# Variability of minimum temperature across Libya (1945-2009)

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## ABSTRACT

Daily and monthly minimum temperature data from fifteen meteorological stations were analysed during the period 1945-2009. The spatial and temporal variability in the daily and monthly temperatures were examined with daily minimum temperature for eight coastal stations during the period 1956-2009 and the monthly minimum temperature for the period 1945-2009 from six coastal and inland stations. Five distinct ten years interval blocks (with the exception of the last nine years for the eight coastal stations and seven years for inland stations) are analysed to examine temperature patterns across Libya. The annual minimum temperature over the last 27 years (1983-2009) for the majority of the coastal stations identified significant warming in the minimum temperature. The mean annual minimum temperature at all study stations (1945-2009) identified significant increases in the minimum temperature, with significant changes in annual minimum temperature over the last 32 years (1978-2009) for the majority of the coastal and inland stations across Libya. Significant changes in minimum seasonal temperature for 33/32 year intervals (1945-1977 and 1978-2009) are identified in the summer (56%) and autumn (67%) at coastal stations (67%) and inland stations (50%).

**KEYWORDS**: *climate; synoptic stations; warming; minimum temperature; temperature variability; Libya.*

## 1. Introduction

During the last four decades a large body of research throughout the world has been undertaken on climatic change and its impact on the environment (e.g. Fowler and Hennessy, 1995; Knappenberger et al., 2001; Wibig and Glowicki 2002; Alexander et al. 2006; Pavia et al., 2009; Tayanc and Dogruel 2009). Several studies have focused on Africa and the Mediterranean basin, indicating significant directional changes in temperature trends at a range of spatial and temporal scales, from the global to the local (e.g. Repapis and Philandras 1988; Arsine and Maheras, 1991; Fontaine and Janico, 1996; Hasanean, 2001; Hulme et al., 2001; Domros and El-Tantawi, 2005; Goubanova and Li, 2007; Giorgi and Lionello 2008; Kafle and Bruins 2009; Tayanc et al. 2009). Few studies have focused on the climate parameters of Libya (Emgely, 1994; Pelag, 2000; El-Tantawi, 2005; Al-Marimee, 2007; El-Kenawy et al., 2009). Libya is an area of particular interest as it includes areas which experience both a Mediterranean and North Africa climates (semi-arid and arid climate) and is in a region where human occupation and lifestyle are highly susceptible to climatic changes.

According to the report of the Intergovernmental Panel on Climate Change (IPCC, 2007) global mean temperature has gradually increased by 0.74 °C ± 0.18 °C over the last 100 years (1906-2005); a finding supported by Alexander et al. (2006) who identified a significant warming throughout the 20$^{th}$ century based on 200 temperature stations over a large area of the northern hemisphere and Australia. Previous studies, such as Domonkos and Tar (2002) indicated that mean annual temperature increased slightly slower than the global average (0.34 °C/100 years) across 14 observed stations in Hungary during the period 1901-1998; whilst Wibig and Glowicki, (2002) have illustrated similar findings when examining mean annual minimum temperature across cites in Poland during the period 1951-1998, though with a significant rise in winter and spring minimum temperatures (by an average 0.55 to 0.75 °C per decade and 0.25 to 0.43 °C per decade respectively). A study by Juan and Antonio (1996) examining meteorological stations on the Spanish peninsular and in the Canary Islands identified that there can be considerable spatial variability, with mean temperature increasing at 36% of stations, decreasing at 10%, and with insignificant change at 54% of the study stations over the period 1901-1989. Whilst Karl et al. (1993) identified considerable variability in changes of temperature range, as minimum temperatures have risen twice as fast as maximum temperature over at least 30% of the Northern Hemisphere.

A number of studies in recent years (e.g. Aesawy and Hasanean 1998; Hasanean, 2001; Hasanean and Abdel Basset, 2006; Goubanova and Li, 2007) identified significant positive trends in surface temperature across the Mediterranean basin. Hasanean (2001) identifying an average surface temperature increase across the Mediterranean of 0.07 °C per decade. Increasing winter temperature trends were observed at 13 of 18 study stations in Egypt for the period 1905-2000, with the warmest period during the 1950s and early-1960s and the coolest period from the early 1960s to the early-1970s, with significant positive trends in mean summer temperature identified at most study stations during the period 1905-2000 (Hasanean and Abdel Basset, 2006). Ben-Gai et al. (1999) identified a warming tendency in annual minimum temperature of 0.01-0.53 °C/decade in 65% of the study stations across Israel, during the period 1964-1994.

Previous research examining Libya identified positive trends in mean annual minimum temperature at all study stations during the period 1946-2000, with trends ranging between 0.03 and 0.55 °C/decade 1976-2000 (El-Tantawi, 2005); a finding supported by El-Kenawy et al. (2009) who found that a number of Libyan meteorological stations have experienced an upward trend in minimum temperature during the period 1951-1999, with trends ranging between 0.19 and 0.27 °C/decade. Negative trends were observed at 50% of study stations in Libya during the period 1946-1975, with trends ranging between -0.32 and -0.04 °C/decade (El-Tantawi, 2005). Al-Marimee (2007) indicated that significant differences in mean annual minimum temperature were observed between Al-Zawyia and Surrman during the period 1988-2005, but no corresponding change in mean annual maximum temperature was observed. While Pelag (2000) identified that the mean annual minimum temperature at western stations increased most during the coldest months (DEC, JAN, FEB) compared to the warmest months (JUN, JUL, AUG) during the period 1961-1990. Rates of change in seasonal minimum temperature across Libya vary, with increases of 0.21 °C/decade in summer, 0.19 °C/decade in autumn, 0.15 °C/decade in spring and 0.10 °C/decade in winter (El-Tantawi, 2005); comparable results were identified by El-Kenawy et al. (2009) with increases of 0.27 °C/decade in summer and autumn and 0.19 °C/decade in spring and winter when examining seasonal minimum temperature over the period 1946-2000.

This paper seeks to examine the changes in minimum temperature in Libya; with a particular focus on examining spatial and temporal variability in minimum temperature over the period 1945-2009. More specifically, the objectives of this paper are as follows:

i. To identify temporal fluctuations and patterns in minimum temperature, across Libya across two climatic regions (coastal and inland) based on (a) annual data, (b) monthly data, and (c) daily data;

ii. To identify and examine any spatial changes and fluctuations within the data; and

iii. To understand any associations between the minimum temperature and geographic parameters (e.g. the height above sea level and distance from the sea).

## 2. Data and Methodology

### 2.1 Study area

Libya is located in the north of Africa on the Mediterranean coast, it encompass a geographical area estimated at (1,750,000 km²) between (20° to 34º N) and (10° to 25º E) (Fig. 1) within which roughly 90.5% of the area is hyper-arid, 7.5% is arid, 1.5% semi-arid and 0.5% is classified as sub-humid (Ben-Mahmoud 1995); with the sub-humid region located in northeast Libya near the cities of Shahat and Al-Bayda (Fig. 1). The shoreline extends for roughly 1950 km from the Libyan-Tunisian border in the west to the Libyan-Egyptian border in the east. In the coastal region, the elevation ranges from 47 m below mean sea level at Sabkhat Al-Ghuzayyil to 891 m above Mean Sea Level (a.m.s.l) in Garyan in the western Mountains. The highest point is Bikku Bitti 2267 m (a.m.s.l) in the Tibesti Mountains in southern Libya. The population of Libya in 2006 was estimated by the General Directorate of Documentation and Information (GDDI) at 5,323,991 and was estimated at 6,901,830 in 2010 with the projected population for the year 2025 near 10 million.

The Libyan climate is generally characterized by hot and dry summers, with high temperatures in June, July and August. The mean annual temperature at meteorological stations across Libya ranges between 10.3 and 21.6 ºC. Annual rainfall along the Libyan coast ranges from 140 to 550 mm (1945-2009), with December and January the wettest months, with the six months of October to March receiving 86-95% of the total annual rainfall (Emgailee, 1995); with 95% of Libya receiving less than 100 mm per year (Wheida and Verhoeven 2006).

### 2.2 Station selection

This paper is based on the mean daily, monthly and annual minimum temperature data collected from the Libyan National Meteorological Centre (LNMC). The sample of the present study involves 15 synoptic stations within the study area selected from a total of 41 meteorological stations distributed across Libya (Fig. 1). Twenty-six Libyan meteorological stations have been omitted, mainly because the meteorological station records are short (less than 30 years) and/or they include large periods for which no records exist, resulting from shortages in technical or human capabilities, as such those stations are considered inappropriate for further evaluation in this study. The names and reference numbers (WMO - World Meteorological Organization) of the proposed stations are provided in Table 1, which includes altitude above sea level, details of record length and resolution and distance from the sea. The division of Libya into two regions (coastal and internal) will permit further analysis into the examination of potential mechanisms responsible for changes within the temperature. Nine stations were selected along the Mediterranean coast (coastal stations) and six stations from central and southern Libya (inland stations). The northern part (coastal region) is located north of 30º 45′ N and includes the nine synoptic stations of Zwarah, Nalute, Tripoli Airport, Musratah, Sirt, Ajdabiya, Binina, Shahat, and Darnah. All of these stations have a typical Mediterranean and semi-arid climate, rain in winter with hot and dry summers, with mean annual surface temperature ranging between 14.2 and 21.6 °C and mean annual relative humidity of about 70%, with total annual rainfall ranging between 140-550 mm year$^{-1}$ and a mean annual number of rainy days of 55. The southern part (inland region) is located south of 30º 45′ N and represented by six synoptic stations: Ghadames, Hon, Sabha, Al-Jaghbub, Tazerbou, and Al- Kufrah. The climate is typically dry arid and characterized by high annually temperature with an average of 26.5 °C, mean annual relative humidity is 52% and the annual number of rainy days ranges between one (Al-Kufrah) and ten days (Hon and Ghadames), with average precipitation not exceeding 100 mm/year. This study focuses on data recorded for the period 1945-2009, as dataset integrity improves considerably after 1945 at the majority of coastal stations, with missing data a significant issue for some stations prior to 1945. Annual and monthly datasets for all stations during the period 1945-2009 are used in this paper, but the daily datasets are only available for the period 1956-2009 for eight coastal stations: Zwarah, Tripoli Airport, Musratah, Sirt, Ajdabiya, Binina, Shahat and Darnah (Nalute excluded as only monthly data available).

A number of the coastal and inland stations are located in urban areas adjacent to urban developments, which could influence the climatology to varying degrees throughout the stations history (e.g. Zwarah, Musratah, Sirt, Darnah and Sabha). To examine the relationships between mean annual minimum temperature and the rate of the population growth, the relationship between population growth and minimum temperature are plotted for six cities (Zwarah, Sirt, Darnah, Hon, Al Kufrah; Fig. 2). No clear relationships exist between rate of temperature changes and population growth for the cities studied. Unfortunately no specific information on individual rates of urban expansion in areas immediately adjacent to the stations are recorded, nor have detailed records have been maintained that would allow a detailed examination of the urban heat island effect in Libya, with stations insufficiently close together to permit nearby station comparison analysis. The meteorological stations at Tripoli airport, Binina, Ghadames, and Sabha are located at the airports, while the station at Ajdabyia, Nalute and number of the inland stations are situated in rural regions; as such they are less influenced by urbanisation. Examination of the population change (a potential surrogate for urban development) in each of the cities shows a steady increase during the period of study (Table 2).

### 2.3 Data quality and management

The original climatic data was stored in a Microsoft Word (1998) document and was quality-checked at the Data Process Unit (DPU) in the Climate Department of the LMNC in Libya. Three obstacles were encountered when processing the data:

1. The original data was stored within a Word document, as such this required transferring into a database structure to permit statistical analyses, a time consuming process.

2. A number of data quality issues arose during the transfer of the data into a database structure, these included: missing data, a result of poor dataset management; incomplete or inaccurate entry of synoptic station records; failure to transfer records during upgrades (data on paper into electronic data) at the DPU, resulting in missing months or years at some stations (the majority of these stations have been excluded from the present study); changes (or failure) in observation practice (Tazerbou); changes in station location (Binina and Shahat); interruption of observation (e.g. Shahat and Sirt). Despite the availability of original records, some files were missing or too many readings were made, a consequence of collating the data through phone calls at DPU. The quantity of missing annual, monthly and daily data is detailed in Table 2; with the number of missing days of the eight coastal stations (1956-2009) ranging between 0.2 and 4.3%, whilst the number of missing months does not exceed 2.2% over the period 1945-2009 at any station.

3. Data reliability was ensured through a number of telephone calls that were made to resolve concerns relating to data completeness and quality. Three different approaches have been used to resolve problems: (i) regular conversations with climatologists in the Climate Department to address data queries; (ii) by comparing the obtained daily data with the annual and monthly average data that had already been checked at DPU; and, (iii) returning to Libya to undertake discussion and review of original records with DPU members.

## 3. Variability of temperature

The mean annual temperature ranges between 14.2 °C to 21.0 °C at the coastal stations and between 21.3 °C to 23.4 °C at the inland stations (1945-2009). The mean monthly maximum temperature across Libya ranges from 17.8 °C to 45.4 °C (Table 3), with the highest temperature (58 °C) observed on 13$^{th}$ September 1922 in Al-Aziziya city. The mean monthly minimum temperature ranges from 12.3 to 16.7 °C, with the minimum recorded temperature of -8.3 °C recorded in January 1935 at Ghadames.

The temperature is characterized by variability, both spatially and temporally, with a standard deviation (SD) in mean annual minimum temperature between 0.53 °C at Hon and 1.33 °C at Al-Jaghbub. The coefficient of variation (COV) represents the ratio of the standard deviation to the mean and is a valuable statistical test for comparing the degree of variation from one data series to another, even if the means are drastically different from each other. The higher values of the annual COV occur in the west and southwest of Libya (Zwarah, Nalute, Al-Kufrah and Hon; Table 3), with the lowest observed values at coastal stations along the Mediterranean, indicating that the main factor influencing spatial variability in COV is the Mediterranean. Generally, the annual average of the COV temperature for stations ranges between 3.65% (Ajdabyia) and 10.57% (Al-Jaghbub). However, the COV of summer temperature ranges between 3.43% (Tazerbou) and 7.45% (Hon), which is much lower than that of average winter (157%), spring (50%) and autumn (42%).

## 4. Results

### 4.1 Multi-decadal variations in temperature

Daily

Daily minimum temperature data for Libya is available for 54 years (1956-2009). The study period is divided into two series of equal length (27 years), 1956 to 1982 and 1983 to 2009, referred to as period 1 and period 2, respectively. The two study periods may be assessed to provide comparison. Statistical analysis of the 27 year period and the nearest comparable 30 year period (1956-1985 and 1980-2009) was undertaken; this identifies no discernable difference in the statistical character of the two groups. As such the analysis within this paper will examine these two periods, whilst it is recognised that the WMO recommends analysis be undertaken on 30 year periods, the WMO recommendation assumes no statistical issues with data limitation.

In order to examine temporal changes in temperature, a time series of 11-day moving average of the mean daily minimum temperature for the eight coastal stations for the two 27 year periods have been analysed (daily data are unavailable for the all inland stations and Nalute). The daily data are considered at the coastal stations as these records provide a much more complete picture of temperature change, a dataset unfortunately unavailable for the inland stations where only monthly data have been made available. Changes in the minimum 11-day daily temperature illustrate that period 2 is characterized by higher temperatures compared to period 1 (Fig. 3), particularly during the days of the year 150-300 (using Gregorian day, i.e. the first of January is the first day of the year) at all stations.

Monthly

An analysis of monthly minimum temperature across Libya (1945-2009) identified increases at the majority of inland stations, particularly in the mid-1980s. To examine the distribution in minimum temperature change, the mean monthly minimum temperature for two 30 years intervals (1945-1977 and 1978-2009) for inland and coastal stations have been analysed. Changes in minimum temperature identified that the period 1978-2009 was characterized as hotter than 1945-1977 at the majority of proposal stations (Fig. 4).

Annual

The estimation of trends in the annual minimum temperature for the fifteen study stations across Libya over the period 1945-2009 are based on the Mann-Kendall test. Positive trends (increase) in minimum temperature are observed at all study stations. The Mann-Kendall trends (Q) are computed according to the Sen’s slope (a positive value indicates positive trend – Salmi et al., 2002) with ranges between 0.013 and 0.059 °C/year with the highest trend at Al-Kufrah, which has the highest mean annual surface temperature (23.4 °C). The annual trends are highly significant (***) at 13 of the 15 study stations (Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Shahat, Ghadames, Al-Jaghbub, Sabha, Tazerbou, and Al-Kufrah), with significant (*) at Hon and significant (**) at Darnah (Table 4).

Analysis of the data from 1945-2009 was undertaken by dividing the whole period in two, providing two periods for analysis, the first 33 years and the second 32 year in length, this permits consideration of general long term changes and differences in rates of change. Error bars are used to demonstrate the significance of differences between group means of minimum temperature for different synoptic stations across Libya (Figure 5). The mean annual minimum temperature of the coastal stations for 33/32 year intervals over the period of 1945-1977 and 1978-2009 are plotted (Fig. 5a). Significant differences in the mean annual minimum temperature at the majority of the coastal stations are found at three standard errors (99.73% confidence level), Zwarah; Tripoli Airport; Nalute; Sirt; Ajdabyia; Binina and Darnah. The site at Shahat is significant at two standard errors (95.4%) and the site at Musratah significant at one standard error 68.3%). Significant differences in mean annual minimum temperature are also recorded at the majority of the inland stations a Ghadames; Al-Jaghbub; Sabha; and Al Kufrah (99.73% confidence level); with the sites at Tazerbou and Hon significant at two and one standards error (95.4% and 68.3%) respectively.

### 4.2 Decadal variations of temperature

To examine the characteristics and distributions of the daily minimum temperature for the stations within the coastal region, analyses of the cumulative 11-day minimum temperature was undertaken with comparison over 10-years intervals (1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2009); except for the final period, which uses only 9 years of data, as daily data for 2010 for all stations is unavailable. The annual minimum temperature for the majority of coastal stations has fluctuated over the period 1961-2009 with a general increase during the summer and autumn season (days 180-300; Fig. 6), at the majority of coastal stations (Zwarah, Tripoli Airport, Ajdabyia, Binina and Darnah), with the temperature during each decade greater than the previous decade.

The cumulative mean daily minimum temperatures for 10-year intervals of the period 1961-2009 for the eight coastal stations are used to show the behaviour of daily minimum temperature (Fig. 7). The summer season temperature (days from 180 to 240) for the 10-years intervals has rapidly increased over the study period, but it was much higher for the period 2001-2009 at all coastal stations, except at Shahat station. Moreover, the cumulative mean monthly minimum temperatures for 10 years intervals of the period (1951-2009) for the six inland stations shows higher increases, except at Sabha and Ghadames.

## 4.3 Seasonal and sub-seasonal variations of temperature

August and July are the warmest months while December and January are the coolest. Summer average temperature range between 22.8 °C to 31.2 °C, with average winter temperature ranges between 10.0 °C to 14.8 °C and spring and autumn between 14.6 °C to 24.1 °C (calculated from 1945-2009). Seasonal minimum temperatures at all study stations demonstrate general warming trends over the period 1945-2009; with increases in summer minimum temperature observed at all study stations and are highly significant (0.001 significance level) at all stations except Musratah, Shahat and Tazerbou, with the highest annual increase of 0.07 °C/year at Hon (Table 4). Increases in minimum temperature are also found at all study stations in autumn, with the highest rates of warming (0.06 °C/year) at Zwarah, Hon and Al-Kufrah. The fluctuations in temperature during spring and winter present a similar pattern with increases at all study stations except Musratah (spring) and Al-Jaghbub (winter), with the highest increase at Al-Kufrah in spring (0.06 °C/year) and winter 0.05 °C/year, with highly significant increases at the majority of stations.

The mean summer and autumn minimum temperature over the 33/32 year intervals (1945-1977 and 1978-2009) show positive increases. The mean minimum temperature shows significant changes in summer at the majority of stations at three standard errors (99.7% confidence level), Zwarah, Tripoli Airport, Ajdabyia, Binina, Darnah, Nalute, Ghadames, Hon, Sabha, and Al Kufrah (Fig. 5b). The site at Sirt, Shahat, Darnah, and Al-Jaghbub are significant at two standard errors (95.4%), with the site at Tazerbou only significant at one standard error (68.3%). Significant changes in mean autumn minimum temperature are recorded at the majority of stations at three standard errors (99.7% confidence level), Zwarah, Tripoli Airport, Sirt, Binina, Darnah, Nalute, Hon, Sabha, and Al Kufrah (Fig. 5c). The site at Musratah, Ajdabyia, Ghadames and Tazerbou are significant at two standard errors (95.4%), with the site at Shahat only significant at one standard error (68.3%). In spring, significant changes in mean minimum temperature are observed at few stations at three standard errors (99.73% confidence level), Zwarah, Binina, Darnah, Hon, and Al Kufrah (Fig. 5d); the site at Musratah, Sirt, and Nalute are significant at two standard errors (95.4%), with the site at six stations; Tripoli Airport, Ajdabiya, Shahat, Ghadames, Sabha and Tazerbou significant at one standard error (68.3%). Significant changes in mean winter minimum temperature are found at five stations at three standard errors (99.7% confidence level), Zwarah, Binina, Ghadames, Sabha and Al Kufrah (Fig. 5e). The site at Tripoli Airport, Ajdabyia, Darnah, Nalute and Hon are significant at two standard errors (95.4%), with the site at Sirt, Shahat and Tazerbou significant at one standard error (68.3%).

## 5 Discussion

The findings of this study support previous findings (Ben-Gai et al., 1999; El-Tantawi, 2005; El-Kenawy et al., 2009) which examined a smaller number of stations, over shorter periods of time. Analysis using 65 years of minimum temperature data from 15 synoptic stations distributed across Libya has revealed significant increases in the minimum temperature (Fig. 4 and Table 4). The mean annual minimum temperature during the period 1945-2009 increases at an average rate of 0.032 °C/year, based on the findings of this study. This is considerably faster than the IPCC (2007) global mean temperature increase of 0.74 °C ± 0.18 °C over the last 100 years, but is notably only derived from land based stations. These findings are comparable to Ben-Gai et al. (1999) in their study of Israeli annual minimum temperature trends (0.01-0.53 °C/decade), but indicate a faster rate of warming compared to previous studies examining Libya (El-Kenawy et al., 2009).

Considerable temporal and spatial temperature variability across Libya has been identified, with particularly rapid increases in minimum temperature during the last 32 years (1978-2009) at the majority of the stations (Zwarah, Tripoli Airport, Sirt, Ajdabyia, Binina, Darnah, Nalute, Ghadames, Al-Jaghbub, Sabah and Al-Kufrah). Seasonal analyses indicate that the most rapid warming is observed in summer and autumn with seasonal minimum temperature (Fig. 5b, c, d, e and Table 4) increases with averages of 0.034 °C/year in summer and 0.036 °C/year in autumn. Generally, no clear differences are found between the coastal and inland stations in annual and seasonal minimum temperature variability; however, increases in mean minimum temperature at inland stations (i.e. Al-Kufrah and Al-Jaghbub) is more noticeable in spring and winter.

## 6 Conclusion

This paper has examined the spatial and temporal variation in minimum temperature (1945-2009) and the potential of the mechanisms responsible for these changes across Libya, the main findings are:

i. Increases in the mean annual minimum temperature for all station across Libya during the period 1945-2009 are identified (Fig. 4 and Table 4).

ii. The mean annual minimum temperature over the last 30 years has increased for the entire sample with significant increases in the annual minimum temperature identified at 88% of the coastal stations, particularly at, Zwarah, Tripoli Airport, Sirt, Ajdabyia, Binina, Darnah and Nalute. Significant increases in the mean annual minimum temperature are identified at 67% of the inland stations, Ghadames, Al-Jaghbub, Sabha, and Al-Kufrah (Fig. 5a).

iii. Significant changes of the minimum temperature are found at coastal (inland) stations for the seasons - summer 56% (67%), autumn 67% (50%), spring 22% (50%) and in winter 33% (33%), respectively at three standard errors (Fig. 5b, c, d, and e).

iv. The mean daily minimum temperature for the 10 years intervals (1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2009) at the majority of coastal stations; Zwarah, Tripoli Airport, Ajdabyia, Binina and Darnah (Fig. 6) and the mean monthly minimum temperature for the 10 years intervals (1951-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2009) at the inland stations; Hon, Sabha, Tazerbou and Al-Kufrah suggest that the mean minimum temperatures are highest during the period 2001-2009 (Fig. 7).

Using 65 years of temperature data from 15 meteorological stations distributed across Libya have revealed significant increases in the minimum temperature. Accordingly, the study has identified that the temporal and spatial temperature variability at stations has been shown to be significant at several locations, with particularly rapid increases in minimum temperature during the last 30 years found at the majority of stations.

The work presented here can be used to support climate studies that aim to examine climate variability or regions in Libya. The results of the work represent an important tool in future environmental management decisions in Libya; particularly in better managing for a changing climate. However, the social and economic implications and their effect on the society still require more and deeply investigation.

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**Table 1:** List of the meteorological stations and the climatic data available assessed within the study.

| Stations | Latitude ( o ) | Longitude ( o ) | High (m) aMSL | WMO No. | Distan. from the sea (km) | Mean Minimum Temperature (ºC) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Daily Data | | Monthly Data | |
| | | | | | | Period Covered | Missing Data ( % ) | Period Covered | Missing Data ( % ) |
| Zwarah | 32º :53′ N | 12 º :05′ E | 3 | 062007 | 0.8 | 1956-2009 | 0.4 | 1945-2009 | 0.8 |
| T. Airport | 32 º :40′ N | 13 º: 09′ E | 81 | 062010 | 2.4 | 1956-2009 | 0.2 | 1945-2009 | 0.0 |
| Musratah | 32º : 19′ N | 15 º: 03′ E | 32 | 062016 | 4.1 | 1956-2009 | 2.2 | 1946-2009 | 0.0 |
| Sirt | 31º : 12′ N | 16 º: 55′ E | 13 | 062019 | 0.7 | 1956-2009 | 1.2 | 1946-2009 | 0.0 |
| Ajdabyia | 30 º: 43′ N | 20 º: 10′ E | 7 | 062053 | 8.5 | 1956-2009 | 0.2 | 1945-2009 | 0.0 |
| Binina | 32 º: 05′ N | 20 º: 16′ E | 129 | 062055 | 19 | 1956-2008 | 0.3 | 1945-2008 | 0.1 |
| Shahat | 32 º: 49′ N | 21º: 51′ E | 625 | 062056 | 0.5 | 1956-2009 | 0.4 | 1945-2009 | 0.0 |
| Darnah | 32 º: 47′ N | 22 º:35 ′ E | 26 | 062059 | 1.0 | 1956-2009 | 4.3 | 1945-2009 | 0.0 |
| Nalute | 31º: 52′ N | 10 º:59′ E | 621 | 062002 | 150 | | | 1945-2008 | 0.7 |
| Ghadames | 30 º: 09′ N | 09 º:42′ E | 357 | 062103 | 390 | | | 1944-2008 | 1.4 |
| Sabha | 32 º: 19′ N | 12 º:05′ E | 432 | 062124 | 500 | | | 1948-2008 | 3.1 |
| Hon | 29 º: 08′ N | 15 º:57′ E | 267 | 062131 | 240 | | | 1948-2008 | 1.3 |
| Al-Jaghbub | 29 º: 45′ N | 24 º:32′ E | 2 | 062176 | 210 | | | 1946-2008 | 0.9 |
| Tazerbou | 25 º: 48′ N | 21 º:08′ E | 259 | 062259 | 700 | | | 1963-2007 | 2.2 |
| Al-Kufrah | 24 º: 13′ N | 23 º:18′ E | 435 | 062271 | 800 | | | 1946-2006 | 1.5 |

**Table 2:** The rate of annual population growth relative to the previous decade in Libya for the period 1954-2006

| Cities | Total population (2006) | The rate of population growth (%) | | | | |
|---|---|---|---|---|---|---|
| | | 1954-1964 | 1964-1973 | 1973-1984 | 1984-1995 | 1995-2006 |
| Zwarah | 287662 | 4.3 | 4.0 | 6.8 | 3.5 | 1.2 |
| Tripoli | 1065405 | 5.2 | 5.3 | 4.8 | 2.6 | 1.6 |
| Musratah | 550938 | 6.6 | 5.2 | 5.0 | 1.3 | 1.6 |
| Sirt | 193720 | 5.2 | 3.4 | 6.5 | 3.2 | 1.5 |
| Ajdabyia | 177047 | 6.8 | 3.7 | 5.2 | 2.9 | 1.1 |
| Benghazi | 670797 | 6.3 | 5.5 | 3.5 | 3.0 | 1.2 |
| Shahat | 203156 | 4.3 | 4.0 | 6.8 | 3.3 | 1.4 |
| Darnah | 163351 | 4.8 | 5.0 | 5.0 | 2.7 | 1.9 |
| Nalute | 93224 | 4.5 | 3.6 | 4.5 | 2.1 | 1.2 |
| Ghadames | 9558 | 4.3 | 4.3 | 7.2 | 2.2 | 1.8 |
| Hon | 19816 | 4.3 | 4.0 | 6.8 | 2.7 | 2.0 |
| Al-Jaghbub | 2868 | 4.3 | 5.5 | 4.9 | 2.7 | 1.9 |
| Sabha | 212694 | 4.2 | 4.0 | 6.8 | 3.5 | 1.6 |
| Tazerbou | 6600 | 4.3 | 4.0 | 6.8 | 2.5 | 2.1 |
| Al-Kufrah | 50104 | 4.3 | 4.9 | 6.8 | 2.1 | 1.6 |
| Libya | 5323991 | 6.3 | 4.0 | 5.5 | 1.5 | 2.4 |

**Table 3:** Mean annual, extremes, seasonal and absolute temperature, coefficient of variation (COV), standard deviation (SD) at 15 synoptic stations over Libya during the period 1945-2009.

| Stations | Mean Annual Temp | S D | CV % | Mean Max. Temp | Mean Min. Temp. | Absolute Temp. | | Mean Seasonal Temp. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max | WIN | SPR | SUM | AUT |
| Zwarah | 20.0 | 0.8 | 4.0 | 24.6 | 15.5 | -1.1 | 53.0 | 13.4 | 18.0 | 25.6 | 22.4 |
| T. Airport | 21.0 | 0.5 | 2.7 | 27.1 | 14.0 | -1.3 | 48.3 | 12.3 | 18.7 | 27.5 | 21.9 |
| Musratah | 20.4 | 0.6 | 3.3 | 25.0 | 15.8 | 1.1 | 47.6 | 13.9 | 18.2 | 25.9 | 22.6 |
| Sirt | 20.5 | 0.5 | 2.5 | 25.1 | 16.0 | 1.0 | 47.0 | 14.5 | 18.8 | 25.6 | 22.8 |
| Ajdabyia | 20.7 | 0.6 | 2.8 | 26.8 | 14.6 | 0.0 | 47.0 | 13.4 | 19.8 | 26.6 | 22.2 |
| Binina | 19.9 | 0.4 | 2.4 | 25.2 | 15.0 | 1.7 | 44.8 | 13.0 | 18.6 | 26.1 | 21.7 |
| Shahat | 14.2 | 0.5 | 2.9 | 20.8 | 12.3 | -1.8 | 42.0 | 9.6 | 14.6 | 22.4 | 17.7 |
| Darnah | 20.3 | 0.4 | 2.1 | 23.4 | 16.7 | 4.4 | 44.8 | 14.7 | 17.9 | 25.3 | 22.3 |
| Nalute | 21.9 | 0.7 | 3.7 | 24.5 | 13.9 | -3.3 | 43.6 | 10.6 | 18.0 | 27.4 | 20.6 |
| Ghadames | 21.3 | 1.1 | 5.1 | 29.6 | 14.2 | -6.9 | 54.2 | 11.8 | 21.7 | 31.5 | 22.8 |
| Hon | 22.0 | 0.5 | 2.3 | 22.5 | 12.6 | -6.9 | 47.2 | 12.2 | 20.9 | 28.5 | 22.2 |
| Al-Jaghbub | 21.4 | 1.1 | 5.3 | 29.1 | 13.7 | -3.0 | 47.5 | 13.0 | 21.0 | 28.9 | 22.7 |
| Sabha | 22.6 | 0.8 | 3.5 | 30.3 | 15.5 | -4.6 | 47.1 | 13.2 | 23.6 | 31.2 | 24.1 |
| Tazerbou | 22.5 | 0.7 | 2.4 | 30.3 | 14.7 | -4.6 | 47.7 | 13.4 | 23.4 | 29.9 | 23.2 |
| Al-Kufrah | 23.4 | 0.7 | 2.9 | 30.8 | 15.9 | -3.3 | 46.7 | 14.2 | 24.3 | 30.8 | 23.9 |

**Table 4:** Annual and seasonal minimum temperature (°C), Sen's slope and Mann-Kendall (Q) test for trend (Test Z) in fifteen synoptic stations across Libya, 1945-2009.

| Stations | Annual | | | Summer | | | Autumn | | | Spring | | | Winter | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Test Z | Sig | Q | Test Z | Sig | Q | Test Z | Sig | Q | Test Z | Sig | Q | Test Z | Sig | Q |
| Zwarah | 7.5 | *** | 0.04 | 6 | *** | 0.04 | 6.7 | *** | 0.06 | 6.1 | *** | 0.04 | 6.3 | *** | 0.04 |
| T.Airport | 4.9 | *** | 0.02 | 4.6 | *** | 0.03 | 3.8 | *** | 0.02 | 3.2 | ** | 0.01 | 2.4 | * | 0.01 |
| Musratah | 5.8 | *** | 0.03 | 2.2 | * | 0.02 | 4 | *** | 0.03 | 1.6 | | 0.01 | 4.2 | *** | 0.02 |
| Sirt | 3.5 | *** | 0.02 | 3.4 | *** | 0.02 | 5.2 | *** | 0.03 | 2.2 | * | 0.01 | 3.3 | *** | 0.01 |
| Ajdabyia | 4.6 | *** | 0.01 | 5.2 | *** | 0.04 | 4.2 | *** | 0.03 | 3.7 | *** | 0.02 | 3.6 | *** | 0.01 |
| Binina | 5.6 | *** | 0.03 | 5.4 | *** | 0.03 | 5.3 | *** | 0.03 | 4.7 | *** | 0.03 | 5.6 | *** | 0.03 |
| Shahat | 5.7 | *** | 0.03 | 2.7 | ** | 0.02 | 2.6 | ** | 0.01 | 2.7 | ** | 0.02 | 1.9 | + | 0.01 |
| Darnah | 3.1 | ** | 0.02 | 4.5 | *** | 0.03 | 3.9 | *** | 0.02 | 5.2 | *** | 0.03 | 5.7 | *** | 0.02 |
| Nalute | 6.3 | *** | 0.02 | 3.7 | *** | 0.02 | 4.5 | *** | 0.03 | 3.3 | *** | 0.02 | 3.7 | *** | 0.03 |
| Ghadames | 5.7 | *** | 0.04 | 5.2 | *** | 0.05 | 4.6 | *** | 0.04 | 4.5 | *** | 0.04 | 2.7 | ** | 0.02 |
| Hon | 2.6 | * | 0.01 | 6.4 | *** | 0.07 | 5.5 | *** | 0.06 | 4.9 | *** | 0.05 | 5.2 | *** | 0.04 |
| Al-Jaghbub | 6.5 | *** | 0.05 | 3.3 | *** | 0.02 | 1.9 | + | 0.02 | 1.2 | | 0.01 | 0.3 | | 0.01 |
| Sabha | 5.9 | *** | 0.03 | 4.8 | *** | 0.04 | 4.2 | *** | 0.03 | 4.7 | *** | 0.04 | 2.4 | * | 0.02 |
| Tazerbou | 3.5 | *** | 0.03 | 2.7 | ** | 0.03 | 3.3 | ** | 0.03 | 1.9 | + | 0.03 | 1.9 | + | 0.03 |
| Al-Kufrah | 7.2 | *** | 0.06 | 6 | *** | 0.06 | 5.3 | *** | 0.06 | 6.2 | *** | 0.06 | 6.4 | *** | 0.05 |

+ 0.1; * 0.05; ** 0.01 & *** 0.001 significance level

**Figure captions**

Fig. 1: Libya and the distribution of meteorological stations.

Fig. 2: The total population and changes in annual minimum temperature for the cities; Zwarah, Sirt, Darnah, Sabha, Hon and Al Kufrah over the period 1964-2006

Fig. 3: Annual mean 11 day moving averages of the mean daily minimum temperature for coastal stations for the period 1956-2009.

Fig. 4; Annual mean minimum temperature of the inland stations for the period 1945-2009

Fig. 5: a) Mean annual minimum temperature for the two periods 1945-1977 and 1978-2009, at the 15 synoptic stations over Libya; b) Mean summer minimum temperature; c) Mean autumn minimum temperature; d) Mean winter minimum temperature; e) Mean spring minimum temperature at the synoptic coastal and inland stations over Libya, with error bars representing three standard errors (99.73% confidence level).

Fig. 6: Decadal mean of 11 day moving averages of the mean daily minimum temperature over near decadal windows for coastal stations for the period 1961-2009, with the curves from a separate decadal block.

Fig. 7: The cumulative monthly minimum temperature of inland stations for 10 years intervals during the period 1951-2009.