CHAPTER 8: CONCLUSIONS

8.1. MAIN FINDINGS.

A network of stations with high-quality and long-term instrumental data of precipitation and temperature has been built to study recent climatic changes in Mexico. The monthly database consists of 175 stations of rainfall data spanning from 1931 to 2001; and a set of 52 stations with monthly temperature data has been extracted, whose length extends from 1941 to 2001. A network of 15 precipitation and 26 temperature stations with daily data goes from 1941 to 2001 has also been developed.

The construction of the meteorological network used in the present study has been a difficult and time-consuming task. The extraction of the data was based on the advent of several efforts (since the early 1990s) to digitise the instrumental records of Mexico. Therefore, having more information among the possible meteorological variables to be analysed, daily data of precipitation and temperature was the main objective of the extraction. In order to fulfil this purpose five different sources of data were used, and a process of cross-checking applied among the databases (see section 3.2). Because of the great importance that agriculture has had in the Mexican economy, the precipitation network has better spatial coverage than temperature, and an addtional monthly database was used to complete the daily records of precipitation, that was not possible in the case of temperature (because there was not a monthly database available). Long-term and completeness were the main conditions used to include a time-series in the database. Nevertheless, one of the main goals of the construction of the network was quality control of the data, in order to assure the reliability of the results on the study of the patterns of climate change in the country.

Mexico is a territory with a complex climatic picture. Many factors (natural amd athropogenic) contribute to modulate the climate of the country. Principal Component Analysis (PCA) was chosen to isolate groups of stations that vary coherently across time.

PCA results were also used to compare directly the climatic fluctuations at regional and local scales. This method was applied to monthly rainfall and mean temperature data to define the different climatic regions across the country.

In most of the Mexican territory the largest percent of the annual total precipitation occurs during the May to October period (Mosiño and García, 1974; Hastenrath, 1967). Therefore, the analysis on precipitation was divided into three parts: annual precipitation, wet (May-Oct) and dry (Nov-Apr) seasons. Due to their clearer results PCA rotated solutions were selected over the unrotated solutions (see section 4.2.1). Varimax and Promax (kappa=2) were used to regionalise the precipitation patterns across the country. Both techniques basically lead to the same results, Promax performing slightly better than Varimax.

Successful regionalisations were found using PCA for rainfall regardless of the season considered. Very similar regions were found for the annual total precipitation and the wet season, basically one replicating the results of the other, but a different climatic picture is seen for the dry season (Nov-Apr, see section 4.2). Nevertheless several interesting differences appear amongst the different seasonal resulting PCA regions.

The North American Monsoon -or Mexican Monsoon- Region (NAMR) and La Huasteca are two regions that only appear for the PCA regionalisation of annual total rainfall. Although the greatest component of precipitation falls during the summer months, the NAMR (Ropelewski et al., 2004; Arritt et al., 2000; Barlow et al., 1998; Stensrud et al., 1997; Higgins et al., 1997; Douglas et al., 1993) can only be extracted by applying PCA to the annual precipitation. This limitation can be linked to the greater importance that winter precipitation (Giddings et al., 2005; Mechoso et al., 2004) has for the NAMR, especially in the north-western part of Mexico. The other region that only appears during the annual rainfall regionalisation is La Huasteca. Here, winter precipitation also plays a key role in the annual precipitation; polar fronts can reach these latitudes during the winter, and when combined with the moisture from the Gulf of Mexico, can enhance the precipitation during this season (Cavazos, 1997). This atmospheric (winter) processes rarely occurs within the large inner area protected by the two mountain ranges barriers of the rest of Mexico.

Two regions are distinctive when applying PCA regionalisation to wet season time series of rainfall. The Nayarit coast region can be considered as the southern limit of the NAMR. Significant amounts of moisture from the Pacific Ocean directly affect the summer precipitation in this area. Nevertheless, it is unlikely that cold fronts can penetrate this far south as is the case for the northern part of the NAMR during the winter season and, therefore, can only be extracted during the wet season. The other group of stations that only appear from the PCA results from the wet season (May-Oct) is the Neovolcanic Belt region (Demant and Robin, 1975). Although explicitly avoided by using standardised time series (Comrie and Glenn, 1998), the influence of altitude plays a key role in this area; capturing the humidity of the convention processes (widely characteristic in Mexico) during the warm Season (Mosiño and García, 1974).

Perhaps, because its rainfall patterns are not affected by the large-scale convection processes characteristic of the summer period, the dry season (Nov-Apr) shows three different regions that do not appear during the annual precipitation or wet season periods. In fact, there can be a fourth region, if we also add the NAMR as a region that is impacted by winter precipitation, as discussed earlier. The NAMR can be climatically linked to the North Baja California Peninsula and defined as a region in which the annual total precipitation is strongly affected by the cold air masses of the winter season. The other two groups of stations only found applying PCA to the dry season (Nov-Apr) time series are the south-eastern and the Yucatán Peninsula regions. Both regions are profoundly affected by hurricanes during the warm season. Therefore, their climatic patterns can be completely disrupted by tropical cyclones, in comparison with their neighbouring stations (Englehart and Douglas, 2002).

Although wet season (May-Oct) rainfall contributes with the largest percent of the annual total precipitation, is the dry season (Nov-Apr) that really helps to identify the large-scale atmospheric processes that are controlling the rainfall patterns in Mexico. For instance, by contrasting the different results by season, we can conclude that more research is needed in several atmospheric phenomena that are controlling the climate of Mexico, and that have not been extensively explored such as: altitude, hurricanes or polar fronts. These topics of future research will be addressed briefly at the end of this chapter.

Extreme events are a direct measure of the effects of a changing climate. The frequency of the weather extremes is more dependent on the variability than in the means (Katz and Brown, 1992). The Climate extremes are rare in terms of frequency but have large impacts on intensity. Therefore, it is very important to study these sorts of events to fully understand climatic changes. We have calculated and analysed weather extreme indices using the Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) approach, and Kendall tau-b to estimate their linear correlations with possible forcing factors.

At regional levels total precipitation is decreasing in southern Mexico, especially in the forests of Los Tuxtlas (near the Gulf of Mexico), the rainforest of south-eastern Mexico and in Michoacán state. In contrast, at local levels, precipitation is increasing above normal over the Yucatán Peninsula and also the northern part of the Baja California.

We have also counted the number of statistically significant results related to extreme rainfall indices, dividing the country north and south considering the Tropic of Cancer as a geographical limit. According to these conditions, decreasing precipitation is observed for the stations close to the Atlantic Coast (Gulf of Mexico), and an upward trend (wetter conditions) for those stations located near the Pacific Coast. Another spatial pattern observed in the results is one of increasing precipitation in both peninsulas (Yucatán and Baja California) and decreasing rainfall for the continental (mainland Mexico) stations.

Extreme temperature indices were also explored in this study. Their correlations at local scales (by station) show warming conditions in the north of Mexico, while in the southern part of the country a cooling trend is observed. The stations with the most pronounced changes are El Paso de Iritu (in the southern tip of the Baja Californian peninsula) that shows a trend towards warmer conditions; and the Ahuacatlán station near the Nayarit (central Pacific) coast whose indices are leading to colder conditions, especially those related to night temperatures.

The same method (applied on precipitation) of counting the most statistically significant results was applied to the temperature time-series, in order to establish their changing climatic patterns. According to this process, warming conditions are seen in the northern part of Mexico, and a downward (cooling) trend is observed in the southern part of the country. Throughout all the results observed in the analysis of extreme temperature indices, a clear national pattern of warming conditions is observed in minimum temperatures.

The last analysis of this thesis tried to relate the climatic variations (rainfall and temperature) in Mexico with a large-scale atmospheric control. Because of their planetary scale, we have selected El Niño Southern Oscillation phenomenon as a good option to be explored. For this purpose, we applied non-parametric (Kendall tau-b) and lag correlations to the selected meteorological variables. We have utilised three different standardised ENSO indices (SOI, Niño 3.4 and MEI) to test the consistency of the results.

As in the case of PCA regionalisation and extreme weather indices, we have found clearer results when correlating the ENSO indices with precipitation than with temperature. This is particularly true at regional scales, i.e., regional precipitation averages. Defining again (as we did for extreme weather indices) the Tropic of Cancer as a limit, we observe a clear climatic transition. Regional above normal precipitation is found in northern Mexico and drier conditions in the southern part of the country during El Niño conditions for the May to October (tropical conditions) and annual versions of the regional Standardised Anomaly Indices (SAIs). In contrast, during El Niño, an almost national pattern of wetter conditions is observed when we correlate the November to April (extra-tropical conditions) version of the regional SAIs. The timing of response is also clearer for regional (rainfall averages) than local (extreme indices) scales.

Regional average precipitation responds close to the peak of El Niño conditions, while the timing of the extreme indices is in general more variable.

Although extreme temperature indices clearly show an upward trend towards warming conditions, especially in minimum (night-time) temperatures; less clear is their spatial distribution, as there is little homogeneous climatic patterns due to changing temperature. Nevertheless, the most significant results are found in the northern part of the country, where increases in minimum temperatures are leading to warming conditions, and the largest correlations (and changes) are observed in the Baja California Peninsula. The timing of the climatic response of extreme temperature indices is first seen in the southern part of the country close to the peak of El Niño-like conditions, after which it gradually moves northwards. The clearest pattern found exploring the ENSO modulation is that precipitation seems more climatically stable in its response to ENSO than temperature, especially regional rainfall averages that respond close to the strongest conditions of El Niño.

Based on a newly constructed long-term and high quality database of temperature and precipitation; the network of precipitation has been successful regionalised using Principal Component Analysis (PCA), while poor regionalisation was found for temperature. This might be due to the markedly fewer stations in the dataset and might be related to elevation effects as well. At both regional (precipitation averages) and local (extreme indices) scales, precipitation shows a clear latitudinal climatic transition, that is directly dependent on tropical or extra-tropical conditions. The timing of response is close to the peak of El Niño-like conditions for regional precipitation averages. The analyses of temperature are not as conclusive as for precipitation. Nevertheless, there are clear changes toward warming conditions for minimum (night-time) temperatures, but their timing of response to ENSO is more variable. As shown –in this chapter- when analysing the regional precipitation averages, and also when the most significant correlations were classified, the climatic latitudinal transition is a topic that needs to be explored more extensively.

8.2. FUTURE RESEARCH.

Although a high-quality database has been constructed for this study, the network of stations can be updated together with the addition of as much recent meteorological data as possible, either from other studies or directly from the Mexican Meteorological Office. Currently, some researchers are working on the homogeneity of the network of meteorological data. This is a topic in which the present study can be certainly linked for a better understanding of the climate of Mexico.

Despite the different methods in this thesis were applied to standardised versions of the data aiming to avoid direct influences, elevation plays an important role in the climate of Mexico; the importance of this permanent control was already mentioned in an early study on the climate of Mexico by Mosiño and García (1974). However, this area has not been sufficiently explored yet. The different analyses used in this research show a clear link of the orography with both spatial and temporal scales. Principal Components (Chapter 4) on precipitation has pointed out that two regions: the Mexican Central Highlands and the Neovolcanic Belt (see Table 4.1) are excellent examples of the mechanism in which altitude is an essential physical feature to explain their coherent variations across time. All the stations in the Transverse Neovolcanic Belt exceeds the 1000 m.a.s.l. The elevation factor is also consistent when we consider the ENSO influence on rainfall (Chapter 7).The three ENSO indices (SOI, Niño 3.4, and MEI) show a strong relationship with the Transverse Neovolcanic Belt. At local scales, Yecora station (within the Mexican Monsoon Region) because its altitude (1500 m.a.s.l.; see table 3.2) has been linked to both secular changes on its rainfall extreme indices (Chapter 5), and to the physical modulation of the three different ENSO indices (Chapter 7).

Seasonal regional precipitation is strong related to the orography as well. Extracting groups that varies coherently across time utilising PCA and exploring the ENSO influence, unveil that during the dry season (Nov-Apr) there is an important link between some large-scale atmospheric controls like the Westerlies (see section 2.3) and Polar Fronts and high altitude stations within the Transverse Neovolcanic Belt and the Mexican

Central Highlands. Therefore, the influence of high-altitude in the climate in Mexico is a topic that warrants more detailed study in the future.

Several studies have dealt with the geographical extension and temporal intervals of the North American Monsoon Region (Mechoso et al, 2004; Hu and Feng, 2002; Castro et al., 2001; Higgins et al., 1997). One indirect result of this study has been the identification of the Mexican Monsoon Region (Douglas et al., 1993) as one of the important climatic regions of this country. Although, Englehart and Douglas (2002) have pointed out that the largest amount of rainfall is concentrated during June, July and August, and the winter precipitation is considerable (Griddings et al., 2005; Mechoso et al., 2004), the Mexican Monsoon Region is only extracted for the annual totals (see section 4.2.1). An appraisal of the precipitation within this north-western area utilising also the definitions of wet (May-Oct) and dry (Nov-Apr) seasons is suggested in order to compare the atmospheric processes that modulate the Monsoon in this region. Another additional aspect that could be explored is the southern limit of this region. The NAME is a promising start to address this objective, but this effort needs to be extended in order to increase our climatic understanding of the region.

The intense precipitation and damage caused by Hurricane Stan and Wilma during the 2005 hurricane season in the south-eastern part of Mexico showed the great importance of these phenomena in the country. Their influence can be so large, that they can completely disrupt the precipitation pattern of an entire region when compared with their neighbouring areas. Mexico is strongly affected by tropical cyclones on both coasts during the hurricane season. Currently, climatologists are still debating if climate change is changing the frequency of hurricanes across the globe, and their impacts in coastal areas. Certainly, this is a topic that (because of its great impact) needs to be studied more profoundly in Mexico.

A climatic pattern is clear in some of the southern regions of Mexico. Decreasing precipitation and warming conditions are observed in several of the forests of the country, like Los Tuxtlas near the Atlantic Coast, in Michoacán state or the south-eastern rainforest. Deforestation can be one of the causes to explain these changes, but the climatic picture is complex; this study has shown that the El Niño Southern Oscillation (ENSO) phenomenon is also affecting the climate of those regions. A further study on this topic can certainly lead to a better understanding of the impact of natural variability or anthropogenic influences on the forests of Mexico.

Although, in most of Mexico, annual precipitation is modulated by large-scale phenomena during the May to October period (tropical conditions); some of the regions in northern Mexico are strongly affected by winter precipitation (extra-tropical conditions). The northern part of the Baja California Peninsula, the North American Monsoon region in north-western Mexico; la Huasteca, near the Atlantic coast, or even far south in the Tehuantepec Isthmus are sometimes strongly affected by polar fronts especially when they bring large amounts of moisture across the country from both the Atlantic and the Pacific Oceans. Furthermore, the impact of cold fronts is strongly linked to altitude, particularly on precipitation. Therefore, it is desirable that cold fronts get more attention within the atmospheric sciences, taking advantage of the recent digital databases of the most important meteorological parameters in Mexico.

The analyses applied in this thesis are geographically limited to the tropical Pacific influence due to the ENSO indices used. A possibility to expand spatially our knowledge of the large-scale ocean and atmosphreric controls on the mexican climate can be explored using the Pacific Decadal Oscillation (Mantua and Hare, 2002; McCabe et al., 2004), as an alternative to the ENSO indices utilised. A reconstruction of the air temperature based on tree rings (along the Pacific ocean) in North America shows the areal extension of the influence of this phenomenon (Minobe, 1997). The climate in the extra-tropics is inter-annually dominated by several tropical influences (like ENSO or the equatorial SSTs), inter-decadal climatic anomalies at sub-tropical latitudes are modulated by a constantly out of equilibrium Pacific Ocean (Trenberth and Hurrell, 1994). The PDO has an important influence on multidecadal winter precipitation in the southwestern USA (Arizona and New Mexico), near the northern Mexican borders (Gutzler, 2002). A latitudinal transition is found in the tropical storm activity in northwestern Mexico: a stronger Southern Oscillation Index (SOI) influence is observed in the northern part of the area; meanwhile, the southern half is modulated by the PDO (Díaz et al., 2008). Precisely, intraseasonal rainfall is more intense and of longer duration for northwestern Mexico than in the Arizona state in the USA (Englehart and Douglas, 2006).

At temporal scales, recurrent, non-linear and multidecadal droughts in the USA are closely correlated to with the North Atlantic Ocean, but these droughts are modulated by the sign of the PDO (Mc cabe et al., 2004). The frequency between PDO manifestations varies from 20 to 30 years, the last undisputable shift in the PDO phase was originated at 1976-77 affecting the Central and North Pacific basin. Nevertheless, tree ring studies have shown a longer 50-70 years oscillation (Minobe, 1997). An assessment of the frequency relations between the PDO and the meteorological digital data can be made, for a better understanding of the climate of Mexico.

About 30% of the total variance of the extratropical winter temperatures in the northern hemispheric can be explained by the North Atlantic Oscillation (NAO) (Perry, 2000). Therefore, another topic to be addressed for future studies is the influence of the NAO on the climate of Mexico using instrumental data. The sign of the NAO has direct influence on the speed and direction of the westerlies across the north Atlantic ocean (Lamb and Peppler, 1987). As the climate of northern Mexico during the boreal winter is partially modulated by the Westerlies (see section 2.3), the influence of the NAO is a topic that needs to be studied. In addition, Huang et al. (1998) have evaluated the spectral density of the relation between the NAO and ENSO, finding two bands of maximum power at the 5-6 and 2-4 years periods. Hence, it is also important to assess the periodicities of the relations of the climate of Mexico and the NAO.

One last area of study in which the database, built for the present research, can be used in the future is to assess climate models. Although there are several studies that evaluate future climatic scenarios in Mexico (Villeras-Ruiz et al., 1998; Magaña et al., 1997), they lack of a strict analysis of the quality of the data. For its spatial extent, the high-quality and long-term characteristics, the constructed database for this thesis is suitable to fill the necessity on future studies that aim to evaluate the outputs of the latest General Circulation Models (GCM).