CHAPTER 4: REGIONAL MODES OF VARIABILITY.

4.1. INTRODUCTION.

Using the climatological network, the development and construction which is explained in the previous chapter; our objective is now to investigate the spatial coherence in the climatic variations at the station level. The determination of these regional coherencies is just a preliminary step to find the relationships between their climatic fluctuations and a large-scale atmospheric control like El Niño–Southern Oscillation (ENSO) phenomenon. In this context, Principal Component Analysis (PCA) provides two important features that can help to achieve this objective: 1) it is the technique most commonly used for regionalisation and 2) its results can generally be easily interpreted in a physical way. The method was selected, therefore, as a suitable tool to be applied to the digital Mexican climatological databases.

Principal Component Analysis has been used in a wide range of scientific and social areas since its development in the early 1900s. But it was not until the discovery in atmospheric sciences around the 1980s of the advantages of rotated versus unrotated solutions that an increasing number of scientific studies have been undertaken (Richman, 1986; Richman and Lamb, 1985; Tabony, 1981). The previous chapter stated that the main purpose of PCA is to reduce the high dimensionality of the data, conserving the highest possible amount of the original variance in a few components, but lately has moved to deal as well with individual modes of variability such as El Niño Southern Oscillation (ENSO) (e.g., Gershunov, 1998) often referred as to teleconnections (Gershunov and Barnett, 1998). Climatology is one of the fields in which PCA has been applied extensively (Dyer, 1975).

4.2. PRINCIPAL COMPONENT ANALYSIS (PCA) ON PRECIPITATION.

There are only a few studies in which PCA has been applied to the climate of México. Amongst the many meteorological variables, precipitation has been more consistently explored using Principal Components (Comrie and Glenn, 1998; Englehart and Douglas, 2002) than temperature (Englehart and Douglas, 2004). This condition has been slowly changing for both parameters since the release of digital databases in the early 1990s. Still, for rainfall the studies lack the best possible (in terms of completeness and homogeneity) coverage at both the temporal or spatial scale. One of the main thrusts of this research has been to obtain the best network of climatological stations, defining precisely at the same time the wet and dry seasons.

In order to help with improving studies of Mexican climate, it was necessary to comply with two essential characteristics: the use of the largest possible set of stations across the nation and also a careful determination of the dry and wet seasons (see section 2.2.1).

4.2.1 ANNUAL RAINFALL.

Considering the total annual precipitation (mm) in Mexico (Fig. 2.1), a climatic bridge can clearly be seen between wet conditions in the southern part of the country and drier northern conditions. The tropic of Cancer can be roughly considered as the limit of such a transition. In the southern region, tropical climatic conditions prevail all year around, and precipitation is mostly convective in nature during the boreal summer, while in the north convection partly accounts moderately for the total amount of precipitation, while monsoon conditions prevail in the north-western part of the country during July, August and September (Higgins et al., 1997, Douglas et al., 1993). Several factors other than convective activity have an influence on Mexican precipitation, including hurricanes, orography, polar fronts, etc. Despite this, total annual rainfall was also considered as one of the temporal resolutions to be studied using PCA along with the wet and dry seasons (see sections 2.2 and 2.3). When fluctuations in climate are considered in the north-eastern Pacific, the warm related to the Inter Tropical Convergence Zone (ITCZ) triggers intense convective activity (Magaña et al., 2003).

In order to observe and clarify some the geographical factors that affect the climate of México and also obtain coherently varying regions, a network of 175 stations has been gathered (see section 3.2.1), and the precise definition of annual, wet and dry seasons has been established in section 2.2.1. The PCA methods applied at the annual time-scale are also valid for the wet and dry season time-series.

Replacing monthly missing values with long-term means for every station should not significantly affect the following results. This is why a database of 175 time series of total annual precipitation was used, in which months not reported were filled with their means and expressed as the ratio of the precipitation of each station to its long-term mean (the average for the base period), for purposes of regionalisation when applying PCA.

Mexico lies in a regional climatic transition between tropical and subtropical conditions, therefore, is useful for the identification -among the network of climatological stations- of the differences and/or similarities in the climatic patterns across the country. But here, this question could be expanded: are the changes occurring in only one geographical region or are they of a particular distinctive nature across regions? If the latter is so, we could also ask: are the changes occurring gradually or abruptly? Therefore, the objective is to determine different sets of stations that vary coherently through time. To reach this target PCA was used.

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The scree test plot is used to determine the number of components above the noise level. Ranking the components in the X axis against the eigenvalues in the Y axis, the plot has the objective to find the scree in which the contribution of the components to the total variance is nearly negligible (see section 3.3.2). Eigenvalues for components between 10 and 11 in Fig. 4.1 are showing a small decrease, after the 11th component the ratio of variation with the next component becomes almost imperceptible. A nearly flat slope can be observed in the graph, so their contributions are not more important to the communality of the variables. The first 11 components contribute with 58.2% of the total variance. Therefore, there was no reason to consider more modes of variation and 11 is the selected number of components analysed for the annual total precipitation.

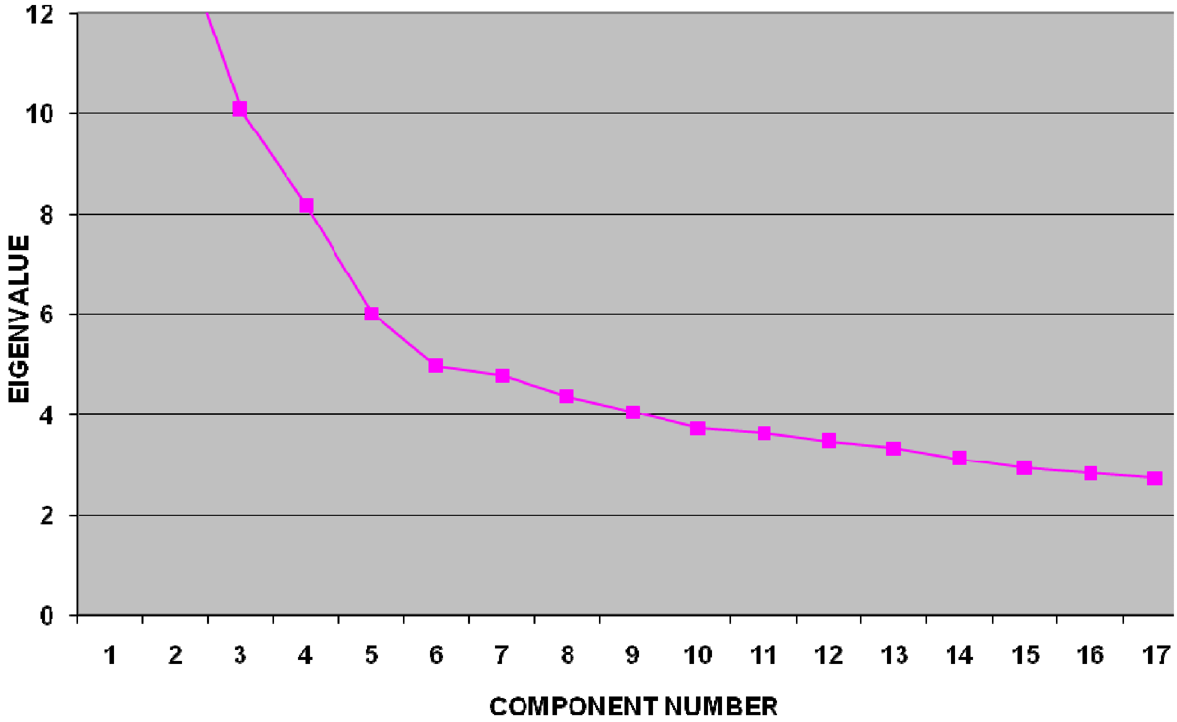

Fig. 4.1. Determination of the number of regions (components) considered in the analysis of the annual precipitation using the cliff analogy (Wuensch, 2005).

It has been suggested that the Scree Test method leads to an overestimation of the components (Horn and Engstrom, 1979), or that the way it distinguishes eigenvalues is somehow arbitrary (Jackson, 1993). Nevertheless, because the purpose of using PCA in this chapter is the identification of a spatial pattern (regionalisation) rather than a data compression, the possibility of an overdetermination of the components must not greatly affect the interpretation of the results.

The mode in which each station is assigned to one corresponding region is explained in section 3.3.2. Briefly, for the extraction of the components only eigenvalues larger than 1.0 are considered, also as missing data were replaced by the long-term mean pairwise or listwise deletion does not affect the final results; and only absolute loading values greater than 0.4 are accepted. The largest loading for each station was then related to one corresponding region. This selection process is repeated for all the precipitation and temperature stations.

When analysing climatological data with PCA for regionalisation purposes, the results from different rotation techniques have subtle differences. For total annual precipitation, the resulting regions show (Fig. 4.2) great consistency between varimax (orthogonal) and promax (oblique) solutions, and also strongly correspond with known Mexican climatic regions (García et al., 1990, García, 1988). Promax (kappa=2) yields clearer results than varimax, as can be observed in the Mexican Monsoon Region (RA11 in table 4.1), where the oblique solution leads to a better grouping of the stations, omitting two stations near the Pacific coast identified by the orthogonal solution. This is also clear in some parts of northeast México (Northeast, RA3 in table 4.1) where again promax has delineated more efficiently the clusters across the region, like in the north-eastern part of the country north of the Tropic of Cancer.

Overall, apart from slight differences, a clear regionalisation of the annual precipitation emerges as a product of the Principal Component Analysis, regardless of the rotation technique applied. The regions developed for annual precipitation totals are listed in table 4.1 and will be discussed according to known features of Mexican climates.

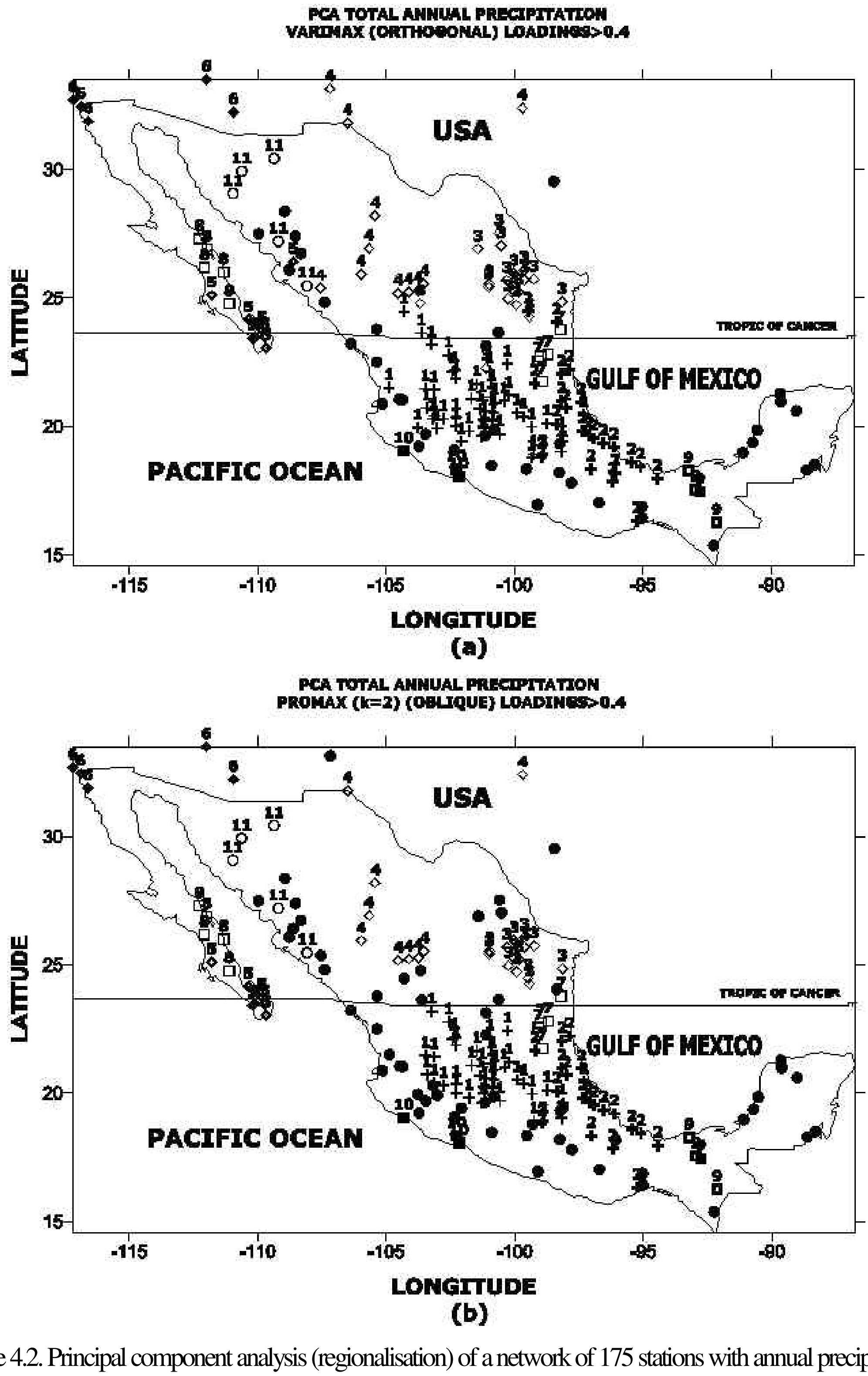

Figure 4.2. Principal component analysis (regionalisation) of a network of 175 stations with annual precipitation totals (1931-2001) using two different solutions: varimax (a) and promax with kappa=2 (b).

Component	Associated region	Climatic characteristics
Region one (RA1)	Central Mexican Highlands	Trends in summer, monsoon from the Pacific, summer rainfall, two temperature maxima
Region two (RA2)	Gulf of Mexico coast	Trends in summer, hurricanes in summer and autumn, polar fronts in winter, two temperature maxima.
Region three (RA3)	Northeast	Trends in summer, polar fronts in winter, hurricanes in summer and autumn, one temperature maximum.
Region four (RA4)	Desertic north, New Mexico and Texas	Little moisture sources, arid regions, one temperature maximum
Region one (RA5)	Humid south Baja California	Summer monsoon, hurricanes y summer and autumn.
Region six (RA6)	North Baja California	Westerlies, winter precipitation, one temperature maximum.
Region seven (RA7)	La Huasteca	Summer precipitation, hurricanes in summer and autumn, polar fronts.
Region eight (RA8)	Desertic south Baja California	Westerlies, one temperature maximum
Region nine (RA9)	Southeast rainforest	InterTropical Convergence Zone (ITCZ), southeastern trades, hurricanes in summer and autumn, two temperature maxima.
Region ten (RA10)	South Pacific coast	InterTropical Convergence Zone (ITCZ), southeastern trades, hurricanes in summer and autumn, low winter precipitation, two temperature maxima.
Region eleven (RA11)	Mexican Monsoon	Summer rainfalll, westerlies, hurricanes in summer and autumn, one temperature maximum.

Table 4.1. Total annual precipitation PCA resulting regions identified according to the known Mexican climatology (García, 1988).

The eleven groups depict a congruent picture of how the stations have been varying coherently across time, and could be clearly differentiated from each other accordingly. Therefore, each group can be identified with one specific climatic region and their main geographic characteristics in terms of precipitation variations (see Table 4.1).

Central Mexican Highlands includes (RA1 in table 4.1) sites like Mexico City -that is one of the capital cities with highest altitude in the world- and its surroundings. High elevations sometimes permit large scale high-altitude atmospheric circulations features to have influence on the local weather, which are often limited by mountain barriers.

The second region (RA2) can be roughly related to the gulf (of México) coast where summer convective precipitation has great influence on annual precipitation totals, but the winter precipitation is also deeply affected by polar fronts (Cavazos, 1997; Jauregui, 1997).

The northeast part of México is the third region (RA3) of the analysis; this set of stations is a good example of the climatic transition in México from tropical to extratropical conditions: the amount of annual precipitation across the stations shows significant decreases in comparison with the stations south of the tropic of Cancer, for instance RA2.

The dry northern region (RA4) is represented by the stations labelled 4 in fig. 4.2; this part of the country is geographically isolated by two mountain ranges that act as barriers for the moisture sources that facilitate the rainfall processes in other regions. The lack of precipitation could easily be observed as some stations only reach 300 mm per year (see fig. 2.1 in chapter 2).

Again, south of the Baja Californian peninsula, a climatic division can be clearly seen for contrasting climatic conditions (tropical to extra-tropical), the southern tip yields wetter conditions (RA5 in table 4.1) when compared with the low precipitation area of the desertic south Baja California (RA8 in table 4.1). Here it can be clearly seen that the Tropic of Cancer is a geographic limit.

The driest climatic regimes of the country are experienced in the most north-western part of México, north of the Baja Californian peninsula and south Arizona in the USA (RA6); this is the only region of all in which the percentage of November-April totals (dry season) exceeds those of the wet season (May-October). More than fifty per-cent of the annual totals occurs during the low rain period in the other regions. Autumn-winter precipitation has a greater influence than spring-summer rainfall in this area.

RA7 can also be considered as a geographical transition, but this time from drier to wetter climatic conditions. This region has been called La Huasteca (humid areas of Tamaulipas, Veracruz, San Luis Potosí and Hidalgo states) and includes mainly stations of the Pánuco

River Basin characterised by dense vegetation and higher precipitation than their surrounding stations in RA2 and RA3.

México's wettest region (RA9) is located in the southeast of the country; here rainfall totals can be as high as 4000mm per year, but one of the remarkable features is the balance between the seasons with the dry season accounting for around 30-40% of the annual totals (see fig. 2.1; García, 1988); not surprisingly it is here that Mexican tropical rainforest areas can be found.

One of the most geographically concentrated PCA resulting groups is RA10, the Michoacán coasts are represented here. Drier conditions are prevalent in RA10 when they are compared with the stations near the mountain ranges (Sierra Madre Occidental) within the southern fringes of what is called the Mexican Monsoon Region (RA11) along the Nayarit and Sinaloa states (coasts bordering the Pacific Ocean).

The last group (RA11) has recently been studied extensively (see chapter 2); precipitation in the Mexican Monsoon Region is characterized by its concentration during the boreal summer season in the lowlands of western side of the North Pacific mountain range (Sierra Madre Occidental). It is important to point out here that, for total annual precipitation, this region does not extend far north beyond the México-USA border but is restricted to only the Mexican side and therefore has been called The Mexican Monsoon region (Douglas et al., 1993).

As can be seen, regions can be clearly related to specific regional precipitation patterns across the country; it is then presumed that rotated PCA solutions, especially oblique methods have succeed in regionalising the Mexican climatic conditions for annual precipitation totals.

4.2.2 SEASONAL PRECIPITATION.

WET SEASON.

It has been shown in section 2.2.1 that most of the precipitation occurs during what has been termed the wet season (May-Oct), for this reason it is expected that PCA results for total annual precipitation will agree closely to those of the rainy season. Conditions for the Principal Component Analysis differ only in that rainfall totals for wet season are only accumulated from May to October. We begin with PCA defining the number of components for regionalisation. For this purpose, we have applied the scree test plot (see section 3.3.2), we observe a small variation between the eigenvalues of the 11th and 12th components (-0.05); these first 11 components contribute with 57.9% of the total variance (fig. 4.4). A nearly flat slope is seen after this point. Therefore, we will consider 11 modes of variation (regions) to study the spatial pattern of the wet season (May-Oct) precipitation.

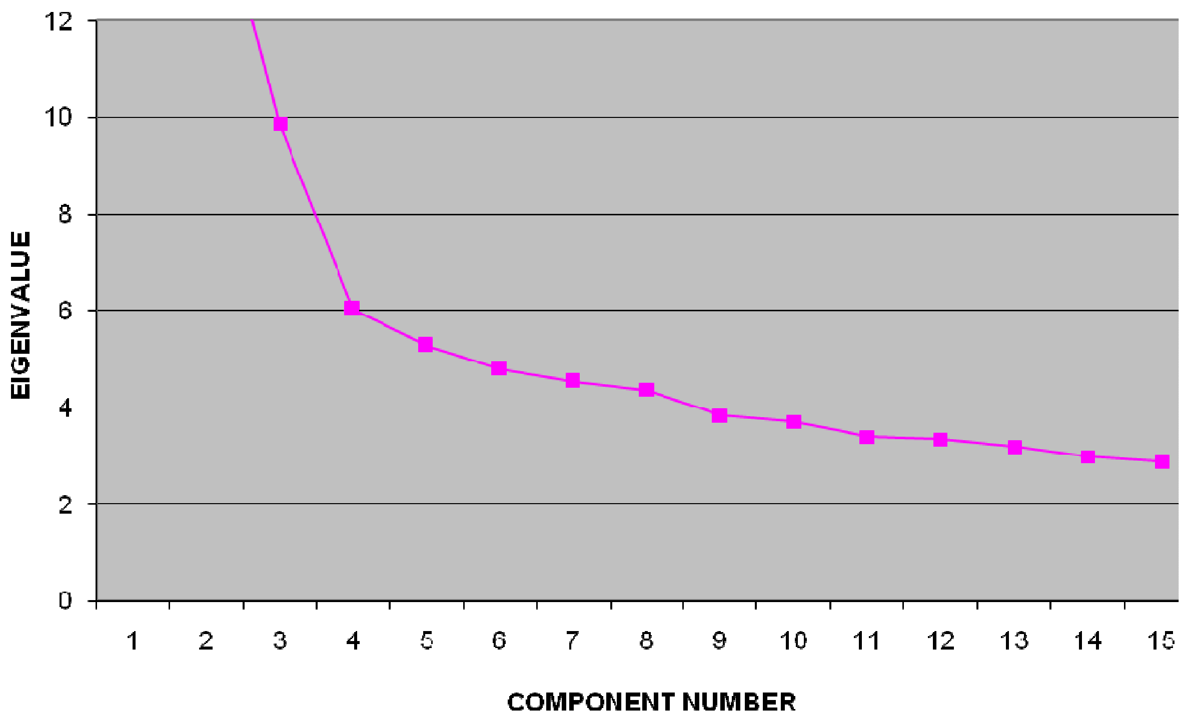

Fig. 4.3. Determination of the number of regions (components) considered in the analysis of the May to October (Wet Season) precipitation using the scree plot technique.

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A strong agreement can be observed between wet season and annual precipitation results (see figs 4.2 and 4.4). The distribution is geographically coincident but a bit different in the order of the components. The Mexican Monsoon Region has disappeared with the rainy season analysis. In the same sense, groups not observed when the PCA was applied on the annual precipitation, the Nayarit State region (stations close to the Pacific coast) has emerged here [some studies (Mitchell et al., 2002; Higgins et al., 1997; Douglas et al., 1993) have pointed this region out as the most southern fringe of the Mexican Monsoon Region]. Some stations classified during the PCA with annual rainfall (like the couple appearing in Arizona State RA9, or those in RA11) have not been grouped here.

The strong coincidence found when annual total precipitation and wet season solutions of PCA are compared can also be seen between the orthogonal and oblique rotated results. Nevertheless, as has been noticed for annual rainfall, the promax (k=2) technique is in general more efficient in showing clearer clusters than varimax (see section 3.3.2). The different resulting regions of applying PCA to the wet season are shown in table 4.2. Promax has better delineated RW2, RW3 and RW5 when contrasted with the orthogonal solution. The Gulf of Mexico climatic group (RW2 in table 4.2) in the case of promax (k=2) is less extended geographically to Central Mexico. In terms of clarity of the clusters, the Northeast (RW3) and humid Baja California (RW5) regions share one characteristic: both have one odd station when analysed with the varimax rotation. In the former group the odd station is located in the state of Coahuila [in which according to the García et al. (1990) regionalisation is a climatic transition from arid to semiarid conditions] while in the latter the additional station was placed in the Mexican Monsoon Region instead of the Baja California peninsula as is the case for promax (k=2).

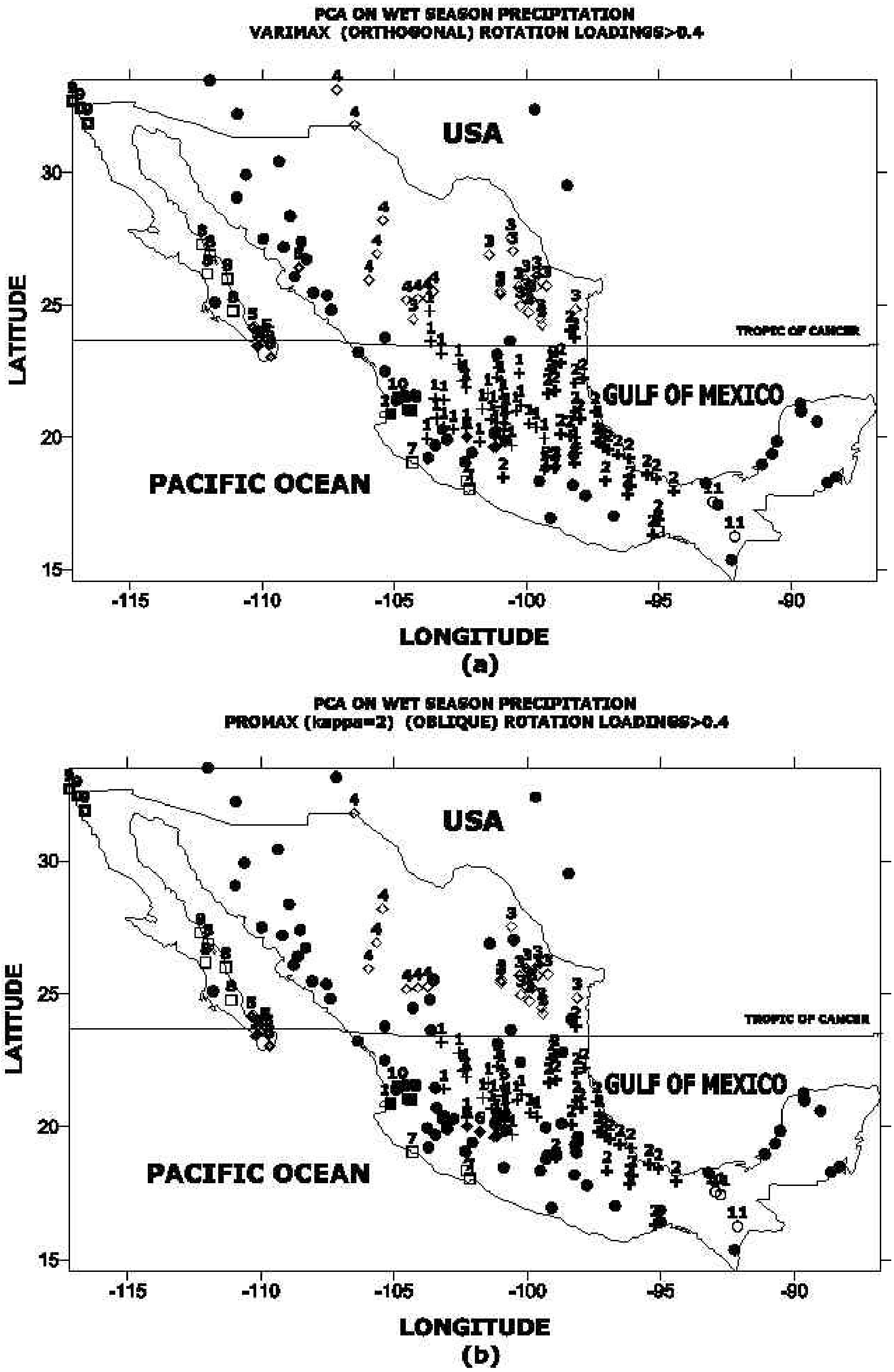

Figure 4.4. Principal component analysis (regionalisation) on a network of 175 stations with wet season (May-Oct) precipitation (1931-2001) using two different solutions: varimax (a) and promax with kappa=2 (b).

RW1 (Central Mexican Highlands, see table 4.2) is smaller and better defined, less geographically extended in the promax solution and concentrated more in central Mexico (probably better avoiding the influence of altitude among the stations). RW2 (Gulf of Mexico coast), RW3 (Northeast) and RW4 (Desertic North, New Mexico and Texas) are basically the same clusters either comparing annual total precipitation versus wet season or the orthogonal against the oblique solutions. Two regions not observed [RW6 (Transverse Neovolcanic Belt) and RW10 (Nayarit state)] when the PCA was applied to the annual total precipitation have produced the same results in the wet season for the varimax and promax solutions; for the oblique solution RW6 is clearer delineated, this cluster could be associated to what is called the transmexican volcanic axis (Eje volcánico Trans-mexicano, Demant and Robin, 1975), the stations in this region are mainly situated in Michoacán State, all of them part of the Transverse neovolcanic belt. Altitudes of these stations easily exceed 1500 metres above sea level (m.a.s.l.) that can be considered as a proof of the influence of altitude on the climate of the region, a variable that it has been frequently disregarded in the studies of the Mexican climatology (see chapter 2). Region ten (RW10) is the most geographically concentrated of the regions, only covering an area of Nayarit State near to the Pacific Coast, the southern tip of the Mexican Monsoon Region in which only one station has an elevation above 1000 m.a.s.l, a topographic factor that is described in section 2.2.2. Finally, region RW11 (Southeast rainforest) can be related to the wettest area of the country, the south-eastern tropical rainforest, and again it is better delineated using promax (k=2) than varimax. Overall, wet season (May-Oct) precipitation clusters extracted with PCA are in accordance with the Mexican climatology (see Table 4.2).

Component	Associated region	Climatic characteristics
Region one (RW1)	Central Mexican Highlands	Trades in summer, monsoon from the Pacific, summer rainfall, two temperature maxima
Region two (RW2)	Gulf of Mexico coast	Trades in summer, hurricanes in summer and autumn, polar fronts in winter, two temperature maxima.
Region three (RW3)	Northeast	Trades in summer, polar fronts in winter, hurricanes in summer and autumn, one temperature maximum.
Region four (RW4)	Desertic north, New Mexico and Texas	Few moisture sources, arid regions, one temperature maximum
Region five (RW5)	Humid south Baja California	Summer monsoon, hurricanes y summer and autumn.
Region six (RW6)	Transverse Neovolcanic Belt	Summer precipitation, Pacific monsoon, high altitude sites, two temperature maxima.
Region seven (RW7)	South Pacific coast	InterTropical Convergence Zone (ITCZ), southeastern trades, hurricanes in summer and autumn, low winter precipitation, two temperature maxima.
Region eight (RW8)	Desertic south Baja California	Westerlies, one temperature maximum
Region nine (RW9)	North Baja California	Westerlies, winter precipitation, one temperature maximum.
Region ten (RW10)	Nayarit state	Summer rainfall, Pacific monsoon, hurricanes in summer and autumn.
Region eleven (RW11)	Southeast rainforest	InterTropical Convergence Zone (ITCZ), southeastern trades, hurricanes in summer and autumn, two temperature maxima.

Table 4.2. Wet season precipitation PCA resulting regions identified according to the known Mexican climatology (García, 1988).

The few former PCA regionalisations in Mexico have mainly been made for the summer season (Englehart and Douglas, 2001; Comrie and Glenn, 1998). The results of the present research, however, are closer to the regionalisation made by Giddins et al. (2005) in terms of the seasonality defined as wet and dry seasons for the May to October and November to April periods. Our resulting regions are also closer to those delineated in García et al. (1990), and also with the clusters proposed by Comrie and Glenn (1998), but unfortunately the latter study does not consider the whole country, as only the northern part of the country was used to define regions based on PCA. Because of the effort dedicated to developing the network, our research can only be compared with the research of Englehart and Douglas (2002) who use a dataset of long-term time-series of approximately 70 years covering practically the entire country.

The regionalisation performed in this chapter for the annual and the wet season has helped us to determine some key features such as highlighting the importance of altitude, for instance the Transverse Neo-Volcanic Belt (RW6 in table 4.2) during the May to October (wet) season regionalisation. The importance of some large-scale atmospheric controls in some regions of the north of the country, such as the Mexican Monsoon Region (Douglas et al., 1993), that only appears in the annual season and not during the wet season that could be the effect of winter precipitation in the region. In the same north-western region but in the Baja Californian peninsula, three very well defined regions (from the southern tip to the northern border) are extracted that are not delineated because of the lack of sufficient stations in this area for the other studies (Englehart and Douglas, 2004; Englehart and Douglas, 2002); and probably because of the hurricane influence no PCA region is found in the Yucatán peninsula for the annual and wet seasons. So far, Promax (k=2) has proved to be the most suitable technique to extract the best results across Mexico using PCA.

DRY SEASON.

As a natural consequence of having defined the period May to October as the wet season, the rest of the year (climatologically speaking), i.e., the months from November to April are considered the dry season. Most of the country then experiences *relatively* scarce rainfall totals through this time-interval. Only in the region north of the Peninsula of Baja California do precipitation totals exceed fifty per cent of the rainfall annual totals during this season. For some regions, the small amounts of precipitation (in the arid areas) have a larger impact than during the wet season even if the ratios of the precipitation with respect to their long-term means are used. Despite these potential problems, we utilised the same methods and approaches to regionalise the dry season.

The number of components selected is a key feature of the PCA, and this is especially true when this technique is used for regionalisation. A nearly horizontal line is seen after the 11th component when the scree test is applied (section 3.3.2). These first 11 components account for 69.2% of the total variance, the change on eigenvalues with respect to the 12th component is approximately -0.134 (Fig. 4.5). Based on this small variation, eleven different regions are considered to study the spatial pattern of the dry season (Nov-Apr) precipitation.

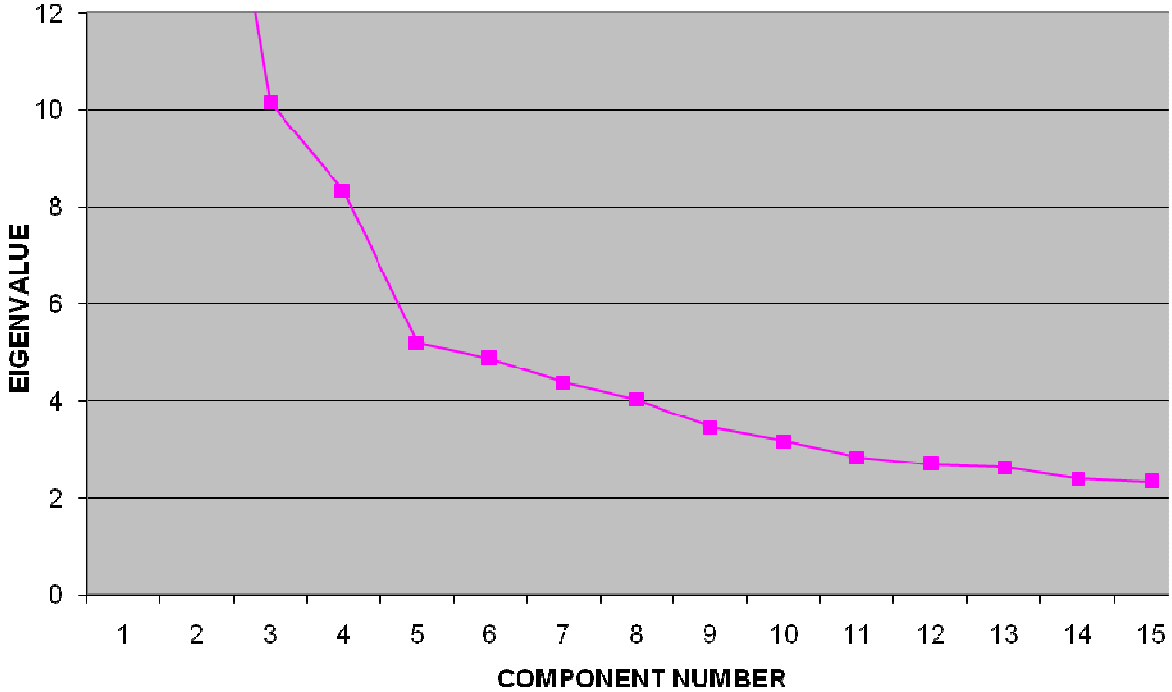

Fig. 4.5. Determination of the number of regions (components) considered in the analysis of the Nov-Apr (Dry Season) precipitation using the the cliff analogy (Wuensch, 2005).

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Regions for the dry season in Table 4.3 show an evident different spatial structure (fig. 4.6) when compared with the annual and wet season analyses. First of all, components reflect a larger spatial coverage for the dry season.

The area named the Mexican Central Highlands region (RD1) in the annual and wet season PCA results has now being geographically extended towards the Pacific Coast. Probably larger scale (than during the annual and wet seasons) dry season phenomena, like polar fronts, penetrate far south in the country despite its orographic barriers (the two mountainous ranges along both coasts). Nevertheless, the tropic of cancer remains as a climatic threshold to delineate the region.

RD2 (Northwest, Arizona and Texas) covers now not only the Mexican Monsoon, but also some stations south of the Baja Californian Peninsula that had been split in the annual and wet season results, and now appears as a single cluster in the peninsula. It can be appreciated that, when compared with varimax, promax (k=2) has better delineated RD2. The spatial coverage in the latter case does not reach any station far East (the state of Texas in the USA) as in the case of varimax. Both techniques are coincident in showing clusters of RD2 on both sides of the Sea of Cortez; it would be worth investigating the role of the thermal inertia of the Gulf of California (Sea of Cortez) in relation with the climate during the dry season in this region.

RD3 (Northeast) extends geographically eastwards just north of the central highlands covering sites that were RA4 and RW4 (Desert north, New Mexico, Texas) in the previous sections.

The Gulf of Mexico Coast Region (RD4) is smaller in extension than its counterparts of the annual and wet seasons, covering now only the south of the Gulf of México, probably because polar fronts generally do not penetrate far south into this area during the cold season, as is the case in northern Gulf of Mexico.

One of the only two coincident resulting regions is not surprisingly the area of North Baja California (RD5). Only in this part of the country the dry season precipitation exceed fifty percent of the annual totals. The cluster replicates identically the annual rainfall one, but when compared with the wet season it spreads westwards covering some parts of Arizona, separating them from part of the RD2 that is related to the Mexican Monsoon region (RA11 in table 4.1) in the PCA regionalisation of the annual rainfall. Therefore, we can say that these stations in Arizona are not affected by the same physical controls of the Mexican Monsoon during the dry season.

Although, RD6 can be still be related to the Transverse Neovolcanic Belt, the stations within it are not the same when compared with the ones of the rainy season results, yet all the sites in the group are above 1000 m.a.s.l., three of them having altitudes greater than 2000 m.a.s.l., reinforcing what has been pointed out before, that altitude should be considered as one of the most important factors in the study of the climate of México (Mosiño and García, 1974).

Probably the PCA's most striking feature for the dry season analysis is the cluster in the Yucatán peninsula (RD7). This area is under the influence of Hurricanes during the rainy season like Hurricane Gilberto in 1988 (one of the strongest of the last century, see section 5.1), and it is likely that the variable nature of hurricane tracks and their associated sudden changes in precipitation impede simultaneous impacts in the stations throughout the entire region during the wet season and therefore the annual totals. Nevertheless, as November to April is a Hurricane-free period, the rainfall patterns are now easier to identify within RD7 and its surroundings.

La Huasteca region can still be linked to RD8 covering the area north of Veracruz and south of Tamaulipas states, in which winter atmospheric controls like polar fronts could penetrate far south directly affecting the precipitation patterns during the dry season.

The humid South Pacific coast is represented as RD9. It has not been classified either for the annual or the wet season analyses, but it is possible (as in the case of the Yucatán Peninsula, RD7 in table 4.3) that tropical-cyclone precipitation have affected the PCA results during those periods, so only allowing its classification for the dry season.

Closely replicating results in the previous sections, RD10 shows the wettest Mexican rainforest area. This is the only region that could be observed in the three different regionalisation analyses using Principal Components. This supports what has already been mentioned above. In this region precipitation amounts are roughly balanced between wet and dry seasons.

Finally, R11 is the least clear region of all; this could be either an artificial effect of PCA or product of the decision of using more components in order to compare with the annual and wet seasons.

Clear regionalisation can be observed either for orthogonal (varimax) or oblique (promax k=2) solutions, when we apply PCA to the dry season. Nevertheless, because of the complexity of the database that has been analysed, clearer results are obtained with promax (see section 3.3.2), in terms of the clusters of stations for the different groups. Reduced regions and omission of the odd classified stations (like in the first PCs: regions RD1, RD2, RD3 and RD4) are two discernible characteristics of using promax (k=2). Overall, dry season regions depict a markedly different structure when compared with the annual and wet season PCA results. These resulting regions support the conclusion that wet season is the most important period for the annual precipitation in most of the country (see section 2.2). However, PCA results on the dry season suggest that precipitation totals during this period are not ignorable, and should be take into account for future studies of the Mexican climatic patterns.

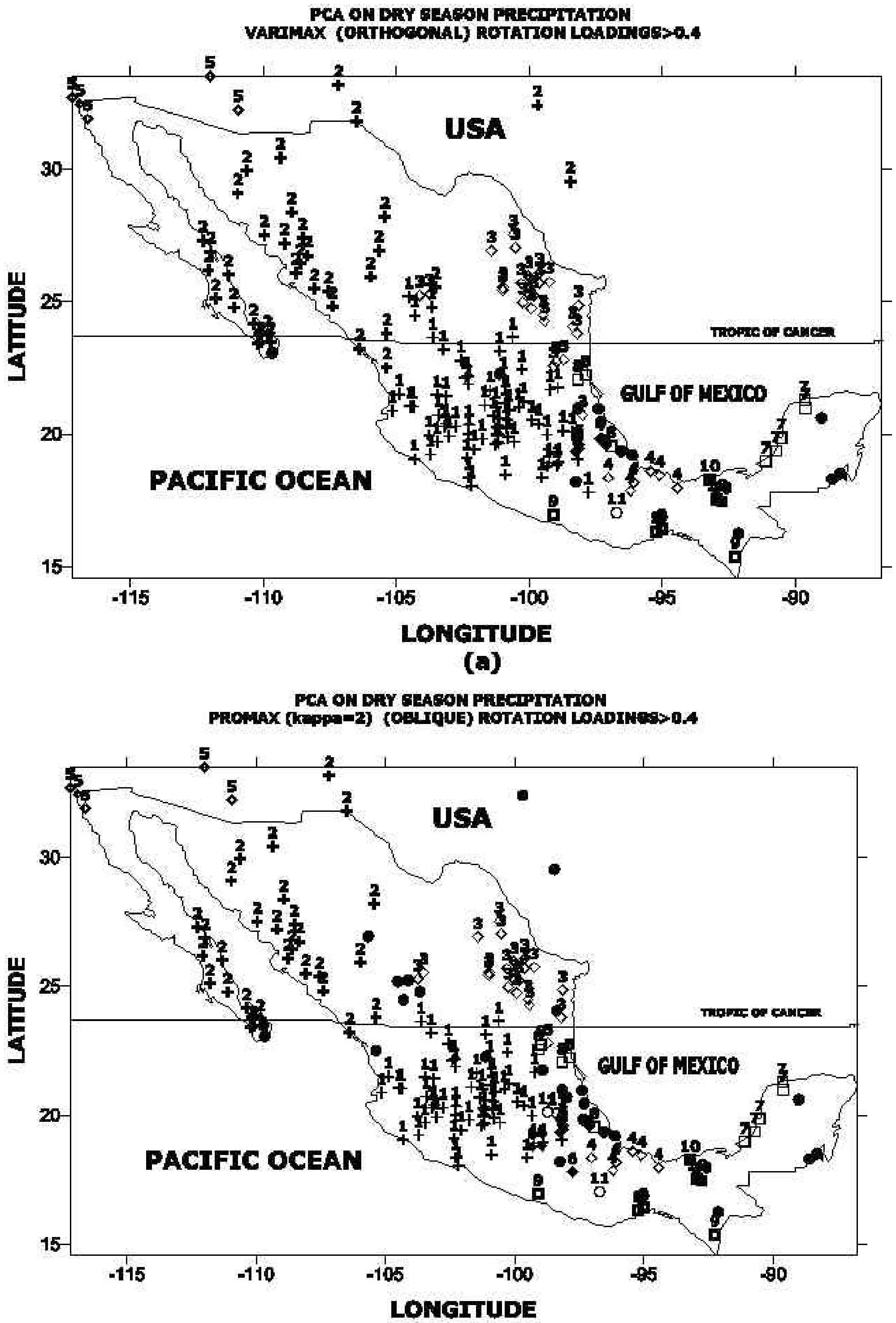


Figure 4.6. Principal component analysis (regionalisation) of a network of 175 stations with dry season (Nov-Apr) precipitation (1931-2001) using two different solutions: varimax (a) and promax with kappa=2 (b).

Component	Associated region	Climatic characteristics
Region one (RD1)	Central Mexican Highlands	Trades in summer, monsoon from the Pacific, summer rainfall, two temperature maxima
Region two (RD2)	Northwest, Arizona and Texas	Subtropical high pressures, westerlies, one temperature maximum.
Region three (RD3)	Northeast	Trades in summer, polar fronts in winter, hurricanes in summer and autumn, one temperature maximum.
Region four (RD4)	Gulf of Mexico coast	Trades in summer, hurricanes in summer and autumn, polar fronts in winter, two temperature maxima.
Region nine (RD5)	North Baja California	Westerlies, winter precipitation, one temperature maximum.
Region six (RD6)	Transverse Neovolcanic Belt	Summer precipitation, Pacific monsoon, high altitude sites, two temperature maxima.
Region seven (RD7)	Yucatán peninsula	East and Northeast trades, hurricanes during summer and autumn, polar fronts in winter, summer rainfall with considerables percetages of winter precipitation, two temperature maxima.
Region eight (RD8)	La Huasteca	Summer precipitation, hurricanes in summer and autumn, polar fronts.
Region nine (RD9)	Humid South Pacific	Westerlies, winter precipitation, one temperature maximum.
Region ten (RD10)	Southeast rainforest	InterTropical Convergence Zone (ITCZ), southeastern trades, hurricanes in summer and autumn, two temperature maxima.

Table 4.3. Dry season precipitation PCA resulting regions identified according to the known Mexican climatology (García, 1988).

4.3. PRINCIPAL COMPONENT ANALYSIS (PCA) ON MEAN TEMPERATURE.

In order to expand the understanding of the climate of México, and also to complete the picture depicted by the PCA on precipitation, it was decided to apply the same sort of analysis to mean temperature. Only a few have been made applying PCA to Mexican temperatures (see section 4.2). As has been pointed out in previous chapters this is not surprising, as it is only relatively recently (late 1990s, see section 3.2) that extended digital databases prepared from instrumental data have been released. Still, the number and spatial coverage of temperature stations is smaller when compared with that of precipitation. This can be explained as the Mexican post-revolutionary economic era before the 1980s being partially linked to agriculture (Liverman and O'Brien, 1991), and therefore the precipitation pattern changes were more important than those for temperature. The meteorological network developed more towards rainfall measurements during the early instrumental periods, instead of developing simultaneously with other climatological variables like temperature. The temperature data network to be used follows the same conditions established for precipitation, i.e., to have as many stations as possible across the nation together with a precise definition of the seasons under study. The smaller number of Surface Air Temperature (SAT) stations than those for precipitation, does not permit a good spatial coverage throughout the country (Fig. 4.7). A database of fifty-two stations containing monthly mean temperature was prepared. Except for those located in the USA, all of them were processed from daily data. Following the same conditions for the PCA on precipitation, the maximum percentage of missing values was restricted to 10%, and missing months were replaced with their respective means. In contrast, the length of the time series is only 61 years, starting in 1941 and ending in 2001; ten years shorter than the rainfall network (see section 3.2.2). Anomalies with respect to their long-term means were also calculated, in order to avoid as much as possible sudden changes in the time-series and well-known direct "external" influences such as altitude (Comrie and Glenn, 1998). Other factors play important roles in the annual temperature cycle, among them latitude is crucial for the determination of the seasonality of the dynamics of temperature (see section 2.2.1).

	STATION NAME	STATE	SMN ID	LONGITUDE	LATITUDE*	ALTITUDE+
1	PABELLON DE ARTEAGA	AGS	01014	-102.33	22.18	1920
2	PRESA CALLES	AGS	01018	-102.43	22.13	2025
3	PRESA RODRIGUEZ	BCN	02038	-116.90	32.45	100
4	ENSENADA	BCN	02072	-116.60	31.88	24
5	COMONDú	BCS	03008	-111.85	26.08	260
6	EL PASO DE IRITU	BCS	03012	-111.12	24.77	140
7	LA PURíSIMA	BCS	03029	-112.08	26.18	95
8	SAN BARTOLO	BCS	03050	-109.85	23.73	395
9	SANTA GERTRUDIS	BCS	03060	-110.10	23.48	350
10	SANTA ROSALíA	BCS	03061	-112.28	27.30	17
11	SANTIAGO	BCS	03062	-109.73	23.47	125
12	LA PAZ	BCS	03074	-110.37	24.15	10
13	MANZANILLO	COL	06018	-104.32	19.05	3
14	MOTOZINTLA	CHIAP	07119	-92.25	15.37	1455
15	EL PALMITO	DUR	10021	-104.78	25.52	1540
16	EL SALTO	DUR	10025	-105.37	23.78	2538
17	GUANACEVI	DUR	10029	-105.97	25.93	2200
18	RODEO	DUR	10060	-104.53	25.18	1340
19	SANTIAGO PAPASQUIARO	DUR	10100	-105.42	25.05	1740
20	IRAPUATO	GTO	11028	-101.35	20.68	1725
21	OCAMPO	GTO	11050	-101.48	21.65	2250
22	PERICOS	GTO	11052	-101.10	20.52	1720
23	SALVATIERRA	GTO	11060	-100.87	20.22	1760
24	SALAMANCA	GTO	11096	-101.18	20.57	1723
25	CUITZEO DEL PORVENIR	MICH	16027	-101.15	19.97	1831
26	HUINGO	MICH	16052	-100.83	19.92	1832
27	CIUDAD HIDALGO	MICH	16152	-100.57	19.70	2000
28	ZACAPU	MICH	16171	-101.78	19.82	1986
29	AHUACATLAN	NAY	18002	-104.48	21.05	990
30	EL CUCHILLO	NL	19016	-99.25	25.73	145
31	LAMPAZOS	NL	19028	-100.52	27.03	320
32	MATIAS ROMERO	OAX	20068	-95.03	16.88	201
33	SANTO DOMINGO TEHUANTEPEC	OAX	20149	-95.23	16.33	95
34	TEZIUTLAN	PUE	21091	-97.35	19.82	2050
35	MATEHUALA	SLP	24040	-100.63	23.65	1575
36	BADIRAGUATO	SIN	25110	-107.55	25.37	230
37	TRES HERMANOS	SON	26102	-109.20	27.20	100
38	SAN FERNANDO	TAM	28086	-98.15	24.85	43
39	ATZALAN	VER	30012	-97.25	19.80	1842
40	RINCONADA	VER	30141	-96.55	19.35	313
41	LAS VIGAS	VER	30211	-97.10	19.65	37
42	EL SAUZ	ZAC	32018	-103.23	23.18	2100
43	BROWNSVILLE	TX	BWVTX	-97.40	25.80	6
44	SAN ANTONIO	TX	SATTX	-98.50	29.50	223
45	MIDLAND	TX	MAFTX	-102.20	32.00	846
46	EL PASO	TX	ELPTX	-106.40	31.80	1150
47	TOMBSTONE	US	TSTUS	-110.10	31.70	1405
48	TUCSON	AZ	TUSAZ	-110.90	32.10	780
49	PHOENIX	AZ	PHXAZ	-112.00	33.40	335
50	SAN DIEGO	CA	SANCA	-117.20	32.70	5
51	CUYAMACA	CA	CYCCA	-116.60	33.00	1414
52	LOS ANGELES	CA	LAXCA	-118.20	34.10	4

Table 4.4. List of stations with monthly mean temperature. The period of records for all the stations is from 1941 to 2001. * meters above sea level.

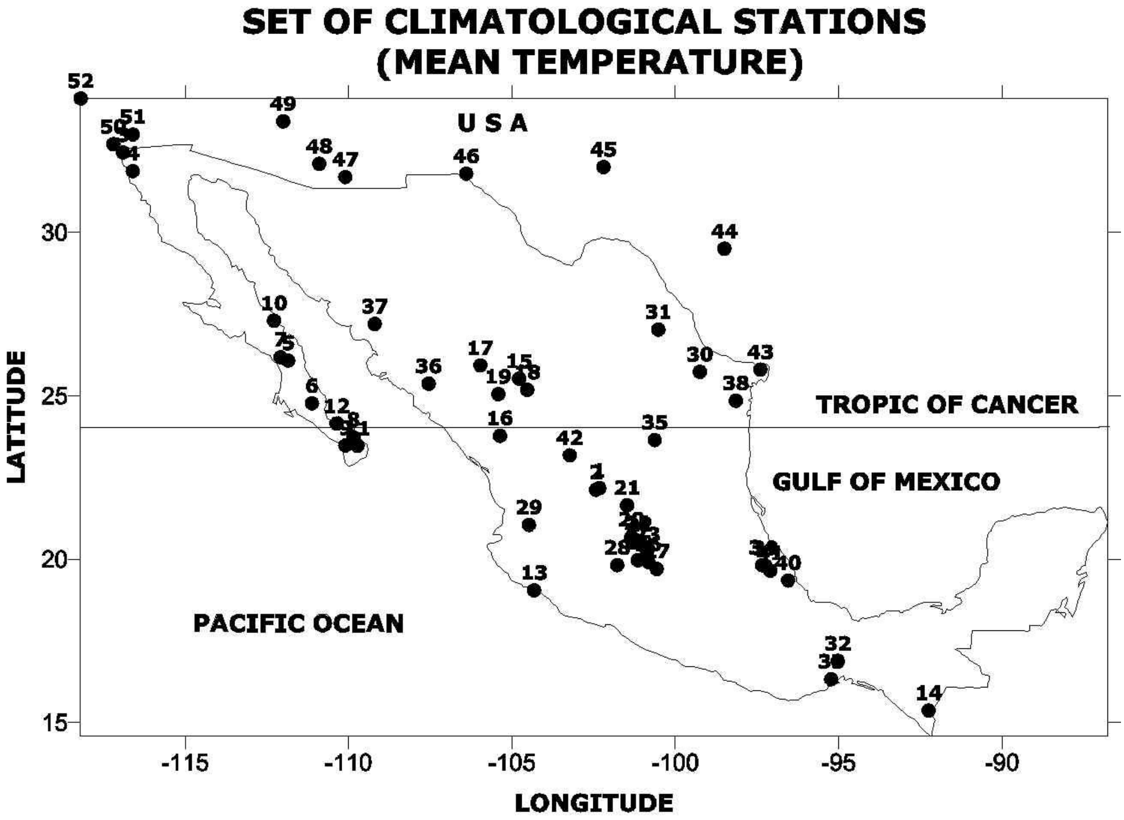
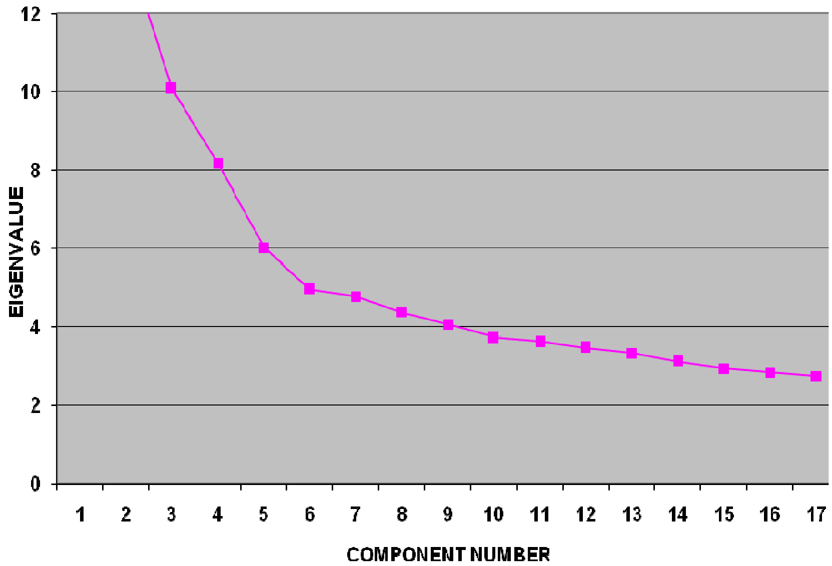


Fig.4.7. Locations of the 52 climatological stations with monthly mean temperature during the period 1941-2001 used in the Principal Component Analysis (PCA).

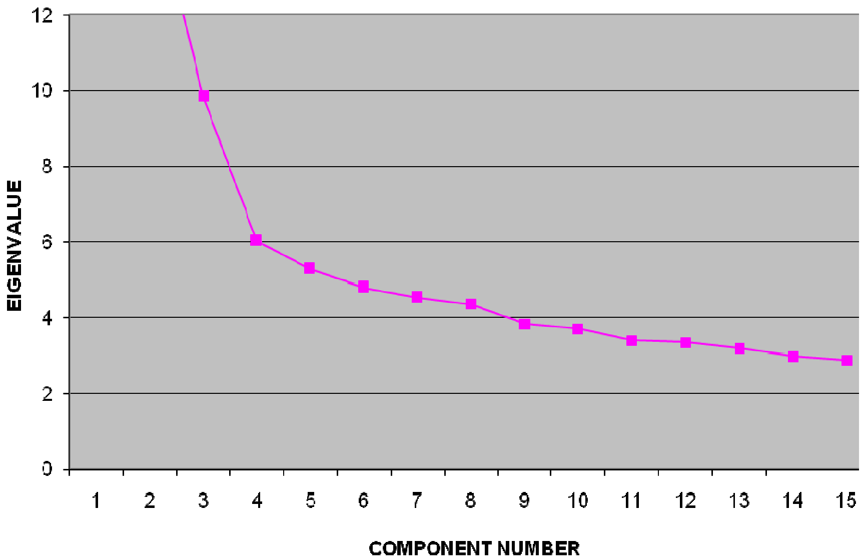
Much of the annual rainfall is concentrated in Mexico in the summer months; and closely agrees with the procession of the seasons modulated by temperature (Mosiño and García, 1974). The progression of the temperature maxima shows a northwards movement starting in May, with exceptions observed along both Mexican coasts. For these reasons, it was decided to define the same three seasons as for precipitation: May to October, November to April and the annual period, and to analyse them applying PCA with S-mode for regionalisation purposes, using the correlation matrix for contrasting climatic conditions (see section 3.3.2). Rotated (orthogonal and oblique) solutions techniques were applied to the databases to obtain the regionalisation.

4.3.1 ANNUAL MEAN TEMPERATURE.

The contrasting conditions for precipitation explained in Chapter two are closely replicated by mean annual temperature. The smallest differences are experienced in the south Pacific coast, whilst the most dissimilar conditions are observed over the north to north-western regions of the country, in a gradual increasing tendency from south to north. Apart of this evident characteristic, to identify different regions that are coherently



a)



b)

Figure 4.8. Scree Test Plot on a) Annual and b) wet season (May-Oct) Mean Temperature.

varying, it was necessary to define how many components were going to be used. For this purpose the scree test and the same separation method of the previous sections was applied. Based on the scree test (see section 3.3.2) of Fig. 4.8 a), we can select the number of components using two different criteria. Firstly, after the 12th component, the variation with respect to the next components is negligible and these first 12 components account for 80.1% of the total variance, and secondly the eigenvalue of the 12th component is close to the unity (1.0), i.e. the Kaiser-Guttman rule (Peres-Neto et al., 2005). Therefore, the number of components is set to 12.

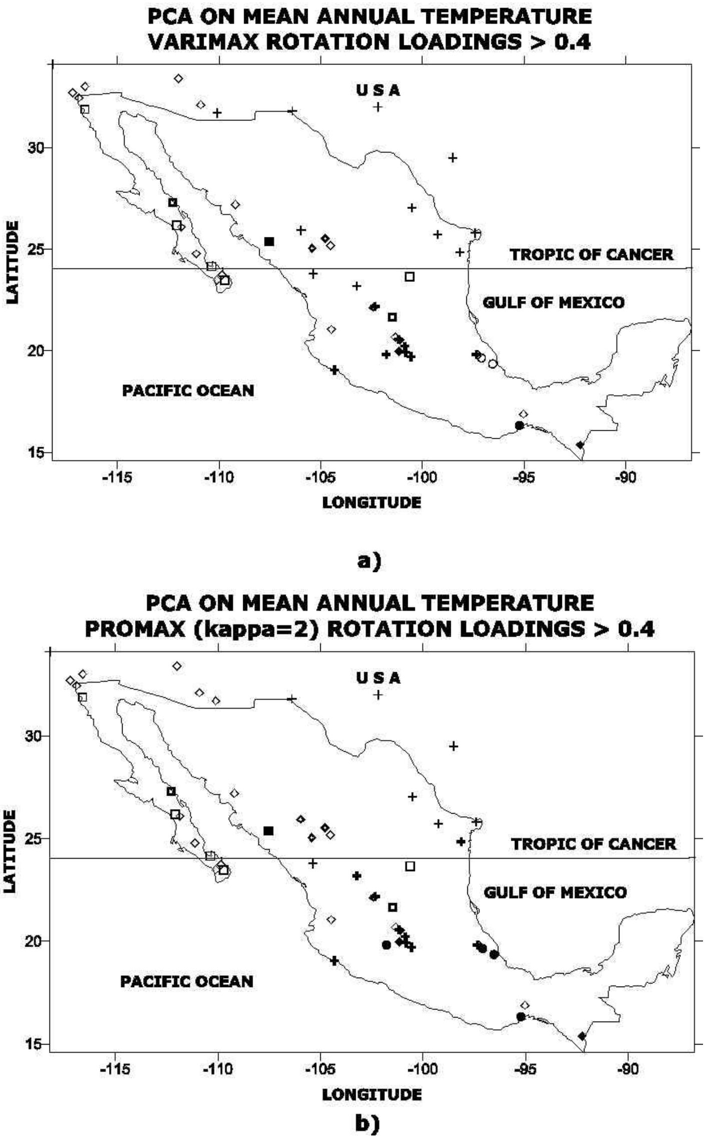


Figure 4.9. Principal Component Analysis (PCA regionalisation) of a network of 52 stations with annual mean temperature (1941-2001) using two different solutions: a) varimax and b) promax with kappa=2.

In contrast to the precipitation results, a lack of clarity in regions can be easily observed (see Fig. 4.9). Probably the only regions reasonably well delineated are located in the north of the country near the border with the USA. One is centred in the north and northeast of México related to the Río Bravo Basin, whilst the other is in North Baja California – California region near to the Pacific coast. No other region can be easily defined and linked to any known climatic features in the country.

4.3.2. MAY TO OCTOBER MEAN TEMPERATURE.

The scree test (see section 3.3.2) on the May to October period reveals that 12 components would be sufficient to explain the climatology of this period. The curve becomes close to a line after the 12th component, the rest of modes of variation are practically not contributing to the communalities (Fig. 4.8). As in the case of annual mean temperature, the regions are not clearly defined except for what seems to be the Río Bravo Basin. None of the rotated solutions improved the results when contrasted with the annual mean temperature regions (Fig. 4.10). These results appear to closely replicate what has been seen in the previous section (annual mean temperature). It is possible that, the smaller fluctuations in mean temperature (in comparison with the larger and easy detectable changes in precipitation) have influenced the unsuccessful regionalisation of the annual and May to October mean temperatures. The only clear regions extracted applying PCA to mean temperature are observed in Northern Mexico where sudden changes in temperature can occur especially during winter, in contrast with the less variable temperatures in Southern Mexico. A latitudinal transition (defined by the tropic of Cancer) can be pointed out in this analysis. PCA is then, going to be applied to the three-monthly periods Dec-Jan-Feb (DJF), Mar-Apr-May (MAM), Jun-Jul-Aug (JJA), Sep-Oct-Nov (SON), in order to explore alternatives for improving the results.

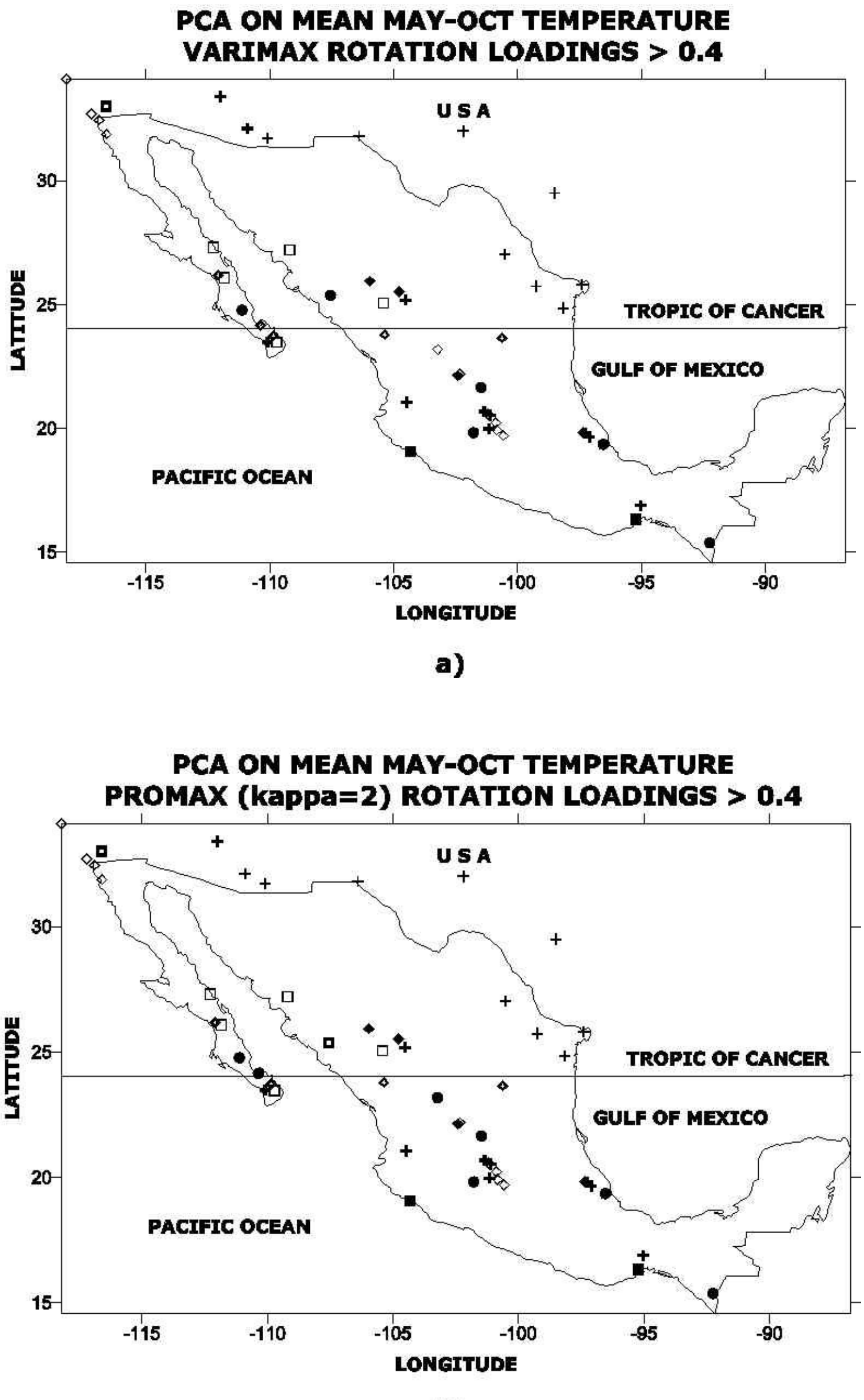


Figure 4.10. Principal Component Analysis (PCA regionalisation) of a network of 52 stations with May-Oct mean temperature (1941-2001) using two different solutions: a) varimax and b) promax with kappa=2.

4.3.3. SEASONAL MEAN TEMPERATURE.

It is clear observing the Figure 4.12 that no regions can be extracted for the mean temperature (as was the case for precipitation), that make sense with the Mexican climatology. These poor results obtained for the cases of annual and May to October (wet season for rainfall) mean temperature enforced the decision to split the periods on a traditional seasonal basis (DJF, MAM, JJA, SON), and analyse them using PCA. Dividing seasonally the mean temperature, we will explore the possibility of improving the PCA regionalisation. The scree tests (see Fig. 4.11) for seasonal mean temperature show an agreement after the 11th component. The rest eigenvalues associated to their modes of variation are no more contributing to the total variance, and not helping in the interpretation of the spatial patterns.

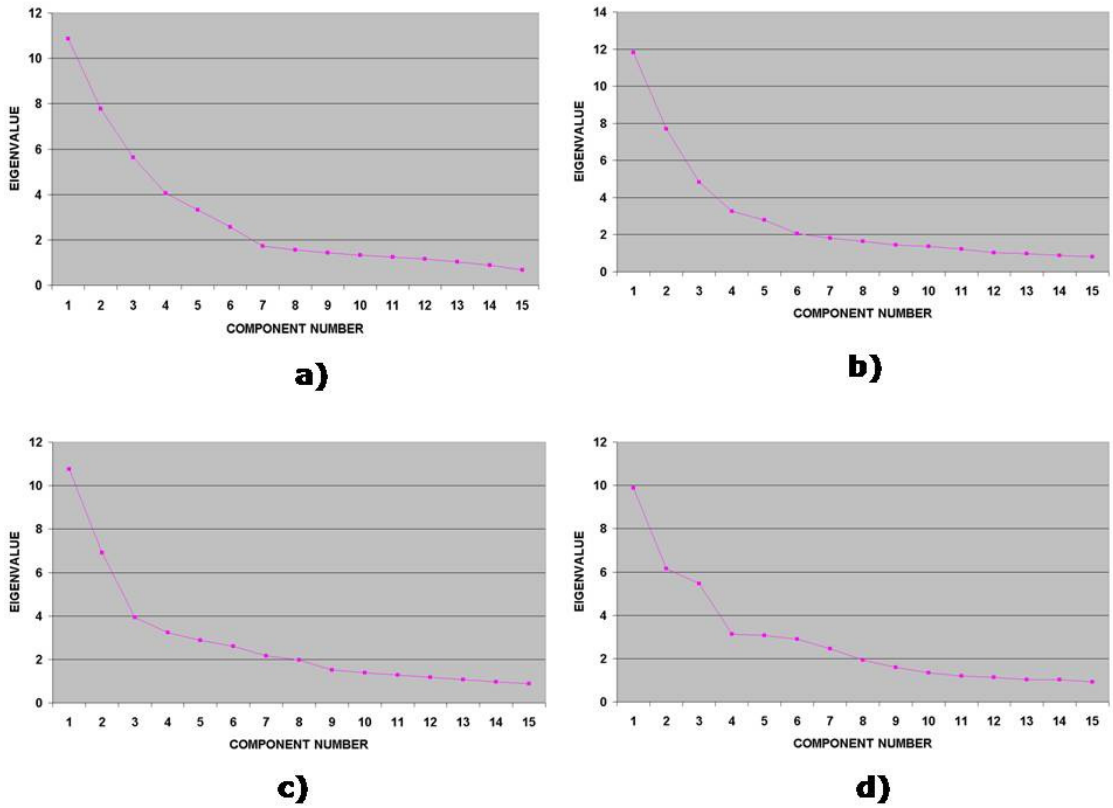


Figure 4.11. Scree Test Plot on a) DJF b) MAM c) JJA and d) SON periods for the selection of number of components.

The resulting distribution of regions (Fig 4.12) of the analysis of PC using an orthogonal rotated solution (Varimax) does not show a clear pattern in any of the (three monthly) periods. The only consistent region across all the periods is the northeast region that we have linked to the Río Bravo Basin in the previous section. Less clear but present is the north-western North Baja California – California region, however, only during the DJF period is this well defined. None of the other results have apparently any relation with those of rainfall.

No improvement in the results (Fig 4.13) is observed when using the rotated oblique solution (Promax), in contrast with the precipitation regionalisation applying PCA (see section 4.2.1). Here, the northern areas of the country, near the USA border are the only regions delineated by the analysis, repeating the clusters linked to the Río Bravo Basin and the north Baja California area. The latter extends eastwards to cover Arizona and New México in the USA during the DJF and MAM periods. These are seasons when polar fronts affect both rainfall and temperature, especially in northern Mexico. The results closely mirrored those of the orthogonal solution; but overall, as in the case of the varimax (orthogonal) solution, the regions do not show a spatial consistency through all the seasons.

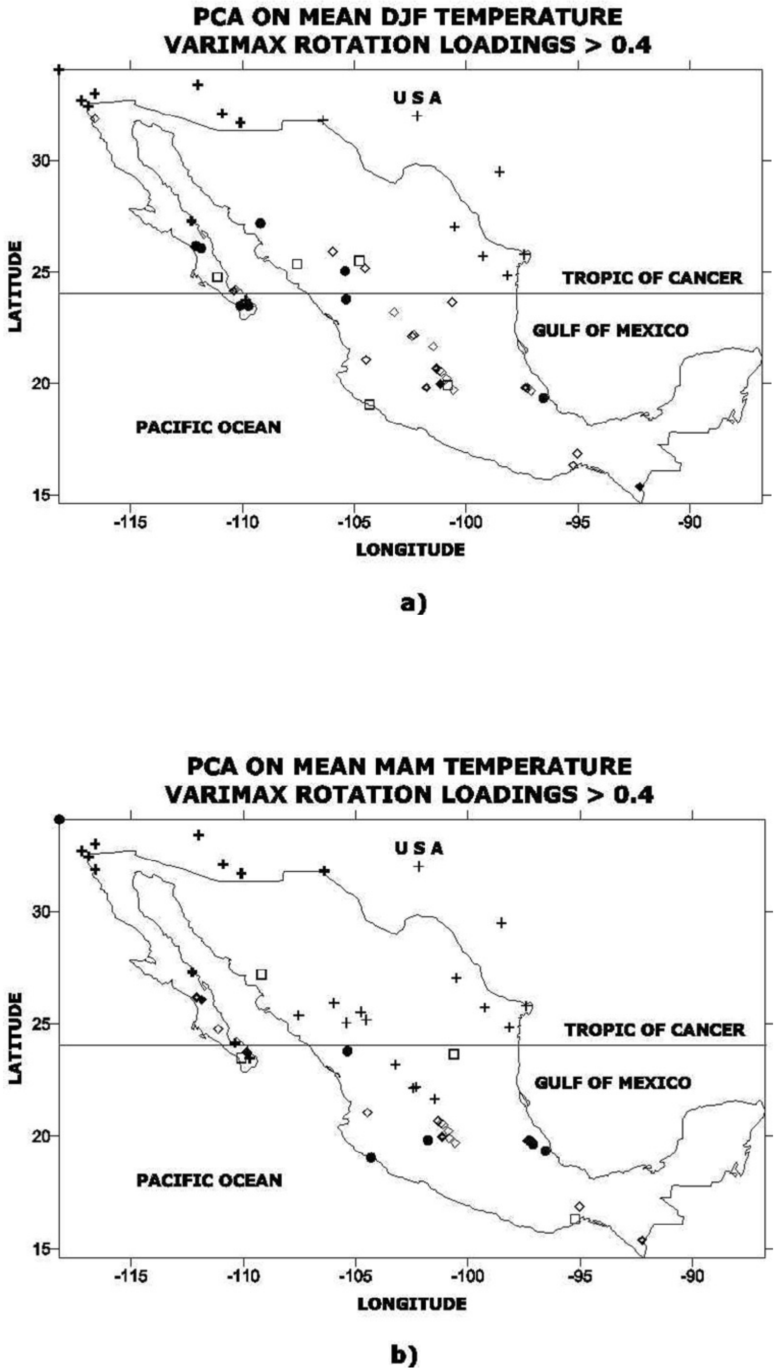
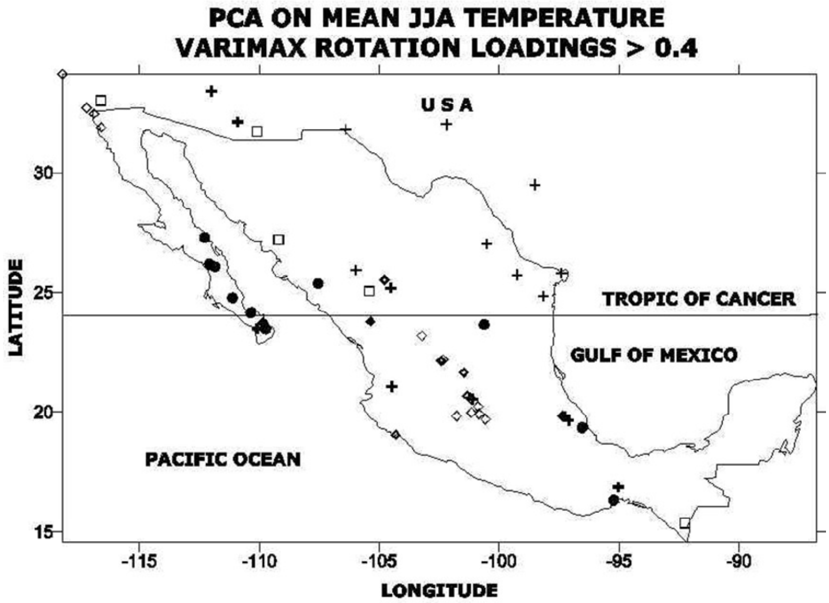
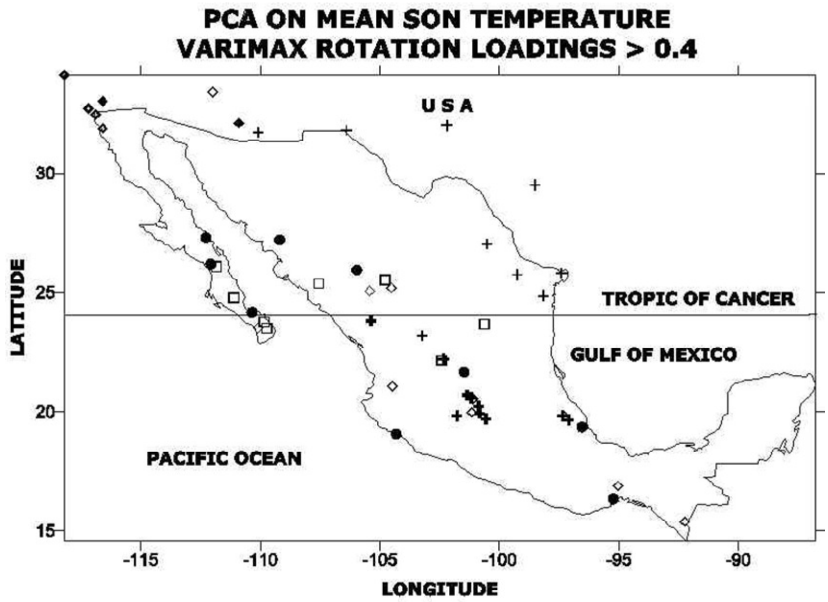


Figure 4.12. Principal Component Analysis (PCA regionalisation) applying an orthogonal rotated solution (Varimax) of a network of 52 stations with a) DJF b) MAM mean temperature (1941-2001).



c)



d)

Figure 4.12. Principal Component Analysis (PCAregionalisation) applying an orthogonal rotated solution (Varimax) of a network of 52 stations with c) JJA and d) SON mean temperature (1941-2001).

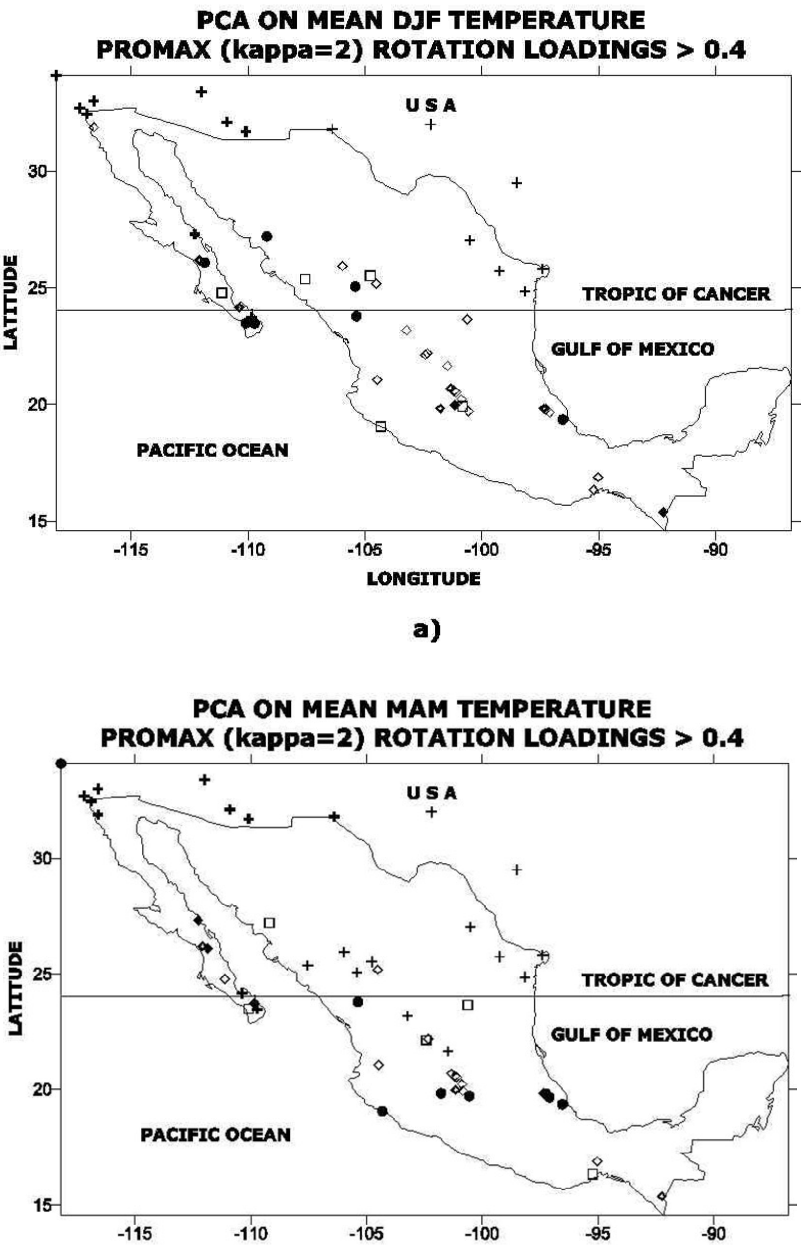
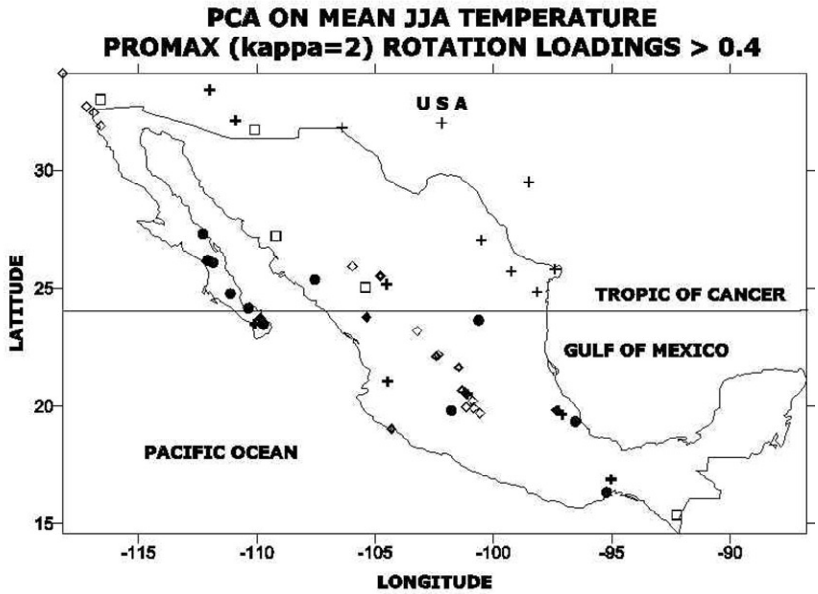
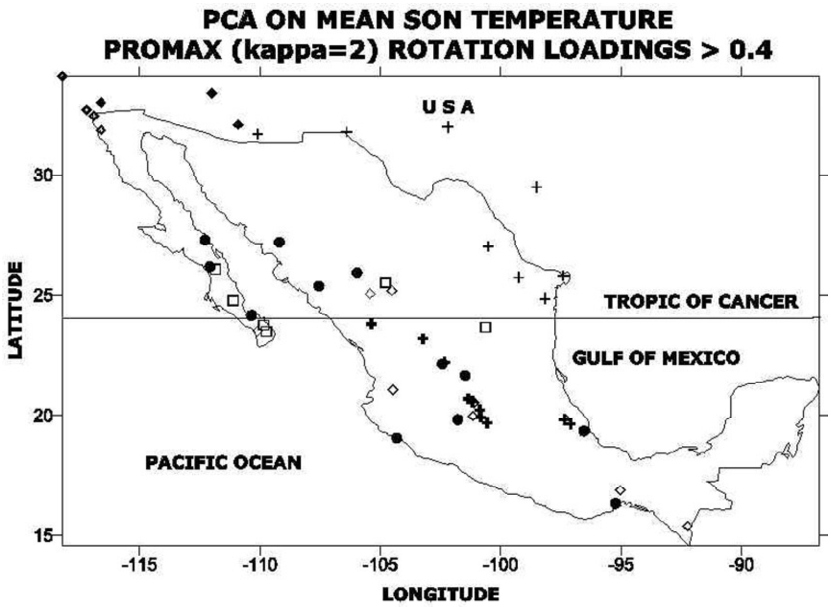


Figure 4.13. Principal Component Analysis (PCA regionalisation) applying an oblique rotated solution (Promax) of a network of 52 stations with a) DJF b) MAM mean temperature (1941-2001).



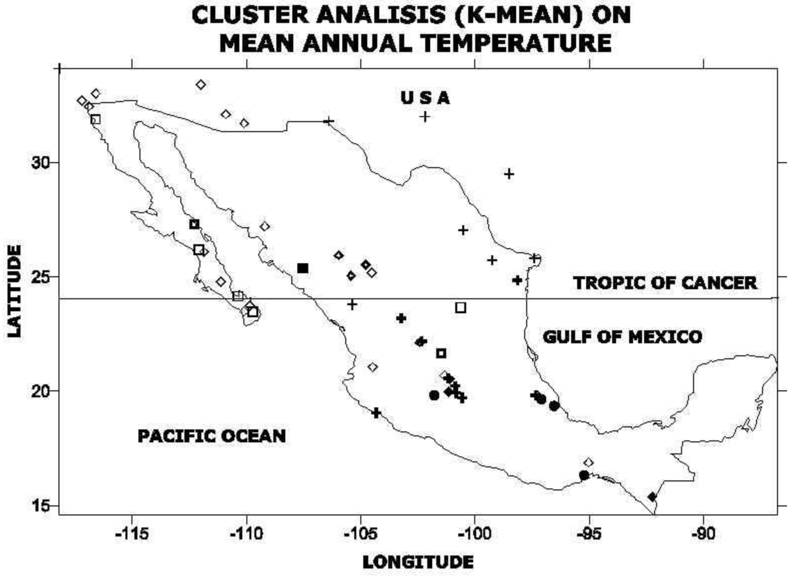
c)



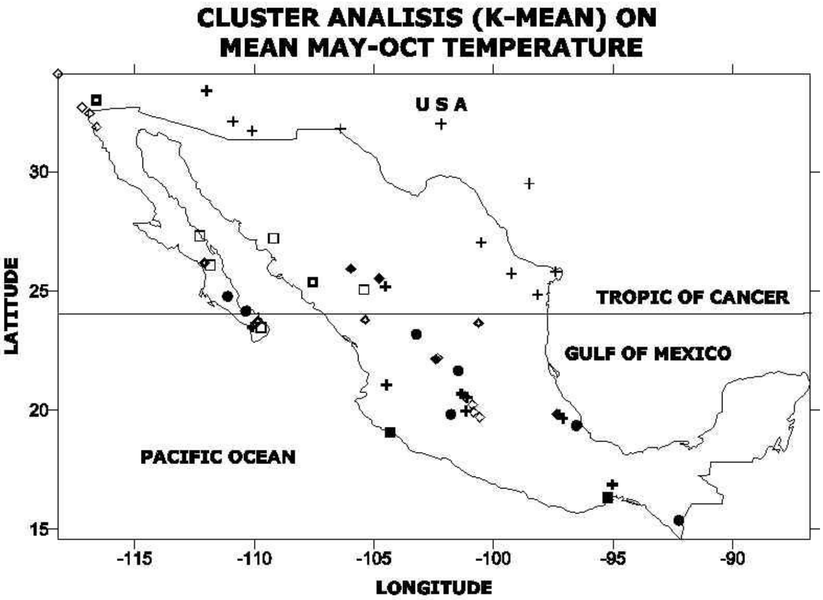
d)

Figure 4.13. Principal Component Analysis (PCA regionalisation) applying an oblique rotated solution (Promax) on a network of 52 stations with c) JJA and d) SON mean temperature (1941-2001).

4.3.4. K-Means Cluster Analysis.



a)



b)

Figure 4.14. Cluster Analysis (K-mean) of a network of 52 stations with a) annual b) wet season mean temperature (1941-2001).

A final option for the purpose of regionalisation of the mean temperature data was to apply what is termed K-means cluster analysis. The resulting regions are shown in Fig. 4.14., but no improvement can really be observed when compared with those obtained by rotated PCA. In fact, what the cluster analysis shows is an agreement with the mean temperature PCA regionalisation, replicating the distribution already observed using that technique. It can be concluded, therefore that the type of analysis has no influence on the final results, but it is very likely that primarily the small number of stations and the length of the time series utilised have impeded a clear outcome in comparison with those obtained in the case of precipitation.

4.4. CONCLUSIONS TO THE CHAPTER.

A process of regionalisation using Principal Component Analysis (PCA) has been applied to two different networks of monthly precipitation and temperature data. Amongst other reasons, because of its better temporal and spatial coverage; successful results have been obtained with precipitation, and poor results for mean temperature. Clearer results are also evident for oblique rotated [in particular (promax, k=2)] solutions than those of orthogonal rotated (varimax) solutions.

The analyses were divided into three main seasons for precipitation: annual, wet (May to October) and dry (November to April) seasons. Annual and wet season results are quite similar. They share most of the PCA regions, but also have slight differences. The North American Monsoon and La Huasteca are regions that only appear during the analysis of annual total precipitation. These regions are sometimes strongly affected by winter rainfall influencing the annual precipitation.

In contrast, Nayarit state and the transverse neovolcanic belt are regions that can only be extracted during the wet season. In the case of the neovolcanic belt region, altitude certainly exerts a large influence on the results. This is an area that needs to be explored in much detail in future research. The great amounts of moisture entering the continent seem to be affecting the Nayarit (Pacific) coast during the wet season. This is the reason the region does not appear during the dry season or the annual totals. Finally, during the rainfall dry season there is a markedly latitudinal transition. The Mexican monsoon and North Baja Californian are regions in which winter precipitation is an important percentage of the annual totals; these two regions are located in the north-western part of the country. November to April is basically a hurricane-free period; therefore, those regions that are deeply affected by these phenomena during the wet season, have now appeared in the dry season results. The Yucatán peninsula and the South Pacific regions clearly show that the heavy precipitation caused by hurricanes can strongly affect their rainfall patterns completely separating them from their (PCA) neighbouring regions during the wet season and the annual totals.

Mean temperature was the other variable analysed using PCA. This method was applied using the rotation techniques to the annual mean temperatures and wet season; nevertheless, no clear results were obtained for these seasons. An alternative approach was used defining three-monthly periods that aimed at obtaining better results. However, no improvement was observed in comparison with the previous analysis. A final attempt was made using K-means cluster analysis but poor results were also evident. Only the northern regions within the border of Mexico-USA appear consistently across all these analyses.