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Observed tendencies in maximum and minimum temperatures in Zacatecas, Mexico and possible causes

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ABSTRACT: At a global level, warming caused by the increase in greenhouse gases has been reported in different parts of the world. This warming resulted in a reduction in the diurnal temperature range (DTR), caused by a faster rate of increase in minimum temperatures. However, the tendency toward warming is not obvious in Zacatecas, Mexico. The tendencies in maximum and minimum temperatures are partly linked to the state of the low frequency variability of large-scale atmospheric flow patterns, as depicted by the 700-mb geopotential height anomalies. Analyses of maximum and minimum temperatures from 23 climate stations, from 1963 to 2002, show that the DTR in southern Zacatecas is increasing from a rise in maximum temperatures and drop in minimum temperatures, while the DTR in northern Zacatecas is decreasing from a faster rate of decline in maximum temperatures than the increase in minimum temperatures. The regional series related to the F1 and F2 leading modes, after applying a Varimax-rotated empirical orthogonal function analysis to the 23 DTR series, acceptably reproduce the north–south dipole of DTR changes, while the point-correlation analysis between the two regional series, the 700-mb geopotential height anomalies and the indices of Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation indicate that the DTR in Zacatecas, Mexico is related to fluctuations in subtropical and extratropical circulations. Copyright © 2008 Royal Meteorological Society

KEY WORDS trend; warming; cooling; diurnal temperature range; Zacatecas

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1. Introduction

Many studies have shown that air temperature near the surface is warming at the global level (Easterling *et al*., 1997; Houghton *et al*., 2001; IPCC, 2007) with a faster rate of increase in minimum temperature than maximum temperature. This pattern results in a decrease in the diurnal temperature range (DTR = daily maximum temperature – daily minimum temperature) in different parts of the world. In Mexico, Englehart and Douglas (2005) report positive trends of the DTR, with a faster rate of increase in maximum temperatures than minimum temperatures. The rising minimum temperature also has been reported for most of the Sonora Desert (Weiss and Overpeck, 2005). However, the trend toward warming is not a general phenomenon in Mexico, since it is possible to find negative (cooling) trends in both maximum and minimum temperatures, such as in the southernmost part of the Sonora Desert (Weiss and Overpeck, 2005) and in other parts of Mexico (Englehart and Douglas, 2005).

Previous work has focused on the study of surface air temperature (SAT) and its relation to urban growth in Mexico City (Jauregui and Luyando, 1998); Guadalajara (Tereshchenko and Filonov, 2001) and large cities in southern Mexico (Jauregui, 1992). More recently, Englehart and Douglas (2004) show robust results for the entire country, indicating that the regional time series of SAT display long-term variability that is partially linked to the state of the large-scale, slowly evolving climate modes of the Atlantic Multidecadal Oscillation (AMO; Barnston and Livezey, 1987; Enfield *et al*., 2001) and the Pacific Decadal Oscillation (PDO; Mantua *et al*., 1997). The same authors also showed that trends in maximum and minimum temperatures in Mexico result in a greater DTR and partly accounted for this pattern by changes in land use (Englehart and Douglas, 2005). In the State of Zacatecas, Mexico, the tendency toward warming SAT is not obvious and there is even a trend toward cooling in some portions of the state.

Zacatecas, located on the northern Central Mexican Plateau, is predominantly a semiarid environment. The region is crossed by the Tropic of Cancer between the major mountain ranges of Sierra Madre Occidental and Sierra Madre Oriental. To the north and northeast of the Sierra Madre Occidental, annual precipitation is less than 500 mm and diminishes to 200 mm in the northernmost part of the state. Surface drainage in area is not well developed and runoff is scarce. This area is dominated by the closed basins of El Salado and Aguanaval. Wetter

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conditions in the Pacific watershed to the west and southwest of the Sierra Madre Occidental increase to more than 500 mm and even reach 1000+ mm in the extreme southwestern part of the state (INEGI, 2008). Unlike the north and southeast, where the mean annual temperature is >18 °C, major extensions of the state on both sides of the Sierra Madre Occidental are between 12 and 18 °C, where temperate conditions dominate and conditions for developing freezing temperatures in winter and >30 °C in summer are very common.

The goal of this study was to show the magnitude of the trends in maximum and minimum temperatures and the DTR in Zacatecas, Mexico and investigate its possible causes.

2. Methods

For the purpose of this study, the portion of Zacatecas located in the Pacific watershed to the south and southwest, largely within the Santiago and San Pedro River basins, is considered southern Zacatecas (Figure 1). The area located to the east of the Sierra Madre Occidental, largely within the El Salado, Aguanaval and Laguna de Viesca closed basins, is considered northern Zacatecas.

Daily maximum and minimum temperature records from 23 meteorological stations in Zacatecas were used (Figure 1). These records were obtained from the National Meteorological Service and are included in the CLImate COMputing Project (CLICOM) and Extractor Rápido de Información Climatológica (ERIC or Fast Extraction of Climatic Information) databases (WMO, 2008), carried out to coordinate the implementation, maintenance and upgrading of automated Climate Database Management Systems (CDMS) in the World Meteorological Organization's member countries. In Mexico, this database is used by the National Meteorological Service and National Water Commission. ERIC was created by the Instituto Mexicano de Tecnología del Agua, Mexico to provide an easy tool for obtaining climatic information of Mexico (ERIC, 1996).

The 23 stations were selected from the 127 stations in the state. They are located outside of large towns and cities to avoid the warming effect of urban land use. The selected stations are approximately equally spaced and distributed throughout the state. Each station has >80% of the temperature records from 1963 through 2002 (40 years). Most of the gaps inside the series occurred in the middle of the 1980s, probably associated with the large earthquake of 1985 in Mexico City, when a large number of records where lost during destruction of the infrastructure in government offices in Mexico City.

Each series of maximum and minimum temperatures was examined to avoid possible errors inside the series caused by digitizing. The highest monthly values from

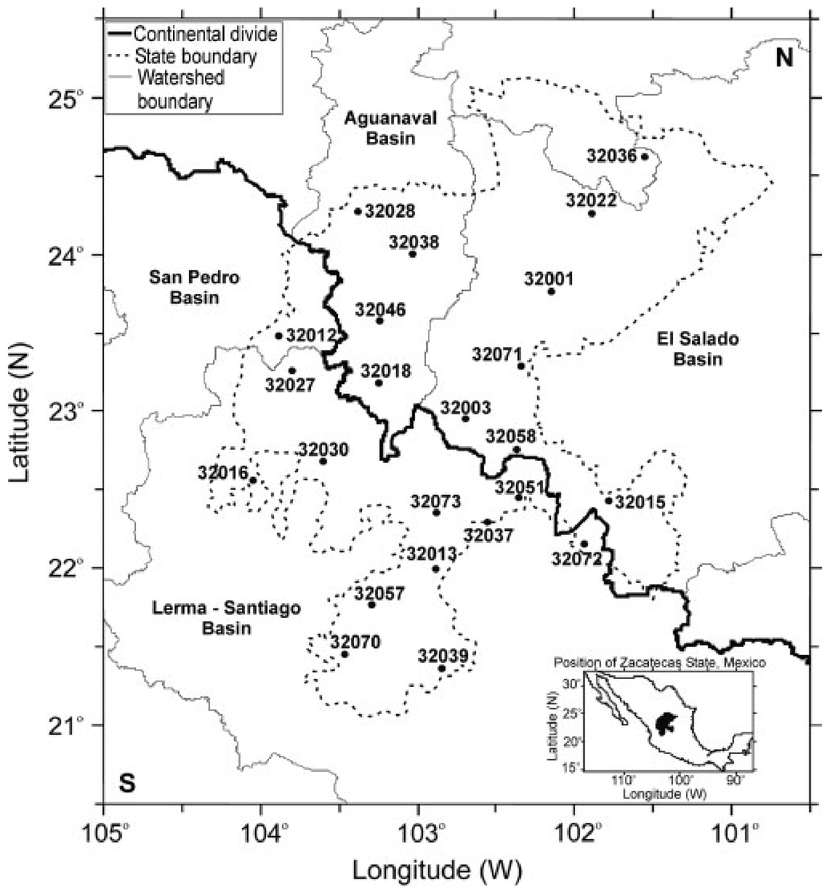

Figure 1. Location of 23 weather stations in the State of Zacatecas, Mexico, with the most nearly continuous records between 1963 and 2002. Numbers indicate the code of each station (National Meteorological Service of Mexico). Bold line represents the continental divide.

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maximum temperatures and lowest monthly values from minimum temperatures were selected from daily records and the seasonal component from these monthly series of records were removed prior to analysis to allow trends to be portrayed more clearly. This was done by substracting average monthly values for the 40-year period from their respective monthly values. DTR was calculated as the difference between maximum and minimum temperatures during the same day. For our analysis, we included only those days when maximum and minimum temperatures were recorded. We also included the months that had no missing days. An average DTR was calculated for each month, using only months with complete data. The seasonal component of monthly DTR values was removed, as previously indicated. To evaluate the magnitude and statistical significance of the trends in maximum and minimum temperature and DTR, the least squares regression procedure was used (for example, see Wigley, 2006) by fitting a linear trend model, with months as an independent variable and standardized series and those series with the seasonal component removed as a dependent variable. This analysis was repeated for each station's monthly series. The slope of the regression line served as the magnitude of the trend with regard to its statistical significance. Computations were performed with STATISTICA for Windows (Statsoft, 1995).

A Varimax-rotated, empirical orthogonal functional (EOF) analysis was applied to the 23 monthly series of the DTR for each 40-years series. The objective was to reduce the large number of original variables into small number of transformed variables, keeping the large proportion of the variation in the original series. The calculations were performed with SYSTAT software (SPSS, 1997) using procedures described by Manly (2005). Factors were extracted from a correlation matrix with 'case-wise deletion' of missing data. In this case, only those values that are common for all the involved series were included in the computations. Initially, provisional, unrotated factor loadings a_{ij} were determined. For this purpose, Principal Components Analysis, with an *a priori* minimum eigenvalue of 1.0, was used. With this procedure, five components were retained. The first two components have variances of 7.81 and 2.97, whereas the other components have variances of 1.64, 1.26 and 1.04. In the second phase of calculations, called *factor rotation*, only the first two factors were considered for the extraction of the parameters with Varimax rotation. This approach was applied because there were a relatively small number of samples (23) and values used in each sample that resulted in 'effective degeneracy' (North *et al*., 1982) when more than two factors were applied to the Varimax-rotated EOF analysis. In this case, the sampling errors of the third and fourth eigenvalues were comparable to the distance of the fourth and fifth eigenvalues and the sampling errors of the third and fourth factors were comparable to the fourth and fifth factors (North *et al*., 1982). When this happens, mixing the true eigenvalues occurs, making the retention of more than two factors unreasonable. Additionally, the F1 and F2 leading modes were sufficient to reproduce the changes observed in DTR trends. The regional series related to F1 and F2 leading modes (e.g. F1-southwest and F2-northeast) were obtained by averaging the values of the series with loading vectors (eigenvectors) of more than 0.50.

Point-correlation maps between the DTR regional series and the 700-hPa geopotential height anomalies (700 mbGH) at each point of a grid of $2.5° \times 2.5°$ were prepared to assess the links of DTR changes and large-scale atmospheric circulation. Although the 500-mb geopotential heights have been used in previous works (for example, see Englehart and Douglas, 2004), the 700-mb geopotential heights have also proved to be well correlated to other variables, such as rainfall and stream flow in northwestern Mexico (for example, see Brito-Castillo *et al*., 2003). Data of the 700-mb geopotential heights were obtained from the online archive of the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL, 2006).

3. Results

3.1. Maximum temperatures

Between 1963 and 2002 in southern Zacatecas, maximum temperatures had a warming trend, with a maximum of $1.12\,°C \times 10^{-1}$ year in the southeastern part of the state. A cooling trend occurred at three stations (of 13), but their magnitude is not statistically significant (Table I); one is located in the extreme southeast and two in the extreme southwest, close to the borders of the state (Figure 2). These results indicate that, in the Pacific watershed in southern Zacatecas, highest maximum temperatures are warming on average at $0.36\,°C \times 10^{-1}$ year (Table I).

Between 1963 and 2002 in northern Zacatecas, maximum temperatures have had a cooling trend with a minimum of $-2.2\,°C \times 10^{-1}$ year in the extreme northeast. Only two stations had warming trends and, at one of these stations, the trend was not statistically significant (Figure 2(a), Table I). These two stations are located in western Zacatecas in the Aguanaval Basin (see Figure 1). In parts of northern Zacatecas within the closed basins, large maximum temperatures are cooling at the average rate of $-0.56\,°C \times 10^{-1}$ year (Table I). The absolute maximum temperature trend (cooling) in northeastern Zacatecas is twice the rate of that in southern Zacatecas.

3.2. Minimum temperatures

In southern Zacatecas, the trends in minimum temperatures from 1963 through 2002 (compare Figure 2(a) and (b)) are largely negative, with a minimum of $-1.14\,°C \times 10^{-1}$ year in the southeastern part of the state. Only four stations (of 13) had the opposite trend and three of these had no statistical significance (Table I). These four stations are located close to the state border, two in

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Table I. Magnitude of the observed decadal trends (1963–2002) in maximum and minimum temperatures and the DTR at 23 weather stations in the State of Zacatecas, Mexico (see Figure 2). Trends are quantified by applying the linear square regression method with data available on a month-by-month basis.

Station	Tmx[a]	Tmn[a]	DTR[a]	Location
32036	−2.20*	0.88*	−3.07*	N
32022	−1.27*	−0.63*	−0.65*	N
32046	−1.18*	0.38*	−1.62*	N
32028	−0.73*	−0.36*	−0.35*	N
32071	−0.64*	0.38*	−1.02*	N
32015	−0.49*	−1.50*	0.97*	N
32003	−0.41*	0.08	−0.50*	N
32001	−0.01	0.11	−0.23	N
32018	0.10	−0.11	0.21	N
32038	1.24*	−2.50*	3.74*	N
Average	−0.56*	−0.33*	−0.25*	
32016	−0.16	−0.62*	0.46*	S
32012	−0.07	0.02	−0.09	S
32072	−0.06	0.18	−0.24	S
32030	0.02	0.12	−0.08	S
32057	0.12	−0.51*	0.60*	S
32073	0.23*	−1.08*	1.29*	S
32039	0.37*	−0.99*	1.36*	S
32058	0.49*	−0.07	0.55*	S
32051	0.50*	−1.13*	1.61*	S
32070	0.62*	−0.36*	0.98*	S
32027	0.70*	−0.17	0.88*	S
32013	0.74*	0.29*	0.46*	S
32037	1.12*	−1.14*	2.26*	S
Average	0.36*	−0.42*	0.77*	

[a] Units are in °C × 10^1 year.
Tmx, maximum temperature; Tmn, minimum temperature; DTR, diurnal temperature range; N, northern Zacatecas; S, southern Zacatecas.
* Values are statistically significant at $P < 0.05$.

the southeast and two in the west. For southern Zacatecas, these results indicate that minimum temperatures are cooling an average of $-0.42\,^{\circ}\mathrm{C} \times 10^{-1}$ year.

In northern Zacatecas, it is not clear what the trend is, since an equal proportion of cooling and warming of minimum temperatures occurs (Figure 2(b)). Of the stations (5 of 10) with a warming trend, two are not statistically significant (Table I). Within the limits of El Salado Basin in the eastern part of the state, warming trends are most common, with a maximum of $0.88\,^{\circ}\mathrm{C} \times 10^{-1}$ year in the extreme northeast. Within the Aguanaval Basin in the western of the state, cooling trends dominate with a minimum of $-2.50\,^{\circ}\mathrm{C} \times 10^{-1}$. On average, northern Zacatecas shows a cooling trend of $-0.33\,^{\circ}\mathrm{C} \times 10^{-1}$ year in minimum temperatures (Table I).

In summary, this means that eastern Zacatecas has rising minimum temperatures and western and southern Zacatecas have falling minimum temperatures. For minimum temperature, the greatest cooling occurs at a rate three times greater than maximum warming. This is the basis for average minimum temperatures throughout Zacatecas, showing a cooling trend (Table I).

3.3. Diurnal temperature range

The DTR has a spread that coincides in sign with the trend in maximum temperatures (Figure 2(c)), that is, a positive trend in southern Zacatecas (with two insignificant exceptions) and a negative trend in northern Zacatecas (with three exceptions, of which one was insignificant). In these cases, the maximum magnitude of positive trends is $2.26\,^{\circ}\mathrm{C} \times 10^{-1}$ year in southeastern Zacatecas and the minimum magnitude of the negative trends is $-3.07\,^{\circ}\mathrm{C} \times 10^{-1}$ year in extreme northeastern Zacatecas. These results indicate that the DTR in southern Zacatecas is increasing as the maximum temperature increases (Figure 2(a)) and the minimum temperature decreases (Figure 2(b)). In northern Zacatecas, particularly in the east, the DTR is decreasing as a result of a faster rate of decrease in maximum temperatures than the increase in minimum temperatures (Table I).

The loading vectors for F1 and F2 leading modes of the DTR series approximately match the north–south dipole of DTR trends (Figure 3). Loading values >0.5 in F1 are primarily distributed in southwestern Zacatecas (F1-southwest), while those in F2 (F2-northeast) are primarily distributed in northeastern Zacatecas. However, there are stations that are not included in the F1-southwest or F2-northeast leading modes, such as Stations 32001, 32015, 32016, 32057 and 32073. These stations are irregularly dispersed among the two regions and were not considered in subsequent analyses. Additionally, from stations included in F1 and F2 leading modes, it is evident that stations 32036, 32038 and 32037 appear as outliers that may have experienced a major site change. The strong trends in these data sets suggest more than just a broad-scale response to climatic shift. The magnitude of the changes suggests that the location of the station was changed with respect to elevation or slope aspect or possibly major land use changes had occurred in the local area. Changes in trends at Station 32036 would be reasonable if there was a relocation to a valley bottom near a mountain, while trends at Station 32038 would be reasonable if there was a move from a valley location to a steep slope. The magnitude of the changes at these three stations all have strong weights in the rotated principal component analysis conducted (Figure 3). All three stations have high loadings in the rotated PCA. Unfortunately, META data of these stations are not available to confirm these suspicions. However, overall spatial coherence of the trends still dominates. The regional series for the F1-southwest and F2-northeast leading modes reflect the asymmetric behavior of the DTR regional series (Figure 4). In both cases, a change in the fluctuation occurred in the mid-1980s, but in opposite directions. The general trend (positive in F1-southwest and negative in F2-northeast) results from low-frequency variations. Although step changes in the mid-1980s were reported in the literature, for example, in the timing of snowmelt runoff in the western United States (McCabe and Clark, 2005), the causes have not yet been determined. The step change and strange variability of the series in the mid-1980s, for example, the DTR

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F2 time series, does not provide high confidence in the results because of the large amount of missing data during that time; therefore, the step change in mid-1980s of the DTR F2 time series should be taken with caution.

To relate the trends in DTR F1 and DTR F2 monthly time series to large-scale circulation, as depicted by the 700-hPa geopotential height anomalies (700-mbGH), point-correlation maps were prepared. The results are presented in Figure 5. Although correlations are weak (0.26 was the highest plotted, although other contours were up to 0.36), higher values, enhanced by the stippled areas in Figure 5(a) and (b) are statistically significant correlations at the 0.01 level of confidence. Correlations across the subtropical Pacific in Figure 5(a), and southeastern Mexico in Figure 5(b) are of particular interest to our purpose.

4. Discussion

4.1. Maximum and minimum surface air temperatures

In the State of Zacatecas, there is evidence of a warming trend defined by measurements of daily maximum and minimum temperatures of SATs or in their difference, the DTR, (Englehart and Douglas, 2004, 2005).

Maximum and minimum values of SAT are fixed in the diurnal cycle, that is, minimum temperatures are recorded near sunrise after a night of radiation cooling, while maximum temperatures usually occur in mid-afternoon. Temperatures depend on numerous factors, including the following: (1) inclination of the sun, intensity and duration of sunlight; (2) surface characteristics (elevation, aspect, soil moisture, ground cover) that control albedo and how the available heat is divided between sensible and latent heat; (3) cloud cover and (4) movement of air masses that regulate local air temperature. The effect produced by (1) and (2) on maximum and minimum temperatures could be reduced by removing the seasonality of the series to avoid the local effect of the station so that comparisons among stations can be made. Relative to (3) and (4), clouds affect air temperature by producing lower maximum and larger minimum temperature anomalies and clear skies produce larger maximum and lower minimum temperature anomalies. During the day, advection, depending on the temperature of the air mass, causes air temperatures to increase more rapidly or slower than usual. If cold air advection is intense, air temperature may continue to drop throughout the day, even though skies are bright and sunny. With advection

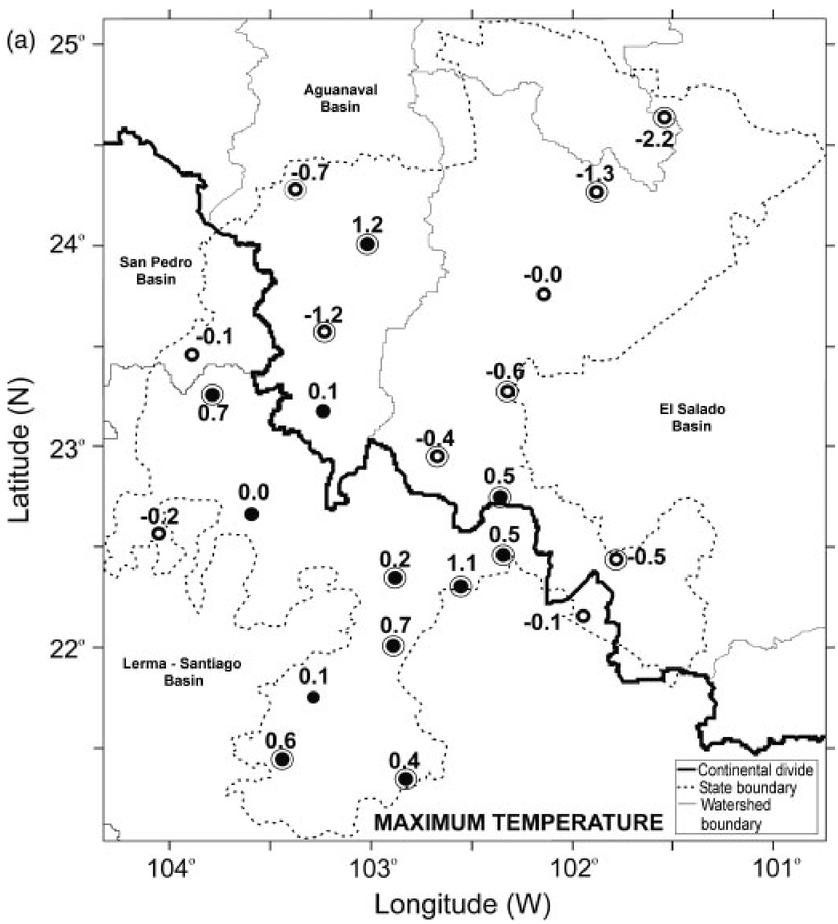

Figure 2. Positive (filled circles) and negative (open circles) trends in (a) maximum temperatures; (b) minimum temperatures and (c) diurnal temperature ranges in the State of Zacatecas, Mexico. Double circles indicate values that are statistically significant. The magnitude of the trend is measured as the slope of the regression by applying the linear square regression method with data available on a month-by-month basis. Bold line represents the continental divide. Northern and southern Zacatecas are indicated by N and S.

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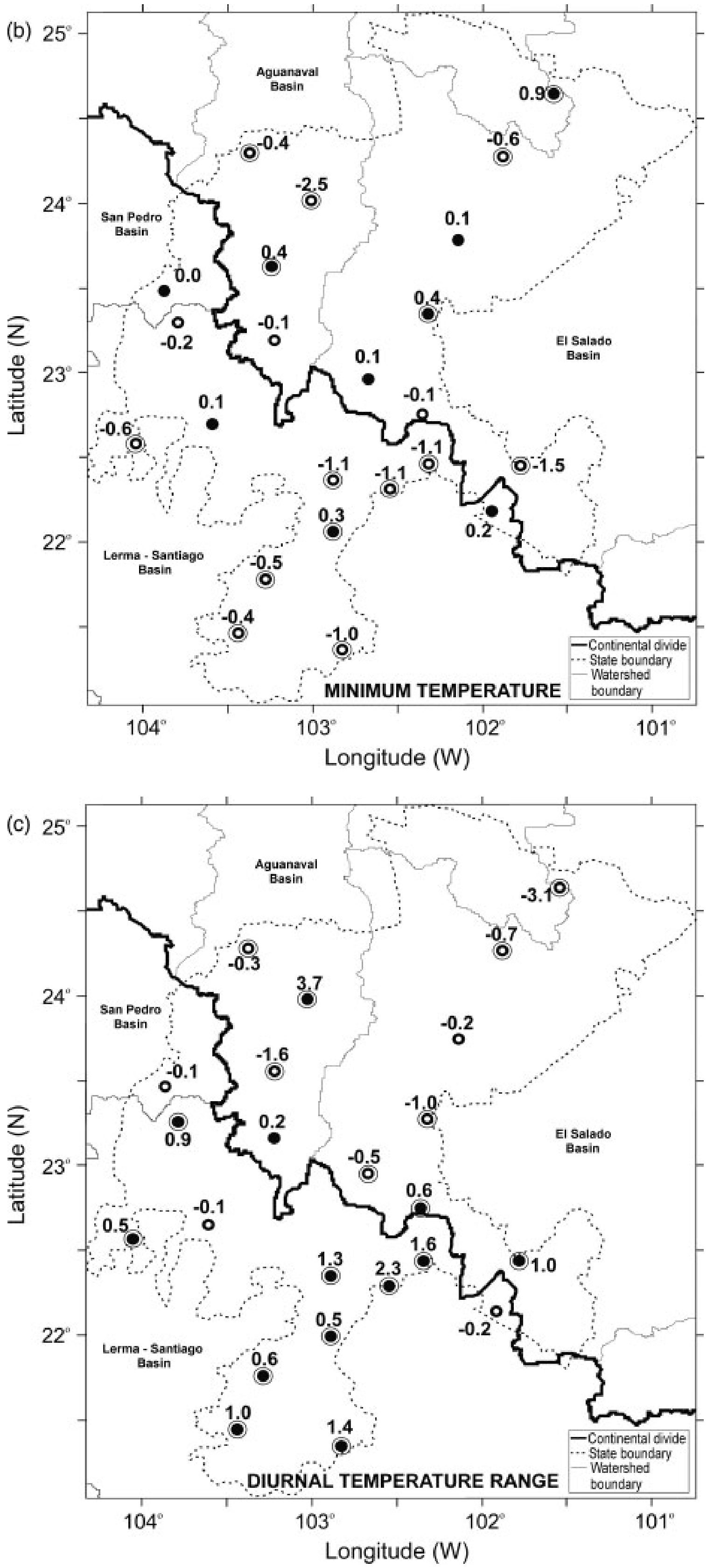

Figure 2. (*Continued*).

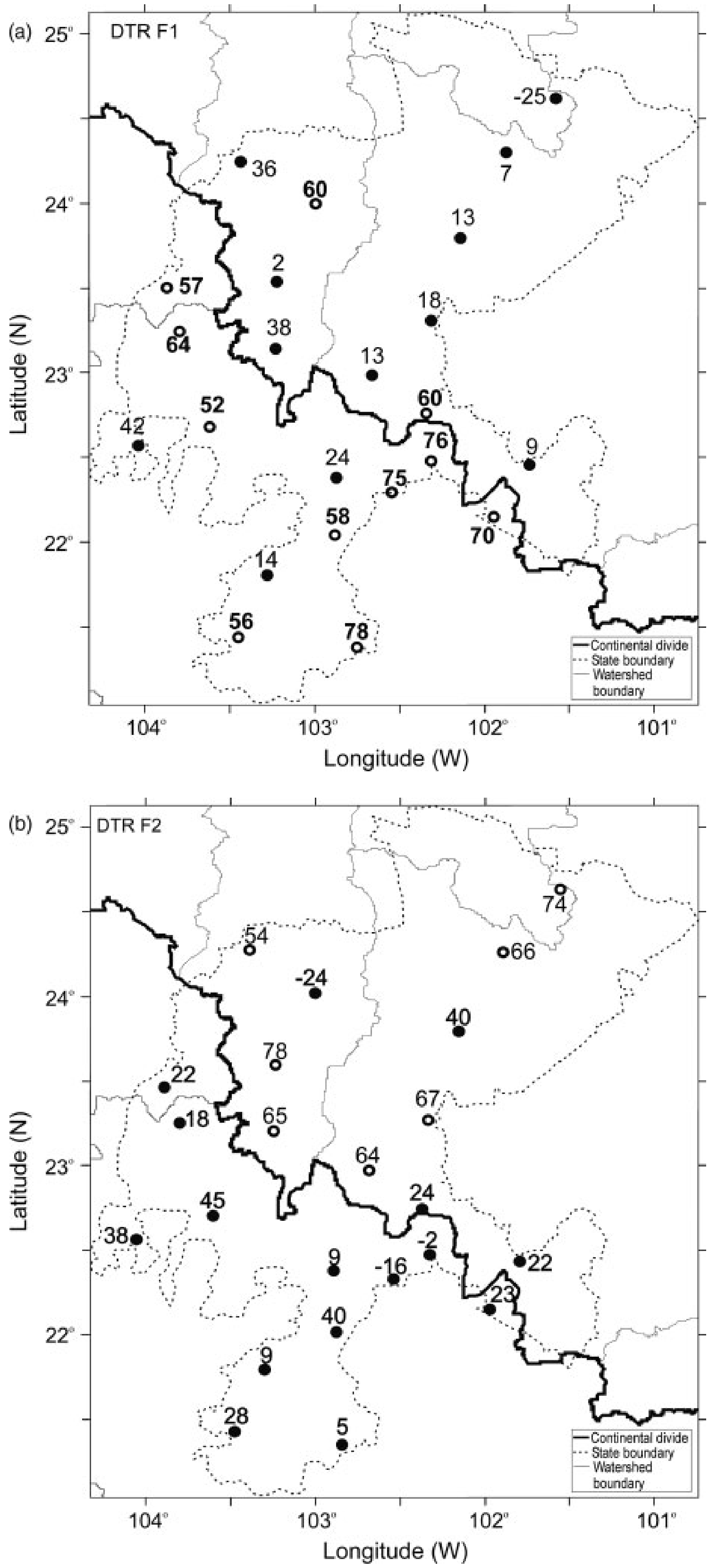

Figure 3. Distribution of higher than 0.5 (open circles) and lower than 0.5 (filled circles) loading values after applying a Varimax-rotated empirical orthogonal functional analysis of the DTR for 1963 through 2002 for (a) F1 and (b) F2. Loading values are multiplied by 100.

of air masses between regions of different regional temperature and humidity, the influence of advection implies phenomena larger than local scale. Although maximum and minimum temperatures vary from the factors listed above from one season to another, the data show trends of different signs (Figure 2) that cannot be determined by differences in altitude or season or unpredictable events, since a trend indicates a change at a relatively constant rate. Such large-scale shifts suggest other causes for the trends in SAT. Changes in large-scale atmospheric flow patterns, as depicted by the 700-mbGH seem to be associated with these trends.

4.2. Trends

The most widely accepted explanation for the rising SAT is the increasing concentration of greenhouse gases (Gates, 1993; Houghton *et al*., 2001). Part of this process includes the rise in minimum temperature at a faster rate than the increase in maximum temperature. This leads to a reduction of the DTR for the globe, as a whole (Easterling *et al*., 1997). Englehart and Douglas (2005) reported that DTR over Mexico are positive, as maximum temperatures are increasing at a significantly faster rate than minimum temperatures and identified regional land use and changes in land cover as forcing mechanisms responsible for part of the DTR.

For Zacatecas, the previous arguments are not sufficient to explain the differences in sign of the trends between the southwestern and the northeastern parts of the state, which are the areas experiencing coherent trends. Increasing CO_2 in the atmosphere would lead to increases in daily maximum and minimum temperatures, but this does not occur (Figure 2). The regional classification of Englehart and Douglas (2004), after applying rotated, principal component analysis to stations in the central region of Mexico, where maximum and minimum temperatures increase in the summer, they found a reversal in trends from negative from 1940 through 1970 to positive between 1971 through 2001 (Englehart and Douglas, 2005), reducing the magnitude of the trend to levels that were largely insignificant from 1940 through 2001. Unfortunately, the SAT dataset used by Englehart and Douglas (2004) only covered the southern (Pacific watershed) and the northeastern border zone, without any data from the rest of the state. As these authors argued, particularly relevant to the central region, land cover changes tend to favor reduced evaporative cooling and increased sensible heat relative to the latent heat flux and promotes higher maximum temperatures and increased DTR. In this case, the warming trend in maximum temperature and DTR reported by Englehart and Douglas, 2005 appears consistent with our findings. Because the Englehart and Douglas (2005) was based on a much longer time series, 1940–2001 in their study *vs* 1963–2002 in our study, trend analysis can have different results if the beginning 24 years are homogeneous in behavior under a persistent climate regime, such as the PDO. Other factors that might explain differences in trend analysis are the 23 stations that are approximately equally spaced and distributed throughout the State of Zacatecas, unlike the Englehart–Douglas study, where only seven stations were within or close to the border of Zacatecas, of which five were located in the south (Pacific watershed) and two in the northeastern border zone.

The large number of stations we used in our study should support a more complete picture of analysis. For instance, the stations neither report a declining trend in minimum temperature at many stations in southwestern Zacatecas (Figure 2) nor the opposite trends observed in maximum and minimum temperatures in the northeast. The most reasonable basis for this is simple: the few series used in their study of this area do not show these kinds of trends, a situation that points out the complexity of the dynamics and the enormous variations in surface temperature trends within a region, for example, as discussed by Pielke *et al*. (2002), although their findings and explanations in trend analysis only partially apply to southwestern Zacatecas. As Englehart and Douglas (2004) have shown, SATs in Mexico are strongly associated with anomalies in the mid-troposphere circulation (500 hPa).

Following the same idea as these authors, in Figure 5, we presented evidence that show that trends in DTR for Zacatecas are associated with the 700-mb height fields. The resulting graphs are opposite in sign (Figure 5).

The western continental divide that separates Zacatecas into two regions, along with air mass advection, seems to play an important role in causing the differences in trends (Figure 2). Located between the Sierra Madre Oriental and the Sierra Madre Occidental, northern Zacatecas is an interior region, which is dry because of general subsidence and relatively infrequent storm development upstream of orographically induced stationary wave troughs (Manabe and Broccoli, 1990). Additionally, mountains reduce transport of moist air into northern Zacatecas from both the Pacific Ocean and the Gulf of Mexico; consequently, agriculture is less developed. Therefore, land use changes are unlikely to force the observed trends. The north is largely a desert region; land clearing has less affect on the weather patterns in a desert region than in the heavily vegetated areas of southwestern Zacatecas.

Point correlation analysis between regional series of DTR (F1-southwest and F2-northeast) and 700-mbGH indicate the influence of large-scale atmospheric circulation, particularly in areas with statistically significant correlations ($P < 0.01$), that is, positive correlations of high pressure air masses over the subtropical Pacific west of the Baja California Peninsula flowing into southwestern Zacatecas (Figure 5(a)) and negative correlations, with center over southeastern Mexico into northeastern Zacatecas (Figure 5(b)). In the latter condition, the pattern of atmospheric flow associated with these kinds of correlations implies the formation of a recurrent high pressure center position over southeastern Mexico. (Since the trend of the DTR in northeastern

Zacatecas is negative, the trend in the 700-mbGH should be positive.)

Although weak, the correlation structures in Figure 5(a) and (b) are opposite in sign. In both cases, anticyclonic anomaly flow dominates, with the northwesterly component associated with the positive trends of the DTR F1 southwest region, and the southwesterly component associated with the negative trend of the DTR F2 northeast region.

The anomalous anticyclonic flow shown in Figure 5(a) brings a recurrence of atmospheric subsidence and less cloudiness; the clear skies increase maximum temperature and decrease minimum temperature across the entire region. Since correlations decrease northeastward, the southwestern region (F1-southwest) appears to be more affected by the anticyclonic flow than the northeastern region (F2-northeast), causing the positive trend of DTR in the southwest (Figure 2(c)).

Areas under the western flank of the anticyclone in southeastern Mexico are moist (Figure 5(b)) and increase cloudiness. Cloud cover and precipitation would decrease maximum temperature across the entire region and raise minimum temperature in the north and south. Since correlations diminish northwestward and the southwest is more affected by subsidence, as discussed earlier, the northeastern region appears to be more affected by this flow than the southwestern region, which in turn causes the negative trend of the DTR in the northeast (Figure 2(c)).

Close examination of the correlation structures in Figure 5(a) and (b) gives insights that changes in the 700-mbGH are likely to be tied to the large-scale changes in the SST that have occurred in the Pacific and Atlantic Oceans. This conclusion comes from the analysis of the F1 and F2 time series (Figure 4). The F1 time series dominates the period after 1994 and the F2 time series dominates from 1963 to 1976. In many respects, inspection of the two time series strongly hints at the combined effects of a cold PDO and warm AMO from 1994 to the present. A steady period in the two PC loadings associated with a warm PDO and cold AMO occurred from 1976 to 1994 and another steady period in the loadings associated with a cold PDO and cold AMO period occurred between 1963 and 1976. Pearson correlations between the time series of the two PCs with the PDO and AMO confirmed these associations. Correlations are positive between DTR F1 time series and the PDO ($r = 0.12$) and DTR F1 and AMO ($r = 0.40$) and negative between DTR F2 time series and the PDO ($r = -0.21$) and DTR F2 and AMO ($r = -0.13$). In both cases, correlations are statistically significant ($P < 0.01$).

The rate of increase in the DTR in southwestern Zacatecas is faster than the rate of decrease in the DTR in northeastern Zacatecas. In the northeast, the decrease in the DTR is based on a faster decrease in maximum temperature than increase in minimum temperature; in the southwest, the increase in the DTR is based on a faster rate of decrease in minimum temperature than increase in maximum temperature. Both scenarios suggest an effective loss of heat in both parts of Zacatecas.

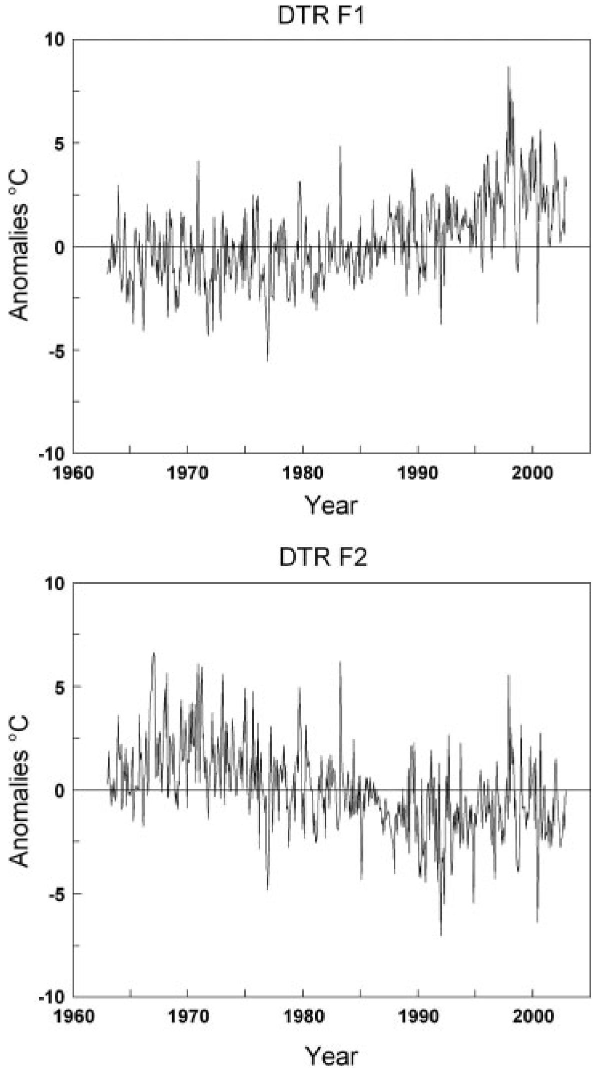

Figure 4. Regional DTR series of F1 (DTRF1) and F2 (DTRF2) leading modes.

5. Conclusions

In Zacatecas, Mexico, differences in maximum and minimum SATs between the northeast and southwest occur at the continental divide. These differences are characterized by a reduction in the DTR in the northeast from a more rapid decline in maximum temperatures than the increase in minimum temperatures and an increase in the DTR in the southwest from the more rapid decrease in minimum temperatures than the increase in maximum temperatures. The possibility that the cause of these differences might be associated with changes of large-scale atmospheric flow patterns, as depicted by the 700-hPa geopotential height anomalies, which in turn are likely to be tied to large-scale changes in SSTs in the Pacific and Atlantic Oceans, is established. The trends in SATs in Zacatecas, Mexico are part of low-frequency

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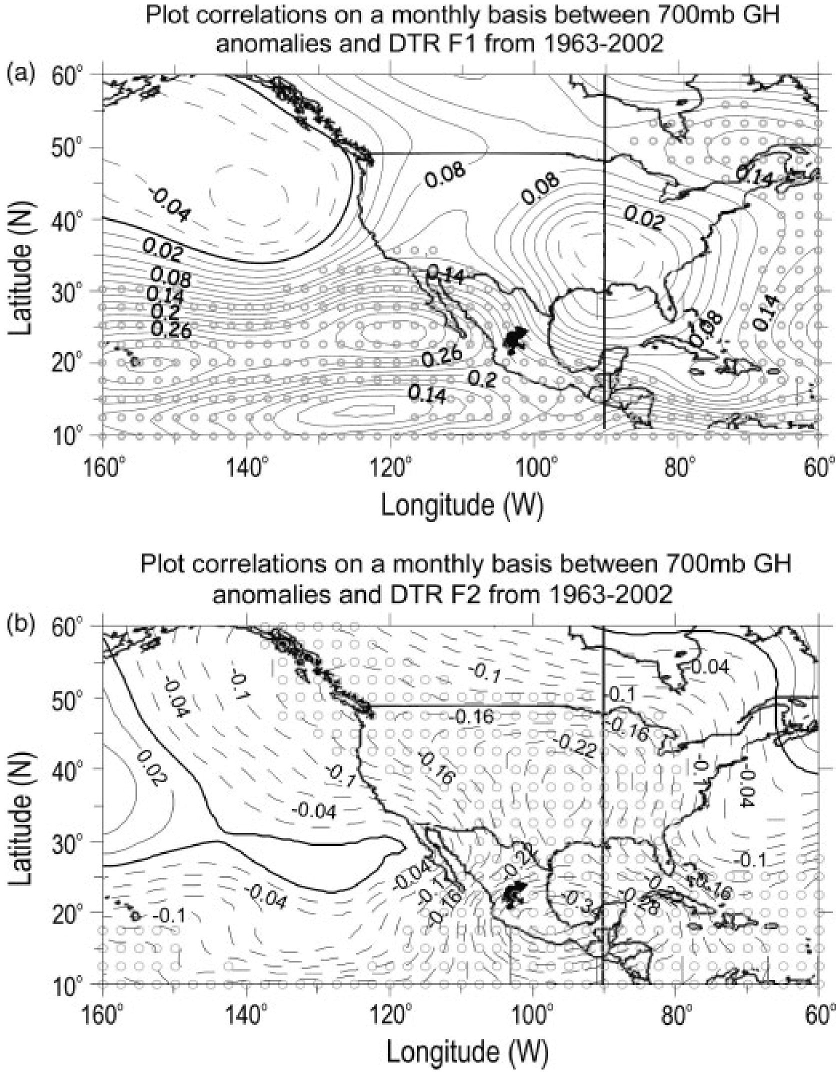

Figure 5. Point correlations on a month-by-month basis between regional series of DTR (a) F1 (DTRF1); (b) F2 (DTRF2) leading modes and the 700-hPa geopotential height anomalies for 1963 through 2002. The stippled areas are statistically significant correlations at the 0.01 level of confidence.

variations. This means that, before the mid-1980s, the trend in F1 southwest region was positive and, after the mid-1980s, the trend was the opposite.

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References

Barnston G, Livezey RE. 1987. Classification, seasonality and low-frequency atmospheric circulation patterns. *Monthly Weather Review* **115**: 1083–1126.

Brito-Castillo L, Douglas AV, Leyva-Contreras A, Lluch-Belda D. 2003. The effect of large-scale circulation on precipitation and streamflow in the Gulf of California continental watershed. *International Journal of Climatology* **23**: 751–768.

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Follan CK. 1997. Maximum and minimum temperature trends for the globe. *Science* **277**: 364–367.

Enfield DB, Mestas-Nuñez AM, Trimble PJ. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river in the continental U.S. *Geophysical Research Letters* **28**: 2077–2080.

Englehart PJ, Douglas AV. 2004. Characterizing regional-scale variations in monthly and seasonal surface air temperature over Mexico. *International Journal of Climatology* **24**: 1897–1909.

Englehart PJ, Douglas AV. 2005. Changing behavior in the diurnal range of surface air temperature over Mexico. *Geophysical Research Letters* **32**: L01701, Doi:10.1029/2004GL021139.

ERIC. 1996. *Extractor rápido de Información climatológica*. IMTA, Instituto Mexicano de Tecnología del Agua: Morelos, México. CD-ROM, http://www.imta.gob.mx/productos/software/meteorologia.html (2008).

Gates DM. 1993. *Climate Change and Its Biological Consequences*. Sinauer Associates: Sunderland, MA.

Houghton JT, Ding Y, Griggs DJ, Noguer M, Van Der Linden PJ, Dai X, Maskell K, Johnson CA (eds). 2001. *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: New York.

INEGI. 2008. Instituto Nacional de Estadística, Geografía e Informática, URL: http://www.inegi.gob.mx (2008).

IPCC. 2007. Intergovernmental panel on climate change. In *Climate Change 2007: The Physical Science Basis, Contribution of Working Group (WG) 1 to the Fourth Assessment Report of the IPCC (AR4)*, Solomon S, Qin D. Manning M. Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: New York, http://www.ipcc.ch/press/index.htm.

Jáuregui E. 1992. Aspects of monitoring local/regional climate change in a tropical region. *Atmosfera* **5**: 69–78.

Jáuregui E, Luyando E. 1998. Long-term association between pan evaporation and the urban heat island in Mexico City. *Atmosfera* **11**: 45–60.

McCabe GJ, Clark MP. 2005. Trends and variability in snowmelt runoff in the western United States. *Journal of Hydrometeorology* **6**: 476–482, DOI: 10.1175/JHM428.1.

Manabe S, Broccoli AJ. 1990. Mountains and arid climates of middle latitudes. *Science* **247**: 192–195.

Manly BFJ. 2005. *Multivariate Statistical Methods*. A primer. Chapman & Hall/CRC: FL, USA.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific decadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079.

NOAA/ESRL. 2006. National Oceanic and Atmospheric Administration/Earth System Research Laboratory, Available online: http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl.

North GR, Bell TL, Cahalan RF. 1982. Sampling errors in the estimation of empirical orthogonal functions. *Monthly Weather Review* **110**: 699–706.

Pielke RA, Stohlgren T, Schell L, Parton W, Doesken N, Redmond K, Money J, Mckee T, Kittel TGF. 2002. Problems in evaluating regional and local trends in temperature, an example from eastern Colorado, USA. *International Journal of Climatology* **22**: 421–434.

SPSS. 1997. *SYSTAT Version 7.0 for Windows*. SPSS: Chicago, IL.

StatSoft. 1995. *STATISTICA for Windows, 1995. General Conventions and Statistics, 1*. StatSoft: Tulsa, OK; 1001–1878.

Tereshchenko IE, Filonov AE. 2001. Air temperature fluctuation in Guadalajara, Mexico from 1926 to 1994 in relation to urban growth. *International Journal of Climatology* **21**: 483–494.

Weiss JL, Overpeck JT. 2005. Is the sonoran desert losing its cool? *Global Change Biology* **11**: 2065–2077.

Wigley TML. 2006. Appendix a: statistical issues regarding trends. In *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*, Karl TR, Hassol SJ, Miller CD, Murray WL (eds). A Report by the Climate Change Science Program and the Subcommittee on Global Change Research: Washington, DC.

WMO. 2008. World Meteorological Organization, CLImate COMputing Project available information online: http://www.wmo.ch/pages/prog/wcp/wcdmp/clicom/index_en.html (2008).