic basins, as well as by the input of tidal water and the rate of evaporation that results from high temperatures. These systems are ruled mainly by the local climate and, on a temporal scale, by the regional climate.

Two aspects of climate variation are at present of central interest in Ecology: 1) the descriptive-quantitative aspect and 2) the intra and interspecific relationships within biological processes (Livingston, 1987). Thus, the climatic variability derived from the regional climate in both the seasonal and the annual scales results in changes in the local climate. This explains how coastal ecosystems present a hydrological mosaic in the patterns of spatial and temporal behaviour, that is reflected in turn in the spatial and temporal distribution of communities (Holland, 1985; Warrent, 1985; Pearson and Barnett, 1987).

Local and regional climate studies in coastal systems are not carried out in the monthly scale, since as climatic changes in temperate and tropical latitudes occur on a seasonal scale, as can be seen in the patterns of salinity and temperature (Harris, 1980; Livingston, 1987; Sánchez-Santillán, 1994; Sánchez-Santillán and De la Lanza, 1994).

2. Background

Among the regional climate studies carried out in Mexico, there is a good amount of research on the lower troposphere. Main aspects include the general circulation of the winds (Mosiño, 1959; García, 1967), rainfall and its causes (García, 1970, 1974), cyclones, tropical storms and northers (Mosiño, 1959, 1964a, 1964b, 1966; Jáuregui, 1967, 1968, 1989; Gray, 1979), the association of climatic types with vegetation (Mosiño, 1966; García, 1970) and the dry seasons and their possible causes (García and Mosiño, 1966). Several papers deal with the relationship between the local climatic behaviour in temporal series of several consecutive years and populations, in temperate systems. In Mexico, however, there is no such information and there are only a few papers that present long-term data, such as that of Sánchez-Santillán and de la Lanza (1994) on climatic variations and their effect on the distribution pattern of temperature and salinity in Laguna de Huizache y Caimanero, Sinaloa, and on the bathymetric variations caused by the dry seasons when the lagoon loses 60% of its total volume. De la Lanza (1992) has pointed out that the repetitive occurrence of the ENSO phenomenon results in regional climatic variations that are seen as positive and negative alterations in rainfall and result in dry periods and heavy rainfall at the local climatic level. These last affect erosion, sedimentation, transport, construction, devastation, floods and transgression of beaches, among others. Increases in the average level of the sea of up to 45 cm have been registered during maximum level of the ENSO years along the coasts of the Mexican Pacific. Horn and Allen (1976) have proposed a classification of coastal systems based on a combination of biotic and abiotic parameters, including the size of the basin, the size of the mouth, the diversity of fish and the associations between populations. With respect to the fish fauna, there are several papers from temperate areas on recruitment and climatic effects (Cushing, 1982). However, they do not include a discussion on climatic complexity.

3. Objectives

The objectives of this paper were: to characterize climatically a NE basin of the Gulf of Mexico that lies between temperate and tropical latitudes and has a bi-seasonal variation: Winter and

Summer, that is reflected in three climatic seasons grouped as the rainy season, the season of northers and the dry season. These are defined with respect to rainfall, the intraestival dry season, temperature and the prevailing winds, and are the result of the orographical and hydrographical characteristics of the area, and to establish the climatic seasons and their effect on temperature, rainfall and winds in Laguna de Tampamachoco, Veracruz, in the Gulf of Mexico.

4. Materials and methods

The topographical and use of the land and vegetation charts (scale 1:250 000) (INEGI, 1983a, 1983b, 1983c, 1983d) were used to define the Tamiahua-Poza Rica hydrological basin. It was thus defined from the watershed of the Sierra Madre Oriental mountain range to the coastal plain where the lagoon is located.

The orographical and hydrographical parameters of the basin were consulted in the hydrographical, topographical and edaphological charts (scale 1:250 000) (INEGI, 1982a, 1982b, 1983c, 1983d, 1983e, 1983f).

The climatic characterization of the basin was carried out in accordance with the criteria proposed by García (1964), using rainfall and atmospheric temperature data registered by the Servicio Meteorológico Nacional (SMN), the Secretaría de Agricultura y Recursos Hidráulicos (SARH) and Comisión Federal de Electricidad (CFE) from 1922 to 1990. Information of 12 meteorological stations was collected in the Tamiahua-Poza Rica basin (Fig. 1) and is considered long-term data as it covers more than 30 years. The data was then subjected to the homogeneity test with the purpose of filling blank spaces and having a continuous series to facilitate the statistical analysis. This test takes the three greatest and the three smallest values around a missing value and obtains a statistical average.

Together with the climatic regionalization, ombrothermal diagrams were made superimposing the ombric curve (curve of the rains) on the thermal curve, at a scale of $2t + 28/2$ corresponding to the specified climates. These diagrams indicated the months for which the ombric curve lays above the thermal curve and those for which it lays below the thermal curve. The first are considered wet months and the second dry months. (García, *et al.*, 1983; Pagney, 1982).

The regime of rains and the mid-summer dry season were established, parting from the gamma function of the rainfall data, in accordance with García (1964). The mid-summer dry season refers to the reduction in the number of days with rains greater than 0.1 mm during the rainy season. Both were calculated for the years of hydrological sampling of 1979, 1980, 1985 and 1986 and for the secular period of 1922 to 1990.

The deficit of rain was estimated taking the area above of the funicular polygon formed by the monthly ordinates between the two maxima of rainfall and the line that joins the extreme points. This was considered to be representative of the recess (García and Mosiño, 1966). The fraction in percentage that resulted from dividing the area representative of the "deficit" by the total rainfall from May to October was selected as indicating the intensity of the relative or intraestival dry season (García and Mosiño, 1966).

The absolute and relative monthly frequencies of the speed, and direction of the wind were calculated from data collected by the meteorological stations of the SMN in the Tamiahua-Poza Rica basin. The frequency and speed of the wind are represented as bars of which the length is proportional to the frequency of the wind. These were placed with respect to direction on an octagon of the rose of the winds. The speed was calculated using Beaufort's scale and was represented as arrows over the bars. The percentage of calm weather was placed in the center of the rose of the winds as proposed by García (1992).

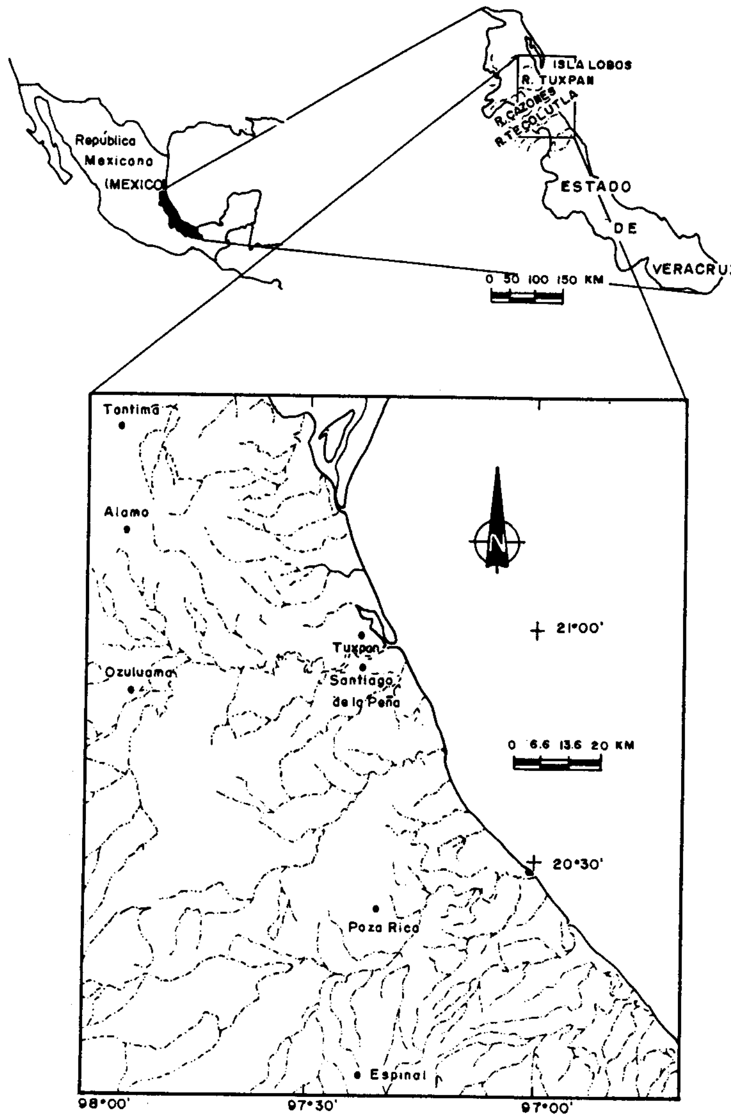

Figure 1. Localization of study area and meteorological stations.

The climatic behaviour of the Tamiahua-Poza Rica basin is graphically shown on charts (scale 1:250,000) of distribution of humidity, temperature, prevailing winds, orography, hydrography and climatic regionalization, in accordance with the methods and criteria derived from the modified system of climatic classification proposed by Köppen, 1948 (García, 1964).

The climatic seasons were established in accordance with the origin of the rains which corresponds to the Trade Winds, cyclones and tropical storms in summer, the northers in winter during the transition phase between both, and the occasional separation of clouds from the Trade Winds system of currents that start moving north in the dry season. The date and rainfall amount were considered following the criteria proposed by García (1964) for the rainy season.

5. Results and discussion

Climatic characterization of the Tamiahua-Poza Rica basin

1) Atmospheric Temperature

The temperature behaviour of the Tamiahua-Poza Rica exorreic basin was established with respect to the altitude (Fig. 2) and the geographical location of nine meteorological stations located within this area. The annual averages for the atmospheric temperature in the basin, as well as for each of the stations during the period from 1922 to 1990, corresponding to: for a temperature of 23.9°C (Aw_2); for a 24.3°C (Aw_1) and for 27.8°C (BS).

Five lapse rates were defined from the local lapse rates, and this last one was calculated using the equation:

$$X = \frac{\Delta t}{\Delta h} x100 \qquad (1)$$

where:

Δt = temperature difference

Δh = altitudinal difference

The orographical criterium was used to establish the pairs of stations: to a gradient between Aw_1 and Aw_2 correspond 0.35 and between Aw_2 and BS correspond 0.40.

The average lapse rate for the basin was 0.35 and differed by 0.30 from the world lapse rate, which is 0.65°C Hm. This means that the temperature in the basin decreases by 0.35°C every 100 m above sea level.

Köppen (1948) proposed a worldwide temperature zonation based on temperature data from different localities, and established a world gradient in which the effect of the local orography on the lower troposphere was not considered. García (1967) suggested a formula to establish a lapse rate for each locality, with regard to the orography and the steepness, and to explain the presence of cold and temperate climates in tropical areas. The Tamiahua-Poza Rica basin is located in a tropical area from the geographical point of view. However, all meteorological stations presented thermal levels that placed them within the temperate climates, for which reason the criterium that was followed in this project was the orographical one, and the specific lapse rate calculated for the basin was 50% smaller than that corresponding to the world, in which the orographical characteristics particular to the area were not considered.

The smallest lapse rate of 0.2 was calculated for the area of the coastal plain where Laguna de Tampamachoco is located. This differed from those of 0.5 for localities with a greater altitude, as the coastal plain is wide and flat in contrast with higher areas that are narrower and markedly sloping.

The orography is quite uneven to the SW of the basin and there is a lack of meteorological stations, because of which it was necessary to calculate some temperature values from the local lapse rate established for the study area using the equation:

$$\text{Temp. of the high place} = \text{Temp. of the low place - dif. in altitude } x\frac{\text{lapse rate}}{100} \qquad (2)$$

Values were substituted and the following was obtained:

$$\text{Xicotepec} = 25.1°\text{C-}(1500\text{-}111)\ x\frac{0.35}{100} = 20.3°\text{C} \qquad (3)$$

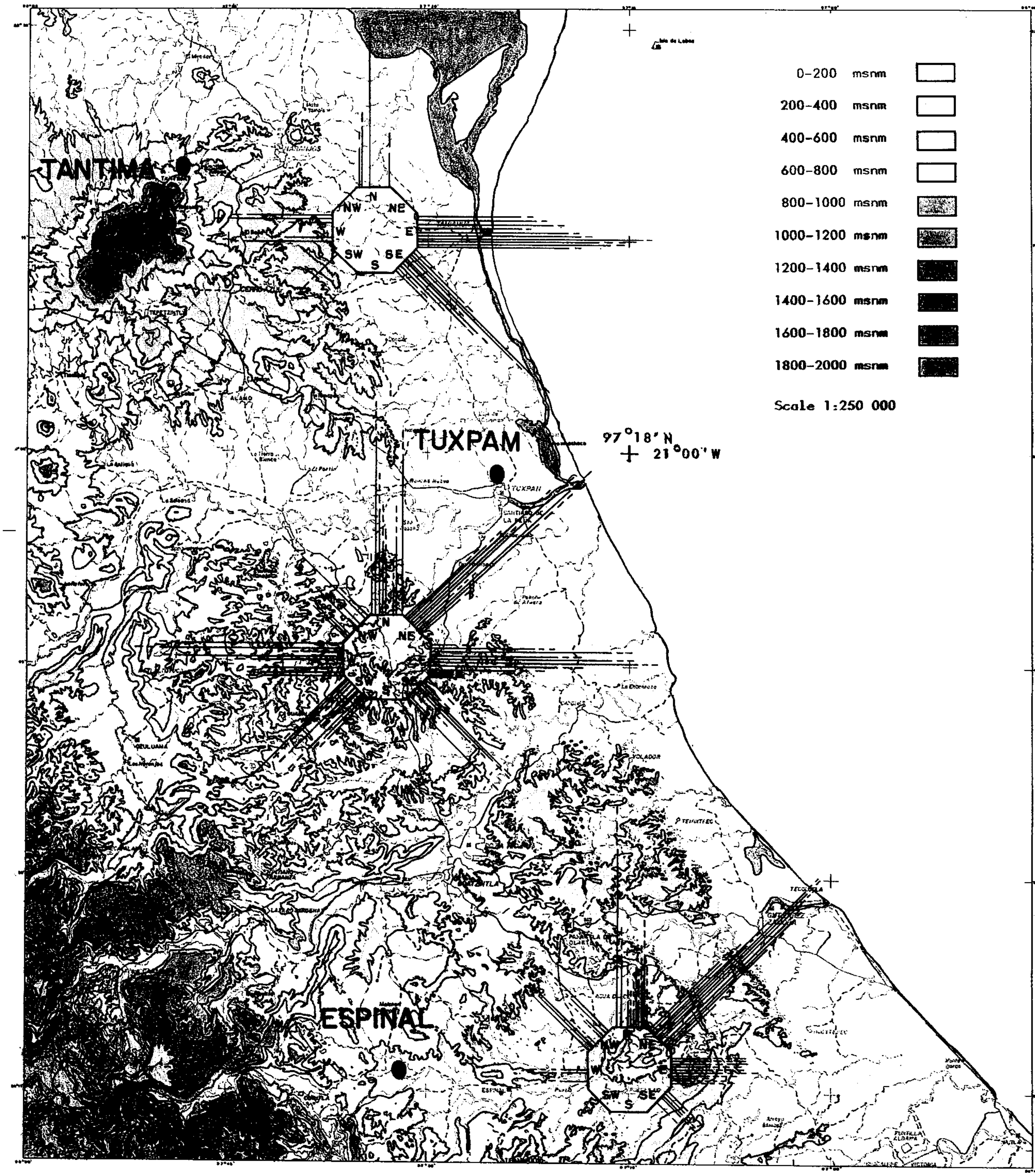

Figure 2. Topographical chart and frequencies of the speed, intensity and direction of the wind

A temperature of 20.3°C was calculated for the highest region of the Sierra de Xicotepec, where the altitude varies from 1280 to 1400 m above sea level.

The isotherms that correspond to 21°C, 22°C, 23°C, 24°C and 25°C that define the five areas, were calculated from the equation:

$$h_{Tx} = \frac{T_{inf} - t_x}{\frac{\Delta t}{\Delta n}} \tag{4}$$

t_{inf} = inferior temperature

T_x = known temperature

Δt = temperature difference

Δn = altitudinal difference

Thus, in order to establish the 22°C isotherm, the following was substituted:

$$\frac{25.1 - 22}{0.35} \times 100 = 885.7 \text{ m above sea level} \tag{5}$$

The altitude of 885.7 was added to the 111 m above sea level corresponding to the altitude of the locality of Espinal and the 22°C isotherm was established at 996.7 m above sea level. For the other isotherms, the following was substituted in the formula:

$$\frac{1^{\circ}C \times 100}{\text{lapse rate}} = 2857 \tag{6}$$

This factor of altitudinal increase was added or substracted according to the case, and the other isotherms were obtained as is shown in Table 1:

Table 1. Isotherms calculated considering the orographical criterium for the Tamiahua-Poza Rica basin.

Isotherm	Altitude
25°C	425.3 - 285.7 = 139.6 m
24°C	711.0 - 285.7 = 425.3 m
23°C	996.7 - 285.7 = 711.0 m
22°C	996.7 m
21°C	996.7 + 285.7 = 1282.4 m

The five areas and the percentage of the approximate area of soil cover were established considering the altitude of each isotherm and were placed within the altitude intervals.

The temperature range between the coldest and the hotest months varied in accordance with the geographical location, the altitude and the type of climate. The following averages for 70 years were calculated for each locality within the Tamiahua-Poza Rica basin: to a local climate Aw_2 corresponds to an oscillation of 9.08°C with a climatic name extreme, Aw_1 with an oscillation of 7.5 with a small oscillation and BS with a range oscillation of 10.1°C or more an extreme.

The temperature range was extreme over 90% of the area as a result of the altitude differences between the Sierra Madre Oriental and the coastal plain, which cause the wind to change direction and create the damming effect. This was more marked during the winter, or northers season (November to March), when outbreaks or masses of modified polar air were registered on the mountain range and contributed to the cooling of the area. The northers included the four types proposed by Mosiño (1988): 1) deep and humid, 2) deep and dry, 3) shallow and humid and 4) shallow and dry. This is the result of the four types of northers directly affecting the whole basin. The temperature range was directly related to the thermal proportion; the temperature range increasing gradually from the coastal plain and the area of influence of the lagoon and Gulf of Mexico, up to higher altitudes.

The thermostatic effect of the water was detected mostly on the coastal plain where Laguna de Tampamachoco is located, as the result of the great heat capacity of the lagoon and Gulf of Mexico, and somewhat in the area of the mountain slope. The average frequency of northers observed on the daily charts was of 26 annual events with a duration of 2 to 7 days each throughout the four months of the season.

The thermal conditions for each locality in the Tamiahua-Poza Rica basin were established taking into account monthly temperature data, the annual average temperature, and the temperature of the coldest and hotest months. The limits established in the Modified System for type A climates dictate that the annual average temperature must be greater than 22°C, that of the coldest month must be either over or below 18°C and that of the hotest month is not specified. The annual and monthly average values for each thermal condition are presented in Table 2.

Table 2. Annual average temperature and coldest month of each local climate.

Local climate	Annual average temperature (°C)	Temperature of the coldest month (°C)
Aw_2	24.3	19.1
Aw_1	24.5	19.6
BS	27.8	18.8

With respect to temperature, all localities within the Tamiahua-Poza Rica basin were warm, with the exception of Ozuluama which is located in a small mountain range 50 km to the west of Tampamachoco Lagoon, and parallel to the Sierra Madre. This small mountain range constitutes a ridge that deflects the Trade Winds, that at this point descend and become dry.

2) Prevailing Winds

The frequency and speed of the prevailing winds in the Tamiahua-Poza Rica basin helped establish the origin of the yearly rains, as well as the thermal influence of the masses of modified polar air over the area. This influence was calculated for three localities at different altitudes, latitudes and positions with respect to Tampamachoco Lagoon and the Gulf of Mexico: 1) the Sierra de Tantima, 2) the coastal plain of Tuxpam and 3) Espinal, after which a northwesterly transect was established (Table 3, Fig. 2).

An easterly dominant component was registered throughout the year (Trade Winds) in the Sierra de Tantima (local climate type BS) with a frequency of 52.3% and an average intensity of 2 to 4 m/s (Trade Winds). The second component was southeasterly with an average speed of 2 to 4 m/s. During November, December, January and February the winds arrived from the N, W and NW (the "northers") and represented 5.8% with an speed of 2 to 4 m/s, as is shown in Table 3 (Fig. 2). This indicates that the Trade Winds come in from the east during the rainy season in summer and from the north in winter. However, the presence of this mountain slope causes both, the Trade Winds and northers, that carry a great amount of humidity gathered while passing over the Gulf of Mexico, to undergo moisture lifting and precipitation after discharging it.

Three dominant components were detected throughout the year on the coastal plain of Tampamachoco Lagoon (local climate type Aw_1). These were from the E, NE and N with an accumulated frequency of 63.4% and an speed of 6 to 8 m/s from March to October, and greater than 8 m/s during the winter months (season of northers). With respect to the directions W, SE, NW and NE, the total frequency represented 35% throughout the year, with an speed of 4 to 6 m/s during the summer (rainy season) and an increase up to 6 to 8 m/s during the winter (Table 3, Fig. 2). This indicates that the local winds are formed by the Trade Winds and, as the coastal plain is wide in this area, they become subhumid.

The most frequent component (58.9%) to the south of the basin in the area of Espinal (local climate type Aw_2) where the land starts to rise, was from the NE (Trade Winds) with an average speed of 2 to 4 m/s throughout the year. The components from the N and NW (northers) were grouped in the second place with an overall frequency of 28%, a greater occurrence from November to March and a decrease from April to October. The frequency and speed of the easterly winds were 8.7% and 2 to 4 m/s respectively, and homogeneous throughout the year. The SE and W winds represented 3.7% and were registered only from January to April. Due to the mountains, the moist air is deflected upwards and cools rapidly giving rise to heavy rains, which explain the presence of humid climates.

Table 3. Direction and speed of the prevailing winds in different localities of Tamiahua-Poza Rica Basin.

Direction	Relative Frequency	Speed (m/seg)	Beaufort's number
Dominant	winds in the Sierra de	Tantima	
E	52.3%	2 to 4	2
SE	30.9%	2 to 4	2
W	10.8%	2 to 4	2
N	4.6%	2 to 4	2
NW	0.8%	2 to 4	2
S	0.4%	2 to 4	2
Dominant	winds on the coastal	plain of Tuxpam-	Tampamachoco
E	22.4%	more than 8	5
NE	21.3%	6 to 8	4
N	19.7%	more than 8	5
W	16.0%	4 to 6	3
SE	10.0%	4 to 6	3
NW	7.4%	4 to 6	4
NE	2.1%	6 to 8	4
Dominant	winds in the locality	of Espinal	
NE	58.9	2 to 4	2
NW	16.7	2 to 4	2
N	11.7	2 to 4	2
E	8.7	2 to 4	2
SE	2.5	2 to 4	2
W	1.2	2 to 4	2

The deflection of the winds to the SE and NW that was registered in Espinal and Tantima respectively, was caused by the position and height of the mountains which affect the lower troposphere and modify the air flow that, in turn, affects the physical processes in the air, as Mosiño (1966) and García and Mosiño (1966) mentioned. This retains the air currents which are then deflected and lifted by convergence, after which there is an adiabatic heating on descent. However, no deflections of the wind were detected over Laguna de Tampamachoco, as it lies outside the area of the orographical effects caused by the Sierra de Tantima.

The E and NE winds registered along the transect from April to October were formed by the northeasterly and southwesterly Trade Winds and by the Bermuda-Azores semipermanent high pressure cell located in the North Atlantic Ocean over the Bermudas. The northwesterly winds are due to the deflection caused by the mountains. Northerly winds originated by the masses of modified polar air that are formed to the south of Canada and the United States were registered from November to March. Other winds were formed by the bifurcation caused by the local mountains.

Both high pressure cells are displaced as the result of the change in the inclination of the Sun's rays from one season to another, in the Intertropical Convergence Zone twice per year. The cells move to the north from May to October and to the south from November to April in the Northern Hemisphere. This gives rise to two climatic seasons in subtropical latitudes, Summer and Winter, together with a transition season, and explains the three existing seasons: the rains from May to October, the season of northers from November to February, and the dry season from March to April.

3) Rainfall

The average annual rainfall for 1922 to 1994 in the basin was grouped into four intervals with respect to the amount of rain: 1) less than 1400 mm was registered in the area of the coastal plain between 0 and 100 m of altitude, including the meteorological stations of Tuxpam and Isla Lobos with 1213.3 mm, Santiago de la Peña with 1390.5 mm, Poza Rica with 1103.7 mm and Papantla de Olarte with 1169.9 mm, 2) more than 1400 mm was registered to the SW where the topography is more irregular between 200 and 2400 m of altitude, including Espinal with 1426 mm and Ozuluama with 1407.6 mm, 3) a small area with 1800 mm was registered in the Sierra de Tantima to the NW of the basin, and 4) the station of Alamo with 687.6 mm to the south of this mountain range (Fig. 3).

The amount of rain that is registered in different areas within the basin varies because the orographical rain shade effect caused by the Sierra de Tantima. The Trade Winds originate the greatest amount of rain which is registered on the windward side of the mountain. These warm and moist winds cool air and humidity condenses when they rise up the top side of the mountain, after which they descend as dry winds. This effect causes the streams that are formed in the leeward side of the watershed of the Sierra de Tantima to be ephemeral and small, for which reason they do not provide the Boca de Galindo area of Tampamachoco Lagoon with epicontinental water.

The effect of the orographical rise in the central and southwestern regions of the basin where the Sierra Madre Oriental begins, explains both the increase in humidity with respect to the coastal plain and the increase in the discharge of water of the Tuxpam River. This last provides a permanent source of epicontinental water to Laguna de Tampamachoco through the Estero de la Mata.

The three areas were defined with respect to the isohyets calculated from the ratio R/T in which the annual rainfall and the annual average temperature were used. In both cases the average was calculated for 1922-1994 for all meteorological stations (Fig. 3).

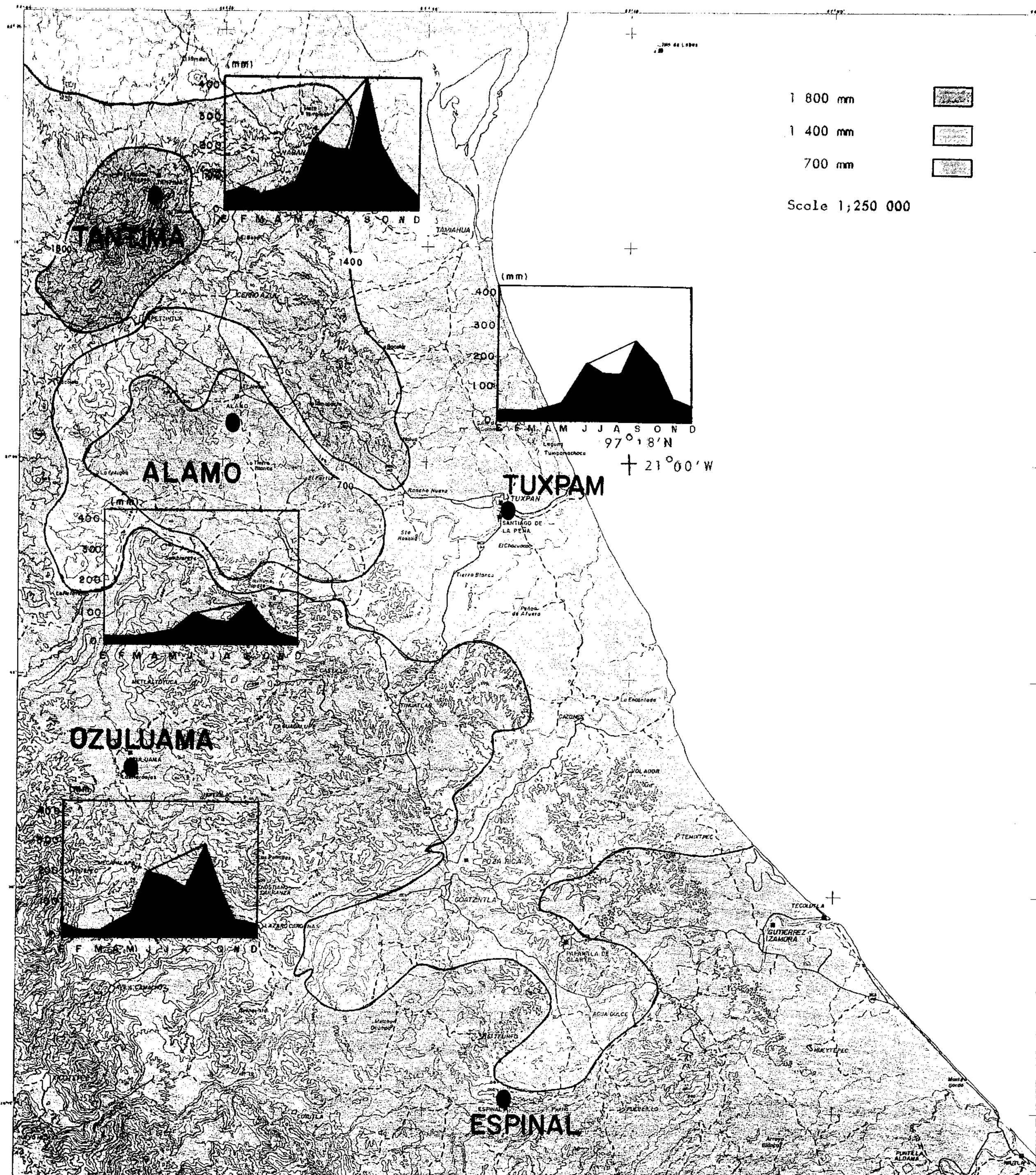

Figure 3. Averages of annual rainfall and relative dryness for 1922 to 1994.

The limits of the isohyets were established using the values of the R/T ratios established by the Modified System, and substituting them in the equation:

$$r = (R/T) \times \text{ annual average } T \tag{7}$$

The values for the limits marked by the Modified System are: 55.3, 43.2 and 22.9. However the R/T ratio was calculated for each station in such a way that when substituting these values in the equation, the following was obtained: $4 = 24.7 \times 27.8 = 687$ mm for the isohyets of 700 mm and $r = 55.3 \times 25.0 = 1382.5$ mm for the isohyet of 1400 mm (this one was calculated to distinguish between climate Aw_o and climate Aw).

In this case, the established R/T of 43.2 was used when $r = 43.2 \times 24.3 = 1049$ mm was substituted, and the isohyet of 1800 mm defined the area of the Sierra de Tantima.

The rains registered during the summer, the hot half of the year (May to October), in accordance with the Modified System of Climatic Classification, were at least 10 times greater than the rainfall of the dryest month, and followed the arrival of the moist Trade Winds that drop their rain in the area as a result of the orographical lifting effect, as well as of cyclones and tropical storms. The winter or northers rains are formed by the wet northers which correspond to two of the four types proposed by Mosiño (1988). The northers that caused the winter rains were the wet and deep northers and the wet shallow northers. The difference in the amount of rain registered within the same area is explained by the effect of the mountain, as the masses of moist air lose their humidity as they get cooled adiabatically resulting in the coastal plain being slightly dryer than the areas between 200 and 1400 m. The area of Alamo (that represents the leeward side of the Sierra de Tantima) captures approximately 50% less rain than the mountain sides because of the rain shadow effect.

The distribution of the rainfall during the rainy season (May to October) was double peaked so that it and presented a decrease in the number of rainy days, the "canícula" which is a mid-summer dry period or intraestival dry period, of the otherwise normal rainy season.

The deficit in the rains was calculated considering as representative of it, the area between the funicular polygon formed by monthly average of the heights rain between the two rainfall peaks and the line that joins these peaks. The estimation of the average relative dryness for 30 years for all localities was carried out with the following equations (Table 4, Fig. 3):

– For one month of intraestival dry period: $A_{1,2,3} = (1/2)Y_1 - Y_2 + (1/2)Y_3$ (8)

– For two months of intraestival dry period: $A_{1,2,3,4} = Y_1 - Y_2 - Y_3 + Y_4$ (9)

Table 4. Percentage of relative drought with respect to the local climate.

Local climate	Relative Dryness	Duration
Aw_1	13.17	July and August
Aw_2	18.74	July and August
BS	13.17	June and August

The intraestival dry period in the basin occurred only during July and August. However, no relationship was registered between the degree of dryness, its position with respect to the mountain range and the climatic type. The intraestival dry period or "canícula" is directly related to the height and the amount of rainfall. This phenomenon is also regularly registered in other intertropical regions of the World, such as Rangún (India), Bogota and Cartagena (Colombia), Mwobaye (Guayanas now Guyana, Surinam and French Guayana) and Timbuctu (Africa) (Köppen, 1948; Richards, 1957; Miller, 1982). García and Mosiño (1966) explained this phenomenon through the changes in the surface circulation that year after year occur over the Gulf of Mexico. These are in someway a return to the winter, that is, that during the rainy summer season the masses of warm dry continental air that enter behind a Tropical Storm that recurves towards the NE in the Gulf of Mexico (Mosiño y Reyna, 1992), causes the "canícula".

The masses of hot and moist air that originate in the tropical seas of the north Atlantic enter the Gulf of Mexico under the influence of the great Bermuda-Azores anticyclone, and are transported by the Trade Winds which move along an ample curve around this high pressure center towards a thermal low pressure area located to the SW of the United States. The hot half of the year is characterized by the increased strength of oceanic anticyclone or center of action of the north Atlantic. The invasion of tropical air adopts the form of a "moist tongue" that penetrates the Mexican territory under the influence of the Trade current that at this time of the year becomes considerably thickened. However, in summer there is an upper air trough between the anticyclone of the Azores, that is located approximately along the east coast of Northamerica. This then generates a temporary interruption in the Trade air current and its humidity, that re-establishes normal rainfall by the disappearance of the upper air trough (Mosiño and García, 1966). No significant differences were found in the hydrological behaviour of the lagoon as a result of this decrease in rainfall during the "canícula" season.

4) River Data

The area of the Tamiahua-Poza Rica Hydrological basin is located within hydrological regions numbers 26 and 27 in accordance with the criterium proposed by the Secretaría de Recursos Hidráulicos in 1954, by which the country was divided into 37 regions based on the location of dams, river basins and agricultural crops. The coastal zone contributes a considerable amount of water to the Gulf of Mexico which is received in the Sierra Madre Oriental. This contribution is permanent and includes the Tuxpam River and the Estuario de la Mata at its mouth. The Tuxpam River increases the volume of water contributed together by the rivers Blanco, Pahuatlán, Rancho Nuevo and Beltrán. The average discharge of the greatest amounts registered during the three seasons for the Tuxpam River is shown in Table 5:

Table 5. Average river data for th three seasons of the year (northers, dry season and rains) for the Tamiahua-Poza Rica basin.

Average discharge (thousands of m^3)	Season
119, 607	northers
24, 124	dry season
310, 197	rains

The differences in the discharge carried by the Tuxpam River indicate there is an increase in the discharge of the rivers both during the "northers" in winter, and the rainy season. Thus, the local climatic behaviour that was registered over the high regions of the basin is reflected on the same scale in the corresponding regions of the coastal plain.

The seasonal variations in discharge/m^3 that were registered in the Tuxpam River affected the depth of the lagoon, as the river and the lagoon are connected by the Estero de la Mata. The greatest depths were registered in the internal regions of the lagoon during the rains. The effect was less noticeable near the Estero as a result of the effect of the semidiurnal tides that are common in the area.

5) Climate

The different types of climate within the Tamiahua-Poza Rica basin were calculated from the temperature and rainfall data of 12 meteorological stations (Fig. 4). The amount of rain was established for each type of climate considering the factors r_h and r_s which, for climates A and C with summer rains and a percentage of winter rain (Table 6) lower than 5 and up to 10.2%, the equations proposed by the Modified System are used:

$$r_h = 2t + 28 \qquad r_s = (2t + 28)/2 \tag{10}$$

where r_h and r_s are = degree of humidity.

For those with a percentage greater than 10.2%, the following equation was used:

$$r_h = 2t + 21 \qquad r_s = (2t + 21)/2 \tag{11}$$

The percentage of winter rain was previously calculated for each station using the equation: Rainfall of J + F + M

$$\% \text{ of winter rain} = \frac{\text{Ranifall of } J + F + M}{\text{Total annual rainfall}} \times 100 \tag{12}$$

The averages for 1922-1994 were used in all cases, and the results are shown in Table 6.

The r_h factor was used to define the degree of humidity in each station and to establish whether it was dry or not. This was carried out comparing this factor with the total annual rainfall (cm). The criterium used was: if the total annual rainfall was greater than r_h, the climate was considered to be wet, and if it was lesser it was considered dry. In this case, the r_s that defines the degree of dryness was considered (Table 6).

Table 6. Percentage of winter rain registered in the Tamiahua-Poza Rica basin.

Local climate	r_h	r_s	Winter rain (mm)	% of Winter rain
Aw_2	76.5		153.0	8.0
Aw_1	76.3		134.5	12.08
BS	83.6	41.8	68.7	9.9

The only climate that turned out to be dry was that around Alamo (located on the leeward side of the Sierra de Tantima). All the other climates turned out to be subhumid. The subhumid type was established by the relationship between the R/T ratio and the percentage of winter rain defined by the Modified System. This mentions three types: w_0, w_1 and w_2. The last two were identified in the basin, and type w_2 is considered the wetest of the subwet.

On the coastal plain, the local climate is type Aw_1, that is, warm subhumid over approximately 35% of the basin. The local climatic characteristics of the stations located within this region are presented in (Fig. 4). The differences that were registered are related to the temperature range in Nautla, which is located near the coast. The thermostatic effect of the sea was greater than in the regions of Papantla de Olarte and Tuxpam de R. Cano which are separated from the coast by 35 and 10 km respectively.

Type Aw_2 climate was recorded, from south to north within the basin and between the point where the mountains reach a height of 2400 m and the start of the coastal plain at an altitude of 100 m. This climate type corresponds to the humid of the subhumid and covered 55% of the area, as a result of the drastic change over the mountains with respect to the coastal plain,

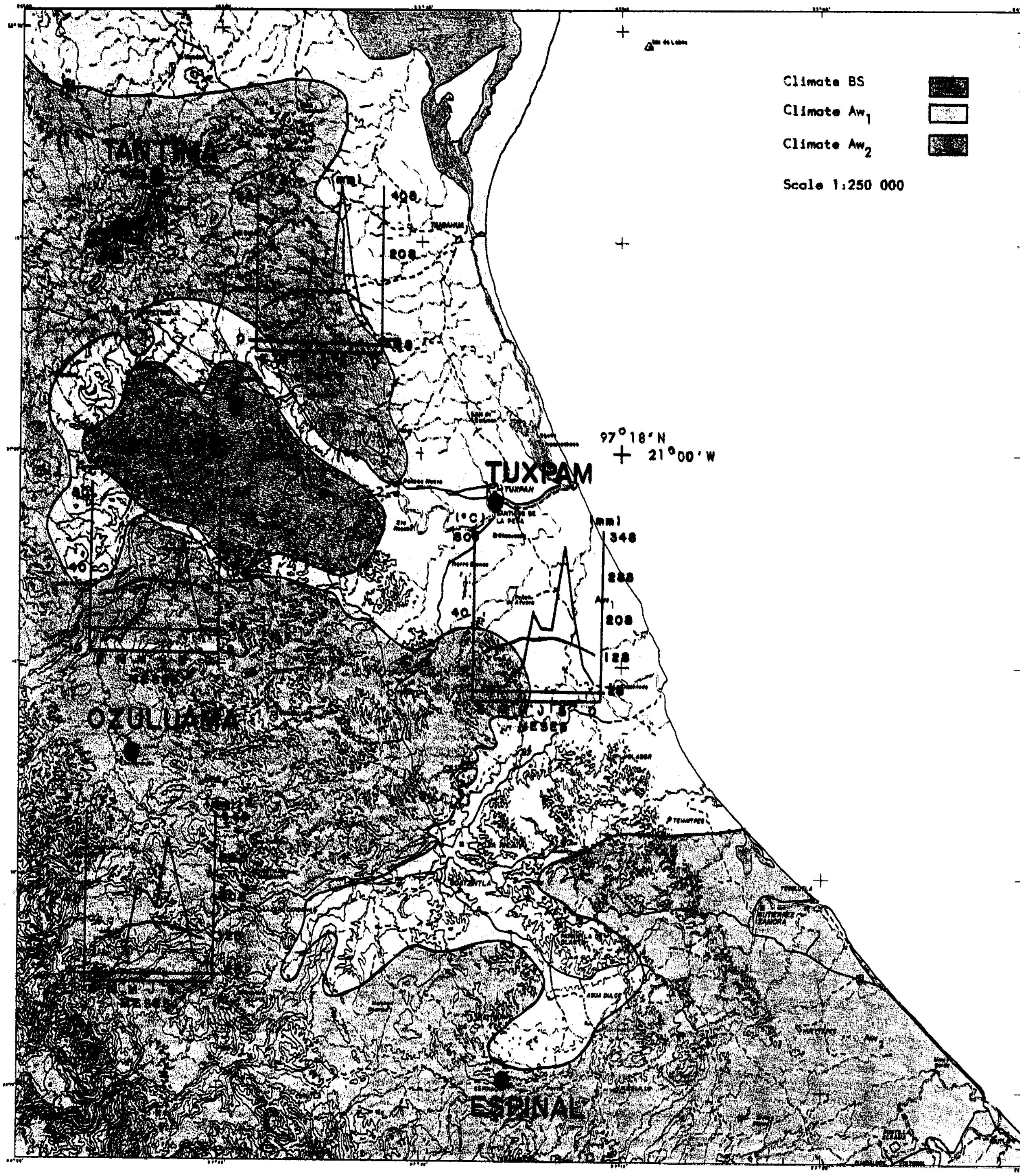

Figure 4. Climates within the Tamiahua-Poza Rica basin and ombrothermal diagrams.

the wind changing direction upwards and adiabatically decreasing air temperature, with the resulting increase in rainfall in the area. The meteorological stations located in this basin have the following characteristics (Fig. 4).

A small area with type BS_1 dry climate was identified to the south of the Sierra de Tantima. The three types of climate calculated for the Tamiahua-Poza Rica basin directly affect the climate of Laguna de Tampamachoco on both the spatial and temporal scales. The Tuxpam River is located in the area with type Aw_2 climate and its discharge depends on the amount of rain. Type Aw_1 climate reflects the buffer effect of the water of the lagoon and Gulf of Mexico. The dry climate registered on the leeward side of the Sierra de Tantima causes the rivers that originate in its watershed to be small and temporary, which results in the Boca de Galindo, located in the shallowest regions to the NW of the lagoon and is connected to the other section of the lagoonal system called Tamiahua through a small canal. The canal losses more than 50% of its volume of water at that point and becomes non-navigable.

The climatic characterization and definition were based on the temperature and rainfall differences caused by the combination of the prevailing winds, the mountains, the type of soil and the vegetation cover, that closely coexist and cause the climatic differences (García, 1964; Pennington and Sarukan, 1968; García, 1974; Lugo, 1974; Gómez-Pompa, 1978).

6) Climatic seasons for the Tamiahua-Poza Rica basin

The climatic seasons in the Tamiahua-Poza Rica basin were defined considering the origin and monthly distribution of the rainfall and the limits proposed by the Modified System. The rainfall pattern was heterogeneous throughout the year, with an increase in the amount from May to October. The criterium established in all meteorological stations was that the amount of rain in the wettest month of the hot half of the year (from April to September) should be at least 10 times greater than that of the dryest month. Thus, the limits established by the summer rains were maintained and the percentage of Winter rain was considered. This must vary between less than 5% and more than 10.2%, as occurred in all areas within the basin.

The daily weather charts were analyzed and interpreted by the Servicio Meteorológico Nacional, together with the monthly behaviour of the winds. The greater occurrence of the moist Trade Winds that directly affect the coastal plain of Veracruz was identified as causing the rains from May to October. The rains increased in September and October as a result of the cyclones and tropical storms formed in the Mexican Caribbean and Gulf of Mexico. During November, December, January and February, rainfall was due to the presence of modified masses of continental polar air or "northers" of the humid sort. The rains decreased during March and April. In this phase, the occurrence of the Trade Winds decreases as the Bermuda-Azores high pressure cell is displaced.

From this, three seasons were established that correspond to: 1) Northers from November to February with 222 mm of rain; 2) Dry Season from March to April with 92 mm and 3) Rains from May to October with 1071 mm. The ombrothermal behaviour calculated from the r_h factor for all meteorological stations showed an increase in the rains from May to October. The rainfall curve was higher than the temperature curve in all cases during this period, between 150 mm in the BS or dry local climate and 500 mm in the Aw_2 or wet climate. This pattern changed drastically from November to April, when the rainfall curve was below the temperature curve in all cases (Fig. 4). The ombrothermal curves show the start of the rainy season in a graphical manner. This season is established when the curve of the rains rises above the temperature curve, and the dry season when the curve of the rains is below that of the temperature.

Conclusions

- The lapse rate calculated for the Tamiahua-Poza Rica basin is 50% lower compared with the mean world lapse rate, as a result of the mountains which cause a lapse rate of 0.35°C per 100 m above sea level instead of 0.65°C.
- The difference in temperature between the coldest and the hottest months is extreme as a result of the outbreaks of masses of polar air or "northers" that arrive from November to February and of the mountains within the basin. The lapse rate is directly proportional to the altitude: a) in low-lying places, the gradient is 7°C/km due to the thermostatic effect of Laguna de Tampamachoco and the adjacent Gulf of Mexico, b) it is only registered in the area of the coastal plains (40% of the basin) and the effect decreases with altitude, and c) increases with altitude up to 10.5°C/km.
- The prevailing wind has an easterly and northeasterly direction and is originated by the Trade Winds in the equatorial margin of the Bermuda-Azores high pressure cell. The northerly component is originated by the "northers" or masses of modified polar air. The westerly, northwesterly, southernly and southeasterly components may be considered modifications of the two previous dominant components, and the result of effects of the basin, the accumulation and the orographical rise, by which the three local climates are generated (Aw_2, Aw_1 and BS) in the Tamiahua-Poza Rica basin.
- Three areas with a different amount of rain were registered within the basin. 1) One to the southeast of the coastal plain that includes Laguna de Tampamachoco with 1390 to 1400 mm and 35% of the basin, 2) the Sierra Madre Oriental on the leeward side of the Sierra de Tantima from 1400 to 1800 m above sea level and 55% of the area with 1800 mm of rain, and 3) the windward side of the Sierra de Tantima with 700 mm of rain and 10% of the area. The differences in the volume are the result of the adiabatic cooling of the damp air and of the orographical rain shadow.
- There is a deficit in the number of rainy days during the rainy season throughout the basin (an average of 30) that has been named the mid-summer dry season or "canícula", which lasts up to two months in July and August. This phenomenon does not modify the hydrological dynamics of Laguna de Tampamachoco.
- The rains that fall during the rainy season, and in a lesser degree the winter rains, affect the amount of water in the estuary of the Tuxpam River. This is doubled during these seasons with respect to the volume registered in the dry season. The average volume range is 695.3 to 1825 m^3 and this affects the volume of water and the area of the lagoon that is covered, mainly in the northwestern region where the small shallow inner lagoons are located.
- Three types of regional climate were detected in the Tamiahua-Poza Rica basin: Aw_1 (55%), Aw_2 (35%) and BS_1 (10%). These were created by a combination of prevailing winds, orography and type of soil. This definition is equivalent to the following areas determined by rainfall data: 1) type Aw_1 corresponds to the lagoon, 2) type Aw_2 to the Tuxpam River over 80% of its extension from its sources in the Sierra Madre Oriental with an increase discharge as a result of the rains, and 3) type BS_1 on the leeward side of the Sierra de Tantima that originates the streams that provide water to the lagoon, particularly important to the northwestern region where the small inner lagoons are located.
- The temporal variations in the climate give way to three conditions: 1) the rainy season from May to October with a volume of 1071 mm originated by the Trade Winds, cyclones and tropical storms, 2) the season of northers from November to February with 222 mm

originated by the arrival of both deep and shallow masses of modified continental polar air, and 3) the dry season from March to April with 92 mm. In consequence, the hydrological behaviour of the lagoon changes significantly during the three seasons.

- Considering the annual differences in rainfall and temperature, the intervals of variation are 411 to 2539 mm of rain and 22.9 to 30.7°C of temperature. These are due to: a) the variations in the intensity of the Trade Winds as a result of the geographical location, the size of the Bermuda-Azores high pressure cell and the annual variability of cyclones and tropical storms during the summer, and b) the "northers" or masses of modified polar air of the shallow humid, shallow dry, deep humid and deep-dry types of northers in winter.
- The temperature variations are not as extreme as the rainfall variations, as a result of the close relation between the solar radiation and that which is absorbed by the ground, as well as of the heat capacity of the water in Laguna de Tampamachoco and the Gulf of Mexico. The rainy condition depends on the combination of the position of the Anticyclonic Bermuda-Azores cell and the local modifications in the troposphere that generate an annual difference in the amount of the rains and, thus, in the salinity of the lagoon water.
- The regional climate of the basin directly affects the local climate of Laguna de Tampamachoco. On the temporal scale, three climatic seasons are defined as: "northers", dry season and rainy season, and on the spatial scale the hydrological behaviour of Laguna de Tampamachoco.

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