Theoretical and Applied Climatology

Variability of maximum and mean average temperature across Libya (1945-2009)

--Manuscript Draft--

Manuscript Number:	TAAC-D-12-00429R1
Full Title:	Variability of maximum and mean average temperature across Libya (1945-2009)
Article Type:	Original Paper
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Response to Reviewers:	A seperate document is provided with clear responses to each of the reviewers comments.

Variability of maximum and mean average temperature across Libya (1945-2009)

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ABSTRACT

Spatial and temporal variability in daily maximum, mean average daily temperature, monthly maximum and mean average monthly temperature for nine coastal stations during the period 1956-2009 (54 years) and annual maximum and mean average temperature for coastal and inland stations for the period 1945-2009 (65 years) across Libya are analysed. During the period 1945-2009 significant increases in maximum temperature (0.017 °C/year) and mean average temperature (0.021 °C/year) are identified at most stations. Significantly warming in annual maximum temperature (0.038 °C/year) and mean average annual temperatures (0.049 °C/year) are observed at almost all study stations during the last 32 years (1978-2009). The results show that Libya has witnessed a significant warming since the middle of the twentieth century, which will have a considerable impact on societies and the ecology of the North Africa region, if increases continue at current rates.

KEYWORDS: *maximum, climate; warming; temperature variability; trends; Libya.*

1. Introduction

During the last four decades, a large body of research has been undertaken on climatic change at local, regional and international levels (e.g. Domonkos and Tar, 2002; Wibig and Glowicki, 2002) examining a variety of climatic parameters, particularly temperature. The Intergovernmental Panel on Climate Change (IPCC, 2007) fourth report concluded that global mean temperature had increased by 0.74 °C ± 0.18 °C over the last 100 years (1906-2005), with considerable spatial variations. The IPCC's rate of change are supported, with varying rates of change, by Jones et al. (1999: ~0.62 °C), Hansen et al. (2006: 0.8 °C), Alexander et al. (2006: 0.74 °C) and Rebetez and Reinhard (2008: 0.8 °C), the later identifying particularly rapid rates of increase during the periods 1920-1945 and 1975-2008.

Within the Mediterranean region a number of studies have investigated temperature change over the last 150 years, with a general pattern of increasing temperatures, but with considerable spatial and temporal variability. Campra et al. (2008) investigated long-term temperature time series (1950-2006) in south-eastern Spain and identified slight increases in annual maximum temperature, with significant warming trends in mean annual surface air temperature during the period 1983–2006, a finding replicated in the study by Brunet et al., (2007) analysing temporal and spatial temperature patterns across Spain (1850–2005) found a significant increase in annual mean surface temperature. Juan and Antonio (1996) examined spatial and temporal temperature variability across the Spanish peninsular (including Canary Islands), identifying mean temperature increases at 36% of stations, decreasing at 10%, with insignificant change at 54% of the study stations over the period 1901-1989. Hasanean and Abdel Basset (2006) investigated variability in summer temperature across Egypt, based on monthly temperatures for 19 stations (1987-2000) found a general warming trend in summer surface air temperature at most of stations, while negative trends in Upper Egypt. Similarly Xoplaki et al. (2003) identified that warmer Mediterranean summers characterize the 1950s, 1980s and 1990s, with a significant increase of 0.05 C/decade over the period 1980 to 1999. Aesawy and Hasanean, (1998) studied variations in mean average temperature at six southern Mediterranean stations (including Tripoli 1944-1991), in which their results identified a significant warming for all stations, except Tripoli; though the suitability of the climatic station used for Tripoli City may require reconsideration, as it is located on the second floor of a building, on a concrete surface with surrounding buildings overshadowing the station. The above studies illustrate the variety of previously identified trends in temperature change around the Mediterranean region.

In Libya, relatively few studies have been undertaken of either long-term climate change or in the spatial variations and trends in temperature data (El-Tantawi, 2005; El-Kenawy et al., 2009; Ageena et al. 2012), with no clear patterns identified. El-Tantawi (2005) identified significant warming trends in mean annual surface temperature (1946-1999), in contrast to El-Kenawy et al. (2009) who identified negative trends in annual maximum temperature at all stations across Libya (1951-1999), with significant decreases at 70% of stations. The later represents something of an anomaly within the wider research, within both Libya and the Mediterranean region.

The present paper seeks to examine temperature across Libya with a particular focus on examining spatial and temporal variability of maximum and mean average temperature during the period 1945-2009. Specifically, the objectives of this paper are as follows:

i. To identify temporal fluctuations and patterns in maximum and mean average temperature across Libya over two climatic regions (coastal and inland) based on (a) annual data, (b) seasonal data, (c) monthly data, and (d) daily data;
ii. To identify and examine any spatial changes within the data;
iii. To understand any associations between temperature and geographic parameters (e.g. altitude or distance from the sea); and,
iv. To provide the most comprehensive analysis of observed temperature across Libya.

2. Method

2.1 Study area

Libya is located in central North Africa; with the Mediterranean as its northern border, with approximately 2000 km of coastline (Figure 1). The country is located between latitude (20° to 34° N) and longitude (10° to 25° E) within which roughly 90.5% of the area is classified as hyper-arid (Ben-Mahmoud 1995). The topography is generally free of steep terrain, with the exception of two regions in the north-west and north-east, where elevation ranges from 500 to ~1000 m above mean sea level (a.m.s.l.; Al-Haram 1995). The climate of Libya is characterized by wet winters and hot dry summers and shows a transition between the Mediterranean and temperate climates to the arid climates of the interior. The population of Libya in 2006 was estimated by the General Directorate of Documentation and Information (GDDI) at 5,323,991, with the projected population for the year 2025 near 10 million.

Suggested Location of Figure 1

2.2 Station selection

Temperature data was collected from the Libyan National Meteorological Centre (LNMC). Daily and monthly data are available for mean maximum and mean average temperature (monthly mean values of average temperature are computed from their corresponding daily values calculated from the maximum and minimum temperatures over the month (maximum temperature + minimum temperature /2) for the study stations across Libya. The sample of the present study involves 18 synoptic stations within the study area, selected from a total of 38 meteorological stations distributed across Libya.

The names and reference numbers (World Meteorological Organization-WMO) of the proposed stations are provided in (Table 1 and), which includes altitude, distance from the sea, details of record length and resolution are provided in Table 2. Twenty 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 the present study.

Suggested Location of Table 1 and Table 2

The initial division of Libya into two regions (coastal and internal) permits further analysis of the potential mechanisms responsible for changes in temperature. Nine stations were selected along the Mediterranean coast (coastal stations) and nine stations from southern Libya (inland stations). The coastal region is located north of 30º 45′ N and includes nine stations (Figure 1): Zwarah, Nalute, Tripoli Airport, Musratah (western-coastal region), Sirt, Ajdabiya (central-coastal region), Binina, Shahat and Darnah (eastern-coastal region); these stations all have a typical Mediterranean and semi-arid climate, rain in winter with hot and dry summers. The inland region is located south of 30º 45′ N and is represented by nine stations: Ghadames, Al-Garyiat, Hon, Jalo, Al-Jaghbub, Sabha, Ghat, Tazerbou and Al- Kufrah; the climate is typically dry arid and characterized by high temperatures.

The present study focuses on data recorded for the period 1945-2009, as dataset integrity improves considerably after 1945 at the majority of stations, with missing data a significant issue prior to 1945. Monthly datasets for all examined stations during the period 1945-2009 are

used in this paper and were checked for completeness (Table 2). Daily datasets are only available for the period 1956-2009 (54 years) at nine coastal stations. An analysis of the data was undertaken to ensure that data quality was of high integrity, with any year consisting of missing data exceeding three months, and/or, any month with ≥11 missing days being removed; approaches recognised by WMO and applied at the Data Process Unit (DPU) in the LMNC. The number of missing days at the nine costal stations (1956-2009) ranges between 0.1% (Tripoli Airport) and 1.6% (Nalute); with the highest number of missing months 1.7% (Al-Garyiat; 1945-2009).

2.3 Method and analyses

In this paper observed time series of daily maximum and mean average daily temperature (1956-2009) from nine coastal stations and monthly maximum and mean average monthly temperature (1945-2009) from six inland stations across Libya, part of the observational network of Libya are used. The daily data were unavailable for the inland stations, so comparison within this paper uses daily and monthly data for the coastal sites and then undertakes comparison between inland and coastal stations on only annual data.

The significance of trends in maximum and mean average temperature for 1945-2009 are tested using the Mann-Kendal significance test (Sneyers, 1990; Mitchell et al., 1996; Salmi et al., 2002). Where trends are identified, the non-parametric Sen's slope test is applied to determine change per unit time, to detect the significance of the trends. The significant of difference trends (0.05%) in daily and monthly maximum and mean average monthly temperature of the two periods are tested using the Mann-Whitney test (Rose 2007; Soltani et al. 2012).

3. Temperature variability across Libya

The mean average annual temperature of Libya is 20.8 °C, with temperatures ranging between 16.5 °C and 24.1 °C (Table 2), with mean average daily temperature ranging between 13.0°C (winter) and 28.4 °C (summer). Across Libya the average annual maximum temperature ranges between 20.8 °C and 31.8 °C (Table 2), with the hottest months July (34.6 °C) and August (34.9 °C) and the coldest January (17.8 °C) (1945-2009).

Temperature is characterized by slight variability (spatial and temporal) within regions, but with greater variability across regions, with a standard deviation (SD) of annual maximum temperature ranging between 0.5 and 1.12 °C and mean average annual temperature between

0.4 and 1.1 °C. The coefficient of variation (COV) represents the ratio of the standard deviation to the mean and is valuable in comparing the degree of variation from one data series to another, even if the means are drastically different from each other. The COV of mean annual maximum temperature ranges between 2.9% (coastal stations) and 3.7% (inland stations), while the COV of mean average annual temperature is 2.6% at coastal stations and a comparable 2.7% at inland stations.

4. Results

4.1 Multi-decadal variations in temperature

4.1.1 Daily variations and trends of maximum and mean average temperature

Daily maximum and mean average daily temperature data are available for nine coastal stations during the period (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. Statistical analysis of the 27 year periods and the nearest comparable 30 year period (1956-1985 and 1980-2009) identifies no apparent difference in the statistical character of the two groups; the WMO recommends that analysis be undertaken on 30 year periods, as it assumes no issues with data limitation.

In order to examine temporal changes in temperature, a time series of 11-day moving average mean daily maximum and mean average daily temperature for the periods 1956-1982 and 1983-2009 were analysed (Figure 2). The daily data are considered at the nine coastal stations as these provide a much more complete depiction of temperature change. Changes in the maximum 11-day daily temperature show (Fig. 2a) that period 2 is characterized by generally higher temperatures compared to period 1 at all stations, particularly during days 30-300 of the year (using Gregorian day, i.e. the first of January is the first day of the year).

Changes in mean average 11-day daily temperature show that period 2 is characterized by higher temperatures compared to period 1, in most days of the year at all examined stations (Fig. 2b). Differences in mean daily maximum and mean average daily temperature are identified when comparing between the two timeframes, with the second period significantly higher (95% confidence level) at most stations: Zwarah, Nalute, Sirt, Ajdabyia and Binina for the maximum temperature and at all coastal stations for mean average daily temperature.

Suggested Location of Figure 2a & 2b

4.1.2 Monthly variations and trends of maximum and mean average temperature

The rates of increase in maximum temperature during the months April-October are greater than the rates of decrease recorded during the months November-March, as such the high rates of change are strongly positive (Table 3). Significant trends are identified at 12 of the 15 stations in September (excluding Al-Garyiat, Ghat and Tazerbou), with increases at Sirt, Ajdabyia (significance level: 0.001), Shahat, Hon, Sabha (0.01), Zwarah, Darnah, Al-Garyiat, Jalo and Al-Jaghbub (0.05, Tripoli Airport, Ghadames and Al-Kufrah (0.1). In April, a positive change is identified at all stations except Binina, increases range from 0.001(Jalo) to 0.031°C/year (Al-Jaghbub, Sirt, Hon and Sabha; 0.01), at Zwarah and Ajdabyia (0.05) and at Ghadames (0.1). Positive trends in maximum temperature are identified during May-October, particularly at central and inland stations, with significant increases (0.001) identified in July (Ajdabyia), August (Ajdabyia and Hon), September (Sirt and Ajdabyia) and October (Al-Jaghbub). In February negative changes (-0.038 and -0.001 °C/year) in maximum temperature are indicated at ten stations: Musratah, Sirt, Binina, Shahat, Darnah, Hon, Jalo, Al-Jaghbub and Al-Kufrah, with a significant decreases at Musratah and the eastern-coast stations (0.05).

Positive mean average temperature trends are identified during the May-October at all stations (0.001 to 0.100 °C/year) particularly during July-October (Table 3). Significant trends are identified at almost all stations during July-September, except Musratah (July and August only). In September significant increases are identified at all stations: Zwarah, Sirt, Ajdabyia, Binina, Hon, Al-Jaghbub, Sabha, Tazerbou, Al-Kufrah (0.001), Tripoli Airport, Shahat, Darnah, Jalo (0.01), Nalute and Musratah (0.1). In February, negative mean average temperature trends ranging between -0.012 and -0.001 °C/year are identified at Musratah, Shahat, Darnah, Hon and Jalo (not significant). A positive trend in mean average monthly temperature is identified for Zwarah for all months (0.001; Table 3).

Suggested Location of Table 3

In order to examine differences in monthly temperature across Libya, the variability of mean monthly maximum and mean average monthly temperature at 15 stations (1945-1977 and 1978-2009) across Libya are analysed; the stations at Al-Garyiat, Ghat and Tazerbou are not included, as these stations have later start dates (see Table 3). Mean monthly maximum

temperature during the last 32 years (1978-2009) show higher maximum temperature for all months at Zwarah, Tripoli Airport, Nalute, Ghadames and Ajdabyia; and during April-October at Sirt, Shahat, Hon, Jalo, Al-Jaghbub and Sabha compared to the earlier period (1945-1977). Mean average monthly temperatures are also higher in the second period (1978-2009) compared to the first (1945-1977) for all months at Zwarah, Tripoli Airport, Nalute, Ajdabyia, Ghadames and Al-Jaghbub; with higher temperatures during April-October at Sirt, Binina, Shahat, Hon, Jalo and Sabha.

4.1.3 Seasonal and sub-seasonal variations of temperature

Seasonal maximum temperatures across Libya for the period 1945-2009 were analysed. Positive changes in seasonal maximum temperature are indicated at most stations in autumn, winter spring and summer (Table 4). In autumn increases in maximum temperature are observed at 13 of the 15 stations, with increases ranging between 0.005 and 0.032 °C/year (Table 4). Increases are identified for the winter season at nine stations, ranging from 0.001 (Ajdabyia) to 0.017 °C/year-Zwarah), with negative changes identified at seven stations, with an average decrease of -0.011 °C/year, with significant decreases found at Sirt, Darnah and Jalo (0.1; Table 4). Positive changes in spring maximum temperature are identified at most stations, ranging from 0.001 (Nalute) to 0.031 °C/year (Tripoli Airport, Ghadames and Sabha). Increases in maximum temperature are observed at 12 of 15 stations in summer, ranging from 0.005 (Darnah and Al-Kufrah) to 0.024 °C/year (Musratah).

Increases in mean average seasonal temperature are identified at most stations, in each season but at different rates across Libya during the period 1945-2009. The mean average temperature shows positive changes at the majority of stations in autumn (0.014-0.028 °C/year), winter (0.001-0.014 °C/year), spring (0.013- 0.019 °C/year) and summer (0.007- 0.024 °C/year). Significant increases in mean average temperature are found at all stations in autumn, winter, spring and summer, with the exception of Musratah (summer; Table 4).

Suggested Location of Table 4

4.1.4 Annual variations and trends of maximum and mean average temperature

To estimate changes and trends in temperature, the annual average maximum and mean average annual temperature of stations during the period 1945-2009 (65 years) are analysed based on the Mann-Kendall test.

Maximum temperature increases are identified at 10 of 15 stations during the period 1945-2009, ranging between 0.002 (Shahat) and 0.024 °C/year (Sabha) of which nine are significant increases: Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia, Ghadames and Hon (0.001); Al-Jaghbub and Sabha (0.01). Negative trends in maximum temperature found at five stations, ranging between -0.009 (Jalo) and -0.002 °C/year (Darnah); non-significant decreases are recorded at Musratah, Darnah and Al-Kufrah, with significant decreases at Jalo (0.05) and Binina (0.1; Table 5).

To estimate changes and trends in maximum temperature for the period 1945-1977, annual average maximum temperature for 15 stations across Libya have been analysed (excluding Al-Garyiat, Ghat and Tazerbou). Positive changes are identified at eight stations, at an average rate of 0.013 °C/year, with a significant increase at only Shahat (0.1). Decreasing annual maximum temperature, at an average rate of -0.027 °C/year are identified at the western stations; Zwarah, Tripoli Airport, Nalute, Musratah, and the southern-east stations: Hon, Jalo and Al-Kufrah, with significant decreases at Jalo (0.001) and Musratah (0.01; Table 5).

An increase in annual maximum temperature at all (18) stations within this study is identified during the last 32 years (1978-2009), ranging from 0.006 °C/year (Shahat) to 0.053 °C/year (Tripoli Airport). Significant increases are identified at 15 of the 18 stations (Table 5): Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Hon, Sabha, Al-Kufrah (0.001), Tazerbou (0.01), Binina, Darnah, Ghadames, Jalo and Ghat (0.05). The result of the Mann-Kendal test identified an increase in mean average annual temperature for the last 33 years (1978-2009) at all stations; with significant increases (Table 5) at 14 of the 18 stations at a 0.001 and at Al-Garyiat, Ghadames, Ghat (0.01) and Shahat (0.05).

A positive trend in mean average annual temperature at all stations (15) within this study is identified during the period 1945-2009, ranging between 0.003 °C/year (Al-Jaghbub) and 0.043 °C/year (Hon; Table 5). Significant positive trends are identified at 9 stations, with analysis of mean average temperature during the period 1945-1977 found weak positive trends at seven stations: Nalute, Sirt, Ajdabyia, Binina, Shahat, Darnah and Sabha at an average rate of 0.012 ºC/year (Table 5); with negative trends ranging from 0.01 to 0.05 ºC/year identified at Zwarah, Ghadames, Hon, Al-Jaghbub and Al-Kufrah, with significant decreases at Musratah (0.001) and Jalo (0.05).

Suggested Location of Table 5

4.2 Decadal variations of maximum and mean average temperature

Daily data

To examine the characteristics and distribution of the daily maximum and mean average daily temperature at the nine coastal stations during the period 1961-2009, analyses of the daily 11-day maximum and mean average temperature was undertaken with comparison over 10-year intervals; 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2009 (only nine years of daily data are available, as the data for 2010 is currently unavailable).

The maximum summer temperature during days 170-270 of the year, for the 10-year intervals has increased rapidly over the study period, with notable increase during the period 2001-2009 at most stations: Tripoli Airport, Musratah, Sirt, Ajdabyia, Binina, Shahat and Darnah (Figure 3). A similar pattern is also present in the mean average temperature days 170-270, with gradual increases over the 10-year intervals, and a rapid increase in the period 2001-2009 at all stations within this study, particularly Tripoli Airport Ajdabyia, Binina and Shahat (Figure 4).

Suggested Location of Figure 3 & 4

Monthly data

Monthly temperature data are used to examine the characteristics and distribution of decadal maximum and mean average temperature for the inland stations during the period 1951-2009. Analyses of the monthly maximum and mean average monthly temperature for six inland stations was undertaken with comparison over 10-year intervals: 1951-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2009 (only nine years of data available). The annual maximum temperature at inland stations fluctuated during the period 1951-2009 with maximum spring temperature (March, April and May) much higher for the period 2001-2009. The south-western stations (Ghadames and Sabha) July-October temperatures were much higher during the last decade (2001-2009) than for the south-eastern stations (Hon, Jalo and Al-Jaghbub; Figure 5). The mean average annual temperature of the inland stations has fluctuated over the period 1951-2009; with temperatures during the months March-October increasing rapidly, with much higher temperatures over the period 2001-2009 at all stations (Figure 6).

Suggested location of Figure 5 & 6

5. Discussion

In this work, time series of daily, monthly, seasonal and annual maximum and mean average temperature data, or subsets of, for the period 1945-2009 (65 years) at 15/18 synoptic stations across Libya are analyzed.

The estimation of differences in mean annual average and maximum temperature for the two study periods (1945-1977 and 1978-2009) at 15 stations across Libya (excluding Al-Garyiat, Ghat and Tazerbou) identifies that the later period is characterized by more rapid warming at all stations for mean average temperature and at nine stations (Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia, Ghadames, Hon, Al-Jaghbub and Sabha) for maximum temperature. Significant increases in maximum temperatures are identified at 13 of the 15 stations for the period 1945-2009; with significant decreases in maximum temperature at seven of 15 stations during the period 1945-1977, and significant increases at 15 stations for the period 1978-2009. This study has identified that maximum temperature has increased at an average rate of 0.012 °C/year during the period 1945-2009 with a rapid warming (0.034 °C/year) for the last 32 years (1978-2009). The rates of change identified above are greater than those previously identified by El-Tantawi (2005), 0.0035 °C/year (1946-2000); are comparable to Jones et al. (1999) of 0.008 °C/year (1950-1993) and contradict the decreases identified by El-Kenawy (2009), -0.0006 °C/year (1951-1999).

Monthly maximum temperature trends identify high rates of increase, ranging between 0.021°C/year (June) and 0.150°C/year (December); with a particularly strong trend identified in September at all stations, with significant increases at 83.2% of stations. The rates of change in monthly maximum temperature vary spatially during the period 1945-2009, with the south-west region experiencing the highest rates of increase in the March-May, and the south-east in June-August for 1978-2009; the cause for this is at present unclear and will require further study, with a higher station density in the inland region required. In February negative changes (-0.038 and -0.001 °C/year) in maximum temperature are identified at 56% of stations, with significant changes identified at Musratah and most eastern stations (Binina, Shahat, Darnah, and Al-Kufrah); this represents a new finding, which may suggest a decrease in the strength of Indian air mass and increasing of Atlantic air mass dominance during the period of study (1945-2009) over Libya.

Mean average annual temperatures showed significant increases at 13 of the 18 stations for 1945-2009, with significant increases at all (18) stations during the last 32 years (1978-2009). This is a result of the mechanism by which mean average temperature is calculated (maximum + minimum/2), as Ageena et al, (2012) has shown significant increases in minimum temperature across Libya during the period 1945-2009 at all stations, at rates greater than identified for maximum temperature within this paper. Decreases in mean average temperature are found at seven of 15 stations, of which two are significant decreases (Musratah and Jalo) at an average rate of -0.003 °C/year during the period 1945-1977, with significant rates of rapid warming (0.048 °C/ year) at all stations during the last 32 years (1978-2009). High rates of mean average seasonal temperature increase (1978-2009) have been identified, 0.016°C/year (winter), 0.023°C/year (spring), 0.028°C/year (summer) and 0.037 °C/year (autumn), with the summer and autumn increases raising concerns for the future. This study has identified that mean average (surface) temperature has increased at an average rate of 0.024 °C/year during the period 1945-2009. The rates of change identified above are higher than those identified by the IPCC (2007), which identified two phases of increasing mean average temperature, 1910-1940 (0.035 °C/decade) and 1970-2005 (0.055 °C/decade). In addition, El-Tantawi (2005), identified increasing mean average temperature, but with low rates of change of 0.014 °C/decade (0.001°C/year) for the period 1946-2000, whilst Jones et al. (1999) identified a rate of 0.062 °C/decade (0.0062 °C/year) during the period 1901-1997.

No evidence is found to relate any of the identified changes directly with maximum temperature and altitude or distance from the sea, these parameters are likely to have a greater influence on other climatic variables e.g. precipitation.

6. Conclusion

The analyses of maximum and mean average temperature observed at 18 meteorological stations across Libya during the period 1945-2009 exposes well-pronounced seasonal and annual patterns, with a warming tendency of both mean average and maximum temperature during both cool and warm seasons. Significant (0.05) increases are identified for maximum daily temperature at four of nine coastal stations and at all (nine) coastal stations for mean average daily temperature during the 1983-2009 period. Significant (0.05) increases are identified at a number (7 of 15) stations for maximum monthly temperature and at all (15) stations for mean average monthly temperature during the period 1978-2009.

A significant increase in maximum seasonal temperature at coastal (inland) stations are identified, with; autumn and spring 67% (67%), summer 45% (67%) and winter 22% (0%), illustrating the stronger trend at inland stations to higher maximum temperatures (1945-2009). Significant increases in mean average seasonal temperature at all coastal (inland) stations are identified, with; autumn 100% (100%), summer 78% (67%), spring 89% (67%) and in winter 78% (50%), illustrating the stronger trend at inland stations to higher mean average temperatures in autumn and summer season (1945-2009).

The trends analysis (1945-2009) shows significant increases in mean average (0.021 °C/year) and maximum temperature (0.017 °C/year). The rates identified within this study are higher than the global average mean average temperature increases identified by the IPCC and support those previously reported for Mediterranean based studies (e.g. Kutiel & Maheras, 1998; Hasanean, 2001; Feidas *et al*., 2004). It also raises an important point of reference for timeframes considered, with differences in trend between the two periods studied.

The comprehensive analysis of a long-term temperature data from 18 synoptic stations across Libya has revealed broad increases in maximum and mean average temperature, though the spatial and temporal rates of change vary. This study has identified significant increases at all locations, with particularly rapid increases in temperature during the last 32 years (1978-2009) at the majority of stations. This research represents an important contribution to current work examining climate variability and change, reflecting an area with limited existing research, where the implications of increasing temperature will be extensive, particularly on human health, rates of desertification, ecosystems, agricultural practice and productivity. The results of this work will help inform decision makers for future environmental management decisions in Libya.

Acknowledgements

This research was funded by the Libyan government as a part of a PhD thesis undertaken at the University of Liverpool. The authors are grateful to the Libyan National Meteorological Centre (LNMC) for providing them with the Libyan meteorological station data.

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Figure Captions

Figure 1: Libya and the distribution of meteorological stations.

Figure 2: a) Annual means 11 day moving averages of the mean maximum daily temperature; b) of the mean average daily temperature of the coastal stations across Libya 1956-2009.

Figure 3: Decadal mean of 11 day moving averages of the mean maximum daily temperature over near decadal windows for coastal stations for the period 1961-2009

Figure 4: Decadal mean of 11 day moving averages of the mean average daily temperature over near decadal windows for coastal stations for the period 1961-2009

Figure 5: Decadal mean monthly maximum temperature over near decadal windows for nine inland stations (1951-2009), with the curves from a separate decadal block.

Figure 6: Decadal mean average monthly temperature over near decadal windows for nine inland stations (1951-2009), with the curves from a separate decadal block.

Table 1: List of the meteorological stations assessed within the study.

Table 2: The mean annual maximum and mean average temperature and daily and monthly data available at 18 synoptic stations assessed within the study.

Table 3: Values of the Mann-Kendall statistic (Q) for monthly precipitation, with statistically significant levels at 15 synoptic stations

Table 4: Values of the Mann-Kendall statistic (Q) for seasonal precipitation, with statistically significant levels at 15 synoptic stations across Libya (1945-2010)

Table 5: Values of the Mann-Kendall statistic (Q) for annual precipitation, with statistically significant levels at 18 synoptic stations across Libya

Table 1

Stations	Latitude (o)	Longitude (o)	Elev. (m) a.m.s.l.	WMO No.	Distance from the sea (km)
Zwarah	32º :53′ N	12 º :05′ E	3	062007	0.8
T. Airport	32 º :40′ N	13 º: 09′ E	81	062010	2.4
Nalute	31º: 52′ N	10 º:59′ E	621	062002	150
Musratah	32º : 19′ N	15 º: 03′ E	32	062016	4.1
Sirt	31º : 12′ N	16 º: 55′ E	13	062019	0.7
Ajdabyia	30 º: 43′ N	20 º: 10′ E	7	062053	8.5
Binina	32 º: 05′ N	20 º: 16′ E	129	062055	19
Shahat	32 º: 49′ N	21º: 51′ E	625	062056	0.5
Darnah	32 º: 47′ N	22 º:35 ′ E	26	062059	1.0
Ghadames	30 º: 09′ N	09 º:42′ E	357	062103	390
Al-Garyiat	30 º: 23′ N	13 º:35′ E	497	062120	150
Hon	29 º: 08′ N	15 º:57′ E	267	062131	240
Jalo	29 º: 02′ N	21 º:34′ E	60	062161	215
Al-Jaghbub	29 º: 45′ N	24 º:32′ E	2	062176	210
Sabha	32 º: 19′ N	12 º:05′ E	432	062124	500
Ghat	25 º: 08′ N	10 º:09′ E	692	062212	900
Tazerbou	25 º: 48′ N	21 º:08′ E	259	062259	700
Al-Kufrah	24 º: 13′ N	23 º:18′ E	435	062271	800

Table 2

Time series	Maximum temperature (°C)					Mean average temperature (°C)				
	Mean annual	Mean daily		Mean monthly		Mean annual	Mean daily		Mean monthly	
		Period Covered	Missing Data (%)	Period Covered	Missing Data (%)		Period Covered	Missing Data (%)	Period Covered	Missing Data (%)
Coastal										
Zwarah	24.5	1956-2009	0.3	1945-2009	0.3	19.9	1956-2009	0.4	1945-2009	0.4
T. Airport	27	1956-2009	0.1	1945-2009	0	20.5	1956-2009	0.1	1945-2009	0
Nalute	24.5	1956-2009	1.5	1945-2009	0.1	19.1	1956-2009	1.6	1945-2009	0.2
Musratah	25.1	1956-2009	1.1	1945-2009	0	20.4	1957-2009	1.3	1945-2009	0
Sirt	25	1956-2009	1.2	1945-2009	0	20.5	1957-2009	1.3	1946-2009	0
Ajdabyia	26.8	1956-2009	0.2	1945-2009	0	20.7	1956-2009	0.5	1946-2009	0
Binina	25.2	1956-2009	0.9	1945-2009	0	19.9	1956-2009	1.1	1945-2009	0
Shahat	20.8	1956-2009	0.6	1945-2009	0	16.5	1956-2009	0.9	1945-2009	0
Darnah	23.4	1956-2009	1.4	1945-2009	0	20.3	1956-2009	1.5	1945-2009	0
Inland										
Ghadames	29.7			1945-2008	1.1	21.9			1945-2008	1.2
Al-Garyiat	27.9			1968-2008	1.5	20.6			1968-2008	1.7
Hon	29.1			1948-2008	0.8	21.4			1948-2008	0.8
Jalo	29.6			1950-2009	1.3	22.5			1951-2009	1.5
Al-Jaghbub	29.4			1946-2008	1.0	20.9			1946-2008	1.1
Sabha	30.3			1948-2008	0.9	22.9			1948-2008	0.9
Ghat	31.8			1979-2007	0.2	24.1			1979-2007	0.3
Tazerbou	30.3			1962-2007	1.4	22.5			1963-2007	1.6
Al-Kufrah	30.7			1946-2007	0.3	23.3			1946-2007	0.5

Table 3

Time series	Temp	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
Zwarah	Max	0.025 +	0.000	0.003	0.025*	0.026+	0.005	0.017	0.024*	0.025*	0.038**	0.026*	0.021 +
	Mean	0.038***	0.026**	0.031***	0.032***	0.032***	0.017**	0.032***	0.042***	0.042***	0.052***	0.036***	0.035***
T. Airport	Max	0.016	0.000	0.016	0.014	0.020	0.008	0.026*	0.014	0.020+	0.046**	0.014	0.017
	Mean	0.014	0.006	0.022*	0.021*	0.024*	0.006	0.029**	0.029**	0.025**	0.038**	0.019*	0.015+
Nalute	Max	0.033*	0.0004	0.015	0.016	0.015	0.004	0.017	0.012	0.007	0.038*	0.022+	0.019
	Mean	0.038**	0.013	0.028*	0.024*	0.017	0.014	0.024*	0.026**	0.020*	0.050***	0.026*	0.027*
Musratah	Max	-0.013	-0.021 *	0.007	0.011	0.003	-0.025 **	-0.015	-0.010	0.002	0.014	-0.008	0.000
	Mean	0.007	0.002	0.013	0.006	0.004	-0.013+	-0.001	0.005	0.013+	0.022*	0.011	0.013+
Sirt	Max	0.005	-0.006	0.020+	0.025 **	0.018	0.007	0.019*	0.024**	0.038***	0.026*	0.010	0.015
	Mean	0.012+	0.001	0.015+	0.017**	0.015+	0.008	0.020*	0.023***	0.037***	0.027**	0.014	0.012*
Ajdabyia	Max	0.022*	0.000	0.019	0.021*	0.017	0.011	0.026***	0.031***	0.04***	0.02	0.01	0.02
	Mean	0.020**	0.008	0.018+	0.016*	0.021*	0.017*	0.030***	0.040***	0.045***	0.023*	0.016+	0.016*
Binina	Max	0.002	-0.021 *	0.000	-0.007	-0.011	-0.014	-0.006	-0.006	0.010	-0.006	-0.014	0.000
	Mean	0.012+	0.001	0.017	0.009	0.009	0.006	0.001+	0.011+	0.026***	0.018+	0.005	0.014*
Shahat	Max	0.003	-0.024 *	0.007	0.007	0.006	0.003	0.014*	0.008	0.023 **	0.016	-0.011	0.000
	Mean	0.009+	-0.009	0.011	0.013	0.001	0.006	0.020**	0.014*	0.023**	0.020+	0.003	0.000
Darnah	Max	0.002	-0.021 *	0.003	0.002	0.000	0.002	0.003	0.001	0.017*	0.010	-0.010	0.000
	Mean	0.009+	-0.001	0.008	0.011	0.021**	0.014*	0.014*	0.013*	0.020**	0.022**	0.001	0.012
Ghadames	Max	0.018	0.003	0.018	0.025+	0.031*	0.003	0.016	0.029**	0.022+	0.041**	0.021	0.008
	Mean	0.017	0.009	0.029*	0.022*	0.035**	0.008	0.032**	0.050***	0.041**	0.041**	0.034*	0.021+
Hon	Max	0.010	-0.007	0.025	0.026 **	0.025*	0.004	0.020+	0.033	0.043 **	0.036*	0.010	0.011
	Mean	0.022	-0.012	0.017	0.031	0.028+	0.003	0.085***	0.070***	0.089***	0.100***	0.076**	0.039+
Jalo	Max	-0.013	-0.025	-0.022	0.001	0.006	-0.006	0.009	0.013+	0.032 *	0.000	-0.011	-0.014
	Mean	0.022	-0.012	0.024*	0.019*	0.024	0.008	0.033**	0.046***	0.078**	0.019**	0.074	0.037+
Al-Jaghbub	Max	0.015	-0.001	0.009	0.011	0.008	0.008	0.020	0.016*	0.043*	0.013	0.009	0.012
	Mean	0.013+	0.000	0.001	0.001	0.007	0.006	0.030***	0.015+	0.047***	0.013	0.004	0.006
Sabha	Max	0.006	-0.002	0.007	0.031 **	0.019+	0.015	0.025*	0.031 **	0.043 **	0.025+	0.007	0.019
	Mean	0.020	0.006	0.029*	0.035**	0.040**	0.017+	0.034**	0.053***	0.051**	0.041**	0.021	0.027+
Al-Kufrah	Max	-0.009	-0.038	-0.015	0.007	0.000	-0.014	0.009+	0.003	0.023+	-0.009	-0.012	-0.007
	Mean	0.019*	0.010	0.021+	0.043***	0.029*	0.022**	0.038***	0.026**	0.046***	0.021+	0.028*	0.021*

For significant trends (***), if trend at a = 0.001 level of significance (**), if trend at a = 0.01 level of significance (*), if trend at a = 0.05 level of significance and + if trend at a = 0.1 level of significance

Table 4

		Autumn		Winter		Spring		Summer	
Time series	Temp	Sig	Q	Sig	Q	Sig	Q	Sig	Q
Zwarah	Max	**	0.028	*	0.017	**	0.030		0.006
	Mean	***	0.045	***	0.036	***	0.029	***	0.031
T.Airport	Max	**	0.027		0.011	**	0.031	*	0.014
	Mean	***	0.025		0.008	**	0.021	***	0.025
Nalute	Max		0.007		-0.008		0.001		-0.005
	Mean	***	0.031	**	0.023	*	0.019	***	0.027
Musratah	Max	**	0.025		0.011	**	0.027	**	0.024
	Mean	+	0.014	+	0.009		0.006		-0.005
Sirt	Max		-0.001	+	-0.013		-0.001	**	-0.023
	Mean	***	0.028	+	0.008	**	0.017	***	0.018
Ajdabyia	Max	**	0.023		0.001	**	0.021	*	0.013
	Mean	***	0.030	***	0.015	***	0.021	***	0.027
Binina	Max	***	0.025	*	0.013	***	0.029	**	0.021
	Mean	**	0.017	*	0.010	*	0.013		0.007
Shahat	Max		-0.003		-0.006		-0.006	*	-0.012
	Mean	**	0.015		0.011	*	0.014	*	0.012
Darnah	Max	+	0.012	+	-0.011	+	0.007		0.005
	Mean	***	0.018	*	0.008	**	0.016	**	0.016
Ghadames	Max	**	0.028		0.011	**	0.031	**	0.019
	Mean	***	0.044		0.014	***	0.028	***	0.038
Hon	Max	***	0.032		0.005	***	0.026	*	0.016
	Mean	***	0.047	***	0.025	***	0.043	***	0.044
Jalo	Max		0.005	+	-0.013		0.011		0.008
	Mean	+	0.018		0.004		0.001	*	0.014
Al-Jaghbub	Max	***	0.031		0.010	***	0.003	***	0.022
	Mean	***	0.025		0.007		0.003	**	0.019
Sabha	Max	***	0.032		0.010	***	0.031	***	0.021
	Mean	***	0.036	*	0.019	***	0.031	***	0.033
Al-Kufrah	Max		0.005		-0.012		0.014		0.005
	Mean	***	0.033	*	0.017	***	0.029	***	0.031

Table 5

Time series		1945-2009		1945-1977		1978-2009	
	Temp	Sig.	Q	Sig.	Q	Sig.	Q
Zwarah	Max	***	0.020		-0.021	***	0.054
	Mean	***	0.029		-0.010	***	0.069
T.Airport	Max	***	0.018		-0.012	*	0.041
	Mean	**	0.021		-0.001	***	0.040
Nalute	Max	***	0.021		-0.014	***	0.054
	Mean	*	0.023		0.010	***	0.052
Musratah	Max		-0.007	**	-0.047	***	0.048
	Mean		0.006	***	-0.045	***	0.076
Sirt	Max	***	0.016		0.010	***	0.052
	Mean	**	0.017		0.010	***	0.046
Ajdabyia	Max	***	0.018		0.020	+	0.052
	Mean	***	0.021		0.012	***	0.052
Binina	Max	+	-0.008		0.010		0.016
	Mean	*	0.013		0.004	***	0.046
Shahat	Max		0.002	+	0.019		0.010
	Mean	*	0.021		0.013	*	0.024
Darnah	Max		-0.001		0.000	*	0.021
	Mean	**	0.016		0.024	***	0.046
Ghadames	Max	***	0.020		0.000	*	0.034
	Mean	***	0.028		-0.011	**	0.036
Al-Garyiat						+	0.033
						**	0.040
Hon	Max	***	0.014		-0.010		0.029
	Mean	***	0.043		-0.014	***	0.048
Jalo	Max	*	-0.009	***	-0.054	+	0.030
	Mean		0.010	*	-0.022	***	0.044
Al-Jaghbub	Max	**	0.019		0.023	***	0.051
	Mean		0.003		-0.010	***	0.047
Sabha	Max	**	0.024		0.019	***	0.041
	Mean	***	0.031		0.014	***	0.053
Ghat						*	0.043
						**	0.024
Tazerbou						**	0.038
						***	0.072
Al-Kufrah	Max		-0.004		-0.028	***	0.045
	Mean	***	0.029		-0.010	***	0.065

Figure 1
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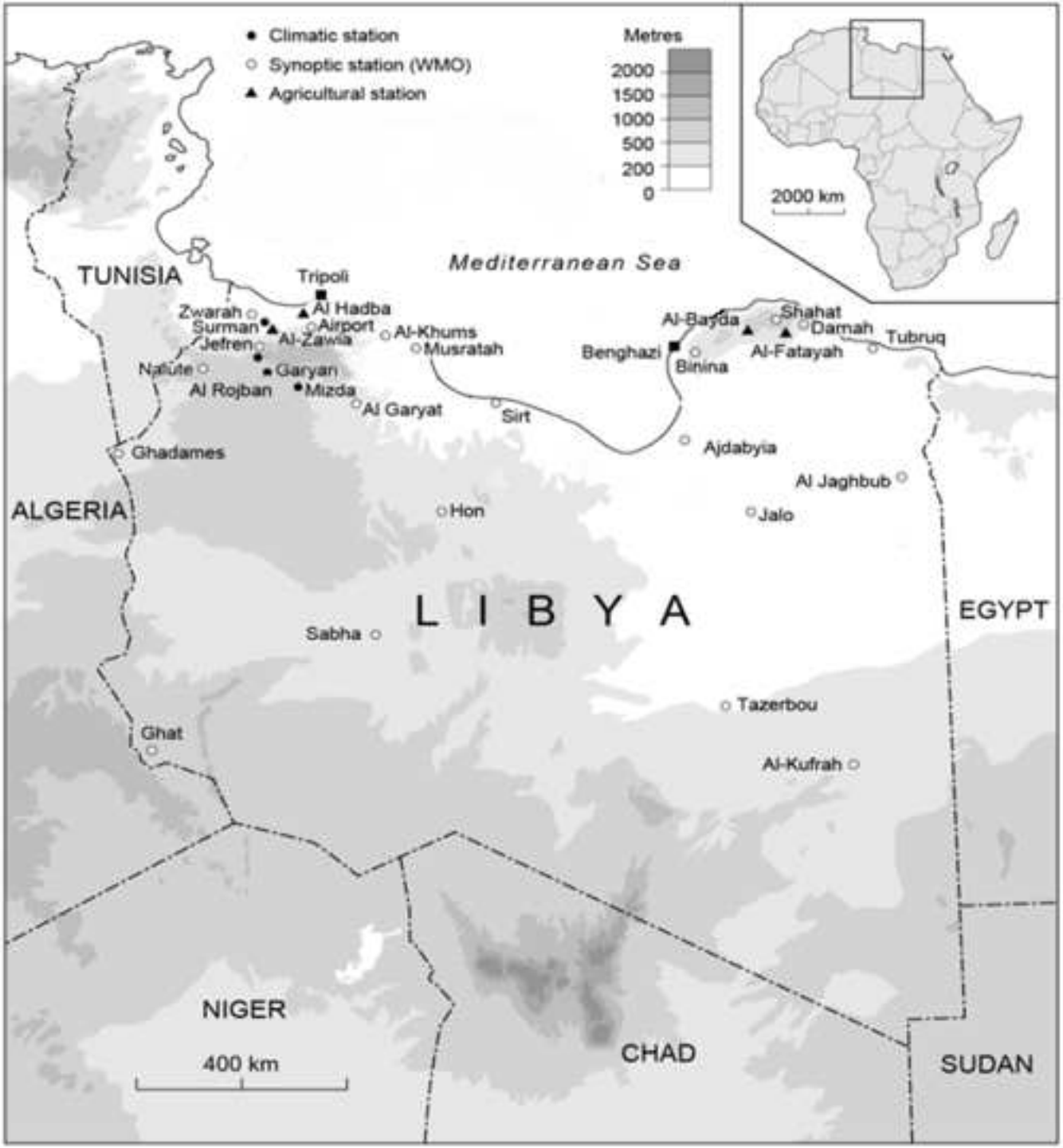

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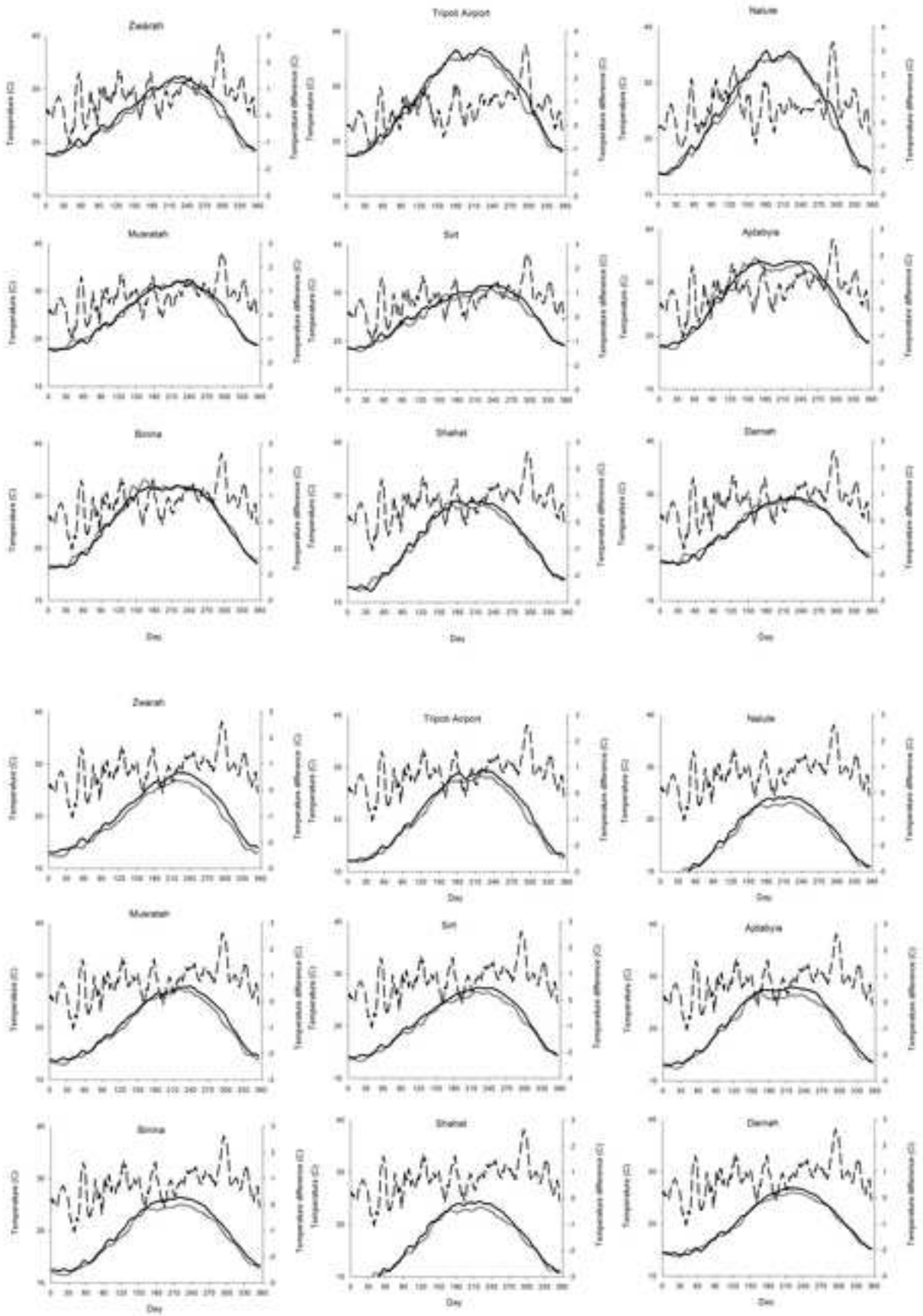

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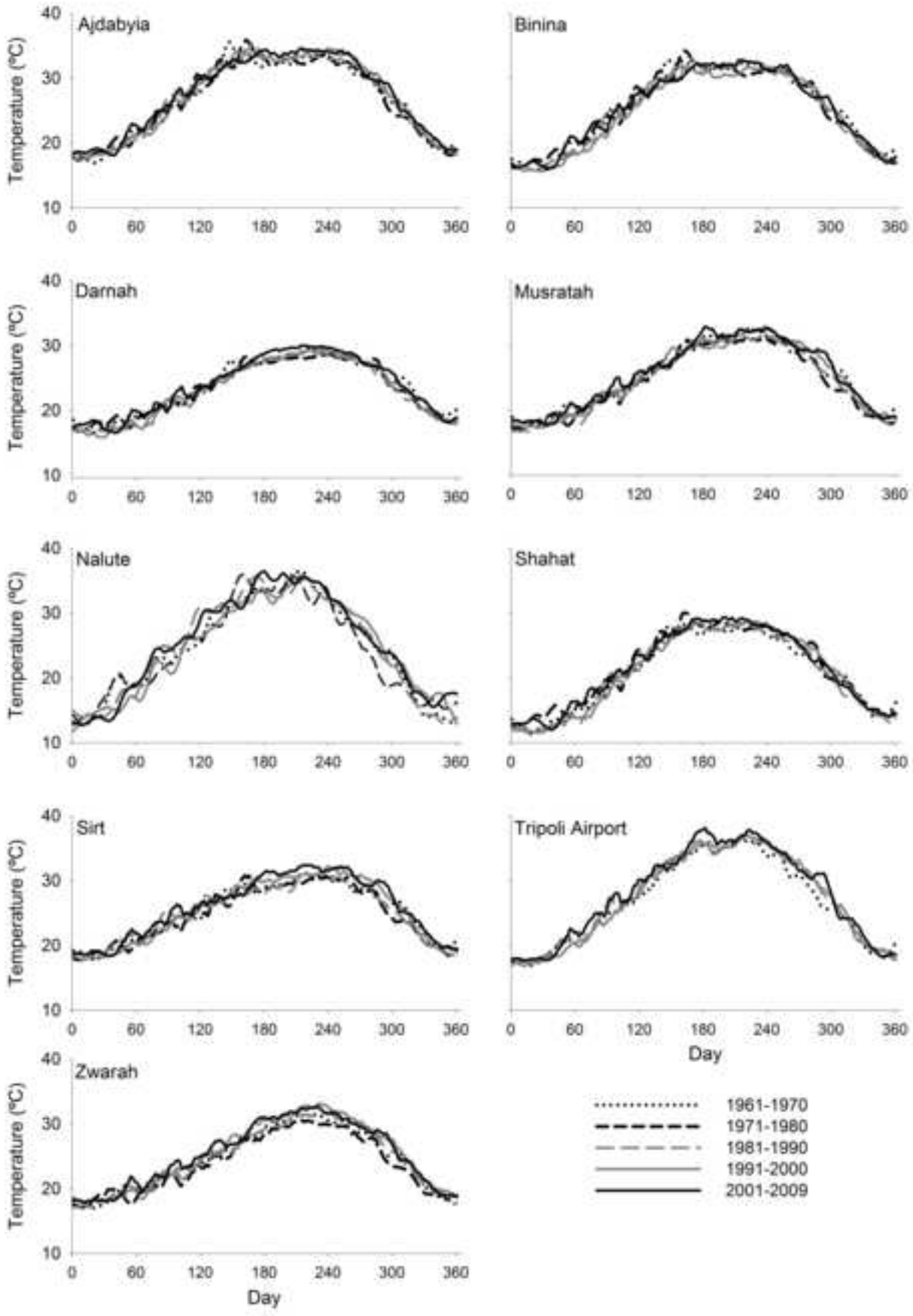

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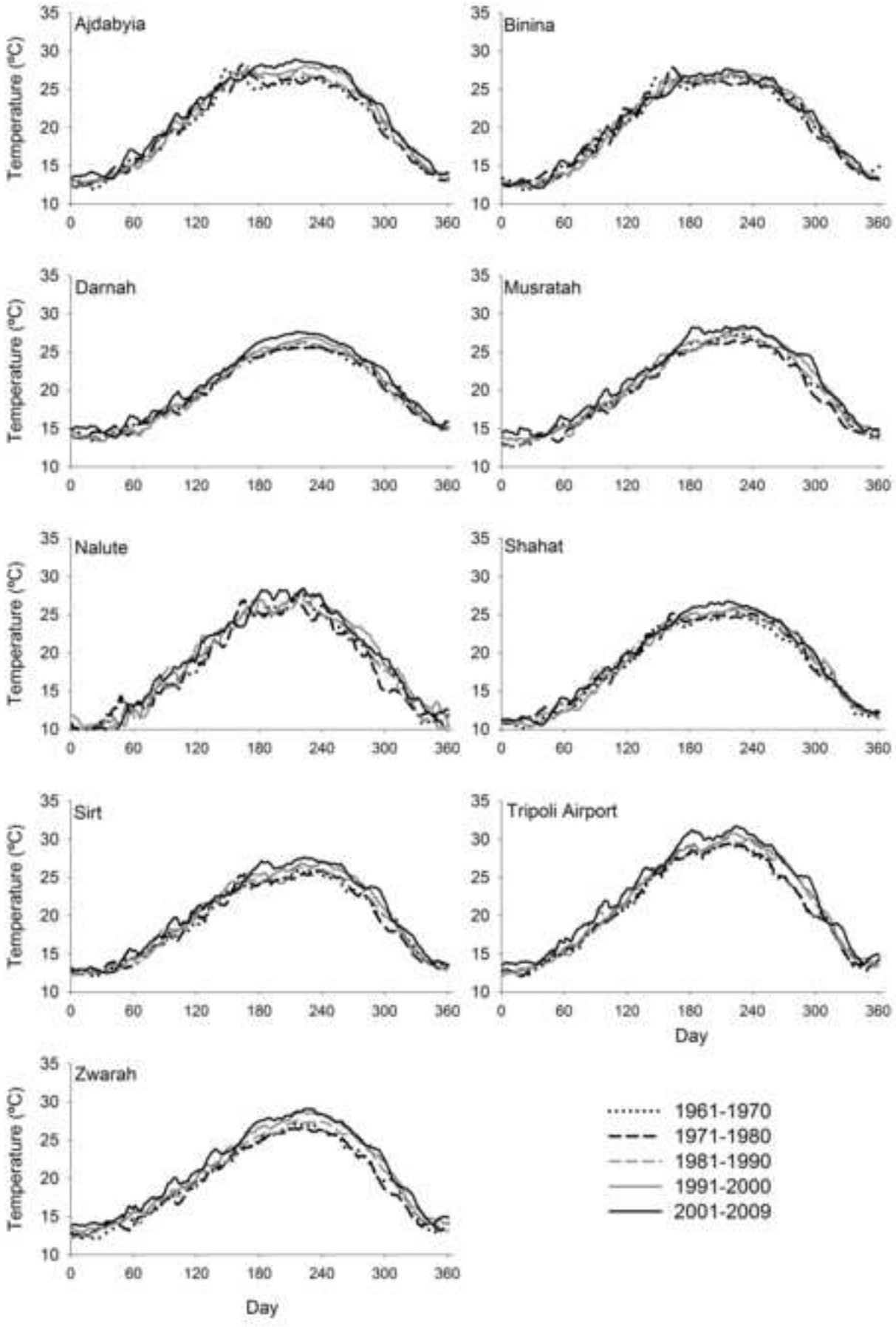

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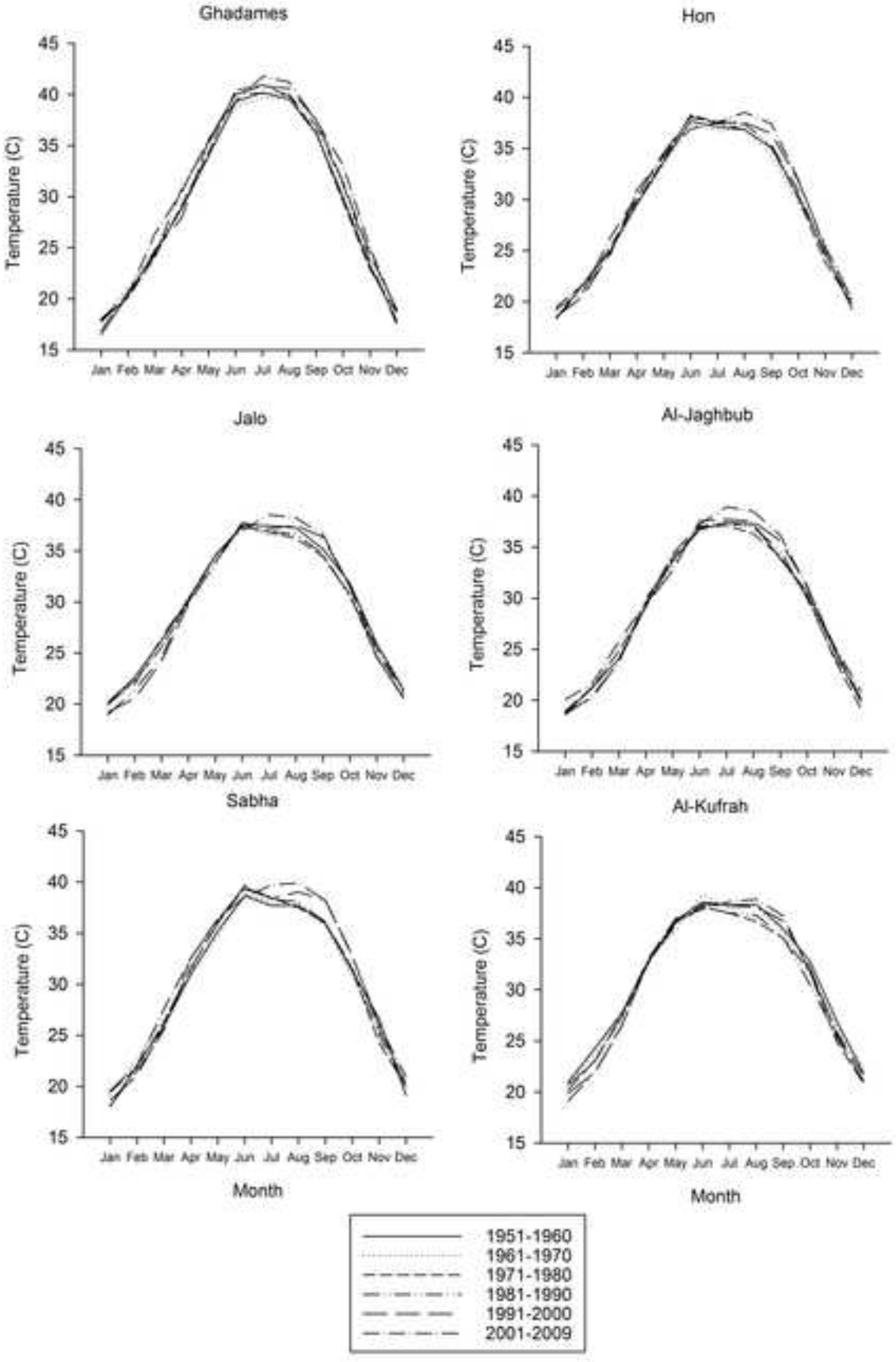

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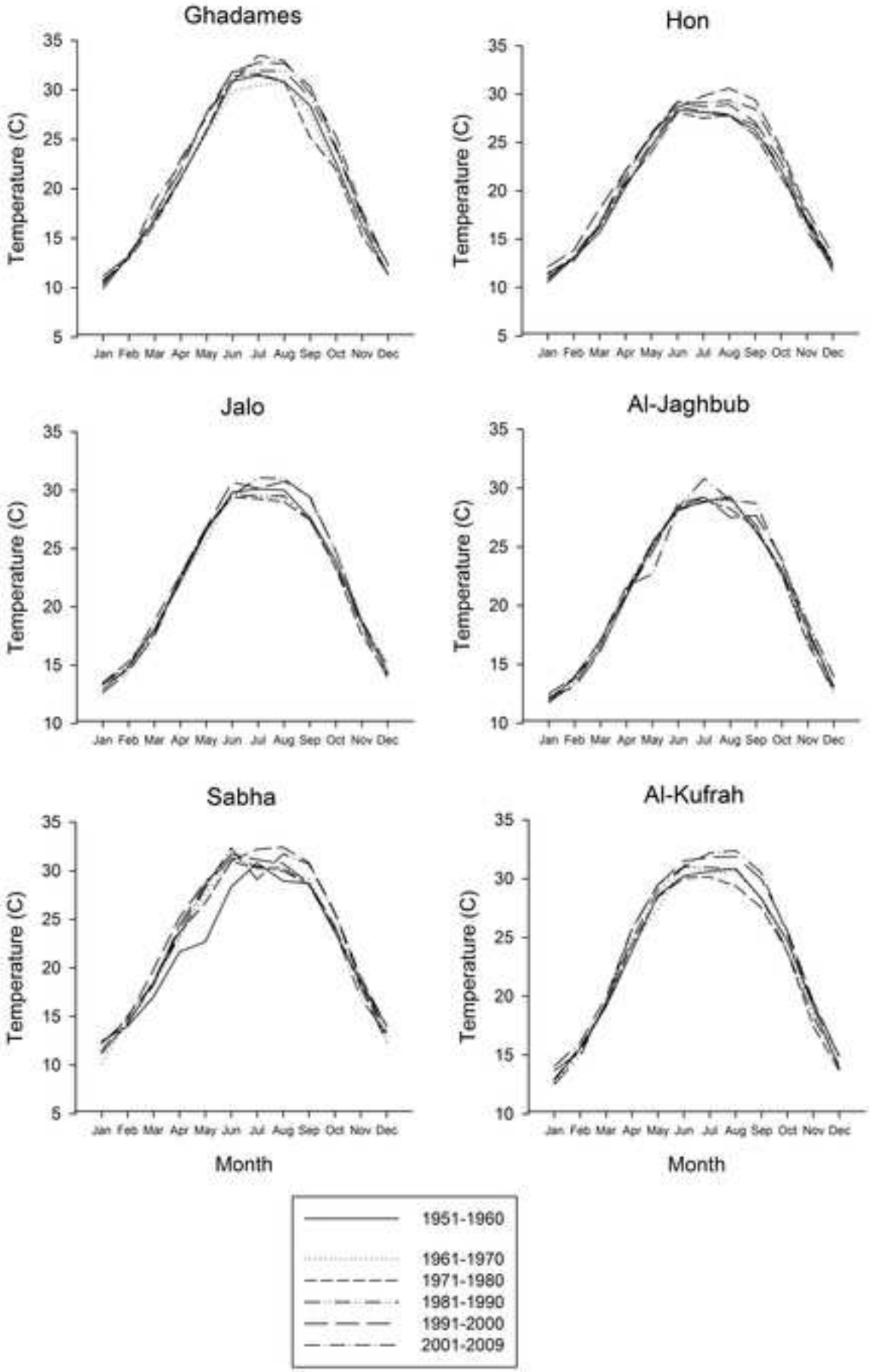

Table; Reviewer Comments and our responses

No.	Reviewer Comments	Our Response
1	The trends differ considerably from period to period. It is not possible to analyse the spatial variability of trends calculated for different periods. It should be improved and the analysis should be made on common period or some stations should be excluded from some parts of analysis.	The removal of stations from the analysis, or restriction of the analysis to only the period including all data would limit the available datasets considerably, we have added a line into the discussion drawing the reader to the fact that all stations are used and that there are some different timeframes with the exception of three stations, which are removed from the analysis (Al-Garyiat and Ghat and Tazerbou), we have also clearly stated this in the methodology section (e.g. Table 1), but that the fact this study is using all available data for analysis is highlighted and provides considerable advancement in current understanding for this region of N. Africa is important. We also identify that the shorter series follow the trends of the longer series during comparable periods.
2	There are four objectives of the paper defined at the end of introduction. There is no discussion on any associations between temperature and altitude or distance from the sea (only the difference between coastal and inland stations).	Accept – a short paragraph has been inserted into the papers discussion clarifying this.
3	It is not clear why the decadal variations are analysed on the ground of daily data for coastal stations and monthly for inland stations. It makes both analysis and comparison more difficult. Figures 3-6 in the form of bar graphs (six bars for each month) could be more informative.	Accept – a short paragraph has been inserted into the papers method 2.3 (first paragraph) clarifying this. This has also been clarified throughout the paper.
4	The changes on the background of standard deviations would be more legible.	We are unclear as to what the reviewer is asking in this point, as we do not present standard deviations on any figures and these are clearly labelled within the text using the convention of +,*,**,*** for different degrees of significance.
5	The discussion of results is poor.	We appreciate the reviewers comment and have improved this section

6	A language should be improved.	Corrections have been made and improvements added were required.
7	Page 5 lines 25-30. The details of record length and resolution are not included in Table 1, they are in Table 2	Accept –this has been clarified by providing a link to Table 2 in this sentence.
8	Page 6 lines 53-60. The Ghat record is much shorter than the others. The data for Ghat are only for the second, warmer period. Because of this the Ghat means are higher than the other. When the range of mean average annual (not monthly as is in the text in line 53) temperature is considered the Ghat station is excluded, but when the range of average annual maximum is considered the Ghat station is taken into account (31.8°C). Why? Reference to table 2 should be made after the first sentence, when the annual values are presented. The monthly values are not presented in this table.	Accept – we appreciate the reviewers comment and the correction has been made to this paragraph. Whilst we believe the inclusion of shorter series are beneficial in some sections, we accept that comparison between periods may be compromised by the shorter series, as such we have removed the shorter series from some sections of the analysis, this is clearly articulated in these sections.
9	Page 7 lines 7-9, the coefficient of variation can be a valuable measure of degree of variation not a statistical test	Accepted, statistical test deleted
10	Page 7 lines 40 page 8 line 2 the differences both series are not well seen on fig. 2. The series of differences should be added to figure 2 with additional scale on the right side. At the moment it is not clear that mean temperature in the second period is significantly higher, especially at Binina.	New graphs of maximum and mean average temperature with a line showing the of differences between values have been inserted (Fig.2)
11	Table 3, the description is not good. The unit of Sen's slope is not indicated. Is it per year or per decade, both units are used in the text. The Mann-Kendall Q test is not shown at all, only some indication on statistical significance, but it is not the same. It table description a period 1945-2009 is mentioned, but some stations have much shorter records. It should be indicated, especially when it was mentioned that the trends in the first 27 year period are quite different than in the second one.	Accepted - all the table headings have been improved and now clearly state the table contents Accepted - all the table headings have been improved and now clearly state the table contents The shorter series are removed from this analysis between periods.

12	Page 8 line 42, the range of trends from 0.002 to 0.15 (why different number of digits?) is mentioned, but the real range in the table is from 0.002 to 0.25 (Ghat). There is no station with trend equal 0.15. Trend 0.25°C/year and more than 60 years make a change of 15 degrees. Is it really happened? At Al Garyiat the trend is 0.13°C/year. It is almost 8 degrees during 60 years. Both stations have much shorter records. Is it possible to compare trends?	The range in Table 3 is from 0.001 (May: Shahat and July: Binina) to 0.100 (October: Hon) Accepted Tables 3,4 & 5 all now present 3 d.p. Accepted; Ghat, Tazerbou and Al-Garyiat have been deleted from monthly and seasonal as well as long-term annual analyses
13	Page 9 lines 7-9. Two periods 1945-1977 and 1978-2009 are being compared in this section. The remark concerning what has happened since the mid 1980s is unfounded at this place.	Accepted the (Mean monthly maximum and mean average monthly temperature has increased at all stations since the mid-1980s)~~.~~ has been deleted, this was a remnant from an earlier draft with a figure that showed this which was subsequently removed.
14	Table 4, the description is not good. It is not clear what the Z test mean (is it a Mann Kendall test?); "sig" is not described, Q being mentioned after Mann - Kendall test, is probably the Sen's slope. "Clim" probably represents mean temperature, but it is mentioned at all.	Titles and contents of tables 3,4,5 have been changed, all Clim replaced by mean.
15	Page 9 lines 27-57, when ranges are described, the highest trends appeared in all seasons at Ghat, the station with much shorter record. You should not compare trends in different periods, especially if you presented in the previous paragraph that they are completely different. It is crazy.	Accepted, Ghat, Al-Garyiat and Tazerbou are excluded from long-term trend analysis monthly and seasonally
16	Table 5 - the same comments as for table 4. Additionally there is not allowed to show a long term trends in Ghat, when you have only data for a shorter period. The records for Al-Garyiat and Tazerbou are also shorter and they should be excluded from long-term trend analysis. At Binina the positive trends appear in both shorter periods but the long-term one is negative. How is it possible? Is it an abrupt change at the beginning of second period?	Accepted – see previous comments. Accepted, Ghat, Al-Garyiat and Tazerbou are excluded from long-term trend analysis, seasonally and monthly, they are now only included in the analysis o the period 1978-2009, and are not included in any comparison to earlier periods. Yes, it is an abrupt change at the start of the second period, we thank the reviewer for commenting on this and a comment has now been added to the paper to reflect this unusual result.

17	Page 10 line 10-page 11 lines 4, the trends from different periods cannot be discussed together.	The three shorter series have now been removed from the analysis on Page 10 line 10 for Maximum temperature (increases are identified at 10 stations during the period 1945-2009) Page 11 line 4 for Mean average temperature (significant increases (Table 5) at 14 of the 18 stations at a 0.001 and at Al-Garyiat, Ghadames (0.01) and Shahat (0.05). This includes the 18 stations. The use of 15 or 18 stations is clarified throughout the text and no comparison is made between time periods without first removing the 3 shorter series (see line in Discussion section)
	Page 11 lines 13-39 and figures 3 and 4. The conclusion that the last period was the warmest is not justified well. May be the numbers of figures 3 and 4 are changed, because for me it is clearer that the mean temperature is the highest in the last period during days 170-270 (fig 4) than for the maximum temperature (fig. 3).	Because of small size of graphs with limited number pages
18	Figures 5 and 6, May be differences between periods can be better seen on bar graphs Page 11 line 47 - page 12 line 10. All increases mentioned in the text are not well seen on the pictures. Especially rapid increases from March to October (page 12 lines 7-8). On figures 5 and 6 the increases in late summer and early autumn can be distinguished but not in spring.	We had explored the possibility of using bar graphs previously, but felt this presented the data in a poorer format. We removed three stations and this helps more clearly illustrates the points made in the text.

19	Page 12 lines 12 - page 13 lines 13, the discussion is chaotic and imprecise. The global trends are mixed with those obtained for Libya. The units change from sentence to sentence, so the understanding of text is made difficult. The trends obtained on the ground of longer periods are mixed with those obtained on the ground of the shorter ones. What does it mean "decreasing strength in the Indian air mass"?	This section has been restructured to improve these issues, with more concise sentences. Accepted, units have been standardised (C°/year) Sentence reworded
20	Page 13 line 58, Significant increases are at all (nine) inland stations (not coastal as it is in the text).	The text is correct, both relate to coastal stations, the first max daily the second mean daily.
21	Page 14 lines 21-30. Comparison of trends calculated for different regions and periods. Previously described trends were both positive and negative, how the present study can support all of them?	We are unclear whether the reviewer means our results or the research we have referenced to. This paper identifies that the early period of records identified a large number of negative trends compared to the later period, during which all stations show a positive trend. The differences identified to previous research differs mainly in rates of change, this in part may be explained by the period of study, number of stations and the length of records used in this study (greater number of years of data within this study), compared to previous studies.