Investigaciones Geográficas, Boletín del Instituto de Geografía, UNAM
ISSN 0188-4611, Núm. 75, 2011, pp. 51-60

Classification and agroclimatic zoning using the relationship between precipitation and evapotranspiration in the state of Yucatán, Mexico

Received: 6 August 2009. Final version accepted 11 January 2011.

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Abstract. The length of the growing period (LGP) is determined by the relationship between precipitation and evaopotranspiration, and it indicates the continuous period during the year in which the humidity is suitable for the development of rainfed crops. The aim was to develop a cartographic model of the LGP at a scale of 1: 250 000 for use in planning rainfed agriculture in the state of Yucatán. Data for 1961-2003 from 40 meteorological stations were used with the graphic method to estimate the characteristics of the LGP by means of the monthly precipitation and the potential monthly evapotranspiration. The meteorological stations were classified with the properties of the LGP using decision trees. The meteorological stations were classified in terms of their LGP as very low (1+2 months), low (5 months), medium (6 months), high (7 months) and very high (8 to 10 months). Geostatistical analysis showed that the LGP data were adjusted to a semivariogram with a spherical model. Cross validation of the interpolation presented a r^2= 0.654 and a mean error of 0.03, which indicates the validity of the interpolation and production of the map. The major part of the state has a LGP longer than seven months.

Key words: Rainfed agriculture, decision trees, evapotranspiration, interpolation, precipitation, geostatistics.

Clasificación y zonificación agroclimática utilizando la relación precipitación evapotranspiración en el estado de Yucatán México

Resumen. La longitud del periodo de crecimiento (LPC) está definida por la relación precipitación/evapotranspiración, e indica el tiempo continuo a través del año en el que se presentan las condiciones de humedad adecuadas para el desarrollo de cultivos de temporal. El objetivo fue la elaboración de un modelo cartográfico a escala 1:250 000 de la LPC de utilidad en la planeación de la agricultura de temporal del estado de Yucatán. Se utilizaron datos de 1961 a 2003 de 40 estaciones meteorológicas, y el método gráfico para estimar las propiedades de la LPC mediante la precipitación mensual y la evapotranspiración potencial mensual. La clasificación de las estaciones meteorológicas se realizó

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con las propiedades de la LPC utilizando árboles de decisión para clasificación. Se realizó un análisis geostadístico para la elaboración del mapa. Las estaciones meteorológicas, según su LPC, se clasifican como: muy bajos (1+2 meses), bajos (5 meses), medios (6 meses), altos (7 meses) y muy altos (8 a 10 meses). El análisis geostadístico mostró que los datos de la LPC se ajustaron a un semivariograma con un modelo esférico. La validación cruzada de la interpolación presentó una r^2= 0.654 y un error medio igual a 0.03, lo cual indica la validez de la interpolación y elaboración del mapa. La mayor superficie del estado tiene una LPC mayor de siete meses.

Palabras clave: Agricultura de temporal, árboles de decisión, evapotranspiración, interpolación, precipitación, geoestadística.

INTRODUCTION

Climate is an environmental factor of great importance in matters connected with agronomy (Villa *et al*., 2001; Granados *et al*., 2004), ecology (Campo and Vázquez, 2004) and environmental risk (Jáuregui, 2003) among others; however, in Latin America the climatic seasons are limited and are spatially distributed in a very heterogeneous manner, so that climatic and meteorological information, too, is scarce, irregular and disjunct. Interpretation of climatic information directed towards sustainable agriculture involves, among other things, the efficient use of rainwater. The FAO (1996) method of agro-ecological zoning consists in defining homogeneous zones of the land in terms of climate, physiography and soils and land use; the climate is included by means of the concept of the length or duration of the growing period (LGP) which is the continuous period of the year in which the conditions of humidity and temperature are suitable for crop production. The relationship between precipitation (P) and potential evapotranspiration (Etp) determines the onset, duration, end and type of the growing period (GP); it begins when P exceeds one-half of the Etp and ends when P is less than one-half of the Etp. The properties of the GP are used to examine the distribution and intensity of the rain during the year, and also they can be compared with the requirements for rainwater of rainfed crops, as well as the behaviour of the potential natural vegetation; however, in Latin America studies of these properties of climate are few (Aguilar, 1995).

Cartographic information on the climate in Yucatán appears in literature that is difficult to access and in a taxonomic language that is difficult to use in agronomy, with its uppercase and lowercase letters and the symbols used to designate the meteorological types and subtypes. However, in rainfed agriculture and under tropical conditions knowledge of the duration of the rainy season is particularly important. In addition, in climate cartography, few studies have analysed the interpolation models; generally, only the maps are presented, with no details of the production process. This does not constitute a problem when the maps are published at scales greater than 1: 1 000 000; however, at cartographic scales less than 1: 250 000 a mathematical validation of the interpolations is required for greater precision in the use of the geographic information, for example in the plans for ecological regulation of the land that have been promoted in Mexico, as well as in the agro-ecological regionalization that FAO (1996) has supported throughout the world.

In the state of Yucatán the altitude, which is low relative to the relief (Ihl *et al.*, 2007), does not influence the climate; under these circumstances, geostatistics can be used in the production of a map with greater precision than previous ones. Geostatistics includes a combination of tools for analysing and predicting the values of a variable that is distributed in space or in time in a continuous form; and it helps to decide whether the number of meteorological stations is sufficient for performing climatological cartography at a determined scale. The semivariogram integrates and expresses the similarities among the sites sampled over all possible distances and spatial directions. Spatial interpolation with kriging allows maps to be produced with greater precision. The purpose of the present study was to identify the duration of the GP in the state of Yucatán with data from 40 meteorological stations in or near Yucatán, to classify the GPs with decision trees, and to evaluate, by means of spatial analysis, the possibility of using the information for producing maps at a scale of 1: 250 000.

MATERIALS AND METHODS

Study area

Yucatán is on the north of the Yucatán Peninsula (Figure 1); its geology corresponds to tertiary and quaternary limestones in plains and karstic landforms. The vegetation of the coast towards the south-south-east is of coastal scrub, mangroves, low forest, grazing lands, subdeciduous medium forest and subperennial medium forest.

The factors that determine its climate are: *a)* absence of appreciable elevations, *b)* marked atmospheric pressure gradient and influence of the Atlantic Bermuda-Azores Anticyclone and summer trade winds; *c)* summer drought; *d)* influence of tropical storms; *e)* cold fronts; and *f)* influence of the warm current of the Yucatán Channel (Orellana *et al.,* 1999). As a result, the climate at the fringe of the extreme north-west between Sisal and Progreso is very warm and arid with rains in summer and a high percentage of rain in winter, BS_0(h')w(x'), surrounded by the warmer semiarid conditions with rains in summer, BS_1(h')w, from Celestún to Telchac. To the south and towards the Gulf of Mexico the climate is warm and very warm, the driest of the subhumids with rains in summer and a high percentage of rain in winter, Aw_0 and Aw_0(x'), as well as warm and very warm climates, and the driest of the subhumids with rains uniformly spread during the year, Ax'w_0. Towards the east the climate is warm subhumid with an intermediate rain regime and a high percentage of winter rain, Ax'w_1(i'), (García, 2004).

Length of the growing period

Data for mean, maximum and minimum monthly temperatures, and monthly precipitation, from 1961 to 2003, were produced by the National Water Commission (CONAGUA); 20 640 data entries for total monthly precipitation (*P*) and monthly mean temperature (T_m) were obtained from 40 meteorological stations in or near Yucatán. With these, the monthly ETP was calculated by the Thornthwaite method using CDBm software (De la Rosa *et al.*, 1996); Bautista *et al.* (2009) recorded that calculation of the ETp by this method leads to values near those calculated by the model of reference, the Penmann-Monteith model (Allen *et al.*, 1998). Climograms were produced with P, ETp and one-half of ETp, and from those the LGP was calculated. The onset was determined when P was greater than one-half of ETp and the end when P was less than one-half of ETp (FAO, 1996). The unit of measurement of the LGP was the month.

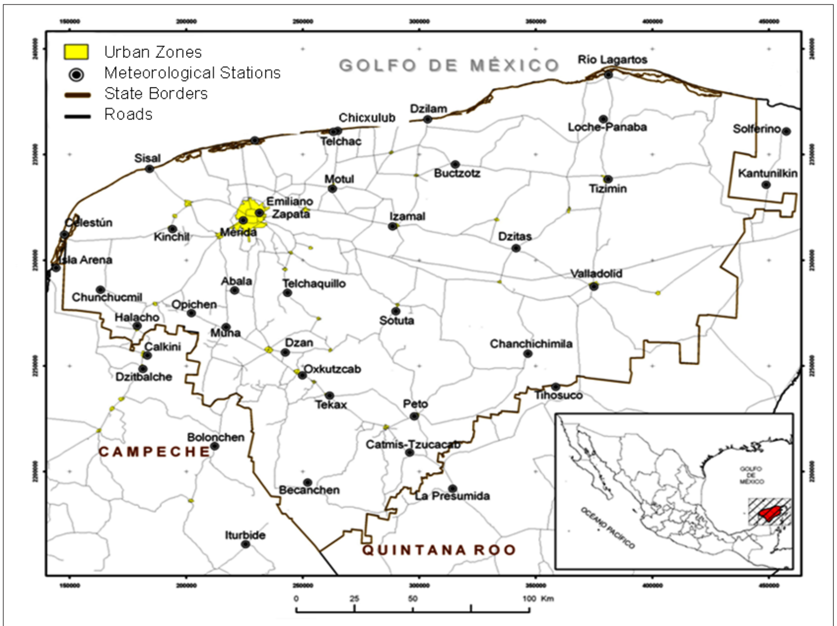

Figure 1. Study area.

The number of the growing period (GP) was determined, together with the type of GP (normal or intermediate), and the presence and duration of the humid period. Levels were assigned to the GPs: very low, low-intermediate, low-normal, medium, high and very high.

The decision tree technique for classification was used to identify the attributes (properties) of the LGP that define the structure of the classification and its statistical validation. The process of assigning classes is a chain of simple decisions based on the result of simple sequential tests to form complex decisions. The sequence of decisions forms the branches of the tree (attribute levels) with tests applied to the nodes. The construction of a decision tree for classification includes the separation of one or more of the values collected on the basis of the applied tests, so that the homogeneity of the new groups formed increases until classes (leaves) are formed (Mahesh and Mather, 2003).

The attributes (nodes) considered for the validation of the classes were: *a)* onset of the GP; *b)* end of the GP; *c)* number of the GP; *d)* type of GP; *e)* months of the GP; *f)* presence of a humid period; *g)* months of humid period, and *h)* classes: very low, low-intermediate, low-normal, medium, high and very high. The algorithm J48 was used, together with the Kappa coefficient with Weka software (Witten and Frank, 2005).

Spatial analysis

A georeferenced matrix was created with the average LGP (1961-2003) for each climatology station. The spatial analysis was performed with GS+ software (Gamma Design Software, 2006). First, the experimental semivariogram was produced in order to select the best theoretical model; then points were interpolated by kriging by points in order to produce a map at a scale of 1: 250 000; lastly, a cross validation of the interpolation and the measured points led to calculation of the mean error (ME).

The kriging method of interpolation allocates the best unbiased linear estimator, as well as an error of the estimation known as the kriging variance which depends on the structure of the selected correlation, based on the theoretical model and on the location of the original data. The interpolation of the attributes gives a weight to each observed value to examine the geometric characteristics of the data and in this way it minimizes the variance of the estimation (Isaacks and Srivastava, 1989; Webster and Oliver, 1990). The precision of the estimations was reported by means of the autocorrelation coefficient, the correlation of the cross validation and the mean error (ME) (Hernández and Ponce, 2006).

The map was done in Arc Gis 9 software (ESRI, 2004), under the UTM zone 16 projection and the ellipsoid and horizontal datum of the World Geodetic System 84 (WGS84). The final map showed the following categories of LGP: <3, 3-5, 5-6, 6-7, 7-8 and >8 months.

RESULTS AND DISCUSSION

Agroclimatic classification

The properties of the LGP are as follows: month of onset and end of the GP; type, number and duration in months of the GP; and presence and duration (months) of the humid period (Table 1). These parameters were used to assess the meteorological stations by means of decision trees for classification, yielding a classification with a Kappa value of 1 and an absolute mean error of 0 for a total of 40 stations. Cross validation indicated that 100% of the cases were correctly assigned to the categories of the agroclimatic classification. In addition, the leaves of the decision tree for classification (rectangles in the figure) included the class, the number of cases well classified and the cases ill classified (Figure 2).

The first branching that the decision tree shows divides the meteorological stations according to the onset of each of the GPs: in June, June-September and May. The first group, the GPs beginning in June, was divided into those that lasted for less than or equal to 5 months and those of more than 5 months. Those less than or equal to five months were subdivided into intermediate and normal. The intermediates were classified as Low-Intermediate and were Celestún, Chunchucmil and Dzilám de Bravo; they did not have a humid period. The

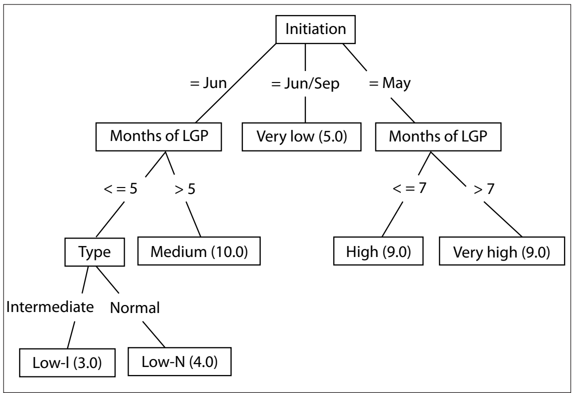

Figure 2. Decision tree for classification of properties of the length of the growing period (LGP).

normal ones were classified as Low-Normal and were Isla Arena, Izamal, Kinchil and Telchaquillo; they had a humid period. Those of more than five months were classified as Medium, and there were ten stations in this group: Bolonchén, Buctzotz, Emiliano Zapata, Halachó, Mérida, Motul, Muna, Opichén, Oxkutzcab and Loche. The agriculture in these zones requires irrigation or the selection of varieties of maize with a development time shorter than the GP. In none of the meteorological stations did the summer drought involve precipitation values lower than 0.5 of the evapotranspiration.

The second group of stations with onset of the GP in June-September were classified as Very low; these were Sisal, Progreso, Chicxulub, Puerto, Telchac Puerto and Río Lagartos, all on the north coast of Yucatán. All these have intermediate type LGP with durations of two and three months and without a humid period (Table 1). During the summer drought, precipitation is lower than 0.5 of the evapotranspiration. Under these climatic conditions rainfed agriculture is virtually non-existent; however, it would be possible to undertake agricultural activities with the aid of back-up irrigation.

The third group of stations, with onset of the GP in May, were subdivided into less than or equal to seven months, and more than seven months. All are of normal type and have a humid period. The nine stations with a LGP less than or equal to seven months were classified as High as follows: Valladolid, Abalá, Dzan, Dzitas, Dzitbalché, Iturbide, Peto, Sotuta and Tizimín. These stations, with onset in May and ending in November, have climatic conditions sufficient for rainfed agriculture. In all these meteorological stations, precipitation during the summer drought has values of more than 0.5 of the evapotranspiration. The humid period varies from three to five months and there is a risk that agrochemicals will be washed towards the aquifer, and so it is recommended that fertilizers be applied in instalments. In these zones, back-up irrigation is desirable only where soils have little residual humidity. The group of more than seven months were classified as Very High and the stations were Becanchén, Calkiní, Catmis, Chanchichimilá, Tekax, Tihosuco, Kantunilkin, La Presumida and Solferino. The GPs begin in May and end in December, January and February. There is a humid period of two to six months. These zones are the best for annual crops. The best zones are those with a humid period of two months, whereas those with a humid period of five or six months are those with the highest risk of contamination of the aquifer.

Spatial analysis

The spatial variation described by an experimental semivariogram of the LGP was adjusted to a spherical model with r^2 equal to 0.95 (Figure 3A).

The structural variance that determines the spatial variance, explained by the model and calculated as [(total variance - nugget variance)/total variance] x 100, was 96%. This indicates that 96% of the spatial variability of the LGP is explained by this model. This is reinforced because the Nugget variance or non-structural variance with a value of 0.29 corresponds to 4% of the total variance, which leads to the supposition that the variability is lower at separations smaller than the minimum encountered at the sites. That is, the separation between the climatological stations is adequate and it appears that if the number of stations were increased the Nugget variance would not be different. The Rank of influence, or the maximum separation in which there is autocorrelation, was 3.0 degrees; beyond this separation, the LGP is not explained by this model.

The precision of the estimation was evaluated by the Pearson correlation coefficient, obtaining a value of 0.81 between the observed values and the

Table 1. Properties of the length of the growing period (LGP) by meteorological station

Station	Onset of GP	End of GP	Number of LGP	Type of LGP	LGP (months)	Presence of humid period	Humid period (months)	Agroclimatic class
Chicxulub	Jun-Sep	Jun-Oct	2	Intermediate	1 and 2	No	0	Very low
Progreso	Jun-Sep	Jun-Oct	2	Intermediate	1 and 2	No	0	Very low
Sisal	Jun-Sep	Jun-Oct	2	Intermediate	1 and 2	No	0	Very low
Telchac-Puerto	Jun-Sep	Jun-Oct	2	Intermediate	1 and 2	No	0	Very low
Río-lagartos	Jun-Sep	Jun-Oct	2	Intermediate	1 and 3	No	0	Very low
Celestún	Jun	Oct	1	Intermediate	5	No	0	Low-Intermediate
Chunchucmil	Jun	Oct	1	Intermediate	5	No	0	Low-Intermediate
Dzilám de B.	Jun	Oct	1	Intermediate	5	No	0	Low-Intermediate
Isla-Arena	Jun	Oct	1	Normal	5	Yes	1 and 2	Low-Intermediate
Izamal	Jun	Oct	1	Normal	5	Yes	1	Low-Normal
Kinchil	Jun	Oct	1	Normal	5	Yes	3	Low-Normal
Telchaquillo	Jun	Oct	1	Normal	5	Yes	3	Low-Normal
Bolonchén	Jun	Nov	1	Normal	6	Yes	1	Medium
Buctzotz	Jun	Nov	1	Normal	6	Yes	4	Medium
Emiliano	Jun	Nov	1	Normal	6	Yes	3	Medium
Halachó	Jun	Nov	1	Normal	6	Yes	2	Medium
Mérida	Jun	Nov	1	Normal	6	Yes	4	Medium
Motul	Jun	Nov	1	Normal	6	Yes	4	Medium
Muna	Jun	Nov	1	Normal	6	Yes	2	Medium
Opichén	Jun	Nov	1	Normal	6	Yes	4	Medium
Oxkutzcab	Jun	Nov	1	Normal	6	Yes	4	Medium
Loché	Jun	Nov	1	Normal	6	Yes	5	Medium
Valladolid	May	Nov	1	Normal	7	Yes	4	High
Abalá	May	Nov	1	Normal	7	Yes	4	High
Dzan	May	Nov	1	Normal	7	Yes	5	High
Dzitas	May	Nov	1	Normal	7	Yes	4	High
Dzitbalché	May	Nov	1	Normal	7	Yes	4	High
Iturbide	May	Nov	1	Normal	7	Yes	4	High
Peto	May	Nov	1	Normal	7	Yes	3	High
Sotuta	May	Nov	1	Normal	7	Yes	4	High
Tizimín	May	Nov	1	Normal	7	Yes	4	High
Becanchén	May	Dec	1	Normal	8	Yes	2	Very high
Calkiní	May	Dec	1	Normal	8	Yes	4	Very high
Catmís-Tz	May	Dec	1	Normal	8	Yes	2	Very high
Chanchichimilá	May	Dec	1	Normal	8	Yes	5	Very high
Tekax	May	Dec	1	Normal	8	Yes	4	Very high
Tihosuco	May	Dec	1	Normal	8	Yes	3	Very high
Kantunilkin	May	Jan	1	Normal	9	Yes	5	Very high
Presumida	May	Jan	1	Normal	9	Yes	6	Very high
Solferino	May	Feb	1	Normal	10	Yes	5	Very high

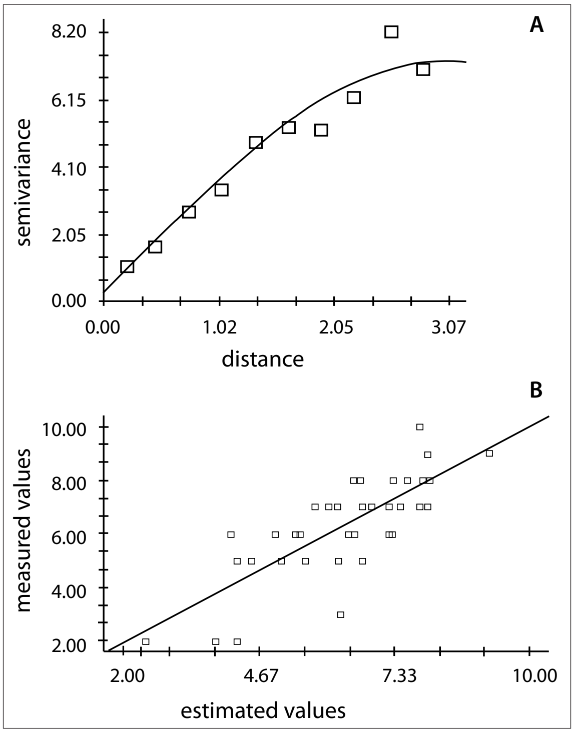

Figure 3. Spatial analysis of the length of the growing period. A., Semivariogram with a value of r2 = 0.95. B, Cross validation with values of r = 0.81 and mean error = 0.03.

estimated values (Figure 3B), and also by mean error values of 0.03 between the observed and estimated values, which indicates that the estimations are not biased.

Despite not having a total of 100 data points as recommended by Webster and Oliver (1990), the results of the interpolation are acceptable because of *i)* the autocorrelation found ($r^2 = 0.95$), *ii)* the value of the correlation of the cross validation (0.81), and *iii)* the low value of the mean error (0.03).

Unlike the existing precipitation maps that include the state of Yucatán, such as those of García (1998) and Orellana *et al.* (1999) which are at a much smaller scale, the gradient in the LGP that is reported in the present study is of high precision as a result of the scale and because of the quantity of data with which the interpolation was performed. In addition, the maps of pluvial precipitation do not include information on the temporal distribution of the precipitation and this is included in the map of the LGP.

Agricultural, ecological and environmental implications

The LGP map is of greater precision than that of the total precipitation since it considers the time of the rainy season; it is of great usefulness when seeking explanations for the presence of plant communities, even with the karstic relief. For example, the spatial distribution of the LGP tallies with the types of vegetation of the state of Yucatán, principally with the map of potential vegetation published by Olmsted *et al*. (1999). Obvious examples are as follows: the low spiny forest, which matches the zone with a LGP of <3 months; the low deciduous forest with the LGP of up to five and seven months; and the median forest with the LGP of >8 months. Similarly, there is agreement with the geomorphological map of the state of Yucatán of Ihl *et al*. (2007) principally shown by the plains of 10, 20 and 30 masl, with LGPs of 5-6, of 7 and of >7 months, respectively.

In the particular case of the zone with more than seven months of LGP, it is not that the precipitation is greater, but that its distribution through the year is more prolonged; for example, at the Mérida weather station the annual precipitation is 1016 mm and the LGP is six months, in comparison with the Catmis station, Tzucacab, at which the annual precipitation is 1 031 mm but the LGP is eight months.

Hence, integration of the climate with the geoforms and the potential vegetation of the state of Yucatán does not pose any problem and constitutes a valuable tool for achieving ecological regulation of the Yucatán land.

A change in the rainfall pattern is one of the factors that most affect the production of rainfed crops, particularly the races and local varieties of maize, beans and chili (Pinedo *et al.*, 2009); for this reason, it is extremely important to recognize the periods of maturation of the crops and to select planting sites according to the months of their GP.

With respect to agriculture, the results of the analysis of the LGP and its distribution tally with the perceptions of the specialists and the country people (Bautista *et al.*, 2005). From the technical point of view, there is apparently no limitation since the GP lasts between six and ten months, except in the most arid northern fringe. Having a large territory with sufficient length of the growing period means that species with a medium and long cycle can be planted or a sequence of crops with a short or medium cycle can be grown (Table 2).

The LGP in Yucatán can be used in planning rainfed agriculture, for example in the case of the varieties of Creole maize with a GP of seven weeks such as *Nal-Tel*, two to three months such as *Xmejen-Nal*, three and one-half months such as *Tsiis-Bacal*, from four to five months such as *Xnuc-Nal* (*Tuxpeño*), etc. Also there is great diversity of local races and varieties of beans, pumpkins and chilis that accompany these maize crops in the cultivation of the milpa and which have similar requirements (Terán and Rasmusen, 1995; Latournerie *et al.*, 2001). However, some farmers nowadays only sow the variety Xnuc-Nal, which has a 4-month cycle, saying that the tradition of sowing those with a short cycle has died out for three reasons: *a)* they are a source of food for wild animals, *b)* the product is stolen by other people and *c)* because of these problems the farmers have not saved the seed.

The ways in which the farmers adapt their practices to the climate are: *a)* to sow in diverse places, *b)* to sow early and late, and *c)* to select and sow varieties with short, medium and long cycles (Graefe, 2003; Bautista *et al.*, 2005). Also, the farmers and local agricultural producers have developed strategies for managing the water resources on the Yucatán Peninsula, such as capturing and storing rainwater, localized irrigation, supplementary irrigation, use of residual water on Vertisols and Gleysols, etc., as has also occurred in other countries (Stigter *et al.*, 2005).

The definition of zones in the state of Yucatán in terms of the LGP is an approximate indication of the intra-annual pattern of the conditions favourable for rainfed agriculture; however, because the unit of measurement here was months, it is necessary to assess the LGP in days also, since, for example, the summer drought can last for days or for months and this is of great importance for some crops.

Table 2. Races of maize in Yucatán and the groups of length of growing period (LGP) concordant with the duration of development of the crop

Race	Variety	Time for maturation (months)	Zones with LGP
Nal-Tel	Nal-Tel		Very low with 2 and 3 months
	Xmeje-Nal	2.5	Very low with 2 and 3 months
	Xmje-Nal x Pix Cristo	3	Very low with 2 and 3 months
Tsiit-Bacal	Tsiit-Bacal	3.5	Low-Intermediate with ≤ 5 months
			Low-Normal with ≤ 5 month
Tuxpeño	Xnuc-Nal	4-5	Low-Intermediate with ≤ 5 months
			Low-Normal with ≤ 5 months
	Xhe-Ub	4	Low-Intermediate with ≤ 5 months
			Low-Normal with ≤ 5 months
	Nal-Xoy	2.5-3	Very low with 2 and 3 months
	V527	3.5	Low-Intermediate with ≤ 5 months
			Low-Normal with ≤ 5 months
	V536	2.5	Very low with 2 and 3 months
Source: Latournerie *et al.* (2006).			

CONCLUSIONS

Six groups of meteorological stations have been identified in terms of the intra-annual variation of the precipitation-evapotranspiration relationship expressed in the LGP. The use of expert systems permits identification of the structure of the characteristics of the LGP, and shows that the properties used to define the groups were, in this order, onset, duration and type of LGP.

The LGP data were adjusted to the spherical model. The cross validation, the Pearson correlation index and the ME between the measured data and the estimated data indicate that the LGP can be represented cartographically at a scale of 1: 250 000 and can be used for agricultural planning. The LGP tended to increase from north-east to south-west.

ACKNOWLEDGMENTS

To Drs E. Batllori, D. Palma and J. L. Hernández-Stefanoni for the observations to the document. To A. Albornoz, Y. Aguilar, M. Bravo, J. Espinola, A. Barrera and J. Cerón for technical assistance. To Fondos Mixtos Yucatán project YUC-2003-C0-054 and to CONACYT for the doctoral scholarship awarded to M.C.D. We acknowledge the valuable comments of two anonymous reviewers on an earlier version of the manuscript.

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