Trends and patterns in the climate of Libya

(1945-2010)

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Philosophy

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This work is dedicated to the

soul of my mother, father mother-in-law and nephew Salah

DECLARATION

I hereby declare that the following thesis is based on the results of investigations conducted by myself, and that this thesis is of my own composition. This thesis has not, in whole or part, been previously presented for a higher degree. Work other than my own is clearly indicated in the text by reference to the relevant researcher or publications.

Ismail M. Ageena

The work presented in this thesis is the work of the candidate Ismail Massoud Ageena. Conditions of the relevant ordinance and regulations have been fulfilled.

Professor: Andy Morse

Dr: Neil Macdonald

The research work was undertaken at the Department of Geography and Planning, School of Environmental Sciences, University of Liverpool.

ABSTRACT

Trends and patterns in the climate of Libya (1945-2010)

Ismail Massoud Ageena

Climate change is one of the most important issues affecting the world at the beginning of the twenty-first century. This thesis explores changes and trends within the principal climatic parameters temperature for 18 synoptic stations, precipitation for 28 meteorological stations and 16 synoptic stations for evapotranspiration *inter alia*, during the last 66 years (1945-2010) across Libya. Eighteen meteorological stations were selected along the Mediterranean coast where ten inland stations were selected from the North and South Sahara regions. The study period of temperature is divided into two series of equal length (27 years), 1956 to 1982 and 1983 to 2010 are used to assess and provide comparison in rate of change.

Significant increases in temperature are identified, with particularly rapid increases in minimum temperature (0.032 °C a^{-1}; 1945-2010). The rates and periods of change are variable across the study period, with a number of stations documenting declining temperatures during the early phase, with significant increases during the second half of the period, while a mix of increasing and decreasing trends in extreme temperature during the last 50 years (1961-2010) are identified. Precipitation was assessed at 16 stations across Libya (1961-2010), with variable results and no clear pattern emerging for Libya as a whole for the total period, though evidence of a decrease in annual total precipitation (-1.95 mm a^{-1}) is found during the second period. Extreme events as consecutive dry days (<1.0 mm d^{-1}), consecutive wet days (≥1.0 mm d^{-1}) and number of precipitation day (≥0.1 mm d^{-1}) were becoming more frequent during the last 33 years (1978-2010). Increasing trends in potential and actual evapotranspiration are found across Libya.

The reanalyses data are applied to compare the results from two commonly used reanalysis datasets, with the station data used to examine the reliability of the gridded products and for the station data to estimate the missing and unreliable data.

A comparison of the observed climate data (temperature and precipitation), with reanalysis data from two commonly used datasets NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010) identified a generally good agreement for temperature, but poorer representation in precipitation datasets, with stations at higher altitudes witnessing a decrease in the reanalysis data accuracy. The implications of this research are far reaching, impacting on the management and provision of water resources, agriculture and societies.

Chapter 1

INTRODUCTION

The purpose of this chapter is to introduce the key themes within this thesis, contextualise the research and present the aims and structure of the thesis.

1.1 INTRODUCTION

There are over 11,000 weather observation stations around the world measuring different weather and climatic parameters over land and sea, as well as satellites, ships and aircraft that also take measurements. According to the World Meteorological Organization (WMO), a large volume of monthly temperature, precipitation and air pressure data from meteorological across the globe have been taken since the late Seventeenth century.

During the late 20th century, natural scientists have increasingly focused on climate change and its implications on the environment. The first World Climate Conference (1979), led to the establishment of the WMO World Climate Programme, followed by the second conference in 1990. The Intergovernmental Panel on Climate Change was initiated in 1988, and published its first four assessment reports in 1990, 1995, 2001 and 2007 respectively; a firth report will be published in 2013. An increasing public awareness of the dangers of pollution in the 1950s coincided with the first evidence of warming temperatures. By the mid-1970s, increasing evidence of human activity influencing the global climate emerged (McMichael et al., 2003).

1.2 THE CLIMATE OF LIBYA

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) within which roughly 90.8% of the area is hyper-arid, 7.4% arid, 1.5% semi-arid and 0.3% is classified as sub-humid (Ben-Mahmoud 1993); with the sub-humid region located in northeast Libya near the cities of Shahat and Al-Bayda (Fig. 1.1). Topography is generally free of steep terrain, with the exception of two regions in the north-west and north-east where the elevation ranges from 500 to ~1000 m above mean sea level (a. m. s. l: Al-Haram 1995). The shoreline extends for roughly 2000 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 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 characterized by hot and dry summers with high summer temperatures. The mean annual temperature in the coastal region of Libya ranges from 14.2 °C (Shahat) to 21.0 °C (Tripoli Airport) and at stations in the interior region (inland) between 21.3 °C (Al-Garyiat) to (Ghat) 23.4 °C (1945-2009). Libya is one of the driest countries in the world, with mean annual rainfall along the Libyan coast ranging between 140 and 550 mm and rarely exceeds 50 mm in the interior region (1945– 2010). December and January are the wettest months, with the six months of October - March receiving 87.1% of the total annual precipitation (Ahmed, 2002). The majority of rainfall occurs in the winter season (DJF), with the rainy season beginning in September-October and ends in March-April.

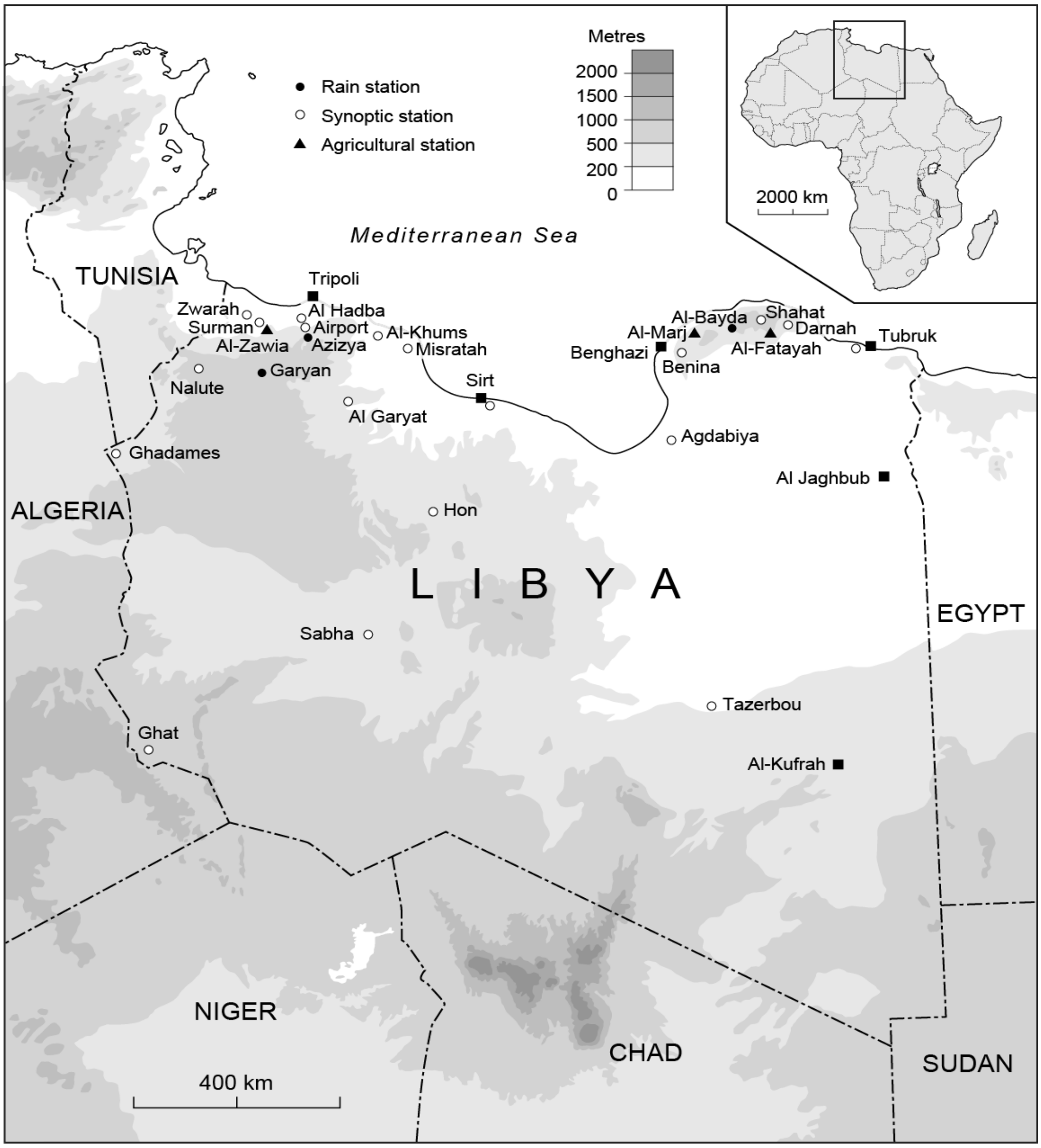


Fig. 1.1: The distribution of meteorological stations across Libya.

1.3 CLIMATE AND CLIMATE CHANGE

Climate refers to the average weather experienced typically over a 30 year period, and can consist of a variety of parameters e.g. temperature, precipitation, humidity, wind, air pressure and dew point temperature. The climate has changed many times during the history of our planet **(**Pidwirny, 2006), as a result of three principal factors:

i. natural events which have changed the climate, either locally, regionally or globally, such as volcanic eruptions,

ii. the amount of energy released from the sun; and,

iii. in response to human activities.

1.3.1 Global climate change

The last four decades have witnessed extensive research concerning climatic fluctuations and trends of climatic parameters in different regions and for different time periods. A large number of studies have examined trends and variability of climatic parameters through a wide range of spatial and temporal scales, from the global to the local (e.g. Jones et al. 1999; Easterling et al. 1999; Hansen et al. 2007; Giannini et al., 2008; Giorgi and Lionello, 2008; Tayanc et al., 2009).

According to the Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007), the global surface temperature has increased by 0.74 °C ± 0.18 °C (the mean values calculated from 1906-2005) and precipitation has risen north of 30° N (the mean values calculated from 1906-2005), with strongest downward trends in precipitation observed in the Sahel region of African occurring during the period 1950-2005. These tends support the predictions of temperature increases made by the National Oceanic and Atmospheric Administration (NOAA), that global warming during the last 25 years has increased at a rate of about 0.02 °C a^{-1}. The 20th century was the warmest century during the past 1000 years, with rapid changes over Libya in the last 40 years (El-Tantawi 2005), with temperature increases identified in many regions throughout the world (Repapis and Philandras 1988; Karl et al 1993; Jones et al., 1999; Hulme et al 2001; Alexander et al 2006; Domonkos and Tar, 2003; Hansen et al, 2007; IPCC 2007). The United Nation Framework Convention on Climate Change (Parry et al., 2009) estimated that annual spending adapting to some of the worst impacts of climate change could be $49-171bn in developed countries and $22-105bn in developing countries by 2030.

1.3.2 Climate change across North Africa and the Mediterranean

Libya is of particular interest as it includes areas which experience both a Mediterranean and North Africa climate, and is in a region where human occupation and lifestyle are highly susceptible to climate change. Over the last 20 years a small number of studies, have considered the climate of Libya; particularly temperature and precipitation, with the findings identifying conflicting patterns and rates of change in temperature and precipitation (e.g. Lama, 1996; Zikree 1998; Ahmed, 2002; Massoud 2004; El-Tantawi, 2005; El Kenawy et al., 2009; Ageena et al., 2012; Ageena et al., 2013).

A large body of research has been undertaken on Mediterranean and North Africa climate variability particularly focused on temperature (e.g. Repapis and Philandras 1988; Nasrallah and Balling 1993; Ben-Gai et al. 1999; Hasanean 2001; Goubanova and Li, 2007; Bartolini et al 2008; Hatzianastassiou et al., 2008; Dousset et al., 2011; Yu et al., 2011; Boccolari and Malmusi, 2013) and precipitation (Goubanova and Li, 2007; Hatzianastassiou et al., 2008; Caloiero et al., 2011; De Luis, 2009; Reiser and Kutiel, 2011; Unal et al., 2012), with most identifying a general decrease in precipitation across the Mediterranean basin; these changes in precipitation patterns have drastically reduced food production capacity and increase the likelihood of short-run crop failures and long-run production declines (Parry et al., 2004)

A number of studies have identified that climate change could significantly modify existing water resources and balance in the: USA (Loáiciga et al 2000; Croley et al., 2003), Australia (Ducci et al., 2008; Ali et al., 2012), Europe (Eckhardt and Ulbrich, 2003), Africa (Brown et al., 2011) and across the Mediterranean (Ceballos-Barbancho et al., 2008; Polemi and Casarano 2008), with increasing temperature and decreasing precipitation directly and indirectly affecting many factors including groundwater budgets (Loaiciga et al., 2000).

Agriculture is extremely vulnerable to climate change across the Mediterranean; with higher temperatures potentially reducing yields of important crops. A considerable literature exists on the potential implications of climatic change on the productivity of crops and impacts of increased aridity (Emgailee 2005; Huntingford et al., 2005; Kafle and Bruins, 2009; Tayanc et al., 2009). In 2005, nearly half (40%) of the economically active population in developing countries of world relied on agriculture for its livelihood, with approximately 75% of the world’s poor living in rural areas (Nelson et al., 2009). Crop and livestock yields are directly affected by changes in climatic parameters such as temperature, precipitation, evapotranspiration as well as the frequency and severity of extreme events like droughts, floods, frosts and wind storms.

Climate change will likely have the strongest effect on developing countries and countries where the agricultural sector is of high importance for the country's economy; for example, Gonzales (2001) has identified that vegetation zones shifted southwest in the West African Sahel by 25 to 30 km during the period 1945-1993, at an average rate of 500 to 600 ma-1.

A number of studies throughout the world have been undertaken on climatic change and potential implications on the environment (e.g., Al-Adiwish, 2000; Bou-Zeid1 and El-Fadel, 2002; Al-Abidee, 2001; Al-Hasee, 2007; Kafle and Bruins, 2009; Schilling et al., 2012), with the studies by Basu and Samet (2002); Vandentorren et al. (2004); Canouï-Poitrine et al. (2006); Pascal et al. (2006); Robine et al. (2008); Gosling et al. (2009) and Yu et al. (2011) addressing concerns relating to the implication of climatic change to human health. The implications of climate change on the environment and human health are notable, particularly in the North Africa and Mediterranean regions and indicate significant increases in morbidity and mortality. The implications of climate change are worrying for the Mediterranean region as socioeconomic scenarios indicate a rapidly growing population and consequently growing human pressure on natural resources (Thomas, 2008; Sowers et al 2011), with the study by Schilling et al. (2012) suggesting that these pressures may contribute to increased social and political instability.

1.4 THESIS AIMS AND OBJECTIVES

The main aim of this thesis is to investigate the evidence of climate change across Libya and to produce a comprehensive study of climate variability change and trends.

More specifically, the objectives are as follows:

1. To digitise and scrutinise all daily/monthly temperature and precipitation data for 18 synoptic stations and monthly precipitation data for 28 meteorological stations across Libya for the last 66 years (1945-2010). Data for 16 synoptic stations of relative humidity, surface wind speed, sun-shine duration and atmospheric pressure for the last 50 years (1961-2010) also included.

2. To identify temporal fluctuations, patterns and trends in temperature, across Libya based on (a) annual data, (b) seasonal data, (c) monthly data, and (d) daily data; and to identify and examine any spatial changes within the data. Extremes in warm and cold temperature across Libya are also analysed.

3. To identify temporal fluctuations, patterns, and trends in precipitation, across Libya based on (a) annual data, (b) seasonal data, (c) monthly data, and (d) daily data; and to identify and examine any spatial changes within the data. Number of precipitation days, intensity of precipitation and extremes in precipitation across Libya are also analysed.

4. To identify temporal fluctuations and patterns in potential and actual evapotranspiration based on (a) annual data, (b) seasonal data, (c) and monthly data and comparison between two potential evapotranspiration of Penman-Monteith and Thornthwaite across Libya. Relationships between potential evapotranspiration and climatic parameters are also considered during the last 50 years 1961-2010.

5. To identify temporal fluctuations and patterns in climatic parameters; surface wind speed, relative humidity, sun shine duration and atmospheric pressure on annual data across Libya for the last 50years (1961-2010).

6. To analysis modelled NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010) temperature and precipitation data at three stations. Comparison of the observational dataset with the reanalysis NCEP/NCAR and ERA-Interim- is also considered.

By achieving these six objectives it is proposed that this thesis will contribute understanding of climate change and variability through the analyses of the important climatic parameters: temperature, precipitation and evapotranspiration. A better understanding of climate change and its implications and risks will be important in improving future decision-making relation to climate change adaption, resource management (e.g. water resource management) and agricultural practice.

1.5 THESIS STRUCTURE

This thesis is presented in eight chapters, addressing the aims and objectives identified previously (Fig. 1.2).

Chapter 2 identifies the data sources and information relating to the meteorological stations across Libya. This chapter includes a review of the literature on the sources of climate data and climatic change mechanisms and provides a detailed examination of the data analysis approaches used in this thesis. A discussion of the key climatic parameters (temperature, precipitation and evapotranspiration) examined in further detail within the thesis are also provided.

Chapter 3 describes the observational climatic data used in this thesis which were provided in a paper based format by the Libyan National Meteorological Centre (LNMC) and digitised for use in this thesis. Data type, observation period and geographical characteristics of the selected meteorological stations are described, as well as the data quality, management and integrity checking. The procedures and techniques of data processing used in this study together with analysis techniques applied are discussed.

Chapter 4 examines temperature variability from 18 synoptic stations across Libya for the period 1945-2010. Temporal and spatial changes and trends in multi-decadal, decadal, annual, seasonal, monthly and daily minimum, maximum and mean average temperature, dry bulb temperature as well as extremes in minimum and maximum temperature have been analysed.

Chapter 5 considers precipitation variability from 27 meteorological stations across Libya for the period 1945-2010. Temporal and spatial changes and trends of multi-decadal, decadal and annual, seasonal, monthly and daily precipitation as well as extremes of precipitation have been analysed in this chapter using a number of statistical tests, with further analysis of the number of rainy days.

Chapter 6 presents a comprehensive study of potential and actual evapotranspiration for the period 1945-2010 from 18 synoptic stations across Libya. Temporal and spatial changes and trends in potential evapotranspiration (PE) for 13 stations for the period 1961-2010 and for actual evapotranspiration (ET) from 18 synoptic stations for the period 1961-2010 using the Penman-Monteith and Thornthwaite methods are considered.

Chapter 7 undertakes an analysis of the differences between the observed and ERA-Interim (European ECMWF) and NCEP (American) reanalysis datasets, with the ERA-Interim reanalysis spanning the period 1979-2010 at a spatial resolution of about 1.5 degree, while the NCEP reanalysis uses the period 1948-2010 and a spatial resolution of about 2.5 degree. This chapter compares the results from these two common reanalysis dataset, with the station data used within this study to examine the reliability of the gridded products.

Chapter 8 discusses the implications and findings at the three individual climatic parameters: temperature, precipitation and evapotranspiration and compares and assesses the performance of the long and short term changes, fluctuations and trends to the previous researches. This chapter also considers the limitations within the sites, data and methods used, together with an assessment of the objectives identified in Chapter 3.

Finally, the thesis is concluded with a summary of findings and a discussion of the implication of climate change on the environment, with particular reference to human impacts.

1.6 SUMMARY

Current climate fluctuations whether anthropogenic, natural or combinations of the two are changing the climate of Libya; any information that potentially improves current understanding of climatic change and potential human impacts is valuable. The additional information that the Libyan sites can provide, in a generally data sparse part of the world, represents a valuable source for future research studies.

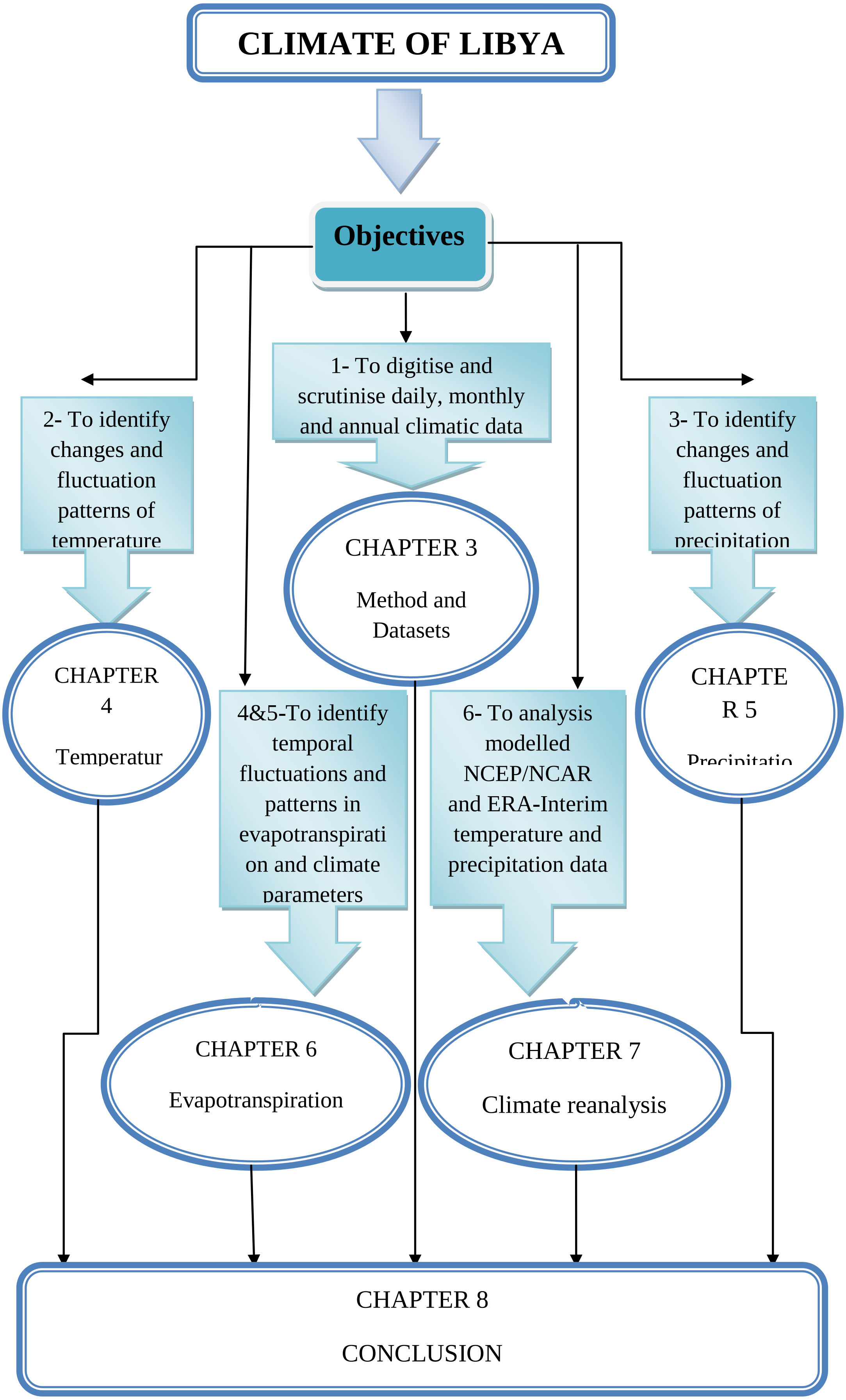


Fig. 1.2: Thesis structure

Chapter 2

LITERATURE REVIEW

This chapter will address past literature and review sources of climatic parameters data for the identification of global, regional and local climate changes, terminology relating to climate and the mechanisms of regional climate change and its implications.

2.1 INTRODUCTION

Climate change is one of the most important issues of the twenty-first century; increasing extremes of temperature, precipitation and evaporation have been identified in recent decades (McMichael et al., 2003). Changes in climate and extreme weather are considered as the most serious environmental challenge that threatens developed or developing countries; Libya is one of the driest countries in the world with significant changes recorded in temperature and precipitation during the last couple of decades, with serious impacts on the environment, human welfare, and socio-economic systems. This is being taken seriously by international authorities and has been received considerable attention from the Libyan government.

2.2 REGIONAL LONG DATA SERIES

2.2.1 Length of record

The first meteorological network was formed in northern Italy in 1653 (Kington, 1988) and reports of temperature observations were published in the earliest scientific journals (Wallis and Beale, 1669). The rain gauge was invented by Father Benedetto Castelli, a pupil of Galileo in 1639, to measure precipitation at Lake Trasimeno.

The scientific academy (Accademia del Cimento) was established by the Grand Duke of Tuscany Ferdinand II and his brother Prince Leopold de’ Medici in 1657, was providing the first network of meteorological observation in the world, it was closed by the Inquisition in 1697 (Camuffo et al., 2013). The earliest recorded rainfall records in the UK come from Burnley, Lancashire and start in 1677 (Craddock, 1976). In Southern France, the earliest weather observations were recorded by the Royal Company excavating the Canal du Midi in 1681. In Italy, daily series of precipitation at Padua and Bologna were initiated in 1716 by Giovanni Battista Poleni and Jacopo Bartolomeo Beccari, respectively. The observation of temperature, precipitation and air pressure data in Spain were initiated in Funchal on the Island of Madeira, between 1747 and 1753 by the English doctor Thomas Heberden.

The World Meteorological Organization (WMO) is a specialized agency of the United Nations, and originates from the International Meteorological Organization (IMO), which was founded in 1873. The WMO has established in 1950 and became the specialized agency of the United Nations in 1951 for meteorology, operational hydrology and related geophysical sciences with 191 Member States and Territories (on 1 January 2013). The WMO started collecting climatic data in 1923 from hundreds of weather observations around the world.

In Libya, precipitation observation started in the late nineteenth century, in the cities of Tripoli (1879) and Benghazi (1881) at Libyan climatic archives, Climate Department, Libyan National Meteorological Center (LNMC). The Libyan National Meteorological Centre - LNMC), the data based on monthly values have been published by Fantooli (1952). The Libyan meteorological department was established in the early nineteen century, during the Italian occupation, with limited climate data collected at meteorological stations in Tripoli, Sirt, Benghazi, Sabha and Ghadames (e.g. temperature, precipitation and air pressure). The LNMC was established in the mid 1940s with additional stations and more climate parameters recorded by the LNMC, who joined the WMO on December 29, 1955, with a total of 45 meteorological stations and 225 rain gauges distributed across Libya (LNMC).

The names and reference numbers (WMO) of the meteorological stations are provided in Table 2.1, which includes altitudes, details of record length and resolution, station type and distance from the sea. The geographical distribution of the meteorological network across Libya is focused on the coast reflecting the distribution of densely populated communities in the western and eastern coastal regions.

The meteorological stations are included in Table 2.1 and consisted of synoptic and climatic stations that are set up to observe the general weather observations, where the synoptic stations are have a unique WMO reference number. Agricultural stations are mainly established to observe the agricultural parameters such as soil temperature and pan evaporation in addition to the basic weather observations.

2.2.2 Resolution

The Libyan meteorological stations are classified according to the observational weather parameters, with 21 synoptic, 16 climatic and 5 agricultural stations (Table 2.1). The synoptic and climatic stations observe nine weather parameters: temperature, precipitation, relative humidity, air pressure, dew point temperature, water vapour pressure, duration of sun-shine, cloud, wind speed and wind direction. In addition, the number of days with mist, fog, frost, snow, sand, haze, dust storm and thunder storms are observed. Four agricultural stations are located along the coastline: Al-Zawyia, Al-Zahra, Al-Hadbah and Al-Fatayah which were established in the 1990s to measure weather parameters, pan-evapotranspiration, wind speed at various heights and soil temperatures at various depths between 5 cm-150 cm.

2.2.2.1 Temperature

The observation of temperature as dry bulb, wet bulb, minimum and maximum temperature is undertaken at most of meteorological stations, using different types of thermometer. The dry and wet bulb temperatures are measuring in °C, on an hourly basis (Tripoli airport and Binina stations) at eight scheduled times each day: 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 (manuals guides of technical regulation; World Meteorological Organization-WMO).

Table 2.1: List of meteorological stations in Libya

Stations	Lat. (º)	Long. (º)	High (m) amsl	WMO No.	distance (km) from sea	Type of station	Started Observ.
Nalute	31º 52′N	10º 59′E	621	62002	157	Synoptic	1945
Al-Zentan	31º 56′N	12º 05′E	713	-	100	Climatic	1967
Al-Rojban	31º 56′N	12º 15′E	688	-	105	Climatic	1964
Zwarah	32º 53′N	12º 05′E	3	62007	< 1	Synoptic	1945
Subratah	32º 49′N	12º 27′E	2	-	< 1	Climatic	1991
Jefren	32º 04′N	12º 31′E	691	62008	81	Synoptic	1983
Surmman	32º 45′N	12º 35′E	23	-	<10	Climatic	1975
Al-Zawia	32º 45′N	12º 46′E	35	-	<10	Agricultural	1989
Al-Zahra	32º 42′N	12º 52′E	80	-	18	Agricultural	1991
Garyian	32º 09′N	13º 01′E	741	-	73	Climatic	1945
Al-Aziziya	32º 32′N	13º 01′E	125		30	Climatic	1981
Al-Swani	32º 44′N	13º 05′E	63	-	20	Climatic	1997
T. Airport	32º 40′N	13º 09′E	81	62010	22	Synoptic	1945
Al-Hadbah	32º 48′N	13º 10′E	48	-	15	Agricultural	1978
Espiah	32º 32′N	13º 10′E	126	-	36	Climatic	1986
T. City	32º 54′N	13º 11′E	30	-	<10	Climatic	1975
T. Seaport	32º 54′N	13º 12′E	0.0	-	< 1	Climatic	1992
Tajorah City	32º 53′N	13º 21′E	10	-	<10	Climatic	1995
Tajorah R	32º 52′N	13º 22′E	11	-	<10	Climatic	1993
Qassr-Khyar	32º 42′N	13º 50′E	133	-	<10	Climatic	1991
Ben-Walid	31º 44′N	14º 01′E	220	-	100	Climatic	1999
Al-Khoms	32º 38′N	14º 18′E	20	62012	<10.0	Climatic	1991
Musratah	32º 19′N	15º 03′E	32	62016	<10.0	Synoptic	1945
Sirt	31º 12′N	16º 55′E	13	62019	<10.0	Synoptic	1945
Ajdabyia	30º 43′N	20º 10′E	7	62053	<10.0	Synoptic	1945
Binina	32º 05′N	20º 16′E	129	62055	19	Synoptic	1945
Al-Maraj	32º 16′N	20º 55′E	655	-	16	Climatic	1993
Al-Bayda	32º 45′N	21º 42′E	537	-	18	Climatic	1979
Shahat	32º 49′N	21º 51′E	621	62056	<10	Synoptic	1945
Darnah	32º 47′N	22º 35′E	26	62059	<10	Synoptic	1945
Al-Fatayah	32º 41′N	22º 40′E	253	-	<10	Agricultural	1981
Tubruq	32º 06′N	23º 56′E	50	62062	<10	Synoptic	1985
Ghadames	30º 09′N	09º 42′E	357	62103	380	Synoptic	1945
Mizda	31º 27′N	12º 59′E	400	-	150	Climatic	1979
Al-Garyiat	30º 24′N	13º 35′E	500	62120	130	Synoptic	1968
Hon	29º 08′N	15º 57′E	267	62131	240	Synoptic	1948
Jalo	29º 02′N	21º 34′E	60	161	190	Synoptic	1950
Al-Jaghbub	29º 45′N	24º 32′E	2	62176	245	Synoptic	1946
Sabha	27º 01′N	12º 05′E	432	62124	500	Synoptic	1945
Obary	26º 47′N	11º 47′E	610	62200	568	Synoptic	1979
Murzuq	25º 54′N	13º 55′E	620	-	520	Climatic	1978
Traghen	25º 56′N	14º 27′E	618	-	509	Climatic	1981
Ghat	25º 08′N	10º 09′E	692	62212	900	Synoptic	1979
Tazerbou	25º 48′N	21º 08′E	259	62259	700	Synoptic	1962
Al-Kufrah	24º 13′N	23º 18′E	435	62271	800	Synoptic	1945

The maximum and minimum temperatures are measured at all stations once per day, in the early morning at 0600 GMT for minimum temperature and in the late afternoon at 1800 GMT for the maximum temperature. Soil temperatures at five agricultural stations are measuring at eight fixed times each day. Measurement of dry and wet bulb temperature and minimum and maximum temperature using specific types of thermometers and thermographs is undertaken at selected stations, with equipment sourced from either the UK or Denmark. At agricultural stations, soil temperatures are measured at multiple depths below the surface (5, 10, 20, 50, 100 and 150 cm; LNMC).

2.2.2.2 Precipitation

Precipitation is measured in mm/day at two fixed schedule times per day at all rain gauges and meteorological stations (synoptic, climatic and agricultural) across Libya; at 06:00 GMT and the second at 18:00 GMT; and at additional times during the day during heavy rainfall, particularly during the winter at coastal stations. Precipitation in Libya is measured by using three different types of graduated cylinder rain gauges from Italy, Germany, and the UK, with three different forms of graduated cylinders.

2.2.2.3 Wind speed and direction

Wind speed (m s^{-1}) and direction observations are required for weather monitoring and forecasting. According to the WMO, wind speed should be measured regularly, with hourly measurements at the airports of Tripoli, Binina, Sirt and Sabha and eight times a day (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00) at other stations. A combined sensor (IM 146) is one of the most common instruments used in Libya, which consists of a direction vane cup anemometer.

2.2.2.4 Relative humidity

The air humidity, relative humidity (%), dew point temperature (°C) and water vapour pressure (hPa) are generally estimated from the relationship between the value of dry bulb and wet bulb temperature, or in relation to saturation vapour density.

Air humidity measurements are made eight times a day (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00) at synoptic stations except, for Tripoli Airport and Binina were observations are made hourly.

2.2.2.5 Air pressure

Air pressure is one of the most important weather parameters observed at synoptic and climatic stations across Libya, using both aneroid and mercury barometers to observe sea level pressure (hPa). Air pressure are measured at synoptic stations on an hourly basis at the airport stations of Tripoli, Sirt, Binina and Sabha and at eight times a day (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00) at other stations. The mean monthly air pressure of sea level (stations level) across Libya ranges from approximately 980 to 1016 hPa (from 964 to 1035 hPa).

2.2.2.6 Sun-shine duration

Sun-shine duration is one of the most important weather parameters observed at meteorological stations: synoptic, agricultural and climatic stations across Libya, daily at 18:00 GTM. Bright sun-shine duration data is measured by the Campbell Stokes recorder in Libya. The mean total daily sun-shine duration across Libya varied spatial and through the year, with an average rate ranging between 4-10 hours (coastal stations) to 8-13 hours (inland regions).

2.3 CLIMATIC VARIABILITY

Temperature, precipitation and evapotranspiration are the main climatic parameters covered within this thesis and are investigated to examine the climate and changes in climate.

2.3.1 Temperature variation

Temperature is one of the basic meteorological elements used for characterising climate change. Temperature changes and fluctuations has been studied globally, regional and locally, with evidence of increasing/decreasing temperatures, cold/warm phases, identified throughout the last 150 years.

In the last few decades, Kostopoulou et al. (2013) identified increases in annual minimum temperature of 0.4-0.5 °C over the Mediterranean region. This finding is comparable to Ben-Gai et al. (1999) in Israeli with 0.01-0.53 ° C/decade, but indicate a faster rate of warming compared to previous studies examining Libya (El-Kenawy et al., 2009). Previous research e.g. El-Tantawi (2005) identified increases in maximum, minimum and mean average temperature ranged across Libya (1946-2000). The findings are supported by Ben-Gai et al. (1999) in Israel trends with an average rate of 0.21 °C/decade. Several heat waves have occurred in regions of the Mediterranean, western and Central Europe (2003, 2006 and 2007; Dousset et al., 2011). To document and assess temperature variability and changes at smaller scales (i.e. regional), to better understanding long-term temperature variability and change, and its associated mechanisms of forcing, at regional scales is required.

2.3.1.1 Global variation of temperature

A large number of previous studies have described global changes and trends in temperature (e.g. Mitchell, 1966; Folland et al., 1990; Hansen, 2001 and 2002; Jones and Kelly, 1983; Jones et al., 1982 and1999; Alexander et al., 2006; Brown et al., 2008). Several studies have described changes and trends in temperature through from the global to the local scale in the north hemisphere (Jones and Kelly, 1983; Repapis, 1984), in African, (Hulme et al., 2001) for Europe (Klein Tank and Konnen, 2003; Kington, 1988, Kelly et al., 1982) and over the Arctic regions (Przybylak, 2000).

The fourth report of the Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that, global mean temperature has gradually increased by 0.74 °C ± 0.18 °C over the last 100 years (1906-2005). Several studies (Jones et al., 1999 and 2001; Hansen et al., 2001; Domonkos and Tar, 2003; Della-Marta et al., 2007; Rebetez and Reinhard, 2008) have identified that the mean annual temperatures are rising globally with some areas warming at greater rates than others; while other regions have even cooled or show no evidence of change (Table 2.2).

Table 2.2: Rates of changes in temperature identified by previous studies

Authors	Study Area	Study period	Temperature changes and trends
Jones et al. (1999)	Global	1860-2000	Annual global temperatures warmed by 0.58 °C over the period 1861–1997 and by 0.63 °C over 1901–1997.
IPCC (2001)	Global	1900-1994	Surface air temperature rose by between 0.3 °C and 0.6 °C
Hansen et al. (2001)	The global and the US	20th century	Temperature change over the long-period at least of the order of 0.1 °C
Domonkos and Tar (2003)	Hungary	1901-1998	Mean average temperature increased by 0.34 °C/100 years
Della-Marta et al. (2007)	Western Europe	1880-2005	Significant changes in mean surface temperature with an average rate of +1.6 ± 0.4 °C.
IPCC (2007)	Global	1906-2005	Mean surface temperature has increased by 0.74 °C ± 0.18 °C.
Rebetez and Reinhard (2008)	Switzerland	1901-2000	Mean decadal trends of +0.13 °C during the 20th century and +0.57 °C based on the last three decades only the world.

Many studies have analysed minimum, maximum and extremes temperatures on large regional and/or local scales (Easterling at el., 2000; Wibig and Glowicki, 2002; Domonkos and Tar, 2003; Domroes and Al-Tantawi, 2005; Alexander et al., 2006; Della-Marta et al., 2007; Goubanova and Li., 2007; Bartolini et al., 2008; Brown et al., 2008; Politano, 2008; Wang et al., 2012; Zhou1 and Ren, 2011; Kruger and Sekele, 2013). Monthly mean maximum and minimum temperature indicate that minimum temperature increasing with three times that of the global maximum temperature, with rate average of 0.84 °C versus 0.28 °C for the period 1951-1990 (Karl et al., 1993), this finding supported by Jones et al., (1999), who identified that global minimum temperatures have warmed by 0.188 °C per decade and maximum temperatures have warmed by 0.088 °C per decade during the period 1950-1993, and be with Folland et al., 2002 who identified considerable variability in temperature range, as minimum temperatures have risen twice as fast as maximum temperature over the Northern Hemisphere, with the rate of temperature increase (1950-1993) has been 0.2 °C and 0.1 °C for the minimum and maximum, respectively. The study by Alexander et al. (2006) analysed globally extremes temperature of 200 stations for the period 1901-2003, they have identified that all indices exhibit a significant change between 1951-1958 and 1979-2003 at all stations, with general warming in all seasons. The study by Della-Marta et al., (2007) analysed daily summer maximum temperature at 54 stations selected from 15 Western Europe countries during the last 126 years (1880-2005), they identified that the length of summer heat waves has doubled and the frequency of hot days has almost tripled. Bermejo and Ancell (2009) investigated variability of daily extreme temperatures across Spain during the period 1957-2002; they showed that maximum temperatures have increase at faster rate than minimum temperatures.

2.3.1.2 Regional variations of temperature

During the last four decades, several studies have focused on North Africa and the Mediterranean basin, indicating changes and trends in temperature, temporally and spatially, but few studies exist concerning temperature variability during long periods covering the whole Mediterranean region (Sahsamanoglou and Makrogiannis, 1992; Kutiel and Maheras, 1998; Maheras et al., 1999; Xoplaki et al., 2003; Miro and Millan, 2006; Politano, 2008), while a number studies have undertaken analysis into changes in temperature in parts of the Mediterranean basin e.g. for Eastern Mediterranean basin (Repapis and Philandras, 1988 and Hasanean, 2001), or for western Mediterranean basin (Maheras, 1989a, Piervitali et al., 1997, Camuffo et al., 2013) and for stations distributed around the Mediterranean (Arseni-Papadimitriou & Maheras, 1991; Goubanova and Li, 2007).

A number of studies have identified trends in temperature across the Mediterranean basin and North Africa (Table 2.2) over the last 30 years (e.g. a study by Juan and Antonio (1996), Aesawy and Hasanean (1998), Ben-Gai et al. (1999), Hasanean (2001), Turkes and Sumer (2004), Hasanean and Abdel Basset (2006), Brunet et al, 2007, Goubanova and Li, 2007, Chaouche et al., 2010).

During the last few decades, a large body of work has been undertaken assessing temperature variations and trends in single countries in the Mediterranean region: Egypt (Domroes and El-Tantawi, 2005, Hasanean and Abdel Basset, 2006), Israel (Goldreich, 1995, Ben-Gai et al., 1999, Kafle and Bruins 2009), Greece (Xoplaki et al., 2002, Feides et al., 2004, Philandras et al., 2008), Turkey (Tayanc et al., 1997, Kahya and Kalayc, 2004, Tayanc et al., 2009), Spain (Onate and Pou, 1996; Brunet et al., 2007, Bermejo and Ancell, 2009, Pablo Campra et al., 2008, El-Kenawy et al., 2012) and Italy (Brunetti et al., 2004, Toreti and Desiato, 2008). Whilst other studies have focused on regional temperature variations and trends at single cities/regions around the Mediterranean basin during the last 40 years: Athens (Arseni-Papadimitriou, 1973, Repapis, 1984, Katsoulis, 1987, Founda et al., 2004), Tuscany (Colacino and Rovelli 1983), Rome (Bartolini et al., 2008), Modena (Boccolari and Malmusi, 2013) and Istanbul (Karaburun et al., 2011).

Hasanean (2001) identified a significant positive trend in annual surface temperature at Malta, Jerusalem, Tripoli, and Amman, but negative trends at Al-Exandaria, Athena, Beirut and Latakia; this is supported by Arseni and Maheras (1991) who also identified positive changes in temperature at Marseille, Rome, Athens, and Jerusalem. Pal et al., (2004) proposed that the Central Mediterranean region is exposed to increased temperatures during the summer season, as a result of increased of greenhouse gases.

Table 2.3: Rates of change in temperature identified by previous studies

Authors	Study Area	Study period	Temperature changes and trends
Piervitali et al. (1997)	The Mediterranean	1860-1955	Increase in mean average temperature of 0.8 °C/century.
Piervitali et al. (1997)	The Mediterranean	1873-1989	Increase in mean average temperature of 0.3 °C/ century
Ben-Gai et al., (1999)	Israel	1964-1994	Increase in minimum temperature of 0.01-0.53 °C
Hasanean (2001)	The Mediterranean	1853-1991	increase in mean average temperature of 0.07 °C/ decade
Xoplaki et al. (2003)	The Mediterranean	1850-1999	Increase in summer temperatures of 0.08 ºC/decade over the 1950 to 1999
Feidas et al. (2004)	Greece	1955-2001	Increase in mean average is nearly zero (0.0) °C
Brunet et al., (2005)	Spain	1850-2003	increase in mean average temperature 0.11 ºC/decade
Hasanean and Abdel Basset (2006)	Egypt	1941-2000	Increases in mean average temperature 0.03 - 0.05 ºC/decade
Bartolini et al. (2008)	Tuscany-Italy	1955-2004	Maximum temperature increase (+0.44 °C/decade) and minimum temperature (+0.38 °C/decade)
Bermejo and Ancell (2009)	Spain	1957-2002	Increase in mean maximum and minimum temperature of 0.27 and 0.17 °C/decade, respectively.

2.3.1.3 Local variations of temperature

Libya is an area of particular interest as it includes areas which experience both a Mediterranean and North Africa climate (semi-arid and arid climate) and is in a region where human occupation and lifestyle are highly susceptible to climatic changes. In Libya, relatively few studies have been undertaken on long-term climate change or examined variations and trends in temperature data (El-Tantawi, 2005; El-Kenawy et al., 2009; Ageena et al 2012). El-Tantawi, (2005) identified significant warming trends in mean annual surface temperature at most examined stations for the period 1946-1999. El-Kenawy et al. (2009) investigated temperature trends at ten meteorological stations across Libya (1951-1999), the study identified negative trends in annual maximum temperature at all stations, with significant decreases at 70% of the examined stations, a finding which contradicts the findings of most studies in the Mediterranean region.

Few studies have focused on climatic parameters in Libya; a small number of studies in recent years have undertaken an assessment of temperature variability and produced estimates of change and trend for either local averages, or individual stations (Emgely, 1994; Pelag, 2000, El-Tantawi, 2005, Al-Marimee, 2007, El-Kenawy et al., 2009, Ageena et al., 2012). Previous research examining Libya has identified positive trends in mean annual minimum temperature at all study stations (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 from between 0.19 and 0.27 °C/decade. Negative trends are observed at 50% of stations in Libya during the early 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 (western Libya) during the period 1988-2005, but no corresponding change in mean annual maximum temperature was observed.

The mean annual minimum temperature at western stations increased most during the coldest months (DJF) compared to the warmest months (JJA) for 1961-1990 (Pelag, 2000). 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 (1946-2000).

2.3.2 Precipitation variations

Precipitation is one of the basic meteorological elements chosen to describe the changes and trends in climate change. Precipitation varies from year to year and over decades, and changes in amount, intensity, frequency, and type (e.g. snow vs. rain) affecting the environment and society. Variability in precipitation has been studied at different scales globally, regional and locally, with several studies having showed evidence of changes and trends in precipitation during the last century, with significant increasing and decreasing precipitation trends across the world over the last century (Moberg and Jones, 2005, IPCC, 2007, Goubanova and Li, 2007).

2.3.2.1 Global variation of precipitation

A large body of work has been undertaken throughout the world investigating change in precipitation during the last century (New et al., 2001, Alexander et al., 2006; IPCC, 2007). Studies have focused on regions and/or countries e.g. the North Hemisphere (Bradley et al., 1987), Africa (Nicholson et at., 1981, Hulme, 1992, Kniveton et al., 2009), Europe (Wibig, 1999, Klein Tank and Konnen, 2003, Pal et al., 2004, Matti et al., 2009), Asia Pacific and China (Xu et al., 2005, Wang et al 2012), Australia (Suppiah and Hennessy, 1998; Hennessy et al 1999), Scotland (Macdonald et al., 2008), North and Central America (e.g. Karl and Knight, 1998, Groisman et al., 2001, Small et al., 2006, Baigorria et al., 2007) and arid and semi arid climate regimes (Raziei, 2005, Shepherd, 2006).

According to the IPCC (2007), precipitation has generally increased over the last 100 years between 30 and 85°N, with a notable increase between 10°N to 30°N during the first 50 years of last century (1900-1950), but declined after about 1970. Remarkably decreases have occurred in the last 40 years from between 10°S to 30°N, with no clear changes in annual precipitation over the ocean. Downward trends in annual precipitation have been observed in many other parts of Africa, and in South Asia, with the largest negative trends since 1901 in annual precipitation observed over western Africa and the Sahel; with increases in precipitation across the Sahel region of Africa and in other parts of tropical Africa since 1979 (IPCC, 2007).

Increasing annual precipitation has been identified at a rate of 7% and 12% for the areas 30–85°N latitude and by about 2% for the areas in 0–55°S, during the 20th century (Mosmann et al. 2004; Xu et al. 2005; Yu et al. 2006). Studies on climate change have shown an increase of 0.5–1% in rainfall per decade in much of the Northern Hemisphere’s mid and high latitude. In Europe, Moberg and Jones, (2005) identified significant increasing precipitation trends over the 20th century in winter, based on about 80 stations situated in Central and Western Europe during the period 1901-1999, with low precipitation trends in summer.

2.3.2.2 Regional variation of precipitation

Many studies have focused on regional precipitation changes and trend in the Mediterranean basin during the last four decades, e.g. for Athens in Greece (Arseni-Papadimitriou, 1973), Israel (Goldreich 1995; Steinbereger and Gazit-Yaari 1996), Italy (Brunetti et al 2004), Greece (Hatzianastassiou et al 2008), Turkey (Tayanc et al., 2009, Cukur, 2010; Yavuz and Erdogan, 2012; Unal et al, 2012).

Decreases in precipitation identified during the last few decades around the Mediterranean basin, primarily in centre and southern regions, while increases have been identified in the northern Mediterranean region, with a general decline in annual precipitation across the Mediterranean Basin (Yosef et al., 2009).

Such studies are particularly important in Northern Africa and the Mediterranean region, which are generally dry regions, receiving relatively light and moderate annual precipitation (**e.g.** Nicholson, 1981; Ben-Gai et al., 1993, 1994 and 1998; Ramos 2001; Raziei et al., 2005; Goubanova and Li, 2007; Reiser and Kutiel 2011). Precipitation changes in the Mediterranean and Southern Europe have been characterized by a decline in annual and extreme rainfall over the 20th century (Goubanova and Li, 2007).

In Greece, mean annual precipitation is increasing in central and northern parts, but decreasing in the south (60.3 mm) over the period 1979-2004 (Hatzianastassiou et al, 2008 and Kahya and Kalayc, 2004). In Turkey, significant decreases have been found at 15 of 91 rainfall stations (Reiser and Kutiel, 2011). Raziei et al. (2005) identified negative non-significant trends in annual rainfall at most stations. Goldreich (1995) illustrated a decreasing trend in rainfall over northern Israel, with increases in rainfall in southern Israel (1961-1990). Ben-Gai et al (1998) identified significant spatial and temporal variability in rainfall across Israel (1931-1990). Increasing trends in annual rainfall have been identified in Northern and Central Italy (Montanari et al., 1996; De Michele et al., 1998), with a negative trend in Sicily-Southern Italy (Aronica et al., 2002; Cannarozzo et al., 2006). In France, annual precipitation has not shown any trend for 13 examined stations across the French Mediterranean region (1970-2006), whereas, monthly rainfall has been found to decrease in June and increase in November over some areas (Chaouche et al., 2010)

2.3.2.3 Local variation of precipitation

Few studies have been undertaken examining precipitation across Libya (e.g. Emgely; 1994; Lama, 1996; Qsoudh, 1996; Zikree, 1998; Ageena, 2002; El-Tantawi, 2005). The study by Lama (1996) found increases in annual precipitation at the stations in the north and west of the Plain of Benghazi. The study by Zikree (1998), has suggested ten geographical precipitation regions over Libya, with considerable variability, with the first region surrounding Shahat (green mountains) with average precipitation >500 mm a^{-1}, the tenth region includes the hyper-arid zone in the south of Libya where annual rainfall does not exceed 1 mm a^{-1}; a finding supported by Ageena (2002), who identified six regions across western Libya.

Al-Adiwish (2000) found significant differences in annual total rainfall in north-western Al-Jafara plain in Libya during two periods (1961-1978 and 1979-1995), a finding supported by Massoud (2004) who found a significant difference in annual rainfall in north-western Libya during two periods (1972-1987 and 1987-2002). The study by Al-Dawee (2002) analysed the geographical characteristics of rainfall across the Al-Jafara region and identified a decrease in annual rainfall during the period 1957-1999. The most recent study by El-Tantawi (2005) identified positive trends in annual precipitation (1946-2000), with a negative trend at most stations from 1976-2000, with positive winter and spring trends at most stations from 1946-2000.

2.3.3 Evapotranspiration variations

2.3.3.1 Global variation of evapotranspiration

Several studies throughout the world have analysed evaoptranspiration changes and trends (Doorenbos and Pruitt, 1977; Jensen et al., 1990; Allen et al., 1998). Similar studies performed on regions around the world included work in India (Chattopadhyay and Hulme 1997), China (Tomas, 2000; Liu et al., 2004a; Xu et al., 2006; Shenbin et al., 2006; Ni et al., 2007) and the USA (Lawrimore and Peterson 2000; Hobbins et al., 2001; Hobbins and Ramirez, 2004; Abtew et al., 2003, 2011; Irmak et al., 2012)

Tomas (2000) identified negative changes in potential evapotranspiration over large area (51 stations) in mainland China and Tibet (1954–1993). Hobbins et al. (2001) found significant increases in actual evapotranspiration at 66% and decreases at 31% of stations across the USA (1962-1988). Abtew et al. (2011) showed significant increasing trends (confidence level 99%) in potential evapotranspiration across South Florida during the period 1948-2009.

2.3.3.2 Regional variation of evapotranspiration

A small number of studies have investigated evapotranspiration and focused on changes and trends of pan, potential and actual evapotranspiration across the Mediterranean basin and North Africa during the last couple of decades (Rana and Katerji 2000; Cohen et al., 2002; Chaouche et al., 2010; Moratiel et al., 2011).

Cohen et al. (2002) analysed pan-evaporation measurements for the period 1964-1998 at Bet Dagan in Israel’s central coastal plain, they found a small statistically significant increase in pan-evaporation. An increase in potential evapotranspiration was found at the annual scale, with significant changes in spring ranges between 60 and 70% of study stations throughout the French Mediterranean region, with rates varying from +0.2 mm a^{-1}

in February to +0.6 mm a^{-1} in June (Chaouche et al., 2010). Moratiel et al. (2011) have suggested that expected climate changes according to the applied scenarios in the Duero Valley (Spain) Basin will cause an increase in potential evapotranspiration between 5-11 % (55-118 mm) in the next 50 years compared to current rates.

2.3.3.3 Local variation of evapotranspiration

Few studies have focused on changes and variability of evapotranspiration across Libya, which explain the geographical distribution of potential evapotranspiration, with most of those unpublished studies (Zikree 1998; Ageena 2002). Zikree (1998) investigated rainfall and precipitation across Libya (1961-1995) suggesting six different regions based on Penman–Monteith (potential) evapotranspiration, ranging from <1900 mm a^{-1} in the north east region to >3100 mm a^{-1} for southern regions. Ageena (2002) calculated potential evapotranspiration for the Al-Jfarah region in north-western Libya for ten climatic weather stations for the period 1971-1999 based on Penman–Monteith, Thornthwaite and Ivanov methods.

2.4 CLIMATE PROJECTION MODELS AND REANALYSIS

Reanalyses data can estimate the atmospheric state at different locations with no weather data observations. In addition, reanalysis data can provide spatially complete and consistent record of atmospheric circulation. Reanalysis from NCEP/NCAR-

1948-2010 and ERA-Interim-1979-2010 using monthly dataset of temperature and precipitation for the grid squares in which the three selected stations; Ajdabyia, Hon and Nalute are located have been analysed.

2.4.1 Reanalysis data

Reanalysis is a relatively new field producing global gridded analyses back to the 1940s; during the earliest decade (1948–57), there were relatively few upper-air data observations (Kistler et al., 2001).

2.4.2 Variability in observations and model data of temperature and precipitation

During the last decade, a number of researchers around the world have developed, adopted and merged different kinds of model (e.g. Caminade and Terray, 2010), with reanalyses widely used in climate studies. Several studies have undertaken a re-evaluation of global and regional models for: mean surface temperature (Kistler et al., 2001, Fiorino, 2001, Rusticucci and Kousky, 2002, Kinter et al., 2004, Schar et al., 2004, Flocas et al., 2005, Nastos, 2011), precipitation (Mo and Higgins, 1996, Janowiak et al., 1998, Poccard et al., 2000) and availability of atmospheric moisture budget (e.g. Trenberth and Guillemot, 1998; Rasmusson and Mo, 1996).

Recent studies have compared NCEP–NCAR gridded data with ground-based observation surface air temperature and precipitation globally (Rusticucci and Kousky 2002, Flocas et al. 2005). Nastos et al., (2011) suggested that the differences between the two datasets of temperature (observed and NCEP/NCAR reanalysis) could be attributed to topographical factors and land–sea distribution within cells, which are challenging for the reanalysis model to accurately represent. Good agreement in temperature for the three reanalysis datasets (ERA-40, ERA-Interim and NCEP/NCAR) with observed data is found at a number of meteorological stations in Ireland (1989–2001) by Mooney et al., (2011), good agreement has been identified between observed and NCEP-NCAR reanalysis maximum and minimum temperatures datasets across Greece 1958–2000 by Flocas et al. (2005)

Comparison of observational station data and satellite measurements identifies different trends, with observed series identifying a decreasing trend compared to a slight increasing trend depicted from satellite measurements in annual and winter temperature (1979-1991) across Greece (Proedrou et al., 1997). Seasonal differences in mean maximum and mean minimum temperature are identified between 26 meteorological series in Greece (1955-2001) and respective NCEP–NCAR gridded reanalysis (Nastos et al., 2011). Good agreement is found when comparing monthly precipitation between NCEP–NCAR reanalysis and the GPCP rain gauge–satellite dataset during the period 1988–1995, with rather poor agreement in some regional areas through the world by Janowiak et al. (1998).

In contrast, Rusticucci and Kousky, (2002) identifies good agreement between daily and monthly observational and reanalysis grid-point temperature data over central and eastern Argentina. Poccard et al., (2000), found that the NCEP reanalysis of precipitation was close to the observation data (1958-1997), with an abrupt shift in the NCEP reanalysis data in 1967, over tropical Africa.

2.5 SUMMARY

This chapter was divided into three parts: the first part concentrated on the regional long climatic data series and includes the length of data record and resolution of weather parameters that have been analysed within this thesis; temperature, precipitation, wind speed and direction, relative humidity, air pressure and sun-shine duration. Moreover, it focused on historical source of climatic data (globally and locally), including record length, type, weather parameters, period of observation, number of observational stations and geographical distribution of the meteorological network across Libya (Table 2.1).

The second part of this chapter presented a comprehensive explanation the previous research of climate, examining global, regional and local climatic parameters: temperature, precipitation and evapotranspiration. In addition, a number of climatic parameters have been included such as wind speed and direction, relative humidity, air pressure and sun-shine duration. Variation and trends of temperature have been studied globally, regional and locally in this thesis, with evidence of changes temperatures, throughout the last 150 years, with more concentration on local changes in minimum, maximum and mean average temperature over the last few decades.

Variability in precipitation has been studied at different scales globally, regional, with more focuses on local variation and trends of precipitation during the last 66 years. Changes and trends in climatic parameters: wind speed and direction, relative humidity, air pressure and sun-shine duration have been included.

The third part of this chapter was addressed by climate projection models and reanalysis which examined reanalysis data (mix between observational data and operational model data) for the ERA-Interim 1948-2010 (European ECMWF) and NCEP/NCAR 1979-2010 (American) reanalysis of temperature and precipitation for three different stations across Libya. It is clear to see that, reanalysis data are widely applied globally, particularly in America and North Europe and is limited regionally; North Africa and the Mediterranean basin but very rare locally.

Chapter 3

DATA SETS AND METHODS

This chapter identifies procedures and techniques for data processing and quality control, methods of analysis and comparison to global reanalysis dataset.

3.1 INTRODUCTION

The datasets and methods used in this thesis are described for the examination of climate variability across Libya. Minimum, maximum, mean average and extremes of temperature, precipitation and evapotranspiration data for selected stations are examined, with additional climatic parameters: wind speed, relative humidity and sunshine duration quality assessed, statistically validated and checked where available. The observed long-term data (1945-2010) were provided by the Libyan National Meteorological Centre (LNMC), but first required digitisation as at the start of this study an incomplete digital record existed, with many series requiring complete digitisation. Data type, study period and geographical characteristics of the meteorological stations across Libya are described.

3.2 DATA TYPE AND AVALIBILITY ACROSS LIBYA

The names and reference numbers (World Meteorological Organization-WMO) of the 41 selection meteorological stations are provided in Chapter 1 (Table 1.1), which includes altitudes, locations, type, length, distance from the sea, details of record length, observation and resolution. The strong coastal presence of stations reflects the dominant populated and agricultural regions of Libya. Dataset integrity improves considerably after 1945 at the majority of stations, with missing data a significant issue prior to 1945. Daily datasets for nine coastal stations: Zwarah, Nalute, Tripoli Airport, Musratah, Sirt, Ajdabyia, Binina, Shahat and Darnah during the period 1956-2010 are included within this thesis. Monthly datasets for all examined stations during the period 1945-2010 are used in this work and were checked for completeness.

The climate data consisted of daily, monthly and annual records of temperature (Chapter 4), precipitation (Chapter 5) and other climatic parameters for individual stations, including data of sunshine duration (h/day), relative humidity (%) and wind speed (m/s^{-1}) are used, particularly in the evaluation of evapotranspiration (Chapter 6). Annual means are derived from the monthly means for all 12 months for each respective year; seasons were defined as follows: winter (December–February); spring (March–May); summer (June–August) and autumn (September–November).

3.3 METOROLOGICAL STATION SELECTION

The stations used within this thesis involve 18 temperature observations representing two regions (north and south) and 28 rainfall observations representing five regions (Table 3.1): coastal western, coastal central, coastal eastern, north Sahara and south Sahara within this study area selected, from a total of 45 meteorological stations distributed across Libya (Fig. 3.1).

The climatic data recorded of sun-shine duration (hours), wind speed (knots) and relative humidity (%) at 16 synoptic stations for the period 1961-2010 are used. The remaining stations have been omitted, mainly because meteorological records are short (<20 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.

Table 3.1: List of the meteorological stations used within this study

Stations	Lat. (º)	Long. (º)	WMO No.	Recorded Period	Data classification
Stations with temperature and rainfall data					
Zwarah	32º 53′N	12º 05′E	62007	1945-2010	Daily and Monthly
T.Airport	32º 40′N	13º 09′E	62010	1945-2010	Daily and Monthly
Nalute	31º 52′N	10º 59′E	62002	1945-2010	Daily and Monthly
Musratah	32º 19′N	15º 03′E	62016	1945-2010	Daily and Monthly
Sirt	31º 12′N	16º 55′E	62019	1945-2010	Daily and Monthly
Ajdabyia	30º 43′N	20º 10′E	62053	1946-2010	Daily and Monthly
Binina	32º 05′N	20º 16′E	62055	1945-2010	Daily and Monthly
Shahat	32º 49′N	21º 51′E	62056	1945-2010	Daily and Monthly
Darnah	32º 47′N	22º 35′E	62059	1945-2010	Daily and Monthly
Ghadames	30º 09′N	09º 42′E	62103	1945-2010	Daily and Monthly
Al-Garyiat	30º 24′N	13º 35′E	62120	1968-2010	Daily and Monthly
Hon	29º 08′N	15º 57′E	62131	1945-2010	Daily and Monthly
Jalo	29º 02′N	21º 34′E	62161	1950-2010	Daily and Monthly
Al-Jaghbub	29º 45′N	24º 32′E	62176	1945-2010	Daily and Monthly
Sabha	27º 01′N	12º 05′E	62124	1945-2010	Daily and Monthly
Ghat	25º 08′N	10º 09′E	62212	1979-2010	Daily and Monthly
Tazerbou	25º 48′N	21º 08′E	62259	1963-2010	Daily and Monthly
Al-Kufrah	24º 13′N	23º 18′E	62271	1945-2010	Daily and Monthly
Stations with rainfall data					
Surmman	32º 45′N	12º 35′E	-	1975-2010	Monthly
Al-Zawia	32º 45′N	12º 46′E	-	1956-2010	Monthly
Al-Hadbah	32º 48′N	13º 10′E	-	1978-2010	Monthly
Garyian	32º 09′N	13º 01′E	-	1956-2010	Monthly
Jefren	32º 04′N	12º 31′E	62008	1982-2010	Monthly
Al-Rojban	31º 56′N	12º 05′E	-	1964-2010	Monthly
Al-Bayda	32º 45′N	21º 42′E	-	1979-2010	Monthly
Mizda	31º 27′N	12º 59′E	-	1980-2010	Monthly
Al-Fatayah	32º 41′N	22º 40′E	-	1989-2010	Monthly
Tubruq	32º 06′N	23º 56′E	62062	1985-2010	Monthly

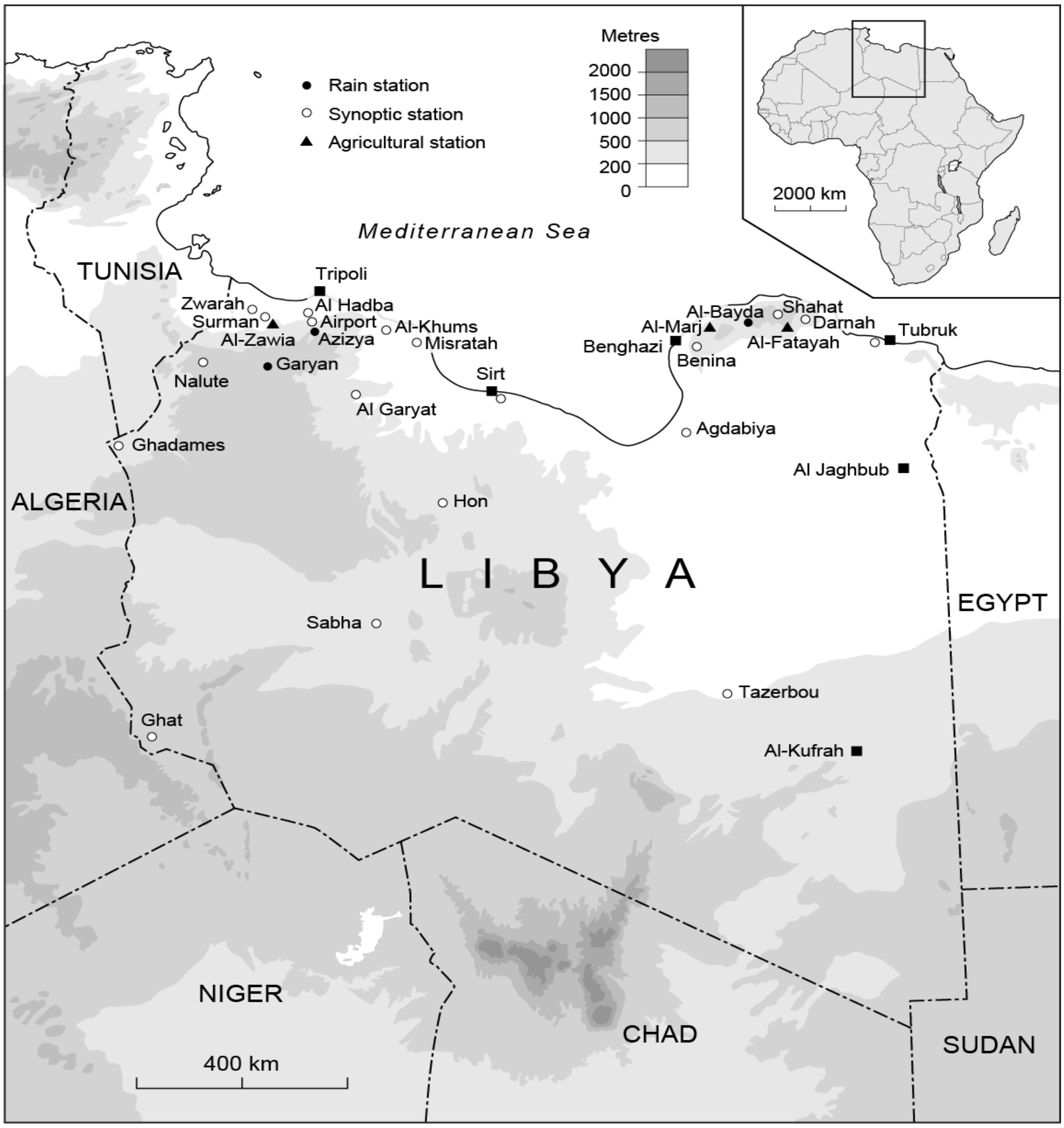


Fig. 3.1: The distribution of meteorological stations across Libya.

3.3.1 Data quality and management

The large amount of original climatic data have been used within this thesis was stored in Microsoft Word (1998) document and was quality-checked at the Data Processing Unit (DPU) in the Climate Department of the LMNC in Libya.

A quality control was performed on the data series of temperature, rainfall, relative humidity, sunshine duration and wind speed which had three main obstacles were encountered when processing the data:

I. 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.

II. A number of data quality issues arose during the transfer of the data into a database structure, these included: missing data, poor dataset management; incomplete or inaccurate entry of meteorological station records:

(i) Failure to transfer records during upgrades (data on paper into electronic data) at the DPU;

(ii) missing days, months or years at a number of stations (the majority of these stations have been excluded from the present study);

(iii) changes (or failure) in observation practice (Tazerbou, Al-Garyiat); changes in station location (Al-Zawyia, Al-Garyiat); and,

(iv) interruption of observation (e.g.

(v) Tazerbou and Sabha). Despite the availability of original records, some files were missing or too many readings were made.

III. 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, LMNC in Libya 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. The extreme and anomalies data have been checked by comparing with climatic Normals (averages computed for a uniform and relatively long period, normally comprised of 30 consecutive years of data - WMO Technical Regulations) derived from adjacent stations.

3.3.2 Localised data quality and checks

In this study, the Anderson-Darling (A-D), (1952) homogeneity test (Grous, 2013) A-D is one of the most powerful tests detecting departure from normality; it gives very high p-value statistics (0.987-0.947) and it is easy to use. The A-D was used to detect non-homogeneity within the climatic parameters: temperature, precipitation, relative humidity, surface wind speed, sun-shine duration, and atmospheric pressure (see Appendix 3.1 for more details).

Temperature series for the period 1945-2010 at most stations were shown to have homogeneous data. In contrast, rainfall series for the period 1945-2010 were shown as inhomogeneous at most stations, particularly at rain gauge stations across Libya, due to the fact that most of these stations are not official branches of the LNMC and furthermore, their rainfall data is questionable to a certain extent. Homogeneous data is found for wind speed, relative humidity series at the majority of stations, with less homogeneous data for sun-shine duration, particularly at inland stations.

The variability in spatial and temporal climate characteristics are derived from daily, monthly and annual climate data from meteorological stations for the 66-year period 1945 to 2010. Initially, the dataset consisted of 45 meteorological stations; however, a total of 28 meteorological stations are found to be suitable for further investigation, those excluded contained either large data gaps/missing data, or exhibited inhomogeneous structures; these are discussed in further detail below.

Missing temperature and rainfall data were a significant issue for some stations after 1945, as detailed in subsequent chapters. Daily datasets of temperature (maximum, minimum, mean average) and precipitation are available for the period 1956-2010 (55 years) at all (18) synoptic stations except for Al-Garyiat (1968), Ghat (1979) and Tazerbou (1963). 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 DPU in the LMNC.

A brief examination of the data is undertaken in this section as the following chapters will consider specific climatic parameters, without consideration of the complete dataset, as such this section will consider data completeness and quality of daily and monthly temperature (maximum, minimum, and mean average temperature) and precipitation data. The quantity of missing data (as percentage of complete series) are detailed within the specific chapters, with rate average missing data for the period 1945-2010 of 1.08% for temperature and 0.86% for rainfall. The number of missing months does not exceed 3.45% for temperature and 3.76% for rainfall at any station.

Where possible records with missing values of less than three months and ≤11 missing days are filled using the two or three adjacent stations with comparable characteristics r > 0.8 (for temperature) and r > 0.7 (for precipitation) (Al-Jadide H., 1998). Where good records are unavailable from adjacent stations data infilling is undertaken using the average of the values of the previous and successive years, with a missing value of the first and last years of the data-series filling by the long-term climatological mean (Normals).

After infilling, the Anderson Darling test for normality detection was applied once again to all the series, were finally no series contained more than 2.5 % of missing values and no missing monthly record since the 1990s. A number of non-climatic influences have affected the meteorological stations across Libya, including:

(i) Changes in observation times and methods;

(ii) Changes in instrumentation, exposure and measurement techniques, particularly, at the climatic and rainfall stations; and

(iii) Changes in the environment and land use around the stations, particularly with respect to the development cities in the coastal regions. The potential impact of these influences are discussed within each the individual case study chapters.

Where there is evidence of this the stations or station data has been carefully reviewed and this considered within the analysis. Changes in instrumentation my explain non-homogeneity within series, though this was not identified within the series used within this study.

3.4 DATA ANALYSIS

In respect of the objectives outlined in Chapter one, a number of statistical approaches are used for the analysis of temporal and spatial changes in temperature, precipitation and evapotranspiration.

3.4.1 Statistics (descriptive statistic tests)

A number of statistical approaches are used: normalized and percentiles, graphical method measures of association, graphical trend analysis methods and number of statistical trend detection methods.

3.4.1.1 Normalized and Percentiles

To facilitate trend computations between the stations, all data are normalized by their long-term 66-year average. Percentiles are a measure of the relative position of a single value within a data set (see Appendix 3.2 for more details). The absolute value of this anomaly time series is also tested for trends to identify changes in climatic parameters (Ramos 2001; Fernandes et al., 2007; Luis et al., 2009). Five particular percentiles are used in this study: P10, P25, P50, P75 and P90 for annual precipitation data during the period 1945-2010 and for the reanalysis NCEP/NCAR-(1948-2010) and ERA-Interim (1979-2010) datasets of mean average temperature and precipitation for three stations: Ajdabyia, Hon and Nalute (Poccard et al., 2000; Ramos 2001; Bartolini et al., 2008).

3.4.2 Graphical methods

A number of descriptive tests are used in this study as a simple way to describe data, and are applied to show and summarize climatic data in a meaningful way.

3.4.2.1 Histogram

A histogram is a graph that represents the quantity of values, it used to graphically summarize and display the distribution of annual precipitation datasets. The main purpose of the test was to clarify the presentation of data to detect linear or nonlinear trends. In this thesis, histograms are used to clarify the presentation of monthly and annual precipitation data for the 28 stations across Libya.

3.4.2.2 Box plot

Box plot descriptive diagrams are applied within this thesis to clarify spatial variability of annual precipitation of 28 stations across Libya for the period 1945-2010 (Ichiyanagi et al., 2007). Moreover, box plot diagrams are also applied to clarify variability of observational and modelled NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010) data for temperature and precipitation of three stations (Ajdabyia, Hon and Nalute) across Libya (see Appendix 3.3 for more details).

3.4.3 Measures of Association

A measure of association is a statistical association used to indicate the strength of the relationship between two variables and can be either positive or negative ranging from -1.0 to +1.0. Pearson Product-Moment Correlation Coefficient (*r*) and the nonparametric Spearman’s correlation coefficient (*rho*) are the most popular correlation coefficient used to describe the strength of the linear association between two variables.

3.4.3.1 Correlation coefficient

Relationships between climatic parameters have been estimated using correlation coefficient measurements to clarify association between two designated variables and/or two periods to indicate the strength and direction of the linear relationships between the variables.

Pearson Product-Moment Correlation Coefficient (*r*) test is widely used (Hatzianastassiou et al., 2008; Macdonald et al., 2008; Kafle and Bruins 2009; see Appendix 3.4 for more information). The test is applied to detect the strength and direction of relationships between potential evapotranspiration and climatic parameters; maximum and minimum temperature, relative humidity, surface wind speed, sun-shine duration and atmospheric pressure. Moreover, this test is applied to detect the relationship between Penman-Monteith and Thornthwaite potential evapotranspiration and is also used to determine if significant correlations exist between observational data and reanalysis NCEP/NCAR and ERA-Interim data for the three stations.

Spearman correlation coefficient (*rho*; see Appendix 3.5 for more information) is used to detect the relationship between observational data and modelled NCEP/NCAR and ERA-Interim data for precipitation; it is also used to detect the relationship between potential evapotranspiration ($PET_{P\text{-}M}$) and annual precipitation. A significant linear relationship between two variables is assessed based on *r* value and the standard normal distribution (see Appendix 3.6).

3.4.3.2 Time series plots

Temporal and spatial changes in temperature and precipitation are plotted using 11-day moving average to examine variability and changes in daily maximum, minimum and mean average temperature and precipitation across Libya (1956-2010). The 7-year moving average is applied to analyses changes in annual minimum, maximum and mean average temperature for the 18 stations across Libya (1945-2010; Stafford et al 2000; Domonkos and Tar 2003; Bartolini et al., 2008; Kafle and Bruins 2009). Changes in annual precipitation data of all (28) meteorological stations for the period 1945-2010 across Libya are analysed using the 10-years moving average (Goldreich, 1995; Steinberger and Gazit-Yaari 1996; Stafford et al 2000; Hatzianastassiou et al., 2008; Kafle and Bruins 2009; Reiser and Kutiel 2011; Altava-Ortiz et al., 2011). To make trends of the climatic parameters easier to see and identify potential decision points, the 11-day, the 7-year and 10-years moving average are applied.

In additional, time series plots are used to assess changes in climatic parameter data of 16 meteorological stations also for the extremes temperature (16 stations) and precipitation (14 stations) across Libya are for the period 1961-2010.

3.4.4 Statistical trend detection methods

Hypothesis testing or significance testing is a method for testing a claim or hypothesis about a parameter within a population.

3.4.4.1 Regression

Regression analysis is the statistical technique that identifies the relationship between two or more quantitative dependent and independent variables. The technique is used to find the equation that represents the relationship between the two variables. A simple linear regression analysis is known by least square method (Thom, 1966), is used to show that the relation between an independent variable X and a dependent variable Y is linear (see Appendix 3.7 for more details). The statistical significant of the linear regression coefficient is estimated using t-test statistic (Jun et al., 2012). A simple linear regression method is recommended for general use by the World Meteorological Organization (Mitchell et al., 1966) to determine trends in evapotranspiration.

In this thesis, the test is applied to detect trends in monthly and annual potential evapotranspiration ($PET_{P\text{-}M}$) for 16 stations across Libya (1961-2010), with the statistical significance of the linear regression coefficient estimated using the t-test statistic (Thomas 2000; Shenbin et al., 2006; Kirono et al., 2009).

3.4.4.2 T-test

The statistical significance of the linear regression line is evaluated using the Student’s t-test. The student’s t-test is most commonly applied when the test statistic would follow a normal distribution, if the value of a scaling term in the test statistic were known. A significance test for the regression coefficient can be identified by the t-test statistic (see Appendix 3.8 for more details).

In this thesis, the test is used to determine the significant mean monthly and annual potential evapotranspiration ($PET_{P\text{-}M,}$) at 16 stations (1961-2010). Moreover, the t-test is used to determine the significant relationships between observed and reanalysed NCEP/NCAR and ERA-Interim data for temperature at the three stations; Ajdabyia, Hon and Nalute, it is also partly applied to support the significance trends for climatic parameters: temperature, precipitation and potential evapotranspiration (Thomas 2000; Shenbin et al., 2006; Kirono et al., 2009; Jun et al., 2012).

3.4.4.3 Standard Error bars

Error bars provide a graphical illustration of the variability of data; they are applied to visually compare two quantities to determine whether differences are statistically significant at one standard error (68.2%), two standard errors (95.4%) and three standard errors (99.7%). In this study, error bars are used to show the differences between annual and seasonal temperature (maximum, minimum and mean average) and daily, monthly, seasonal and annual precipitation data during two different time periods. The observed and reanalysis NCEP/NCAR and ERA-Interim data of mean average temperature and annual total precipitation are also considered.

3.4.4.4 Mann-Kendall Trend Test

The Mann-Kendall (MK) test was applied to detect the significance of trends in temperature, precipitation and evapotranspiration data; with the MK test more suitable where monotonic trends are found in data series. Trends in maximum, minimum and mean average temperature at all (18) meteorological stations (1945-2010) are analysed using the Mann-Kendall test (Mann, 1945; Mitchell et al., 1966; Sen, 1968; Kendall, 1975; Sneyers, 1992), recommended by the World Meteorological Organization (Mitchell et al., 1966) and applied extensively in previous studies (Ben-Gai et a., 1999; Hasanean 2001; Wibig and Glowicki 2002; Domonkos and Tar 2003; Hasanean and Abdel Basset 2006; Bartolini et al., 2008; El Kenawy et al., 2009; Tayanc et al., 2009; Zhou and Ren 2011), to identify the significance (0.05) of trends e.g. in annual potential and actual evapotranspiration, temperature and precipitation. The significance of the trends is calculated using the MAKESENS Microsoft Excel template developed by the Finnish Meteorological Institute: Helsinki (Salmi et al., 2002; see Appendix 3.9 for more details).

The Mann-Kendall trend is applied to detect significant trends of daily, monthly, seasonal and annual temperature (minimum, maximum and mean average) also annual dry bulb temperature for 18 synoptic stations (1945-2010; (Ben-Gai et al., 1999; Hasanean 2001; Wibig and Glowicki 2002; Domonkos and Tar 2003; Hasanean and Abdel Basset 2006; Bartolini et al., 2008; El Kenawy et al., 2009; Tayanc et al., 2009; Zhou and Ren 2011). The temporal and spatial patterns of changes and trends for warm extremes; warmest day (TXx), warm days (TN90p) and warm nights (TX90p) and the cold extremes; coldest night (TNn), cold night percentile (TN10p) and cold day percentile (TX10p) for the 16 stations (1961-2010) are also considered.

The test is applied to detect significant trends in monthly, seasonal, and annual rainfall for all (28) stations (Salmi et al., 2002; Cislaghi et al 2005; Ichiyanagi et al., 2007; Hatzianastassiou et al., 2008; Kysely 2009; Altava-Ortiz et al., 2011; Lupikasza et al., 2011; Unal et al 2010; Altava-Ortiz et al., 2011; Caloiero et al., 2011; Tabari and Talaee 2011). Number of precipitation days and extremes precipitation; intensity of precipitation (IP), consecutive dry days (CDD), consecutive wet days (CWD), heavy precipitation days (R10), and maximum 1day precipitation (Rx1day) for 14 stations (1961-2010) are also considered (Reiser and Kutiel, 2011; Lupikasza 2010; Hidalgo-Munoz et al., 2011; Twardosz et al., 2012).

Trends in potential and references evapotranspiration for 16 synoptic stations across Libya (1961-2010) assessed (Thomas 2000; Yu et al., 2002; Fernandes et al., 2007; Abtew et al., 2011).

Moreover, trends in climatic parameters; relative humidity, surface wind speed, sunshine duration and atmospheric pressure are assessed (Aksoy., 1999; Makrogiannis and Sahsamanoglou, 1999; Abu-Taleb et al., 2007.

Significant trends in the observed and reanalysis NCEP/NCAR and ERA-Interim data of mean average temperature and total precipitation are detected based on the Mann-Kendal test (Nastos et al., 2011; Proutsos et al., 2010).

3.4.4.5 Sen's Slope Estimator

The non-parametric Sen's slope test is the most popular nonparametric technique for estimating linear trend and can be significantly more accurate than simple linear regression. For this nonparametric alternative method for finding a slope, the slopes between each set of points in time and the median value of all these slopes are calculated first (see Appendix 3.10 for more details). In this study the non-parametric Sen's slope estimator test is used to detect the slope for climatic data; temperature, precipitation, evapotranspiration and the climatic parameters; wind speed, relative humidity and sun-shine duration (Salmi et al., 2002).

3.4.4.6 The Mann-Whitney test

The Mann–Whitney–Wilcoxon (U-test; Wilcoxon, 1945) is a rank-order; nonparametric test developed by H. B Mann and D.R Whitney in 1947. The Whitney test is used as an alternative to the t-test where the data are not normally distributed and/or the sample is large (Wibig and Glowicki 2002; Hasanean and Abdel Basset 2006; Soltani et al. 2011). The test can detect differences in shape and spread as well as just differences in median value (see Appendix 3.11 for more details).

The Mann-Whitney test is applied to evaluate whether the medians on a test variable differ significantly (95% confidence level) between two groups of daily maximum, minimum and mean average temperature during two periods (1956-1982 and 1983-2010) and whether or not trends in monthly and annual precipitation series at 28 meteorological stations across Libya are significant (0.05 level). In addition the Mann-Whitney test is applied to evaluate whether the medians on a test variable differ significantly (95% confidence level) between the observed and reanalysis NCEP/NCAR and ERA-Interim data of mean average temperature and annual total precipitation.

3.5 Potential evapotranspiration

The mean daily and monthly potential evapotranspiration (PET) at 16 synoptic stations (1961-2010) across Libya are estimated by Penman-Monteith (1990). According to the FAO, (Allen et al 1994a; 1994b and 1998; Raja and Katerji 2000), reference evapotranspiration is calculated based on values of potential evapotranspiration and crop coefficient (Kc).

The Kc values is dependent on type of crop and changing characteristics of crop over the growing season and also on the climate parameters in particular, on humidity and wind speed.

3.5.1 Penman-Monteith method ($PET_{P\text{-}M}$)

Penman-Monteith (PM) is used to determine daily potential evapotranspiration (PET) for the period 1961-2010 [Equation 3.1] (Thomas 2000; Yu et al., 2002; Shenbin et al., 2006; Abtew et al., 2011). The PM was calculated using the CropWat 8.0 programme, which requires the following input parameters: temperature (maximum and minimum), relative humidity, sunshine duration and winds peed.

The Penman–Monteith model predicts the evapotranspiration rate of the total amount of water as evaporation and transpiration from the earth’s surface, based on commonly measured weather data (solar radiation, temperature, vapour content and wind speed). Many software packages already use the Food and Agricultural Organisation of the United Nations (FAO) developed the FAO Penman-Monteith equation to assess the reference evapotranspiration, following identified differences between observed and modelled evapotranspiration rates.

CROPWAT 8.0 program, a software package developed by the FAO, for determining levels of irrigation is applied in this thesis, for estimating potential evapotranspiration. CROPWAT 8.0 is a Windows program based on the previous DOS versions. ; It calculates crop conditions water requirements and irrigation requirements based on soil, climate and crop data. CLIMWAT for CROPWAT contains monthly data from meteorological stations contained on five separate diskettes. Monthly averages of maximum and minimum temperatures, mean relative humidity, wind speed, sunshine hours, radiation data as well as rainfall and ETo calculated with the FAO Penman-Monteith method are listed on the diskettes for mean long-term conditions

.

To calculate a daily potential evapotranspiration PET based on the FAO Penman-Monteith; (Allen et al. 1998) using different weather parameters (Example determinations of ($PET_{P\text{-}M}$) with mean monthly data using Penman-Monteith formula (see Appendix 3.12 for more details).

The Penman-Monteith method for *PET* (mm/d) can be expressed as:

$$PET = \frac{0.408\,\Delta\,(Rn - G) + \gamma\,\frac{900}{T+273}\,u^2(e\text{ş} - e_{\mathrm{a}})}{\Delta + \gamma\,(1 + 0.34\,u^2)} \qquad \text{[Equation 3.1]}$$

Where,

PET	reference crop evapotranspiration (mm/d),
Rn	net radiation at crop surface (MJ/ m^2d),
G	soil heat flux (MJ/ m^2d),
T	average temperature (°C),
U_2	wind speed measured at 2m height (m/s),
Δ	slop vapour deficit (kPa),
γ	psychometrics constant (kPa °C),
(e_a –e_x)	vapour pressure deficit (kPa) and
900	conversion factor

3.5.2 The Thornthwaite approach (PET-$_{TW}$)

Thornthwaite (1948) found empirically that the relationship between mean monthly temperature (T) and potential evapotranspiration. The Thornthwaite and Mather's (1955) method of estimating potential evapotranspiration is based on air temperature.

The $PET_{T\text{-}W}$ estimates are based upon a 12-hour day (amount of daylight) and a 30-day month was represented by the formula (Yoshida, 1981);

$$PET_{T\text{-}W} = 1.6\,(10\,T/I)^{a} \qquad \text{[Equation 3.2]}$$

Where, $PET_{T\text{-}W}$ = potential evapotranspiration in mm

T= monthly mean temperature in °C

b = correction factor for actual day length of hours and days in a month,

I = is annual heat index defined as the summation of the 12 monthly heat indices (i): $i = (t/5)^{1.514}$,

a = cubic function of I and

$a = 6.75 \text{ X } 10^{-7} \text{ X } - 7.71\text{X } I^3 - 7.71\, I \text{ X } 10^{-5} \text{ X } I^2 + 1.792 \text{ X}10^{-2} \text{ X } I + 0.49239$

3.5.3 Actual evapotranspiration (reference evapotranspiration)

The UN Food and Agriculture Organization (FAO) recommended using the (Penman-Monteith model 1990) to estimate “reference” evapotranspiration (ET_0) on croplands (Allen et al., 1998). The estimation of actual evapotranspiration, reference (actual) evapotranspiration (AET) is estimated by using the Penman potential evapotranspiration based on the crop coefficient (Kc) approach (Jensen et al. 1990; Allen at al. 1998; Kotsopoulos et al., 2003).

The actual evapotranspiration (AET) estimated by reference crop evapotranspiration (ETc) [Equation 3.3] depending on the Penman-potential evapotranspiration (ETP) and crop coefficient (Kc) of the Alfalfa crop based on relative humidity, wind speed, soil evaporation, crop growth stages and crop development state which is estimated by 0.85 mm/d for all period of time at all the selected station across Libya and following the form:

$$ETc = Kc * ETO \qquad \text{[Equation 3.3]}$$

Where: Etc crop evapotranspiration (mm d^{-1}),

Kc crop coefficient (dimensionless),

Etc reference crop evapotranspiration (mm d^{-1})

The periods over which evaporation are considered varies, from daily d^{-1}, monthly M^{-1}, season S^{-1} and annual a^{-1}, these symbols are used throughout this thesis.

3.6 REANALYSIS METHODOLOGY

Reanalysis products are created by assimilating observations from multiple sources (e.g. radiosondes, satellite products, surface pressure measurements etc.) into a climate model. This allows estimation of the complete past state of the atmosphere using an atmospheric ocean coupled global climate model. By using proximate observations and knowledge of the mechanics of the climate system it is possible estimate the state at locations and times for when there were no observations. The American NCEP–NCAR reanalysis model (1948-2010) and The ERA-Interim is the most recent global atmospheric reanalysis (1979-2010) for temperature and precipitation are applied for three different synoptic stations across Libya.

3.6.1 Site selection

The four most widely used reanalysis datasets have been created by the National Centres for Environment Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF):

i the NCEP–National Centre for Atmospheric Research (NCAR) Reanalysis Project (NNRP),

ii the NCEP Climate Forecast System Reanalysis (CFSR),

iii the 40-yr ECMWF Re-Analysis (ERA-40); and

iii the interim ECMWF Re-Analysis (ERA-Interim),

Comparison of surface-station temperature and precipitation observations at three stations across Libya (1948-2010) are made with grid point analyses available from the National Centre for Environmental Prediction–National Centre for Atmospheric Research (NCEP–NCAR) reanalysis project for the period 1979-2010, and the ERA-

Interim latest global atmospheric reanalysis dataset (1948-2010) produced by the European Centre for Medium Range Weather Forecasts (ECMWF).

3.7 SUMMARY

This chapter has identified that the use of climatic data requires a complete awareness of the different statistical tools available when using temperature, precipitation, and evapotranspiration data, which require careful assessment concerning data quality and reliability.

There are number of approaches to climatic data analysis, which vary as identified within this chapter. Descriptive approaches can be applied as represented by a number of tests and approaches, such as time series, histogram, anomalies, correlation coefficient, skewness, error bars and box plots, as well as the use of the Anderson-Darling normality test.

Analytical approaches used to assess climatic data trends and significance levels are: the non-parametric Mann-Kendall test (Mann 1945, Kendall 1975); the Mann-Whitney test (U-test; Wilcoxon, 1945) and Sen’s slope (Sen, 1968). For determining effective rainfall, the U.S. Department of Agriculture's Soil Conservation Service method for estimating effective rainfall has also been applied. The following chapters (4-7) apply the methodologies identified within this chapter. These chapters will study the changes and trends in temperature, precipitation, and evapotranspiration and compare the observation results to those derived from reanalysis data.

Chapter 4

TEMPERATURE

This chapter examines temporal and spatial variability in temperature using daily (1956-2010 – 55 years), monthly (1945-2010 - 66 years) and annual data. Maximum, minimum, mean average, dry bulb and temperature extremes for 18 synoptic stations across Libya are considered. Comparison of temperature among population, carbon dioxide and cloud cover is also considered.

Temperature is one of the most easily measured climatic variables, as such changes within the climate can be directly assessed and series are generally longer than for other climatic variables. The implication of climate change to temperature are considerable in the Mediterranean and North Africa regions, considering the potential sensitivity of agriculture and population to temperature change and the pressure placed on water resources (Loaiciga et al., 2000; Gonzales, 2001; Huntingford et al, 2005; Kafle and Bruins, 2009). Studies examining global, regional and localised temperature change have increased over the last couple of decades, as a result of increasing recognition of the spatial variability in the rates of change over the last couple of decades (e.g. Hansen et al., 2001; Della-Merta et al., 2007), regional (e.g. Ben-Gai et al., 1999; Hasanean, 2001; Xoplaki et al., 2003; Bartolini et al., 2008; Bermejo and Ancell, 2009) and local studies (e.g. El-Tantawi, 2005; El-Kenawy et al., 2009).

4.1 STUDY AREA

The climate of coastal 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 climate of Libya is influenced by a variety of topographical and geographical parameters, with varying significance within the two (coastal and inland) regions, with considerable temporal and spatial variability in temperature identified across Libya (Fig. 4.1). Temperature is partly controlled by the Al-Gibli a south-westerly dry-hot wind from the end of spring through the summer months and a north-western cold wind in winter. Therefore, some of the coastal and the inland region of the country, particularly, the Sahara region are extremely vulnerable to high diurnal variability.

The mean annual average temperature across Libya is 20.8 ° C, with an annual average range between 14.2 ° C to 21.0 ° C at coastal stations and between 21.3 ° C and 23.4 ° C at inland stations during the period 1945-2010. The highest temperature (57.8 ° C) was observed on 13th September 1922 in Al-Aziziya city (coastal station), with the lowest recorded temperature: -8.3 ° C recorded at Ghadames, (inland station) on 11th January 1935. The western-coastal and inland regions are historically prone to heat waves leading to frequent drought events in Libya, with particularly severe arid phases in the central and southern regions. The initial division of Libya into two regions (coastal and inland) will permit further analysis into the potential mechanisms responsible for changes in temperature.

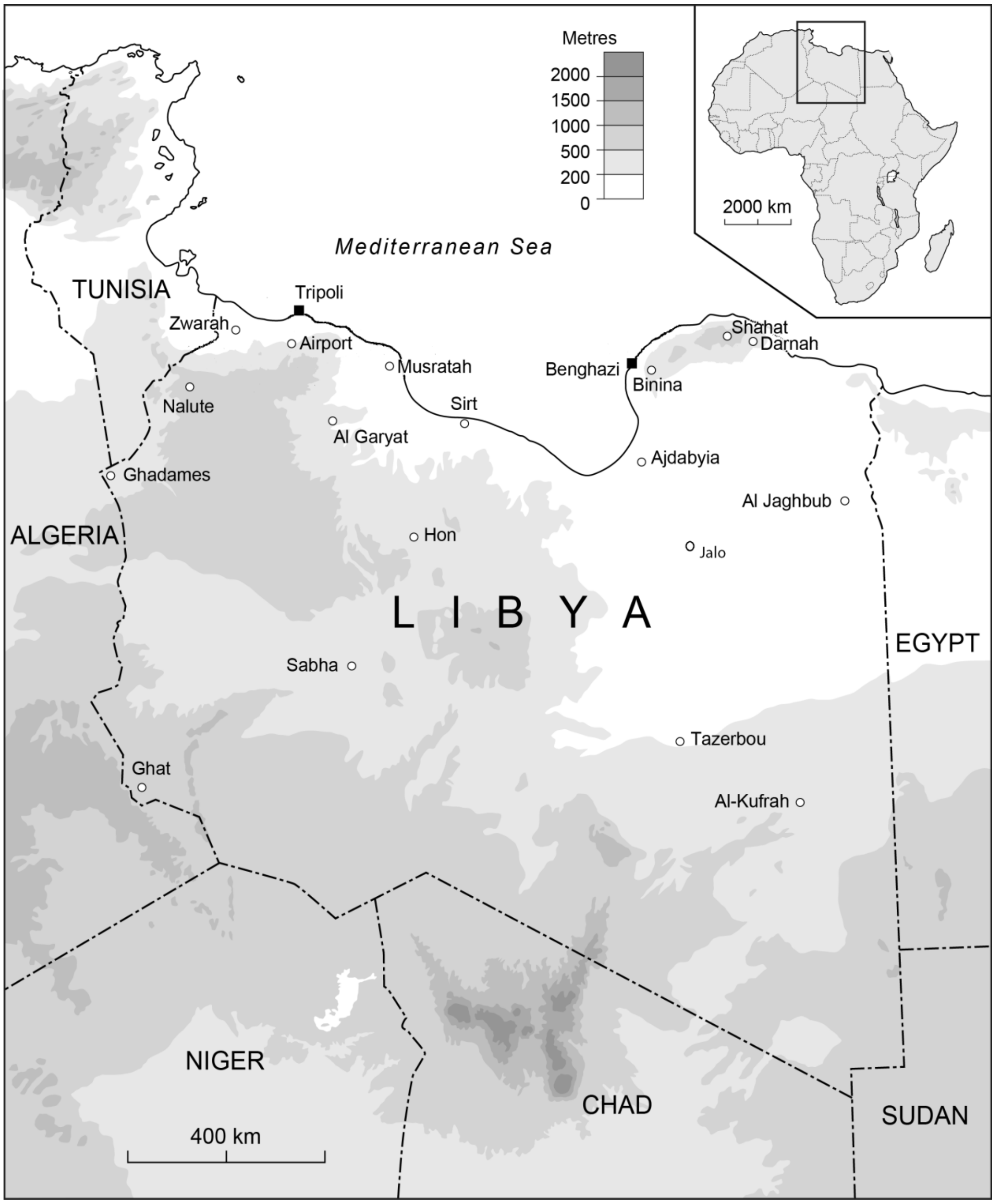


Fig. 4.1: The distribution of synoptic stations within this study across Libya.

4.2 DATA QUALITY (SOURCE) AND MANAGEMENT

Temperature data were collected from the Libyan National Meteorological Centre (LNMC). The sample of the present study involves 18 synoptic stations selected from a total of 42 meteorological stations distributed across Libya. Nine stations were selected along the Mediterranean coast (coastal stations): 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 a^{-1} and a mean annual number of rainy days of 55 days. The southern part (inland stations) is located south of 30º 45′ N and represented by nine synoptic stations: Ghadames, Al-Garyiat, Hon, Jalo Al-Jaghbub, Sabha, Ghat, 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%, with an average precipitation not exceeding 100 mm a^{-1} at most of stations.

Daily and monthly data are available for mean maximum, minimum, mean average temperature, and dry bulb temperature were the mean monthly average temperature is computed from their corresponding daily values calculated from the maximum and minimum temperatures over the month, (maximum + minimum temperature /2) for stations across Libya. Warm and cold extremes based on daily minimum and maximum temperature are only available for the period 1961-2010 (50 years) and for 15 stations (with Al-Garyiat, Tazerbou and Ghat not included).

This study focuses on data recorded for the period 1945-2010, as dataset integrity improves considerably after 1945 at the majority of coastal stations, with missing data a significant issue prior to 1945. Daily datasets for the period 1956-2010 and monthly datasets for the period 1945-2010 for all examined stations are used in this thesis and were checked for completeness. An analysis of the data was undertaken to ensure that the data quality and integrity was high, with any year consisting of missing data exceeding three months, and/or, any month with ≥11 missing days being removed; approaches recognised by Data Process Unit (DPU) in the LMNC.

Table 4.1: The data used within the study, with missing temperature data

Stations	Daily	Monthly	Missing data (%)			Months and annual missing data
	data period	data period	T. Min	T. Max	T. Mean	
Zwarah	1956-2010	1945-2010	0.84	1.25	1.52	1949
T. Airport	1956-2010	1945-2010	0	0	0	
Nalute	1956-2010	1945-2010	0.22	0.22	0.22	(2/1949), (9/1969) and (5/1989)
Musratah	1956-2010	1945-2010	0	0	0	
Sirt	1956-2010	1946-2010	0	0	0	
Ajdabyia	1956-2010	1946-2010	0	0	0	
Binina	1956-2010	1945-2010	0	0	0	
Shahat	1956-2010	1945-2010	0	0	0	
Darnah	1956-2010	1945-2010	0	0	0	
Ghadames	1956-2010	1945-2010	1.32	2.23	2.29	(8.9/1946),(11/1948),(7/1961),(9,10/1969),(9/1997) and (1987)
Al-Garyiat	1968-2010	1968-2010	3.24	3.5	3.45	(1/1968), (9,10/1969), (8,9/1977), (5/1980), (4,5/1988) and (1989)
Hon	1956-2010	1948-2010	2.12	1.81	2.65	(1/1948), (9,10/1969), (1/1981), (12/1982) and (1995)
Jalo	1958-2010	1950-2010	1.27	2.55	2.62	(1950), (12/1951), (10/1952), (9/1969) (8/9/1991) and (8,12/1994)
Al-Jaghbub	1957-2010	1951-2010	0.82	1.28	1.42	(9,10/1969), (8/1999), (5/2003) and (3/2006)
Sabha	1956-2010	1947-2010	2.12	2.41	2.66	(1960), (8,12/1961), (9,10/1969) and (7/1996)
Ghat	1979-2010	1979-2010	1.05	1.05	1.05	(4/1979),(9,10/1969) and (10/1986)
Tazerbou	1963-2010	1963-2010	2.25	2.94	3.12	(1,3/1962), (9, /1969), (6/1977), (9,11/1980), (2005) and (2/2006)
Al-Kufrah	1957-2010	1946-2010	0.34	0.41	0.45	(9,10/1969) and (4,6/1949)

The number of missing months (1945-2010) at coastal stations ranges between 0.02% (Nalute) and 1.52 % (Zwarah), with comparable missing monthly data at the inland stations ranging from 0.92% (Al-Jaghbub) to 3.45% (Al-Garyiat), with no missing monthly data at most of coastal stations; Tripoli Airport, Musratah, Sirt, Ajdabyia, Binina; Shahat and Darnah (Table 4.1).

4.3 MAXIMUM TEMPERATURE

The climate of Libya is varied, from the Mediterranean regime found in the Green Mountain region in north-eastern Libya, through sub-arid tropical regimes (coastal area), to arid and hyper-arid climates in southern Libya. The Libyan climate is highly varied, with most of the climates exhibiting differing degrees of temporal and spatial variability, particularly with regard to precipitation and temperature.

4.3.1 Multi-decadal variations and trends in maximum temperature

The mean monthly maximum temperature across Libya ranges from 17.8 °C to 45.4 °C, with extreme maximum temperature in the coastal region, ranging between 42.0 °C (Shahat) and 53.0 °C (Zwarah, August 1959) and from 45.8 °C (Ghat) to 54.2 °C (Ghadames, June 1975) at inland regions. The coefficient of variation (COV) of mean annual maximum temperature is 2.6 and 2.7 % at coastal and inland stations respectively, indicating that the main factor influencing spatial variability in COV is the Mediterranean. The COV in annual maximum temperature ranges between 1.9 and 2.7%, with the highest at Ghadames (3.8%).

4.3.2 Daily variations and trends in maximum temperature

Daily maximum data are available for 16 coastal and inland stations (with Ghat and Al-Garyiat) not included during the period (1956-2010). The study period is divided into two series of equal length (27 years), 1956 to 1982 and 1983 to 2010, referred to as period 1 and period 2, respectively. The two study periods are used to assess and provide comparison in rate of change.

Statistical analysis of the 27 years periods and the nearest comparable 30 year period (1956-1985 and 1980-2010) was undertaken; this identifies no apparent difference in the statistical character of the two groups. As such the analysis within this work 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 issues with data limitation.

In order to examine temporal changes in temperature, a time series of an 11-day moving average of the mean daily maximum temperature for the periods 1956-1982 and 1983-2010 has been analysed. The daily data of two periods are considered at the 16 synoptic stations as these records provide a more complete depiction of temperature change. Changes in the maximum 11-day, daily temperature shows that period 2 is characterized by generally higher temperatures compared to the 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; Fig. 4.2; see Appendix 4.1 for figures for all sites.

The Mann-Whitney test (Wibig and Glowicki 2002; Hasanean and Abdel Basset 2006; Soltani et al. 2011) is used as an alternative to the t-test where the data are not normally distributed and/ or the sample is large. Significant differences in trends of mean daily annual maximum temperature were calculated using a nonparametric approach. The Mann-Whitney test is applied when comparing between two timeframes, with the second period significantly higher (95% confidence level) at Zwarah, Nalute, Sirt, Ajdabyia, Binina and Sabha.

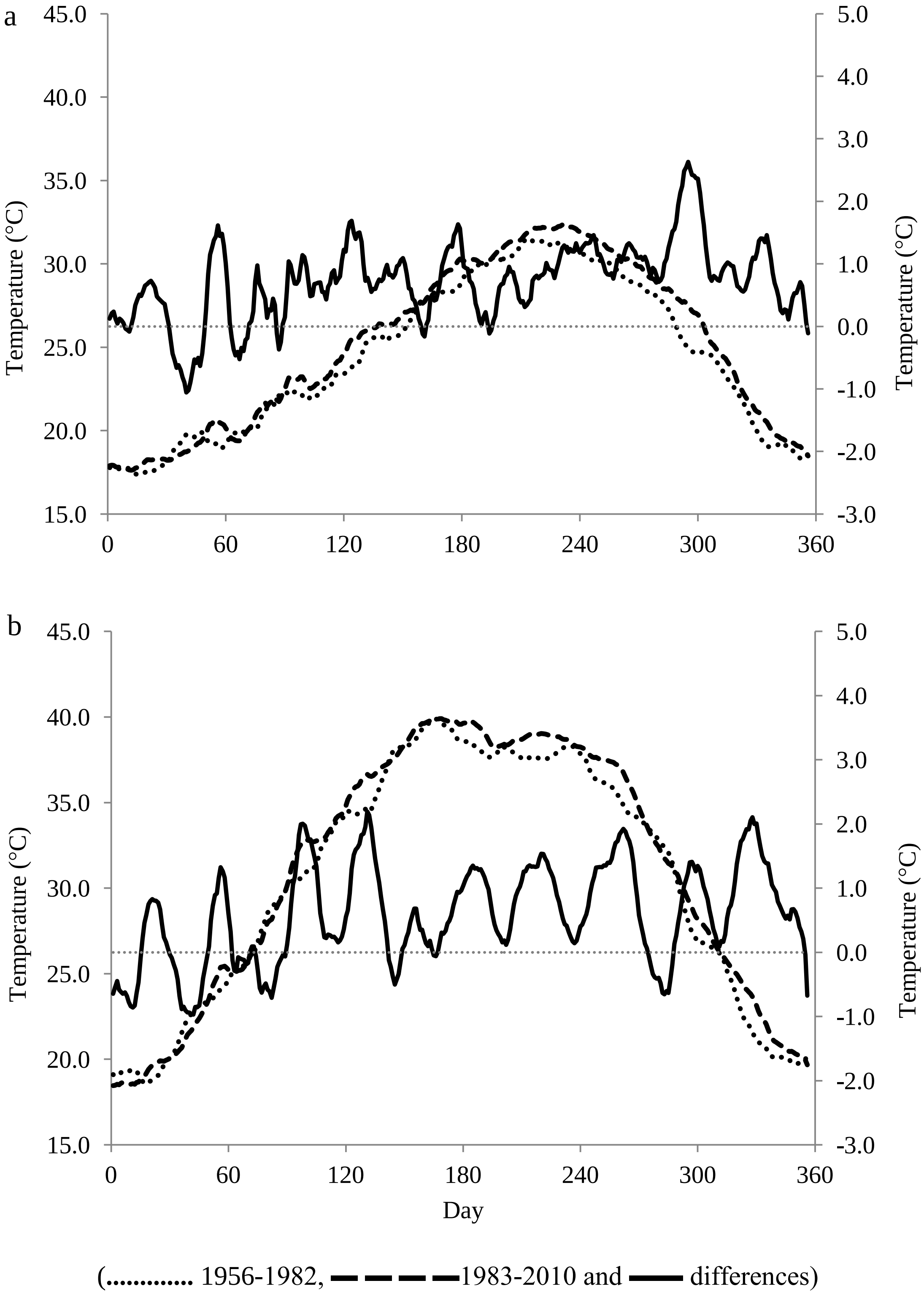


Fig. 4.2: Annual means 11-day moving averages of the mean daily maximum temperature for the two periods 1956-1982 and 1983-2010 at a) Zwarah and; b) Sabha.

4.3.3 Monthly variations and trends in maximum temperature

The estimation of changes in monthly maximum for the study stations across Libya (1945-2010) are based on the non-parametric Mann-Kendall test (Mitchell et al., 1966; Sneyers, 1992), which is used to estimate the statistical significant of temperature trends within the series. The trends are identified and; the non-parametric Sen's slope test is applied to determine change per unit time, to detect the significance of the trends. The statistical significances levels are (*** = 0.001 level of significance, ** = 0.01 level of significance, * = 0.05 level of significance, + = 0.1 level of significance).

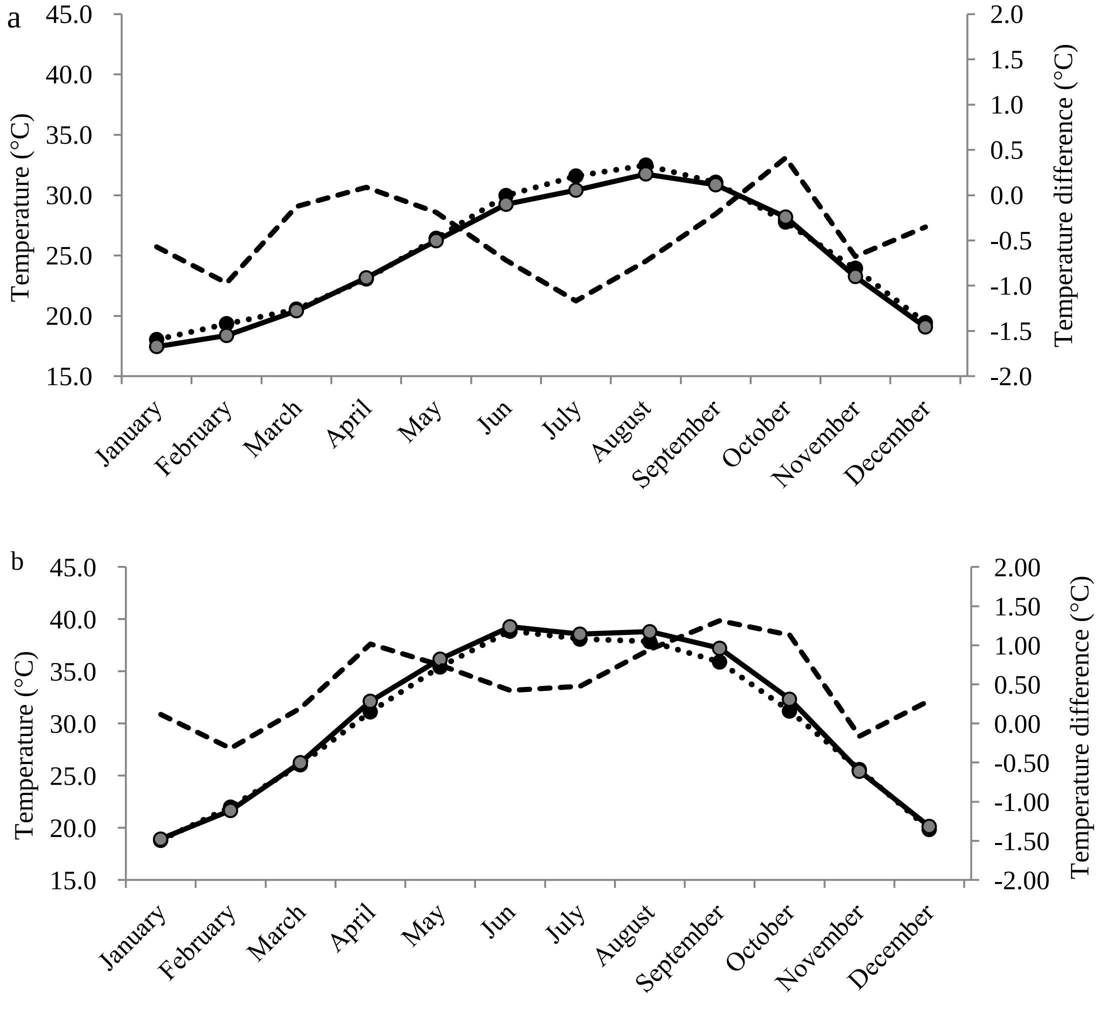
In order to examine changes and trends in temperature, a time series of mean monthly maximum temperature for 15 synoptic stations during the periods 1945-2010 has been analysed (the stations at Al-Garyiat, Ghat and Tazerbou are not included, as these stations have later start dates). Trends in maximum temperature are positive (increase) during the warm months (May-October), particularly, at central and inland stations, with highly significant (***) increases identified in July (Ajdabyia), August (Ajdabyia and Hon), September (Sirt and Ajdabyia) and October (Al-Jaghbub). Positive trends in monthly maximum temperature were identified in September at all stations, ranging between 0.001 and 0.040 ° Ca-1 (Table 4.2). In April, positive changes are found at all stations except Binina, ranging between 0.001 and 0.031 ° Ca-1, with significant increases at seven stations; Sirt, Hon, and Sabha (**), Zwarah and Ajdabyia (*) and Ghadames (+). In February, negative trends ranging between -0.038 and -0.001 ° Ca-1 in maximum temperature are indicated at ten stations; Musratah, Sirt, Binina, Shahat, Darnah, Hon, Jalo and Al-Kufrah, with significant (*) decreases at Musratah, Binina, Shahat, and Darnah (Table 4.2).

Table 4.2: a) Values of the Mann-Kendall statistic (Q) for monthly precipitation, with statistically significant levels at the synoptic stations, with; b) significant changes (95% confidence level) for the two periods 1945-1977 and 1978-2010 across Libya.

Stations		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Zwarah	a	0.025	0.000	0.003	0.025*	0.026+	0.005	0.017	0.024*	0.025*	0.038**	0.026*	0.021 +
	b									*	*		
T. Airport	a	0.016	0.000	0.016	0.014	0.020	0.008	0.026*	0.014	0.020+	0.046**	0.014	0.017
	b									*	*		
Nalute	a	0.033*	0.0004	0.015	0.016	0.015	0.004	0.017	0.012	0.007	0.038*	0.022+	0.019
	b					*					*		
Musratah	a	-0.013	-0.021 *	0.007	0.011	0.003	-0.025 **	-0.015	-0.010	0.002	0.014	-0.008	0.000
	b						*						
Sirt	a	0.005	-0.006	0.020+	0.025 **	0.018	0.007	0.019*	0.024**	0.038***	0.026*	0.010	0.015
	b				*								
Ajdabyia	a	0.022*	0.000	0.019	0.021*	0.017	0.011	0.026***	0.031***	0.04***	0.02	0.01	0.02
	b	*					*	*	*	*			
Binina	a	0.002	-0.021 *	0.000	-0.007	-0.011	-0.014	-0.006	-0.006	0.010	-0.006	-0.014	0.000
	b		*										
Shahat	a	0.003	-0.024 *	0.007	0.007	0.006	0.003	0.014*	0.008	0.023 **	0.016	-0.011	0.000
	b		*										
Darnah	a	0.002	-0.021 *	0.003	0.002	0.000	0.002	0.003	0.001	0.017*	0.010	-0.010	0.000
	b		*										
Ghadames	a	0.018	0.003	0.018	0.025+	0.031*	0.003	0.016	0.029**	0.022+	0.041**	0.021	0.008
	b				*	*			*	*	*	*	
Hon	a	0.010	-0.007	0.025	0.026 **	0.025*	0.004	0.020+	0.033	0.043 **	0.036*	0.010	0.011
	b				*	*			*	*	*		
Jalo	a	-0.013	-0.025	-0.022	0.001	0.006	-0.006	0.009	0.013+	0.032 *	0.000	-0.011	-0.014
	b		*						*	*			
Al-Jaghbub	a	0.015	-0.001	0.009	0.011	0.008	0.008	0.020	0.016*	0.043*	0.013	0.009	0.012
	b							*	*				
Sabha	a	0.006	-0.002	0.007	0.031 **	0.019+	0.015	0.025*	0.031 **	0.043 **	0.025+	0.007	0.019
	b				*				*	*	*		
Al-Kufrah	a	-0.009	-0.038	-0.015	0.007	0.000	-0.014	0.009+	0.003	0.023+	-0.009	-0.012	-0.007
	b						*			*			

The significance levels tested are 0.001 (***), 0.01 (**), 0.05 (*) and 0.1 (+). If the cell is blank, the significance level is >0.1

In order to examine differences in monthly maximum temperature across Libya, the variability of the mean monthly maximum temperature of 15 stations for two 30 years intervals 1945-1977 and 1978-2010 were analysed to show the variability of monthly maximum temperature during the last 33 years of the record compared to the 33 first years of the record (1945-1977) . Comparison of the two time periods for mean monthly maximum temperature shows higher maximum temperature for most stations except Musratah and Binina during the last 33 years (1978-2010), with particularly notable increases in maximum temperatures during the warm season (May-October) in the second period 1978-2010 at eleven stations; Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia, Ghadames, Hon, Al-Jaghbub, Sabha and Al-Kufrah (Fig. 4.3; and see Appendix 4.2 for figures for all sites).



(.....1945-1977, ▬1978-2010 and ----- difference)

Fig. 4.3: Mean monthly maximum temperature for the two periods 1945-1977 and 1978-2010 at a) Musratah and; b) Sabha.

The Mann-Whitney results show that the warmest months (August-October) were higher (95% significance level) for the period 1978-2010 at Zwarah, Sirt, Ajdabyia, Ghadames, Hon, Jalo, Al-Jaghbub and Sabha. The coldest months (November and December) show no significant trends at any stations. The eastern coastal stations of Binina, Shahat and Darnah record significant differences in February (Table 4.2).

4.3.4 Seasonal and sub-seasonal variations in maximum temperature

Mean seasonal maximum temperature across Libya for the period 1945-2010 was analysed (Table 4.3). In autumn positive trends in maximum temperature are found at 13 of the 15 stations, with exception of Sirt and Shahat, ranging between 0.005 and 0.032 ° Ca-1. Highly significant increase were identified at Binina, Hon, Al-Jaghbub and Sabha (***), with significant increases at Zwarah, Tripoli Airport, Musratah, Ajdabyia and Ghadames.

Positive trends are identified in the winter season at nine (53%) stations, with the highest (0.017 °Ca-1) at Zwarah. Significant increases (*) in maximum temperature were found at Zwarah and Binina. Negative changes are identified at seven stations (47%), with the highest negative -0.013 ° Ca-1 (Jalo and Sirt), with significant decreases (+) at Sirt, Darnah and Jalo.

Positive changes in spring maximum temperature are identified at 87% of stations, with exception of Sirt and Shahat, ranging between 0.001 and 0.031 ° Ca-1, with highly significant increases at Hon, Al-Jaghbub and Sabha (***) and Zwarah, Tripoli Airport, Musratah and Ghadames (**). In summer, increases in maximum temperature are observed at 13 of the 15 (87%) stations, ranging from 0.005 (Darnah and Al-Kufrah) to 0.024 ° Ca-1 (Musratah). Significant increases in maximum summer temperature are identified at eight stations, with highly significant (***) increases at Al-Jaghbub and Sabha, Musratah, Binina and Ghadames (**) and Tripoli Airport, Ajdabyia and Hon. Negative trends are found at Nalute, Sirt (**) and Shahat (*).

Table 4.3: Values of the Mann-Kendall statistic (Q) for seasonal maximum temperature (° C), with statistically significant levels at 15 synoptic stations across Libya (1945-2010)

Stations	Autumn		Winter		Spring		Summer		Sig. differences (95% - *) 1945-1977 and 1978-2010			
	Sig	Q	Sig	Q	Sig	Q	Sig	Q	Aut.	Win.	Spr.	Sum.
Zwarah	**	0.028	*	0.017	**	0.030		0.006	*	*		
T.Airport	**	0.027		0.011	**	0.031	*	0.014	*			
Nalute		0.007		-0.008		0.001		-0.005	*			*
Musratah	**	0.025		0.011	**	0.027	**	0.024				*
Sirt		-0.001	+	-0.013		-0.001	**	-0.023				
Ajdabyia	**	0.023		0.001	**	0.021	*	0.013		*	*	*
Binina	***	0.025	*	0.013	***	0.029	**	0.021		*		*
Shahat		-0.003		-0.006		-0.006	*	-0.012		*		
Darnah	+	0.012	+	-0.011	+	0.007		0.005		*		
Ghadames	**	0.028		0.011	**	0.031	**	0.019	*			*
Hon	***	0.032		0.005	***	0.026	*	0.016	*		*	*
Jalo		0.005	+	-0.013		0.011		0.008		*		
Al-Jaghbub	***	0.031		0.010	***	0.003	***	0.022	*			*
Sabha	***	0.032		0.010	***	0.031	***	0.021			*	*
Al-Kufrah		0.005		-0.012		0.014		0.005		*	*	

*●= stations not included at Mann-Whitney test

Analysis of the seasonal data from 1945-2010 was undertaken by dividing the whole period in two, providing two periods for analysis of 33 years in length, this permits consideration of general long term changes and differences in rates of change. In addition, to show the variability of seasonal maximum temperature during the last 33 years compared to the 33 first years (1945-1977). Seasonal maximum temperature is assessed using the Mann-Whitney test, data for 15 synoptic stations across Libya for two 33 year intervals over the period of 1945-1977 and 1978-2010.

In summer, the sites at Tripoli Airport, Musratah, Ajdabyia, Binina, Ghadames, Hon, Al-Jaghbub and Sabha have significant differences between the two time periods (95% confidence level; Fig.4.4), with increases during the more recent period. Table 4.3 shows significant differences (95%) in autumn at Zwarah, Tripoli Airport, Nalute, Ghadames, Hon and Al-Jaghbub; in winter at Zwarah, Ajdabyia, Binina, Shahat, Darnah, Jalo and Al-Kufrah, and in spring at Ajdabyia, Hon, Sabha and Al-Kufrah, with increases trends in maximum temperature during the more recent period.

Error bars have also been applied to provide a clearer depiction of the seasonal differences over the two 33year intervals. The site at Tripoli Airport was found to have significant increases in winter, spring and summer maximum temperature at one standard error 68.4%, with similar differences identified at Musratah (winter), Ghadames (spring), Sirt, Ajdabyia and Sabha (autumn).

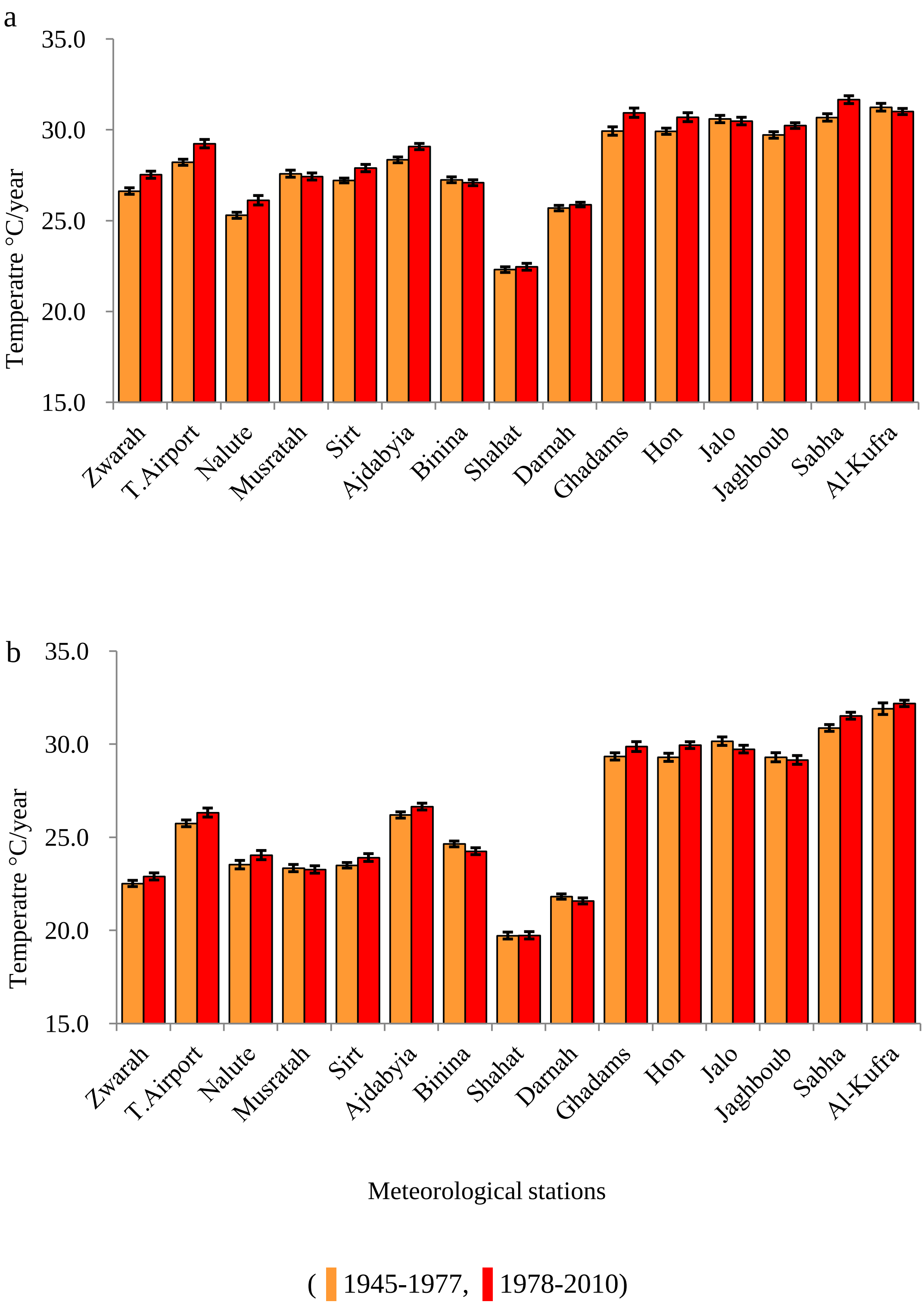


Fig. 4.4: Mean maximum temperature for the two periods 1945-1977 and 1978-2010 at a) autumn; and, b) spring, with error bars representing two standard errors (95.4% confidence level).

4.3.5 Annual variations and trends in maximum temperature

Analysis of the data from 1945-2010 was undertaken by dividing the whole period in two, providing two periods for analysis of 33 years in length. This permits consideration of general long term changes and differences in rates of change and to show the variability of annual maximum temperature during the last 33 years compared to the 33 first years (1945-1977). Changes and trends in annual maximum temperature for the synoptic stations during the period 1945-2010 are analysed.

Positive changes are found at most stations within this study (Fig. 4.5; see Appendix 4.3). To estimate trends in temperature during the period 1945-2010, the annual average maximum temperature of 15 stations is analysed. According to the Mann-Kendall test, positive trends in maximum temperature are identified at ten stations with the exception of Musratah, Binina, Darnah, Jalo and Al-Kufrah, with positive significant increases at all stations except Shahat (Table 4.4).

Table 4.4: Values of the Mann-Kendall statistic (Q) for annual maximum temperature, with statistically significant levels at the synoptic stations across Libya

Time series	1945-2010			1945-1977			1978-2010		
	Mean	Sig	Q	Mean	Sig	Q	Mean	Sig	Q
Zwarah	24.6	***	0.020	24.3		-0.021	24.8	***	0.053
T.Airport	27.1	***	0.018	26.7		-0.012	27.4	*	0.041
Nalute	24.6	***	0.021	24.3		-0.004	24.8	***	0.048
Musratah	25.1		-0.007	25.3	**	-0.047	24.9	***	0.048
Sirt	25.1	***	0.016	24.9		0.010	25.2	***	0.052
Ajdabyia	26.8	***	0.018	26.5		0.020	27.1	+	0.013
Binina	25.1	+	-0.008	25.4		0.000	24.8		0.016
Shahat	20.9		0.002	20.8	+	0.019	21.0		0.006
Darnah	23.4		-0.002	23.5		0.000	23.7	*	0.019
Ghadames	29.6	***	0.020	29.4		0.000	29.9	*	0.033
Al-Garyiat							27.9	+	0.029
Hon	29.3	***	0.014	29.1		-0.002	29.5		0.015
Jalo	29.6	*	-0.009	29.8	***	-0.054	29.5	+	0.031
Al-Jaghbub	29.0	**	0.019	28.8		0.023	29.3	***	0.047
Sabha	30.3	**	0.024	30.1		0.019	30.6	***	0.043
Ghat							30.9	*	0.038
Tazerbou							30.5	**	0.044
Al-Kufrah	30.7		-0.004	30.8		-0.028	30.6	***	0.040

Significant increases in mean annual maximum temperature are observed at eight stations ranging between 0.002 (Shahat) and 0.024 ° Ca-1. Highly significant trends (***) are found at Al-Jaghbub and the western and central coastal stations: Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia (**). Negative trends (-0.006 ° Ca-1) are found at four stations, with significant decreases at Jalo (*) and Binina (+).

Decreasing annual maximum temperature (Fig. 4.5; see Appendix 4.3) at an average rate of -0.024 ° Ca-1 is identified for the first 33years (1945-1977) at the western coastal station: Zwarah, Tripoli Airport, Nalute, Musratah and the southern-east stations; Hon, Jalo and Al-Kufrah, with highly significant at Jalo (***) and Musratah (**). Positive trends in maximum temperature are found at five stations, with significant at Shahat (+) and no changes at the remaining stations.

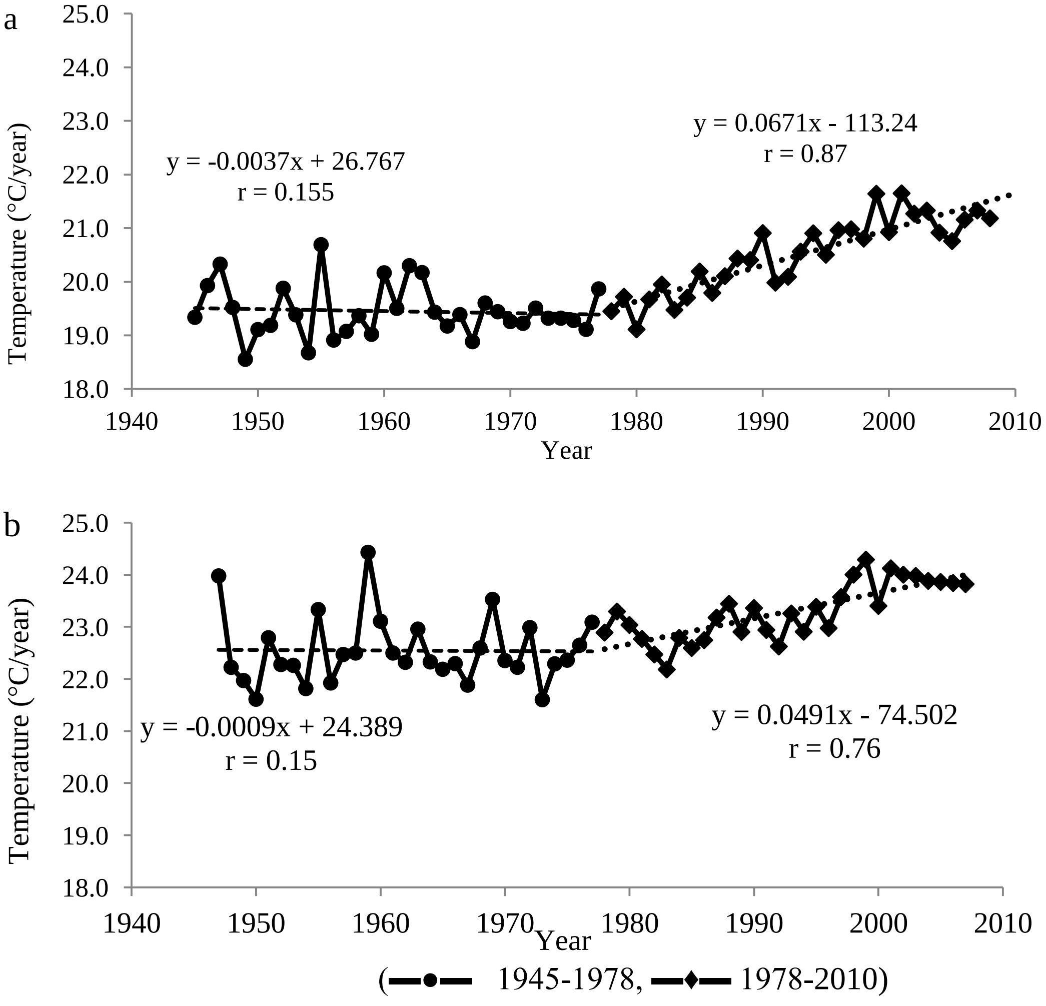


Fig. 4.5: Annual means maximum temperature for the two periods 1945-1977 and 1978-2010 of a) Zwarah and; b) Sabha

An increase in annual maximum temperature (Fig. 4.5; see Appendix 4.3) is found at all stations (15) within this study during the last 33years (1978-2010), with the highest 0.053 ° Ca-1 (Tripoli Airport). Significant increases are identified at 87% of the positive stations, with non-significant trends at Binina, Shahat and Hon (Table 4.4).

From the Fig. 4.5 it is clear to see that, the first half 1945-1977 shows little changes ‘warming’ whereas the second 33 years (1978-2010) does show warming trend, they make a good set of data to compare. The annual mean maximum temperature for 15 stations across Libya have been analysed by dividing the study period into two series of 33years (1945-1977 and 1978-2010), referred to as period 1 and period 2 respectively. Changes in the annual maximum temperature show the period 2 is characterized by higher temperature compared to the period 1 at all stations.

Error bars show significant differences in mean annual maximum temperature between the two time periods (1945-1977 and 1978-2010) at all stations at three standard errors (68.2% confidence level; Fig. 4.6), with the exception at eastern-coast and inland stations: Shahat, Darnah, Hon and Al-Kufrah.

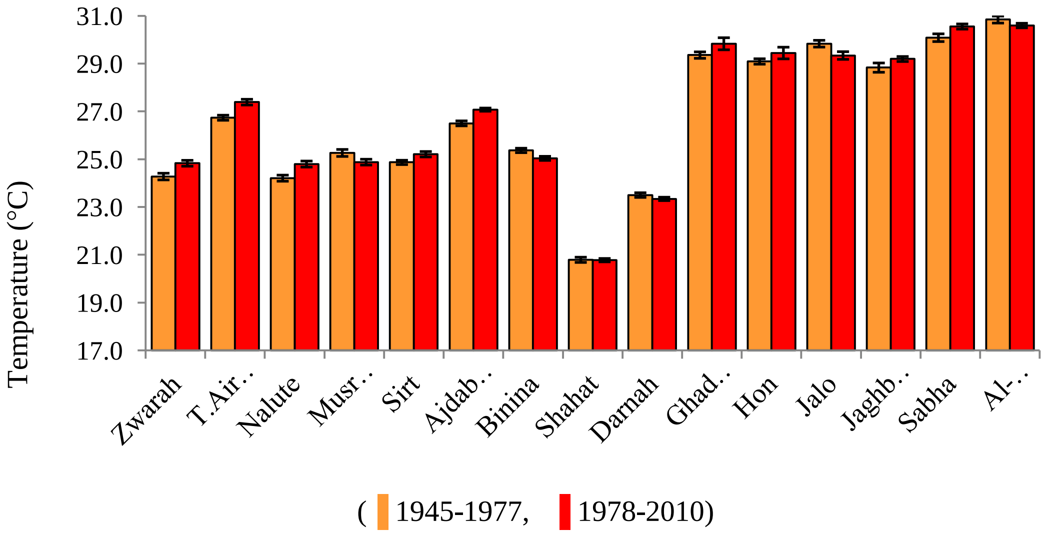


Fig. 4.6: Mean annual maximum temperature for the two periods 1945-1977 and 1978-2010 at the synoptic stations across Libya, with error bars representing one standard error (68.4% confidence level).

4.3.6 Decadal variations in maximum temperature

To examine the distribution of maximum temperature across Libya during the period 1961-2010, analyses of the daily 11-day maximum temperature for all (15) coastal and inland stations was undertaken with comparison over 10-years intervals; 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2010. The annual maximum temperature for the investigated stations has changed during the period 1961-2009 (Fig.4.7; see Appendix 4.4 for all stations).

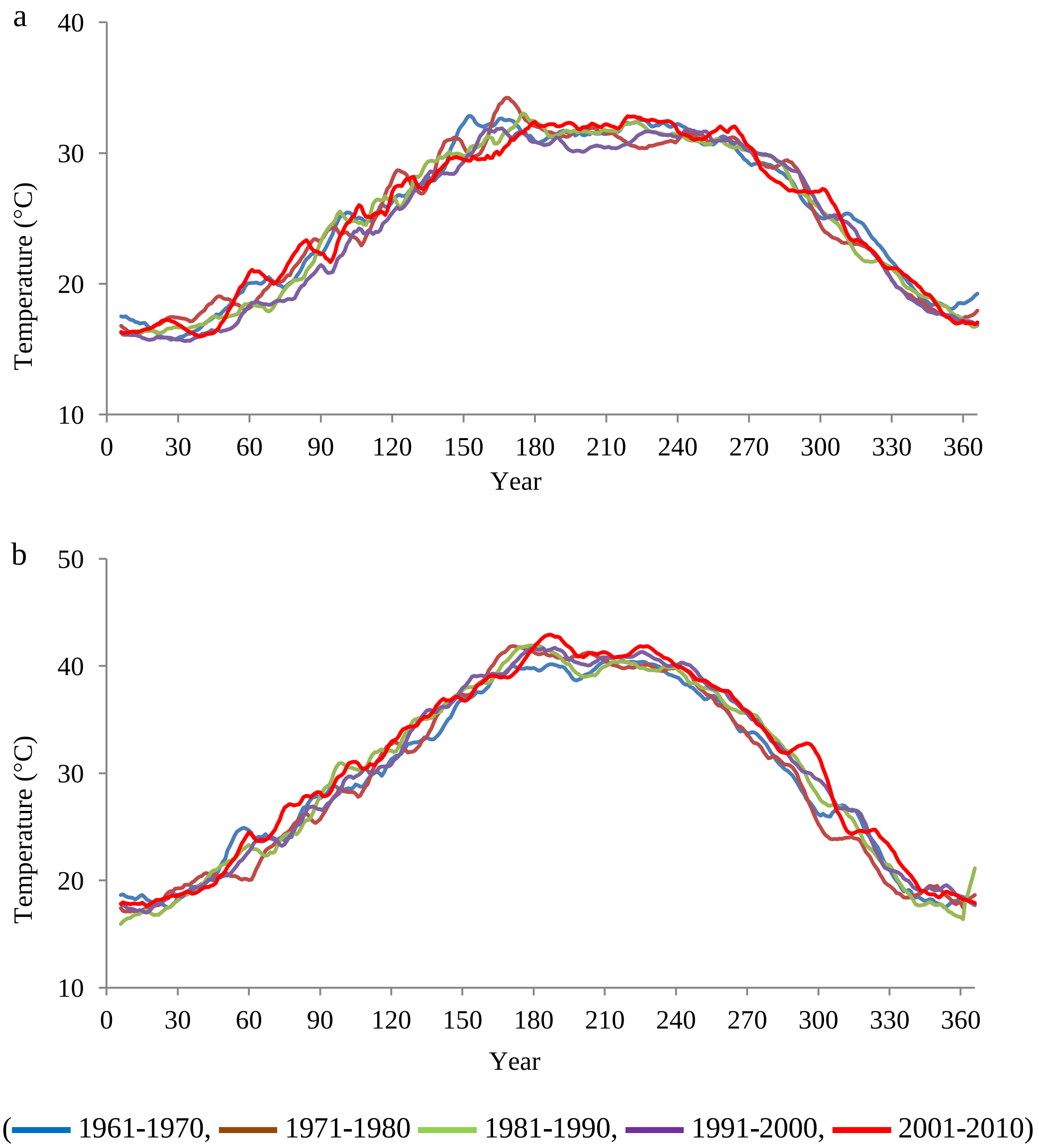


Fig. 4.7: Decadal mean of 11-day moving average of the mean daily maximum temperature during the period 1961-2010 over near decadal windows for, a) Binina: and, b) Ghadames.

The mean annual maximum temperature during the summer days (170-270) for the 10-years intervals has increased rapidly over the study period, with a notable increase for the period 2001-2010 against previous decades at 10 of 15 stations, with the exception of the western coastal stations; Zwarah, Nalute, Musratah.

4.4 MINIMUM TEMPERATURE

The same datasets described within the maximum temperature analysis (section 4.3.1) will be used within the analysis of minimum temperature.

4.4.1 Multi-decadal variations and trends in minimum temperature

The mean monthly minimum temperature ranges from 12.3 to 16.7 °C, with a minimum temperature recorded of -8.3 °C, January 1935 at Ghadames. The temperature is characterized by variability, both spatially and temporally, with a standard deviation (SD) in mean annual minimum temperature ranging from 0.53 to 1.1 °C (Ghadames). Generally, the mean annual minimum of the COV temperature for coastal stations ranges between 2.3% (Darnah) and 4.1% (Zwarah) and for inland stations from 2.2% (Jalo) to 5.1% (Ghadames).

4.4.2 Daily variations and trends in minimum temperature

Daily minimum data are available for 16 coastal and inland stations (with Ghat and Al-Garyiat) during the period 1956-2010. The study period is divided into two series of equal length (27 years), 1956-1982 and 1983-2010, referred to as period 1 and period 2, respectively.

In order to examine temporal changes in temperature, a time series of 11-day moving average of the mean daily minimum for the periods 1956-1982 and 1983-2010 has been analysed. The daily data of two periods are considered at the 16 stations, as these records provide a much more complete depiction of temperature change. Changes in the minimum temperature over 11-day intervals shows that, daily temperature during period 2 is characterized by higher temperatures compared to the period 1 in most days of the year at all stations, with a clearer difference at the inland stations for the latter part of the year (using Gregorian day, i.e. the first of January is the first day of the year Figure 4.8; see Appendix 4.5 for all stations).

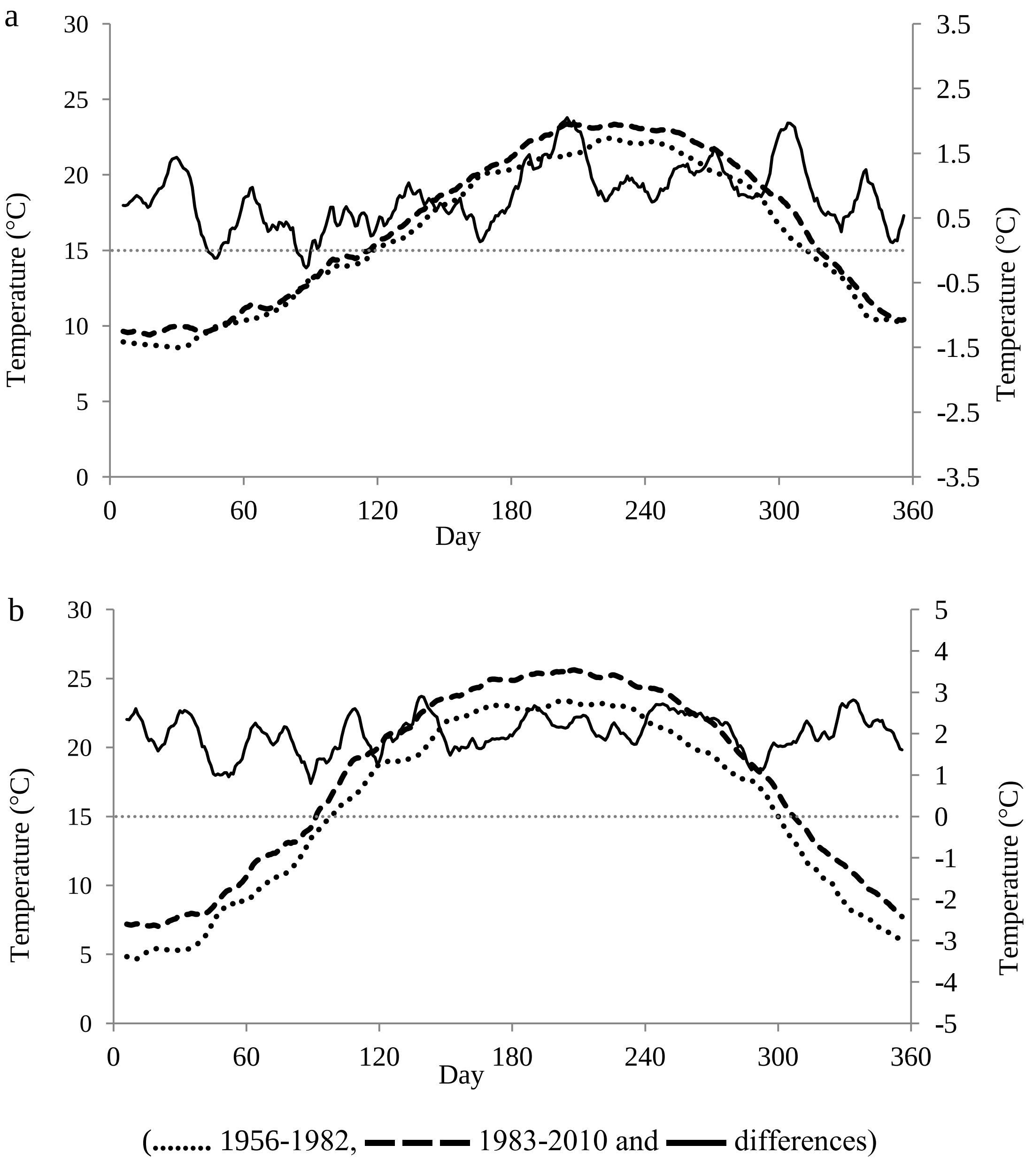


Fig. 4.8: Annual means 11-day moving averages of the mean daily minimum temperature for the two periods 1956-1982 and 1983-2010 at a) Sirt and; b) Al-Kufrah.

The Mann-Whitney test is applied to assess the differences in mean daily minimum temperature between the two timeframes, with the second period significantly higher (95% confidence level) at the all examined stations, except Tripoli Airport and Al-Jaghbub.

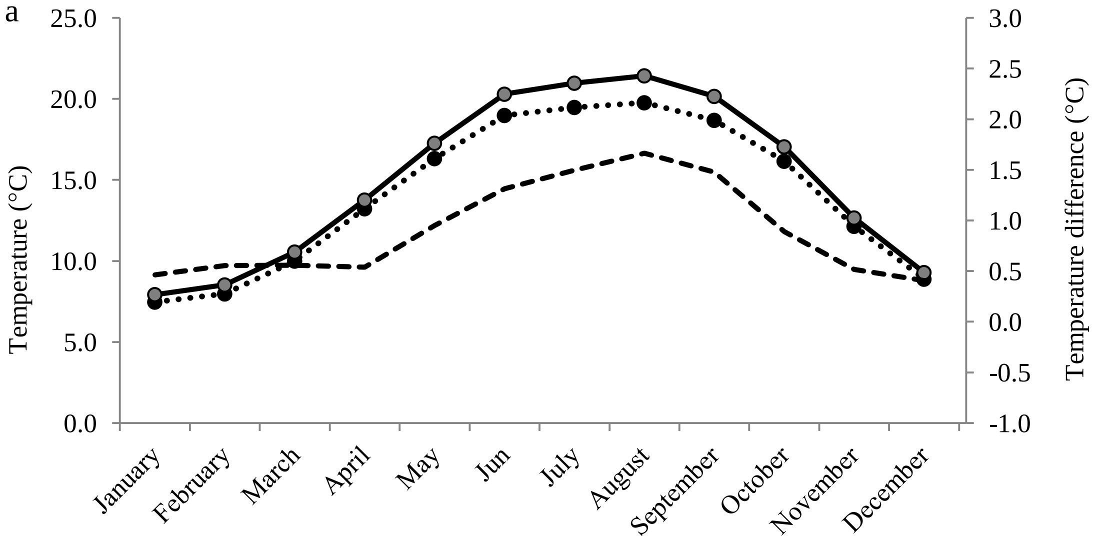
4.4.3 Monthly variations and trends in minimum temperature

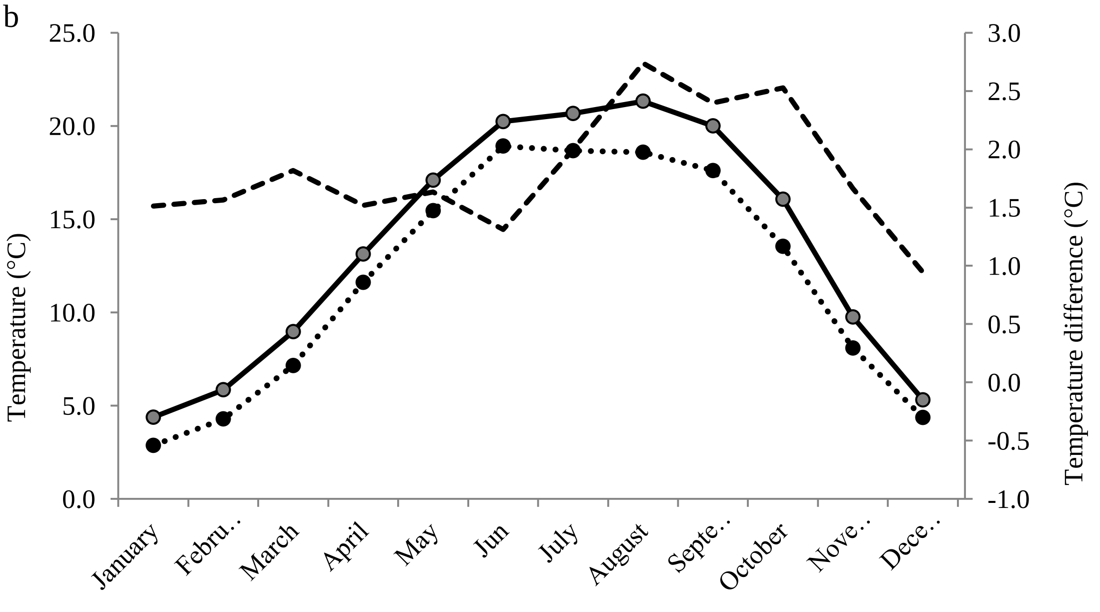
Positive changes (increase) in monthly minimum temperature are identified at 15 stations (1945-2010) using the non-parametric Mann-Kendall test. The analyses identified that mean monthly minimum temperature showed more increases, with comparatively higher positive Mann-Kendal values than mean maximum temperature at most stations, with positive changes in monthly minimum temperature identified for all months at all stations (Table 4.5). The warm months (May-October) showed slightly higher positive values than moderate months (November-April), with positive changes in monthly minimum temperature identified at all stations in August, with ranges between 0.021 and 0.109 ° Ca-1.

In order to examine differences in monthly minimum temperature across Libya, the variability of the mean monthly minimum temperature of 15 stations for two 30 years intervals 1945-1977 and 1978-2010 were analysed to show the variably of monthly minimum temperature during the last 33 years compared to the 33 first years (1945-1977) .

The mean monthly minimum temperature for 15 stations (1945-1977 and 1978-2010) across Libya have been plotted (Fig. 4.9; see Appendix 4.6 for all figures detailing) to examine differences in monthly minimum temperature and to show the variability of monthly minimum temperature during the last 33 years compared to the 33 first years (1945-1977) .

Changes in monthly minimum temperature show higher minimum temperature at all stations for all months, except at Musratah (May and June) and Al-Jaghbub (November and December) during the last 33-years (1978-2010), with higher minimum temperature at all examined (15) stations except Musratah during the warm season (April-October) in the second period (1978-2010). The Mann-Whitney test result show that the mean monthly minimum temperature in July-October are more significant (95%) than the cold months November-February at all stations (Table 4.5).





(**.....**1945-1977, **━━**1978-2010 and ----- difference)

Fig. 4.9: Mean monthly minimum temperature for the two periods 1945-1977 and 1978-2010 at a) Ajdabyia and; b) Hon

4.4.4 Seasonal and sub-seasonal variations and trends in minimum temperature

Summer average minimum temperature ranges between 22.8 to 31.2 °C, with an average minimum temperature in winter (7.8 °C), spring (13.5 °C), summer (21.2 °C) and autumn (16.3 °C). Seasonally, station trends in all seasons are dominated by positive changes for minimum temperature as illustrated in Table 4.6. However, the mean average rate of seasonal trend for the 15 examined stations (0.033 °C a^{-1}) in autumn, (0.035 °C a^{-1}) summer, (0.027 °C a^{-1}) spring and (0.023 °C a^{-1}) winter, with the largest seasonal trends values at Hon (0.067 °C a^{-1}; autumn and summer). Significant increases are identified at all stations except at Al-Jaghbub (winter), Musratah and Al-Jaghbub (spring), with highly significant (***) at 80%, (summer and autumn), 69%, (winter) and 64% (spring).

Table 4.5: Values of the Mann-Kendall statistic (Q) for monthly minimum temperature, with statistically significant levels at the synoptic stations, with; b) significant changes (95% confidence level) for the two periods 1945-1977 and 1978-2010 across Libya.

Stations		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Zwarah	a	0.048 **	0.042***	0.045***	0.038***	0.038***	0.029***	0.047***	0.065***	0.056***	0.095***	0.086***	0.047***
	b	*	*	*	*	*	*	*	*	*	*	*	*
T Airport	a	0.017*	0.010	0.017*	0.015*	0.025**	0.013+	0.033***	0.036***	0.035***	0.048***	0.031*	0.011
	b					*		*	*	*	*		
Nalute	a	0.039***	0.023+	0.038***	0.032**	0.020*	0.020*	0.028**	0.036***	0.023**	0.075***	0.055**	0.026*
	b	*	*	*	*		*	*	*	*	*	*	*
Musratah	a	0.032***	0.014*	0.019**	0.007	0.011	0.003	0.019*	0.029***	0.031***	0.063***	0.077***	0.029**
	b	*	*	*					*	*	*	*	*
Sirt	a	0.021**	0.002	0.013+	0.006	0.012+	0.011	0.025**	0.027***	0.036***	0.043***	0.037*	0.009
	b			*				*	*	*	*	*	
Ajdabyia	a	0.019*	0.017*	0.025**	0.021*	0.032**	0.036**	0.051***	0.06***	0.053***	0.069***	0.072***	0.013+
	b					*	*	*	*	*	*		
Binina	a	0.025***	0.024***	0.031***	0.032***	0.032***	0.021*	0.031***	0.032***	0.037***	0.04**	0.051**	0.031***
	b	*	*	*	*	*		*	*	*	*	*	*
Shahat	a	0.017**	0.001	0.011	0.021*	0.014+	0.009	0.025***	0.021**	0.023**	0.036*	0.025+	0.001
	b	*			*	*		*	*	*	*		
Darnah	a	0.023***	0.018**	0.022***	0.024***	0.042***	0.033***	0.033***	0.029***	0.025***	0.048***	0.057***	0.026***
	b	*	*	*	*	*	*	*	*	*	*		*
Ghadames	a	0.001	0.017*	0.045***	0.026**	0.047***	0.025	0.059***	0.064***	0.056***	0.051***	0.033*	0.024*
	b		*	*	*	*	*	*	*	*	*	*	*
Hon	a	0.047***	0.048***	0.066***	0.046***	0.048***	0.039***	0.072***	0.094***	0.084***	0.066***	0.048***	0.042***
	b	*	*		*	*	*	*	*	*	*	*	*
Jalo	a	0.026***	0.028**	0.025*	0.024**	0.021*	0.015+	0.027**	0.042***	0.051***	0.036**	0.017+	0.013+
	b	*	*	*	*			*	*	*	*		
Al-Jaghbub	a	0.014+	0.013	0.013	0.014*	0.020*	0.011	0.036***	0.030***	0.041***	0.020+	0.002	0.004
	b							*	*	*			
Sabha	a	0.021*	0.011	0.04**	0.044***	0.031**	0.023*	0.044***	0.065***	0.045***	0.033***	0.025*	0.026*
	b	*		*	*	*	*	*	*	*	*		
Al-Kufrah	a	0.057***	0.062***	0.052***	0.064***	0.046***	0.047***	0.066***	0.069***	0.068***	0.053***	0.057***	0.041***
		*	*	*	*	*	*	*	*	*	*	*	*

Table 4.6: Values of the Mann-Kendall statistic (Q) for seasonal minimum temperature, with statistically significant levels at 15 synoptic stations across Libya (1945-2010) and Mann-Whitney test in 15 stations for two periods 1945-1977 and 1978-2010.

Stations	Autumn		Winter		Spring		Summer		Sig. differences (95%- *) 1945-1977 and 1978-2010			
	Sig	Q	Sig	Q	Sig	Q	Sig	Q	Aut	Win	Spr	Sum
Zwarah	***	0.047	***	0.047	***	0.040	***	0.047	*	*	*	*
Tripoli Airport	***	0.029	*	0.013	**	0.016	***	0.029	*	*	*	*
Nalute	***	0.026	***	0.027	***	0.026	***	0.026	*	*	*	*
Musratah	*	0.017	***	0.027		0.012	*	0.017	*	*		*
Sirt	***	0.021	***	0.015	*	0.011	***	0.021	*	*	*	*
Ajdabyia	***	0.044	***	0.016	***	0.024	***	0.044	*	*	*	*
Binina	***	0.030	***	0.029	***	0.033	***	0.030	*	*	*	*
Shahat	**	0.019	+	0.008	**	0.017	**	0.019	*	*	*	*
Darnah	***	0.031	***	0.022	***	0.027	***	0.031	*	*	*	*
Ghadames	***	0.049	**	0.020	***	0.039	***	0.049	*	*	*	*
Hon	***	0.067	***	0.036	***	0.049	***	0.067	*	*	*	*
Jalo	**	0.025	**	0.021	*	0.018	**	0.025	*	*	*	*
Al-Jaghbub	***	0.022		0.001		0.009	***	0.022	*			*
Sabha	***	0.040	*	0.018	***	0.037	***	0.040	*		*	*
Al-Kufrah	***	0.058	***	0.053	***	0.056	***	0.058	*	*	*	*

*= stations not included at Mann-Whitney test

Analysis of the seasonal data from 1945-2010 was undertaken by dividing the whole period in two, providing two periods for analysis of 33 years in length, this permits consideration of general long term changes and differences in rates of change. In addition, to show the variability of seasonal minimum temperature during the last 33 years compared to the 33 first years (1945-1977).

Significant differences in seasonal minimum temperature have been identified in the group means for the two 33 year periods (1945-1977 and 1978-2010), for the 15 synoptic stations across Libya (Table 4.6). The error bars show significant increases in mean summer minimum temperature (95% confidence level) from the first to second of the two periods (1945-1977 and 1978-2010) at all stations (Fig. 4.10).

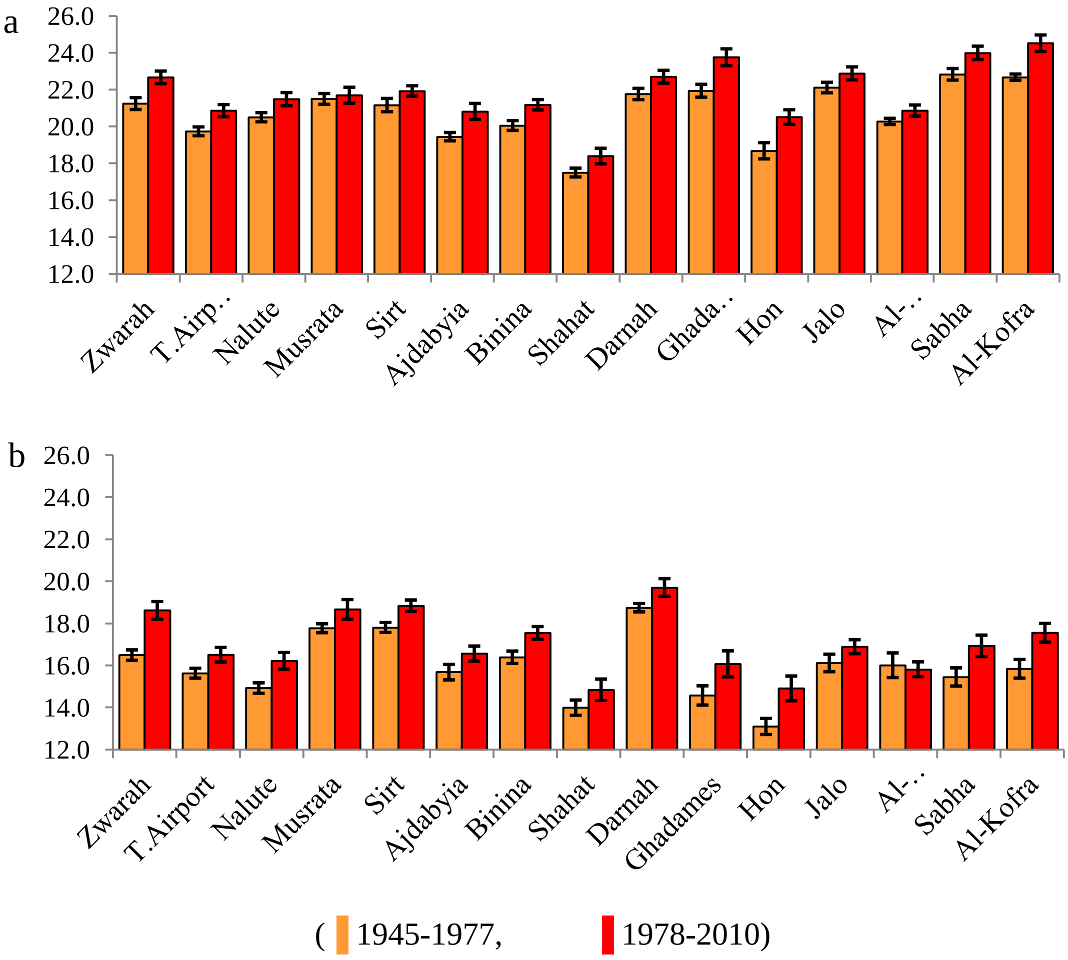


Fig. 4.10: Mean minimum temperature for the two periods 1945-1977 and 1978-2009, at a) summer; and b) autumn with error bars representing two standard errors (95.4% confidence level).

Significant changes (95.4%) in mean autumn minimum temperature are found at most stations with the exception of Shahat, Jalo and Al-Jaghbub, with significant changes in mean spring minimum temperature at all stations except Musratah, Sirt, Shahat, Jalo and Al-Jaghbub. Significant changes (68.2%) in mean winter minimum temperature are found at 50% of stations (see Appendix 4.7 for additional stations.

4.4.5 Annual variations and trends in minimum temperature

An analysis of mean annual minimum temperature across Libya (1945-2009) identified increases at most of stations, particularly in the mid-1980s. The Mann-Kendall test shows positive trends (increase) in minimum temperature at all stations (excluding Al-Garyiat, Ghat and Tazerbou) across Libya (1945-2010). Analysis of the data from 1945-2010 was undertaken by dividing the whole period in two, providing two periods for analysis of 33 years in length, this permits consideration of general long term changes and differences in rates of change and to show the variability of annual minimum temperature during the last 33 years compared to the 33 first years (1945-1977).

The mean annual minimum temperature (1945-2010) showed increases for stations (Fig. 4.11 and see Appendix 4.8 for all stations), with an average of 0.032 °Ca-1, with the highest trend at Al-Kufrah 0.058 °Ca-1, which has the highest mean annual average temperature (23.4 °C).

Significant increases are identified at all stations across Libya, with highly significant (***) increases identified at Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Darnah, Al-Garyiat, Hon, Jalo, Sabha, Tazerbou and Al-Kufrah, with significant (**) increases at Shahat and Al-Jaghbub (Table 4.7).

Examining annual minimum temperature changes and trends for the first period (1945-1977), the mean annual minimum temperature for 15 stations across Libya are plotted (Fig. 4.11; see Appendix 4.8 for remaining stations). Positive trends with an average rate of 0.011 °C a^{-1} are indicated at six stations; Zwarah, Tripoli Airport, Ajdabyia, Binina, Darnah and Sabha, with a significant positive trend at Binina (***) and Tripoli Airport (+).

Table 4.7: Values of the Mann-Kendall statistic (Q) for annual minimum temperature, with statistically significant levels at the synoptic stations across Libya

Time series	1945-2010			1945-1977			1978-2010		
	Mean	Sig.	Q	Mean	Sig.	Q	Mean	Sig.	Q
Zwarah	15.4	***	0.053	14.5		0.012	16.2	***	0.075
T.Airport	14.0	***	0.021	13.7	+	0.016	14.3	***	0.04
Nalute	13.8	***	0.030	13.3		-0.003	16.2	**	0.037
Musratah	15.8	***	0.022	15.5	**	-0.022	16.2	***	0.083
Sirt	16.0	***	0.020	15.7		-0.008	16.4	***	0.035
Ajdabyia	14.6	***	0.035	14.1		0.001	15.0	***	0.085
Binina	15.0	***	0.031	14.5	***	0.037	15.5	*	0.027
Shahat	12.2	**	0.015	11.9		-0.010	12.5	+	0.025
Darnah	16.8	***	0.027	16.4		0.007	17.3	***	0.064
Ghadames	14.2	***	0.037	13.4	*	-0.028	14.9	**	0.040
Al-Garyiat							13.8	***	0.055
Hon	12.7	***	0.058	11.8		-0.014	13.4	***	0.074
Jalo	15.4	***	0.028	15.0	**	-0.029	15.7	***	0.050
Al-Jaghbub	13.8	**	0.014	13.6		-0.003	13.9	***	0.047
Sabha	15.5	***	0.037	14.9		0.006	16.1	***	0.051
Ghat							16.5		0.046
Tazerbou							15.1	*	0.026
Al-Kufrah	15.9	***	0.058	14.9		-0.003	16.9	***	0.067

In contrast decreasing annual minimum temperature (see Appendix 4.8 for all stations) for the period 1945-1977 are found at nine of the 15 stations, with an average rate of -0.012 °C a^{-1} (Table 4.7), with significant decreasing trends identified at Musratah and Jalo (**) and Ghadames (*).

An increase in the annual minimum temperature is identified at all (18) stations across Libya during the period 1978-2010 (see Appendix 4.8 for all stations), with an average rate of 0.052 °C a^{-1}, with the highest 0.085 °C a^{-1} (Ajdabyia). Significant increases are identified at twelve stations: Zwarah, Tripoli Airport, Musratah, Sirt, Ajdabyia, Hon, Darnah, Jalo, Al-Jaghbub, Sabha, and Al-Kufrah (***) during the second period (1978-2010). The sites at Nalute and Ghadames are significant (**), with weakly significant (*) increases observed at Binina and Tazerbou (Table 4.7).

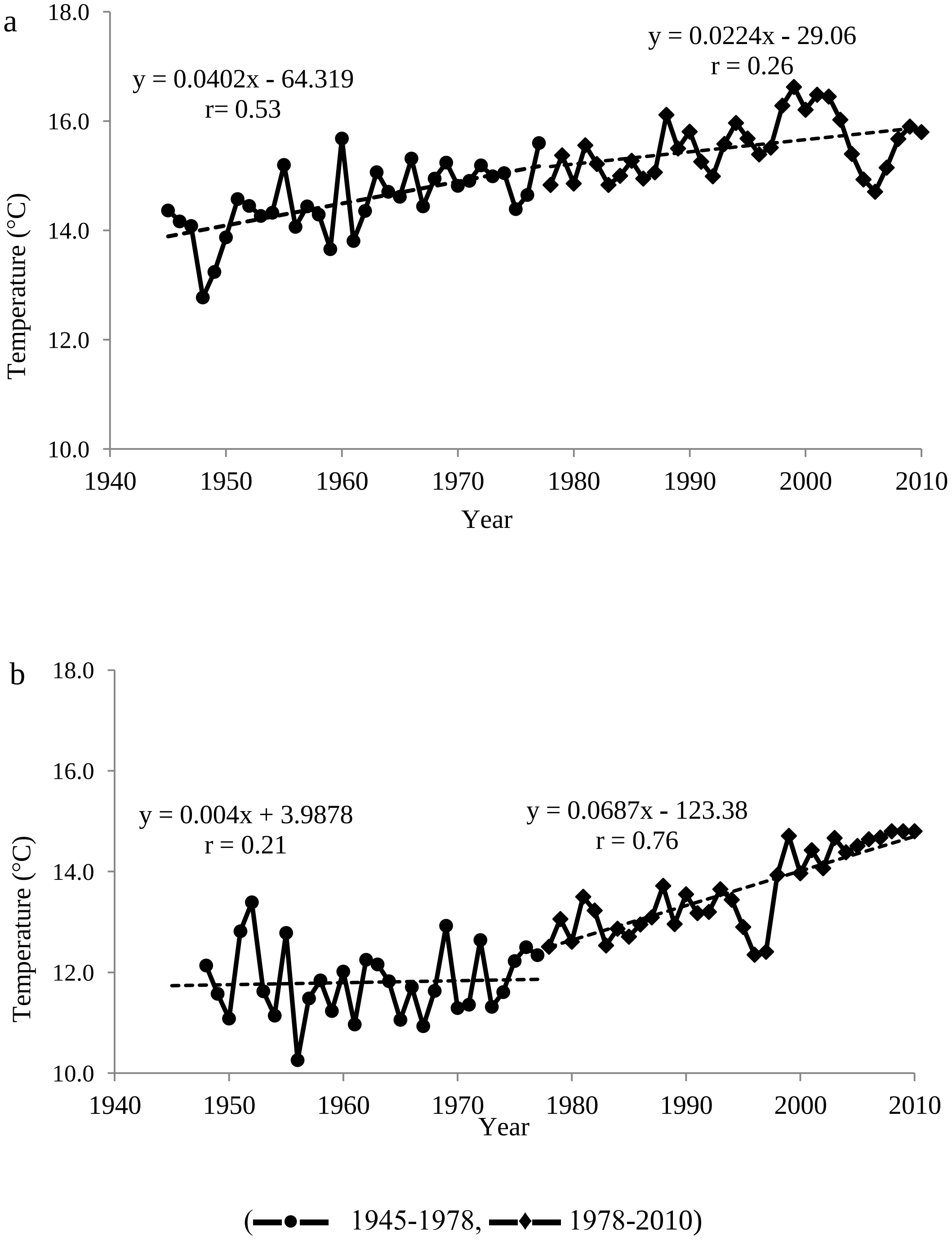


Fig. 4.11: Annual mean minimum temperature at a) Binina and; b) Hon.

Error bars show significant differences in mean annual minimum temperature between the two time periods (1945-1977 and 1978-2010) at all stations at two standard errors (95.4% confidence level; Fig. 4.12), with the exception of Musratah and Hon.

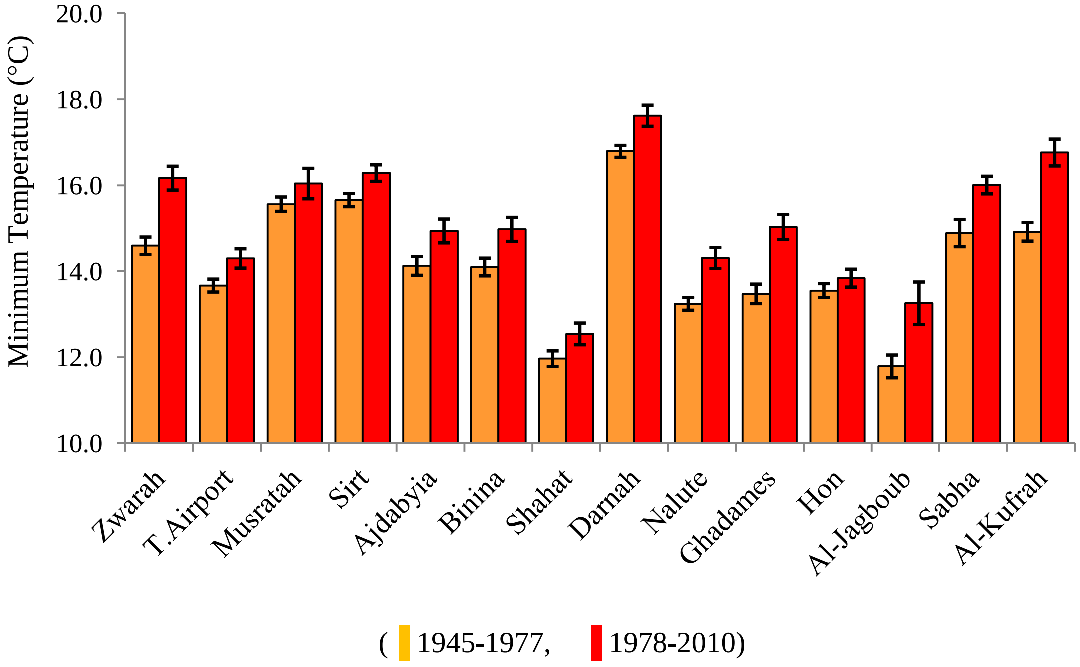


Fig. 4.12: Mean annual minimum temperature for the two periods 1945-1977 and 1978-2010 at the 15 synoptic stations across Libya, with error bars representing two standard errors (95.4% confidence level).

4.4.6 Decadal variations in minimum temperature

To examine the characteristics of daily minimum temperature for the stations within the coastal and inland regions, analysis of minimum temperature over an 11-day moving average was undertaken, with comparison over the 10-years intervals (1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010). The annual minimum temperature for the majority of stations has fluctuated over the period 1961-2009 (Fig. 4.13; see Appendix 4.9 for all examined stations). Increases are identified during the summer and autumn season (days 180-300), at the majority of coastal stations (Zwarah, Tripoli Airport, Ajdabyia, Binina and Darnah), and at all inland stations, with the minimum temperature during each decade greater than the previous decade.

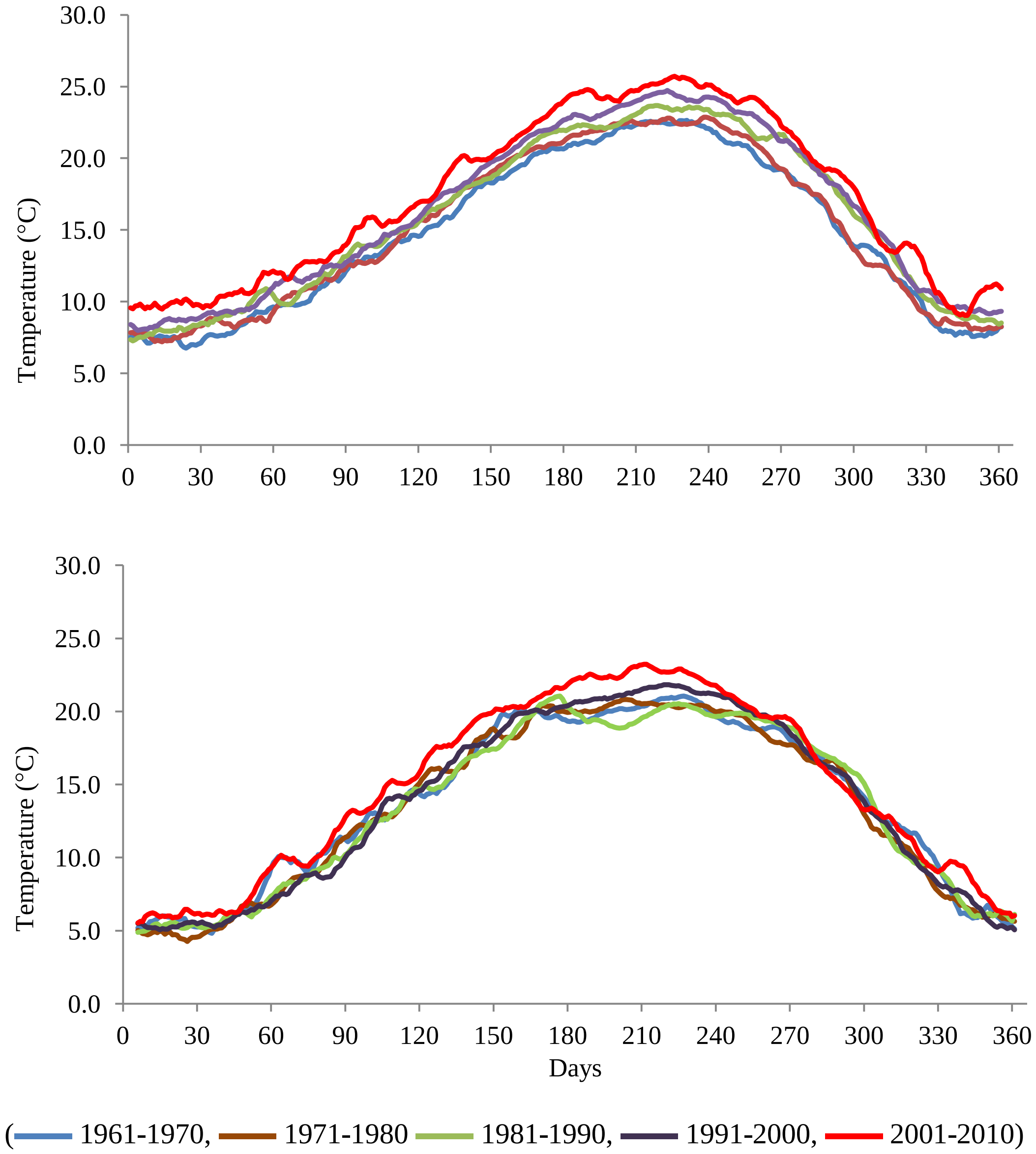


Fig. 4.13: Decadal mean of 11 day moving averages of the mean daily minimum temperature over near decadal windows for a) Zwarah and; b) Al-Jaghbub for the period 1961-2009, with the curves from a separate decadal block.

4.5 MEAN AVERAGE TEMPERATURE

Mean average temperatures are computed from daily values calculated from the maximum and minimum temperatures over the month, (maximum temperature + minimum temperature /2) for the stations across Libya. The mean annual average temperature is 20.8 °C, with the mean monthly average temperature ranges between 16.5 °C and 23.3 °C, and ranging seasonally from 13.0 °C (winter) to 28.4 °C (summer).

4.5.1 Multi-decadal variations and trends in mean average temperature

Global mean average temperature has increased over the last 150 years by 0.62 °C, (Jones et al., 1999); with most studies identifying an increasing trend in global mean average temperature over the twentieth century, with spatial variability identified in these rates. The IPCC fourth Assessment Report, 2007 and several subsequent studies identified that worldwide behaviour of temperature, can be defined by three phases; 1910-1945 (first warming period), 1946-1975 (period of little temperature change) and 1976-2005 (the warmest period; Alexander et al. 2006; IPCC, 2007). The 1990s were the warmest decade, with 1998 the warmest year, globally, associated with the 1997/98 El Niño event, since instrumental records began 1861 (Houghton et al., 2001).

4.5.2 Daily variations and trends in mean average temperature

Daily mean average data are available for 16 coastal and inland stations (with Al-Garyiat and Ghat excluded) during the period (1956-2010). The study period is divided into two series of equal length (27 years), 1956 to 1982 and 1983 to 2010, referred to as period 1 and period 2, respectively.

Examining temporal changes in mean average temperature, a time series of 11-day moving average of the mean daily average temperature for the periods 1956-1982 and 1983-2010 are plotted. Changes in the mean average 11-day, daily temperature show s that period 2 is characterized by higher temperatures compared to the period 1 in most days of the year at all stations, with a clearer difference over the days 60-300 for most of stations.

The Mann-Whitney test identified that mean daily average temperature for the second period is significantly higher (95% confidence level) at all coastal stations except Darnah and Nalute, with significant differences (95%), at all inland stations, with exception of Jalo and Al-Jaghbub (Fig 4.14; see Appendix 4.10 for all stations).

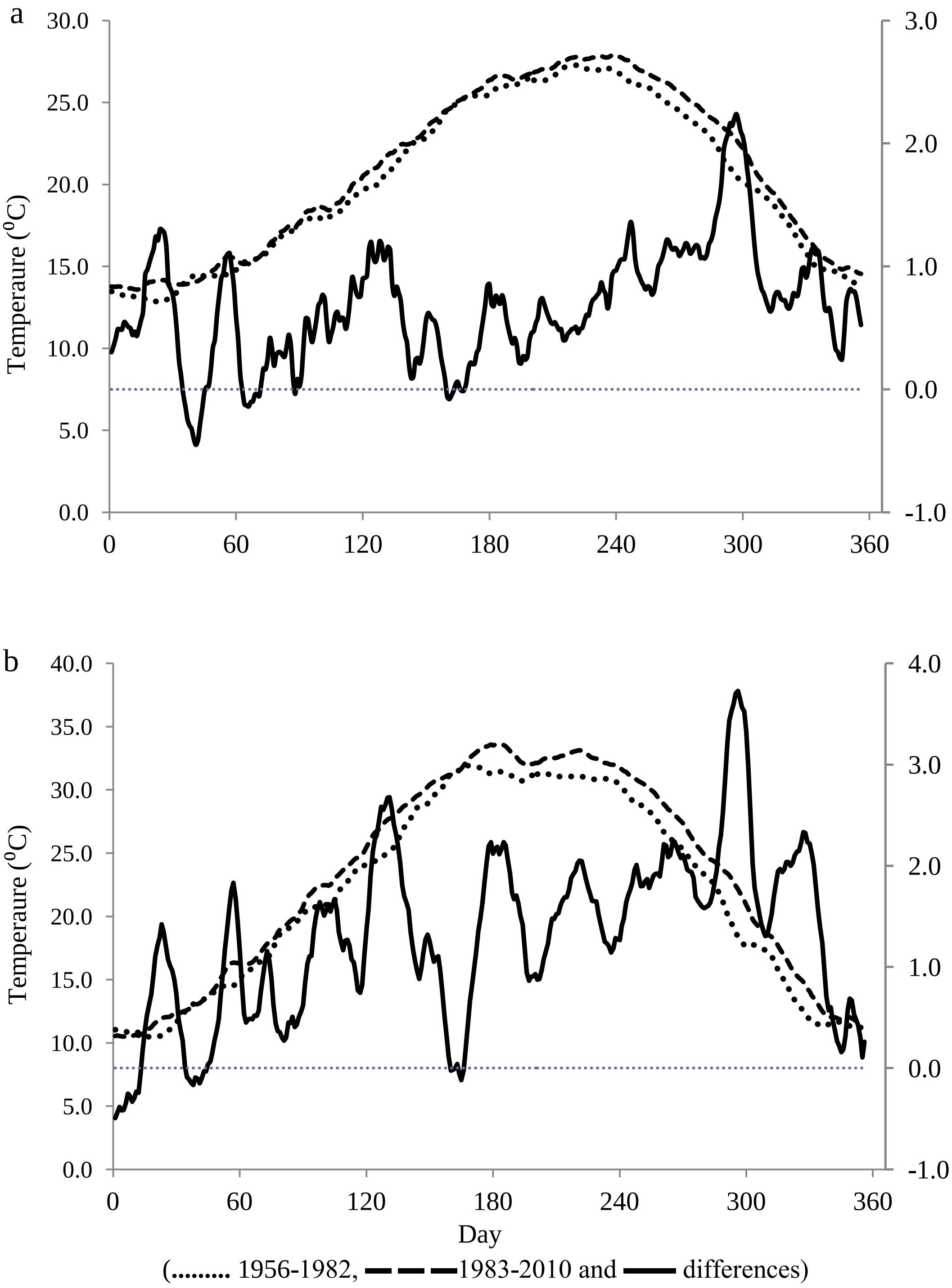
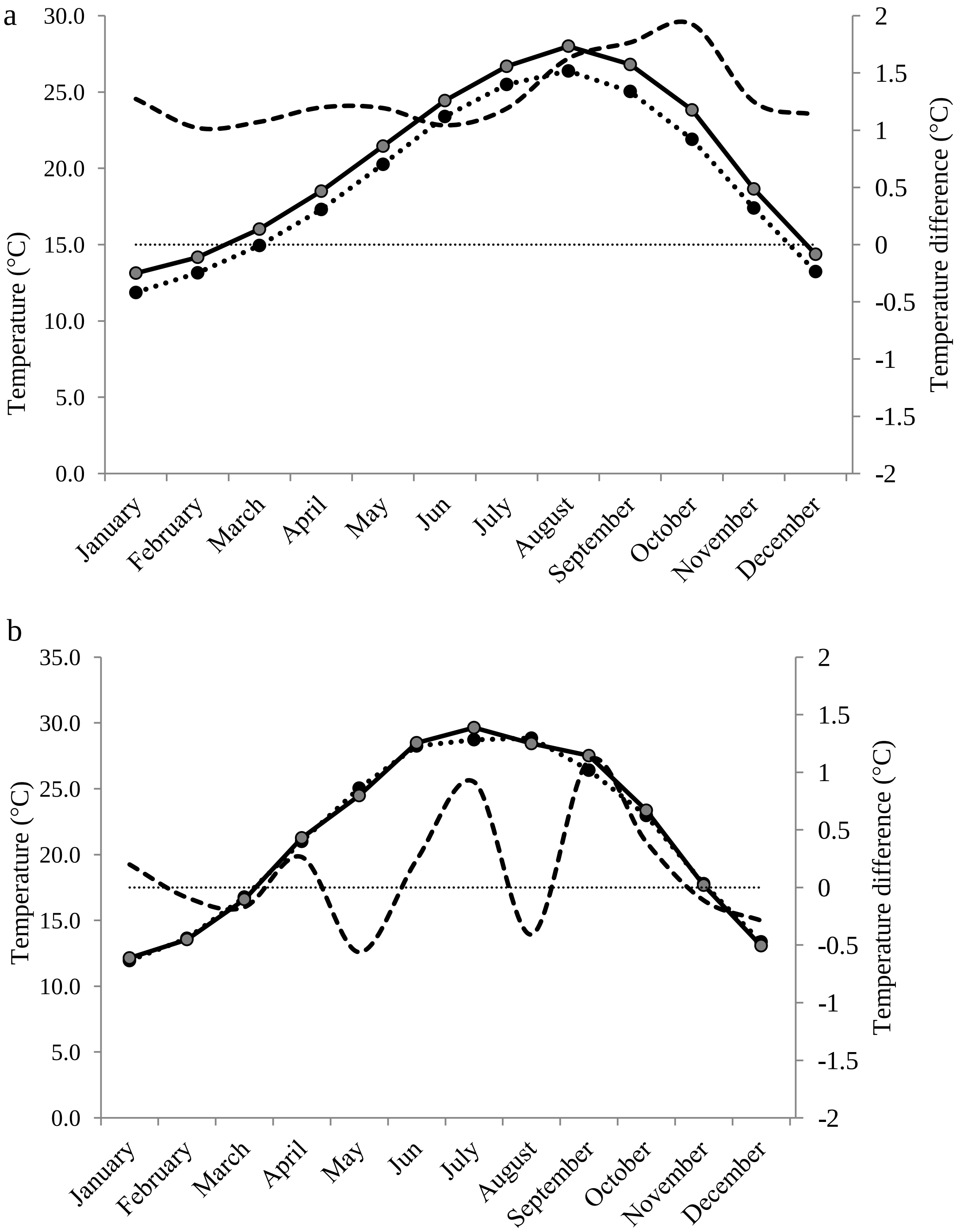


Fig. 4.14: Annual means 11-day moving averages of the mean daily average temperature for the two periods 1956-1982 and 1983-2010 at a) Musratah and; b) Ghadames.

4.5.3 Monthly variations and trends in mean average temperature

Positive changes (increases) in mean monthly average temperature are found at most stations; with a positive trends ranging from 0.002 °C a^{-1} to 0.15 °C a^{-1} (October at Al-Garyiat), with significant positive trends identified July-October at most stations, particularly Sirt, Ajdabyia, Ghadames, Al-Garyiat, Al-Jaghbub, Sabha and Tazerbou (Table 4.8). In September significant increases are identified at all stations except Nalute, Musratah and Binina, with highly significant increases (***) at Sirt and Ajdabyia, with significant (**) increases at Shahat, Hon, Sabha and Tazerbou. In February, negative trends in mean monthly average temperature ranges between 0.012 and -0.001 °C a^{-1} (Musratah, Sirt, Binina, Shahat, Darnah, Al-Garyiat, Hon, Jalo, Tazerbou and Al-Kufrah; Table 4.8).

In order to examine differences in monthly average temperature across Libya, the variability of the mean monthly average temperature of 15 stations for two 33 years intervals 1945-1977 and 1978-2010 were analysed to show the variability of monthly average temperature during the last 33 years compared to the 33 first years (1945-1977). Changes in mean monthly average temperature for the two periods (1945-1977 and 1978-2010) show higher average temperature at all stations, except Musratah, Binina and Jalo in the second period 1978-2010 (Fig. 4.15; see Appendix 4.11 for all stations). The Mann-Whitney test results show, that the warm months (July-October) had much higher temperatures, significant at 95% for the period 1945-2010 at all stations, with the except at Musratah, Binina and Jalo (Table 4.8).



(**.......**1945-1977, ▬▬1978-2010 and ------- difference)

Fig. 4.15: Mean monthly average temperature for the two periods 1945-1977 and 1978-2010 at a) Tripoli Airport and; b) Al-Jaghbub.

Table 4.8: Values of the Mann-Kendall statistic (Q) for monthly precipitation, with statistically significant levels at the synoptic stations, with; b) significant changes (95% confidence level) for the two periods 1945-1977 and 1978-2010 across Libya.

Stations		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Zwarah	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a b	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	a	0.019*	0.010	0.021+*	0.043****	0.029**	0.022***	0.038****	0.026***	0.046****	0.021+*	0.028**	0.021**

4.5.4 Seasonal and sub-seasonal variations and trends in mean average temperature

The mean seasonal average temperature is generally changes at stations across Libya in autumn, winter summer, and spring during the period 1945-2010. The mean average temperature shows positive trends (0.028 °Ca-1) in autumn, (0.014 °Ca-1) in winter, (0.019 °C a^{-1}) in spring and (0.022 °C a^{-1}) in summer (Table 4.9).

In autumn, a significant positive in climatic temperature was more generalized at all examined stations, with highly significant (***) at 11 of 15 stations, and significant (**) at Binina and Shahat. Increases significantly in winter average temperature are identified at ten of 15 stations, with highly significant (***) at Zwarah, Ajdabyia, and Hon, Nalute (**) and Nalute and Binina, Darnah, Sabha and Al-Kufrah. The feature is almost the same in the spring with only two exceptions since Tripoli Airport replaces Binina as a significant (Table 4.9). Highly significant (***) are identified at Zwarah, Ajdabyia, Ghadames, Hon, Sabha, and Al-Kufrah, with significant at Tripoli Airport, Sirt and Darnah (**). In summer, all stations except for Musratah (- 0.005 °C a^{-1}) show a positive trend, with a part from coastal region; Musratah and Binina, all stations have experienced a significant, with highly (***) at all west-coast stations; Zwarah, Tripoli Airport and Nalute and most of inland stations; Ghadames, Al-Garyiat, Hon, Sabha and Al-Kufrah.

Analysis of the seasonal data from 1945-2010 was undertaken by dividing the whole period in two, providing two periods for analysis of 33 years in length, this permits consideration of general long term changes and differences in rates of change. In addition, to show the variability of seasonal average temperature during the last 33 years compared to the 33 first years (1945-1977). Significant differences of mean average seasonal temperature of 15 stations for the periods 1945-1977 and 1978-2010 at different standard errors are showed in Table 4.9. The mean average temperature shows significant differences (95% confidence level) in autumn and summer at all stations, with exception of Musratah (autumn and summer), Binina (autumn), Jalo and Al-Kufrah (summer).

The sit at Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia, Ghadames, Hon, Sabha and Al Kufrah are significant (95%) in spring, with the site at Zwarah, Nalute, Sirt, Ajdabyia and Hon in winter.

Table 4.9: Values of the Mann-Kendall statistic (Q) for seasonal mean average temperature, with statistically significant levels at 15 synoptic stations across Libya (1945-2010) and Mann-Whitney test in 15 stations for two periods 1945-1977 and 1978-2010.

Stations	Autumn		Winter		Spring		Summer		Significant (955 *) 1945-1977 and 1978-2010			
	Sig	Q	Sig	Q	Sig	Q	Sig	Q	Aut.	Win.	Spr.	Sum.
Zwarah	***	0.045	***	0.036	***	0.029	***	0.031	*		*	*
T.Airport	***	0.025		0.008	**	0.021	***	0.025	*		*	*
Nalute	***	0.031	**	0.023	*	0.019	***	0.027	*	*	*	*
Musratah	+	0.014	+	0.009		0.006		-0.005				
Sirt	***	0.028	+	0.008	**	0.017	***	0.018	*		*	*
Ajdabyia	***	0.03	***	0.015	***	0.021	***	0.027	*	*	*	*
Binina	**	0.017	*	0.01	*	0.013		0.007				*
Shahat	**	0.015		0.001	*	0.014	*	0.012	*			*
Darnah	***	0.018	*	0.008	**	0.016	**	0.016	*			*
Ghadames	***	0.044		0.014	***	0.028	***	0.038	*		*	*
Hon	***	0.047	***	0.025	***	0.043	***	0.037	*	*		*
Jalo	+	0.018		0.004		0.005	*	0.014	*			
Al-Jaghbub	***	0.025		0.007		0.003	**	0.019	*			*
Sabha	***	0.036	*	0.019	***	0.031	***	0.033	*		*	*
Al-Kufrah	***	0.033	*	0.017	***	0.029	***	0.031	*		*	

*= stations not included at Mann-Whitney test

4.5.5 Annual variations and trends in mean average temperature

The mean annual average temperature for the period 1945-2010 exhibits a slight increase across the 15 stations (with Al-Garyiat, Ghat and Tazerbou excluded), with a clearer increase by the mid-1980. The Mann-Kendall results identify positive trends in mean annual average temperature at all stations, with an average of 0.021 °C a^{-1}, with the highest 0.043 °C a^{-1} (Hon). Significant trends in mean annual average temperatures are identified at twelve of 15 stations (Fig. 4.16; see Appendix 4.12 for all stations), with three exceptions Musratah, Jalo and Al-Jaghbub. Highly significant increases (***) are identified at stations: Zwarah, Ajdabyia, Ghadames, Hon, Sabha and Al-Kufrah, with significant increases (**) at Tripoli Airport, Sirt, Darnah and (*) at Nalute, Binina, Shahat (Table 4.10).

Table 4.10: Values of the Mann-Kendall statistic (Q) for annual mean average temperature, with statistically significant levels at the synoptic stations across Libya

	1945-2010			1945-1977			1978-2010		
Time series	T. Mean	Sig.	Q	T. Mean	Sig.	Q	T. Mean	Sig.	Q
Zwarah	20.0	***	0.029	19.2		-0.010	20.5	***	0.069
T.Airport	20.5	**	0.021	20.2		-0.001	20.9	***	0.040
Nalute	19.1	*	0.023	18.8		0.010	19.5	***	0.052
Musratah	20.4		0.006	20.4	***	-0.045	20.5	***	0.076
Sirt	20.5	**	0.017	20.3		0.010	20.7	***	0.046
Ajdabyia	20.7	***	0.021	20.3		0.012	21.0	***	0.052
Binina	19.9	*	0.013	20.0		0.004	20.2	***	0.046
Shahat	16.5	*	0.021	16.4		0.013	16.7	*	0.024
Darnah	20.3	**	0.016	20.0		0.024	20.3	***	0.046
Ghadames	21.8	***	0.028	21.4		-0.011	22.3	**	0.036
Al-Garyiat							21.0	**	0.040
Hon	21.4	***	0.043	20.4		-0.014	21.5	***	0.048
Jalo	22.5		0.005	22.3	**	-0.022	22.6	***	0.044
Al-Jaghbub	20.9		0.003	21.2		-0.010	21.4	***	0.047
Sabha	22.9	***	0.031	22.5		0.014	23.2	***	0.053
Ghat							24.1	**	0.024
Tazerbou							22.8	***	0.072
Al-Kufrah	23.3	***	0.029	22.7		-0.010	23.7	***	0.065

Analysis of the data from 1945-2010 was undertaken by dividing the whole period in two, providing two periods for analysis of 33 years in length, this permits consideration of general long term changes and differences in rates of change. Decreasing (increasing) mean average temperature (Fig. 4.16; see Appendix 4.12 for all stations) is identified at eight (seven) of 15 stations, with an average rate of -0.015 ºCa-1 (0.012 ºCa-1) for the first 33 years (1945-1977; Table 4.10), with statistically significant decreases at Musratah (***) and Jalo (**).

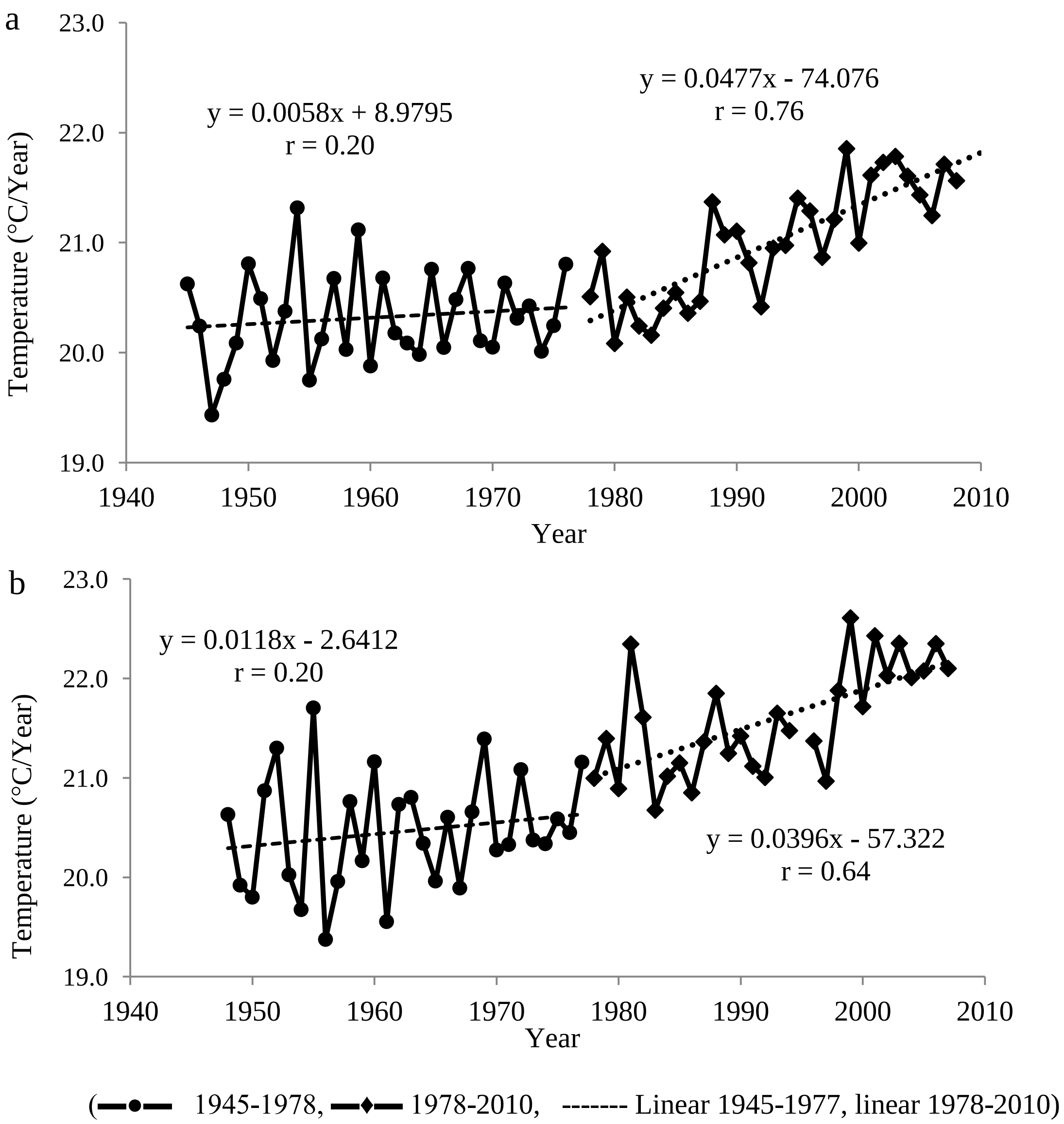


Fig. 4.16: Mean annual average temperature for the period 1945-2010 at a) Ajdabyia and; b) Al-Jaghbub.

Increases in annual mean average temperature are identified at all (18) stations over the last 33 years (1978-2010; Fig. 4.16 and see Appendix 4.12 for all stations), with an average rate of 0.049 ºCa-1, with the highest 0.076 ºCa-1 (Musratah; Table 4.10). These increases are significant at all 18 stations, with highly significant (***) at 14 stations, Shahat (*), Al-Garyiat, Ghadames, and Ghat (**). Increases (13 stations) or no change (Musratah and Jalo, with Al-Garyiat, Tazerbou and Ghat excluded) in average temperature (Fig. 4.16; see Appendix 4.12 for all stations) are identified when comparing between the two timeframes (1945-1977 and 1978-2009), with increases identified in period 2 compared to period 1 (Appendix 4.12 for all stations).

Significantly higher (95% confidence level) mean annual average temperatures are identified at nine stations; Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia, Ghadames, Al-Jaghbub, Sabha and Al-Kufrah. Error bars shows significant differences in mean annual average temperature for the two periods 1945-1977 and 1978-2010 at all stations except Musratah, Shahat, Hon, and Jalo at one standard error (68.4% confidence level; Fig. 4.17).

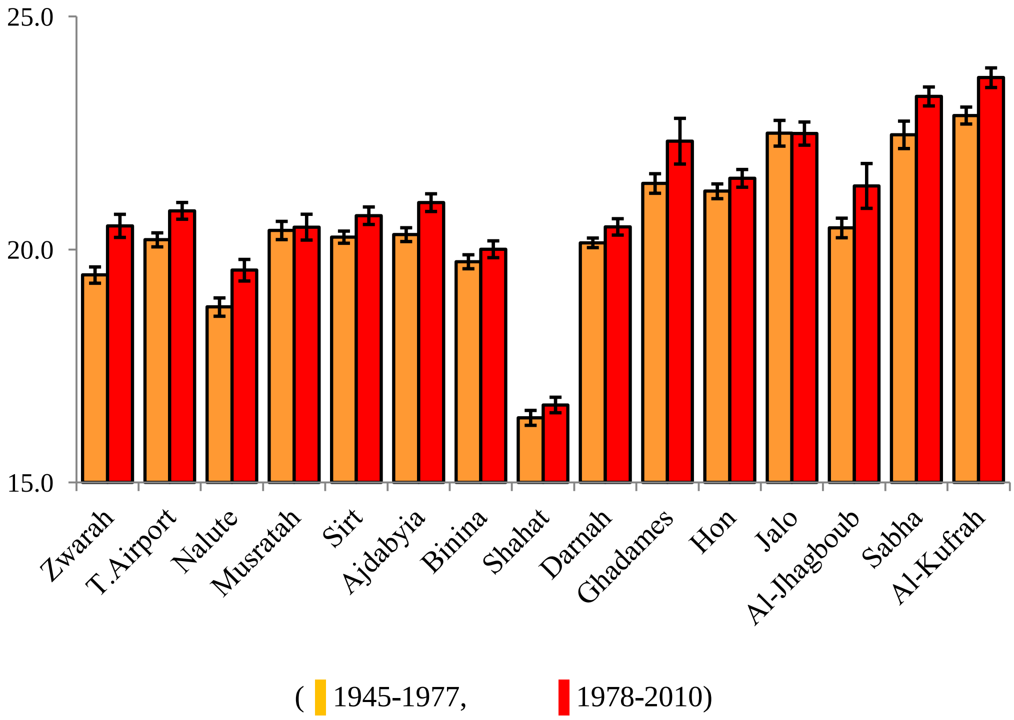


Fig. 4.17: Mean annual average temperature for the two periods 1945-1977 and 1978-2010 at the 15 synoptic stations across Libya, with error bars representing two standard errors (95.4% confidence level).

4.5.6 Decadal variations and trends in mean average temperature

To examine the characteristics of daily mean average temperature for the stations within this study, analyses of the cumulative 11-day average temperature was undertaken with comparison over the 10-years intervals (1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010; Fig 4.18).

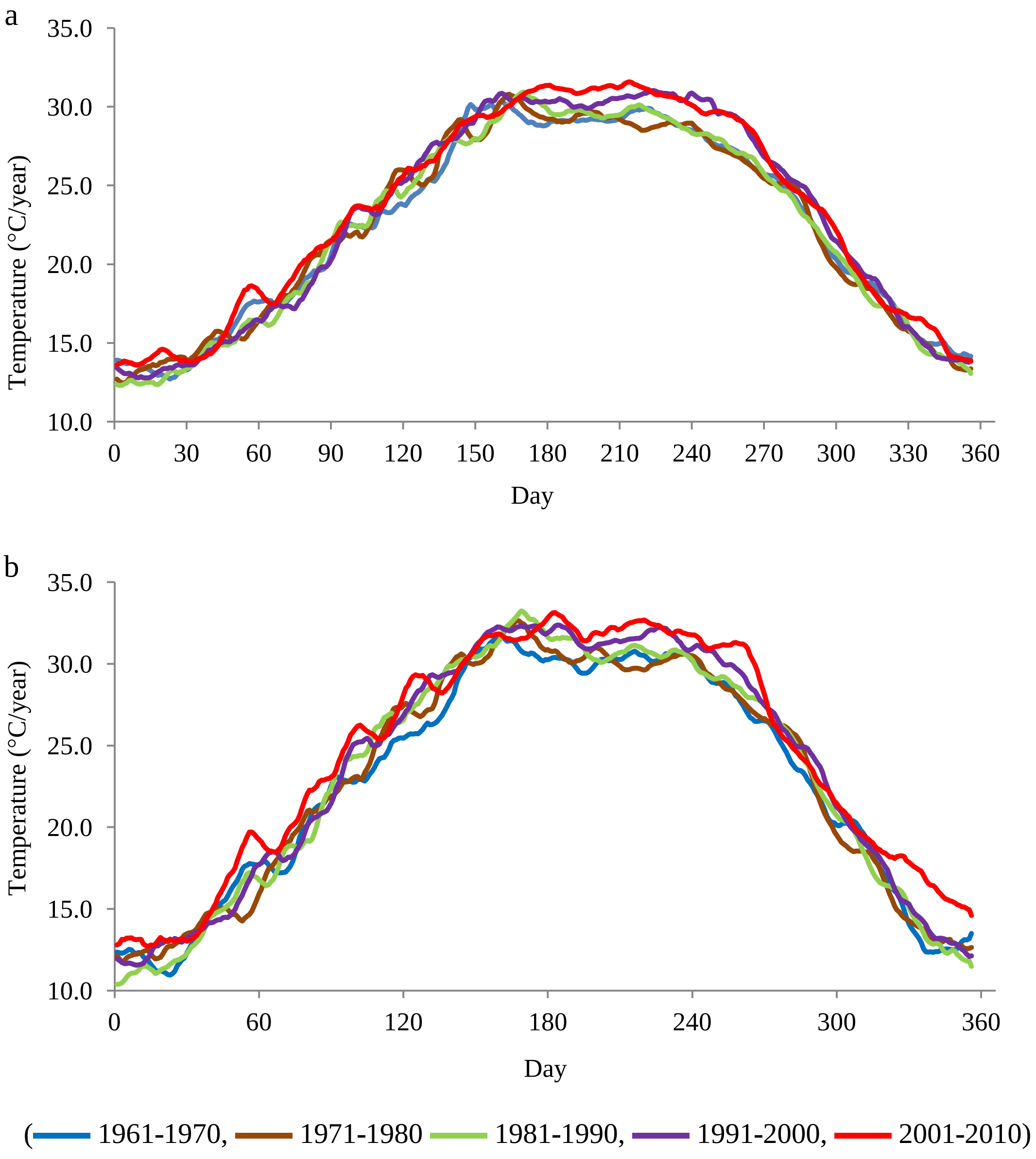


Fig. 4.18: Decadal mean of 11-day moving averages of the mean daily average temperature over near decadal windows for a) Jalo and; b) Sabha, for the period 1961-2010, with the curves for each separate decadal block.

The mean annual average temperature for the stations has fluctuated over the period 1961-2010, with a general increase over the period 2001-2010 at the majority of stations; Zwarah, Tripoli Airport, Ajdabyia, Binina and Darnah, Ghadames, Hon, Jalo, Al-Jaghbub, Sabha, Tazerbou and Al-Kufrah, with the temperature during each decade greater than the previous decade (Fig. 4. 18; see Appendix 4.13 for all stations).

4.6 DRY BULB TEMPERATURE (DBT)

The temperature of the air measured by an ordinary thermometer is known as the dry bulb temperature (DBT) of air. The dry bulb temperature is usually measured at all stations across Libya, with the mean annual temperature ranging between 19.0 and 22.5 ° C at coastal and in land stations, respectively.

4.6.1 Annual variations and trends

Positive trends in annual DBT are the dominated feature in Table 4.11. These trends are, in general, consistent with changes and trends in mean annual average temperature, which show rapid increases by the mid 1980s and positive significant increases at most stations during the period 1945-2010.

Positive trends are found in annual DBT at all stations across Libya (Table 4.11), with nearly similar average trend at coastal (0.027 °Ca-1) and inland (0.033 °Ca-1) stations, with the highest value (0.054 °Ca-1) at Hon and the lowest (0.013 °Ca-1) at Jalo. Highly positive trends (***) are identified, with except at Jalo (**)

Table 4.11: Values of the Mann-Kendall statistic (Q) for annual mean dry bulb temperature (° C), with statistically significant levels at 15 Libyan synoptic stations

Time series	Mean Annual	Standard Deviation	Significant.	Q
Zwarah	19.9	0.82	***	0.040
T.Airport	19.3	0.60	***	0.035
Nalute	19.2	0.71	***	0.026
Musratah	19.5	0.55	***	0.029
Sirt	20.4	0.53	***	0.017
Ajdabyia	20.4	0.65	***	0.029
Binina	19.8	0.46	***	0.015
Shahat	15.5	0.52	***	0.026
Darnah	17.2	0.71	***	0.028
Ghadames	22.0	0.86	***	0.032
Hon	23.2	0.48	***	0.054
Jalo	21.4	0.80	**	0.013
Al-Jaghbub	21.0	0.73	***	0.038
Sabha	21.7	0.50	***	0.037
Al-Kufrah	23.2	0.95	***	0.024

4.7 CORRELATION BETWEEN TEMPERATURE AND REGIONAL FACTORS

4.7.1 Temperature and population growth

To illustrate the relationships between temperature and the population growth the mean annual minimum temperature and the rate of the population growth at the most densely populated cities; Tripoli, Musratah, Benghazi and Sabha, which are represented by Tripoli Airport, Musratah, Binina and Sabha stations respectively, have been plotted (Fig. 4.19).

No clear relationships exist between the rates of temperature change and population growth for the cities studied, based on the results in Fig.4.19, unfortunately no specific information on individual rates of growth in areas immediately adjacent to the stations are recorded.

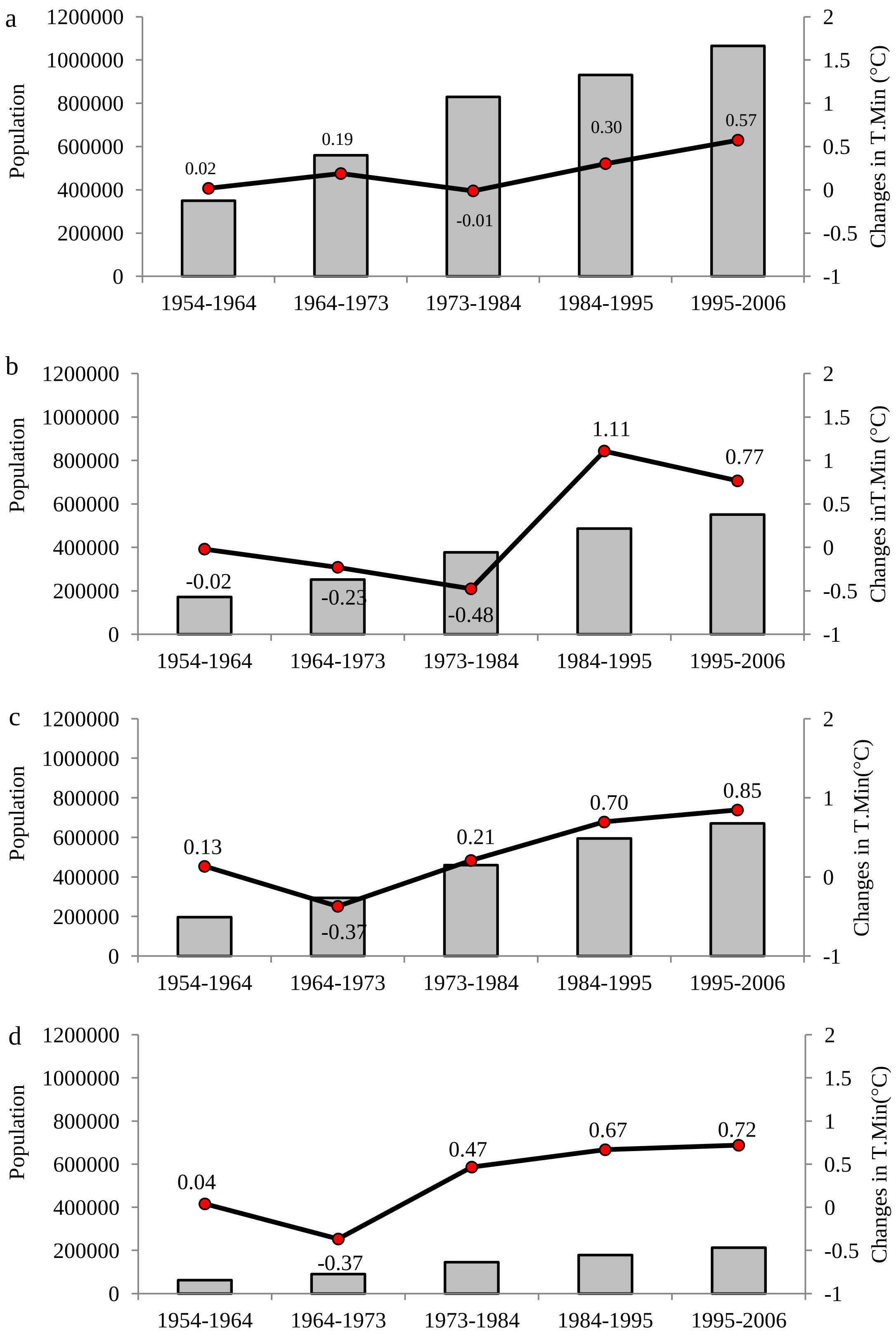


Fig. 4.19: The total population and changes in annual minimum temperature for the cities; a) Tripoli Airport; b) Musratah; c) Binina; d) Sabha (1964-2006).

The meteorological stations at Tripoli, Binina and Sabha are located at the airport, within the periphery of the old cities but now within the broader city region, while the majority of the inland stations are situated in rural regions; as such less influenced by urbanisation. In contrast most of coastal stations are situated in urban areas; as such they are could be high influenced by urbanisation, or changing patterns of urbanisation over the study period. 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.

4.7.2 Temperature and Carbon Dioxide (CO_2)

Correlation coefficients (Pearson product-moment) were computed to determine the relationship between Carbon Dioxide (CO_2) emissions (Table 4.12) and mean annual average temperatures across Libya (Fig. 4.20) for the most densely populated cities (production and industrialized); Zwarah, Tripoli Airport, Musratah, Ajdabyia, Binina, Darnah and Sabha for the period 1960-2009.

Table 4.12: Total carbon dioxide (CO_2; million tons), emissions across Libya for the period 1960-2009

Year	CO_2	Year	CO_2	Year	CO_2
1960	693.06	1977	20,106.16	1994	44,132.34
1961	1,195.44	1978	21,239.26	1995	46,020.85
1962	1,048.76	1979	26,032.03	1996	44,158.02
1963	1,463.13	1980	26,904.78	1997	44,975.75
1964	663.73	1981	28,811.62	1998	45,474.47
1965	1,015.76	1982	30,762.46	1999	44,620.05
1966	2,629.24	1983	30,414.10	2000	47,113.62
1967	18,507.35	1984	28,624.60	2001	48,100.04
1968	30,139.07	1985	31,418.86	2002	47,832.35
1969	35,551.57	1986	34,059.10	2003	49,167.14
1970	32,331.94	1987	32,566.63	2004	50,358.91
1971	21,646.30	1988	36,398.64	2005	52,100.73
1972	15,232.72	1989	37,322.73	2006	53,780.22
1973	14,587.33	1990	36,780.01	2007	54,201.93
1974	9,347.18	1991	42,863.56	2008	60,384.49
1975	11,580.39	1992	37,260.39	2009	62,874.38
1976	17,916.96	1993	38,947.21		

Index mundi; http://www.indexmundi.com/

Significant (95% confidence level) relationships between mean annual average temperature and CO_2 emissions exists (except at Binina), with positive correlations at all stations, with values ranging between 0.84 (Zwarah) and 0.18 (Binina; Table 4.13).

The relationship between mean annual maximum temperature and CO_2 emissions appears somewhat complex, with a variety of different positive/negative and no significant relationships evident (Table 4.13). For the mean annual minimum temperature, all correlations are positive and significant ranging between 0.89 (Zwarah) and 0.56 (Tripoli Airport; Table 4.13).

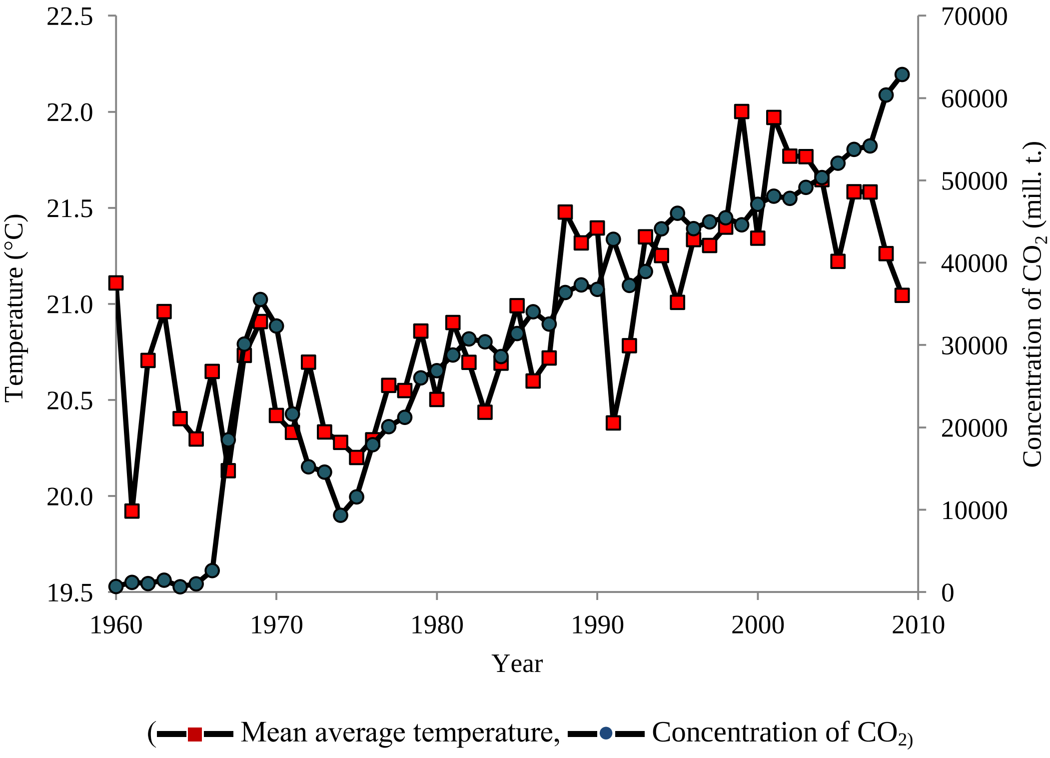


Fig. 4.20: Mean average temperature (°C) and concentration of carbon dioxide (CO_2) in (mill. t.) across Libya (1960-2009).

Table 4.13: Correlation coefficient between mean annual temperature (maximum, minimum and average) among cloud cover amount (1945-2010) and carbon dioxide emission (1960-2009) at stations and the regions across Libya

Cloud cover and Temperature				CO2 emission and Temperature			
	Min	Max	Mean		Min	Max	Mean
Zwarah	-0.34*	-0.22*	-0.14	Zwarah	0.89*	0.26	0.84*
T.Airport	0.38*	-0.11	0.18	T.Airport	0.56*	0.50*	0.70*
Musratah	-0.29*	-0.45*	-0.20	Musratah	0.66*	0.12	0.55*
Nalute	-0.46*	-0.13	-0.41*	Ajdabyia	0.66*	0.48*	0.79*
Sirt	-0.14	-0.44*	-0.19	Binina	0.59*	-0.22*	0.18
Ajdabyia	-0.51*	-0.54*	-0.56*	Darnah	0.71*	-0.14	0.56*
Binina	0.38*	-0.09	0.05	Sabha	0.76*	0.53*	0.70*
Shahat	-0.58*	-0.01	-0.42*				
Darnah	-0.32*	-0.45*	-0.47*				

4.7.3 Temperature and cloud cover

In order to determine the relationships between temperature and cloud across Libya, correlation coefficients was computed between mean annual cloud cover and mean annual average temperature at the nine coastal stations; Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Shahat and Darnah for the last 66 years (1945-2010; Table 4.12). The correlation coefficients show generally negative correlation between amount of cloud and average annual minimum temperature at the coastal stations, with except at Tripoli Airport and Binina; with significant correlations at most sites, with the exception of Sirt (Fig. 4.21).

The mean maximum temperature shows a negative relationship with cloud cover at all stations, with significant changes at Zwarah, Musratah, Sirt, Ajdabyia and Darnah. The relationship between cloud cover and mean annual average temperature is varied, but reflects the same trend patterns in mean annual minimum temperature, but with less significant changes.

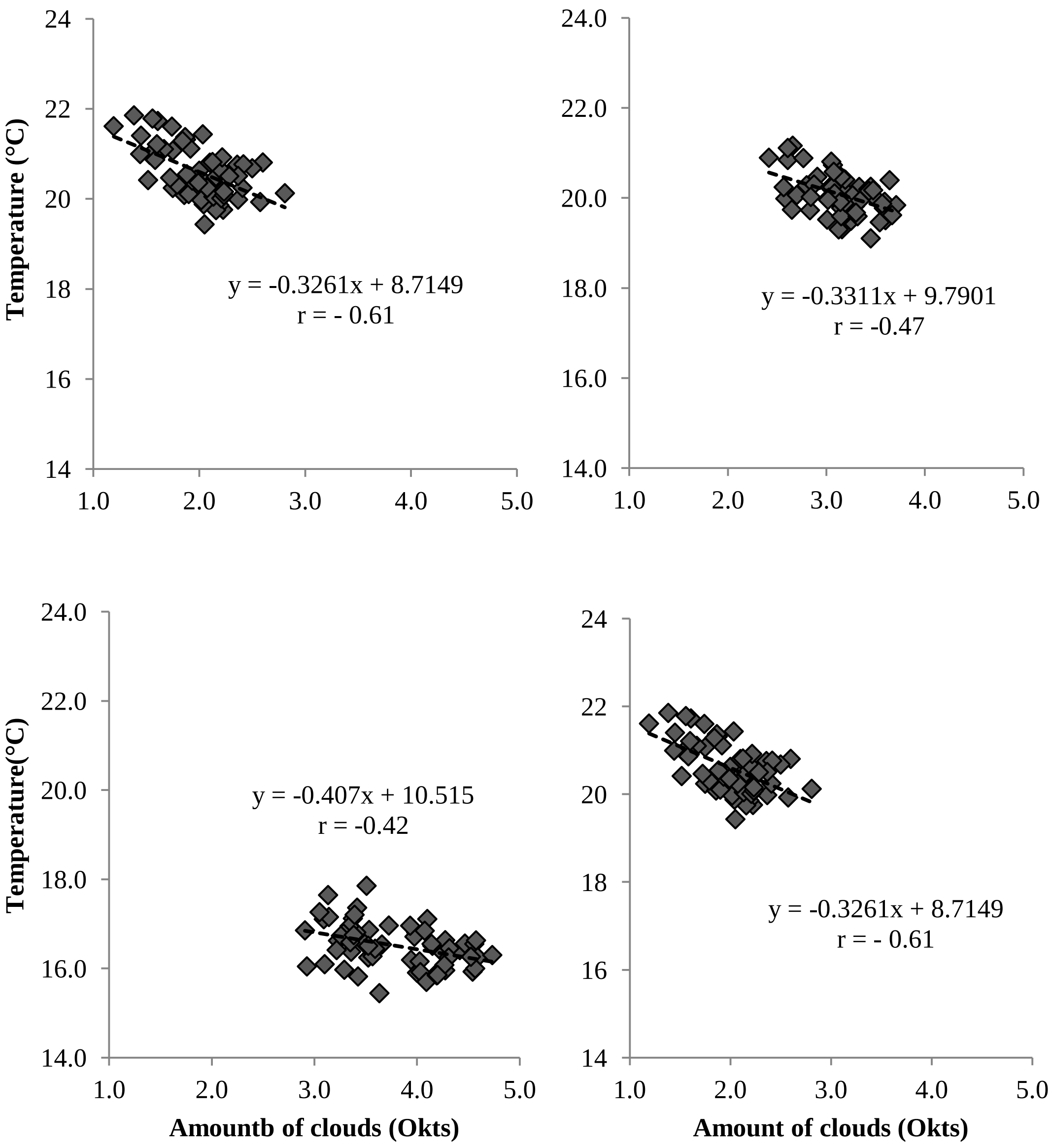


Fig. 4.21: The mean average temperature and mean annual total amount of cloud (Oktas) for the significant stations; a) Ajdabyia; b) Darnah; c) Shahat and; d) Nalute for the period 1945-2010. Line is the linear trend, r is the correlation coefficient.

4.8 EXTREMES OF TEMPERATURE

Climate extremes can be analysed by estimation of changes in extreme weather and climate parameters, which are divided by Alexander et al., (2006) into four different indices classes: percentile-based, absolute, duration and threshold-based, with regional and global (e.g. Revadekar, 2006; Bartolini et al., 2008; Baoying et al., 2012; Boccolari & Malmusi, 2013; Kostopoulou et al., 2013).

Percentile-based indices represent the amount (percentage) of temperature falling above a fixed value. Absolute indices refer to counts of days crossing a specified absolute value that can for example be a minimum or maximum value within a month, season or year. Threshold-based indices consist of a number of days on which temperature/precipitation values fall above or below a fixed threshold. Duration indices define periods of extreme warmth, cold, wetness or dryness. From the internationally agreed WMO list of about 50 climate change indices available on line at htt://www.knmi.nl/samen/eca and recommended by Jones et al 1999; Klein and Konnen 2003. The most important climate indices related to the temperature and those most widely for analysis of extremes in temperature are analysed in this chapter (Table 4.14).

Table 4.14: Definition of six temperature indices used in this thesis for 1961-2010

Index	Descriptive name	Definitions	Units
TXx	Warmest day	Monthly maximum value of daily max.	° C/y
TN90	Warm nights	Percentage of days when TN > 90th percentile	d/y
TX90	Warm days	Percentage of days when TX > 10th percentile	d/y
TNn	Coldest night	Monthly minimum value of daily min.	° C/y
TN10	Cold nights	Percentage of days when TN < 10th percentile	d/y
TX10	Cold days	Percentage of days when TX < 10th percentile	d/y

Notes: *, all indices are calculated based on; TX, daily maximum temperature; TN, daily minimum temperature

4.8.1 Annual variations and trends of warm extremes temperature

The estimation of changes and trends in warm extremes temperature (TXx, TN10p, TX90p) for the 16 stations (Al-Garyiat and Ghat excluded) during the period 1961-2010 is based on the Mann-Kendall test.

The results of previous sections (e.g. section 4.3.1) identified that maximum temperature showed increasing trends at most stations across Libya. The changes in warm extremes exceed the respective rates of change in temperature. The temporal and spatial patterns of changes and trends for warm extremes; warmest day (TXx), warm days (TN90p) and warm nights (TX90p) are analysed. The number of stations with significant positive/negative, non-significant positive/negative and no change trends (0.00) for those indices are listed in Table 4.15.

Regional averages of warmest day (TXx) showed positive trends (0.16 ° Ca-1) at all stations (Table 4.15), with three exceptions at the eastern-coastal stations of Binina, Shahat and Darnah (-0.011 °Ca-1), but no changes at 15 stations in TX90p, except Al-Jaghbub (-0.043 da-1). The increases in TXx are significant (**) in all the western and central-coastal stations of Zwarah, Tripoli Airport, Nalute and Musratah and at the inland stations of Ghadames, Al-Jaghbub, Sabha and Tazerbou. High negative trends (0.099 da-1) in warm nights (TN90p) are identified at Zwarah, Shahat, Al-Jaghbub and Al-Kufrah with a significant decreases at Zwarah, Al-Kufrah, (***), Shahat (**) and at Al-Jaghbub (*) (Fig.4.22 and see Appendix 4.14 for the significant stations)

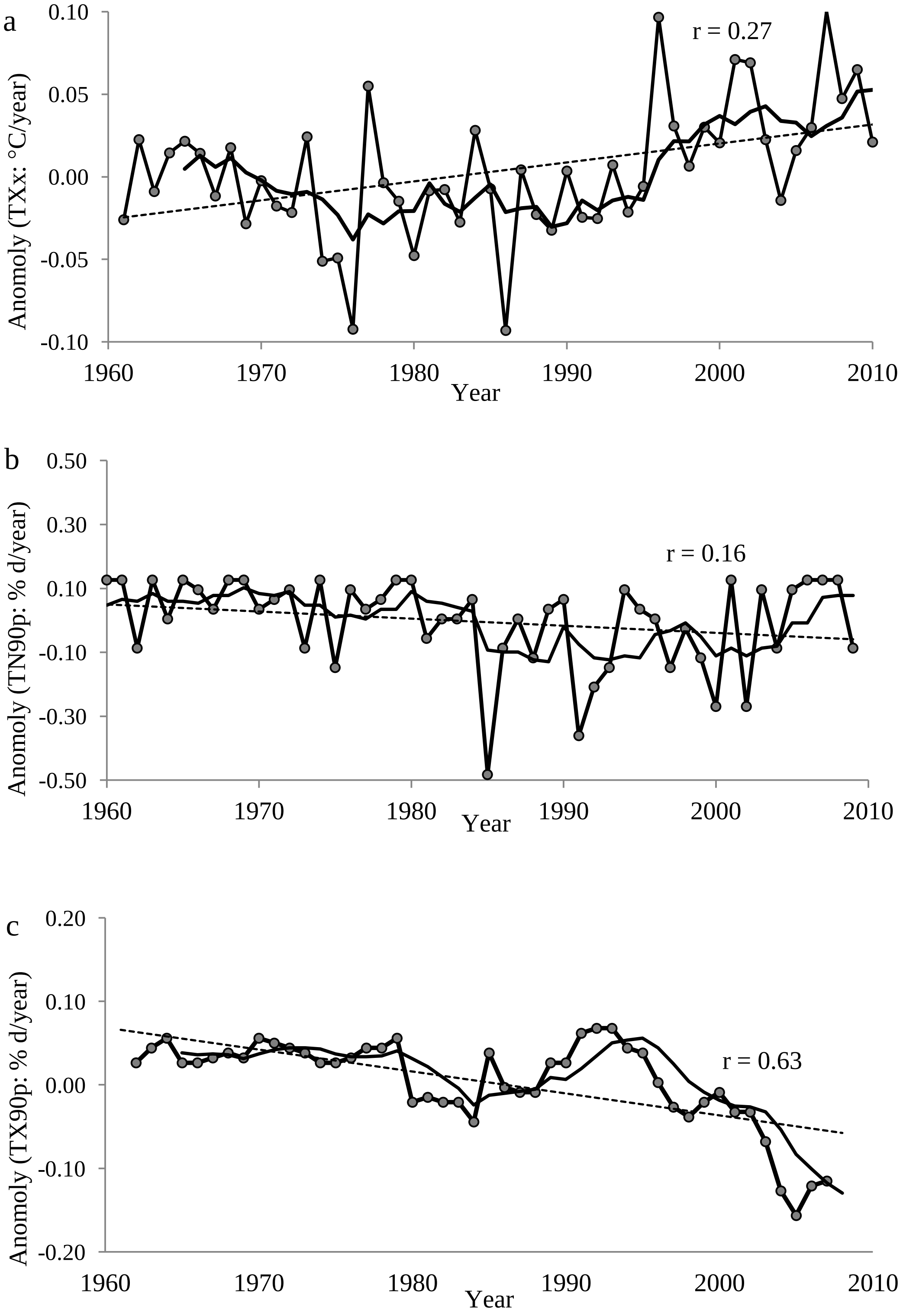


Fig. 4.22: Regional annual anomalies series during 1961-2010 for a) TXx (Zwarah); b) TN90 (Shahat); and c) TX90 (Al-Jaghbub). Line is the linear trend, R is the correlation coefficient and smoother line is the 5-yeras smoothing average.

Table 4.15: Values of the Mann-Kendall statistic (Q) for indices trends calculating from minimum and maximum temperature, with statistically significant levels at 15 synoptic stations across Libya for the period 1961-2010

Time series	Cold extremes						Warm extremes					
	TNn ° Ca-1		TN10p da-1		TX10p da-1		TXx ° Ca-1		TN90p da-1		TX90p da-1	
	Sig	Q	Sig	Q	Sig	Q	Sig	Q	Sig.	Q	Sig	Q
Zwarah	***	0.085		-0.042		0.000	**	0.036	***	-0.138		0.00
T. Airport	***	0.041		0.000	**	0.037	*	0.024		0.000		0.00
Nalute	***	0.046		0.000		0.000	**	0.023		0.000		0.00
Musratah	***	0.056		0.000		0.000	**	0.028		0.000		0.00
Sirt	**	0.025		0.000		0.000	*	0.024		0.000		0.00
Ajdabyia	***	0.072		0.000	+	0.001	*	0.017	+	0.001		0.00
Binina	***	0.045		0.000		0.000		-0.008		-0.040		0.00
Shahat	***	0.035		-0.032		0.000		-0.011	**	-0.111		0.00
Darnah	***	0.038		0.000		0.000		-0.014		0.000		0.00
Ghadames	***	0.091	*	0.033		0.000	**	0.025		0.000		0.00
Hon	***	0.083		0.000		0.000		0.012	**	0.071		0.00
Jalo	***	0.043		0.000		0.000		0.012		0.000		0.00
Al-Jaghbub	***	0.029	**	-0.077	**	-0.043	**	0.033	*	-0.129	*	-0.043
Sabha	***	0.056		0.000		0.000	**	0.029		0.000		0.00
Tazerbou		0.006		0.000		0.000	**	0.035		0.000		0.00
Al-Kufrah	***	0.083	**	-0.044		0.00		0.014	***	-0.077		0.00

4.8.2 Seasonal variations and trends of warm extremes temperature

Seasonally, all stations except Binina and Darnah have positive changes in the warmest autumn day (TXx), with an average increase of 0.02 ° Ca-1, with significant (**) increases at Tripoli Airport, Ghadames and Tazerbou, significant (*) at Zwarah, Nalute, Hon and Sabha, with the central stations: Sirt and Ajdabyia weakly significant (+). In spring, positive trends (+0.0015 ° Ca-1; Table 4.16) in warmest day are identified at 56% of stations with only one significant (**) at Sabah.

Table 4.16: Values of the Mann-Kendall statistic (Q) for Seasonal extremes maximum (warmest day; TXx) temperature (° C), with statistically significant levels at 16 synoptic stations across Libya for the period 1961-2010

Stations	Winter		Spring		Summer		Autumn	
	Sig	Q	Sig	Q	Sig	Q	Sig	Q
Zwarah		0.018		-0.003		-0.014	*	0.048
T. Airport		0.006		-0.008		0.001	**	0.044
Nalute		0.016		0.007	+	0.012	*	0.024
Musratah		-0.020		-0.003		-0.007		0.023
Sirt		-0.010		0.020		-0.010	+	0.026
Ajdabyia		0.002		0.014		0.017	+	0.017
Binina		-0.002		-0.015	**	-0.029		-0.008
Shahat		-0.013		-0.007		-0.019		0.008
Darnah	+	-0.021		-0.020		-0.014		-0.007
Ghadames		0.004		0.004	+	0.018	**	0.029
Hon		-0.018		0.000		0.000	*	0.028
Jalo		-0.008		-0.021		-0.007		0.000
Al-Jaghbub		0.00		0.007	+	0.018		0.016
Sabha		-0.010	**	0.032	**	0.022	*	0.029
Tazerbou		-0.038		0.014	+	0.029	**	0.044
Al-Kufrah		-0.016		0.003		-0.001		0.000

Negative winter trend (+ 0.0167 ° Ca-1) in warmest day are the dominated features, with the trends ranges from -0.021 (Jalo) to -0.003 ° Ca-1 (Zwarah and Musratah; Table 4.16) identified at 50% of stations. Positive summer trends (+0.015 ° Ca-1) in warmest day are identified at 50% of total stations, with significant summer (**) increases at Sabha and Nalute, Ghadames, Al-Jaghbub and Tazerbou (+). The other 50% of stations identified a decrease at an average rate of -0.009 ° Ca-1, with summer decreases significant (**) at Binina; indicating that southern sites are exhibiting an increase and coastal sites decreases in the warmest days.

4.8.3 Annual variation and trends of cold extremes temperature

The estimation of changes and trends in extremes of cold temperature, for the 16 stations (1961-2010) are based on the Mann-Kendall test. The results of the previous sections for minimum temperature (section 4.4.5) showed that there were increasing trends for temperature at all stations across Libya. Increases in cold temperature extremes are smaller than those found for mean minimum temperature.

Smoothed curves of the exceedance of the coldest night (TNn), cold night percentile (TN10p) and cold day percentile (TX10p) index anomalies (relative to 1961-2010) are shown in Fig 4.23 (see Appendix 4.15 for significant stations). Except for coldest day (TNn), the analysis of cold days and cold nights showed almost no change at most stations, with slight fluctuation at the remaining stations.

Positive trends in coldest night (TNn) are found at all stations, ranging from 0.006 ° Ca-1 (Tazerbou) to 0.091 ° Ca-1 (Ghadames), with significant increases at all stations except Tazerbou, with a significance (**) at Sirt and highly significant (***) at all remaining stations (Table 4.16).

Significant increases (***) is identified at all stations, with except at Sirt (**). The decreases in cold night (TN10p) are identified at Zwarah, Shahat, Al-Jaghbub (**) and Al-Kufrah (**) ranging between -0.077 and -0.033 da-1, with no changes at the remaining stations.

Positive trends in cold days (TX10p) are found at Tripoli Airport (0.037 da-1) and Ajdabyia (0.001 daya-1), with significant trends (**) at Tripoli Airport and no changes at remaining stations (Table 4.16).

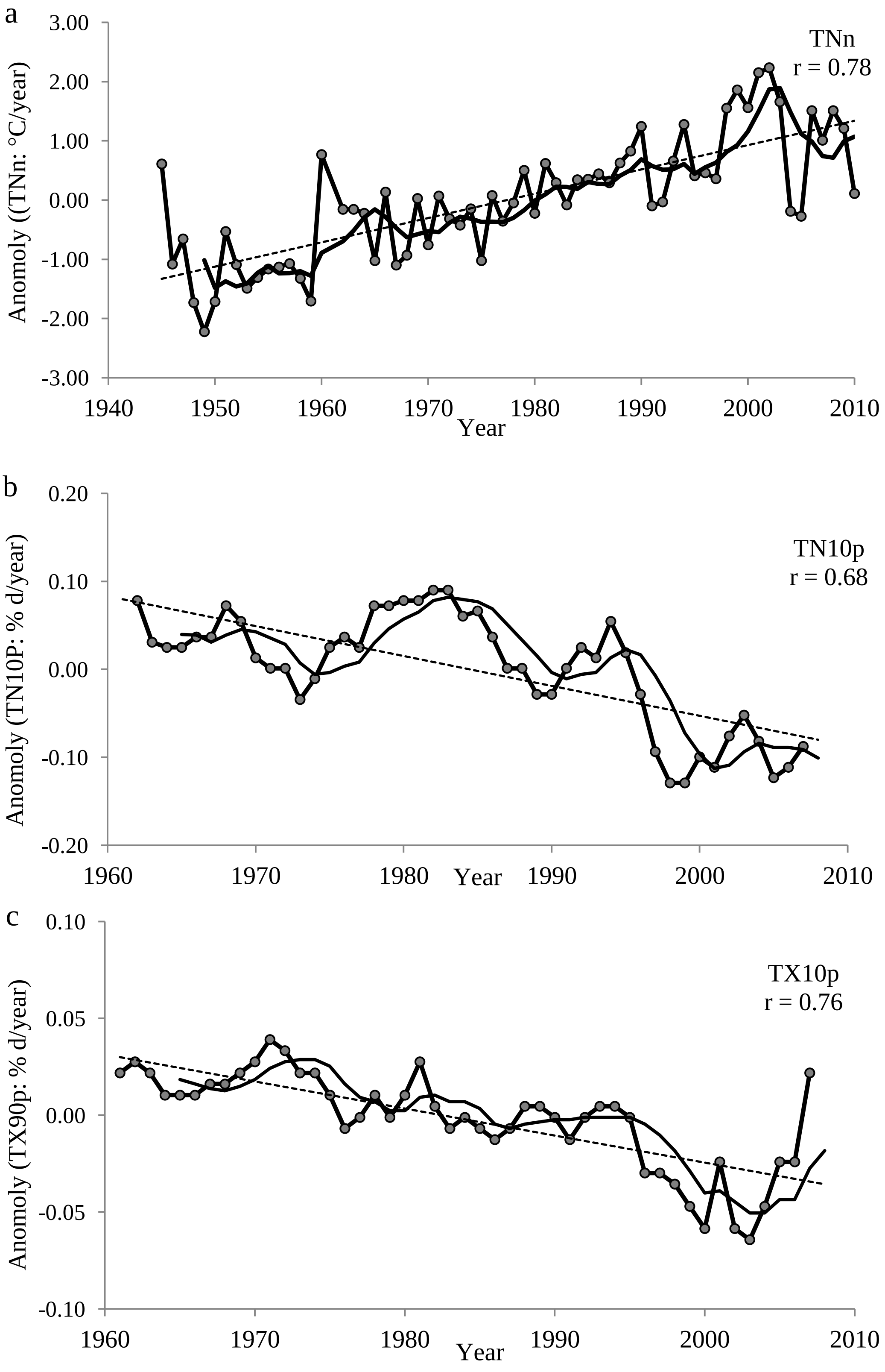


Fig. 4.23: Regional annual anomalies series during 1961-2010 for a) TNn (Binina); b) TN10 (Al-Jaghbub) and; c) TX10 (Al-Kufrah). Line is the linear trend, *r* is the correlation coefficient and smoother line is the 5-yeras smoothing average

4.8.4 Seasonal variation and trends of cold extremes temperature

Seasonally, positive (warming) trends in coldest day (TNn) are found at all stations, in winter (0.0373 ° Ca-1), summer (0.0343 °Ca-1) and autumn (0.0380 °Ca-1). The coldest spring days shows increased trends with an average rate of 0.037 °C a^{-1} at all stations with one exception for Al-Jaghbub (-0.013 °C a^{-1}). High positive significant trends (***) are identified at 56% (winter), 50% (spring and summer) and 43% of stations (autumn; Table 4.17).

Table 4.17: Values of the Mann-Kendall statistic (Q) for Seasonal extremes minimum (coldest day; TNn) temperature (° C), with statistically significant levels at 16 synoptic stations across Libya for the period 1961-2010

Stations	Winter		Spring		Summer		Autumn	
	Sig	Q	Sig	Q	Sig	Q	Sig	Q
Zwarah	***	0.054	***	0.060	***	0.071	***	0.063
T. Airport	*	0.017	***	0.037	***	0.038	**	0.024
Nalute	***	0.037	*	0.023	+	0.014	**	0.035
Musratah	***	0.044	+	0.016		0.011	**	0.032
Sirt	**	0.026	*	0.014		0.006	*	0.021
Ajdabyia		0.013	**	0.029	**	0.036	*	0.022
Binina	***	0.048	***	0.057	***	0.043	***	0.039
Shahat	**	0.027	***	0.033	*	0.023	*	0.022
Darnah	***	0.027	***	0.040	***	0.052	***	0.032
Ghadames	***	0.051	***	0.049	***	0.056	***	0.053
Hon	***	0.062	***	0.063	***	0.059	***	0.074
Jalo	***	0.051	**	0.025		0.011	***	0.045
Al-Jaghbub	*	0.015		-0.013		0.002		0.005
Sabha	***	0.039	**	0.040	***	0.037	***	0.044
Tazerbou		0.006	*	0.035		0.012	+	0.027
Al-Kufrah	***	0.080	***	0.079	***	0.079	***	0.070

4.9 DISCUSSION

In this chapter, time series of daily, monthly, seasonal and annual maximum, minimum and mean average temperature data for daily (1956-2010; 56 years) and annual (1945-2010; 66 years) data at 18 synoptic stations across Libya are analyzed.

The findings of temperature variability are comparable with previous studies over the last half of the 20th century that have studied the changes and trends of temperature across the Mediterranean region (e.g. Aesawy and Hasanean 1998; Domroes and El-Tantawi 2005; Hasanean, 2001; Ben-Gai 1999; Hasanean and Abdel Basset 2006; Bartolini et al., 2008; El-Kenawy et al., 2009; Chaouche et al, 2010; Baoying at al., 2012), though the rates identified are generally higher than those previously documented and provide a much more detailed depiction of climate changes across Libya compared to previous studies. The findings of extremes temperature variability are also comparable to a number of previous studies during the last 20 years (Goubanova and Li, 2007; Nie et al., 2012; Fan et al., 2012; Zhou and Ren 2011; Kostopoulou et al., 2013).

4.9.1 Mean maximum temperature

Increasing maximum temperatures are identified at all stations, ranging from 0.013 to 0.052 °C a^{-1} during the last 33 years (1978-2010); with decreases in maximum temperature (-0.024 °C a^{-1}) at 47% of study stations during the period 1945-1977 (Table 4.4). Previous research e.g. El-Tantawi (2005) identified increases in maximum temperature ranged between 0.02 and 0.19 °C/decades at approximately 73% of the study stations across Libya (1946-2000). The findings are supported by Ben-Gai et al. (1999) in their study of median maximum temperature in Israel trends with an average rate of 0.21 °C/decade. However, El-Kenawy et al. (2009) identified a significant decrease in maximum temperature at an average rate of –0.06 °C/decade at approximately 70% of the study stations across Libya during the period of 1951-2000, which clearly contradicts the findings of this study.

Changes in maximum temperature were identified, with a general increases at most stations, with a particularly warm period in the mid-1980s with rapid increases in climatic temperature at all stations. Seasonal temperatures indicates that rapid increases took place in autumn, summer and spring, with seasonal maximum temperature increasing at an average rate of 0.010 °C a^{-1} (winter), 0.015 °C a^{-1} (summer), 0.020 °C a^{-1} (spring) and 0.022°C a^{-1} (autumn; Table 4.4). This finding is supported by Aesawy and Hasanean (1998), who indicate increases in seasonal climatic temperature in Tripoli, but at much higher rates at 0.64 °C/decadal (summer), 0.38 °C/decadal (autumn) and 0.33 °C/decadal (spring).

The estimation of differences in annual maximum temperature for two study periods (1945-1977 and 1978-2009) at 15 stations across Libya identified changes in the latter (1978-2010) period compared to the former (1945-1977) at all stations. Differences in maximum temperature are statistically identified as significant (95% confidence level) when comparing between the two timeframes (1945-1977 and 1978-2010) at nine stations: Zwarah, Tripoli Airport, Nalute, Sirt, Ajdabyia, Ghadames, Hon, Al-Jaghbub and Sabha (Fig 4.6).

4.9.2 Mean minimum temperature

The findings concerning minimum temperature support previous trends (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 revealed significant increases in minimum temperature. The mean annual minimum temperature (1945-2010) increased at an average rate of 0.032 ° Ca-1 (Table 4.7). This is considerably faster than the IPCC (2007) global mean temperature increase of 0.74 °C ± 0.18 °C over the last 100 years, and is supported by Kostopoulou et al. (2013) who identified increases in annual minimum temperature of 0.4-0.5 °C over the Mediterranean region during the period 1961-1990, but 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; Fig. 4.12).

Seasonal analyses indicate that the most rapid warming is observed in summer and autumn with an increasing trend (0.035 °Ca-1) in seasonal minimum temperature in both summer and 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) are more noticeable in spring and winter.

4.9.3 Mean average temperature

Mean average temperature increased at an average rate of 0.024 °C a^{-1} during the period 1945-2010, with a drastic warming rate of 0.048 °C a^{-1} for the last 32 years (1978-2010; Table 4.11) identified within this study; as a result of rapid increases in annual minimum temperature bringing the overall mean value up. This is considerably faster than the IPCC (2007) global average temperature increase; which can be attributed to two phases of warming, 1940-1940 (0.35 °C/ decade), and 1970-2005 (0.55 °C/decade). The findings of rates of changes are supported by Jones et al., (1999) and El-Tantawi (2005), who identified rates of increased mean average global temperatures of 0.33 °C a^{-1} (1978-1999) and (0.05-0.31 °C a^{-1}) respectively.

The mean seasonal average temperature shows much higher rates of increase compared to maximum temperature, with an averages rate of 0.028 °C/decadal (autumn), 0.022 °C a^{-1} (summer), 0.020° C/decadal (spring), with lower increases in winter (0.014 °C/decadal; Table 4.9). Our findings are comparable particularly to others observed during the last half of the 20th century (Xoplaki et al., 2003; Della-Marta et al., 2007). El-Kenawy et al, (2009) identified an increase in seasonal climatic temperature at an averages rate of 0.02 °C/decadal (winter) and 0.15

°C/decadal (autumn), with warming in seasonal maximum temperature at 0.07 °C/ decadal in winter and 0.20 °C/ decadal in autumn. Examination of annual average temperature for the two study periods (1945-1977 and 1978-2009) identified statistically significant (95% confidence level) increases, with the later period 1978-2009 warmer at all stations.

4.9.4 Warm and cold extremes temperature

Trends for extreme seasonal and annual minimum and maximum temperature at the 16 stations for the period 1961–2010, providing a valuable contribution to better understanding of local or regional scale change compared to the literature which has focused on large scale variability (Easterling at el., 2000; Domonkos and Tar, 2003; Domroes and Al-Tantawi, 2005; Nie et al., 2012). The findings generally support previous trends identified (e.g. Goubanova and Li, 2007), with extremes in cold conditions increasing more rapidly than warm extremes, with a pattern of warming at most Libyan stations (Table 4.15 and 4.16).

Significant increases in the coldest extreme (TNn) temperature are found in autumn and spring (94% of stations), in winter (88%) and in summer (69%). A mix of increasing and decreasing trends in warmest day (TXx) are found, with significant changes more evident in autumn and spring than in winter and summer.

4.10 SUMMARY

The key results of this chapter are:

1. The analyses of trends and patterns in minimum, maximum and mean average temperature observed at 18 meteorological stations across Libya during the period of 66 years (1945-2010), expose in general well pronounced seasonal and annual pattern, with warming tendency in minimum and mean average temperature during the cool and warm season, though the rates of change are not uniform across or stations or consistent throughout the period, indicating that climate drivers may vary through time and space across Libya.

2. A significant increase in mean annual maximum temperature is found at coastal (56%) and inland (78%) stations (1945-2010), while the mean annual average temperature identified increases at 89% and 56% at the coastal and inland stations respectively, with increases in minimum temperature at 100% at coastal and inland stations.

3. The Mann Kendall test identified significant increases in maximum seasonal temperature at coastal (inland) stations during autumn 67% (78%), winter 44% (44%), spring 67% (78%) and summer 45% (78%). Seasonal climatic temperature indicated significant increases at coastal (inland) stations for winter 78% (56%), spring 89% (56%), summer 78% (100%) and autumn 100 % (100%). 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, all at three standard errors.

4. The results of extremes temperature identified that the Libya is more affected by cooling trends, rather than warming for the coastal region, with the inland region more affected by cooling trends compared to the coastal region.

5. The mean daily temperature for the two periods (1956-1982 and 1983-2010), identifies significantly increases in minimum and mean average temperatures during the period 2001-2009 over the warm days 170-270 of the year at all stations, with increases in maximum temperature at 63% of stations for days 170-270.

Chapter 5

PRECEPITATION

This chapter examines temporal and spatial variability in precipitation using daily (1956-2010 – 55 years), monthly (1945-2010 – 66 years) and annual data. The number of precipitation days, intensity of precipitation and precipitation extremes are also examined.

Precipitation is vital for agricultural systems and in the provision of potable water, within Libya and droughts, with serious risk to human lives and properties. Precipitation is a highly unpredictable weather variable across North Africa and is rapidly changing (temporally and spatially) affecting populations and societies across North Africa. The IPCC (1996; 2001a) warned that global changes in precipitation regime and warming will lead to increases in both floods global and regional precipitation trends have increased over the last couple of decades as a result of increasing interest in the potential impacts and responses to climate change.

5.1 STUDY AREA

The climate of Libya is characterized by a mixed of subtropical and Mediterranean climate which is interposed between the subtropical desert (hot, dry summers) and temperate maritime (mild, relatively wet winters) climate. In addition, Mediterranean region is considered as the moderately magnitude precipitation and transition zone, with strongly influenced by the Mediterranean cyclones (Emgailee 1995). The climate of the coastal region is controlled by westerly winds in winter and is dominated by the expanded Azores anticyclone in summer. Approximately 98% of Libya can be classified as arid or hyper-arid (Ben-Mahmoud 1993).

The area is mostly considered as water scarce, with large parts of Southern Libya and some sections in the north receiving little precipitation (<100 mm a^{-1}) with weather systems dominated by dry and hot winds blowing from Great Desert (Sahara) during the spring and summer months (Emgailee 1995).

However, the climate of Libya shows notable variability and significant changes from the north (coastal region) to the south (Great Desert). The lack of precipitation is the prevailing characteristics across much of Libya, with approximately 93% of the total land surface of Libya receiving less than 100 mm a^{-1} (Elfadli, 2009), with precipitation rare, irregular, and reducing progressively towards zero from north to south. The Jabal Nafusah (north-western mountains, near the border with Tunisia) and Jabal al-Akhdar (northeast) highlands; Figure 5.1) are both over 500 m a.m.s.l and experience a plateau climate with higher precipitation and low winter temperature.

The mean annual precipitation along the Libyan coast ranges between 140.0 mm (Nalute; 150 km from the sea) and 557.0 mm (Shahat; 10 km from the sea); with few years exceeding 50.0 mm in southern Libya. Libya is heavily dependent on the groundwater from five basins (regional aquifer systems) in the interior arid zones, with groundwater resources supplying about 80% of the total water consumption (Alghariani, 2007), with 97% of the consumption used for agricultural purposes (Bindra et al., 2003).

5.2 DATA QUALITY (SOURCE) AND MANAGEMENT

Precipitation data were collected from the Libyan National Centre (LNMC). The present study uses 28 stations, of which 18 are synoptic stations, selected form a total of 45 stations and around 250 rain-gauges distributed across Libya. This study focuses on monthly precipitation data recorded for the period 1945-2010, as dataset integrity improves considerably after 1945 at the majority of coastal stations, with missing data and issue prior to 1945. Daily datasets for the period 1956-2010 at 16 stations with the exception of Al-Garyiat, Ghat are examined.

Libya occupies an enormous area extending from the Mediterranean coast at the north to the great Sahara at the south, with variety of different of the land surfaces. Therefore, there are five different climatic zones that can be found in Libya, but the two dominant ones come from the influences of the Sahara desert (semiarid, arid and hyper-arid regions and the Mediterranean (mid latitude and Mediterranean regions). However, the initial division of Libya into five geographical regions (western coastal, central coastal, eastern coastal, north Sahara and south Sahara; Fig. 5.1) will permit further analysis of the potential mechanisms responsible for changes in precipitation. Eighteen stations were selected along the Mediterranean coast: Zwarah, Surrman, Al-Zawia, Tripoli Airport, Al-Hadbah, Garyan, Jefren, Al-Rojban, Nalute and Musratah (western-coastal region- 1), Sirt and Ajdabia (central-coastal region- 2) and Binina, Al-Bayda, Shahat, Darnah, Al-Fatayah and Tubruq (eastern-coastal region- 3). The coastal stations all have a typical Mediterranean and semi-arid climate, with the annual total number of precipitation days ranging from 25 (Nalute) to 73 days at Shahat (1945-2010), with the maximum recorded daily precipitation of 130 mm at Tripoli Airport (October 1986).

Ten inland stations were selected from the North Sahara regions- 4): Mizda, Ghadames, Al-Garyiat, Hon, Jalo and Al-Jaghbub are arid, with the mean total annual precipitation ranging from 9.3 mm a^{-1} (Jalo) to 62.6 mm a^{-1} (Mizda) with a mean total number of precipitation days of 10. The stations; Sabha, Ghat, Tazerbou and Al-Kufrah (South Sahara region- 5) are arid to hyper arid, with the maximum total annual precipitation not exceeding 50.0 mm a^{-1}, with mean annual total precipitation less than 10.0 mm a^{-1} (Fig. 5.1).

Daily and monthly precipitation data are available for 15 stations: Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Shahat, Darnah Ghadames, Hon, Jalo, Al-Jaghbub Sabha, and Al- Kufrah. The number of precipitation days (NPD) and extreme precipitation (intensity of precipitation (IR), Maximum 1day precipitation (Px1day), Consecutive dry days (CDD), Consecutive wet days (CWD), heavy of precipitation days (P10) are based on daily data for the period 1961-2010 (see section 5.7).

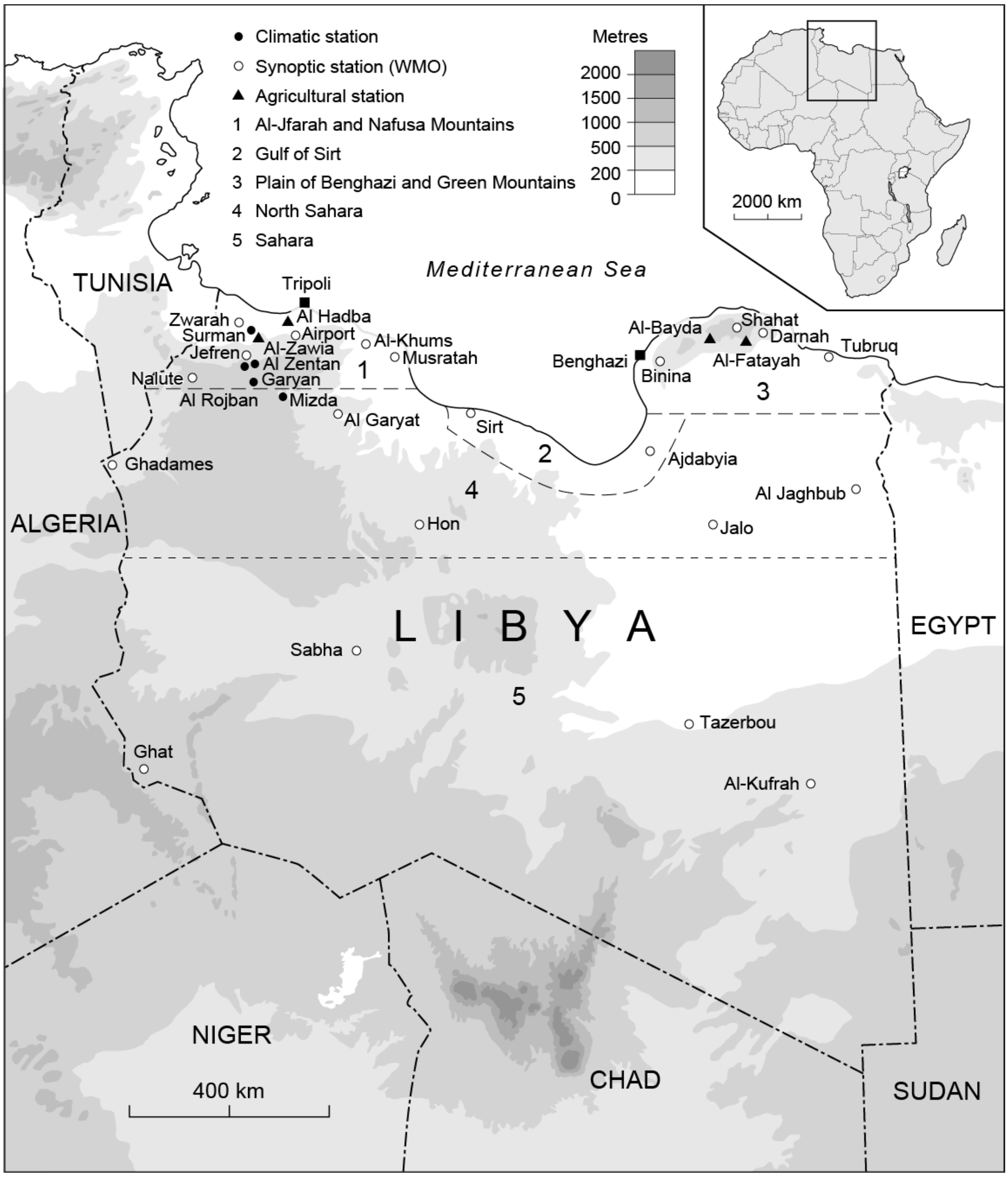


Fig. 5.1: The distribution of stations within this study across Libya.

Missing precipitation data are recorded at most of stations across Libya, with the number of missing months at coastal stations ranging from 0.01% (Sirt) to 1.82% (Al-Bayda), with comparable missing data at inland stations ranging between 0.52% (Ghat) and 3.76% (Mizda; Table 5.1). An analysis of the precipitation data was undertaken to ensure that the data quality and integrity was high, with any year consisting of missing data exceeding three months, and/or, any month with ≥11 missing days being removed. An Anderson-Darling homogeneity test was undertaken to detect non-homogeneity within the precipitation data (Chapter 3.3.2).

Table 5.1: The data used within the study, with missing precipitation data

Stations	Daily period	Monthly period	Missing data	Missing months and years precipitation data
Zwarah	1956-2010	1945-2010	0.00	
Surmman		1975-2009	0.00	
Al-Zawia		1957-2009	0.93	(2/1958), (12/1966), (9/1969), (11/1975), (1/1980), (10/1987) and (2, /1996)
T. Airport	1956-2010	1945-2010	0.00	
Al-Hadbah		1978-2009	0.51	(1/1988) and (2/1989)
Musratah	1956-2010	1945-2010	0.00	
Garyian		1945-2010	0.69	(5/1966), (9/1969), (11/1971), (9/1976), (1/1980) and (10/2001)
Jefren		1983-2010	0.00	
Al-Rojban		1965-2009	1.60	(9/1969), (1,4/1983), (1,5/1987), (11/1991), (12/1995), (4/1997) and (1,5
Nalute	1956-2010	1945-2010	0.00	
Sirt	1956-2010	1946-2010	0.01	(9, 10/1969),
Ajdabyia	1956-2010	1949-2010	0.64	(11/1967)
Binina	1956-2010	1945-2010	0.00	
Al-Bayda		1979-2010	1.82	(4/1979), (3,4/1980), (2,3/1981), (1/1987) and (4/1992)
Shahat	1956-2010	1946-2010	0.00	
Darnah	1956-2010	1946-2010	0.00	
Al-Fatayah		1981-2009	1.11	(2,12/1986) and (11,12/1989)
Tubruq		1985-2009	1.62	(3/1990), (12/1991), (12/1994), (4/1995) and (9/2003)
Mizda		1980-2009	3.76	(1990) and (11, 12/1995)
Ghadames	1956-2010	1945-2010	1.28	(11,12/1948), (1,10/1955), (1,2/1961) (11,12/1987) and (2, 4/2010)
Al-Garyiat		1968-2010	1.55	(10/1977), (2,12/1985), (4,11/1988),(1,2/1989) and (9/1994)
Hon	1956-2010	1948-2010	1.01	(1/1948), (1/1981), (12/1982), (1,4/1987), (10/1988) and (3,4/1995)
Jalo	1956-2010	1950-2010	0.96	(1,2/1950), (12/1951), (10/1952), (2,3/1953) and (10/1964)
Al-Jaghbub	1956-2010	1949-2010	0.63	(10, 12/1949), (1,2/1950) and (3/2005)
Sabha	1960-2010	1945-2010	2.53	(3,11/1957), (2, 5/1959), (1960), (1,21961) and (5.10/1962)
Ghat	1979-2010	1979-2010	0.52	(4/1979) and (10/1986)
Tazerbou	1962-2010	1962-2010	2.92	2005 and (9, 11/1980)
Al-Kufrah	1956-2010	1946-2010	0.00	

5.3 DATA ANALYSIS

5.3.1 Temporal variability of precipitation

The Libyan rainy season is defined as follows: autumn (September, October and November), winter (December, January and February) and spring (March, April and May), with ~99% of the total annual precipitation occurring within these months, during summer (June, July and August) virtually no precipitation occurs and is considered as the dry season.

Precipitation is generally characterized by high spatial and temporal variability. The coefficient of variation (COV) of mean total annual precipitation at coastal stations is 63.0%, ranging from 22.7% (Shahat; which has the highest total precipitation in the eastern coastal region, ~10 km from the coast, is located at 621 m a.m.s.l) to 58.3% (Gharyan, which has the highest total precipitation in the west coastal region, >70 km from the coast is located at 891 m a.m.s.l). The COV of the mean total annual precipitation at inland stations ranges between 63.5% (Al-Garyiat) and 184% (Al-Kufrah). However, variability of precipitation indicates more stability at coastal stations than inland stations, indicating that the main factor influencing spatial variability in COV maybe proximity to the Mediterranean Sea.

The annual precipitation for the 14 western stations (Table 5.2) over the last 63 to 81 years (depending on length of the individual station record) illustrates that most of the annual precipitation ranges between 100 and 300 mm (Fig 5.2), representing approximately 69% of the years within the series, with considerable spatial variability, with 90% at Nalute and 45% at Al-Hadbah of years receiving below 300 mm (Table 5.2). The eastern stations, receive annual precipitation between 100 and 300 mm during 52% of the years studied, with less than 300 mm received during only 3% of years at Shahat and 72% of years at Tubruq (Table 5.2). The annual total precipitation for inland stations indicates that 88% of the years receive <50 mm, with 26% at Mizda, 10% at Al-Garyiat, 2.6% at Ghadames and Hon.

Table 5.2: Total precipitation record length at each station (all years not necessarily used in this study, see Table 5.1), number of years of missing data, record duration and annual total precipitation broken down into intervals (with percentage of precipitation within each interval in brackets).

Stations	Interval: Annual total precipitation [mm a^{-1}]						Missing data (years)	Record length years	Duration
	≤ 100	100-200	200-300	300-400	400-500	> 500			
Zwarah	6 (7.9)	27 (35.5)	29 (38.2)	10 (13.2)	4 (5.3)	0.0	4	76	1931-2010
Surmman	0.0	11 (30.5)	16 (44.4)	5 (13.8)	4 (11.1)	0.0	0	36	1975-2010
Al-Zawyia	3 (5.5)	14 (25.9)	19 (35.1)	13 (24.0)	4 (7.4)	1 (1.9)	0	54	1957-2010
Tripoli Airport	1 (1.3)	14 (17.5)	38 (47.5)	18 (22.5)	7 (8.8)	2 (2.5)	0	80	1931-2010
Al-Hadbah	0.0	2 (6.0)	13 (39.4)	11 (33.3)	6 (18.2)	1 (3.0)	0	33	1978-2010
Jefren	1 (3.6)	6 (21.4)	11 (39.3)	8 (28.6)	2 (7.1)	0.0	0	28	1983-2010
Garyan	0.0	11 (16.6)	18 (27.3)	18 (27.2)	8 (12.2)	11 (16.6)	0	66	1945-2010
Al-Rojban	7 (15.2)	16 (34.7)	15 (32.6)	6 (13.0)	2 (4.3)	1 (2.1)	0	46	1965-2010
Nalute	24 (30.0)	45 (56.3)	9 (11.3)	1 (1.3)	0.0	1 (1.3)	0	80	1931-2010
Musratah	0.0	16 (23.9)	31 (46.3)	19 (28.4)	0.0	1 (1.5)	0	67	1944-2010
Sirt	10 (12.5)	36 (45.0)	21 (26.3)	6 (7.5)	2 (2.5)	0.0	4	76	1931-2010
Ajdabyia	13 (21.0)	37 (59.7)	10 (16.1)	2 (3.2)	0.0	0.0	0	62	1949-2010
Binina	0.0	16 (24.2)	27 (40.9)	18 (27.3)	5 (7.6)	0.0	0	66	1945-2010
Al-Bayda	0.0	1 (3.3)	0.0	5 (15.6)	6 (18.7)	20 (62.5)	0	32	1979-2010
Shahat	0.0	1 (3.2)	0.0	4 (2.9)	6 (19.4)	20 (64.5)	0	65	1946-2010
Darnah	0.0	16 (24.6)	31 (47.7)	14 (21.5)	4 (6.2)	0.0	0	65	1946-2010
Al-Fatayah	1 (3.2)	4 (12.9)	8 (25.8)	12 (38.7)	5 (16.1)	1 (3.2)	0	31	1981-2010
Tubruq	2 (7.6)	17 (65.3)	7 (26.9)	0.0	0.0	0.0	0	26	1985-2010
Mizda	19 (63.3)	11 (36.6)	0.0	0.0	0.0	0.0	1	30	1980-2010
Ghadames	78 (98.7)	0.0	1 (1.3)	0.0	0.0	0.0	1	79	1931-2010
Al-Garyiat	37 (88.1)	5 (11.9)	0.0	0.0	0.0	0.0	1	42	1968-2010
Hon	77 (97.5)	2 (2.5)	0.0	0.0	0.0	0.0	1	79	1931-2010
Jalo	60 (100)	0.0	0.0	0.0	0.0	0.0	1	60	1950-2010
Al-Jaghbub	59 (100)	0.0	0.0	0.0	0.0	0.0	1	59	1951-2010
Sabha	77 (100)	0.0	0.0	0.0	0.0	0.0	3	77	1931-2010
Ghat	33 (100)	0.0	0.0	0.0	0.0	0.0	1	33	1979-2010
Tazerbou	48 (100)	0.0	0.0	0.0	0.0	0.0	1	48	1962-2010
Al-Kufrah	74 (100)	0.0	0.0	0.0	0.0	0.0	3	74	1933-2010

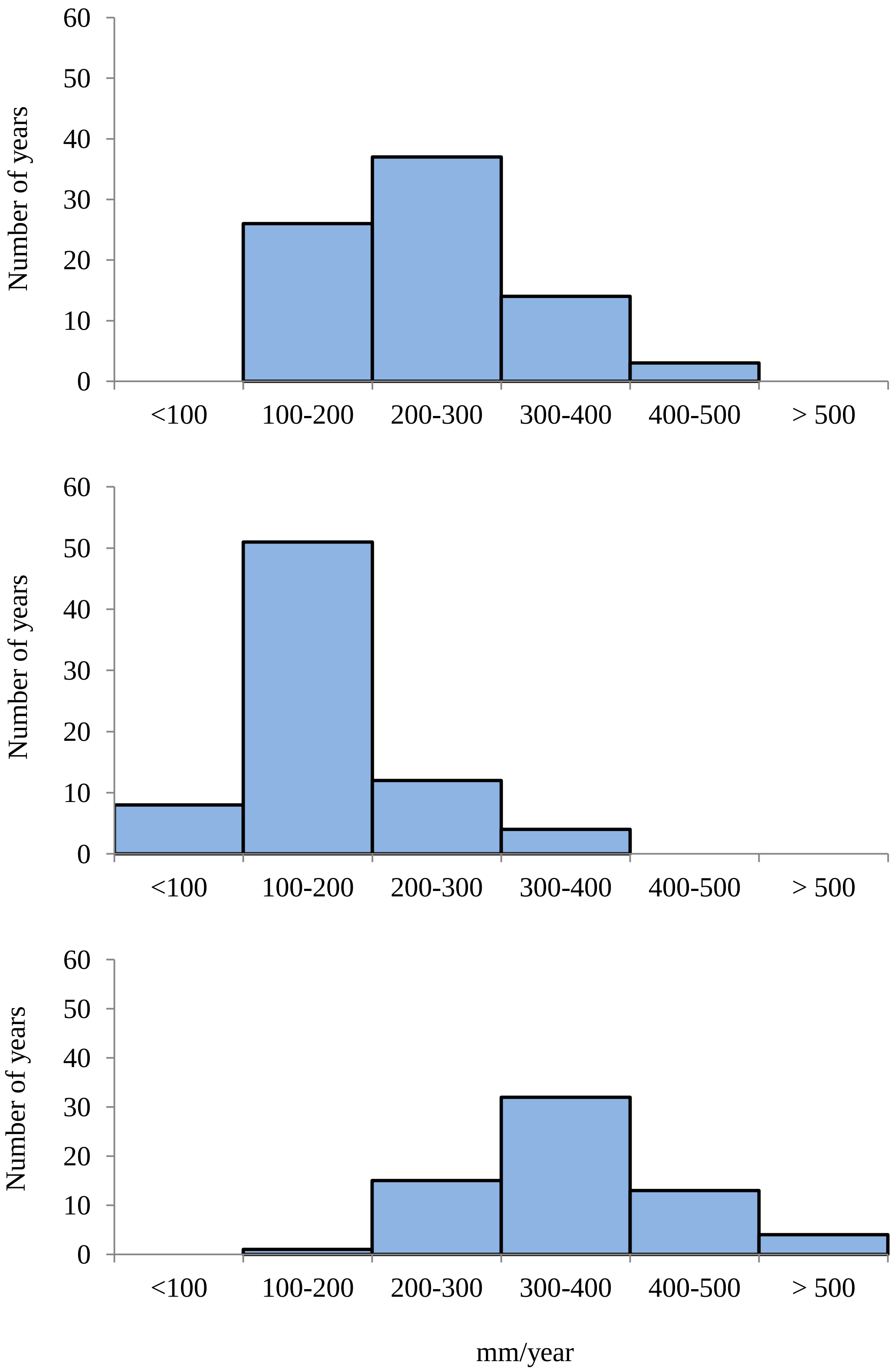


Fig. 5.2: Histograms of mean annual total precipitation at coastal a) western; b) central; c) eastern stations across Libya.

5.3.1.1 Multi-Decadal variation and trends

Precipitation has been studied at different scales, with many studies identifying variable precipitation trends during the last century, with significant trends in precipitation identified globally (Folland et al., 1990; IPCC 2001; Goubanova and Li, 2007) over the last few decades. According to the fourth IPCC Assessment Report (IPCC, 2007) precipitation has increased over the last 100 years between 30 and 85°N, with a notably rise between 10°N to 30°N during the first 50 years of last century (1900-1950), but declined after ~1970. Remarkably decreases have occurred in the last 40 years from between 10°S to 30°N, with no clear changes in annual precipitation over the ocean.

5.3.1.2 Daily variation and trends

To examine temporal changes in precipitation, a time series of 11-day moving average of mean daily precipitation for 14 coastal and north Sahara stations: Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Shahat, Darnah, Ghadames, Hon, Jalo, Al-Jaghbub and Sabha during the period 1956-2010 have been analysed (with the remaining stations excluded as daily data was unavailable, or is only available for shorter periods).

The study period is divided into two series of length, the first 27 years (1956 to 1982) and the second 28 years (1983 to 2010), referred to as period 1 and period 2, respectively. The two study periods are used to assess and provide comparison in rates of change. Statistical analysis of the 27/28 year periods and the nearest comparable 30 year period (1956-1985 and 1980-2010) was undertaken; this identifies no apparent difference in the statistical character of the two groups. As such the analysis within this work 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 issues with data limitation.

Changes in the 11-day moving average precipitation shows no single trend, with period 2 characterized by slightly higher (not statistically significant) precipitation at Musratah and Ghadames compared to Ajdabyia, Darnah, Hon, Jalo, Al-Jaghbub and Sabha were higher mean daily precipitation were identified in period 1 (not statistically significant); with no observable difference identified at Zwarah, Binina and Nalute. Statistically significant differences between the two periods are only identified at Shahat and Tripoli Airport (Fig. 5.3; see Appendix 5.1 for figures for the coastal stations).

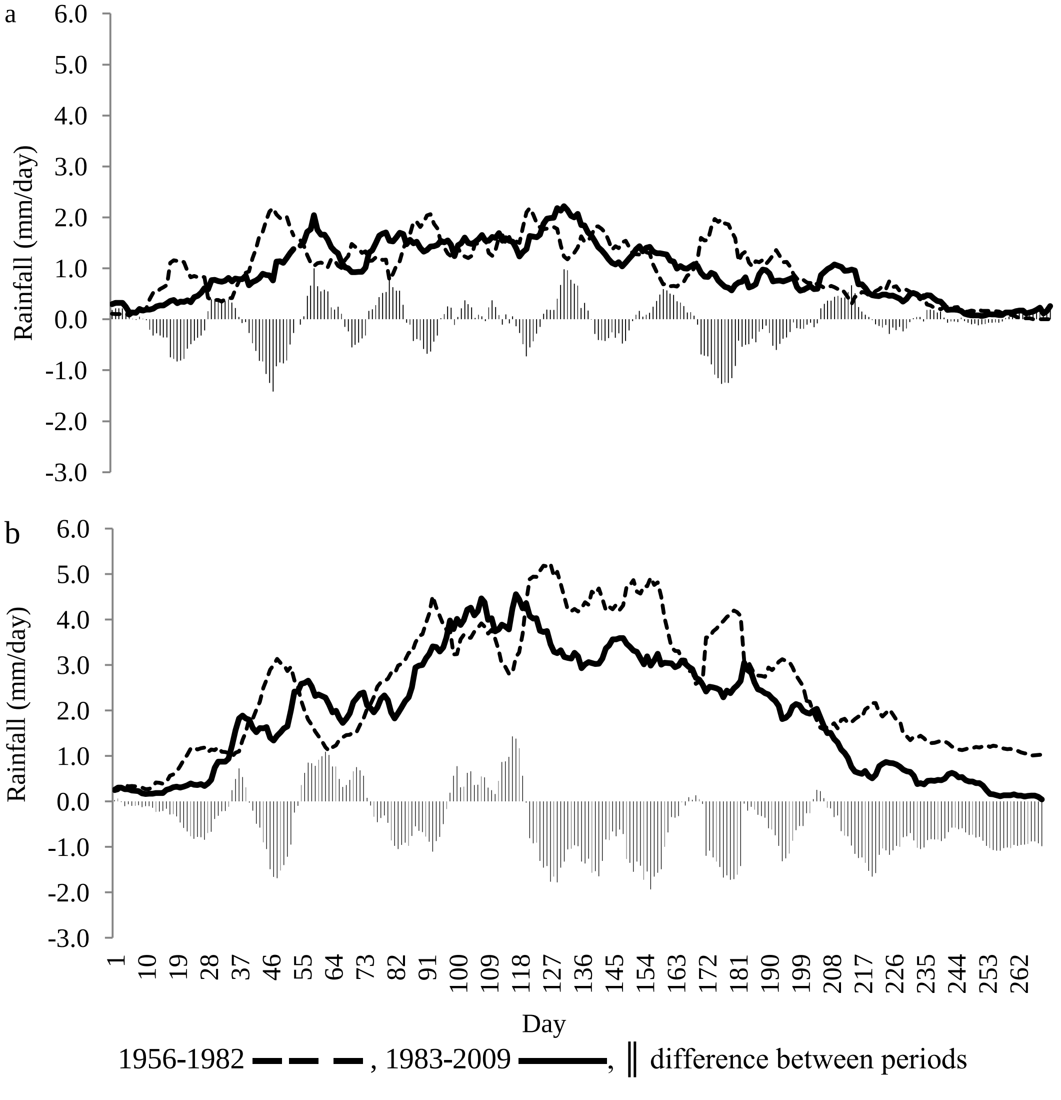


Fig. 5.3: An 11 day, moving mean daily precipitation variation with differences between two periods(1956-1982 and 1983-2010) at; a) Tripoli Airport; b) Shahat.

Significant differences between the two periods (1956-1982 and 1983-2010) based on the Mann-Whitney test are identified at Tripoli Airport, Shahat, Ghadames and Al-Jaghbub. Error-bars (Fig. 5.4) show similar results of significant differences (95% significance level) in daily precipitation during the two study periods.

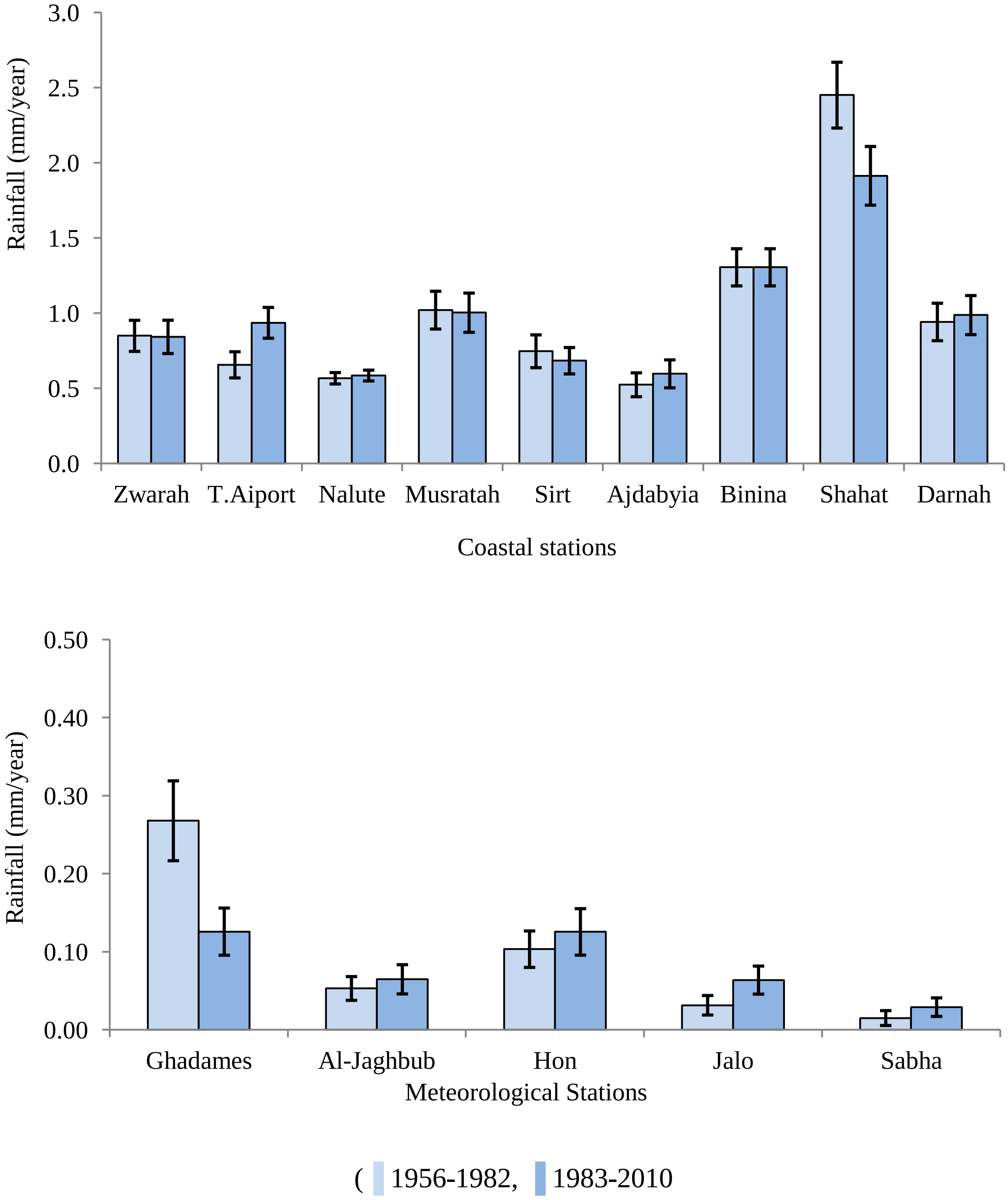


Fig. 5.4: Mean annual precipitation for the 30 year intervals of two periods 1956-1982 and 1983-2010 for coastal stations, with error bars representing two standard errors (95.4% confidence level).

5.3.1.3 Monthly variation and trends

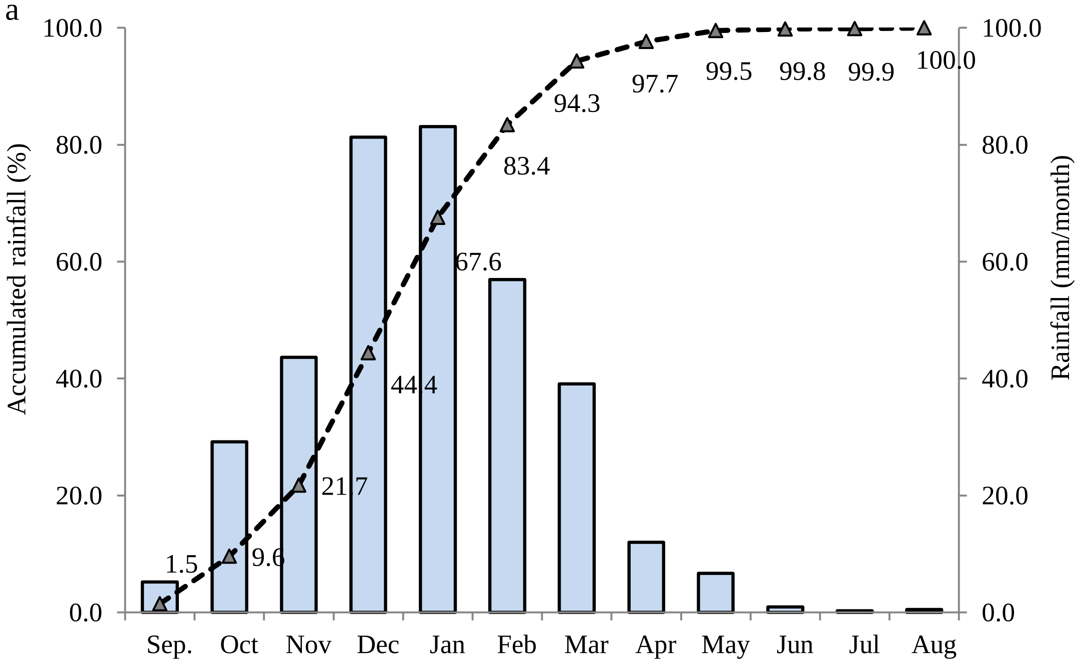
The rainy season can be characterised as increasingly heavy rain until January and decreases thereafter (except at Nalute which has a peak in precipitation during March), where December and January are the wettest months with the six months of October to March receiving approximately 87% of the total annual precipitation (Ahmed, 2002).

By January or February almost three quarters of annual total precipitation has fallen at coastal stations (Fig. 5.5). The mean monthly precipitation is roughly symmetrical around the mid-season peak and has a sinusoidal shape for most coastal stations, with non-symmetrical distributions identified in the western mountain region and all inland stations. The mid-season month is January (March) at North Sahara (South Sahara) stations, with almost three quarters of annual total precipitation accumulated by March (April) in north (south) Sahara stations.

The estimation of changes in monthly precipitation for 13 stations (Table 5.3; with the remaining stations excluded as they have shorter records or/and low monthly amounts of rainfall) during the period 1945-2010 have been analysed using the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975), which is used to estimate the statistical significant of precipitation trends within the series.

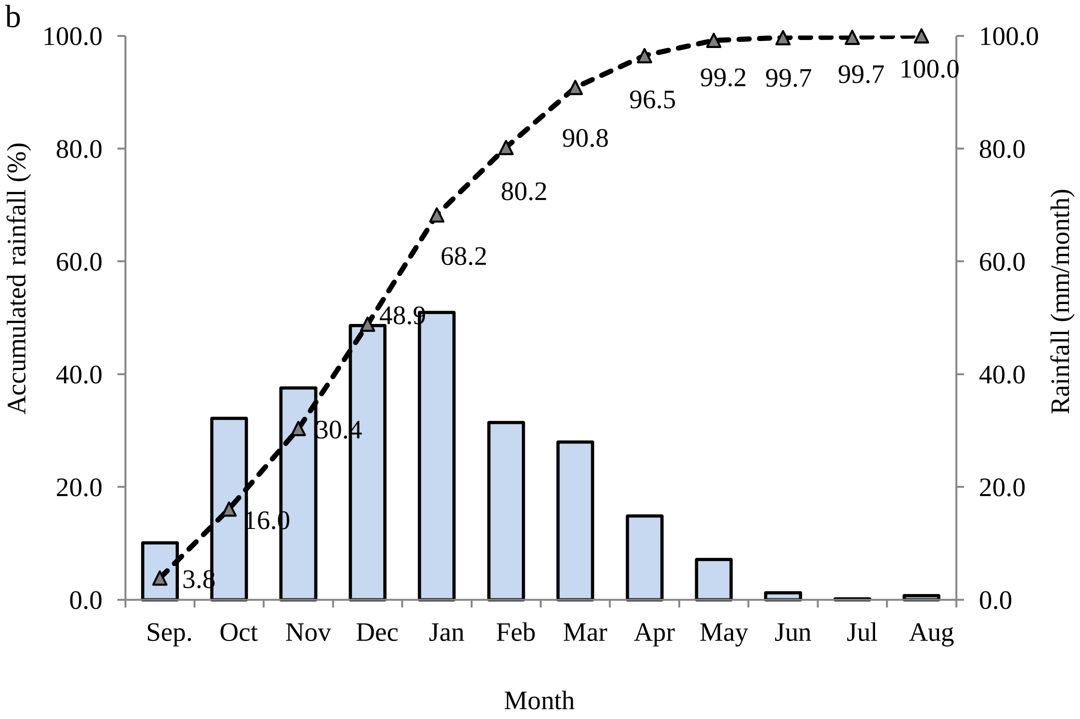
Mean monthly precipitation data shows that, the cold months, November-March are more variable, while the driest moths are more stabile with no changes in monthly precipitation identified; April (62%), May and September (69%) of stations during the period 1945-2010. Positive increases in monthly precipitation are identified in December (54%) with an average rate of 0.141 mm/month, with no statistically significant trends at any stations. About 54%, of stations show increasing trend in January, ranging between 0.006 and 0.537 mm/month, with significant increases at Musratah (*) and Zwarah (+). Increases at 84% (62%) of study stations in February (March), with an average rate of 0.137 (0.066) mm/month, with significant increase (*) at the central stations of Sirt and Ajdabyia (Table 5.3).

a



Accumulated rainfall (%)
Rainfall (mm/month)
100.0
80.0
60.0
40.0
20.0
0.0
1.5
9.6
21.7
44.4
67.6
83.4
94.3
97.7
99.5
99.8
99.9
100.0
Sep.
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug

b



Accumulated rainfall (%)
Rainfall (mm/month)
100.0
80.0
60.0
40.0
20.0
0.0
3.8
16.0
30.4
48.9
68.2
80.2
90.8
96.5
99.2
99.7
99.7
100.0
Sep.
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Month

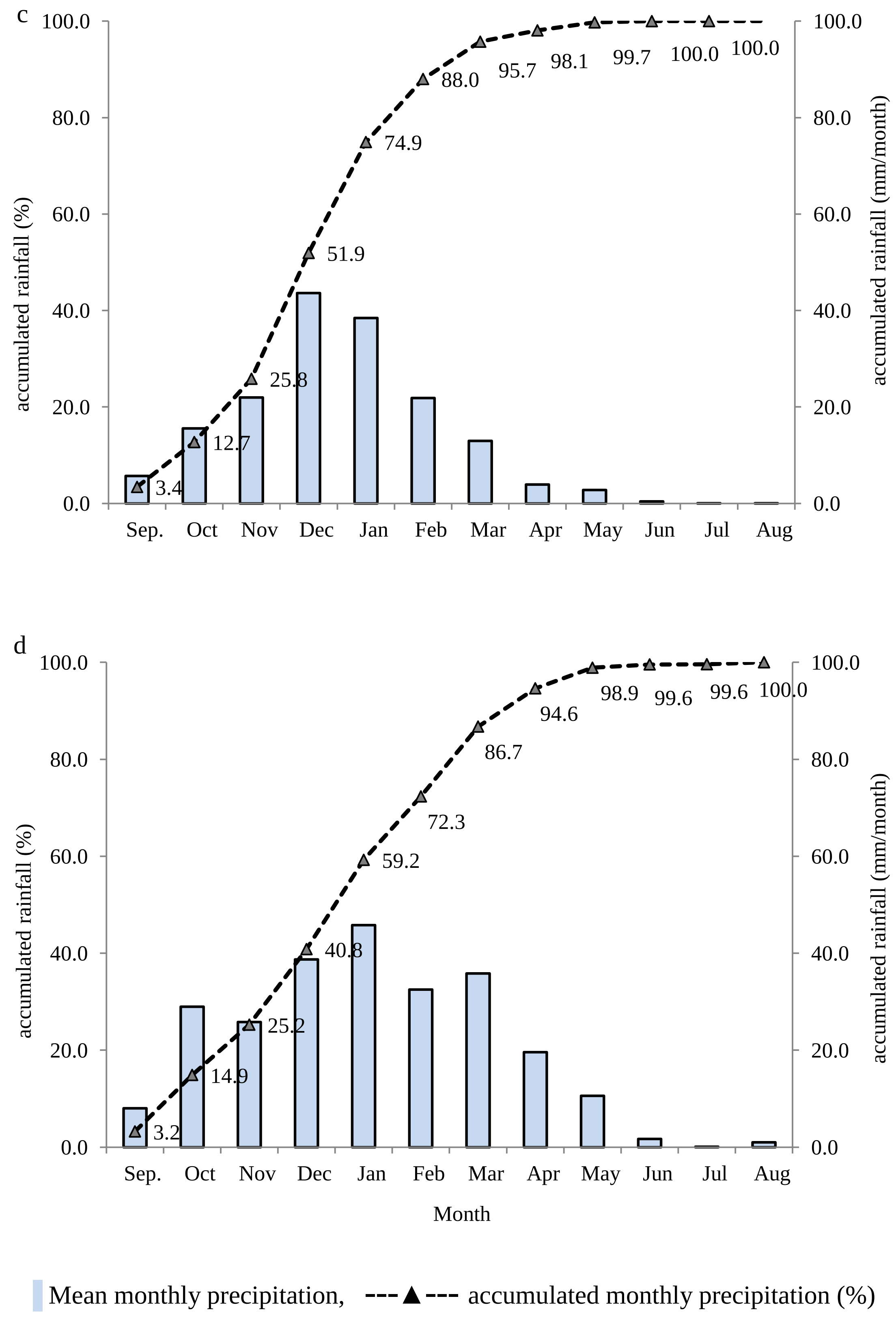


Fig. 5.5: Histogram and cumulative monthly precipitation (1945-2010), at; a) eastern-coastal region; b) western-coastal region; c) central-coastal region and; d) western mountains region

Table 5.3: Values of the Mann-Kendall statistic (Q) for Mean monthly precipitation (MMP), with statistically significant levels at eleven stations across Libya for 1945-2010

Stations		Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Zwarah	Q	0.029	-0.188+	0.121	0.109	0.246	0.14	-0.005	0.000	0.000
	M MP	13.5	35.0	38.1	46.3	36.4	22.1	17.3	12.3	5.6
Al-Zawyia	Q	0.000	-0.22	0.409	0.455	0.537+	0.252	0.038	0.000	0.000
	M MP	15.0	41.0	41.4	54.9	50.0	29.0	23.2	10.4	4.1
T. Airport	Q	0.000	-0.205+	-0.094	-0.371	0.026	0.069	0.007	0.000	0.000
	M MP	10.8	35.4	40.3	53.7	54.4	33.0	25.8	15.4	4.4
Gharyan	Q	0.000	-0.044	-0.078	0.057	0.356	0.041	0.000	-0.125	0.000
	M MP	9.7	43.0	29.1	53.5	61.9	42.6	55.5	20.6	11.7
Nalute	Q	0.003	0.000	-0.031	0.039	-0.091	0.011	0.138	-0.045	0.000
	M MP	5.3	18.6	14.0	18.5	16.1	19.2	26.0	16.5	10.7
Musratah	Q	0.01	-0.231	0.239	-0.15	-0.04	0.064	0.082	0.011	0.000
	M MP	11.3	37.9	45.9	58.4	56.5	29.0	21.8	9.8	4.5
Sirt	Q	0.009	0.007	0.03	0.017	0. 394*	0.257*	0.053	0.000	0.000
	M MP	10.0	23.3	24.5	43.4	38.8	23.2	15.2	4.5	3.0
Ajdabyia	Q	0.000	0.000	0.025	0.156	-0.08	0.267*	0.048	-0.015	0.267
	M MP	1.5	9.1	18.9	44.7	39.1	20.4	11.1	3.4	2.5
Binina	Q	0.000	-0.059	0.003	-0.281	-0.035+	0.22	0.095	0.000	-0.004
	M MP	3.2	19.4	34.5	66.3	66.0	40.9	25.9	6.3	4.4
Shahat	Q	0.000	-0.068	-0.206	-0.226	-0.626	0.26	-0.052	0.000	-0.006
	M MP	9.2	52.2	68.5	116.3	123.8	87.5	66.9	22.7	8.9
Darnah	Q	0.000	-0.121	-0.07	0.151	0.238	0.173	-0.066	0.000	0.005
	M MP	5.6	34.7	28.7	56.8	60.1	39.6	23.6	8.3	5.7
Ghadames	Q	0.000	0.010	0.000	0.000	0.000	0.000	0.046	0.000	0.000
	M MP	1.6	3.6	1.7	5.2	5.9	5.3	5.9	2.9	1.8
Hon	Q	0.000	-0.013	0.000	0.000	0.006	0.000	0.000	0.000	0.000
	M MP	2.6	5.2	3.6	2.6	4.5	3.0	3.3	2.9	3.2

The significance levels tested are 0.001 (***), 0.01 (**), 0.05 (*) and 0.1 (+). If the cell is blank, the significance level is >0.1

According to previous studies of climate, that refers to a change in climate at the beginning of the seventies of the last century and a reference to the results of Chapter 4; increases of temperature in Libya during the last 33 years. However, analyses of precipitation variation during the two periods are applied in this thesis. The study period (1945-2010) is divided into two series of equal length (33-year), 1945-1977and 1978-2010, referred to as period 1 and period 2, respectively to examine differences in monthly precipitation for 13 stations across Libya over the period 1945-2010. Comparison of the two time periods for monthly precipitation does not show clear or/and little significant difference based on Mann-Whitney test (U-test; Wilcoxon, 1945) (confidence level 95%) for most of months except September (Nalute, Musratah, Sirt), December (Ghadames), April (Hon) and May (Shahat and Darnah). Error-bars (Fig. 5.6) show that differences (95% significance level) in monthly precipitation between the two periods 1945-1977 and 1978-2010 in September (Hon), October (Darnah), November (Zwarah, Al-Zawia, and Musratah), January (Al-Zawia), Febrarury (Ajdabyia), March (Sirt and Hon), April (Garyan) and May (Sirt, Ajdabyia and Binina).

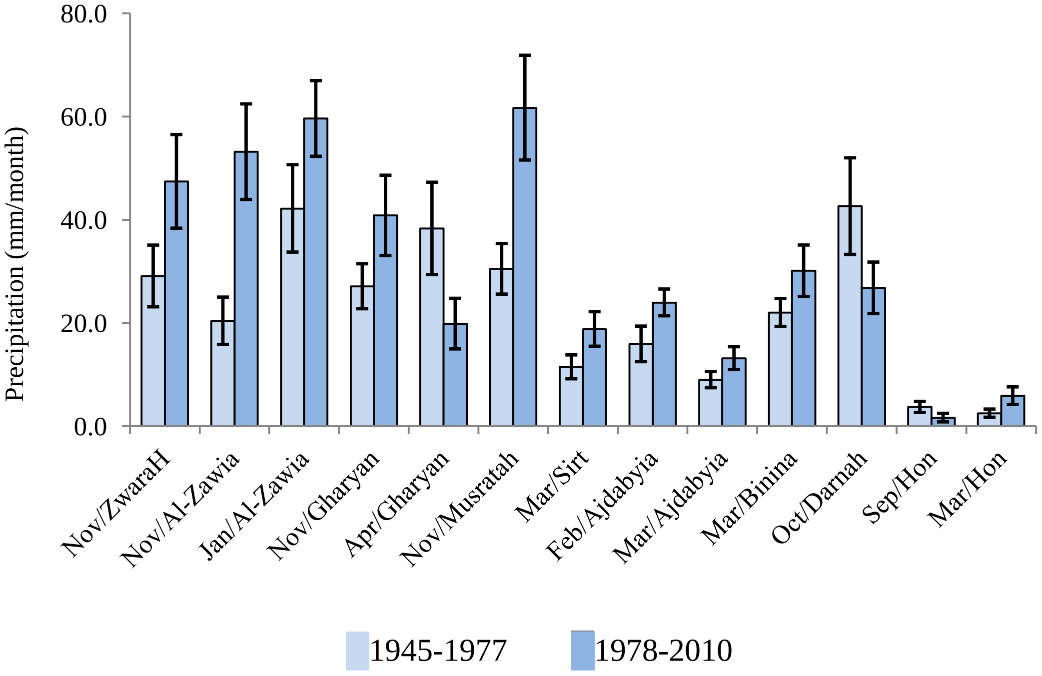


Fig. 5.6: Mean monthly precipitation for the 30 year intervals of two periods 1945-1977 and 1978-2010 for significant months with one standard error (68.2% confidence level).

5.3.1.4 Seasonal and sub-seasonal variations and trends

The highest percentage of total annual precipitation occurs in the winter season (53%) at coastal stations and inland stations (39%). Autumn and spring account for 18% and 28% (coastal stations) and both account for 28% (inland stations) of annual total precipitation, with low amounts of summer precipitation, contributing below 1% and approximately 4% of the annual total precipitation in coastal and inland stations respectively. Mean seasonal precipitation at 15 stations across Libya for the period 1945-2010 was analysed ((Table 5.4; with the remaining stations excluded as they have shorter period or/and low seasonal amounts of precipitation).

Table 5.4: Values of the Mann-Kendall statistic (Q) for seasonal precipitation at 15 stations across Libya (1945-2010), with statistically significant levels

	Autumn			Winter			Spring		
Time series	Mean autumn (mm)	Q	Sig.	Mean winter (mm)	Q	Sig.	Mean spring (mm)	Q	Sig.
Zwarah	86.6	-0.352		103.5	0.566		35.1	-0.113	
Al-Zawyia	94.5	0.445		128.2	1.563	*	36.5	-0.043	
T.Airport	86.0	-0.596	*	139.3	-0.618		45.6	0.027	
Garyian	82.6	-0.200		167.7	0.498		89.2	0.024	
Nalute	37.9	0.039		53.1	0.082		53.2	-0.160	
Musratah	94.8	-0.027		141.9	-0.211		36.1	0.058	
Sirt	57.9	-0.035		103.8	0.791	*	22.7	0.149	
Ajdabyia	29.1	0.114		102.5	0.325		16.9	0.060	
Binina	57.1	0.005		170.6	-0.264		36.6	0.078	
Shahat	129.9	-0.456		321.3	-0.448		97.5	-0.177	
Darnah	69.0	-0.470	+	154.0	0.633		37.5	-0.006	
Ghadames	5.9	0.000		15.7	-0.022		10.4	0.022	
Hon	11.7	-0.036		9.5	0.015		9.3	-0.013	
Jalo	1.9	-0.001	*	4.6	0.000		2.7	0.000	
Al-Jaghbub	1.4	0.000		8.7	0.073	*	3.9	0.023	

The significance levels tested are 0.001 (***), 0.01 (**), 0.05 (*) and 0.1 (+). If the cell is blank, the significance level is >0.1

In autumn, negative trends in precipitation (-0.241 mm/season) are found at 60% of stations, with significant decrease (*) at Tripoli Airport. About 30% of stations have positive trends in autumn precipitation (0.121 mm/season), with significant increases (*) at Jalo and (+) Darnah. Positive changes in winter precipitation are identified at 60% of stations (0.505 mm/season), with significant increases (*) at Shahat and Al-Jaghbub. A significant decrease (-0.313 mm/season) is found at Al-Zawyia. In spring, positive (negative) trends 0.025 mm/season (-0.073 mm/season) are identified at 53% (40%) of the stations, with no significant trends at any stations (Table 5.4).

Seasonal precipitation for 33 years intervals over the two periods analysed provides a clearer depiction of the seasonal differences. The sites at Zwarah, Zwarah, Garyan and Sirt are found to have significant differences (68.2% confidence level) in spring, with significant differences at Al-Zawia and Darnah in winter (Fig. 5.7).

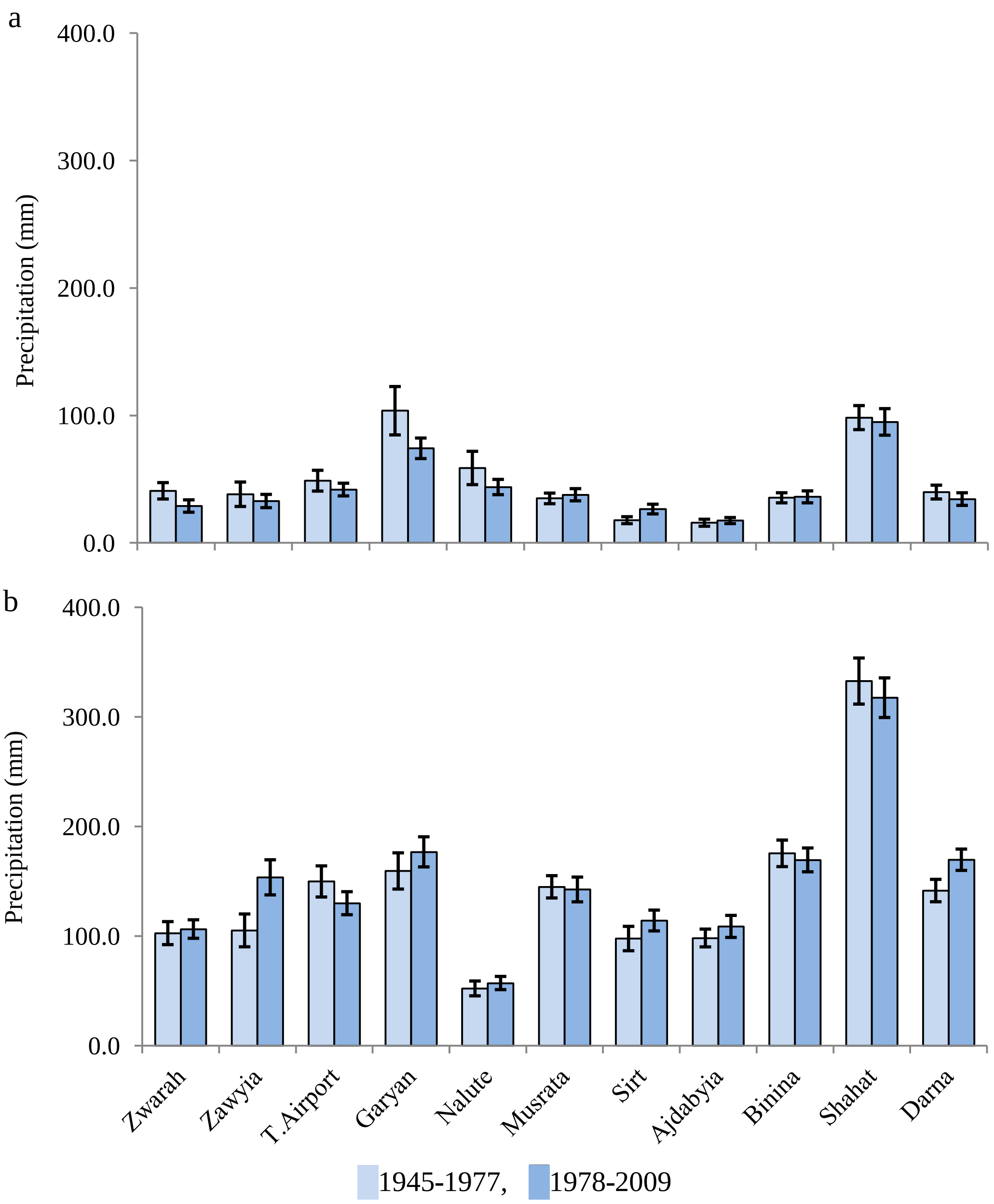


Fig. 5.7: Mean seasonal precipitation for the two periods 1945-1977 and 1978-2010 for coastal stations, at; a) Spring and; b) winter with error bars representing three standard errors (68.2% confidence level).

5.3.1.5 Annual variations and trends

Since precipitation is highly variable both temporally and spatially across Libya, the 28 stations are used to properly capture precipitation patterns, during the different time periods: 1945-2010; 1945-1977 and 1978-2010. Changes and trends in annual total precipitation for 16 stations during the period 1945-2010 (66 years) are analysed (with the remaining stations excluded as they have shorter records; Table 5.5) using 10-year windows. The 10-year annual precipitation time-steps show increasing precipitation at most of stations during the first 30 years (1945- mid-1970), with decreases during the later years, dominated by the coastal stations (Fig. 5.8).

The Mann Kendal test identifies positive increases in annual precipitation (1945-2010) at seven of the ten coastal stations ranging between 0.052 and 0.402 mm a^{-1} (Table 5.5). Negative trends are found at Tripoli Airport, Binina and Shahat, with weakly significant at Tripoli Airport (+).The four inland stations examined identify positive trends (0.104 mm a^{-1}), with a significant increase at Al-Jaghbub (*). A negative trend is found at Hon, with no decrease trends at inland stations (Table 5.5).

The annual total precipitation for 16 stations across Libya for the first 33 year period (1945-1977) is analysed (with the remaining stations excluded as they have shorter records). Analysis of the variation in precipitation patterns reveals positive trends in annual precipitation at six coastal stations (1.998 mm a^{-1}), with the highest (4.982 mm a^{-1}) and with significant increases (+; 1.711 mm a^{-1} at Ajdabyia). Negative trend are found at four coastal stations (-0.843 mm a^{-1}). At inland stations, Ghadames and Hon were decreases trends (-0.229 mm a^{-1}), with the remaining inland stations were positive, with a significant increase (+) at Jalo (Table 5.5).

The annual precipitation at all 28 stations for the last 33 years (1978-2010) across Libya are analysed; the Mann-Kendall test identifies decreasing trends at 14 of the coastal stations (78% of coastal stations; -2.126 mm a^{-1}), with positive trends at Ajdabyia and the eastern stations of Al-Bayda, Shahat and Darnah (1.075 mm a^{-1}).

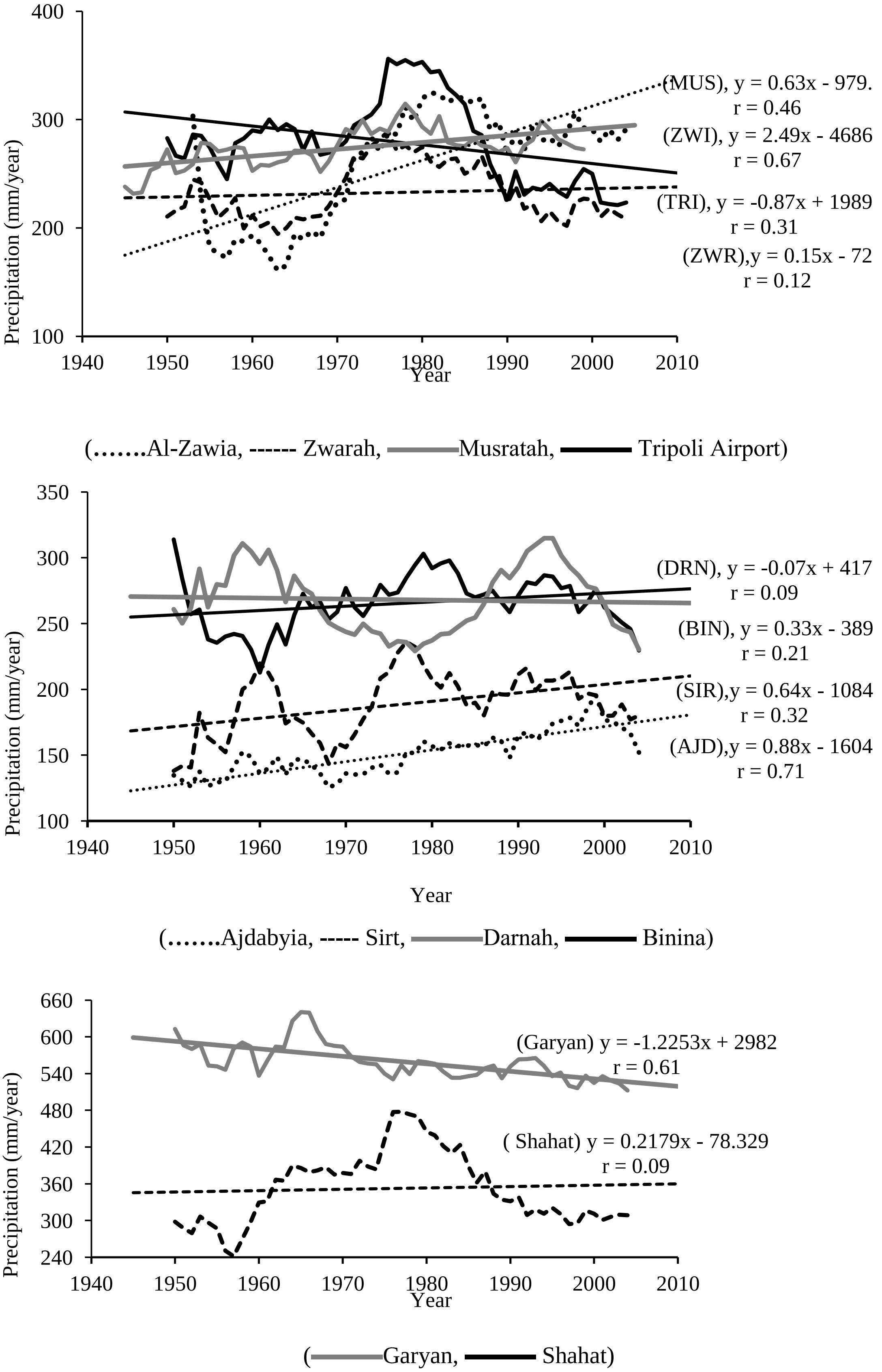


Fig. 5.8: Annual means 10-year moving averages of the mean annual total precipitation during the period 1945-2010 at number of coastal stations

Significant decreases are identified at Al-Rojban (*), Tripoli Airport and Tazerbou (*) and Jefren (+). At inland stations, positive (negative) trends 0.395 mm a^{-1} (-0.225 mm a^{-1}) are identified at six (four) stations, with a significant increase at Ghat (**) and decreases at Al-Jaghbub (+) and Tazerbou (**) (Table 5.5).

Table 5.5: Values of the Mann-Kendall statistic (Q) for annual precipitation at 28 stations across Libya, with statistically significant levels

Time series	Mean annual total (mm)	COV %	1945-2010		1945-1977		1978-2010	
			Sig.	Q	Sig.	Q	Sig.	Q
Zwarah	226.3	38.5		0.167		2.742		-1.961
Surmman	257.1	35.7						-0.444
Al-Zawia	262.9	42.5						-1.879
T. Airport	276.5	34.8	+	-1.025		2.443	*	-2.972
Al-Hadbah	321.7	27.8						-3.433
Garyan	343.6	58.3		0.052		4.982	+	-4.74
Jefren	264.9	29.0						-0.123
Al-Rojban	220.2	55.0					**	-7.35
Nalute	145.1	54.5		0.104		-0.348		-1.500
Musratah	269.7	29.7		0.152		0.224		-1.576
Sirt	185.1	44.3		0.402		1.818		-0.295
Ajdabyia	149.2	43.8		0.628	+	1.711		0.333
Binina	266.1	31.0		-0.662		-1.505		-2.561
Al-Bayda	533.1	41.2					+	3.833
Shahat	555.4	26.0		-1.761		-0.890		0.080
Darnah	264.4	30.1		0.278		-0.632		0.054
Al-Fatayah	311.7	37.2						-0.017
Tubruq	174.3	27.8						-0.911
Ghadames	34.0	93.4		0.100		-0.311		0.300
Mizdah	62.6	67.4						1.217
Al-Garyiat	55.3	63.0						0.371
Hon	29.6	90.6		-0.015		-0.147		-0.396
Jalo	9.5	116.8		0.001	+	0.094		-0.113
Al-Jaghbub	14.6	110.5	*	0.107		0.359	+	-0.362
Sabha	8.0	114.7		0.001		0.001		0.125
Ghat	9.9	75.8					**	0.355
Tazerbou	2.6	184.1					*	-0.022
Al-Kufrah	1.8	174.6		0.001		0.001		0.001

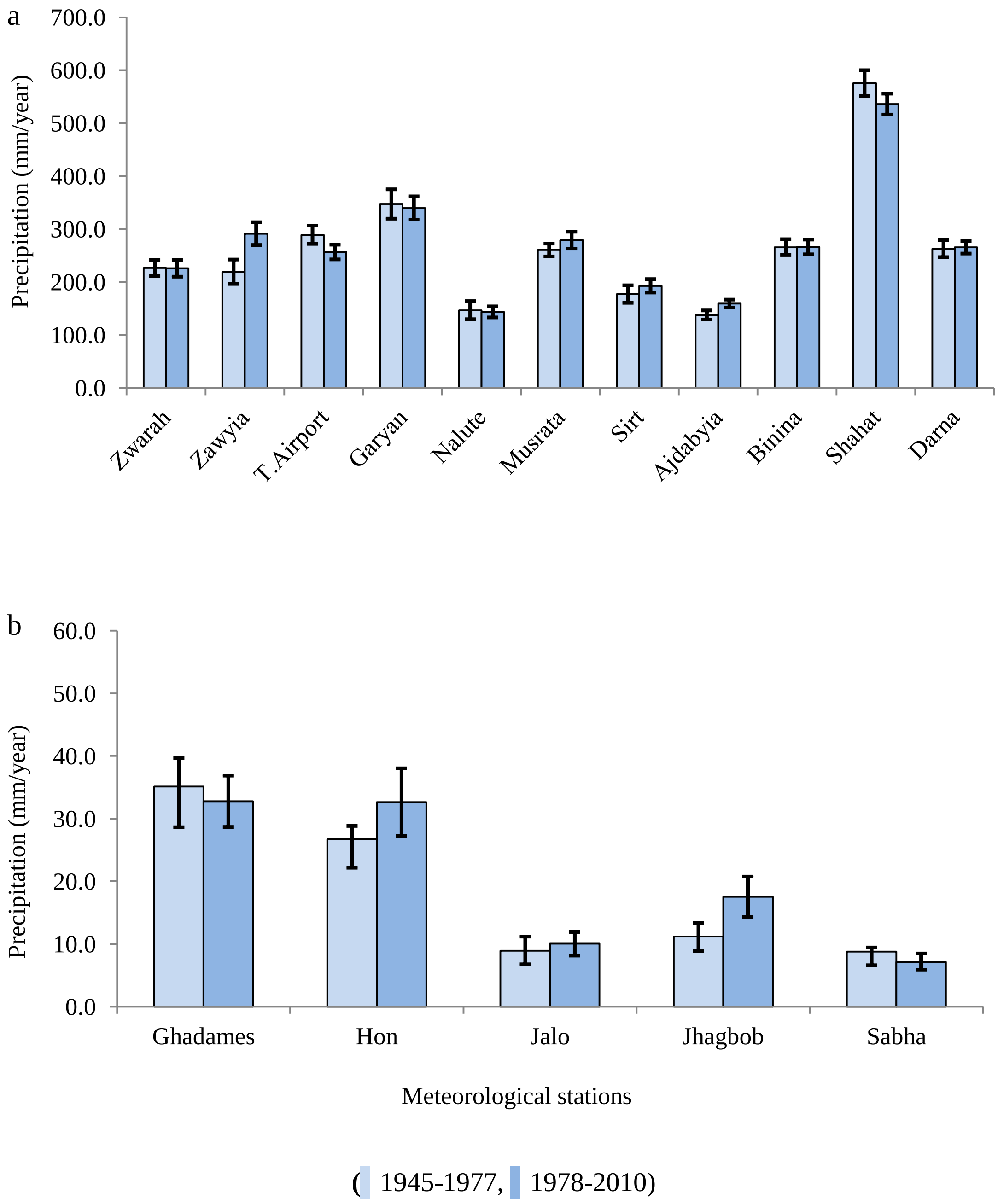


Fig. 5.9: Mean annual total precipitation for the two periods 1945-1977 and 1978-2010); a) coastal stations; and b) inland stations, with error bars representing one standard error (68.2% confidence level).

A time series of mean annual total precipitation over the two 33 year intervals for 16 stations across Libya (1945-1977 and 1978-2010) are analysed to provide a clear depiction of annual precipitation change (with the remaining stations excluded as they have shorter records).

Changes in mean annual total precipitation show that period 2 is characterized by higher precipitation compared to the period 1, at 43% of the stations, with no changes at Zwarah and Binina. Significant differences in mean annual total precipitation are found when comparing between the two timeframes, with the second period significantly higher (68.2% confidence level) at Tripoli Airport, Al-Zawia and Al-Jaghbub (Fig. 5.9).

5.4 SPATIAL VARIABILITY OF PRECIPITATION

Libya is divided into five geographical regions; Al-Jfarah and Nafusa Mountains, Gulf of Sirt, plain of Benghazi and Al-Jabal Al-Akhdar, the North Sahara, and South Sahara (Fig. 5.1). In general, precipitation decreases gradually towards the centre of the Libyan coastline (near Sirt) and decreases sharply with latitude, reaching nearly zero in the south-east of Libya (Al-Kufrah, it has recorded no rain for last 10 years).

The mean average annual total precipitation at the eastern region is 350.8 mm a^{-1}, at western stations 253.7 mm a^{-1} and at the central stations 168.1 mm a^{-1}, with the lowest annual total precipitation in the Sahara region 22.3 mm a^{-1}. The highest annual total precipitation was 555.4 mm a^{-1} (Shahat) followed by 534.1 mm a^{-1} (Al-Bayda) and 345.6 mm a^{-1} (Gharyan), with the lowest precipitation in the coastal region recorded at Nalute (147.6 mm a^{-1}) followed by Ajdabyia (149.2 mm a^{-1}). The mean total annual precipitation in the northern Sahara region does not exceed 62.6 mm a^{-1} at Mizda, with the mean annual total precipitation across the southern Sahara region 10 mm a^{-1} (Table. 5.5).

The distribution of precipitation data at each station is illustrated in Fig. 5.10, with median, mean, 25th percentile, 75th percentile, and standard deviation, minimum and maximum precipitation shown. The precipitation statistics in the coastal regions (eastern, western and central), are relatively comparable, with the median annual precipitation ranging between 348.8 mm a^{-1} (eastern), 264.4 mm a^{-1} (western) and 162.1 mm a^{-1} (central). The mean median annual precipitation at the coastal stations ranges from132.1 mm a^{-1} (Ajdabyia) to 545.1 mm a^{-1} (Al-Bayda).

However, low variability in precipitation is identified at stations located at the greatest elevations e.g. Garyan (741 m a.m.s.l), Nalute (621 m a.m.s.l), Al-Rojban (688 m a.m.s.l), Jefren (691 m a.m.s.l), Al-Bayda (537 m a.m.s.l) and Shahat (621 m a.m.s.l), with these stations also receiving the highest maximum precipitation.

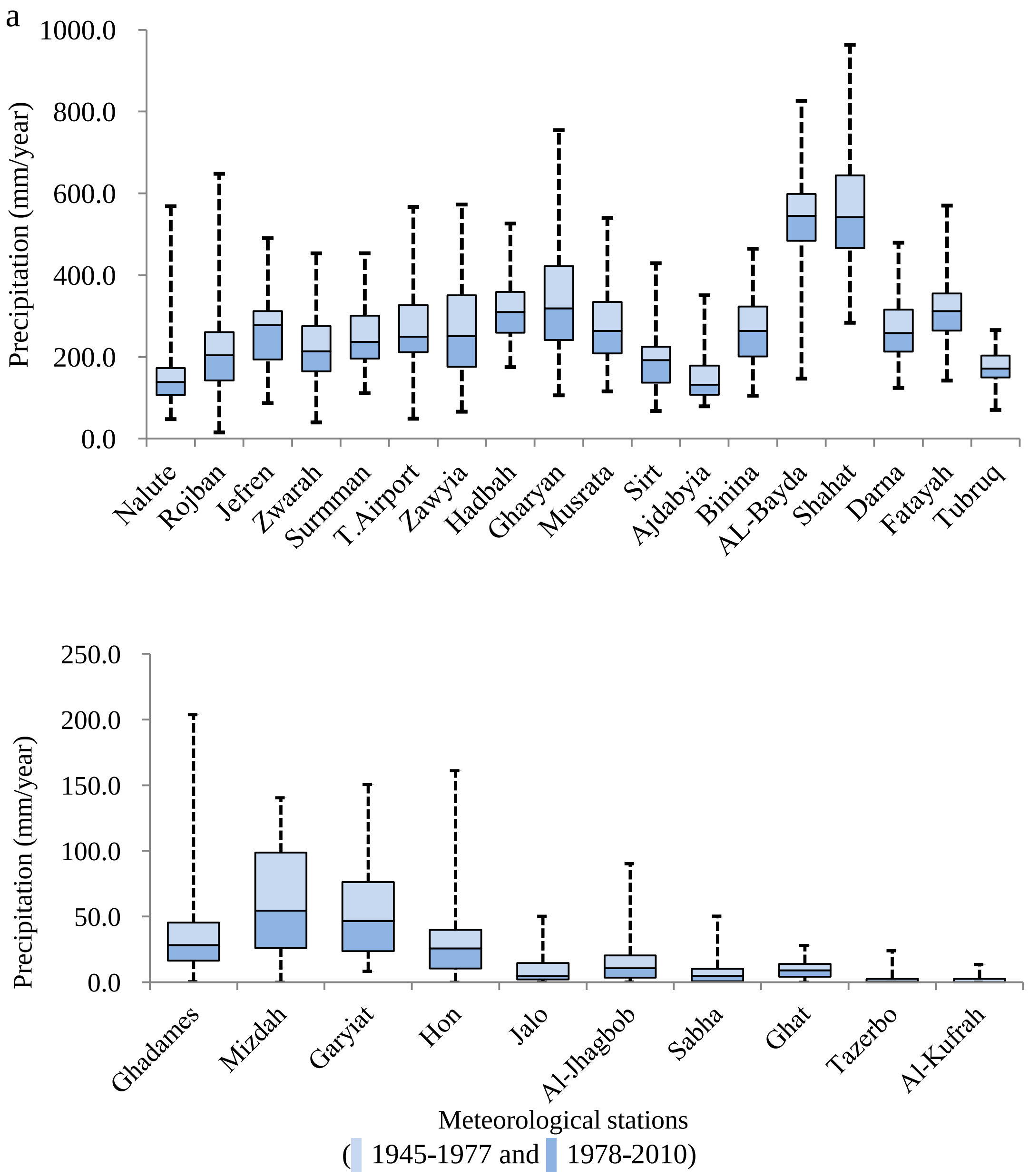


Fig. 5.10: Ranges in annual total precipitation for the 28 stations across Libya (1945-2010); a) coastal stations; and b) inland stations, with maximum, minimum, lower quartile (first quartile -25%), median (50%) and the upper quartile (third quartile – 75%).

5.4.1 Multi-decadal changes

The distribution and changes in mean annual total precipitation patterns for the stations across Libya have been analysed. Precipitation data are normalized and percentiles thresholds presented (0.10, 0.25, 0.50, 0.75 and 0.90) which are calculated to categorize whether they were very dry, dry, normal, wet or very wet periods, respectively and are shown in Figures 5.11 and 5.12

5.4.1.1 Western-coastal station

Ten stations; Zwarah, Surrman, Al-Zawia, Tripoli Airport, Al-Hadbah, Gharyan, Jefren, Al-Rojban, Nalute and Musratah are included in the western-coastal region. Changes in the normalized precipitation data are identified over the period 1945-2010, with more stability identified during the last 40 years (1965-2010), particularly during the period 1973-1988 (Fig 5.11). About 50% of the study years (1945-2010) witnessed positive precipitation anomalies, with 75% of the years characterized by dry or normal precipitation years, with very dry (11%) and very wet (8%) years. Most of the positive (wet) years recorded during the last 40 years (1970-2010).

Mean annual average total precipitation in the western region increased by 28.2% from 220.2 mm (1951-1980) to 282.4 mm (1981-2010) over the two contrasting 30-year blocks, with the wettest (302.8 mm) 30-year block occurring between 1971-2000 and the driest (220.2) mm between 1951-1980. The normalized values are within one deviation of the mean at all western stations, except during 1976. The normalized values which correspond to the 0.10, 0.25, 0.5, 0.75 and 0.90 percentiles, are 180.1 mm, 217.1 mm, 248.2 mm, 280.0 mm and 334.3 mm, respectively.

5.4.1.2 Central-coastal region

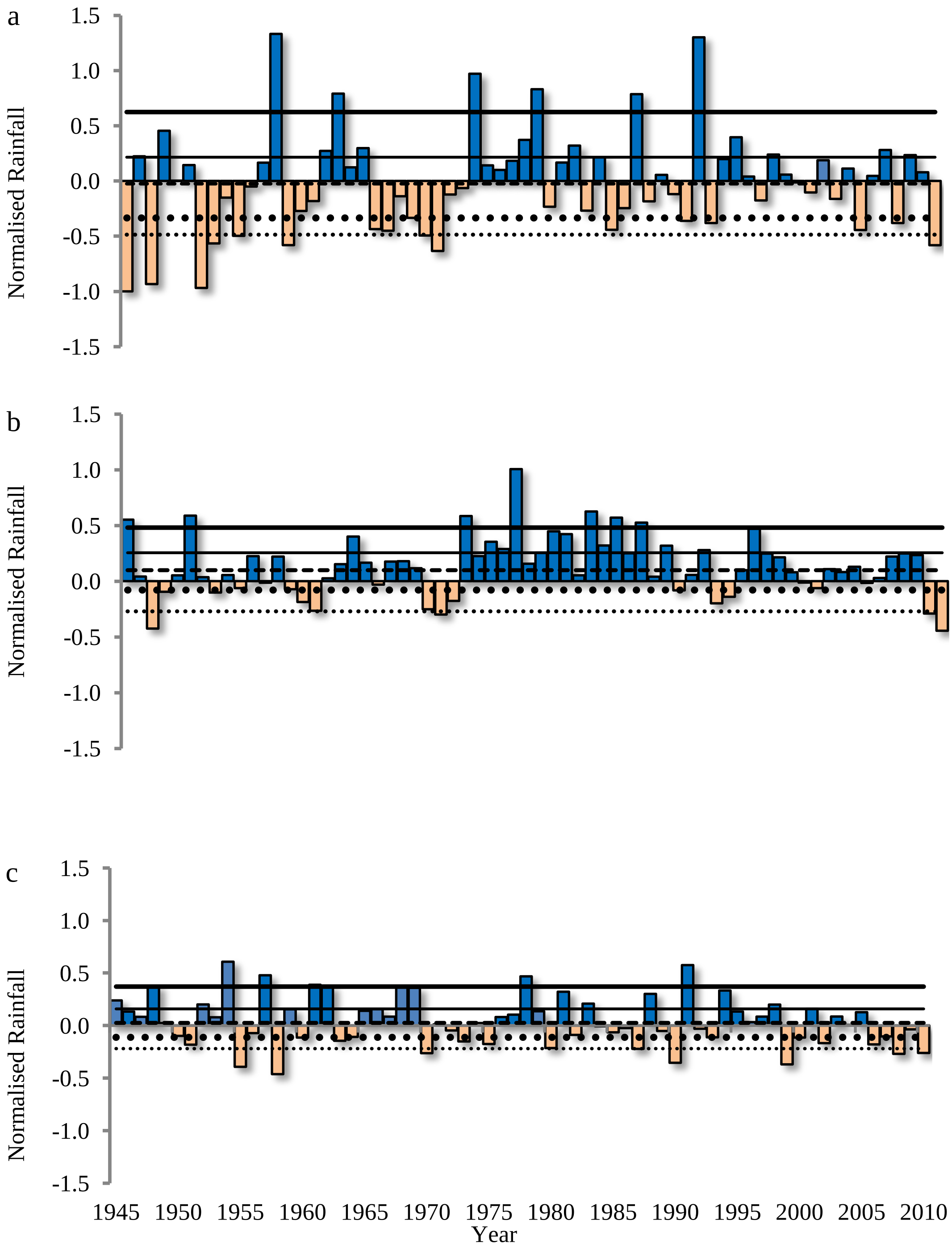
The central region is represented by two stations; Sirt and Ajdabyia (Fig. 5.11). High variability and changes in mean annual total precipitation are found during the period 1945-2010, with less variability identified during the last 15 years (1995-2010), with dry and very dry (17 years) and normal is found in the most of the first 25 year.

The anomalies during the precipitation period 1975-2010 are in the majority of years positive, with six years classed as very wet. An increase in average annual total precipitation is found in the central region, with a 19% increase from 141.0 mm (1951-1980) to 168.5 mm (1981-2010), with the highest normal (182.3 mm) in 1971-2000 and the lowest normal (141.0 mm) in 1951-1980. Small interannual variations in total precipitation occur, with lower variability from year to year observed during last two decades (1990-2010; Fig. 5.11). The normalized values are within one deviation of the mean at the central-coastal stations in 91% of the cases except during 1957 and 1991. The normalized values correspond to the 0.10, 0.25, 0.50, 0.75 and 0.90 percentiles, are 46.6 mm, 67.3 mm, 92.5 mm, 112.2 mm and 132.2 mm, respectively.

5.4.1.3 Eastern-coastal region

Binina, Al-Bayda, Shahat, Darnah, Al-Fatayah and Tubruq are included in eastern-coastal region (Fig. 5.11). High variability in distribution of annual precipitation is identified in the eastern region during the period 1945-2010, with stability identified during the last 10 years (2000-2010), with the most notable values found during the last 15 years. Annual precipitation anomalies are negative (positive) in 45% (55%) of the years. Only 17% of the years are classed as very dry, with 20% of the positive years classed as wet during the period 1945-2010.

Mean average annual total precipitation in the eastern-coastal region decreased by 1.4% from 355.1 mm (1951-1980) to 349.9 mm (1981-2010) over the two contrasting 30-year blocks. The normalized values which correspond to the 0.10, 0.25, 0.50, 0.75 and 0.90 percentiles are 261.6 mm, 305.6 mm, 353.0 mm, 399.3 mm and 472.3 mm, respectively.



(Percentiles: ……. 0.1, •••••• 0.25, - - - - 0.50, ——— 0.75, ▬▬ 0.90)

Fig. 5.11: Normalised annual precipitation anomalies and values corresponding to the limits of very dry (< percentile 0.10), dry (percentile 0.25), normal (percentile 0.50), wet (percentile 0.75) and very wet (> percentile 0.90) for coastal regions (1945-2010) a) western; b) central; and c) eastern-coastal region.

5.4.1.4 North Sahara region

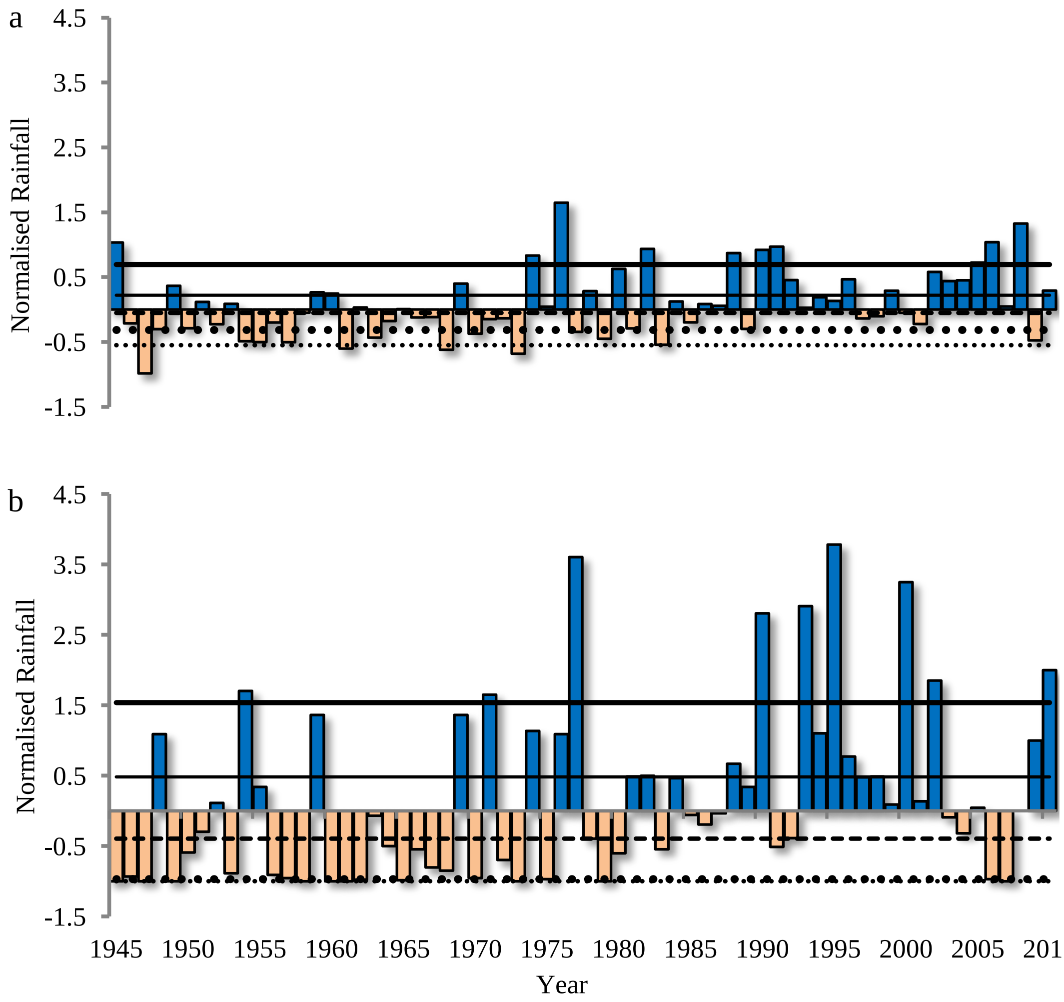
Six stations; Mizdah, Ghadames, Al-Garyiat, Hon, Jalo, and Al-Jaghbub are included in the north Sahara region (Fig 5.12). Negative precipitations anomalies occur more frequently during the first 30 years (1945-1975), with about 23% of years classed as dry and very dry. Positive annual precipitation anomalies are identified during most years during the period study (1975-2010), with wet (11 years) and very wet (10 years), ranged from 0.30 to 1.65 (Figure 5.12).

The mean total annual precipitation of north Sahara stations is 71.7 mm a^{-1}, with average annual total precipitation increasing by 47% from 22.8 mm (1951-1980) to 33.6 mm (1981-2010), with the lowest (21.1 mm) 1951-1980 and the highest 33.6 mm (1981-2010) periods. The highest annual precipitation recorded at each station is 203.9 mm (Ghadames), (140.6 mm) Mizda (133.0 mm) Al-Garyiat, (161.2 mm) Hon, (50.3 mm) Jalo and (90.4 mm) in Al-Jaghbub.

Normalized values which are correspond to the 0.10, 0.25, 0.5, 0.75 and 0.90 percentile, whose values are 13.7, 19.7, 27.9, 37.7 and 51.3 mm, respectively. The result of using normalized values with small precipitation values is that the relative differences in any given year as a percentage can appear very large, with little difference in precipitation (mm's), as such this analysis must be treated with careful consideration to the level of precipitation experienced in north and south Sahara.

5.4.1.5 South Sahara region

The Sahara region is represented by four stations; Sabha, Ghat in the western part, Tazerbou and Al- Kufrah in the eastern part. The 55% (45%) of the years 1945-2010 are negative (positive) precipitations anomalies; below the median (above the median), with more obvious negative precipitations anomalies in 27 years (68%) of the years during the first 40 year (1945-1985), reaching the level of very dry and dry periods. A highly positive value of wet was recorded in few years after, 1975, ranged from 0.25 to 3.60, with a few negative years in the late 1980s (Fig. 5.12). The mean total annual precipitation of the south Sahara stations is 2.2 mm, with highest precipitation recorded at each station of: Sabha (50.4 mm-1976), Ghat (28.0 mm-1995) Tazerbou (24.1 mm-1990) and Al-Kufrah (13.6 mm-1993). Normalized values correspond to the 0.10, 0.25, 0.5, 0.75 and 0.90 percentile are 0.0, 0.4, 2.1, 4.1, and 6.1 mm, respectively.



Percentiles: 0.1……., 0.25 ••••••, ----- 0.50, ——0.75, ▬▬ 0.90

Fig. 5.12: Normalised annual precipitation anomalies and values corresponding to the limits of very dry (< percentile 0.10), dry (percentile 0.25), normal (percentile 0.50), wet (percentile 0.75) and very wet (> percentile 0.90) for inland regions (1945-2010) a) North Sahara; and b) South Sahara.

5.5 REGIONAL CORRELATION ANALYSIS OF TEMPERATURE

5.5.1 Analysis of annual total precipitation at adjacent stations

An analysis of the relationships between adjacent stations of annual total precipitation at all (28) stations across Libya for the period 1945-2010 is undertaken. An analysis is also undertaken examining the relationship between the five regions of Libya (Table 5.6).

The spatial relationship between annual total precipitation is assessed using the Spearman's rank correlation coefficient calculated, with positive correlations and higher magnitude correlation coefficients between adjacent coastal stations (western, central and eastern), with 46% ≥5.0. Low correlations are found between the inland stations (North and South Sahara) with all cases ≤5.0. The correlations are mostly positive, with significant correlation identified at most coastal stations, particularly the western-coastal stations.

Analysis of the five different regions western-coastal (R_1), central-coastal (R_2), eastern-coastal (R_3), North Sahara (R_4) and South Sahara (R_5), identifies positive correlations in most cases except between eastern-coastal and North Sahara regions (Table 5.6). Higher correlation values are found between nearby regions (e.g. R_1 and R_2 (0.36), R_2 and R_3 (0.45)), with four significant cases R_1andR_2, $R_1$and R_2, $R_2$and R_3, $R_4$and R_5 (Table 5.6)

Table 5.6: Correlation coefficient between annual total precipitation at the adjacent stations and the regions across Libya

	Zwarah	Surrman	Al-Zawyia	T. Airport	Al-Hadbah	Gharyan	Jefren	Al-Rojban	Nalute	Musratah
Zwarah		0.71*	0.54*	0.55*	0.48*	0.50*	0.33	0.33	0.48*	0.30*
Surrman			0.63*	0.59*	0.40*	0.52*	0.66*	0.37	0.43*	0.33
Al-Zawyia				0.46*	0.60*	0.50*	0.55*	0.24	0.25	0.24
T. Airport					0.73*	0.67*	0.57*	0.51	0.37*	0.35*
Al-Hadbah						0.65*	0.22	0.50	0.24	0.18
Gharyan							0.70*	0.60	0.38*	0.33*
Jefren								0.23	0.13	0.48*
Al-Rojban									0.47	0.13
Nalute										0.19

	Sirt	Ajdabyia	Binina	Al-Bayida	Shahat	Darnah	Al-Fatayah	Tubruq
Sirt		0.36*						
Ajdabyia								
Binina				0.71*	0.70*	0.36*	0.34	0.29
Al-Bayida					0.77*	0.54*	0.41	0.32
Shahat						0.44	0.45	0.46
Darnah							0.61*	0.33
Al-Fatayah								0.33

	Ghadames	Mizdah	Al-Garyiat	Hon	Jalo	Al-Jaghbub
Ghadames		0.20	0.36*	0.27*	0.11	-0.01
Mizdah			0.31	-0.11	-0.07	-0.13
Al-Garyiat				0.47*	0.17	0.27
Hon					0.15	0.18
Jalo						0.55*

	Sabha	Ghat	Tazerbou	Al-Kufrah
Sabha		0.26	0.19	0.35*
Ghat			0.30	0.04
Tazerbou				0.51*

	W-coastal	C-coastal	E-coastal	N-Sahara	S-Sahara
W-coastal		0.36*	0.06	0.40*	0.23
C-coastal			0.45*	0.10	0.17
E-coastal				-0.13	0.16
N-Sahara					0.32*

*Statistically significant correlation at the 95 % confidence level

5.5.2 Correlation between precipitations and mean temperature

To analyze the relationship between total annual precipitation and annual maximum, minimum and mean average temperature, correlation coefficient is considered for 18 synoptic stations across Libya (1945-2010). In general, negative correlations are found between total annual precipitation and annual temperature (minimum, maximum and average; Table 5.7). For maximum temperature, negative correlations are found at most sites except Binina, with significant (95% confidence level) negative correlation found at five stations, with the highest at Tripoli Airport (-0.47; Table 5.7).

Table 5.7: Correlation coefficient between mean annual temperature and annual total precipitation at the synoptic stations across Libya

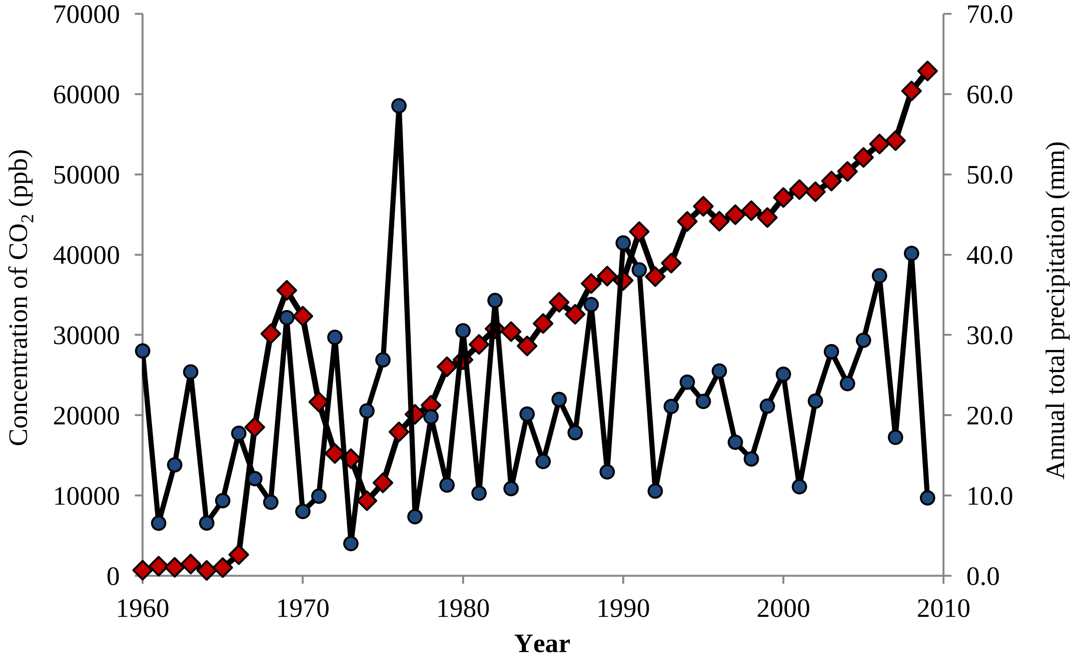
	Correlation between precipitation and temperature		
	Maximum	Minimum	Mean average
Zwarah	-0.31*	0.03	-0.13*
T.Airport	-0.47*	-0.19	-0.40*
Nalute	-0.40*	-0.23	-0.34*
Musratah	-0.14	-0.17	-0.19
Sirt	-0.20	-0.10	-0.17
Ajdabyia	-0.12	0.19	0.08
Binina	0.17	-0.13	0.03
Shahat	-0.27*	-0.22*	-0.32*
Darnah	-0.35*	-0.01	0.05
Al-Garyiat	-0.12	-0.10	0.00
Ghadames	-0.04	-0.04	0.01
Hon	-0.05	0.01	-0.02
Jalo	-0.21	0.15	0.04
Al-Jaghbub	-0.07	0.14	-0.02
Sabha	-0.14	0.05	-0.03
Ghat	0.30	0.23	0.32
Tazerbou	-0.11	-0.12	-0.16
Kufrah	0.00	-0.21	-0.10

*Statistically significant correlation at the 95 % confidence level

For minimum temperature, only Shahat provides a significant correlation, with a variety of negative/positive relationships for the stations (Table 5.7). For mean average temperature, negative correlation are found at eleven of the 17 stations, including the all western-coastal stations, with significant correlations (95% confidence level) at Zwarah, Tripoli, Nalute and Shahat.

5.5.3 Precipitation and Carbon Dioxide (CO_2)

Correlation coefficients (Spearman's *rho*) are computed to determine the relationship between CO_2 emissions and mean annual average temperatures across Libya for the period 1960-2009. Significant (95% confidence level) positive correlation coefficients are found between annual total precipitation and CO_2 emissions for the inland region (Fig. 5.20), with low positive links at the coastal region and Libya as whole. No clear relationships exist between total annual precipitation and rate of carbon dioxide emission for the coastal region and Libya as whole.



(—■— Concentration of CO_2, —●— Annual total precipitation)

Fig. 5.13 Total annual precipitation (mm) and concentration of carbon dioxide in **(**parts per billion- ppb) for the inland region (1960-2009).

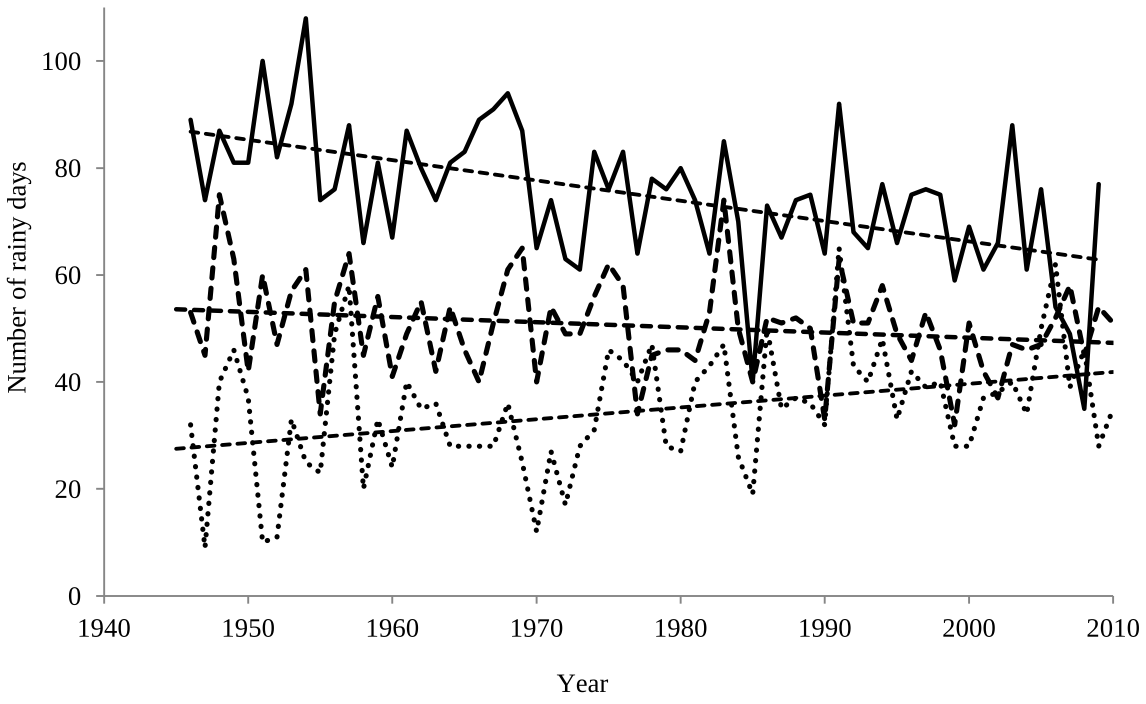
5.6 NUMBER OF PRECIPITATION DAYS

Variations in total precipitation can be affected by changes in the frequency of precipitation events and the intensity of precipitation per event. In order to improve the understanding of precipitation behaviour as an indicator of climate change, the number of rainy days for 14 stations across Libya during the period1945-2010 are analysed (with the remaining station excluded as data is unavailable). In general, the annual number of precipitation days (NPD) is defined, as a day with precipitation equal to or above 0.1 mm/0.01 inches (World Weather Information Service-WMO)

5.6.1 Annual changes and trends in number of precipitation days (NPD).

Total annual number of precipitation days (NPD) for coastal stations ranges from 25 d. a^{-1} at Nalute, to 75 d. a^{-1} at Shahat (Table 5.8), with 108 days of precipitation recorded in 1954. At inland stations, the annual average NPD ranges from 3 to 16 days, with the highest (32 days) recorded at Hon (1957).The mean annual NPD shows slight changes for the period 1945-2010 (Fig. 5.14).

Negative trends in the annual total NPD are identified at four of nine coastal stations; Zwarah, Nalute, Shahat and Darnah (-0.023 d. a^{-1}) and at two of five inland stations; Hon and Jalo, with lower trends (-0.035 d. a^{-1}) to -0.023 d. a^{-1} (Hon), with highly significant decrease at Shahat (***) and Darnah (+). Positive trends in the annual total NPD are found at five of nine coastal stations (0.070 d. a^{-1}), with significant increase at Sirt (**). Increases trend are found at three of five inland stations (0.071 d. a^{-1}), with significant increase (**) at Ghadames.



(…….Sirt, ----- Darnah and ——Shahat)

Fig. 5.14: Time series of mean annual number of precipitation days (NPD) in Shahat, Darnah and Sirt for the period 1945-2010.

Table 5.8: Values of the Mann-Kendall statistic (Q) for annual and seasonal number of precipitation days (NPD), with statistically significant levels at 14 stations across Libya (1945-2010)

Time series	Annual			Winter			Autumn			Spring		
	NPD	Q	Sig.	NPD	Q	Sig.	NPD	Q	Sig.	NPD	Q	Sig.
Zwarah	36	-0.027		16	0.030		11	-0.037		7	0.000	
T.Airport	45	0.023		22	0.077	+	13	-0.022		10	0.000	
Nalute	25	-0.056		11	-0.023		7	0.000		7	-0.029	
Musratah	48	0.031		24	0.063		14	0.000		8	0.000	
Sirt	35	0.227	**	18	0.159	**	10	0.000		6	0.044	
Ajdabyia	35	0.071		22	0.071		7	0.000		6	0.000	
Binina	56	0.000		32	0.027		12	0.000		11	0.000	
Shahat	75	-0.350	***	39	-0.107	+	19	-0.133	***	16	-0.103	*
Darnah	50	-0.136	+	28	0.034		12	-0.063+	+	10	0.071	
Ghadames	16	0.151	**	4	0.000		2	0.000		3	0.000	
Hon	10	-0.023		4	0.000		3	0.000		3	0.000	
Jalo	5	-0.053		2	0.000		1	0.000		1	0.000	
Al-Jaghbub	6	0.038		4	0.000		1	0.000		2	0.000	
Sabha	3	0.025		1	0.000		1	0.000		1	0.000	

5.6.2 Seasonal changes and trends of number in the precipitation days (NPD)

Mean seasonal NPD for coastal stations are 23 d. a^{-1} (winter), 12 d. a^{-1} (autumn) and 9 d. a^{-1} (spring; Table 5.8). The mean seasonal NPD shows a slight fluctuation during the period1945-2010 (Fig. 5.15).

In winter, a general positive trend in NPD is identified for all stations with trends identified at 50% of individual stations, with significant increases at Sirt (**) and Tripoli Airport (+). Negative trends are identified at the stations located at the highest elevations, Shahat and Nalute (621 m a.m.s.l), with a significant change (+) at Shahat (-0.107 d. a^{-1}). In autumn, a general negative trend is identified for all stations (-0.064 d. a^{-1}), with a significant changes found at two stations: Shahat (***) and Darnah (+) (Table 5.8). A general negative trend is found across all stations in spring (- 0.066 d. a^{-1}). The two stations with the highest elevation: Nalute and Shahat, both show negative trends, with a significant trend at Shahat (*). Positive trends are found at Sirt and Darnah. No seasonal trends are identified in the NPD at all inland stations and at most of coastal stations particularly in autumn and spring; this may result from the small number of rainy days recorded at these stations, making trend analysis difficult.

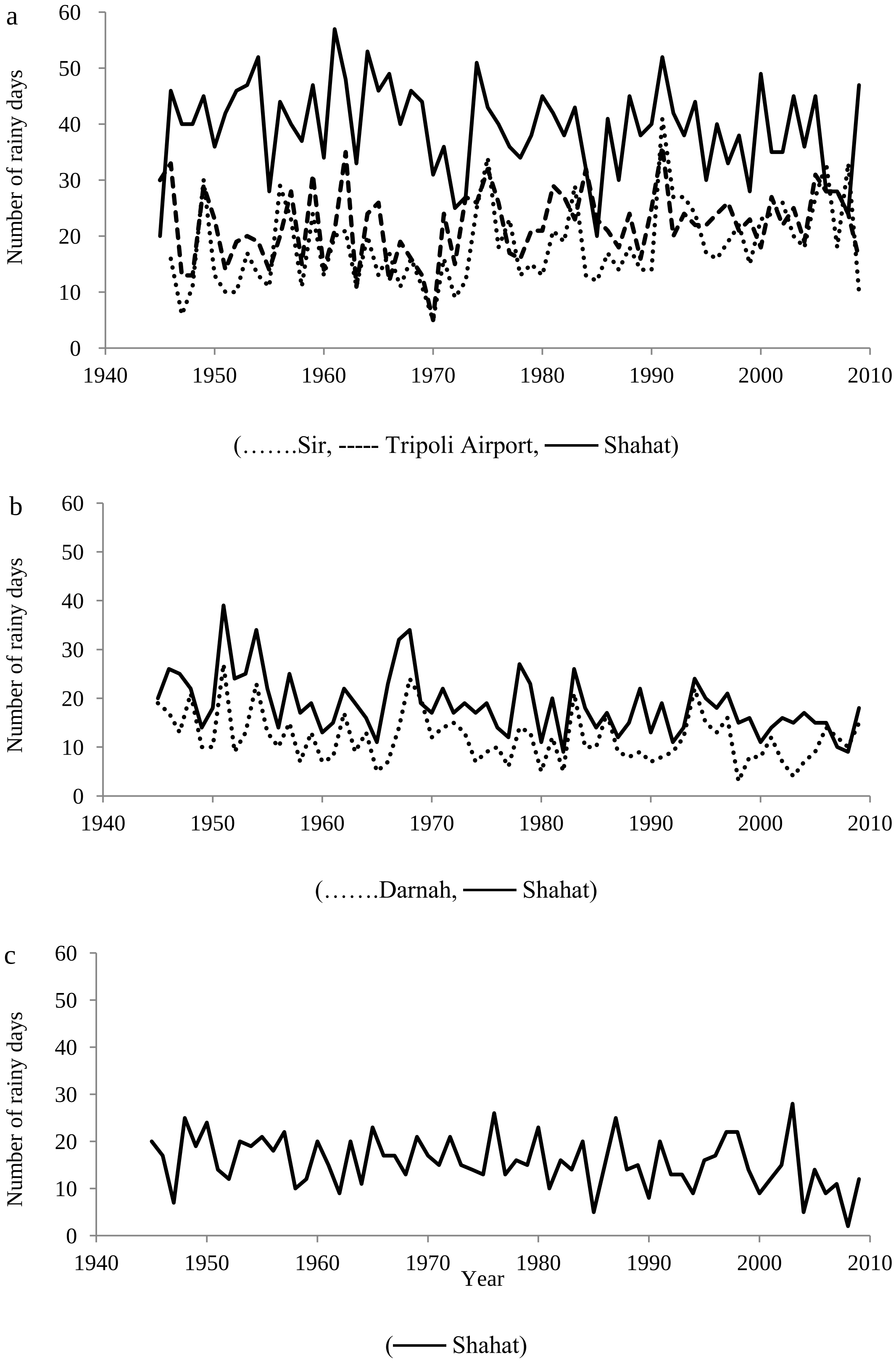


Fig. 5.15: Time series of mean seasonal number of precipitation days (NPD) for the period 1945-2010; a) winter; b) autumn and; c) Spring

5.7 PRECIPITATION EXTREMES

Different definitions for extreme precipitation have been previously applied (Suppiah and Hennessy, 1998; Easterling et al., 1999; Peterson et al., 2002; Reiser and Kutiel, 2010; Lupikasza et al., 2011; Kostopoulou et al., 2013), within this study several different definitions are examined; Intensity of precipitation (IP), Consecutive dry days (CDD), Consecutive wet days (CWD), Heavy precipitation days (R10), and Maximum 1day precipitation (Rx1day) are selected to examine extremes in precipitation as indicative climatic variables to determine recent local climatic changes across Libya for the period 1961-2010. The most important climate indices related to the precipitation and those most widely for analysis of extremes in precipitation have been selected from the internationally agreed WMO list of about 50 climate change indices available on line at htt://www.knmi.nl/samen/eca.

5.7.1 Intensity of precipitation (IP)

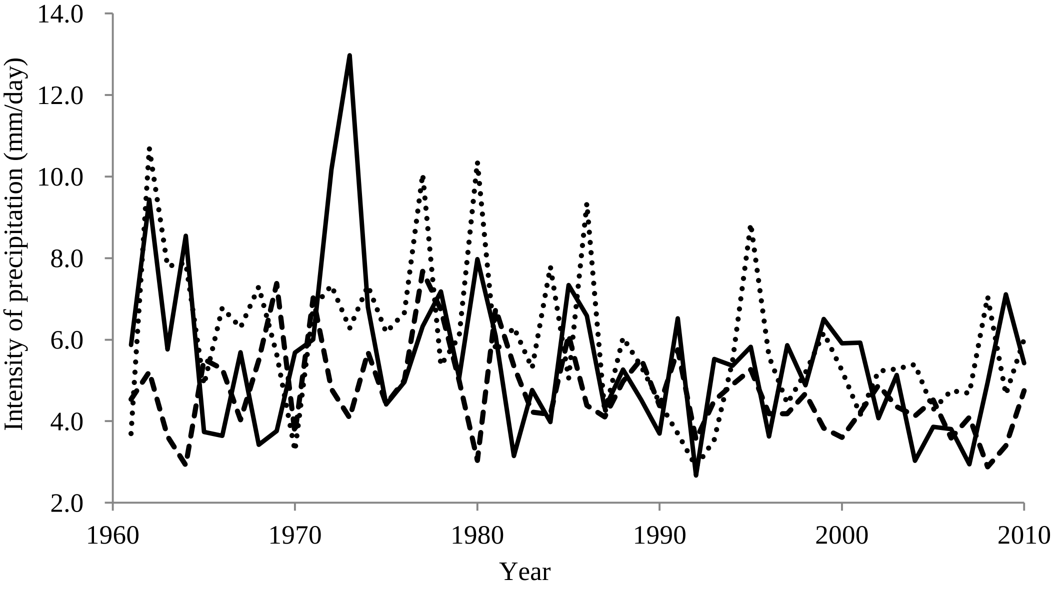
Intensity of precipitation (IP) is very important in precipitation studies because it plays a key role in precipitation efficiency as the main important water source supply, particularly in arid and semi-arid regions. Agricultural practices across Libya can be heavily affected by intensity of precipitation and therefore soil erosion, especially in the central-coastal and inland regions of Libya, which can be extreme when precipitation occurs, though rare. The IP is the main characteristic used to describe precipitation, three categories are used: heavy, moderate or mild precipitation. In general, the IP is defined as the average rate of precipitation (mm per day) divided by the number of rain days per year (n), where a precipitation day is defined as, one day with precipitation equal to or above 0.1 mm/0.01 inches (World Weather Information Service-WMO). The annual and seasonal IP is computed for 14 stations across Libya (1961-2010).

5.7.1.1 Changes and trends of annual intensity of precipitation

The mean annual IP ranges between 5.9 mm d^{-1} at coastal stations and 2.2 mm d^{-1} at inland stations. The mean annual IP shows slight fluctuation during the 1961-2010 (Fig 5.16). Negative trends in annual IP are identified at six of nine coastal stations (67%; - 0.026 mm d^{-1}), with a significant decreases at Tripoli Airport (**), Binina

(*) and Sirt (+). Negative trends (0.013 mm d^{-1}) are found at three coastal stations Nalute, Ajdabyia and Darnah.

At the inland stations, positive trends (0.19 mm d^{-1}) and negative trends (- 0.12 mm d^{-1}) are identified at three and two stations, respectively, with no significant at inland stations (Table 5.9).



(Binina ------, Tripoli Airport .... Sirt ——)

Fig. 5.16: Time series of annual intensity of precipitation at Binina, Tripoli Airport and Sirt (1961-2010)

5.7.1.2 Seasonal changes and trends in intensity of precipitation

Mean seasonal IP for coastal stations ranges between 4.4 mm d^{-1} (spring), 6.0 mm d^{-1} (winter), and 6.2 mm d^{-1} (autumn), while inland stations range from 3.5 mm d^{-1} (spring), and 4.6 mm d^{-1} (autumn) and 4.7 mm d^{-1} (winter; Table 5.9).

Positive trends in winter IP are found at 56% of coastal (0.027 mm d^{-1}) and 60% of inland (0.008 mm d^{-1}), with a significant increase at Nalute (**). Negative trends are found at four stations, with a significant decreases at Binina (-0.026 mm d$^{-1,}$ *), Musratah (-0.032, +) and a significant positive increase at Nalute (-0.074 mm d^{-1}, **), with no significant changes at inland stations.

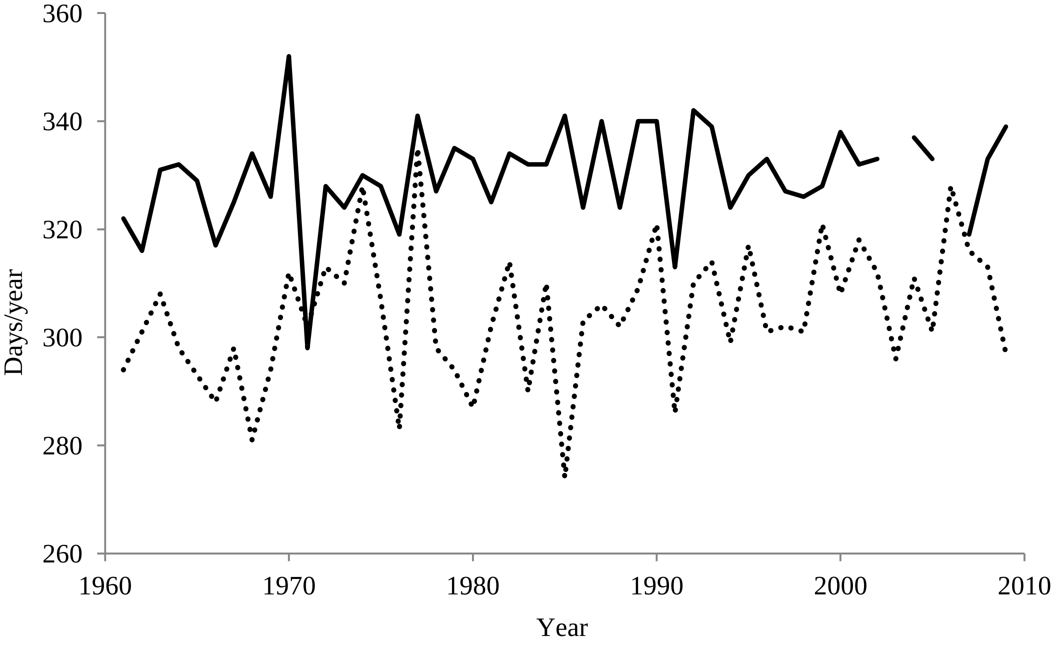
In autumn, negative trends are identified at seven of nine coastal stations with a general decrease across all stations (-0.035 mm d^{-1}), with significant decreases at Sirt (*) and Binina (+), with no trends at 80% of the inland stations. The mean spring IP showed increases at five coastal stations with an average change of 0.023 mm d^{-1} across all stations, significant changes (+) at Shahat and Sabha (*).

Table 5.9: Values of the Mann-Kendall statistic (Q) for the intensity of precipitation (IP), with statistically significant levels at 14 stations across Libya (1961-2010)

Stations	Annual			Winter			Autumn			Spring		
	Mean IP (mm d^{-1})	Q	Sig.	Mean IP (mm d^{-1})	Q	Sig.	Mean IP (mm d^{-1})	Q	Sig.	Mean IP (mm d^{-1})	Q	Sig.
Zwarah	6.4	-0.019		6.3	0.019		7.3	-0.049		4.4	-0.005	
T.Airport	6.0	-0.050	**	6.4	-0.018		10.4	-0.004		4.4	-0.034	
Nalute	5.8	0.016		5.1	0.074	**	5.3	-0.014		7.0	-0.021	
Musratah	5.8	-0.020		5.9	-0.032	+	6.7	-0.031		4.5	0.026	
Sirt	5.4	-0.034	+	5.9	-0.029		5.7	-0.069	*	3.3	0.011	
Ajdabyia	4.2	0.019		4.7	0.006		3.7	0.035		2.9	0.001	
Binina	4.7	-0.024	*	5.4	-0.026	*	4.4	-0.033	+	3.3	-0.004	
Shahat	7.3	-0.009		8.3	0.012		7.0	0.000		6.1	0.050	+
Darnah	5.3	0.004		5.6	0.022		5.7	-0.031		3.4	0.025	
Ghadames	3.3	-0.007		3.1	0.025		0.2	0.000		3.1	0.002	
Hon	2.9	0.004		2.3	0.009		3.7	-0.028		2.3	0.000	
Jalo	1.8	0.008		1.7	0.004		0.9	0.000		1.0	0.000	
Al-Jaghbub	4.1	-0.014		2.5	-0.033		0.9	0.000		1.5	0.000	
Sabha	2.2	0.026		1.4	0.000		1.3	0.000		1.1	0.004	*

5.7.2 Changes and trends of consecutive dry days (CDD)

Consecutive dry days (CDD) are defined as a maximum number of consecutive days with precipitation less than 1.0 mm d^{-1} and are analysed for nine coastal satiations; Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Shahat and Darnah. The number of CDD ranges between 305 (Shahat) and 343 days (Ajdabyia), with the highest (356 days) recorded at Zwarah (1956). Positive trends in the CDD are found at four of eight (63%) stations ranging from 0.001 day to 0.138 day, with weakly significant (+) at Musratah (1.723 mm d^{-1}) and Shahat (1.703 mm d^{-1}; Table 5.10 and Fig. 5.17). Negative trends are found at Tripoli Airport Ajdabyia and Binina, with no significant trends at any stations.



(........ Shahat, —— Musratah)

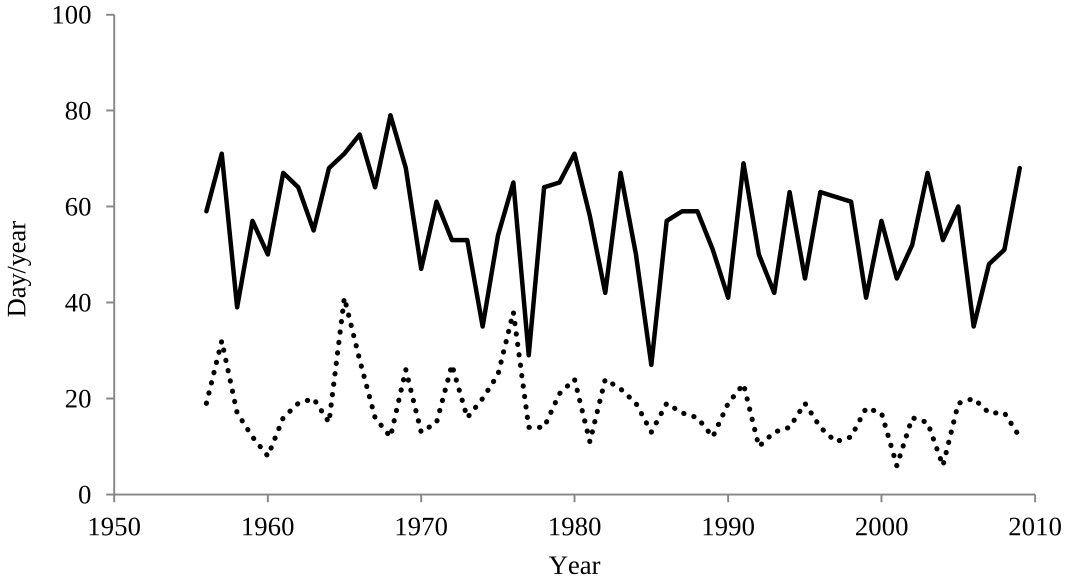
Fig. 5.17: Time series of maximum number of consecutive days (CDD) with precipitation less than 1.0 mm at Shahat and Musratah for the period1961-2010.

Table 5.10: Values of the Mann-Kendall statistic (Q) for extremes precipitation; Consecutive dry days (CDD), Consecutive wet days (CWD), Heavy precipitation days (P10), with statistically significant levels for the period (1961-2010)

	Consecutive dry days			Consecutive wet days			Heavy precipitation days		
Time series	Mean mm d^{-1}	Q	Sig	Mean mm d^{-1}	Q	Sig	Mean mm d^{-1}	Q	Sig
Zwarah	337	0.031		25	0.000		7	0.000	
T.Airport	331	-0.111		35	0.111		8	0.000	
Nalute	331	-0.032		18	-0.111		4	0.023	
Musratah	330	0.138		36	-0.075		8	-0.048	
Sirt	338	0.000		25	-0.059		6	0.000	
Ajdabyia	343	0.000		25	0.036		4	0.000	
Binina	314	-0.067		36	0.000		7	0.000	
Shahat	305	0.190		56	-0.192		18	-0.050	
Darnah	328	0.096		50	-0.081		7	0.000	
Ghadames	355	-0.024		6	0.023		1	0.000	
Hon	358	0.000		6	0.000		1	0.000	
Jalo	356	0.000		2	0.000		0	0.000	
Al-Jaghbub	358	0.000		3	-0.023		0	0.000	
Sabha	363	-0.031	*	1	0.000		0	0.000	

5.7.3 Changes and trends of consecutive wet days (CWD)

Consecutive wet days (CWD) are defined as a maximum number of consecutive days with precipitation equal or greater than 1.0 mm (≥1 mm). The number of (CWD) ranges from 25 days at the driest three stations (Zwarah, Sirt and Ajdabyia) to 56 days at Shahat (1961-2010), with the highest recorded at Shahat (79 days) in 1968. Positive trends in maximum number of (CWD) index are found at 4 of 8 (50%) stations, with a weakly significant change at Shahat (-0.192; Table 5.10 and Fig. 5.18).



(........ Shahat, ——— Musratah)

Fig. 5.18: Time series of maximum number of consecutive wet days (CWD) with precipitation greater than 1.0 mm at Shahat and Nalute for 1956-2010

5.7.4 Changes and trends of heavy precipitation days (P10)

Heavy precipitation days (P10) are defined as a number of days with precipitation greater than 10.0 mm per day. The number of P10 is computed for nine coastal stations across Libya (1961-2010). P10 values in Libya are small with values ranging between 4 d a^{-1} (Nalute) and 18 d a^{-1} (Shahat), with the highest P10 (30 d a^{-1}) recorded in 1991 (Table 5.10). The mean total number of P10 at coastal stations during the period 1961-2010 (50 years) ranges from 216 d^{-1} (Nalute) to 955 d a $^{-1}$ (Shahat).

The mean average rate of the maximum (minimum) number of P10 at coastal stations was 16 (8) d a^{-1}. Inland stations only receive a very low number of IP (one d a^{-1}), with the mean total number of P10 during the period 1961-2010 (50 years) ranging from 8 d $^{-1}$ (Sabha) to 45 d $^{-1}$ (Ghadames). No trends in the number of the P10 are computed at six of nine coastal stations and all inland stations, with negative trends at Musratah (-0.041 d a $^{-1}$) and Shahat (-0.050 d a^{-1}) and a positive trend at Nalute (0.023 d a $^{-1}$; Table 5.10).

5.7.5 Changes and trends of maximum 1day precipitation (Px1day)

The maximum 1-day precipitation (Px1day) is defined as the day in any month with the highest amount of precipitation .The study focused on maximum precipitation in any given day for each month and annually for the period 1961-2010 for the 14 stations across Libya (Table 5.11). Generally, the Px1day for the nine coastal stations identified that 69% of the total (Px1day) are between 20 and 40 mm d^{-1}.

Table 5.11: Values of the Mann-Kendall statistic (Q) for maximum 1day precipitation (Px1day), with statistically significant levels for the period (1961-2010)

	Maximum 1day precipitation			Interval; maximum 1day precipitation (mm)					
Time series	Px1day (mm/date)	Sig	Q	≤ 10	10-20	20-30	30-40	40-50	>50
Zwarah	82.3/2002		-0.012	0	0	5	14	12	3
T.Airport	130.2/198	+	-0.175	0	0	4	9	19	5
Nalute	125.2/199		0.203	0	1	12	6	10	6
Musratah	104.0/199		-0.064	0	0	3	14	14	5
Sirt	99.2/1973		-0.005	0	0	8	22	11	2
Ajdabyia	73.0/2002		0.109	0	4	19	13	8	1
Binina	108.0/197		-0.042	0	0	13	17	12	2
Shahat	86.5/1989		-0.015	0	0	0	9	14	10
Darnah	105.7/199		-0.055	0	0	6	15	9	7
Ghadames	44.0/1974	+	0.167	0	22	18	6	1	1
Hon	42.7/1986		0.038	0	27	14	5	2	1
Jalo	17.2/2007		0.001	10	32	7	0	0	0
Al-Jaghbub	30.0/1988		0.039	0	40	7	2	0	0
Sabha	29.0/2006		0.015	16	25	6	1	0	0

Approximately 84% of the total frequencies of Px1day at Shahat range between 40->50 mm d^{-1}. The Px1day for inland stations during the period 1961-2010 indicates that 85% of Px1day is less than 20 mm d^{-1} (Table 5.11). Negative trends are observed at seven of nine coastal stations -0.0.046 mm d $^{-1}$, with a significant decrease (+) at Tripoli Airport (Table 5.10).

Positive trends are found at the two driest coastal stations Nalute and Ajdabyia (0.156 mm d^{-1}), with no significant increase at any coastal stations. Positive trends are observed at all inland stations (0.082 mm day $^{-1}$), with significant increase only at Ghadames (+).

Negative trends are observed at seven of nine coastal stations (-0.0.046 mm d $^{-1}$), with a significant decrease (+) at Tripoli Airport (Table 5.11). Positive trends are found at the two driest coastal stations Nalute and Ajdabyia (0.156 mm d^{-1}), with no significant increase at any coastal stations. Positive trends are observed at all inland stations (0.082 mm day $^{-1}$), with significant increase only at Ghadames (+).

5.8 DISCUSSION

The main objective of this work is to identify the temporal and spatial changes in precipitation and to analyze the characteristics and trends of precipitation across Libya based on a long-term daily, monthly and annual precipitation data observed from 28 stations for 80 years (1931-2010).

Generally, precipitation decreases sharply in a southward direction from the coast to the inland region and then more gradually to the central coast regions of Libya. At the coastal stations about 52% of the years receive precipitation of 100 to 300 mm, whereas about 90% of the years at inland stations (Sahara) receive less than 50 mm. The mid-season (50%) accumulated total annual (water year: September-May) precipitation or more roughly occurs early in December in the western plain and at central and eastern stations, while it occurs later in January in the western mountains and north Sahara stations.

This study has identified that increase trends (0.166 mm a^{-1}) in annual precipitation have been found at 69% of stations (1945-2010), with significant increases at Al-Jaghbub (*). Negative trends are found at 31%, with significant decreases (+) at Tripoli Airport. During the first 33 years period (1945-1977) positive trends in annual precipitation are identified at 60% (66%) of the coastal (inland) stations, with a significant increase (+) at Ajdabyia and Al-Jaghbub.

The variations in total precipitation can be caused by a change in number of precipitation days and the frequency of precipitation extremes per event, or a combination of both.

Previous research e.g. Fontaine et al., (2011), have identified a slight general increase in North Africa since the mid-90s with significant northward migrations of rainfall amounts. The findings are supported by Yosef et al., (2009) who found that, increase trend in annual total rainfall across Israel for the period 1950-2003. However, El-Tantawi, 2005 identified positive trends (0.170 mm $^{-1}$) in annual precipitation was computed at most of study stations were observed during the period 1946-2000.

Negative changes in the annual precipitation are observed at 18 stations across Libya by 78% and 40% at coastal and inland stations during the second 33 years period (1978-2010), with statistical significant decreases at Al-Rojban (**), Garyan, Tripoli Airport, Tazerbou (*) and Al-Jaghbub (+).This finding supported by Philandras et al., 2011, who found a slight positive trends in northern Africa during the long period 1901-2009, with no statistically significant appeared.

Previous research e.g. Boccolari and Malmusi, (2013) they found that decreases in precipitation trend (-6.33 mm/decade) over Modena during the 1831-2010. A general decreasing trend (-2.32 mm $^{-1}$) in mean annual precipitation for the 26 years (1979-2004) showing, with increase trend in parts of central and northern Greece have been identified by Hatzianastassiou et al., (2008). This findings supported by Meddi et al., 2010 they have observed decrease total annual rainfall for the north-eastern Algeria after 1970. Moreover, the IPCC (2007) report illustrated that the linear trends of rainfall decreases for 1900 to 2005 in western Africa.

Drying has been observed in the Mediterranean for 1900 to 2005, with the largest negative trends in annual precipitation were observed over western, eastern Africa and the Sahel during the past 50 years. However El-Tantawi, (2005) identified decrease trends (-0.20 mm $^{-1}$) in annual rainfall at most of stations across Libya from 1976 to 2000.

Negative precipitation evolution in the western parts of Northern Africa, with no significant precipitation trends have been observed Mediterranean Tunisia central, and the Mediterranean parts of Libya and Egypt, Schilling et al., (2012) during the last decades. During the 20th century, general decreased in annual total rainfall has been found in Turkey and apparently during the 1930-1993, with none of the decreasing trends in precipitation were significant, with about 19% of total stations showed a significant trend, with majority of these trends are downward (Turkes, 1996).

Autumn precipitation identified a negative trend (- 0.241 mm $^{-1}$) at nine stations across Libya (60%), with 40% of stations were positive (0.100 mm $^{-1}$), significant decreases (*) at Tripoli Airport and Jalo (+) during the period 1945-2010. Winter precipitation showed positive trends (0.435 mm^{-1}) at ten stations (76%), with five stations showed negative trends (-0.313 mm^{-1}), with significant increases (*) at Al-Zawia, Sirt and Al-Jaghbub. In contrast, nine stations (60%) showed slightly positive spring trends (0.049 mm^{-1}), where 40% of the stations were decreased (-0.085 mm^{-1}), with no significant trends at any stations.

These results are in agreement with the established fact in the literature, e.g. Hatzianastassiou et al., (2008) who found a significant changing winter precipitation patterns in Greece during the period1979-2004. This findings supported by El-Tantawi, (2005) who showed positive trends in winter (0.06 mm/decade) and spring (0.07 mm/decade) rainfall, while negative autumn rainfall found at most stations across Libya from 1946-2000.

The analyses of monthly precipitation based on data of 66 years (1945-2010) of observation from 13 stations across Libya identified positive changes in September, February at all stations, with no significant at any stations.

The maximum number of stations with monthly positive trends has also been observed in rainy months; May (0.136), March (0.051 mm $^{-1}$), and April (0.006 mm $^{-1}$) with the minimum in October (-0.108 mm $^{-1}$), with few significant changes have been observed.

Significant differences in the 30-year intervals of 11-day moving average precipitation are found at Tripoli Airport and Shahat (95% confidence level). The mean daily precipitation during the last decadal (2001-2009) was characterized by high variability. Average annual precipitation of western stations decreases from 303.5 mm to 223.8 mm during the last four decades.

The spatial and temporal changes in precipitation during the last 66 years (1945-2010) illustrated that, with 75% of the years at western coastal region characterized by dry or normal precipitation years, with very dry (11%), with dry and very dry (17 years) and normal is found in the most of the first 25 year at central-coastal region. Only 17% of the years are classed as very dry and about 23% of years at North-Sahara region classed as dry and very dry. Most of wet years recorded during the last 35-40 years at the western, central-coastal and the north Sahara regions, with the most notable precipitation values found during the last 15 years at eastern-coastal region (Fig. 5.11 and 5.12)

The annual total number of precipitation days (NDP) shows positive trends (0.0108 d. a^{-1}) identified at 53% of stations, with significant positive at Shahat (*) and Darnah (+). Negative trends (-0.108 d. a^{-1}) are identified at 47% of stations, with significant at Sirt (***) and Ghadames (**). Significant seasonal changes have been found at few stations in winter, autumn and spring NDP (Table 5.6). Mean annual intensity of precipitation (IP) ranges between 1.8 and 6.4 of stations across Libya (Table 5.7), with significant decreases are found at Tripoli Airport (**), Binina (*) and Sirt (+). The positive and negative trends (significant or not) observed in IP is generally associated with a raise in total precipitation and number of precipitation days and with heavy precipitation events, where the relationship between IP and NDP against total precipitation is not common.

The precipitation extremes identify that the number of consecutive dry days (CDD) range between 305 days (Shahat) and 363 days (Sabha; Table 5.8), with a significant decrease at Sabha (*) during the period of study (1956-2009). The number of Consecutive wet days (CWD) of coastal stations ranges from 18 days (Nalute) to 56 days (Shahat). Positive trends in number of heavy precipitation days (P10 mm) are computed at Nalute, with negative trends at Musratah and Shahat. Significant decrease (increase) in maximum precipitation in day (Px1day) are found at Tripoli Airport (+) and Ghadames (+). The changing trends precipitation and extremes of precipitation described in this chapter have important implications for water resource in Libya will be investigated later chapters. A strong evidence of decrease in annual total precipitation has been found indicating that extreme events as CCD, CWD and NDP were becoming more frequent during the last 33 years (1978-2010).

Boccolari and Malmusi, 2013 they identified that, significant trends (2.70 day/decade) in R10mm also negative trend in CDD, with slight positive trends in CWD are found across Modena, Italy over the period 1831–2010, with no significant trends. These results are in agreement with the third report of IPCC, (2007) they have found that the number of events with heavy precipitation has increased over the period 1900–2005, over the continental regions.

However, Ramos and Martìnez-Casasnovas (2006) have identified that, extreme events are increasing in the analysed periods in the north-east Spain region during the period 1923 and 2002. This findings are also supported by Moberg and Jones (2005) found that no significant in CDD index trend in almost in summer and winter seasons over central and western Europe, during 1901–1999.

5.9 SUMMARY

The key findings of this chapter are:

1. The analyses of trends and patterns of precipitation observed at 28 meteorological stations across Libya during the period of 80 years (1931-2010), expose in general well pronounced monthly, seasonal and annual

pattern, with increasing tendency in precipitation during the last 33 years (1978-2010). Notable temporal and spatial variability and significant in precipitation has been shown, with the rates of change are differ and higher toward to the south Sahara of Libya consistent throughout the period, indicating that climate drivers may vary through time and space across Libya.

2. Increase trends in annual precipitation have been found at 69% of stations across Libya (0.166 mm $^{-1}$) for the 66 years (1945-2010) and higher trend (1.437 mm $^{-1}$) for the first 33years (1945-1977). Decrease trends (-1.703 mm $^{-1}$) have been identified at about 65% of the total 28 stations across Libya and -2.126 mm $^{-1}$ at about 80% of the coastal stations for the last 33 years 1978-2010, with significant decreases at few stations at different confidence levels.

3. Changes trends has been found in seasonal precipitation through the 66 years (1945-2010), with positive trends (0.435 mm $^{-1}$) at 67% in winter and (-0.241 mm $^{-1}$) of 60% in spring, with significant trend at three station. Negative trends (-0.241 mm $^{-1}$) is found at 60% of stations across Libya, with significant decreases at three stations. The maximum number of stations with monthly positive trends has been observed in rainy months, with few significant changes have been observed.

Chapter 6

EVAPOTRANSPIRATION

This chapter examines temporal and spatial variability in potential (Penman-Monteith and Thornthwaite formulas) and actual evapotranspiration using monthly and annual data for 50 years (1961-2010). Additional climatic parameters; relative humidity, wind speed, sunshine duration and atmospheric pressure are also examined.

Evapotranspiration is the second largest flux in the water cycle thus any changes, would affect the whole water cycle. Evapotranspiration is possibly the most difficult and complicated component of the water cycle (Xu and Singh, 2005) and also a very important indicator for climate change (Peterson et al., 1995; Brutsaert and Parlange, 1998). In the surface water balance, approximately 60-80% of the precipitation on the terrestrial surface returns back into the atmosphere, where it becomes the source of future precipitation (Tateishi and Ahn, 1996). Evapotranspiration is an important climatic parameter controlling surface energy exchange, energy transport and transformation in the global atmospheric system, with increases in global warming leading to get higher surface temperatures, which may generate more evaporation. The fluctuations in temperature and precipitation trends resulting from changes of climate are expected to have a strong effect on the spatial and temporal distribution of water resources (IPCC, 2007) and thus impact on patterns of evaporation.

6.1 STUDY AREA

The climate of Libya is characterized by wet winters and hot dry summers. The area is characterized by dry and hot winds blowing from the Sahara desert, which are dominate in the spring and summer months, with the mean annual average temperature across Libya ranging between 14.2 °C to 23.4 °C.

Therefore, the climate of Libya shows notable variability, with mean annual maximum temperature ranges between 24.7 °C and 29.7 °C and means annual precipitation ranges between 279.3 mm to 22.8 mm for coastal and inland regions respectively. The initial division of Libya into two geographical regions (coastal and inland: Fig.6.1) will permit further analysis into the potential mechanisms responsible for changes in potential evapotranspiration (PET) and actual evapotranspiration (AET).

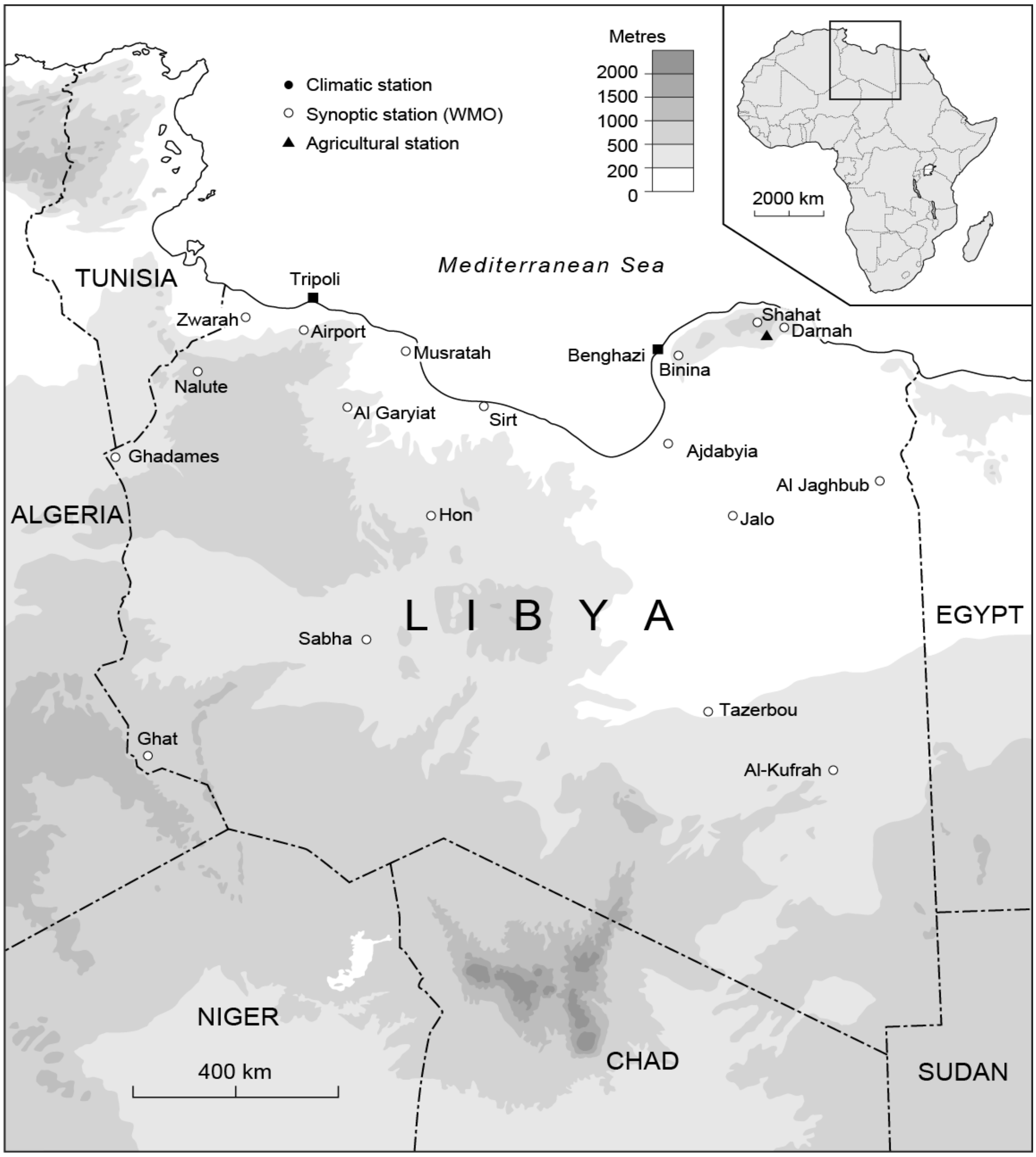


Fig. 6.1: The distribution of synoptic stations within this study.

The coastal region includes nine stations; Zwarah, Tripoli Airport, Nalute, Musratah, Sirt, Ajdabyia, Binina, Shahat and Darnah, where the inland region includes seven stations: Ghadames, Hon, Halo, Al-Jaghbub, Sabha, Tazerbou and Al-Kufrah.

6.2 DATA QUALITY (SOURCE) AND MANAGEMENT

Climatic data for 16 synoptic stations across Libya were collected from the Libyan National Meteorological Centre (LNMC). The study focuses on climatic data: temperature, wind speed, relative humidity, atmospheric pressure and sunshine duration collected from the LNMC. Data recorded for the period 1961-2010 is used, as dataset integrity improves considerably after 1961 at the majority of stations. Monthly datasets of the climatic parameters for the last 50 years (1961-2010) for the 16 stations across Libya are used (Table 6.1).

Table 6.1: The data used within the study, with missing climatic parameter data of maximum (T. max), minimum temperature (T. min), wind speed (SW), relative humidity (RH), atmospheric pressure (AP) and sunshine duration (SSD).

Stations	Covered period	Missing data (%)					
		T. max	T.min	SW	RH	AP	SSD
Zwarah	1961-2010	0.00	0.00	0.00	0.00	0.00	3.06
T. Airport	1961-2010	0.00	0.00	0.00	0.00	0.00	2.50
Nalute	1961-2010	0.22	0.22	0.50	0.00	0.00	2.10
Musratah	1961-2010	0.00	0.00	0.00	1.10	0.00	2.01
Sirt	1961-2010	0.00	0.00	0.32	0.00	0.00	3.11
Ajdabyia	1961-2010	0.00	0.00	0.17	0.50	0.00	2.90
Binina	1961-2010	0.00	0.00	0.00	0.17	0.00	1.55
Shahat	1961-2010	0.00	0.00	0.30	0.30	0.00	2.88
Darnah	1961-2010	0.00	0.00	0.00	0.00	0.00	2.24
Ghadames	1961-2010	1.01	0.91	2.21	2.72	1.20	3.10
Hon	1961-2010	1.12	1.17	2.3	2.30	0.00	2.66
Jalo	1962-2010	1.07	1.65	0.27	0.86	0.85	2.23
Al-Jaghbub	1961-2010	0.82	1.28	0.67	0.89	0.00	2.86
Sabha	1961-2010	1.95	2.01	0.17	0.17	0.00	3.57
Tazerbou	1963-2010	2.25	2.49	0.85	0.52	1.80	2.54
Al-Kufrah	1961-2010	0.50	0.45	0.50	0.17	0.00	2.66

An analysis of the data was undertaken to ensure that the data quality and integrity was high, with any year consisting of missing data exceeding three months, and/or, any month with ≥11 missing days being removed; approaches recognised by Data Process Unit (DPU) in the LMNC. The number of missing months of climatic data is shown in Table 6.1.

6.3 VARIATIONS AND TRENDS OF ANNUAL METEOROLOGICAL VARIABLES

Data of the climatic parameters of maximum and minimum temperature, sunshine duration, relative humidity, atmospheric pressure and wind speed are key elements to estimate potential evapotranspiration based on the CROPWAT 8.0 program (see Chapter 3: 3.4.6.1 for more details).

6.3.1 Mean maximum and minimum temperature

The mean monthly and annual data for maximum and minimum temperature for 16 stations across Libya (1961-2010) is used. Changes and trends in maximum and minimum temperature were analysed in Chapter 4. Mean annual maximum and minimum temperature shows increases at most of stations. The Mann-Kendall test shows positive trends (increase) in mean annual minimum temperature at all stations (4.3.4) across Libya over the period 1945-2010. Positive trends in mean annual maximum temperature are observed at most of stations (4.4.5).

6.3.2 Precipitation (PPT)

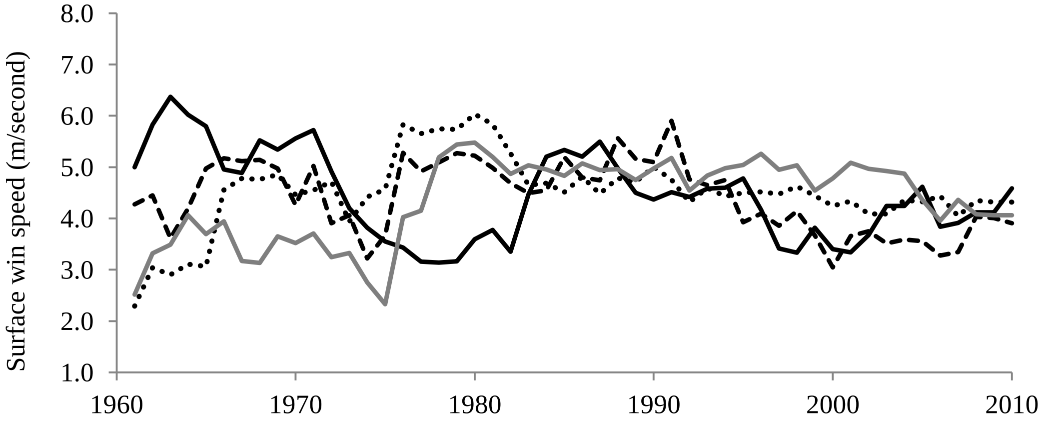
The mean monthly and annual precipitation data for 16 stations across Libya (1961-2010) is used. Changes and trends in precipitation were analysed in Chapter 5. Precipitation for the long period (1945-2010) shows increasing trends (0.166 mm a^{-1} in annual precipitation at 69% of stations with significant increases (*) at Al-Jaghbub, with significant decreases (+) at Tripoli Airport (Table 5.5).

Autumn precipitation identified a negative trend (- 0.241 mm a^{-1}) at nine stations across Libya, with significant decreases (*) at Tripoli Airport and Jalo (+). Winter precipitation showed positive trends (0.435 mm a^{-1}) at ten stations (76%), with significant increases (*) at Al-Zawia, Sirt and Al-Jaghbub. In contrast, nine stations (60%) showed slightly positive spring trends (0.049 mm; Table 5.4).

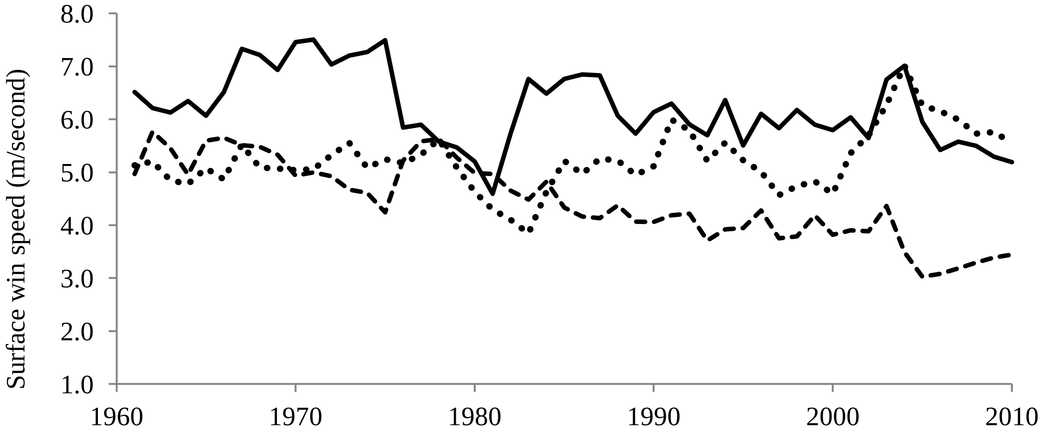
6.3.3 Wind speed (SW)

Several studies identified significant linear wind speed (SW) trends, mostly toward declining winds, global and locally (Pirazzoli and Thomasin 2003; McVicar et al., 2008; Guo et al., 2010; Vautard et al., 2010). Table 6.2 shows that the mean annual SW of stations across Libya ranges from 3.2 to 6.2 m s^{-1} (coastal stations) and from 3.1 to 4.7 m s^{-1} (inland stations). Mean seasonal SW in the coastal (inland) region ranges between; 4.6 (4.4 m s^{-1}) in winter, 4.0 (4.9 m s^{-1}) in autumn, 4.9 (4.9 m s^{-1}) in spring and 4.4 (3.9 m s^{-1}) in summer. Changes in mean annual SW for the stations during the period 1945-2010 are analysed. Figure 6.2 shows negative changes in mean annual wind speed at most of stations (1961-2010), with an increase in SW being found in seven of 16 stations.

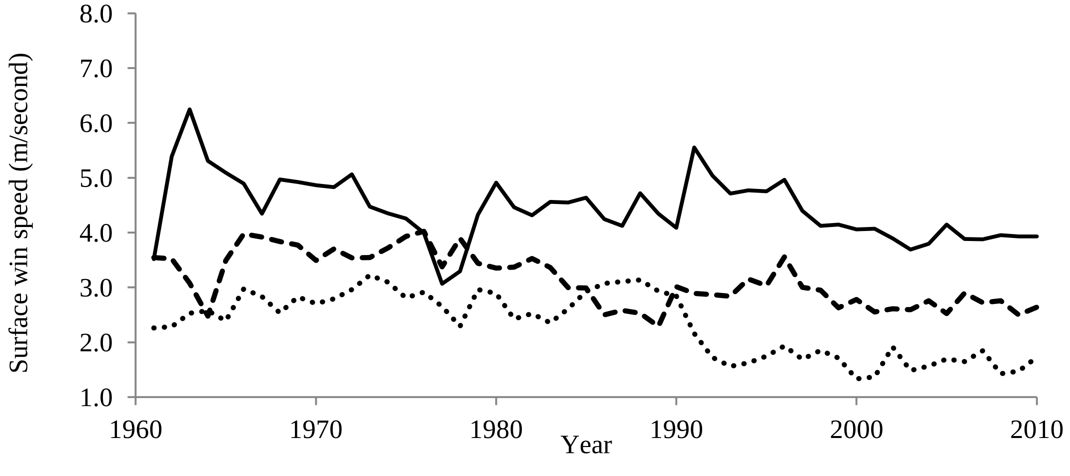
The estimation of changes in annual SW for the study stations across Libya (1961-2010) are based on the non-parametric Mann-Kendall test (Mitchell et al., 1966; Sneyers, 1999), which is used to estimate the statistical significant of SW trends within the series (chapter 3.4.4.4) An analysis of mean annual SW identified decreasing trends (– 0.0071 m s^{-1}) in coastal region and inland regions (-0.006 m $s^{-1;}$ Fig. 6.4). Table 6.2 shows decrease at nine stations with significant trends identified at all decreasing stations except Jalo. Highly significant decreases in SW are found at Shahat, Darnah, Ghadames, Al-Jaghbub, Tazerbou (***) and at Nalute and Sirt (**). The six stations indicated low positive annual average trends (0.009 m s^{-1}), with the highest 0.03 m s^{-1} (Hon), with significant increases at Binina (**) and Musratah (*).



(……. Zwarah, -------- Sirt, ——Musratah, —— Nalute)



(……. Binina, -------- Shahat, —— Darnah)



(……. Tazerbou, -------- Al-Jaghbub, —— Ghadames)

Fig. 6.2: Year to year variation of annual mean wind speed for significant changes for the period 1961-2010.

Table 6.2: Values of the Mann-Kendall statistic (Q) for climatic parameters; wind speed, relative humidity, sunshine duration and atmospheric pressure (°C), with mean annual values and statistically significant levels for the period (1961-2010)

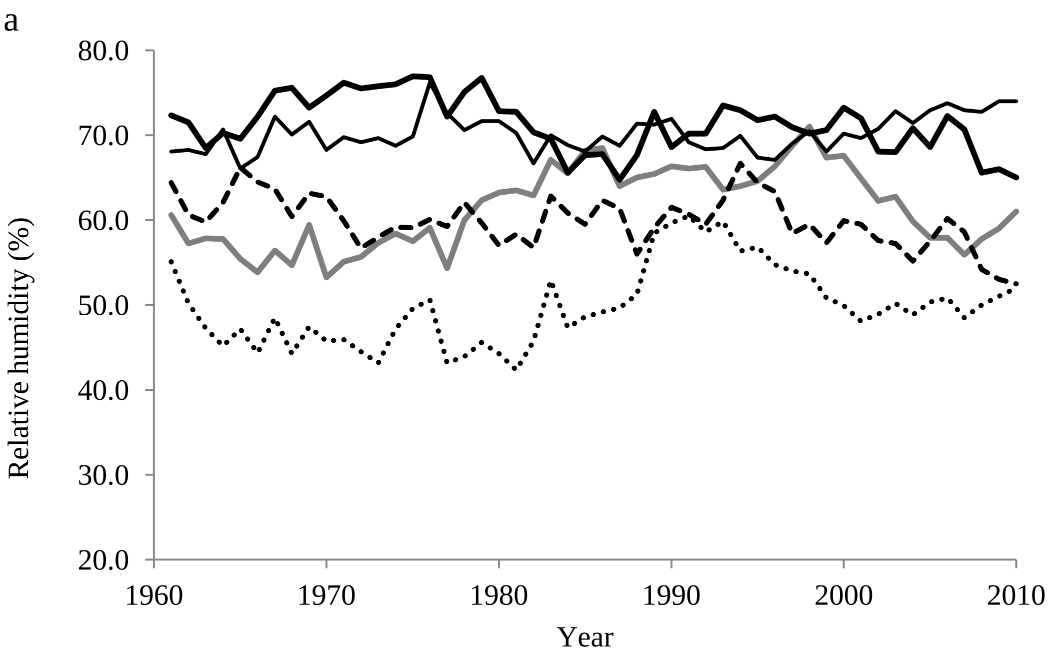
Stations	Wind speed			Relative humidity			Sun-shine duration			Atmospheric pressure		
	Mean annual (m/s)	Sig	Q	Mean annual (%)	Sig	Q	Mean annual (h/d)	Sig	Q	Mean annual (hPa)	Sig	Q
Zwarah	4.5	+	-0.007	73.0		0.035	8.11	***	0.019	1015.8		0.001
T. Airport	3.8		0.001	61.5	***	0.208	8.82		-0.002	1016.2	*	0.019
Nalute	4.5	**	-0.029	49.8	**	0.114	9.05	***	0.018	945.8	***	0.039
Musratah	4.4	*	0.023	70.0	*	0.050	8.58	**	0.012	1016.3		-0.014
Sirt	4.4	**	-0.023	70.3		0.021	8.77		-0.003	1016.2		0.001
Ajdabyia	3.2		0.004	60.2	**	-0.081	9.18	+	0.004	1016.3	**	0.044
Binina	5.2	**	0.013	64.6		0.042	8.87	*	0.009	1033.2	***	0.041
Shahat	4.5	***	-0.047	68.7		0.017	8.03		0.006	944.9		0.004
Darnah	6.2	***	-0.024	71.6	*	-0.092	7.98	***	0.039	1015.8	***	0.052
Ghadames	4.4	***	-0.022	34.7	***	0.266	9.50		0.002	1014.3	**	0.030
Hon	4.1		0.005	46.6		0.030	9.43	***	0.016	1016.0		-0.003
Jalo	3.6		-0.005	44.5	*	-0.116	9.64		0.005	1017.3	*	0.018
Al-Jaghbub	3.1	***	-0.026	49.1	***	0.177	9.74	**	0.015	1015.0	*	0.015
Sabha	4.8		0.012	33.3		-0.060	9.90	+	0.008	1015.3	***	-0.027
Tazerbou	2.3	***	-0.028	36.7		-0.046	10.29		0.003	1015.3	*	0.032
Al-Kufrah	4.3		0.007	28.5		0.021	10.62	***	0.014	1015.2	***	0.064

6.3.4 Relative humidity (RH)

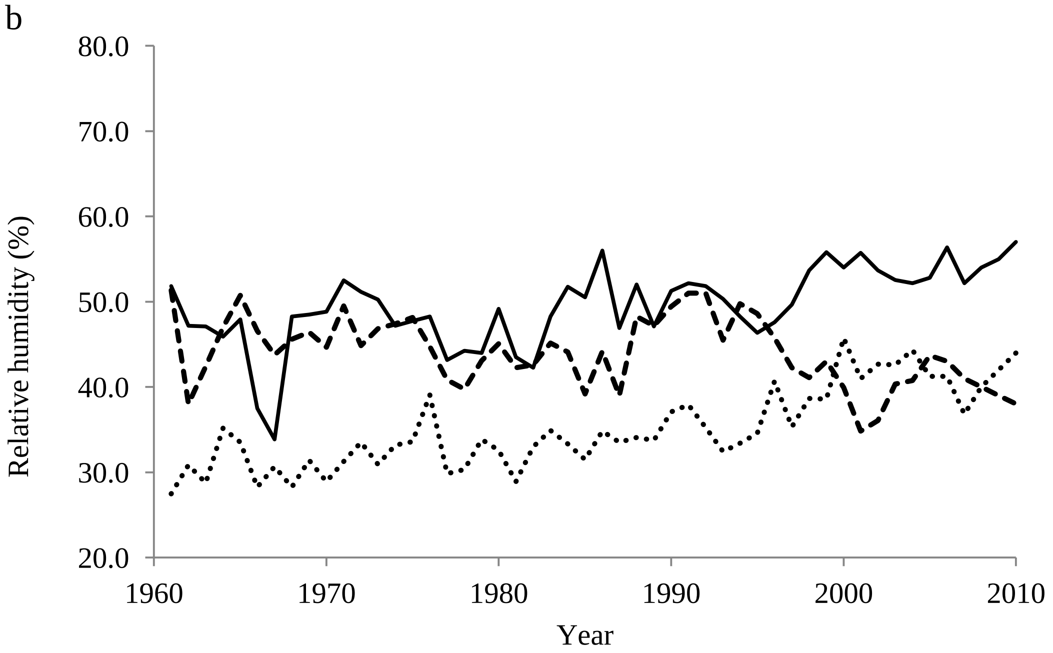
Atmospheric humidity is a key variable in determining the geographical distribution and intensity of precipitation. The relative humidity (RH) is defined as the amount of water vapour in an air sample compared to the saturation vapor pressure (Abu-Taleb et al. 2007). Moreover, the RH is a function of water vapour concentration and air temperature, directly affecting atmospheric visibility and the formation of weather phenomenon such as clouds, fog and mist (Elliott and Angell 1997). Many studies of global and local atmospheric moisture indicate little change in RH during recent years (e.g. Boucher et al. 2004; Dai 2006; Santer et al. 2007; Min et al. 2008; Willett et al. 2008; Brwon and Arthur, 2013).

The mean annual RH of stations across Libya ranges from 28.5% to 49.1% (inland stations) and from 49.8% to 73.0% (coastal stations: Table 6.2). The mean seasonal RH in coastal (inland) stations is: 69.6 (48.9%) in winter, 66.4 (41.0%) in autumn, 62.6 (32.8%) in spring, with the lowest values at both coastal (62.0%) and inland (30.1%) regions recorded in the summer season, with a mix of increases and decreases in annual relative humidity across Libya (Fig. 6.3).

According to the result of Mann-Kendall test, positive trends in mean annual RH are found at most of stations (1961-2010) ranging between 0.017% a^{-1} (Shahat) and 0.266% a^{-1} (Ghadames). An increasing trend (0.089 % a^{-1}) in mean annual RH is found at 69% of stations, with significant increases (Table 6.2) at Tripoli Airport, Ghadames, Al-Jaghbub (***), Nalute, (**) and Musratah (*).The results identified decreasing trends in mean annual RH at five stations (0.079% a^{-1}), with significant negative trends at Ajdabyia (**), Darnah and Jalo (*), and non-significant decreasing trend (0.002% a^{-1}) observed at Tripoli Airport and Sirt.



(…… Nalute, ------Ajdabyia, —— Musratah, ━━ T Airport ━━ Darnah)



(…….. Ghadames, --------Jalo, —— Al-Jaghbub)

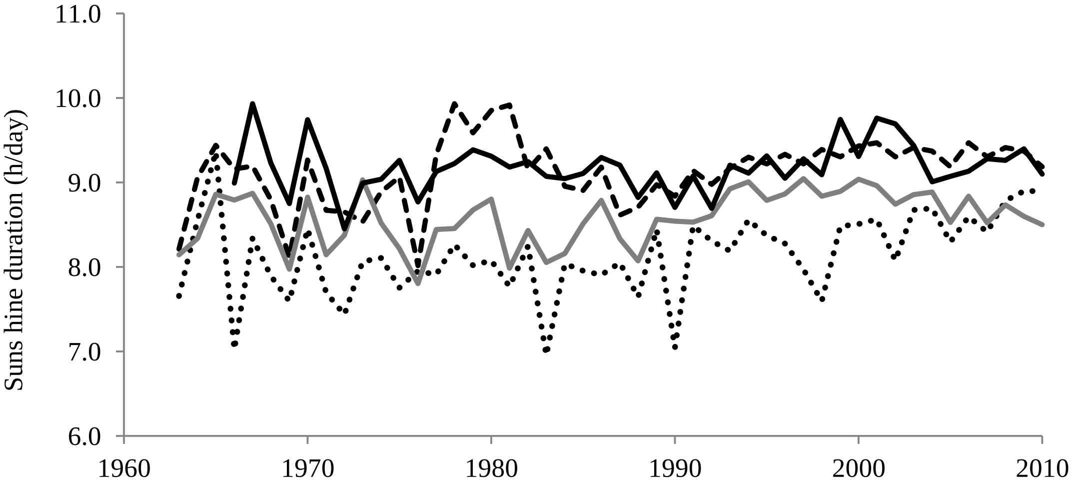
Fig. 6.3: Year to year variation of annual mean relative humidity for significant changes at a) coastal stations and; b) inland stations across Libya for the period 1961-2010.

6.3.5 Sun-shine duration (SSD)

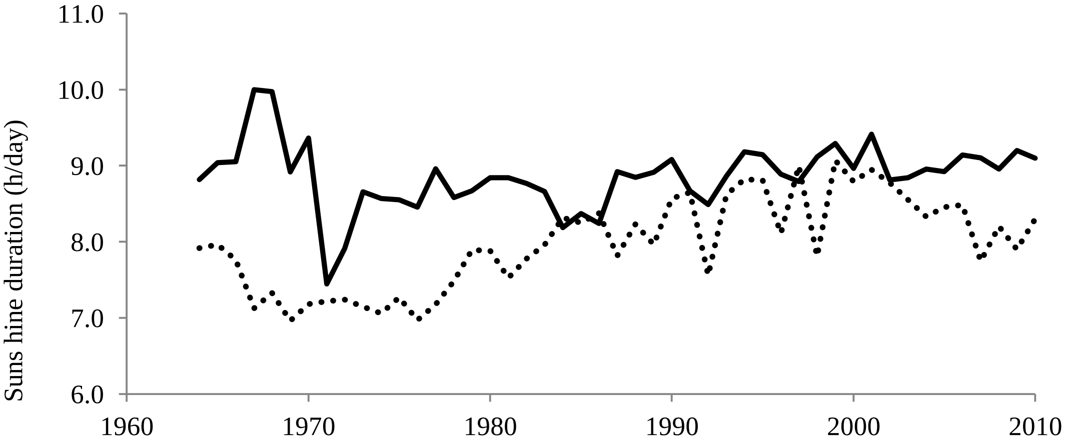
According to the WMO, (2003), sun-shine duration is defined as the period during which direct solar irradiance exceeds a threshold value of 120 watts per square meter (W/m^2). In addition, the sun shine duration (SSD) is the length of time that the ground surface is irradiated by direct solar radiation. The measurements, variations and trends of the long-term sun shine duration have been undertaken globally and locally during the last four decades (e.g. Angell, and Korshover, 1978; Morawska-Horawska 1985; Steurer, and Karl, 1991; ECSN, 1995; Aksoy, 1999; Palle, and Butler, 2001).

The present study is limited to the period 1961-2010, at the 16 synoptic stations across Libya. The mean annual SSD of stations across Libya ranges from 8.62 h d^{-1} (coastal stations) to 9.87 h d^{-1} (inland stations), with the highest (10.62 h d^{-1}) recorded in Al-Kufrah. The mean seasonal SSD at coastal (inland) stations ranges between: 6.3 (8.3 h d^{-1}) in winter, 8.1 (9.5 h d^{-1}) in autumn, 8.6 (9.5 h d^{-1}) in spring and the highest 11.3 (11.8 h d^{-1}) in summer (Table 6.2).

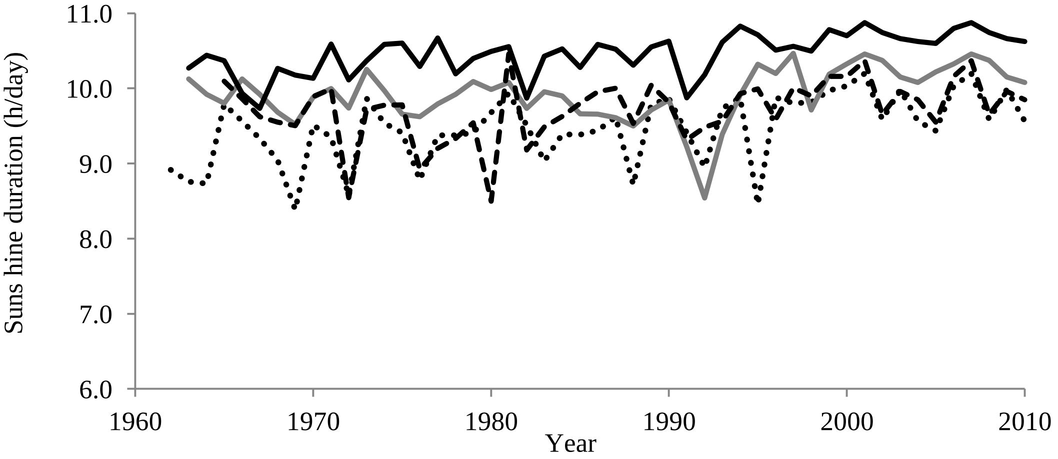
According to the Mann-Kendall test, positive trends SSD identified at most stations across Libya over the period 1961-2010 (Fig. 6.4). Increases trends are detected at all stations (average of 0.012 h d^{-1}) except Tripoli Airport and Sirt, with the highest (0.039 h d^{-1}) at Darnah (Table 6.2). **S**ignificant increases are found at ten (63%) stations, with highly significant increases at Zwarah, Nalute, Darnah, Hon and Al-Kufrah (***); Musratah and Al-Jaghbub (**), Binina (*) and weakly significant (+) at Ajdabyia and Sabha (Table 6.2).



(……. Zwarah, -------- Nalute, ——— Musratah, ——— Ajdabyia)



(……. Darnah, ——— Binina,)



(……. Hon, -------- Sabha, ——— Al-Jaghbub, ——— Al-Kufrah)

Fig. 6.4: Year to year variation of annual mean daily sunshine duration 1961-2010.

6.3.6 Atmospheric pressure (AP)

Atmospheric pressure (AP) also known as (mean sea level pressure MSLP) is used in this thesis, denoted by hPa. In recent years, there has been a significant increase in interest in global atmospheric circulation (**e.g.** Jones et al., 1997; Polyakov et al., 2003), with some researchers analysing the relationships between AP and climatic parameters such as temperature (Slonosky et al., 2001). The AP is the force per unit area exerted on a surface by the weight of air above that surface in the atmosphere of Earth, with standard AP of 1013.25 millibars (or hPa). The AP is a very important factor controlling changes in weather and climate, particularly on regional and local scales.

The present analysis of monthly means of atmospheric pressure for 16 stations across Libya for the last 50 years has been used to characterize changes and trends. In general, a spatial change in AP shows that, annual and seasonal AP in the coastal (1002.3 hPa) region is lower compared to the inland region (1015.7 hPa; Table 6.2). The mean annual AP of stations across Libya ranges from 1000.4 hPa (coastal stations) to 1015.5 hPa a-1 (inland stations: Fig. 6.5), with the lowest values (945.8 and 944.9 hPa a-1) recorded at the highest stations (621 m a.m.s.l); Nalute and Shahat. The mean seasonal AP at coastal (inland) stations ranges between 1002.6 (1020.1 hPa a-1) in winter, 1008.7 (1016.3 hPa a) in autumn, 1002.6 (1013.8 hPa a-1) in spring, with 998.7 (1011.8 hPa a) in summer.

Positive trend in AP are found at 13 of 16 (81%) stations using the non-parametric Mann-Kendall test (Fig. 6.5). Increasing trends (0.028 hPa a-1) are identified at the majority of stations, many of which were below 5.0 hPa and the greatest positive value at Al-Kufrah (6.4 hPa), with Musratah, Hon and Sabha having decreasing trends (0.147 hPa). Significant increases are found at Nalute, Binina, Darnah and Al-Kufrah (***); Ajdabyia and Ghadames (**); Tripoli Airport, Jalo, Al-Jaghbub and Tazerbou (*).

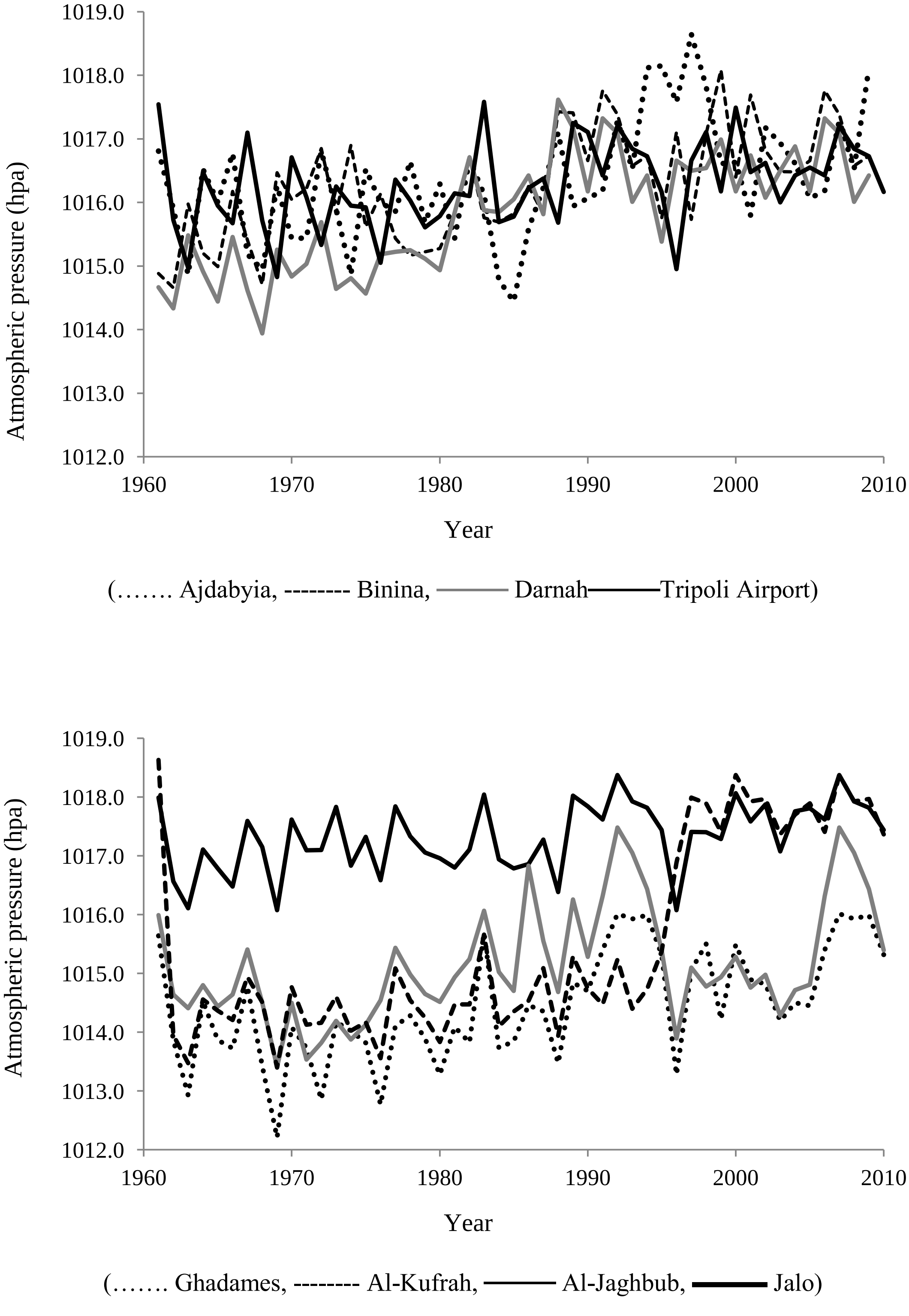


Fig. 6.5: Year to year variation of annual mean atmospheric pressure for significant changes across Libya for the period 1961-2010 at: a) coastal stations: and b) inland stations

6.4 POTENTIAL EVAPOTRANSPIRATION (PET)

Potential evapotranspiration (PET) is defined as the maximum amount of water removed from surface through the processes of evaporation and transpiration, when water availability is not limited. The PET represents the effect of climate factors and is essential for estimation of actual evapotranspiration. There are about 50 methods or models available for the estimation of PET, but these methods and models can give conflicting values and give different trends.

Thomas (2000), identified that negative trends can occur over large areas and are more pronounced than positive trends over China (1954-1993). Cohen et al. (2002) found no changes in the reference crop evapotranspiration over Israel for the period 1964-1998. According to the IPCC (2007), decreasing trends during recent decades are found in pan-evaporation over the USA (Peterson et al., 1995; Golubev et al., 2001; Hobbins et al., 2004), India (Chattopadhyay and Hulme, 1997), Australia (Roderick and Farquhar, 2004) and China (Liu et al., 2004a; Qian et al., 2006) and over smaller regions e.g. the significant increasing trends in PET identified by Abtew et al. (2011) over South Florida during the period 1948-2009. In the thesis, spatial and temporal characteristics of PET are analyzed across Libya based on the Thornthwaite and Penman-Monteith methods.

6.4.1 The Thornthwaite approach (PET-$_{TW}$)

Many studies have estimated potential evapotranspiration based on Thornthwaite approach (e.g. Rana et al., 1997; Ageena 2002; Ahmadi et al., 2008). Thornthwaite (1948) found empirically that the relationship between mean monthly temperature (T) and potential evapotranspiration adjusted to a standard month of 30 days (PET-$_{TW}$), each having 12 h of possible sunshine, was well represented by the formula (Yoshida, 1981):

$$\text{PET-}_{TW} = 1.6\,(10\,t/I)^{a}$$

Where:

PET-$_{TW}$ = potential evapotranspiration in mm

t= monthly mean temperature in °C

b = correction factor for actual day length of hours and days in a month, and

I = is annual heat index defined as the summation of the 12 monthly heat indices

(i): $i = (t/5)^{1.514}$,

a = cubic function of I,

$a = (6.75 * 10^{-7}) I^3 - (7.71\, I * 10^{-5}) I^2 + (1.792 * 10^{-2}) I + 0.49239$

6.4.1.1 Observation, changes and trends of annual potential evapotranspiration (PET_{TW})

Mean annual and seasonal potential evapotranspiration are based on the Thornthwaite formula, which is dependent on temperature which is calculated for 16 stations for the period 1945-2010 (Table 6.3). Mean annual potential evapotranspiration ($PET_{T\text{-}W}$) of stations across Libya during the period 1961-2010 is 1171.0 mm a^{-1}, ranging between 1026.1 mm a^{-1} (coastal stations) and 1357.3 mm a^{-1} (inland station), with the highest $PET_{T\text{-}W}$ estimate of 1524.3 mm a^{-1} at Al-Kufrah, which has the highest mean annual average temperature (23.3 °C).

Table 6.3 shows that the highest seasonal $PET_{T\text{-}W}$ occurs in summer, with an average rate of 47.5%; with the highest seasonal evapotranspiration percentage at Ghadames (54.3%). The winter evapotranspiration is the lowest seasonal evapotranspiration at all satiations, ranging from 3.2% (Ghadames) to 9.8% (Darnah) of the annual total evapotranspiration; with the mean seasonal $PET_{T\text{-}W}$ in spring and autumn accounting for 21.8% and 25.0% respectively.

Linear regression of $PET_{T\text{-}W}$ (1961-2010) was performed on monthly and annual estimates; for coastal and inland regions, a spatially averaged time series was analysed for all stations. For explanation of the significance of the results a t-test of regression coefficient was undertaken. Mean linear trends in the $PET_{T\text{-}W}$ show increasing trends (2.818 mm a^{-1}) for all stations, with good agreement with significant increase in temperature identified in Chapter 4, with annual trends ranging between 1.597 mm a^{-1} at coastal stations with much higher trends (4.39 mm a^{-1}) at inland stations.

The highest trend occurs at Ghadames (6.159 mm a^{-1}) followed by Al-Kufrah (6.043 mm a^{-1}), with the lowest trend found at eastern coastal stations, which do not exceed 1.263 mm a^{-1}). Significant increases (95% confidence level) are found at all western-coastal stations, except Musratah, and all inland stations, with exception of at Al-Jaghbub and Al-Kufrah.

Table 6.3: Absolute values of annual and seasonal potential evapotranspiration (mm a^{-1}); Thornthwaite evaporation for the 16 stations, with significant (95% confidence level) for the period (1961-2010).

Time series	Trend rate	Annual	Autumn	Winter	Spring	Summer
Zwarah	2.499*	1022.6	283.9	80.2	204.0	461.6
T. Airport	2.122*	1114.1	286.2	67.2	224.4	536.3
Nalute	2.049*	1027.0	248.5	52.7	210.8	514.9
Musratah	0.499	1059.5	294.2	85.0	207.8	472.6
Sirt	1.719*	1048.8	293.9	89.8	217.9	447.2
Ajdabyia	2.711*	1091.9	281.3	76.4	246.2	488.1
Binina	0.935	1038.7	272.4	77.8	221.5	467.0
Shahat	0.575	826.3	213.9	67.5	174.7	430.1
Darnah	1.263	1006.0	280.1	98.9	196.6	370.1
Ghadames	6.159*	1406.7	305.3	45.6	298.5	764.3
Hon	4.055*	1182.9	286.8	58.0	273.1	582.6
Jalo	2.044*	1329.3	304.1	57.5	291.8	665.9
AL-Jaghbub	1.924	1212.3	290.0	68.0	266.4	596.3
Sabha	5.504*	1496.4	340.5	61.9	353.2	731.5
Tazerbou	4.991*	1349.2	309.2	57.6	351.7	666.2
Al-Kufrah	6.043	1524.3	329.7	57.9	383.2	756.1

The mean monthly $PET_{T\text{-}W}$ at the coastal stations ranges from 24.7 mm M^{-1} (January) to 156.7 mm M^{-1} (August), with inland stations ranging from 15.3 mm M^{-1} (January) to 243.1 mm M^{-1} (July), where August and July represents approximately 15.5% and 17.3% respectively of the annual total $PET_{T\text{-}W}$ at both coastal and inland regions (Table 6.4), during the period 1961-2010.

Table 6.4: Values of the trend rate for mean monthly PET_{T-W}, with statistically significant levels (mm/month) in coastal and inland regions for the period 1961-2010

	Coastal region			Inland region		
	Mean monthly (mm)	Trend rate (mm/M)	Sig.	Mean monthly (mm)	Trend rate (mm/M)	Sig.
January	24.7	0.017		15.3	-0.042	*
February	26.8	-0.050	*	22.5	-0.092	*
March	42.5	0.017		50.2	0.007	
April	64.9	0.063		100.5	0.147	
May	102.1	0. 140		172.4	0.213	
June	136.5	0.127		235.6	0.553	*
July	154.3	0.273	*	243.1	1.042	*
August	156.7	0.322	*	229.9	1.142	*
September	127.7	0.352	*	171.1	0.900	*
October	93.6	0.206	*	102.8	0.269	*
November	52.8	0.014		42.2	-0.019	
December	30.8	0.010		19.0	-0.048	*

Positive trends in monthly PET_{T-W} are found for all months in the coastal region, with the exception of February (-0.050 mm M^{-1}), with the highest monthly trends occurring in September and August. Significant (95% confidence level) trends are found in February and during the warmest months; July-October in the coastal region (Fig. 6.6). Positive trends in monthly PET_{T-W} are found during all months for the inland region (0.534 mm M^{-1}), except during the coldest months, November-February (-0.050 mm M^{-1}). The highest trend occurs in July (1.042 mm M^{-1}) and August (1.142 mm M^{-1}). Significant (95% confidence level) trends of PET_{T-W} in the inland region have been shown in most months, with exceptions in March-May and November (Fig. 6.6).

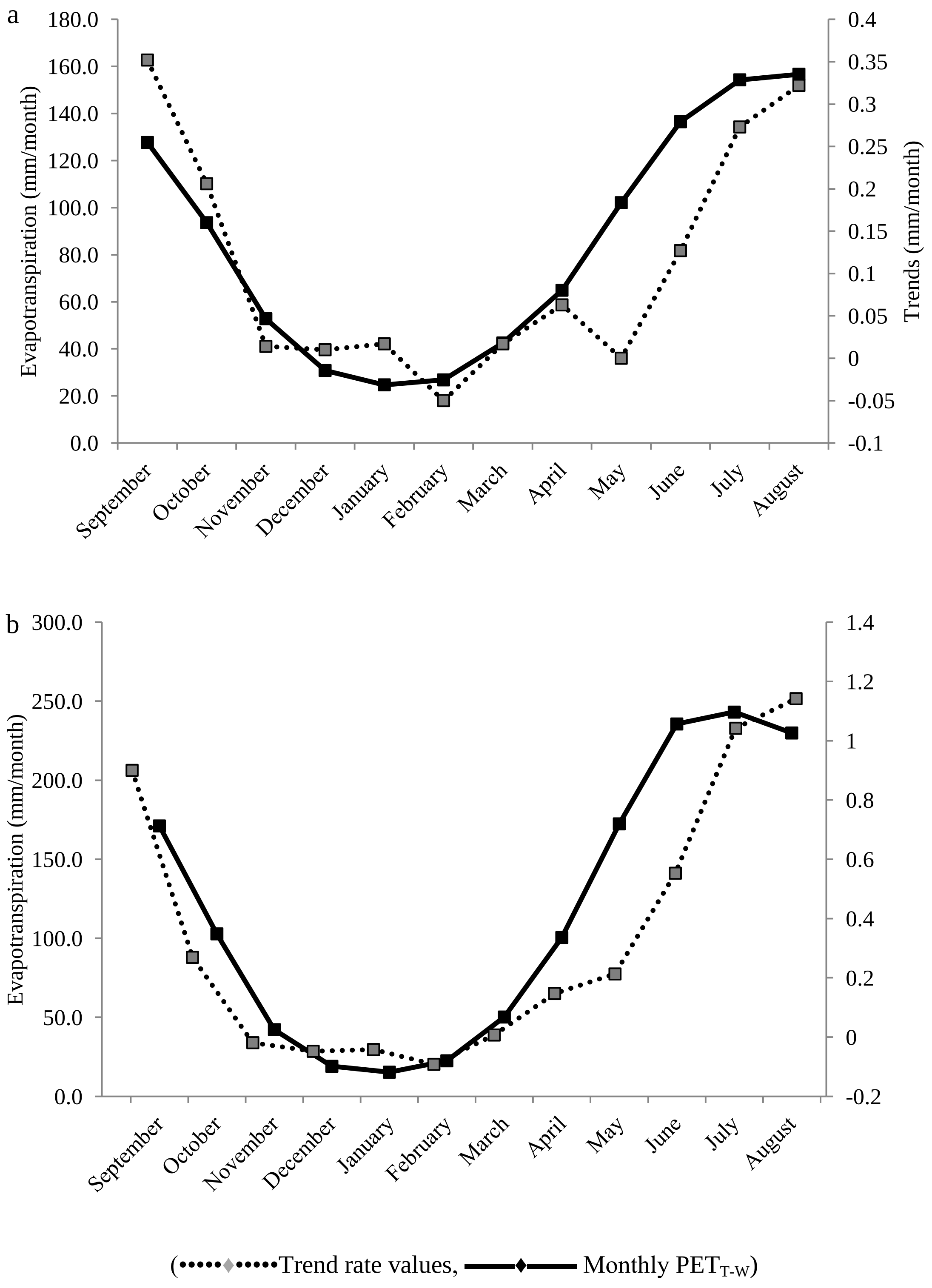


Fig. 6.6: Mean monthly $PET_{T-W,}$ with trend rate at a) coastal region and; b) inland region across Libya (1961-2010).

6.4.2 The Penman-Monteith approach (PET-$_{TW}$)

The P-M method (Jensen et al., 1990) requires data for the following variables for calculation: sunshine duration (hours), humidity (percentage) and wind speed (km), minimum and maximum temperature (°C) and atmospheric pressure (Hectopascal-hPa); unfortunately several of these are not recorded before 1961 at most meteorological stations across Libya. Therefore, the geographic density of stations allowing for ET calculation is restricted to the limited number of 16 synoptic stations distributed across Libya during the period of study (1961-2010).

The P-M method based on CropWat 8.0 software program for water resources is applied to estimate potential evapotranspiration. The CropWat program has been applied by a number of researchers e.g. Arnold 2008; Abdalla et al., 2009; Raja 2010 in the examination of evapotranspiration. Mean average monthly maximum and minimum temperature, sunshine duration, wind speed and relative humidity are used within the CropWat 8.0 software program (3.4.6.). All calculation procedures used in CropWat 8.0 are based on the FAO publications Series in Irrigation and Drainage paper, No. 24 (1977) and FAO Irrigation and Drainage Paper No. 56 Crop Evapotranspiration 56 (2009). According to the FAO (Allen et al. 1998), the Penman-Monteith method for *PET* (mm/d) for a discussion of the application please see Chapter 3 (Appendix 3.12), it can be expressed as:

$$\frac{0.408\,\Delta\,(Rn - G) + \gamma\,\frac{900}{T + 273}\,u_2\,(e\text{ş} - e_{\mathrm{a}})}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

Where,

PET	reference crop evapotranspiration (mm/d),
Rn	net radiation at crop surface (MJ/ m^{2}d),
G	soil heat flux (MJ/ m^{2}d),
T	average temperature (°C),
U$_2$	wind speed measured at 2m height (m/s),
Δ	slope vapour deficit (kPa),

γ psychometric constant (kPa °C),

$(e_a - e_x)$ vapour pressure deficit (kPa),

900 conversion factor

6.4.2.1 Observation, changes and trends of potential evapotranspiration ($PET_{P\text{-}M}$)

The mean annual and seasonal of potential evapotranspiration based on the P-M equation (using the CropWat 8.0 software program based on Allen et al. 1998; Raja 2010) was estimated for 16 stations for the period 1961-2010 (Table 6.5; see Chapter 3: Appendix 3.12 for practical example).

The mean annual potential evapotranspiration ($PET_{P\text{-}M}$) of stations across Libya during the period 1961-2010 ranges between 2052.5-1703.5 mm a^{-1} at coastal stations and 2501.1 mm a^{-1} for the inland station, with the highest estimated $PET_{P\text{-}M}$ of 3026.3 mm a^{-1} at Sabha. Table 6.5 shows that the highest seasonal $PET_{P\text{-}M}$ is summer, with an average rate ranges between 33% and 39% of annual total evapotranspiration with the lowest in winter (13%). The mean seasonal $PET_{P\text{-}M}$ of spring (28%) and autumn (23%) are similar.

Linear regression of $PET_{P\text{-}M}$ (1961-2010) was performed on monthly and annual estimates. For coastal and inland regions, a spatially averaged time series was analysed from all stations. For explanation of the significance of the results a t-test of regression coefficient was applied. Mean linear trends for the nine coastal stations show that, the $PET_{P\text{-}M}$ rates have a decreasing annual trend at five coastal stations (-1.863 mm a^{-1}; Fig. 6.7), with the highest trend (-5.555 mm a^{-1}) at Nalute, with significant decreases (95% confidence level) at the stations located at the highest elevations, Shahat and Nalute (621 m a.m.s.l).

Increases trends (Fig. 6.7) are identified at four coastal stations (2.733 mm a^{-1}), with significant (95% confidence level) trends at Zwarah, Musratah and Ajdabyia. The mean linear trends for the inland region illustrate decreases (-7.101 mm a^{-1}) in annual

$PET_{P\text{-}M}$ at four stations, with highest value (-11.173 mm a^{-1}) at Tazerbou, with significant (95% confidence level) decreases at Al-Jaghbub and Tazerbou. Increasing trends are identified at three inland stations (2.879 mm a^{-1}), with no positive significant trend at any inland stations.

Table 6.5: Absolute values of annual and seasonal $PET_{P\text{-}M}$ (mm a^{-1}) for the 16 stations, with significant (95% confidence level) for the period (1961-2010)

Time series	Trend rate	Annual	Autumn	Winter	Spring	Summer
Zwarah	2.867 *	1512.4	373.8	245.4	380.5	512.7
T. Airport	-0.448	1851.3	416.7	219.3	493.0	722.2
Nalute	-5.555 *	2054.1	462.3	264.1	547.2	781.2
Musratah	2.899 *	1585.6	381.1	240.6	412.2	551.7
Sirt	-0.131	1599.5	389.9	251.7	424.8	533.2
Ajdabyia	3.655 *	1813.1	412.2	217.3	520.3	663.3
Binina	1.511	1865.3	443.4	217.2	517.3	687.3
Shahat	-2.960 *	1541.0	343.8	181.1	407.6	608.5
Darnah	-0.223	1509.4	365.2	245.9	399.3	519.0
Ghadames	-6.834 *	2757.0	619.8	304.1	763.2	1069.9
Hon	3.400	2375.3	529.4	301.6	684.4	860.0
Jalo	-1.636	2332.4	513.0	306.0	665.6	847.8
AL-Jaghbub	-8.759 *	2128.2	453.4	257.7	612.4	804.7
Sabha	3.640	3026.3	697.2	363.6	868.5	1096.9
Tazerbou	-11.173 *	2133.1	479.4	285.8	636.0	731.9
Al-Kufrah	1.598	2756.5	641.1	363.3	779.6	972.5

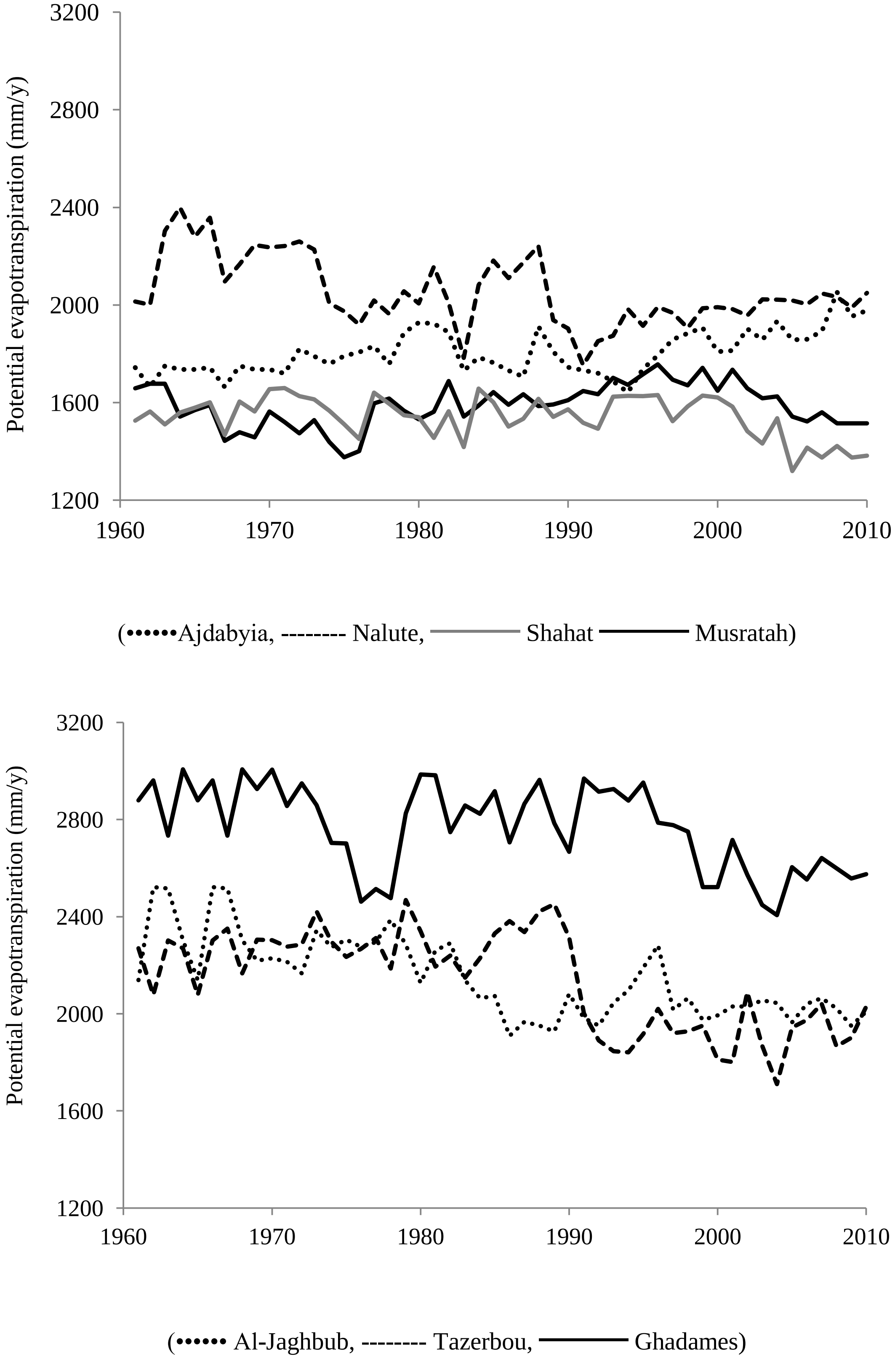


Fig. 6.7: Time series of significant trends in $PET_{P\text{-}M}$ for a) coastal stations; and; b) inland stations during the period 1961-2010.

6.4.2.2 Changes and trends of monthly potential evapotranspiration

The mean monthly $PET_{P\text{-}M}$ during the period 1961-2010 ranges from 71.4 mm M^{-1} (January) to 212.1 mm M^{-1} (July) at the coastal stations and between 96.2 mm M^{-1} (January) to 3118.8 mm M^{-1} (July) at inland stations; where July represents approximately 12.4% of the annual $PET_{P\text{-}M}$ at both coastal and inland regions (Table 6.6).

Table 6.6: Values of the trend rate for mean monthly $PET_{P\text{-}M}$, with statistically significant levels (mm/month) in coastal and inland regions for the period 1961-2010

	Coastal region			Inland region		
	Mean monthly (mm)	Trend rate (mm/M)	Sig.	Mean monthly (mm)	Trend rate (mm/M)	Sig.
January	71.4	-0.123		96.8	-0.118	
February	83.6	-0.263	*	118.7	-0.248	*
March	117.5	-0.116		183.6	-0.121	
April	150.4	0.024		239.2	0.114	
May	187.9	-0.061		292.8	0.201	
June	206.7	0.193	*	308.0	0.108	
July	212.1	0. 29		311.8	0.249	
August	202.4	0.054		292.2	0.438	
September	168.1	0.170		246.4	0.534	*
October	134.7	0.233		190.8	0.286	
November	95.9	-0.069		124.7	0.129	
December	76.4	-0.180	*	96.2	-0.162	*

Negative trends in $PET_{P\text{-}M}$ (0.150 mm M^{-1}) are found November-June, with the exception for April at coastal stations (Fig. 6.8), with the highest value (-0.263 mm M^{-1}) in February. Significant decreases (95% confidence level) are found in February, June and December. Positive trends (0.120 mm M^{-1}) are identified during the warm months July-October and in April, with the highest value (0.233 mm M^{-1}) in October (not significant).

Positive trends in monthly PET_{P-M} prevail at inland stations during the period April-November (0.257 mm M^{-1}; Fig. 6.8), with the highest rates (0.543 mm M^{-1}) in September (*). Negative trends (-0.163 mm M^{-1}) are found in the coldest months (December-March), with significant (95% confidence level) decreases in (February and December) and at inland stations in February, September and December.

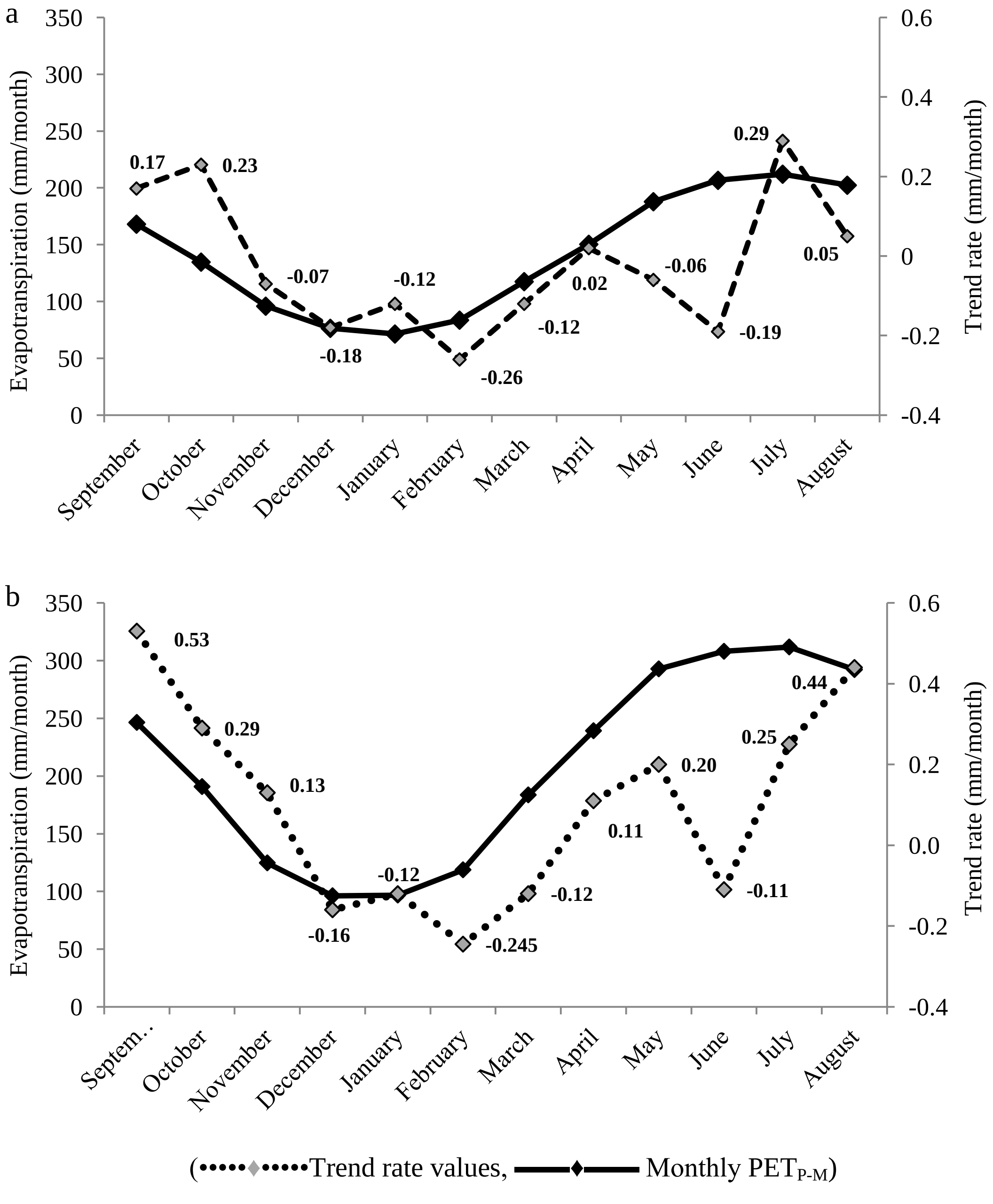


Fig. 6.8: Mean monthly PET_{P-M}, with values of trend rate values at a) coastal region and; b) inland region across Libya (1961-2010)

6.4.2.3 A comparison of two annual potential evapotranspiration methods of $PET_{T\text{-}W}$ and $PET_{P\text{-}M}$ for coastal and inland region across Libya (1961-2010).

The temporal patterns of the $PET_{T\text{-}W}$ and $PET_{P\text{-}M}$ data for the coastal region are in good agreement, particularly during most of the period 1980-2000, with a couple of poorer years, particularly prior to 1970 and after 2000 (Fig. 6.9a). The $PET_{P\text{-}M}$ (1961-2010) shows considerably higher evapotranspiration compared to $PET_{T\text{-}W}$ at both annual and seasonal scales for all stations, with an annual average rate of $PET_{T\text{-}W}$ ranging from 966.8 mm a^{-1} to 1133.6 mm a^{-1} and between 1174.9 mm a^{-1} to 1597.2 mm a^{-1} in $PET_{P\text{-}M}$ (Fig. 6.9b).

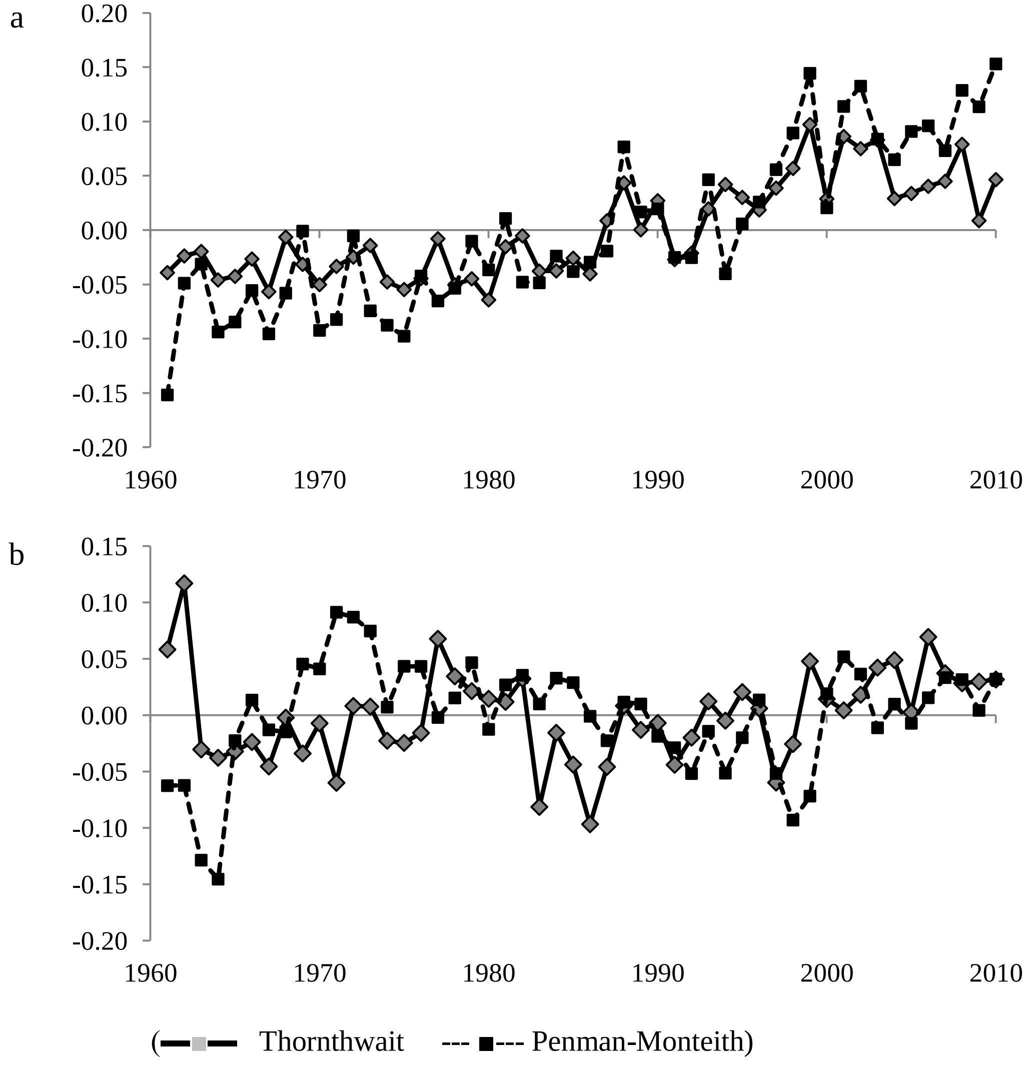


Fig. 6.9: Normalized annual potential evapotranspiration anomalies of Thornthwait and Penman-Monteith formula at; a) coastal region and: b) inland region for the period 1961-2010

The temporal patterns of PET_{T-W} and PET_{P-M} data for the inland region are in reasonable agreement over most of the period 1961-2010, with a couple of poorer years during the first 30 years (1961-1990). There are greater differences for the inland region compared to the coastal region, with more accurate capture during the period after 1990. The Pearson correlation coefficients are calculated based on the two methods, weakly positive values at ten of the 16 stations are found ranging from 0.07 to 0. 43.

6.4.2.4 Relationships between PET_{P-M} and climate variables

The meteorological factors which determine evapotranspiration (ET) are weather parameters which provide energy for vaporization and removal of water vapour from the surface. The principal weather parameters that contribute to changes in PET rates are: temperature, wind speed, relative humidity, sunshine duration, precipitation and atmospheric pressure which are assessed for the 16 synoptic stations (1961-2010).

A change in ET is mainly dependent on moisture supply, energy availability and wind speed and direction (IPCC, 2007).

Annual correlations

To analyze the meteorological parameters that contributed most to the observed reduction of PET_{P-M} rates across Libya, correlations between seasonal and annual PET_{P-M} and mean meteorological variables used to estimate PET_{P-M} were calculated for the last 50-years 1961-2010.

The annual PET_{P-M} is strongly positively correlated with the annual mean wind speed (WS) at inland stations, (r = 0.72; Fig. 6.10). The mean annual relative humidity (RH) and atmospheric pressure (AP) are negatively correlated with the annual PET_{P-M} in the inland region (Table 6.7).

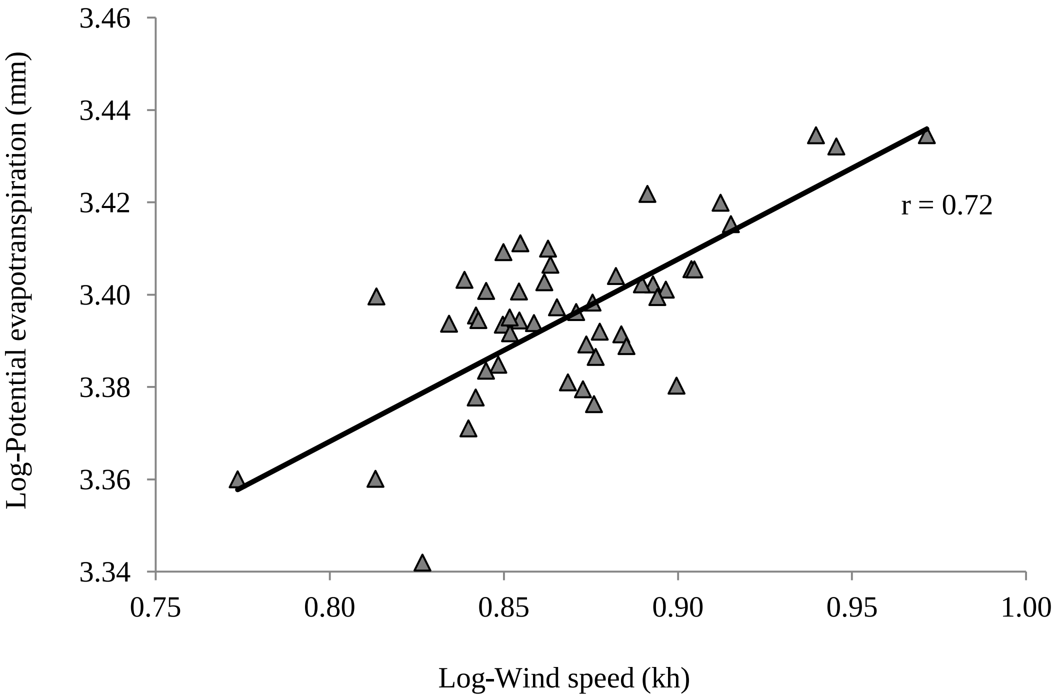


Fig. 6.10: The annual $PET_{P\text{-}M}$ as a function on wind speed of the inland stations for the period 1961-2010

The mean annual maximum temperature ($T_{.Max)}$ is strongly correlated (positively) with annual $PET_{P\text{-}M}$ (*r*=0.58) in the coastal region; while strongly negatively correlated with annual mean relative humidity (RH) at coastal stations (*r* = 0.56; Table 6.7). The results show little relationship between $PET_{P\text{-}M}$ and sun-shine duration (SSD).

The results indicate that RH and $T_{.Max}$ are the most important factors influencing annual $PET_{P\text{-}M}$ at coastal stations and WS at inland regions. The decreasing trend in $PET_{P\text{-}M}$ was likely caused by an increase in $T_{.Max}$ and a decrease in the RH for the coastal region (northern-Libya). Analysis of the impacts of meteorological variables indicates that the increase in $PET_{P\text{-}M}$ most likely results from an increase in WS for inland region (southern-Libya).

Table 6.7: Correlation coefficient *(r)* between PET_{P-M} and meteorological parameters

Stations	WS	RH	SSD	AP	PPT	T.min	T. max
			Coastal region				
Annual	-0.01	-0.56	0.14	0.00	-0.08	0.11	0.58
Autumn	0.07	-0.70	0.03	0.16	-0.51	0.50	0.78
Winter	-0.25	-0.65	0.05	-0.53	-0.06	0.06	0.51
Spring	-0.18	-0.68	0.22	0.06	-0.31	-0.12	0.76
Summer	-0.07	-0.66	0.01	-0.46	-0.10	-0.04	0.70
			Inland region				
Annual	0.72	-0.33	0.29	-0.29	-0.17	-0.17	0.04
Autumn	0.51	0.23	0.17	-0.13	-0.25	0.07	0.32
Winter	0.24	-0.13	0.04	-0.61	-0.35	-0.35	0.52
Spring	0.25	-0.27	0.21	-0.47	-0.03	-0.13	0.46
Summer	0.59	0.04	-0.05	-0.23	-0.09	-0.06	0.18

Seasonal correlations

Correlations between seasonal PET_{P-M} and meteorological variables used to estimate PET_{P-M} were analysed for the last 50-years (1961-2010). In the coastal region, seasonal PET_{P-M} is strongly negatively correlated with the all mean seasonal RH, particularly, in autumn (-0.70; Fig. 11c) and strongly positive correlated with T.max, particularly, in spring (0.76) and summer (0.70; Fig. 6.11a and b).

Strongly correlations are noted in autumn PPT (negative) and T. min (positive) relative to the other months (Table 6.7). At the inland region, seasonal PET_{P-M} is strongly negatively correlated with the all mean seasonal AP, *r* of -0.61 (winter) and 0.47 (spring); while strongly positively correlated with WS, *r* of 0.59 (summer) and 0.51 (autumn). In general, PET_{P-M} is less responsiveness to SSD and SW in the coastal region relative to the inland region (Table 6.7). The results of seasonal correlations indicate that the seasonal SW is more effectiveness in inland stations, with the RH is in coastal stations, where the climate variables of SSD, T. min and T. max having the same effect.

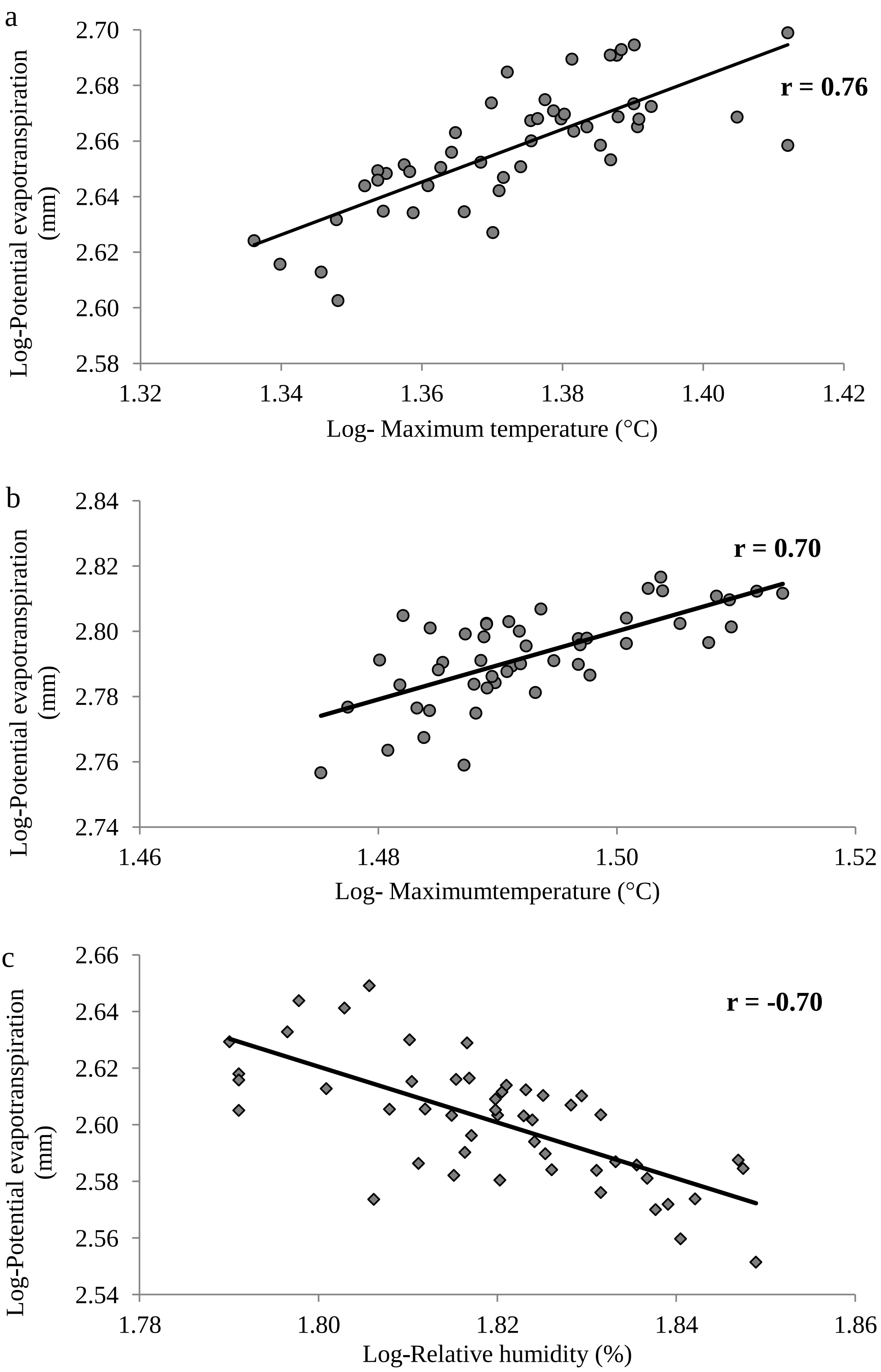


Fig. 6.11: The seasonal $PET_{P\text{-}M}$ as function of; a) spring T. max for the coastal region; b) summer T. max; c) autumn RH for the coastal region for the period 1961-2010.

6.5 ACTUAL EVAPOTRANSPIRATION (AET)

Actual evapotranspiration (AET) is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration. According to the Third Assessment Report 2001 (IPCC, 2001) increasing AET during the second half of the 20th century has been found over most dry regions of the USA and Russia. Golubev et al. (2001) identified that increasing AET results from increased precipitation and larger atmospheric moisture demand due to higher temperature, a finding supported by the IPPC (2001).

The most important methods for measuring AET are summarized by Rana and Katerji (2000). The methods can be divided depending on the purpose into hydrological, micrometeorological and plant physiological, with Rana and Katerji (2000) suggesting three approaches for ET estimations: methods based on the analytical modelling of ET, methods based on soil water balance modelling and methods where the AET is deducted from the evapotranspiration of a reference surface. All these methods have their advantages and disadvantages.

For example, a weighing Lysimeter can provide detailed information about the water balance; however, it is practically and economically impossible to measure ET over widespread areas for long time periods (Xu et al., 2006). Therefore, AET is usually estimated through less complex physically-based or empirical approaches where available input data exists, such as long-term water balance, a fraction of PET estimates, or through hydrological water balance models using soil moisture functions. The P-M method considers aerodynamic resistance and surface resistance and has been successfully used to estimate AET from different land covers (Allen et al., 1998). The method is based on the water consumption of a crop estimated as a fraction of the reference evapotranspiration; it depends on the accuracy of the reference chosen, ET_{Ref} estimation and the crop coefficient (Rana and Katerji, 2000). The most used method to estimate ET_{Ref} is based on the P-M model. The P-M method is used as the standard for comparison and for estimating the actual evapotranspiration (ET_{Ref}) depending on the accuracy of the reference chosen estimation and crop coefficient (KC; Rana and Katerji, 2000).

Irmak et al. (2012) concluded that P-M model method is the most important, using physically-based equations to estimate ET_{Ref}, which requires a number of meteorological variables to solve for grass- or alfalfa-reference evapotranspiration.

The methods used in estimating the AET utilize hydrological and micrometeorological methods; these are commonly used globally, but are rarely used in Libya, as a lack of data reflects the limited instillation of the required equipment. However, the plant physiological method is a widely used method. The PET is gradually being replaced with ET_{Ref} to conform to standard terminology (Allen et al. 1994a, b), particularly in the field of water resources management and irrigation applications according to Senay et al. (2008).

In this thesis, crop evapotranspiration (PE_{Ref}) is analysed as a compensation for AET that based on PET that can be estimated based on a standard crop coefficient (KC) and PET obtained by the P-M method which is the most often used method of estimating evapotranspiration. For the estimation of AET, the UN Food and (FAO) recommended using the P-M model to estimate *reference* evapotranspiration (ET_{Ref}) on croplands (Allen et al., 1998). This method overcomes the shortcoming of previous FAO-24 Penman method and previous PET estimates more consistently used worldwide (Jensen et al 1990; Smith et al. 1996). The evaluation of crop water requirements (PET) is based on the ET_{Ref} (Jensen 1996; Allen at al. 1998) and the crop coefficient approach. Additionally, and in order to estimate the actual water consumption by crops (AET) Kotsopoulos, et al., 2003.

ET_{Ref} is estimated using the KC approach whereby the effect of the various weather conditions is incorporated into PET and the crop characteristics into the KC coefficient. However, ET_{Ref} is calculated by multiplying $PET_{P\text{-}M}$ by standard crop (KC), a coefficient expressing the difference in ET between the cropped and reference grass surface following on this model:

$$ET_{Ref} = KC * PET_{P\text{-}M} \qquad \text{[Equation 6.3]}$$

The KC values are dependent on type of crop and changing characteristics of crop over the growing season and also on the climate parameters in particular, humidity and wind speed.

KC values for the various crops and growth stages, is dependent on the climate and, in particular, on the relative humidity and the wind speed. The alfalfa crop is used as a reference crop and it is applied to estimate the field crop of ET_{Ref}. The ET_{Ref} for 16 coastal and inland synoptic stations across Libya for the period1961-2010 has been estimated based on Equation 6.3.

6.5.1 Changes and trends in the Reference evapotranspiration (ET_{Ref})

Reference evapotranspiration has been studied at different scales, with many studies identifying variable evapotranspiration trends during the last century, with significant trends in the ET identified globally (Kousari and Ahani, 2012; Moratiel et al., 2011; Irmak et al., 2012) over the last few decades. According to the fourth IPCC Assessment Report (IPCC, 2007) ET has increased over the last 100 years between 30 and 85°N, with a remarkable increase between 10°N to 30°N during the first 50 years of the last century (1900-1950), but declined after about1970. An increasing trend in actual evapotranspiration over the last 50 years over most dry region of the USA and Russia is identified by (Golubev et al., 2001)

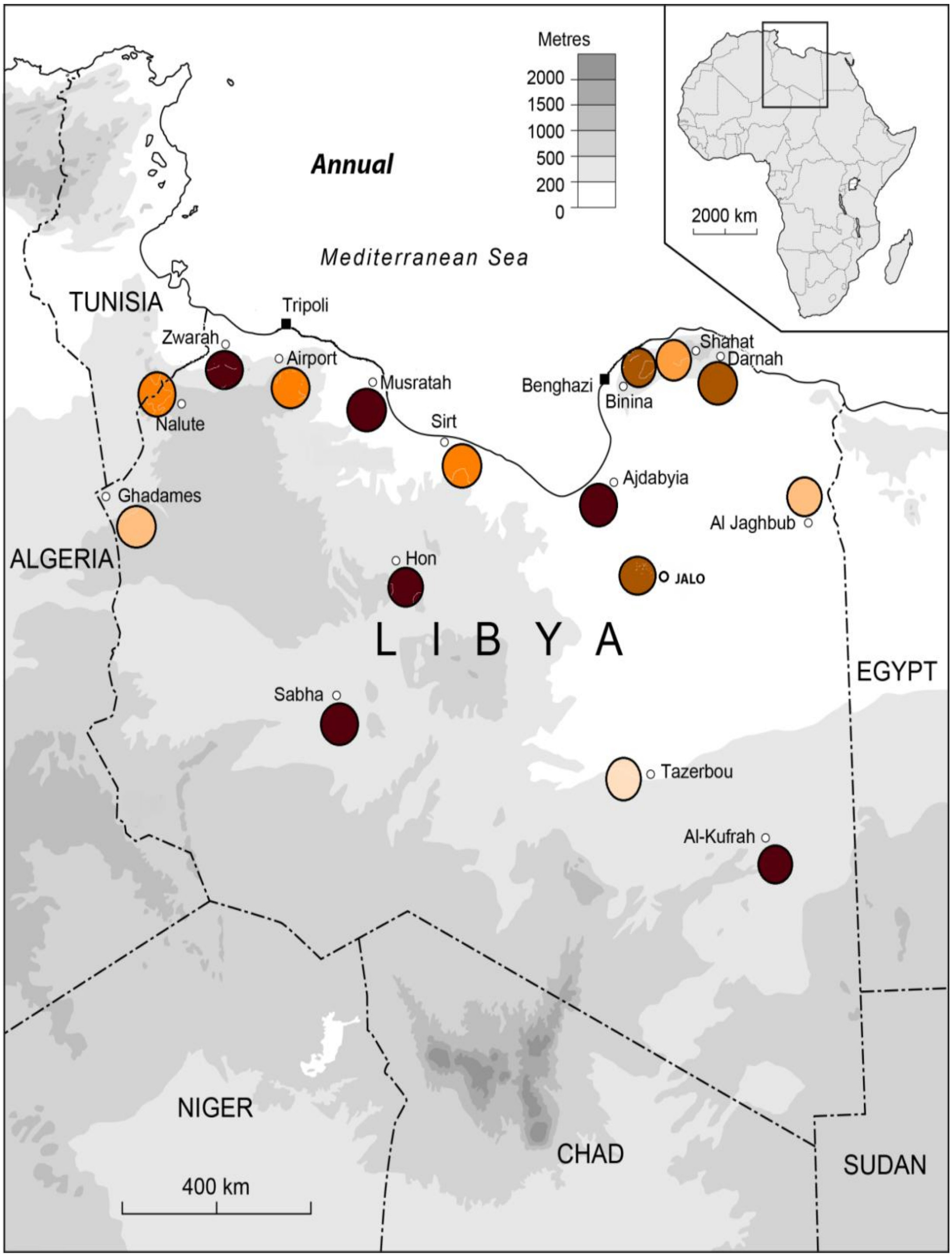
6.5.1.1 Annual changes and trends

The mean annual total ET_{Ref} showed relatively high fluctuations in stations; 1285.5 mm (Zwarah) and 1694.2 (Nalute) and within regions, ranging from 1444 mm to 2171 mm at coastal and inland region respectively, with the highest (2374 mm) at Sabha (Table 6.8). According to the Mann-Kendall test, the mean average trend in annual ET_{Ref} across Libya increases at1.942 mm a^{-1}, with an average increase of 0.053 mm a^{-1} at coastal region and decrease of -1.836 mm a^{-1} at inland region, with the highest (-8.769 mm a^{-1}) at Tazerbou. Spatial distribution of annual trends in ET_{Ref} of 16 stations for 50 years (1961-2010) is presented in Fig. 6.12.

Table 6.8: Values of the Mann-Kendall statistic (Q) for mean annual (mm a^{-1}) and seasonal (mm/seasonal) total of references evapotranspiration, with statistically significant levels at 16 synoptic stations across Libya (1961-2010)

Time series	Annual			Autumn			Winter			Spring			Summer		
	Mean mma^{-1}	Sig	Q	Mean mms^{-1}	Sig	Q	Mean mms^{-1}	Sig	Q	Mean mms^{-1}	Sig	Q	Mean mms^{-1}	Sig	Q
Zwarah	1285.5	**	2.230	317.8	**	0.903	208.6	**	-0.738	323.4		0.263	435.8	*	0.751
T. Airport	1573.6		-0.449	354.2		0.262	186.4	***	-1.456	419.1	**	-1.426	613.9		0.006
Nalute	1694.2	**	-5.187	330.5		-0.477	224.5		0.333	465.1		0.158	674.2	**	-2.549
Musratah	1347.8	*	2.498	323.9	***	1.477	204.5		-0.291	350.4	+	-0.569	468.9		0.233
Sirt	1359.6		-0.851	331.4	*	0.503	213.9		0.197	361.1	+	0.743	453.2		-0.216
Ajdabyia	1541.2	***	3.129	350.4	***	1.078	184.7		0.158	442.3		-0.026	563.8	***	1.203
Binina	1585.5		0.971	376.9	+	0.721	184.6	***	-0.832	439.7	+	-0.697	584.2		0.039
Shahat	1309.9	*	-2.024	292.2		-0.202	153.9		-0.519	346.5		-0.341	517.2	+	-0.680
Darnah	1300.0		0.157	310.4		0.161	209.0	***	-1.695	339.4	**	-1.911	441.1		0.257
Ghadames	2343.5	***	-6.462	526.9		-0.422	258.5		-0.425	648.7		0.436	909.4	**	-2.217
Hon	2019.0	**	2.930	450.0	***	1.562	256.4		-0.137	581.7		0.227	731.0	*	1.032
Jalo	1982.6		0.195	436.0		0.670	260.1	***	-1.004	565.8	***	-1.768	720.7		-0.188
AL-Jaghbub	2128.2	***	-6.118	453.4		-0.257	257.7		-0.250	612.4		0.969	804.7	***	-2.049
Sabha	2374.3	+	2.216	592.6	*	1.255	309.1	***	-1.607	738.2	**	-2.101	932.4	+	0.872
Tazerbou	2010.8	***	-8.769	407.5	***	-1.637	242.9		0.061	540.6		0.474	622.1	***	-3.212
Al-Kufrah	2343.0		3.156	544.9		1.484	308.8		0.079	662.7	*	0.470	826.7		0.825

The significance levels tested are 0.001 (***), 0.01 (**), 0.05 (*) and 0.1 (+). If the cell is blank, the significance level is >0.1



●: ≥ -6.0 mm a^{-1}, ●≥ -6.0 and ≤ -4.0 mm a^{-1}, :● -4.0 and ≤ -2.0 mm a^{-1}

●: ≥ -2.0 and ≤ 0.0 mm a^{-1}, ●≥ 0.0 and ≤ 2.0 mm a^{-1}, : ● 2.0 mm a^{-1}

Fig. 6.12: Spatial distribution of annual references evapotranspiration at stations across Libya, trend values are given as (mm a^{-1}).

The annual trend analyses of $ET_{Ref,}$ in the coastal region identifies an increase at five coastal stations (1.797 mm a^{-1} with significant increases at Ajdabyia (***), Zwarah (**) and Musratah (*). Declining trends in annual ET_{Ref} (2.128 mm a^{-1}) are found at four coastal stations, with the lowest values (-5.187 and -2.024 mm a^{-1}) recorded at the highest elevations stations Nalute (**) and Shahat (*).

Ghadames, Al-Jaghbub and Tazerbou showed relatively rapid declining trends (-7.116 mm a^{-1}) in annual ET_{Ref}, with the highest (-8.769 mm a^{-1}) at Tazerbou, with highly significant decreases (***) at the three sites. Positive trends are found at four inland stations (2.124 mm a^{-1}), with a significant increase at Hon (**) and Sabha (+).

Large changes occurred mainly within the inland region (Sahara), particularly, south-eastern Libya where the weather parameters are more variable relative to the coastal region. Positive trends in annual ET_{Ref} are found at five of the nine coastal stations with an average annual rate of 1.797 mm a^{-1} and in four of seven inland stations with an average annual rate of 2.124 mm a^{-1}. Negative trends are identified in four coastal stations with an average rate of -2.128 mm a^{-1}, with an average rate of -7.116 mm a^{-1} at inland stations. Considerably higher negative trends (with the highest negative -8.769 mm a^{-1}) are shown for part of the inland region; Tazerbou, Ghadames and Al-Jaghbub (Fig. 6.12), while moderate positive trends (with an average rate of 1.924 mm a^{-1}) are found at a number of stations.

6.5.1.2 Seasonal reference evapotranspiration (ET_{Ref}*) changes and trends*

Mean seasonal reference evapotranspiration (ET_{Ref}) of the total 16 stations across Libya for the period 1961-2010, with trend values in mm/season analysed by the Mann-Kendall test are presented in Table 6.8 and shown in Fig 6.13.

In autumn, eleven stations (65%) show positive trends in ET_{Ref}, with an average seasonal rate of 0.916 mm S^{-1}) at seven coastal stations (0.729 mm S^{-1}) and four inland stations (1.242 mm S^{-1}). Negative trends in ET_{Ref} are found at five stations, with low negative trends at two (-0.340 mm S^{-1}) and three (-0.772 mm S^{-1}) in coastal and inland stations, respectively. Positive autumn trends in ET_{Ref} all remain below 2.0 mm S^{-1}, with the highest increases in the coastal region at Musratah (1.477 mm S^{-1}), with the highest observed for the inland region at Hon (1.562 mm S^{-1}). Negative trends in ET_{Ref} are identified over a small number of stations, five of 16 examined stations (1.477 mm S^{-1}), with maximum values at Tazerbou (-1.637 mm S^{-1}) in the inland region. Table 6.4 shows significant increases at Musratah, Ajdabyia, Hon (***), Zwarah (**), Sirt, Sabha (*), Binina (+), and a significant decrease at Tazerbou (***).

Negative trends in winter ET_{Ref} are found at six coastal stations (-0.922 mm S^{-1}) and five inland stations (-0.685 mm S^{-1}). Low negative and positive trends are found at most of the stations across Libya, with the negative winter trends all remaining below 2.00 mm S^{-1}. Positive trends are identified at Nalute, Musratah and Sirt and most of the south–eastern region of Libya, with an average rate of 0.166 mm S^{-1}. Negative significant trends in winter ET_{Ref} are found at Tripoli Airport, Binina, Darnah, Jalo and Sabha (***) and Zwarah (**), with no significant positive trends at any stations.

Summer ET_{Ref} shows positive (negative) trends in nine (seven) stations across Libya (Fig. 6.10), with a positive trend (0.415 mm S^{-1}) at six coastal stations, with higher rate of increase at inland stations (0.952 mm S^{-1}). The positive trends mostly occur at coastal stations, with trend values below1.3 mm S^{-1}, while the inland stations present negative trends at 57% and positive trends at 43% of stations with average rates of 0.952 mm S^{-1} and -1.917 mm S^{-1}, respectively.

The largest positive trend in summer ET_{Ref} occurs at Ajdabyia (1.203 mm), with the largest negative at Tazerbou (-3.212 mm S^{-1}). Significant trends are identified at nine stations across Libya, with a positive trends at Ajdabyia (***), Zwarah, Hon (*) and Sabha (+), while negative trends are found at Tazerbou, Al-Jaghbub (***), Nalute, Ghadames (**) and Shahat (*).

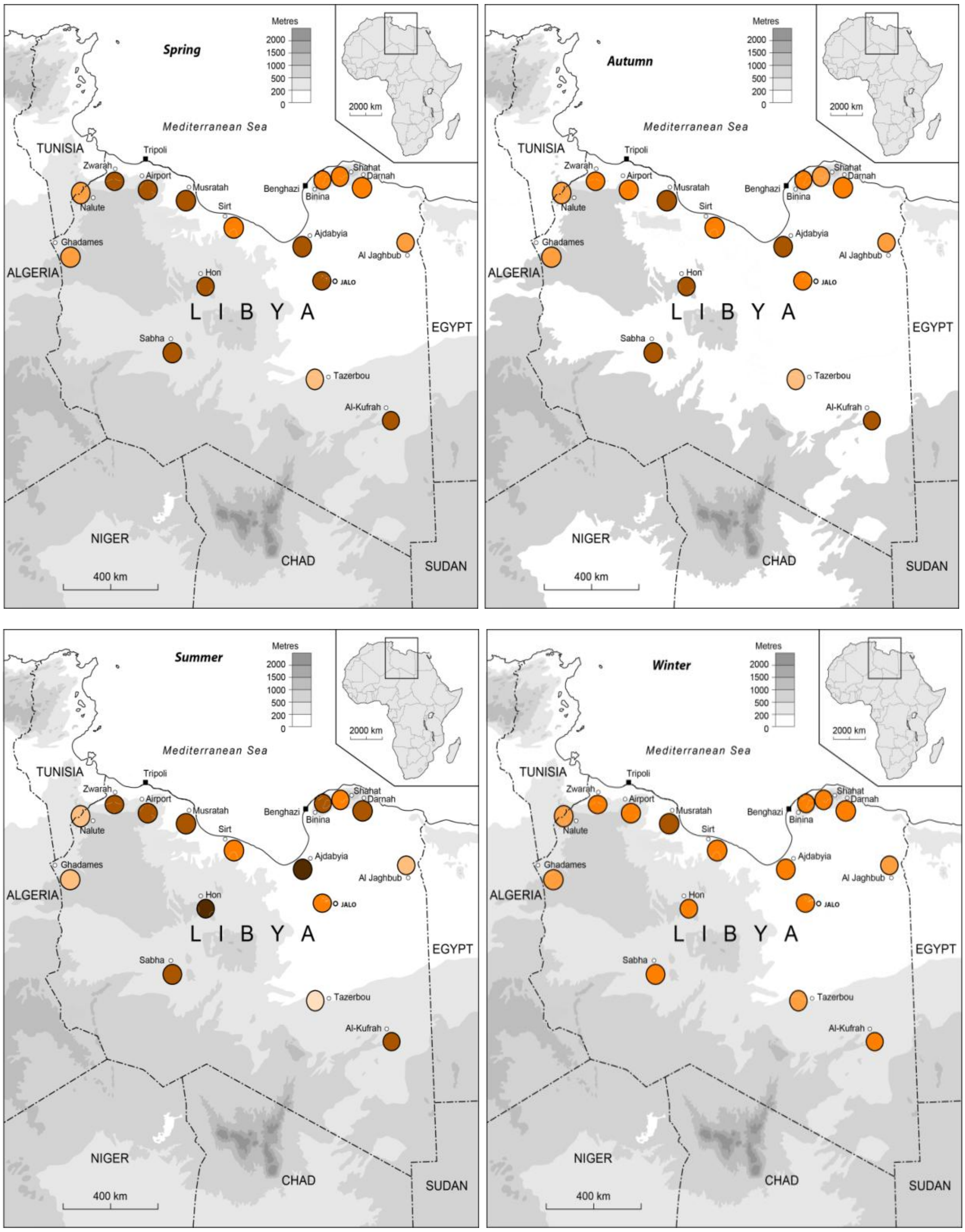
In the spring season, the ET_{Ref} shows that 50% of stations across Libya have positive trends (with an average of 0.467 mm S^{-1}) and negative (with an average of -1.115 mm S^{-1}).

Increases in spring ET_{Ref} are found at three (five) coastal (inland) stations, with an average rate of 0.388 mm S^{-1} (0.515 mm S^{-1}). Decreasing trends in spring ET_{Ref} are found at six (two) coastal (inland) stations across Libya at -0.828 mm S^{-1} (-1.935 mm S^{-1}). Table 6.8 shows significant trends in spring ET_{Ref} at eight stations, with significant negative trends at Jalo (***), Tripoli Airport, Darnah, Sabha (**), Musratah and Binina (+), with positive trends only at Al-Kufrah (*) and Sirt (+).

6.5.1.3 Monthly reference evapotranspiration (ET_{Ref}*) changes and trends*

Mean monthly reference evapotranspiration (ET_{Ref}) of the total 16 stations across Libya for the period 1961-2010, with trend values in mm/month are analysed by Mann-Kendall test are presented in Table 6.9.

Monthly trend rates of ET_{Ref} range from -0.0330 mm M^{-1} (June) to 0.207 mm M^{-1} (September). A mix of positive, non-varying and negative trends in monthly ET_{Ref} are observed in both coastal and inland regions. The warm months (May-October) showed higher positive compared to the moderate months (November-April), with positive trends in monthly ET_{Ref} observed for all months at Nalute, Ghadames and Tazerbou (Table 4.9). In February, negative trends (-0302 mm M^{-1}) are observed at all stations except Musratah and Al-Kufrah, with positive trends (0.029 mm M^{-1}) observed at 12 of 16 stations in October. Significant monthly changes (positive and negative) ET_{Ref} are found for all months and are more frequent in the warm months July-September (Table 6.9).



● : ≥ -4.0 and ≤ -3.0 mm^{-1}, ● : ≥ -3.0 and ≤ -2.0 mm^{-1}, ● : ≥ -2.0 and ≤ -1.0 mm^{-1},

● : ≥ -1.0 and ≤ 0.0 mm^{-1}, ● ≥ 0.0 and ≤ 1.0 mm^{-1}, : ● 1.0 and ≤ 2.0 mm^{-1}

Fig. 6.13: Spatial distribution of seasonal references evapotranspiration at stations across Libya, trend values are given as (mm M^{-1}).

Table 6.9: Values of the Mann-Kendall statistic (Q) for monthly references evapotranspiration, with statistically significant levels at the synoptic stations for 16 stations across Libya during period 1961-201

Time series		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Zwarah	Q	0.033	-0.024	0.171	0.096	0.323	0.197	0.273	0.294	0.222	0.362	0.200	0.098
	Sig.					*	*	*	*	*	*	*	
T. Airport	Q	-0.198	-0.238	0.075	0.077	0.160	0.153	-0.011	-0.013	0.097	0.264	-0.085	-0.171
	Sig.	+	+										
Nalute	Q	-0.194	-0.615	-0.675	-0.397	-0.721	-1.016	-0.548	-0.764	-0.212	-0.021	-0.529	-0.527
	Sig.		**	**	*	*	*	*	**			*	*
Musratah	Q	0.155	0.021	-0.051	0.146	0.080	0.009	0.224	0.132	0.317	0.613	0.424	0.161
	Sig.							+		*	***	**	
Sirt	Q	-0.099	-0.100	-0.248	-0.088	-0.151	-0.216	0.060	0.009	0.186	0.285	-0.015	-0.066
	Sig.									+	*		
Ajdabyia	Q	0.084	-0.090	0.076	0.274	0.391	0.010	0.650	0.558	0.551	0.444	0.271	0.088
	Sig.				+	+		***	***	**	*	+	
Binina	Q	0.033	-0.134	-0.075	-0.059	0.079	-0.368	0.346	0.158	0.435	0.097	0.310	0.284
	Sig.							*		*		+	*
Shahat	Q	-0.082	-0.351	-0.053	-0.220	-0.344	-0.537	-0.039	0.001	-0.061	0.001	-0.117	-0.347
	Sig.		**			*	**						**
Darnah	Q	-0.141	-0.279	-0.297	0.046	0.041	0.019	0.225	0.134	0.119	0.077	-0.025	-0.129
	Sig.		+										
Ghadames	Q	-0.481	-0.762	-0.575	-0.956	-0.346	-1.066	-0.536	-0.489	-0.232	-0.033	-0.104	-0.357
	Sig.	**	***	**	***		**	*	+				**
Hon	Q	-0.042	-0.291	-0.216	0.467	0.320	0.029	0.586	0.632	0.809	0.607	0.291	0.016
	Sig.		*		**			**	**	***	**	*	
Jalo	Q	0.011	-0.119	0.013	-0.092	0.205	-0.201	0.004	-0.135	0.308	0.185	0.217	-0.058
	Sig.											+	
Al-Jaghbub	Q	-0.369	-0.536	-0.620	-0.627	-0.916	-1.115	-0.887	-0.204	-0.011	-0.394	0.043	-0.310
	Sig.	**	***	**	**	**	***	***			*		***
Sabha	Q	-0.055	-0.165	0.132	0.481	0.250	0.081	0.316	0.664	0.759	0.155	0.383	0.081
	Sig.				+				**	*			
Tazerbou	Q	-0.459	-0.519	-0.944	-0.579	-0.735	-1.333	-1.113	-0.831	-0.595	-0.735	-0.396	-0.662
	Sig.	***	***	***	*	*	***	***	***	**	***	**	***
Al-Kufrah	Q	0.224	0.079	0.146	0.218	0.459	0.069	0.511	0.498	0.623	0.391	0.342	-0.020
	Sig.												

6.6 DISCUSSION

The main objective of this chapter is to identify the temporal and spatial changes in potential evapotranspiration and to analyze the characteristics and trends of evapotranspiration across Libya, based on long monthly climatic parameters observed from 16 stations for 50 years (1961-2010). Time series of annual climatic data parameters: surface wind speed, relative humidity, sunshine duration and atmospheric pressure data for daily (1956-2010; 56 years) and annual (1945-2010; 66 years) timescales at 16 synoptic stations across Libya relative to potential evapotranspiration are analyzed. The findings of potential and actual evapotranspiration variability are comparable with previous studies over the last half of the 20th century across the Mediterranean region and North Africa.

6.6.1 Climatic variability

Most of examined stations (69%) across Libya showed positive trend in relative humidity (RH), ranging from 0.017% a^{-1} to 0.266% a^{-1}, with significant increases at five stations; with five stations showing negative trends in RH (0.079% a^{-1}). Previous research, Abu-Taleb et al. (2007) found a significant increasing trend (0.13% a^{-1}) at Amman Airport Meteorological (AAM) during the period 1929-20005 (confidence level 95%). This finding is supported by Hosseinzadeh et al. (2012) who showed increases by 1.03 % d^{-1} in the northern and 0.28% d^{-1} in southern regions of Iran (1966-2005). However, Irmak et al. (2012) have shown a significant increase in RH (0.0159% a^{-1}) where wind speed did not exhibit any noticeable trend over central Nebraska–USA (1893-2008).

Positive trends in atmospheric pressure (AP) with an average annual rate of 0.028 hp a^{-1} are found at 81% of stations across Libya (1961-2010), with significant increases at 56% of the 16 examined stations. The same 56% of stations showed decreasing trends in wind speed (WS), with an average annual rate of -0.023 m s^{-1}, with significant decrease at eight of the stations. Previous studies (e.g. Pirazzoli and Thomasin, 2003) have shown that WS was decreasing from 1951 to the mid-1970s, and increased after this in the central Mediterranean and Adriatic areas.

A positive trend (0.012 h d^{-1}) in annual sun-shine duration (SSD) is identified at most stations across Libya (1961-2010) except at Tripoli Airport and Sirt, with significant increases at most stations. Previous research by Aksoy (1999) found decreases in sun-shine duration over Ankara, Turkey for the period 1928-1996; this finding is supported by Kaiser and Qian (2002) who have identified decreases in sun-shine duration for Western Europe from the 1950s until the 1980s, followed by an increase until 2000. However, Sanchez-Lorenzo et al. (2007) identified a decrease in sun-shine duration for the Iberian Peninsula (Spain) from the 1950s to the early 1980s, followed by a positive trend until the end of the 20th century.

6.6.2 Potential evapotranspiration

Annual PET_{T-W} (1961-2010) calculated from temperature data for 16 stations across Libya, shows increasing trends (average of 1.597 mm $a^{-1)}$ in coastal stations and an average increase of 4.389 mm a^{-1} at inland stations. Significant increases (95% confidence level) are found at most of coastal stations, except Musratah and the eastern stations, with significant increases at most of inland stations except Al-Jaghbub and Al-Kufrah. This increase in PET_{T-W} is mainly consequence of significant warming across Libya as illustrated in Chapter 4, as the Thornthwaite method is heavily dependent on temperature and solar radiation to estimate the evapotranspiration.

Monthly PET_{T-W} showed increasing trends in most months (with an average of 0.141 mm a^{-1}) (with the exception of February) at coastal stations, with more rapid trends during the warm months (with an average of 0.534 mm a^{-1}). The inland stations also showed a slightly decreasing trend (-0.050 mm a^{-1}) during the colder months November-February.

Annual PET_{P-M} (1961-2010) calculated from meteorological data for 16 stations across Libya shows decreasing trends at nine of the 16 stations (an average rate of -4.191 mm a^{-1}) with the highest trend (-11.173 mm a^{-1}) at Tazerbou, with significant decreases (95% confidence level) at five coastal and inland stations. Increasing trends in annual $PET_{P-M,}$ are lower (an average increasing rate of 2.796 mm a^{-1})

compared to the decreasing trends found at the remaining seven stations, with significant increases (95% confidence level) identified at only three coastal stations. In general, trends in potential evapotranspiration follow a high/low transect from the north (coastal) to the south (Sahara), reflecting the trends in the weather parameters that affect the rate of evaporation.

The period of November-June (with exception for April) presents negative trends (0.150 mm M^{-1}) at most coastal stations; with significant decreases (95% confidence level) identified in February, June and December. Positive trends in monthly PET_{P-M} (0.257 mm M^{-1}) are found during the period between April-November for the inland region, with significant increase in September.

Temporal patterns of PET_{T-W} and PET_{P-M} are in generally good agreement for the coastal region, with reasonable agreement for the inland region. This could be an effect of the greater influence of the climatic parameters; relative humidity, wind speed and sun-shine duration on the PET_{P-M} compared to the $PET_{T-W.}$ No clear relationships are found between potential evapotranspiration of PET_{T-W} and $PET_{P-M,}$ with generally low correlation coefficients identified. Analyses of the relationships between PET_{P-M} and the weather parameters indicate a strong positive correlation with SW, RH and SSD in the inland region and a strong negative correlation with RH at the coastal stations.

6.6.3 Reference evapotranspiration

Trends of ET_{Ref} show an increase in annual evapotranspiration at 56% of stations at an average rate of 1.942 mm a^{-1}, with a decrease at remaining stations averaging -4.265 mm a^{-1}. Large changes in ETRef occurred mainly within the Sahara region, with negative trends identified (-7.116 mm a^{-1}), with significant positive and negative trends at five stations.

In autumn, 65% of stations show positive trends in ET_{Ref}, with an average rate of 0.916 mm S^{-1}, with negative trends found at the remaining stations (-0.556 mm S^{-1}).

Significant increases (with confidence levels 95%) are found at seven stations, with significant decrease only at Tazerbou (***).

During the winter season ET_{Ref} trend at 69% of stations are negative (0.916 mm S^{-1}), with significant trends found at six stations. The warmest months (summer) show positive trends (0.952 mm S^{-1}) at 55% of stations, which mostly occur at coastal stations. In spring, 50% of stations appear to have positive trends (0.467 mm S^{-1}) and the remaining have negative trends (-1.115 mm S^{-1}) with significant decreases observed at six stations. The mean monthly ET_{Ref} shows positive trends at 56% and 41% of coastal and inland stations, respectively. The warm months (May-October) showed higher positive values compared to the moderate months (November-April).

6.7 SUMMARY

The analyses of trends and patterns of potential and actual evapotranspiration observed at 16 stations across Libya during the period of 50 years (1961-2010), expose in general well pronounced seasonal and annual patterns, with increasing (decreasing) tendency in potential evapotranspiration at the coastal (inland) regions, though the rates of change are not uniform between stations or consistent throughout the period. The principal findings of this chapter are:

1. The annual PET_{T-W} showed general increases trends (1.597-4.389 mm a^{-1}) at all coastal and inland stations (1961-2010). Significant increasing trends (95% confidence level) in annual PET_{T-W} are found at most coastal and inland stations. Monthly PET_{T-W} showed general increasing trends in most months (not February) at coastal stations and in the warm months; March-October at inland stations. About 56% of the total stations showed decreasing trends in PET_{P-M} with five stations showing significant decreases (95% confidence level) and two coastal stations presented significant increases.

2. The temporal patterns of PET_{T-W} and PET_{P-M} data are in good agreement for the coastal region, with general reasonable agreement for the inland region. Penman-Monteith is the most widely accepted method for estimating monthly

potential evapotranspiration across Libya, where weather parameters are available.

3. Decreasing trends in ET_{Ref} rates are observed across Libya as a whole (-0.774 mm a^{-1}) and within the inland region (-1.836 mm a^{-1}), with an increase in ET_{Ref} in the coastal region (0.053 mm a^{-1}), with significant trends identified at 59% of stations. The analyses presented suggests the decreases and increases in ET_{Ref} are most likely due to significant increases and decreases in meteorological variability, such as relative humidity, surface wind speed, maximum temperature, sun-shine duration and precipitation.

4. About 70% of stations showed positive trend (0.191% a^{-1}) in RH, with positive trends at all coastal stations, with significant increases at a third of stations.

5. Significant positive trend (0.012 h d^{-1}) in SSD is identified at 88% of stations, with positive trends at all inland stations.

6. Positive trends (0.028 hPa a^{-1}) in AP are found at 81% of stations, with significant increases at about two-third of stations across Libya. A higher degree of responsiveness for the inland $PET_{P\text{-}M}$ to changes in meteorological variables than coastal $PET_{P\text{-}M}$ of WS, SDS and AP has been observed.

Chapter 7

CLIMATE REANALYSIS

This chapter analyses the relationships between the observation data and the reanalysis NCEP/NCAR-1948-2010 and ERA-Interim-1979-2010 dataset of mean average temperature and total precipitation at Ajdabyia, Hon and Nalute based on monthly data. Comparison of the observational dataset with the reanalysis NCEP/NCAR and ERA-Interim- is also considered.

Sequential and non-sequential assimilation are the two main approaches used in climatic reanalysis, with the sequential analysis considering past observational data and the future climatic by non-sequential assimilation. Reanalysis products are produced by assimilating climate observations from many sources (e.g. radiosones observation, satellites, ground stations, ships and radar) into climate models. This allows estimation the complete past state and future of the atmospheric circulation. Reanalyses data can estimate the atmospheric state at positions with no weather and climatic data monitoring by using proximate observations and information of the mechanics of the climate system. It can provide spatially complete and consistent record of global atmospheric circulation. Recently, the most recognized reanalysis datasets are National Centres for Environmental Prediction (NCEP)/National Centre for Atmospheric Research (NCAR) (NNRP-1), and ERA-Interim (Mooney et al., 2011).

During late 1960s, reanalysis project data has been produced using global gridded analyses using a fixed assimilation system. Over the last 15 years, reanalysis data has found common application in many scientific areas of research in climatic studies (e.g. Poveda et al., 2006; Ciccarelli et al., 2008; Stammerjohn et al., 2008), climate modelling (Wang et al., 2011; Fealy and Sweeney, 2007) and atmospheric moisture (Rasmusson and Mo, 1996; Trenberth and Guillemot, 1998).

Results from the National Centers for Environmental Prediction–National Centre for Atmospheric Research (NCEP–NCAR) global reanalysis project (Kalnay et al. 1996) became available coincident with the GPCP precipitation analyses. Higgins et al., 1996 examined the precipitation over the United States during the years 1985–89. The annual and intra-seasonal timescales of reanalysis precipitation during the period 1985–93 has been analysed by Mo and Higgins, (1996).

7.1 DATA AND METHOD

7.1.1 Stations data

The station data used in this study was obtained from by the Libyan National Meteorological Centre (LNMC) for three stations; Ajdabyia, Hon and Nalute covering the period 1948–2010. The geographical distribution of the examined weather stations used in this study together with the respective NCEP–NCAR and ERA-Interim grid points are shown in Fig. 7.1. The stations reflect three broad regional climates, an inland region (Hon), a coastal region (Ajdabyia) and a coastal mountain station (Nalute; Chapter 2: Table 2.1). In order to make a comparison with reanalysis data, station data have been converted from monthly averages of mean average temperature and total precipitation.

7.1.2 NCEP/NCAR reanalysis temperature and precipitation dataset

The American Precipitation Climatology Project NCEP–NCAR reanalysis model is a global spectral model covering the period from 1948 to present day, with 28 sigma levels in the vertical and a triangular truncation of 62 waves, which corresponds to a horizontal resolution of approximately 200 km (Kalnay et al., 1996 and Janowiak et al., 1998). The NCEP has produced and released monthly mean estimates of climatic data on a spatial resolution of about 2.5 degree. A forecast from the NCEP global spectral model was used as the first-guess fields for this reanalysis, with more details information of the assimilation system used in NCEP/NCAR reanalysis is described by (Kalnay et al., 1996).

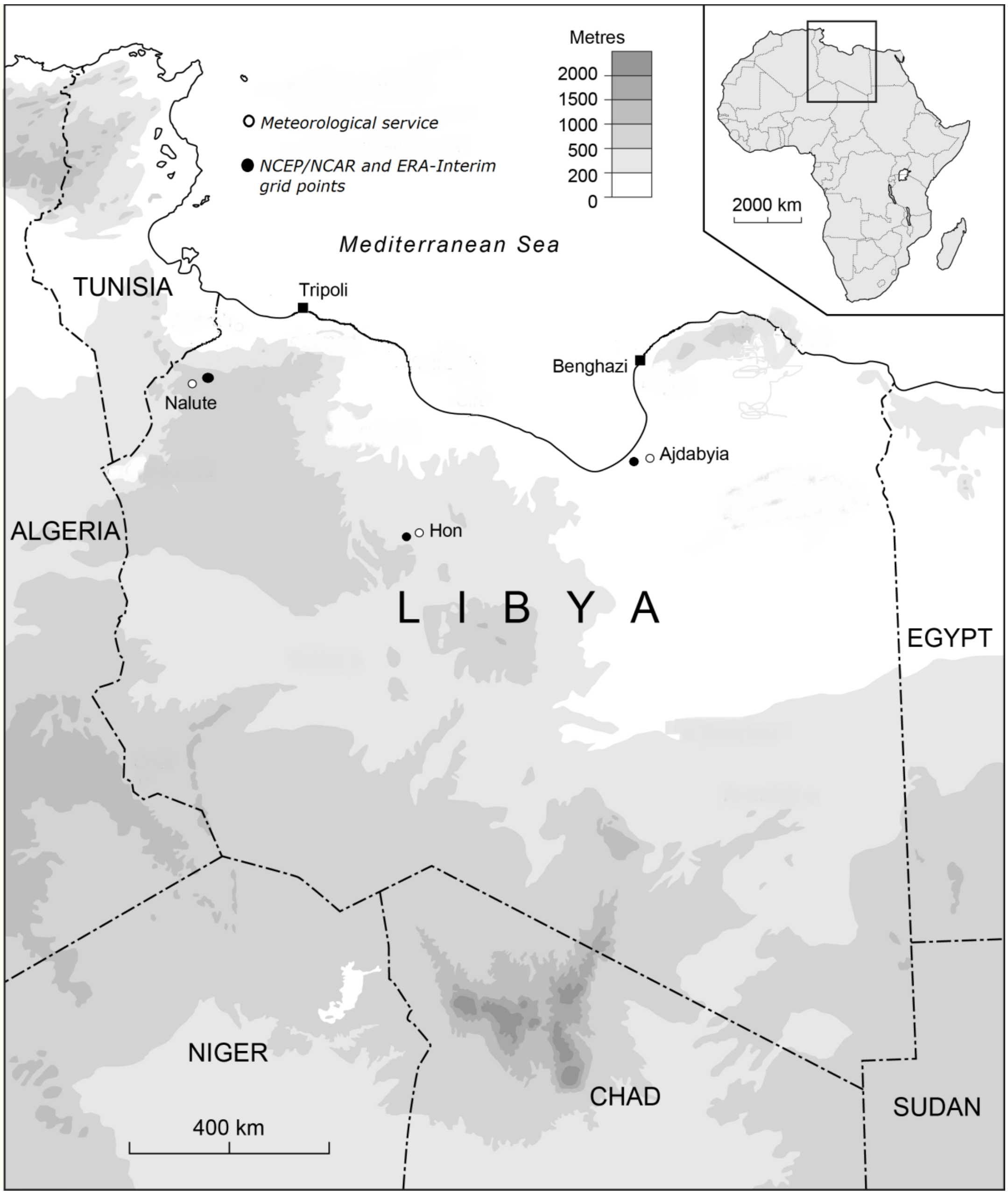


Fig. 7.1: The distribution of meteorological service (stations) and both NCEP/NCAR and ERA-Interim grid points within this study.

7.1.3 ERA-Interim reanalysis temperature and precipitation dataset

The ERA-Interim is the most recent global atmospheric reanalysis with series generated back to 1979-2010, which were produced by the European Centre for Medium Range Weather Forecasts (ECMWF). The reanalysis ERA-Interim model produced is the most recent global atmospheric reanalysis from 1979, with spatial resolution about 1.5 ° longitude grids. ERA-Interim analysis daily products from 1979 and is available are twice daily ten-day forecasts and monthly means. The ERA-Interim uses 4D-variational analysis on a spectral grid with triangular truncation of 255 waves (approximately 80 km). ERA-Interim products are also widely available on the ECMWF Data Server, at fixed grid of 1.5° resolution http://www.ecmwf.int/research/era/do/get/era-interim

7.2 SPATIAL VARIABILITY OF MEAN AVERAGE TEMPERATURE

The representative stations; Ajdabyia, Hon and Nalute have been analysed to compare, in terms of annual variability of the observation and each of NCEP–NCAR and ERA-Interim reanalysis data. In addition, degree of the reliability of temperature reanalysis is estimated. The observational mean average annual temperature is 19.1 °C (Nalute), 20.7 °C (Ajdabyia) and 21.4 (Hon). The distribution of observation and reanalyse mean average temperature data of each station is showed in Fig. 7.2, with median, mean, 25th percentile, 75th percentile, and standard deviation, minimum and maximum temperature shown.

Mean average temperature statistics are relatively comparable to the NCEP/NCEP and ERA-Interim reanalysis data. Fig.7.2 shows two different observations boxes whisker plots with the two reanalysis NCEP/NCEP (1948-2010) and ERA-Interim (1979-2010) temperature data. The annual median values of temperatures are general close to the NCEP/NCEP, particularly at Hon for the period 1948-2010, with the highest difference of 3%, with slightly different to the ERA-Interim, with the highest (6%) at Nalute during the period 1979-2010. The modelled ERA-Interim median values are characterized by slightly higher compared to the observation data at Ajdabyia (3.8%) and higher at Nalute (10%), where changes in the NCEP/NCAR at Nalute slightly higher (2.6%).

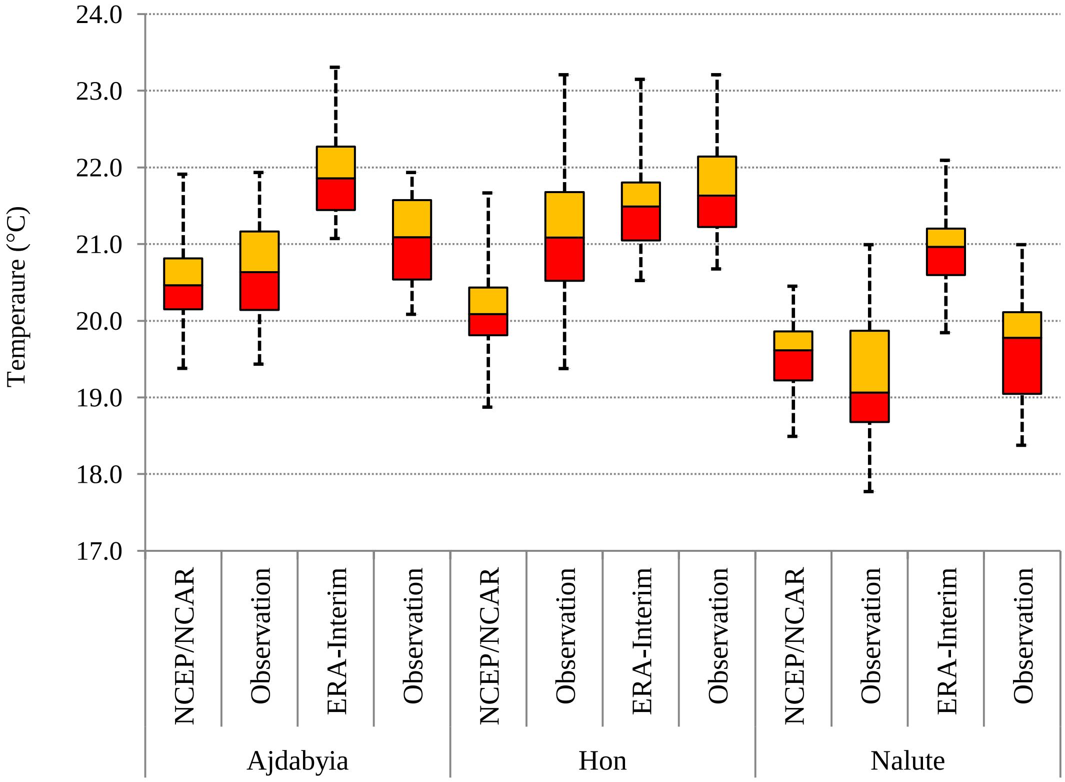


Fig. 7.2: Ranges in mean annual average temperature for observation and modelled data (NCEP/NCEP and ERA-Interim) data at Ajdabyia, Hon and Nalute, with maximum, minimum, lower quartile (first quartile -25%), median (50%) and the upper quartile (third quartile –75%).

7.3 INTERANNUAL OF VARIABILITY IN TEMPERATURE

Recent studies have compared NCEP–NCAR gridded data with ground-based observation mean average global temperature data (Rusticucci and Kousky, 2002; Flocas et al. 2005). Seasonal differences in mean maximum and minimum temperature are identified at 26 meteorological stations across Greece (1955-2001) and respective NCEP–NCAR gridded reanalysis (Nastos et al., 2011). Annual accumulations of the NCEP and ERA-Interim data are compared with the observed data combined for three stations over the two periods 1948–2010 and 1979-2010.

7.3.1 Interannual of NCEP/NCAR and ERA-Interim with observation data of annual means average temperature

Plots of mean annual average temperature of the observation and both modelled NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010) temperature data for Ajdabyia, Hon and Nalute (Fig. 7.3) shows that the temporal patterns of the NCEP/NCAR and observation data for the three stations are in general good agreement (with the trend lines of both the observed and reanalyses data are very close and seems to be well matched) on the large scale during most of the period 1948-2010, with a couple of poorer years, particularly after the year 2000 at the three stations. The values of NCEP/NCAR and observation data are different by 0.22 °C (Ajdabyia) and 0.34 °C (Nalute), with the highest (1.03 °C) at Hon. Ajdabyia shows accurate capture of the mean average temperature during the study period in the NCEP/NCAR reanalysis, with poorer performance at all stations over the last 10 years and at Hon during the years 1952-1953, 1964-1968 and 1986-1990 and at Nalute during the period1950-1953, 1962-1968 and 1993-1995.

The mean average temperature data for observational and the reanalysis ERA-Interim data shows general good agreement on the large scale during most of the period 1979-2010 at the three stations, with captures slightly accurate compared to NCEP/NCAR temperature data. A more accurate pattern in the temperature has been found at Ajdabyia compared to Hon and Nalute. Slight changes in observed and ERA-Interim temperature data are at Hon and Nalute, with poorer performance is found during the 5-years (1995-2000) at both stations Hon and Nalute and during the period 1995-1998 at Nalute (Fig.7.4). The rate varies of ERA-Interim values is slightly more than NCEP/NCAR at Ajdabyia (0.78 °C) and Nalute (1.03 °C), but relatively low at Hon (0.16 °C).

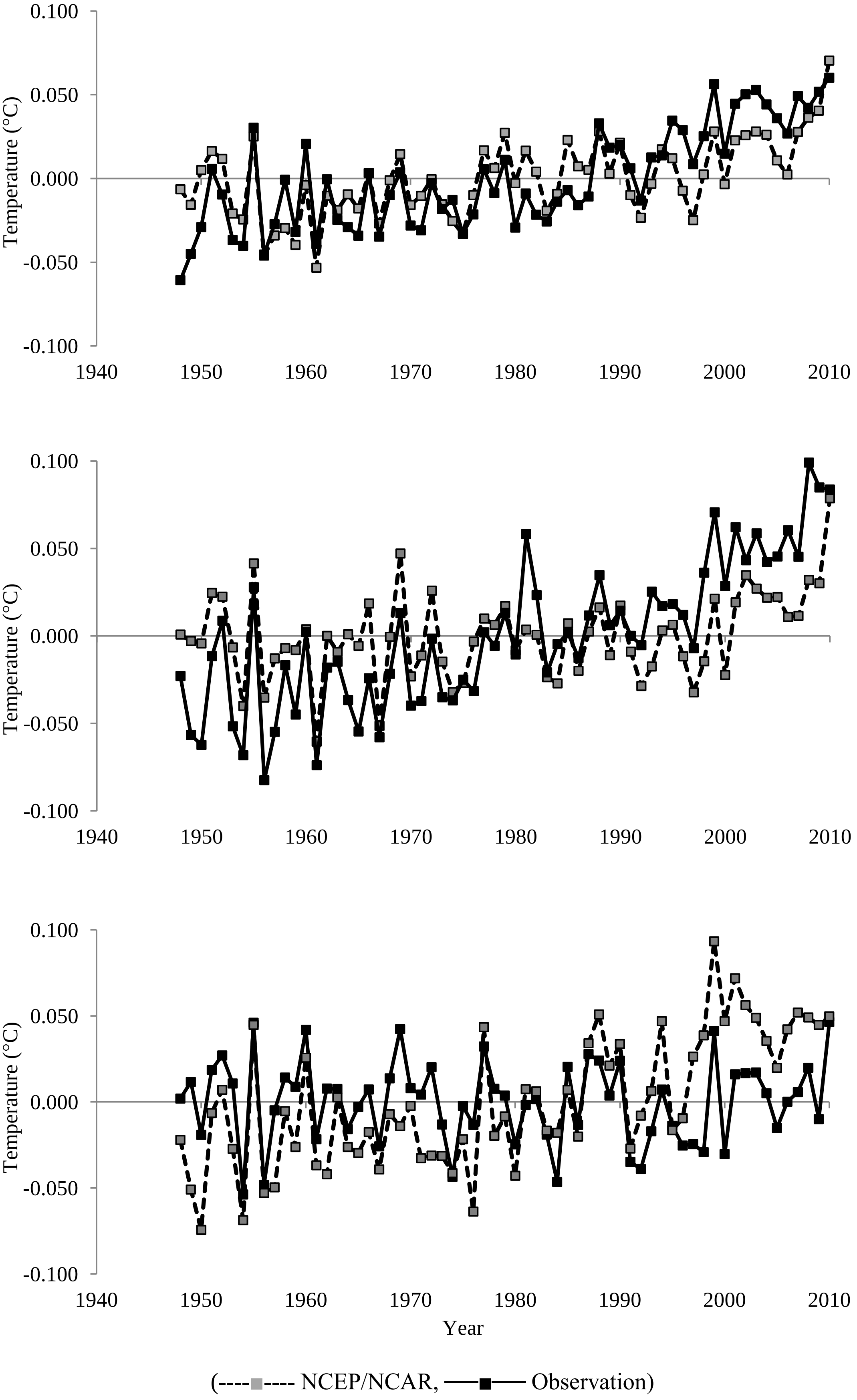


Fig. 7.3: Normalised annual mean average temperature anomalies of observation and NCER/NCAR data at; a) Ajdabyia; b) Hon and: c) Nalute for 1948-2010

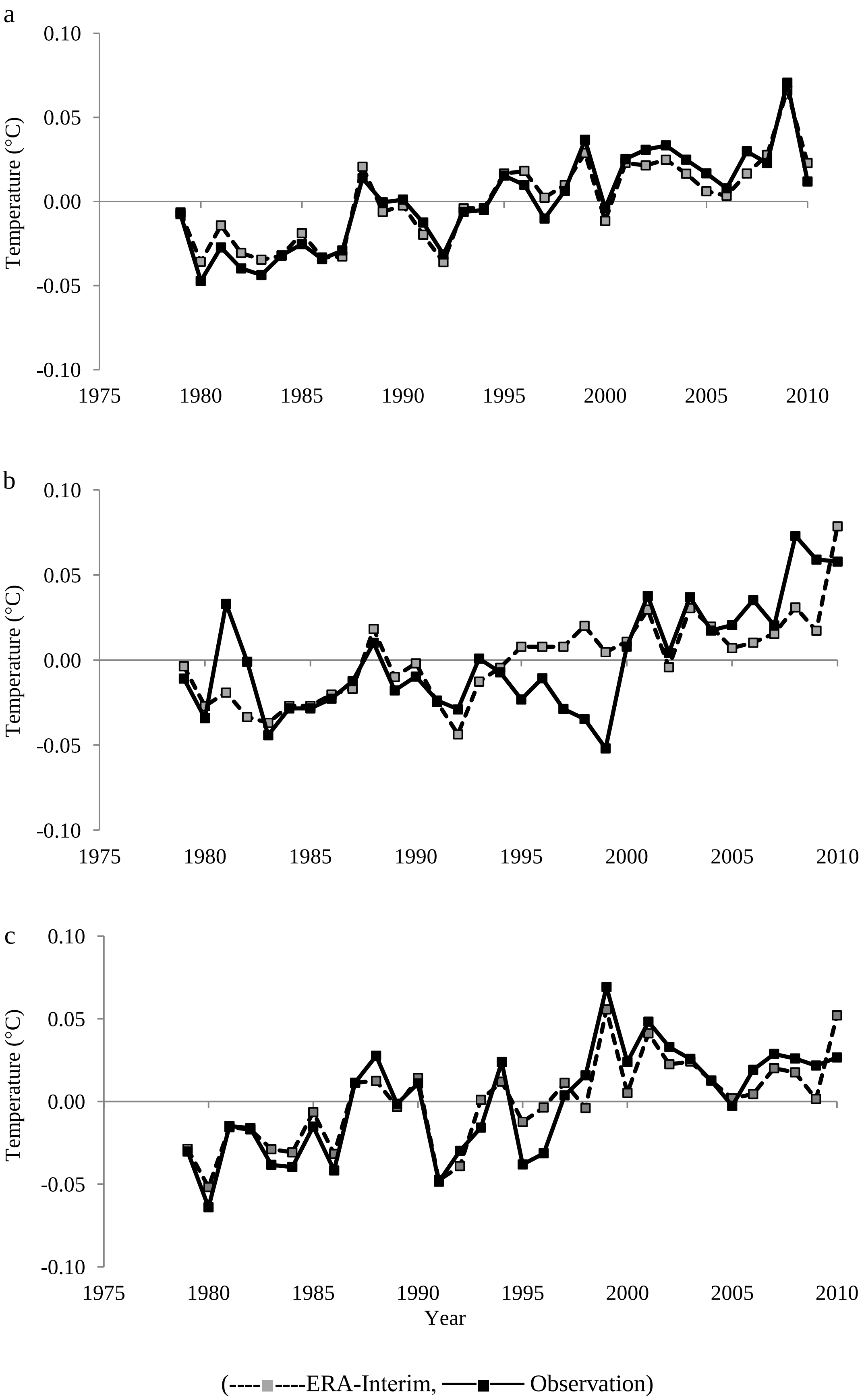


Fig. 7.4: Normalised annual mean average temperature anomalies of observation and ERA-Interim data at; a) Ajdabyia; b) Hon and: c) Nalute for 1979-2010

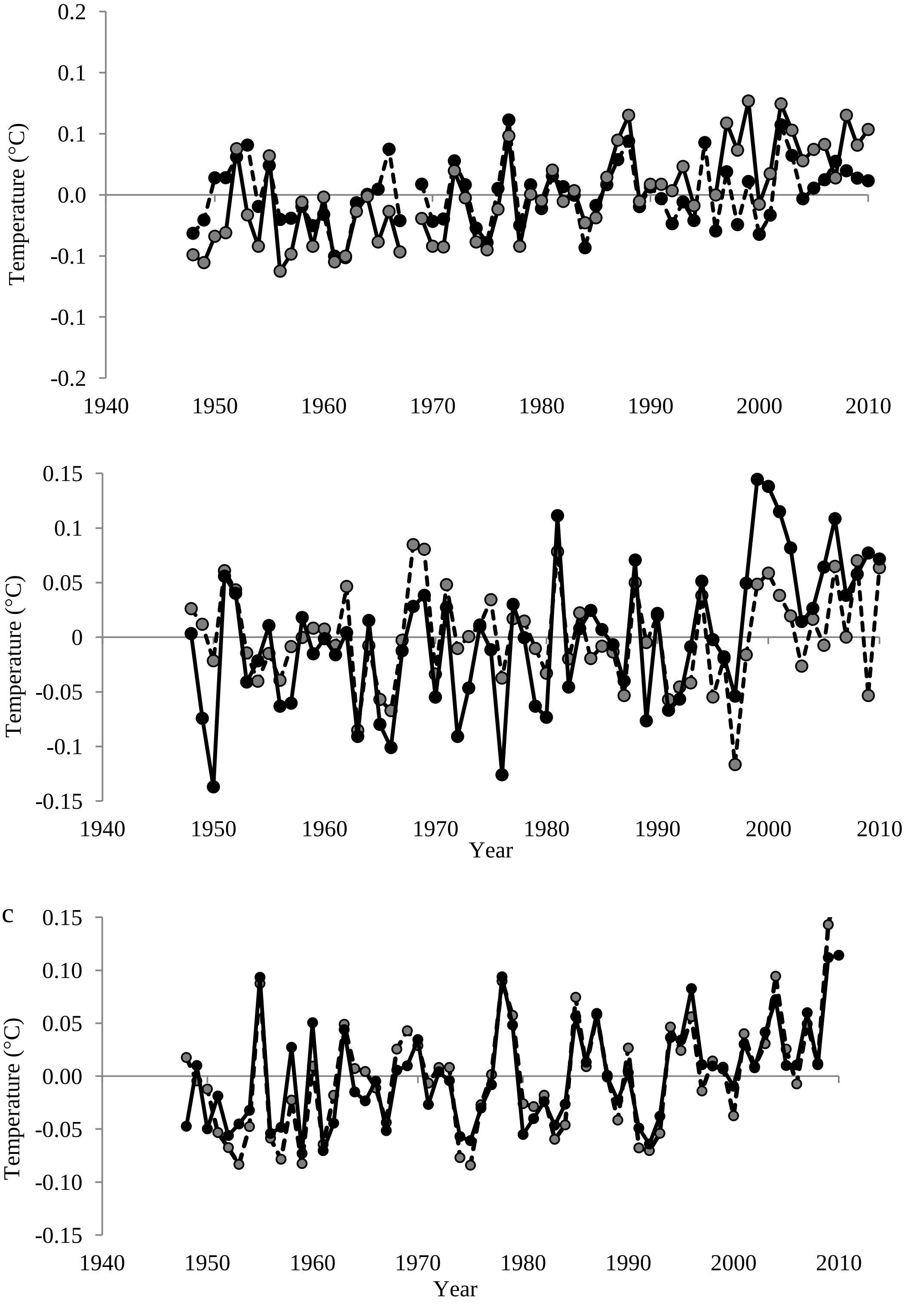
7.3.2 Interannual of NCEP/NCAR and ERA-Interim with observation data of seasonal and sub-seasonal means average temperature

The mean seasonal average temperature representative at stations; Ajdabyia, Hon and Nalute of the observation and the both reanalysis NCEP/NCAR and ERA-Interim data are showed) Fig. 7.5). The temporal patterns of the NCEP/NCAR and observation data of mean annual average temperature are good agreement, particularly during the winter time at the three stations.

In general, seasonal trends of observational mean average temperature during spring (MAM), summer (JJA) and autumn (SON) over the three stations are good relationships to NCEP/NCAR at most cases, indicating some differences at Hon (summer) and Nalute (spring). The observational data (1948-2010) shows considerably higher temperatures compared to NCER/NCAR in all seasons at Hon and in winter and autumn at Nalute (see Appendix 7.1for the remaining stations).

On the other hand, NCER/NCAR reanalysis is relatively higher during the warmer seasons; spring and summer compared to the observational data at Nalute, with very close agreement at Ajdabyia during all seasons. December-February (DJF) means also show reasonable good agreement to the NCEP/NCAR at the three stations during most of the time period.

NCEP/NCAR data indicates good agreement at the three stations, but considerable differences exist during the last 10-15 years at Hon during all seasons and in winter and autumn (Nalute) and in summer (Ajdabyia). The winter values of NCEP/NCAR reanalysis are very close at the three stations, ranging about 0.1 °C (Ajdabyia) and slightly less than 1.0 °C (Nalute). The summer (spring) values varies are very close at Ajdabyia (Hon) about 0.1 °C (0.5 °C), with relatively close agreement at Nalute, with ranges between1.5 °C (summer) and 1.6 °C (spring). The autumn values are rather different at Hon (1.4 °C) and Ajdabyia (1.1 °C); with relatively lower values at Nalute (0.85 °C)



(----■---- NCEP/NCAR, ——■—— Observation)

Fig. 7.5: Normalised seasonal mean average temperature anomalies of observation and reanalysis NCER/NCAR data at; a) Hon (summer); b) Nalute (spring) and; c) Ajdabyia (winter).

The reanalysis ERA-Interim and observation temperature are in general good agreement particularly at Ajdabyia, with some differences is found in autumn at Hon and Nalute and in summer at Hon (Fig. 7.6; see Appendix 7.2 for the remaining stations).

The ERA-Interim reanalysis winter data indicating a general good agreement between the three stations, with very close values exist at the three stations, at average temperature differences of 0.6 °C and during the 91% of the period (1979-2010) at Nalute is higher than 1.0 °C. Comparing the observational and reanalysis ERA-Interim of autumn mean average temperate showed reasonable or and good agreement to at Ajdabyia and Nalute, but slightly lower (0.44 °C) at Hon and 0.80 °C at Ajdabyia and Nalute, where the differences between observational and reanalysis ERA-Interim temperate data are equal 1.0 °C at Nalute recorded in 31% of the years (1979-2010). The warm seasons; spring and summer values of ERA-Interim are very close to observed data at both Hon and Ajdabyia less than 1.0 °C but considerable values at Nalute at 1.71 °C in spring and 2.32 °C in summer. The ERA-Interim spring data at Nalute indicates high difference (>1.0 °C) compared to the observed data for all years.

Comparing the seasonal mean average temperature in ERA-Interim and NCEP/NCAR reanalysis found the ERA-Interim more accurately captures the observed data at the three stations, in part this may reflect the different time periods used, with rather relatively good relationship to observation data between the two reanalysis at most cases, with poorer performance observed at Nalute, particularly warm seasons; spring and summer

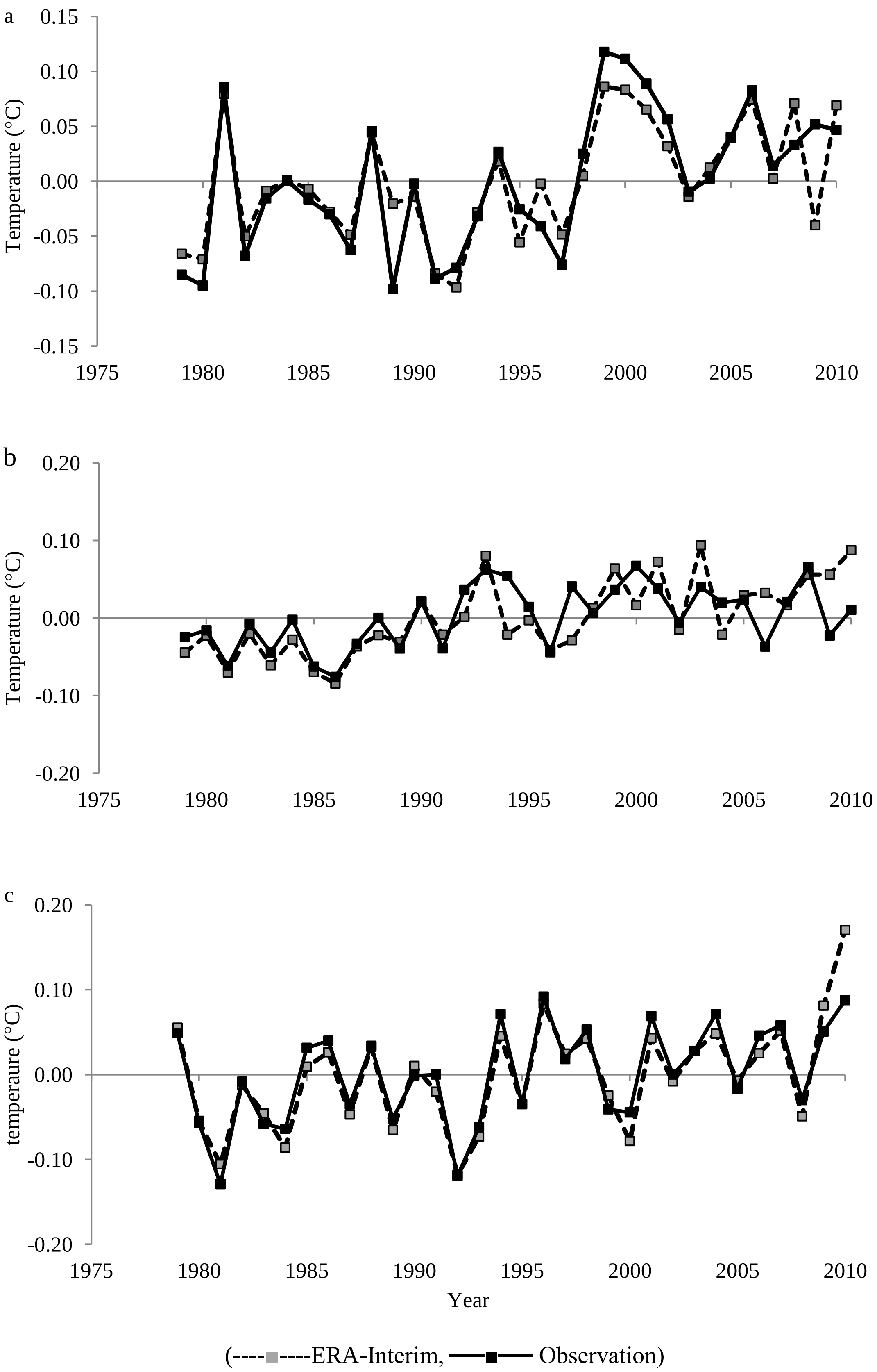


Fig. 7.6: Normalised seasonal mean average temperature anomalies of observation and ERA-Interim data at; a) Nalute (spring); b) Hon (autumn) and c); Ajdabyia (winter).

7.4 TEMPORAL CHANGES AND TRENDS IN TEMPERATURE

In order to examine changes and trends in temperature, a time series of the observed and modelled (NCEP/NCAR-1948-2010 and ERA-interim-1979-2010) data of mean average temperature for Ajdabyia, Hon and Nalute has been analysed based on the nonparametric Mann-Kendall test, which is used to estimate the statistical significance of trends within series. Trends in mean average temperature are general positive (increase) during the time period. The temporal trend patterns of the observed and modelled NCEP/NCAR and ERA-interim data of mean average temperature are in reasonable agreement during the study period for the three stations (Fig.7.3-7.6).

7.4.1 Annual variations and trends

The result of the Mann-Kendall test shows general positive trends in mean annual average temperature (Table 7.1). The observation data (1948-2010) shows significant (***) increases in mean average temperature at Ajdabyia (0.028 °C a^{-1}), Hon (0.063 °C a^{-1}) and Nalute (0.028 °C a^{-1}), with a positive trend (0.015 °C a^{-1}) in the NCEP/NCAR reanalysis only at Ajdabyia. Negative trends are showed in the NCEP/NCAR data at Hon (-0.009 °C a^{-1}) and Nalute (-0.001 °C a^{-1}), with significant decrease (+) at Hon.

Table 7.1: Mann-Kendall statistic (Q) for annual mean average temperature of observed and modelled NCEP/NCAR and ERA-Interim data, with statistical significance levels

Data		NCEP/NCAR (°C a^{-1})	Observation (°C a^{-1})	ERA-Interim (°C a^{-1})	Observation (°C a^{-1})
Stations	Time period	1948-2010		1979-2010	
Ajdabyia	Sig	***	***	***	***
	Q	0.015	0.028	0.044	0.051
Hon	Sig	+	***	*	***
	Q	-0.009	0.063	0.008	0.041
Nalute	Sig		***	***	***
	Q	-0.001	0.028	0.037	0.040

The observed data indicate highly significant (***) increases in trends during the period 1979-2010 at the three stations, with : Ajdabyia (0.051 °C a^{-1}), Hon (0.0413 °C a^{-1}) and Nalute (0.040 °C a^{-1}), with significant (***) increases trends in the ERA-interim reanalysis data indicating at Ajdabyia (0.044 °C a^{-1}), and Nalute (0.037 °C a^{-1}) and significant (*) at Hon (0.008 °C a^{-1})

7.4.2 Seasonal and sub-seasonal variations and trends

In order to examine changes and trends in temperature, a time series of seasonal observation and modelled (NCEP/NCAR and ERA-interim) data of mean average temperature for Ajdabyia, Hon and Nalute are analysed based on the nonparametric Mann-Kendall test (Mitchell et al., 1966; Sneyers, 1999).

7.4.2.1 Variations and trends of NCEP/NCAR and observed seasonal and sub-seasonal means average temperature

The result of the Mann-Kendall test identified a general positive trends in mean seasonal temperature in both observed and modelled NCEP/NCAR data for most seasons at the three stations during the period 1948-2010, with the exception of NCEP/NCAR data at Hon (summer and autumn) and Nalute (winter; see Table 7.2).

Positive trends in observed winter temperature are identified at the three stations (0.017 °C a^{-1}) and in the NCEP/NCAR datasets for Ajdabyia and Hon (0.031 °C a^{-1}) in NCEP/NCAR, with the winter rate of observed trends characterized by generally higher trends compared to the NCEP/NCAR at three stations.

Positive trends are identified in spring mean average temperature at the three observation stations (0.008 °C a^{-1}) and in the NCEP/NCAR data (0.050 °C a^{-1}), with the observed station trends characterized by considerably higher rates compared to the NCEP/NCAR, with rates of change which are different at Hon and Nalute.

Increases trend in mean average summer temperature is found in the observational data at the three stations (0.034 °C a^{-1}) and lower trends are found in the NCEP/NCAR data at Ajdabyia and Nalute (0.009 °C a^{-1}), with the observational trend generally characterized by much higher rates compared to the NCEP/NCAR at these two stations and with similar trend rates at Ajdabyia

Table 7.2: Mann-Kendall statistic (Q) for seasonal mean average temperature of observed and modelled NCEP/NCAR and ERA-Interim data, with statistical significant levels

Stations	Seasonal		Sig	Q		Sig	Q
Ajdabyia	Winter	NCEP/NCAR	**	0.014	ERA-Interim	*	0.042
		Observation	***	0.016	Observation	*	0.034
	Spring	NCEP/NCAR	*	0.011	ERA-Interim	*	0.040
		Observation	***	0.032	Observation	**	0.044
	Suer	NCEP/NCAR	*	0.013	ERA-Interim	**	0.035
		Observation	***	0.025	Observation	***	0.057
	Autumn	NCEP/NCAR	***	0.021	ERA-Interim	***	0.047
		Observation	**	0.021	Observation	***	0.052
Hon	Winter	NCEP/NCAR	**	0.019	ERA-Interim		0.005
		Observation	***	0.055	Observation	***	0.027
	Spring	NCEP/NCAR		0.011	ERA-Interim	+	0.011
		Observation	***	0.090	Observation	***	0.042
	Summer	NCEP/NCAR	***	-0.048	ERA-Interim		0.008
		Observation	***	0.048	Observation	***	0.040
	Autumn	NCEP/NCAR	+	-0.012	ERA-Interim	+	0.013
		Observation	***	0.061	Observation	***	0.052
Nalute	Winter	NCEP/NCAR		-0.008	ERA-Interim		0.035
		Observation	**	0.021	Observation	+	0.032
	Spring	NCEP/NCAR		0.003	ERA-Interim	*	0.057
		Observation	***	0.028	Observation	**	0.069
	Summer	NCEP/NCAR		0.006	ERA-Interim	*	0.039
		Observation	***	0.029	Observation	*	0.041
	Autumn	NCEP/NCAR		0.001	ERA-Interim	*	0.031
		Observation	***	0.034	Observation	*	0.047

Positive trends in observed autumn temperature are found at the three stations (0.011 °C a^{-1}) and NCEP/NCAR (0.039 °C a^{-1}) at Ajdabyia and Nalute, with higher observed trend rates compared to the NCEP/NCAR (about 66%) similar rates at Ajdabyia.

Significant increases are identified in both observed and NCEP/NCAR reanalysis temperature data at the three stations, with different confidence levels. The observational data are characterized by higher and or equal significant trends compared to the modelled NCEP/NCAR data at most cases, with except at Ajdabyia (autumn; Table 7.2).

7.4.2.2 Variations and trends of ERA-interim and observation data seasonal means average temperature

The result of the Mann-Kendall test identified generally positive trends in mean average temperature in the observed and modelled data (ERA-interim), at the three stations in all seasons during the period 1979-2010 (Table 7.2). The trend rates in mean average temperature of the ERA-interim reanalysis dataset are characterized by generally higher trends compared to the NCEP/NCAR, with ranges from 58% (winter) to more than 300% (spring).

Positive trends in observed winter temperature are identified at the three stations (0.027 °C a^{-1}) and in the ERA-Interim datasets (0.031 °C a^{-1}) , with the rate of trends in observed trend characterized by generally higher trends compared to the ERA-Interim (14%) and are similar at Nalute and different at Hon (see Table 7.2).

Positive trends are identified in observed spring mean average temperature (0.036 °C a^{-1}) and in the ERA-Interim datasets (0.052 °C a^{-1}) at the three stations, with the rate of observed trends characterized by higher rates compared to the ERA-Interim (44%), with rates of changes are similar at Hon and Ajdabyia.

Increases trend in mean average summer temperature is found in the observational data(0.027 °C a^{-1}) and in the ERA-Interim (0.046 °C a^{-1}) at the three stations, with observational trend generally characterized by higher rates compared to the ERA-Interim (70%) and with different at Hon.

Positive trends in observed autumn temperature (0.030 °C a^{-1}) and the ERA-Interim (0.050 °C a^{-1}) are identified at the three stations, with higher observed trend rates compared to the ERA-Interim about (66%) and similar rates at Nalute and different at Hon. Significant increases are identified in both observed and ERA-Interim reanalysis temperature at the three stations with different confidence levels.

7.5 DIFFERENCES BETWEEN THE OBSERVATIONS AND MODELLED MEAN AVERAGE TEMPERATURE DATA

In order to examine significant differences in temperature, variability of the observed and reanalysis (NCEP/NCAR 1948-2010 and ERA-Interim 1979-2010) annual, seasonal and monthly mean average temperature for the selected stations; Ajdabyia, Hon and Nalute were analysed based on a student's t test at 95% confidence level Rusticucci and Kousky, 2002). The observed and NCEP/NCAR reanalysis data (1948-2010) showed significant annual differences at Hon and Nalute (Fig 7.7). Significant seasonal differences are found at Hon, Nalute and Ajdabyia, with except in winter and summer at Ajdabyia. Significant differences are found in all months at Hon and number of months at Nalute and Ajdabyia (Table 7.3).

The observed and ERA-Interim reanalysis data (1979-2010) showed significant seasonal and annual differences at Ajdabyia and Nalute, except in winter at Nalute, with no significant seasonal and annual differences at Hon. (Fig 7.7). Significant differences are found in most of months at Ajdabyia and Nalute (Table 7.3).

Table 7.3: Significant (95% confidence level *) annual, seasonal and monthly differences in mean average temperature of observed and modelled NCEP/NCAR and ERA-Interim data.

	Observed and NCEP/NCAR				Observed and ERA Interim		
	Ajdabyia	Hon	Nalute		Ajdabyia	Hon	Nalute
Annual		*	*	Annual	*		*
Winter		*	*	Winter	*		
Summer		*	*	Summer	*		*
Spring	*	*	*	Spring	*		*
Autumn	*	*	*	Autumn	*		*
Jan.	*	*	*	Jan.	*		
Feb.	*	*		Feb.	*		
Mar.		*		Mar.	*		*
Apr.		*	*	Apr.	*		*
May		*	*	May	*		*
Jun.	*	*	*	Jun.	*		*
Jul.		*	*	Jul.	*		*
Aug.		*	*	Aug.	*		*
Sep.	*	*		Sep.	*		*
Oct.	*	*	*	Oct.	*		
Nov.	*	*	*	Nov.			
Dec.		*	*	Dec.			

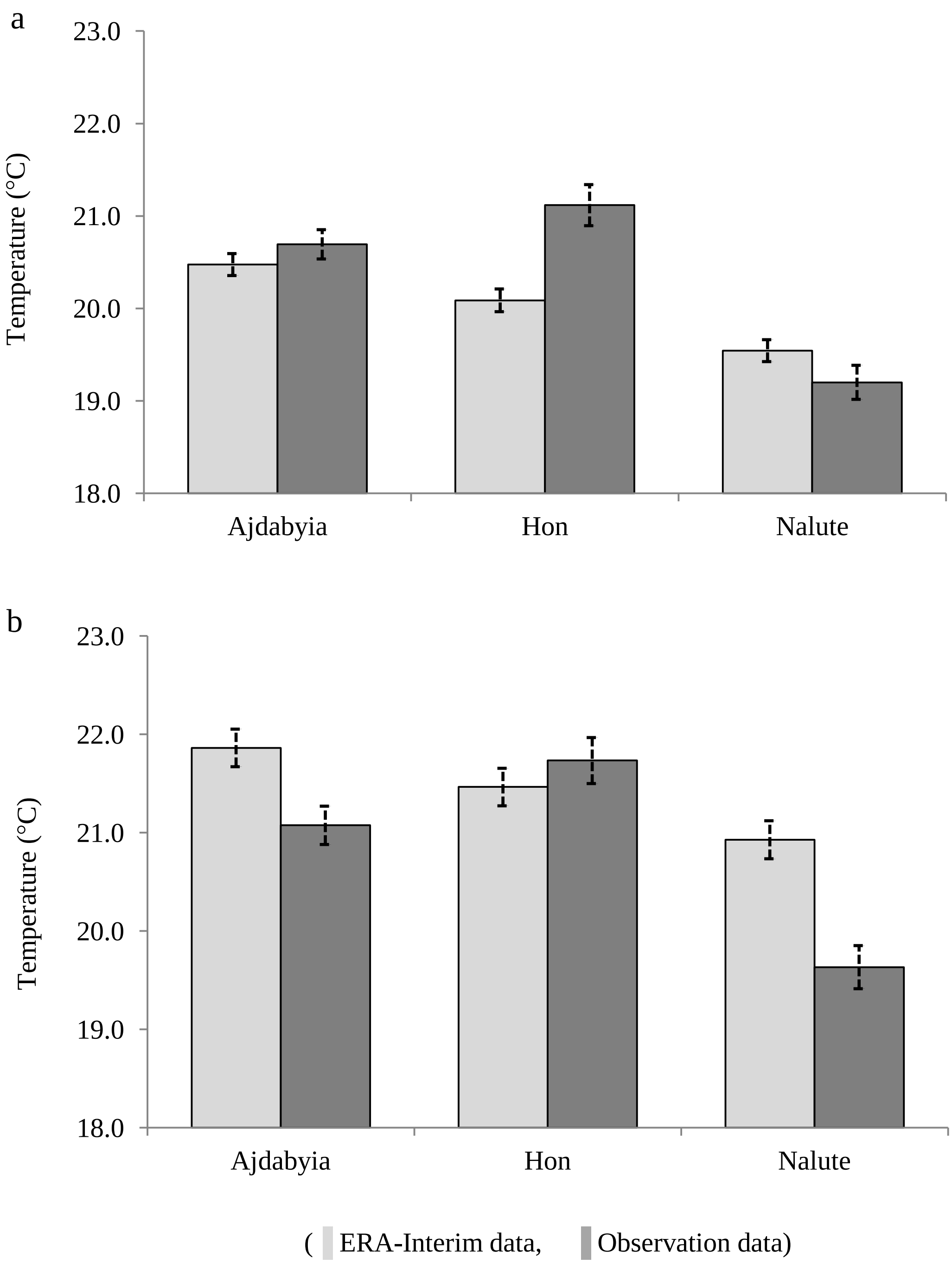


Fig. 7.7: Mean annual average temperature for a) observation and ERA-Interim data; b) observation and NCEP/NCAR data with error bars representing two standard errors (95.4% confidence level).

7.6 CORRELATION BETWEEN THE OBSERVATIONS AND MODELLED MEAN AVERAGE TEMPERATURE DATA

On the basis of the correlation between seasonal and annual mean average temperature of the observational and modelled NCEP/NCAR and ERA-Interim data at the representative stations of Ajdabyia, Hon and Nalute for the periods study have been calculated based on Person Product-Moment correlations coefficient (Rusticucci and Kousky, 2002; Mooney et al., 2011).

7.6.1 Annual correlation

Strongly significant positively correlation is identified between the annual observed and modelled NCEP/NCAR data (Table 7.4), with a correlation coefficient (*r)* of 0.77 (Ajdabyia), 0.68 (Hon) and 0.55 (Nalute) during the period 1948-2010 (Fig. 7.8).

Table 7.4: Correlation coefficient *(r)* between observations and modelled (NCEP and ERA-Interim) data

		Correlation coefficient (*r)*	
Stations	Seasonal	NCEP/NCAR	ERA-Interim
Ajdabyia	Annual	0.77	0.96
	Winter	0.91	0.94
	Spring	0.68	0.90
	Summer	0.82	0.94
	Autumn	0.79	0.95
Hon	Annual	0.68	0.66
	Winter	0.74	0.75
	Spring	0.67	0.88
	Summer	0.72	0.90
	Autumn	0.76	0.68
Nalute	Annual	0.51	0.91
	Winter	0.70	0.82
	Spring	0.77	0.92
	Summer	0.67	0.89
	Autumn	0.72	0.83

The correlations between observed annual mean average temperature and modelled ERA-Interim reanalysis data are in most cases characterized by considerable higher values compared to those observed when assessing the observed and NCEP/NCAR reanalysis dataset, with a (*r*) of 0.96 (Ajdabyia),0.91 (Nalute) and 0.66 (Hon; Fig. 7.8). This is result of less influence from climatic change due to the different periods of the study between the ERA-Interim (32 years) and NCEP/NCAR (62 years)

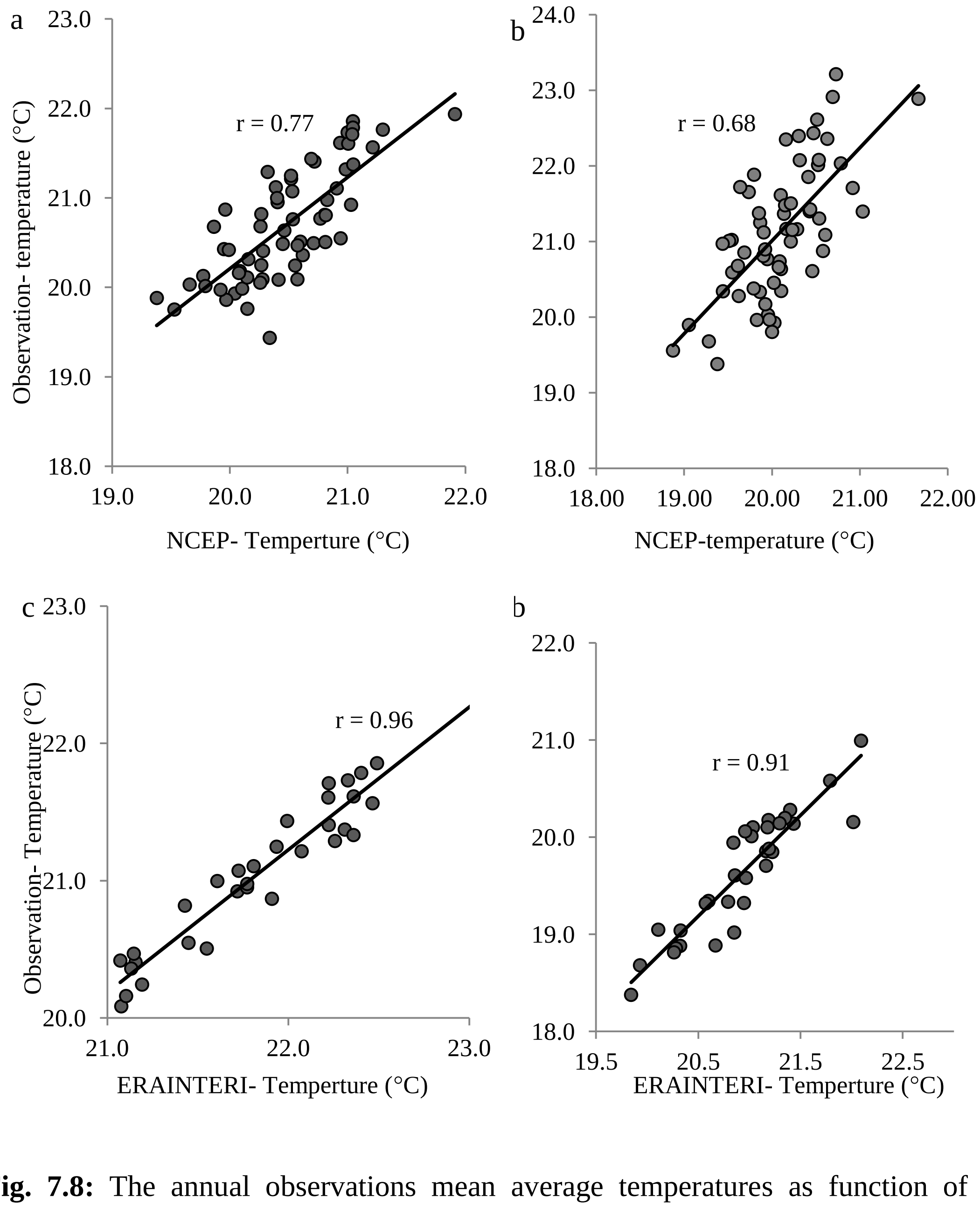


Fig. 7.8: The annual observations mean average temperatures as function of a) NCEP/NCAR at Ajdabyia; and b) Hon; b) Nalute c) ERA-Interim at Ajdabyia; and d) Nalute.

7.6.2 Seasonal correlation

The correlations between seasonal observations and modelled NCEP/NCAR mean average temperature were analysed for the period 1948-2010. Strong positive correlation between all mean seasonal observations and modelled NCEP/NCAR data re found, with correlation coefficient (*r)* ranges between 0.91 (Ajdabyia) in winter and 0.67 (Nalute) in spring (see Appendix 7.3a and b).

Strong positive correlations are found for all seasons between observed and modelled ERA-Interim temperature data, with (*r)* ranges between 0.95 (Ajdabyia) in autumn and 0.75 (Nalute) in winter. The relationships between observed and modelled ERA-Interim temperatures characterized by considerable higher correlation values compared to those derived from the NCEP/NCAR data. Moreover correlation between observed and modelled NCEP/NCAR and ERA-Interim temperatures data at Ajdabyia characterized by considerable by higher correlation values compared to the Hon and Nalute and in winter compared in other seasons at all stations, The differences attributed to the shorter period of the ERA-Interim (1979-2010) data compared to the NCEP/NCAR data (1948-2010).

7.7 SPATIAL VARIABILITY OF PRECIPITATION

In this paragraph, spatial and geographical variability and distribution annual precipitation based on reanalysis and observed data for the three stations is analysed, focusing on annual total precipitation. The synoptic stations; Ajdabyia, Hon and Nalute are distributed across Libya, represented coastal and inland regions have been selected for comparison of monthly and annual variability in the reanalysis data (NCEP/NCAR, 1948-2010 and ERA-Interim, 1979-2010) and observed temperature data. In addition, an assessment of the ability of the reanalysis data to predict precipitation is undertaken. Two different observations boxes whisker plots with the two reanalysis NCEP/NCEP (1948-2010) and ERA-Interim (1979-2010) precipitation data (Fig. 7.9). The mean average annual total precipitation is 149.5 mm (Ajdabyia), 29.6 mm (Hon) and 146.5 mm (Nalute).

The distribution of observed and reanalysed precipitation data at each station is illustrated in Fig. 7.9, with median; mean, 25th percentile, 75th percentile, and standard deviation, minimum and maximum precipitation shown.

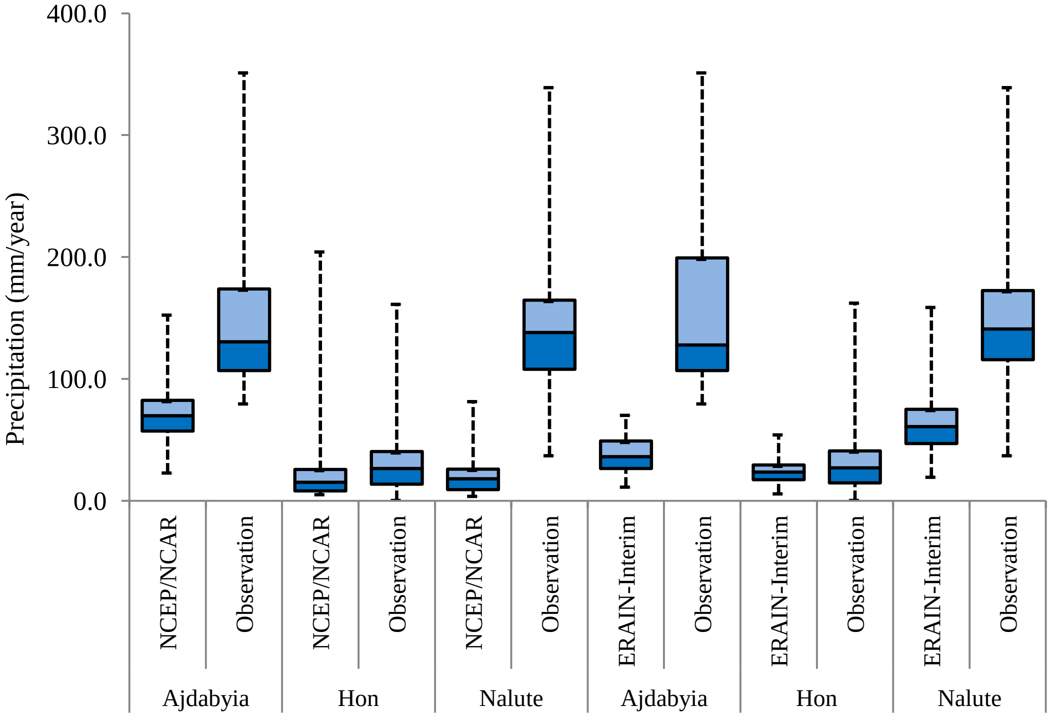


Fig. 7.9: Ranges in annual total precipitation of observation and modelled data (NCEP/NCEP and ERA-Interim) data at Ajdabyia, Hon and Nalute, with maximum, minimum, lower quartile (first quartile–25%), median (50%) and the upper quartile (third quartile –75%).

The precipitation statistics in observation and reanalysis data are relatively comparable, with the median observational precipitation at Ajdabyia ranging between 148.6 mm a^{-1} (1948-2010), 159.2 mm a^{-1} (1979-2010), with the median precipitation reanalyse ranging between 72.1 mm a^{-1} (NCEP) and 37.7 mm a^{-1} (ERA-Interim) .

The median observed precipitation at Nalute ranges between 148.1mm a^{-1} (1948-2010), 145.3 mm a^{-1} (1979-2010), with the median precipitation reanalyse ranging between 22.3mm a^{-1} (NCEP/NCAR) and 64.1mm a^{-1} (ERA-Interim). The median observed precipitation in Hon ranges from 31.3 mm a^{-1} (1948-210) and 33.2 mm a^{-1}

(1979-2010), with the median precipitation reanalyse ranging between 28.2 mm a^{-1} (NCEP/NCAR) and 33.2 mm a^{-1} (ERA-Interim).

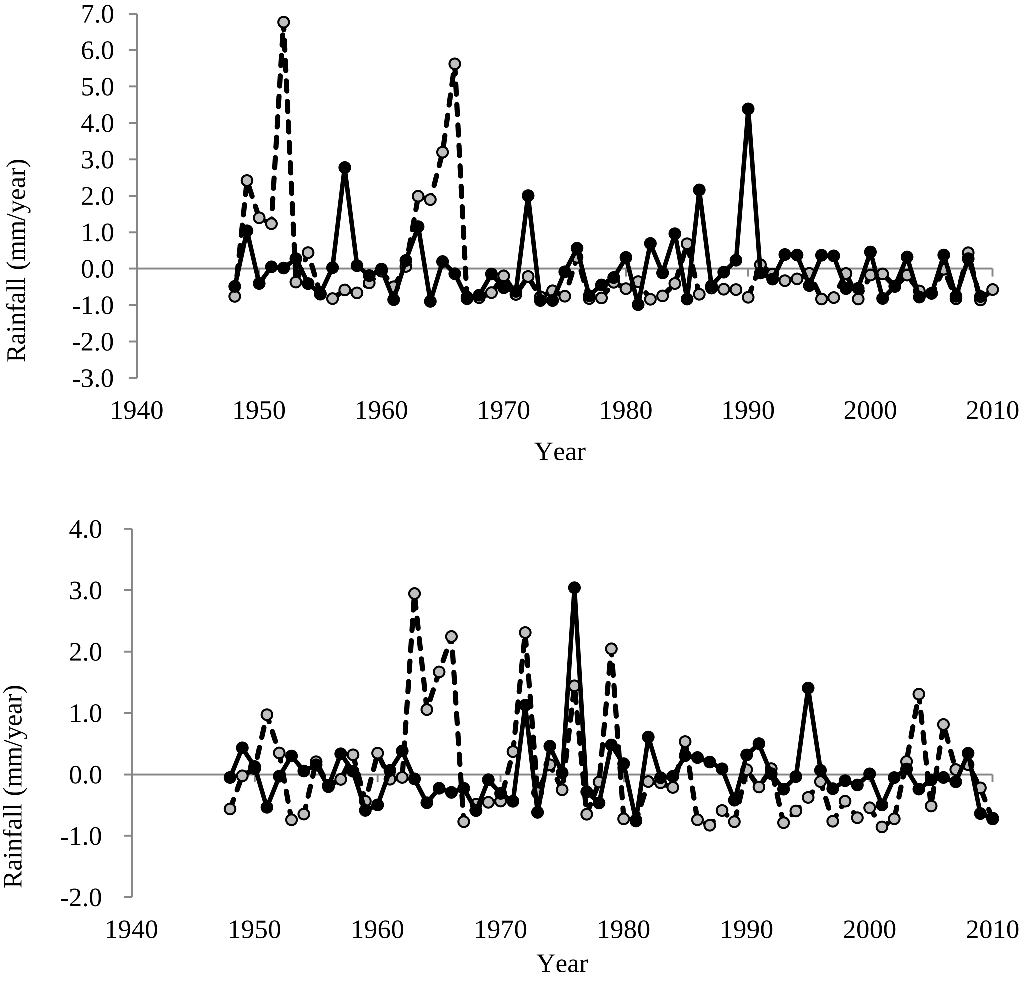
However, low variability in precipitation between observed and reanalyse data are identified at the inland station (Hon). The observed precipitation data characterized by higher annual compared to both NCEP/NCAR and ERA-Interim precipitation data

7.8 INTERANNUAL VARIABILITY IN PRECIPITATION

A number of studies have undertaken analysis of reanalysis datasets relative to observational series at a variety of temporal scales (Mooney et al., 2011). Xie and Arkin, 1997; Trenberth and Guillemot, (1998) have been conducted by Annual accumulations of the NCEP/NCAR and ERA-Interim data are compared with the observed data combined of three stations over the two periods of time 1948–2010 and 1979-2010.

7.8.1 Interannual of NCEP/NCAR and ERA-Interim with observation data of annual means total precipitation

The mean annual precipitation of three representative stations (Ajdabyia, Hon and Nalute) from the observed and reanalysis NCEP/NCAR and ERA-Interim are shown in Fig. 7.10 and 7.11. They show that reanalysis slightly captures the annual precipitation of both of both NCEP/NCAR and ERA-Interim during a few year of the study period. The temporal patterns of the NCEP/NCAR and observed data are in general agreement. Annual total precipitation is accurately captured at Ajdabyia within the NCEP/NCAR reanalysis dataset, with poorer performance at Hon during the periods 1952-1953, 1964-1968 and 1986-1990 and at Nalute during the periods 1950-1953, 1962-1968 and 1993-1995.



(-------- NCEP/NCAR, ——— Observation)

Fig. 7.10: Normalised annual precipitation anomalies of observation and NCEP/NCAR data at; a) Hon and: b) Nalute for the period 1979-2010.

The ERA-Interim reanalysis precipitation dataset accurately slightly more captures compared to the NCEP/NCAR reanalysis at all station. More accurate reanalysis is found at Hon (with the lowest total precipitation) compared to both Ajdabyia and Nalute. Slight changes are shown at Ajdabyia and Nalute, with poorer performance during periods e.g. the 5-years (1984-1988) at Ajdabyia and Nalute (Fig.7.11).

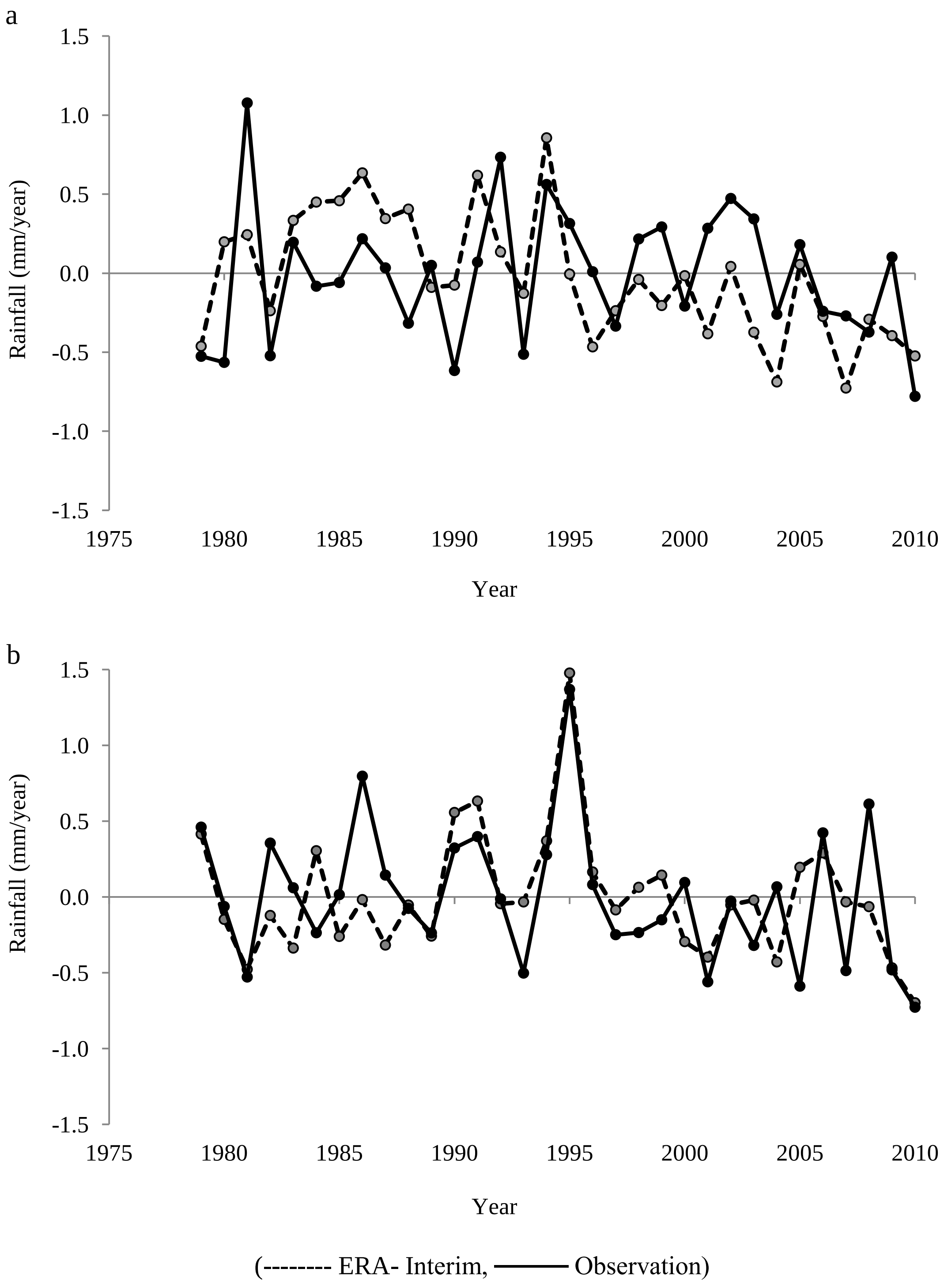


Fig. 7.11: Normalised annual precipitation anomalies of observation and ERA-Interim data at; a) Ajdabyia and: b) Nalute for the period 1979-2010.

7.8.2 Interannual of NCEP/NCAR and ERA-Interim with observation data of seasonal means total precipitation

The observed mean seasonal precipitation at Ajdabyia, Hon and Nalute provides reasonable agreement to both reanalysis datasets (NCEP/NCAR and ERA-Interim). The NCEP/NCAR reanalysis dataset captures the observed variability in seasonal precipitation during the period 1948-2010 in most seasons, with poorer performance at Hon in spring and at Nalute during all seasons (see Appendix 7.4a for all stations). The ERA-Interim reanalysis dataset and the observed seasonal precipitation provide comparable results during the period 1979-2010 for most seasons, with slightly poorer performance in spring and autumn (Fig. 7.12; see Appendix 7.4b for the remaining stations).

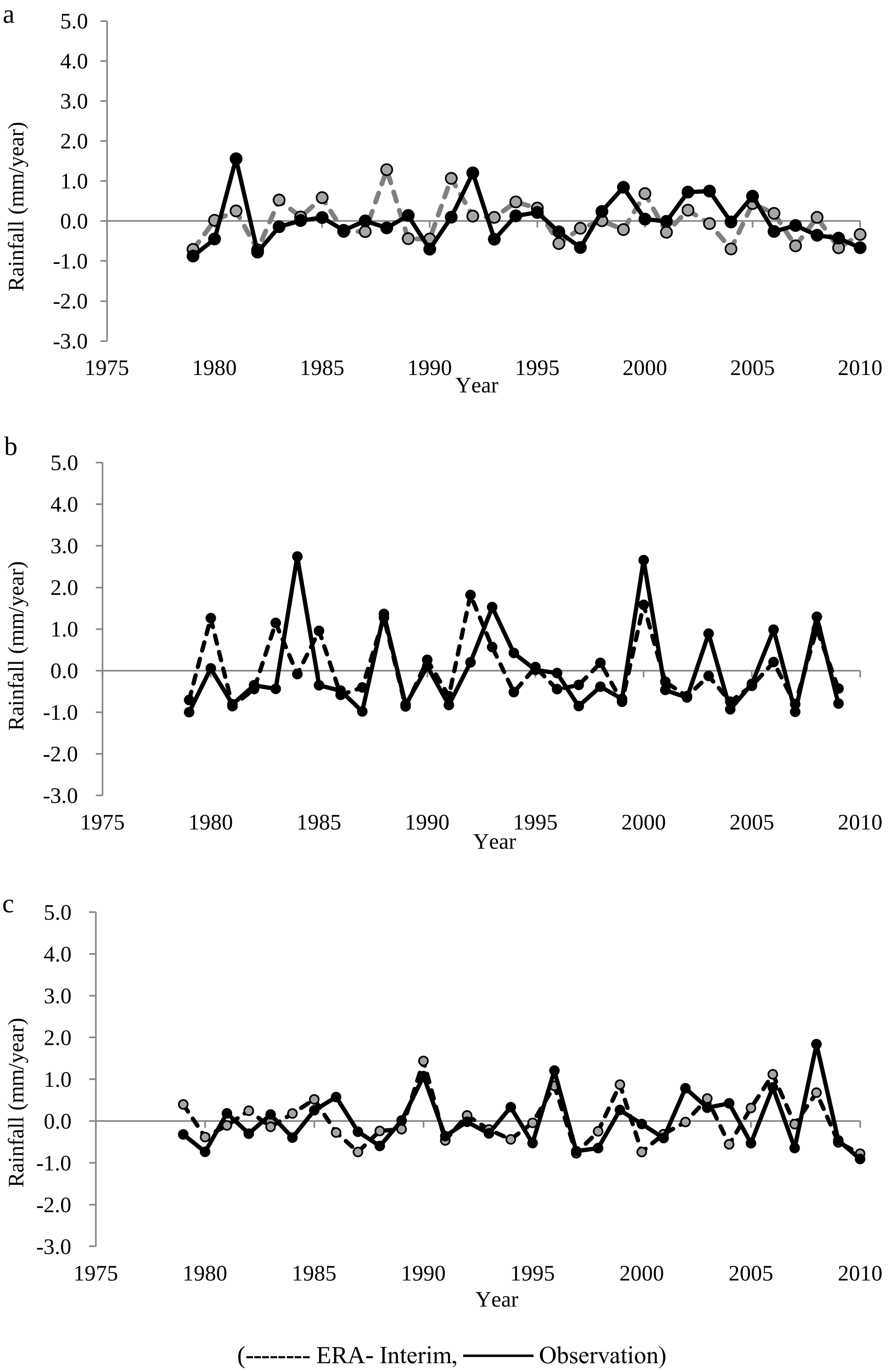


Fig. 7.12: Normalised seasonal precipitation anomalies of observation and ERA-Interim data at; a) Nalute (autumn), b) Ajdabyia (spring) and; Hon (winter) for the period 1979-2010.

7.9 TEMPORAL CHANGES AND TRENDS IN PRECIPITATION

The statistical significant of changes and trends in annual precipitation in the observed of observation and modelled (NCEP/NCAR, 1948-210 and ERA-Interim, 1979-2010) time series data for three stations Ajdabyia, Hon and Nalute are analysed using the nonparametric Mann-Kendall test (Mitchell et al., 1966; Sneyers, 1999). Observed precipitation is highly variable both temporally and spatially across Libya, as seen in Chapter 5 (Table 5.2 and Fig. 5.2) during the period 1945-2010.

7.9.1 Annual variations and trends

The temporal trend patterns of mean annual observed and modelled NCEP and the ERA-interim data are in general agreement at the study stations, with a few exceptions. The result of the non-parametric Mann-Kendall test shows negative trends in both observed and modelled precipitation at Nalute and Hon, with positive trend of observed and modelled data of NCEP/NCAR at Ajdabyia (Table 7.5).

Table 7.5: Values of the Mann-Kendall statistic (Q) for mean annual total precipitation of Observation and the modelled data of NCEP/NCAR and of ERA-Interim, with statistically significant levels at Ajdabyia, Hon and Nalute

Data		NCEP/NCAR (mm a^{-1})	Observation (mm a^{-1})	ERA-Interim (mm a^{-1})	Observation (mm a^{-1})
Stations	Time period	1948-2010		1979-2010	
Ajdabyia	Sig	+		***	
	Q	0.372	0.347	-1.02	-0.072
Hon	Sig			*	
	Q	-0.126	-0.015	-0.58	-0.416
Nalute	Sig	*			*
	Q	-0.169	-0.075	-0.167	-2.418

The NCEP/NCAR data (1948-2010) and Nalute (-0.169 mm a^{-1}), which are comparable, to the observational data which showed lower trend values of -0.015 mm a^{-1} at Hon and -0.075 mm a^{-1} at Nalute, with a significant decrease (*) of reanalysis NCEP/NCAR data at Nalute. Positive trend are identified at Ajdabyia in both observed and reanalysis (NCEP/NCAR) data, with significant (+) in reanalysis NCEP/NCAR.

Negative trends in precipitation are found in both the observed and modelled of ERA-interim (1979-2010) data during the study period at the three stations. The highest trend of modelled ERA-interim trend is -1.02 mm a^{-1} at Ajdabyia and the highest of observed trend is -2.42 mm a^{-1} at Nalute.

Annual total precipitation shows highly significant (***) increases in the ERA-interim reanalysed precipitation data at Ajdabyia and (*) at Hon, while data shows significant decrease (*) at Nalute and (+) at Ajdabyia in the NCEP/NCAR data (Table 7.5). The observed precipitation data characterized by generally lower compared to the both modelled of NCEP/NCAR (1948-2010) and ERA-interim (1979-2010) at the three stations.

7.9.2 Seasonal and sub-seasonal variations and trends

The Mann-Kendall test is used to estimate the statistical significance of trends in seasonal precipitation within the observed and reanalysis (NCEP/NCAR, 1948-2010 and ERA-Interim, 1979-2010) data at Ajdabyia, Hon and Nalute. The temporal patterns of mean seasonal precipitation in observed and reanalysis data are in agreement for most seasons (Table 7.6). In general, trend patterns in the modelled NCEP/NCAR seasonal precipitation data are very different to the observed trends at the three stations.

The results of Mann-Kendall test identify that the reanalysis NCEP/NCAR precipitation data showed decrease trends in spring at the three stations: -0.096 mm a^{-1} (Ajdabyia), -0.050 mm a^{-1} (Hon) and -0.049 mm a^{-1} (Nalute), these results are consistent with the observed spring data, except at Ajdabyia where a positive trend is identified. The reanalysis NCEP/NCAR Autumn data showed a negative trend at

Hon (0.030 mm a^{-1}) and Nalute (-0.006 mm a^{-1}), but a positive trend at Ajdabyia (0.030 mm a^{-1}), with agreed only at Hon.

Positive trends are found in reanalysis NCEP/NCAR and observational precipitation data at Ajdabyia and Hon, with negative at Nalute. Significant increase trends are identified at few cases; in spring at Hon and Nalute (*), autumn at Hon (**) and significant increase in winter at Nalute (*).

Table 7.6: Values of the Mann-Kendall statistic (Q) for seasonal precipitation (mm) of observation and reanalysis NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010), with statistically significant levels at Ajdabyia, Hon and Nalute.

Stations	Seasonal		Sig	Q		Sig	Q
Ajdabyia	Winter	NCEP	*	0.308	ERA-Interim		-0.178
		Obs.		0.221	Observation		0.547
	Spring	NCEP		-0.096	ERA-Interim	***	-0.265
		Obs.		0.054	Observation		-0.127
	Autumn	NCEP		0.030	ERA-Interim	**	-0.274
		Obs.		0.154	Observation		-0.580
Hon	Winter	NCEP		0.002	ERA-Interim		-0.019
		Obs.		0.039	Observation		0.017
	Spring	NCEP	*	-0.050	ERA-Interim	+	-0.153
		Obs.		-0.026	Observation		-0.196
	Autumn	NCEP	**	-0.030	ERA-Interim	*	-0.204
		Obs.	+	-0.054	Observation		-0.058
Nalute	Winter	NCEP		-0.043	ERA-Interim		-0.093
		Obs.		-0.100	Observation		0.195
	Spring	NCEP	*	-0.049	ERA-Interim		-0.178
		Obs.		-0.189	Observation	*	-1.418
	Autumn	NCEP		-0.006	ERA-Interim		-0.055
		Obs.		0.102	Observation		-0.888

The results of Mann-Kendall test (Table 7.6) identify that the reanalysis ERA-Interim precipitation data (1979-2010) showed decrease trends in all seasons at the three stations, with an average seasonal rate of the stations -0.097 mm a^{-1} (winter), -0.199 mm a^{-1} (spring) and -0.178 mm a^{-1} (autumn). The reanalysis ERA-Interim precipitation data showed negative are identified at three stations (-0.097 mm a^{-1}), in spring (-0.199 mm a^{-1}) and (0.0178 mm a^{-1}) in autumn, with higher decrease in reanalysis ERA-Interim data (-0.278 mm a^{-1}) in autumn, with the highest observed (-1.418 mm a^{-1}) in spring.

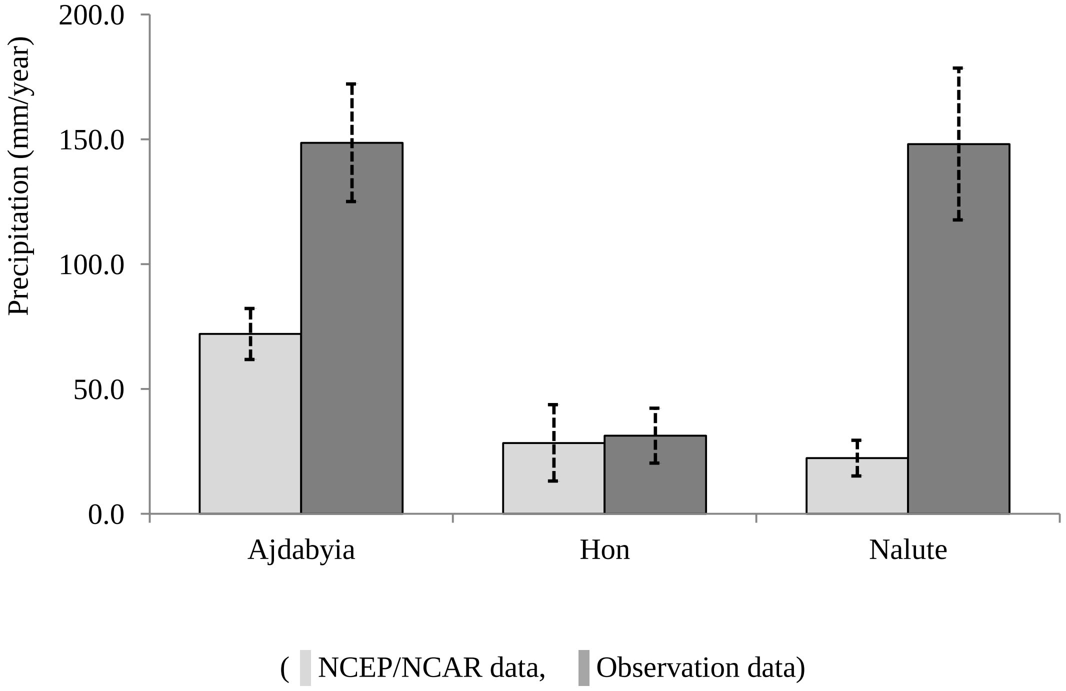
The rate of seasonal trends in observed data characterized by generally higher trend compared to the ERA-Interim at most of cases. In general, trend patterns of the reanalysis ERA-Interim seasonal precipitations characterized by lower rates compared to the observation data at the three stations (Table 7.6).

7.10 DIFFERENCES BETWEEN THE OBSERVATIONS AND MODELLED TOTAL PRECIPITATION DATA

In order to examine differences in precipitation, the variability of the observed and reanalysis data (NCEP/NCAR -1948-2010 and ERA-Interim-1979-2010) annual seasonal precipitation for the three stations; Ajdabyia, Hon and Nalute stations were analysed based on the Mann-Whitney test.

The observed and NCEP/NCAR reanalysis data (1948-2010) showed significant differences (95%) at Ajdabyia and Nalute (Fig 7.13). In contrast, a significant difference (95%) in monthly differences is found only at Hon. A significant in autumn is found at the three stations, while significant winter and spring at Hon and Nalute.

The observed and ERA-Interim reanalysis data (1979-2010) showed significant differences (95%) at Ajdabyia and Nalute, with not at Hon (Fig 7.13). In contrast, significant differences (95%) in monthly differences is found only at Hon. A seasonal significant is found in autumn at the three stations, while winter and spring are significant at Hon and Nalute.



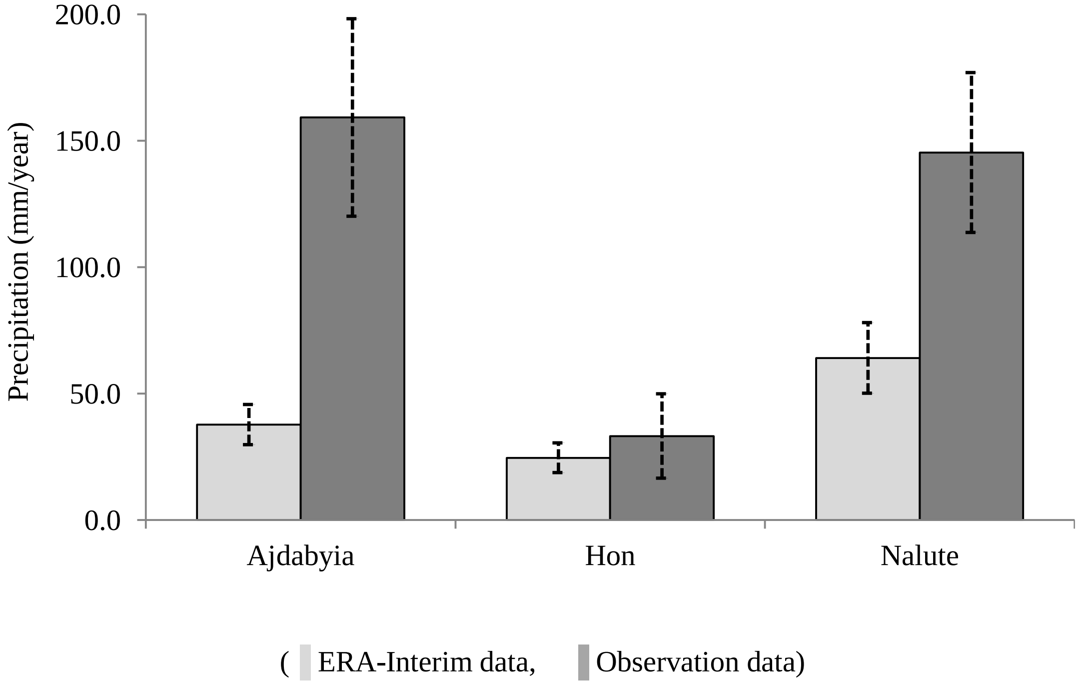


Fig. 7.13: Annual mean total precipitation for a) observation and NCEP/NCAR data; b) observation and ERA-Interim data with error bars representing two standard errors (95.4% confidence level).

7.11 CORRELATION BETWEEN THE OBSERVATIONS AND MODELLED PRECIPITATION DATA

To analyze precipitation across Libya, correlations between observation and both modelled of NCEP/NCAR and ERA-Interim seasonal and annual mean total precipitation at the representative stations of Ajdabyia, Hon and Nalute are plotted for the period's study (Fig. 7.14 and Table 7.7). Strongly positively correlation in the annual precipitation is found at Ajdabyia between the observations and modelled data of NCEP/NCAR data with a correlation coefficient (*r)* of 0.63, with high relationship between observational and reanalysis ERA-Interim with correlation coefficient *r* of 0.76 at Nalute (Table 7.7)

Table 7.7: Correlation coefficient *(r)* between observations and modelled (NCEP and ERA-Interim) data

		Correlation coefficient (*r)*	
Stations	Seasonal	NCEP/NCAR	ERA-Interim
Ajdabyia	Annual	0.63	0.43
	Winter	0.69	0.34
	Spring	0.49	0.43
	Autumn	0.68	0.59
Hon	Annual	0.10	0.41
	Winter	0.32	0.57
	Spring	0.24	0.47
	Autumn	0.14	0.43
Nalute	Annual	0.24	0.76
	Winter	0.28	0.61
	Spring	0.56	0.77
	Autumn	0.17	0.85

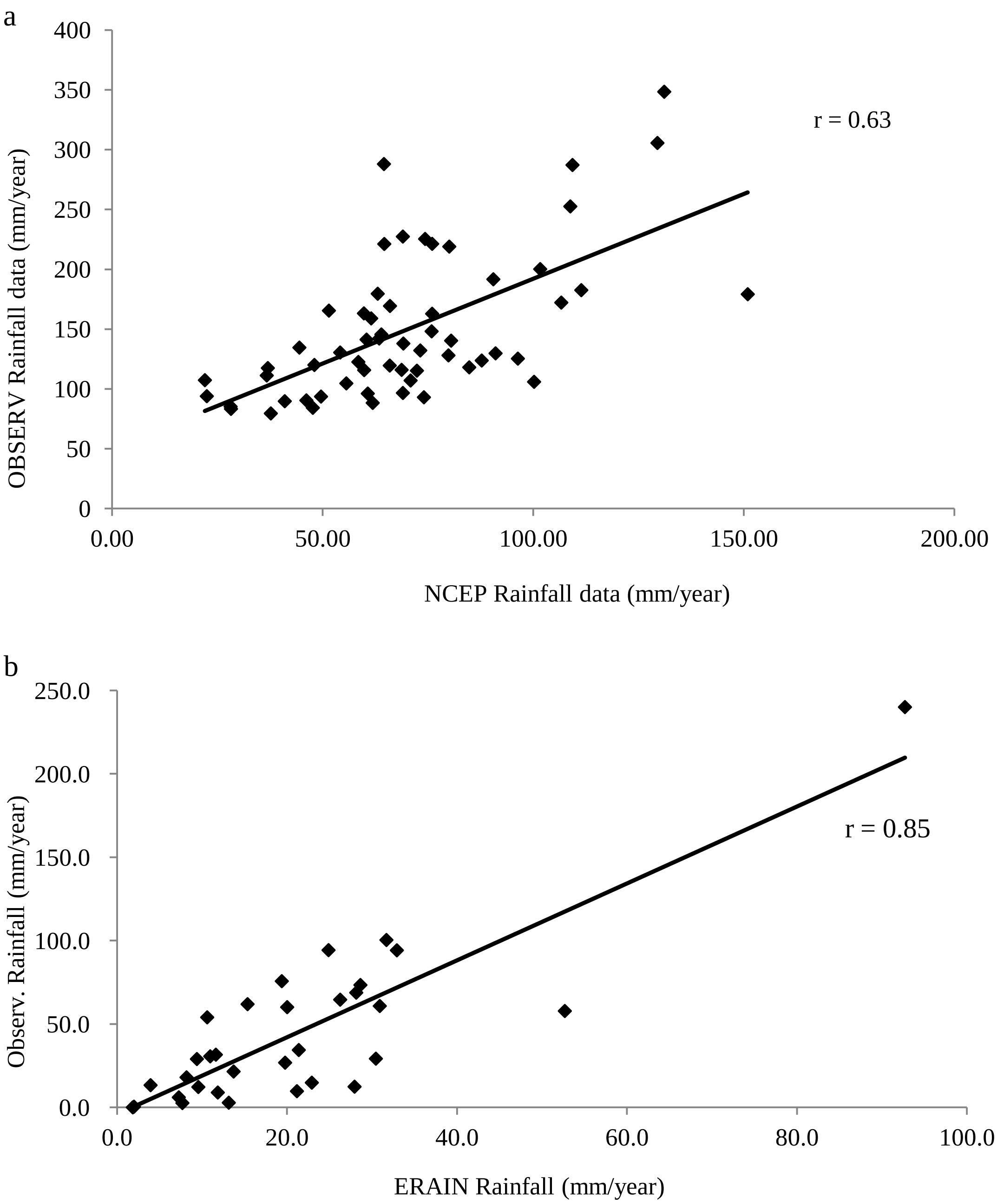


Fig. 7.14: The annual observation total precipitation as function on modelled data a) Ajdabyia of NCEP/NCAR; b) Nalute ERA-Interim

Correlations between observed and both modelled NCEP/NCAR and ERA-Interim seasonal precipitation are analysed. Strong positive correlations are found at Ajdabyia during all mean seasons, with a correlation coefficients (*r)* ranging between 0.49 (spring) and 0.69 (winter) against the NCEP/NCAR data, with (*r)* not exceed 0.59 against the modelled data in autumn.

A strong positive correlation is found at Nalute during winter, spring and autumn between the observed and modelled ERA-Interim data, with the lowest correlation coefficient (*r)* 0.85 in autumn, in comparison the NCEP/NCAR reanalysis data does not exceed *(r)* 0.65 at Nalute in spring. Moderate positive correlation are identified between observed and modelled ERA-Interim seasonal data at Hon, with the highest correlation coefficient (*r)* of 0.57 (winter) and no correlation coefficient (*r)* against NCEP/NCAR at Hon.

7.12 DISCUSSION

A comparison of the relationships between the observed and reanalysis NCEP/NCAR and ERA-Interim datasets for mean average temperatures and total precipitation at the three stations; Ajdabyia, Hon and Nalute have been made. Change and trends in the observed and modelled data of temperature and precipitation for the three stations also considered. Changes in mean average temperature and total precipitation are comparable changes and trends identified at both global and regional levels in previous studies (e.g. Janowiak et al., 1998; Poccard et al., 2000; Flocas et al., 2005; Mooney et al., 2011; Nastos et al., 2011).

7.12.1 Mean average temperature

The modelled ERA-Interim median values are characterized as higher compared to the observed data at Ajdabyia (3.8%) and Nalute (10%), where the NCEP/NCAR data is similar, except at Nalute (higher 2.6%). There is general good agreement in mean average temperature between the NCEP/NCAR reanalysis and observed data, showing variations of about 0.22 °C for Ajdabyia, 0.34 °C for Nalute and about 1.03 °C for Hon (the series with the highest annual temperature). The changes in the ERA-Interim values are slightly more than NCEP/NCAR values at Ajdabyia (0.78 °C) and Nalute (1.03 °C), but is relatively low (0.16 °C) at Hon. The spring and summer ERA-Interim values are very close at both Hon and Ajdabyia.

Mooney et al., (2011), identified good agreement in air surface temperature the three reanalysis datasets (ERA-40, ERA-Interim and NCEP/NCAR) with observed data at

11 synoptic stations in Ireland (1989–2001) and with each other. This finding is supported by Flocas et al. (2005) who found good agreement between observed and NCEP-NCAR reanalysis maximum and minimum temperatures datasets, with some regional and seasonal differences existing across Greece 1958–2000.

Significant increases are identified in observed and NCEP/NCAR and ERA-Interim reanalysis seasonal temperature datasets at the three stations with different confidence levels, where the observed data shows stronger significance compared to both NCEP/NCAR and ERA-Interim reanalysis data.

Strongly positive correlation in annual temperature are identified between the observed and reanalysis data (NCEP/NCAR), with correlation coefficient (*r)* of 0.77 (Ajdabyia) and 0.68 (Hon) and moderately positively correlation (*r)* of 0.55 at Nalute (1948-2010). The correlations between observation and ERA-Interim reanalysis data is characterized by considerable higher values compared to the NCEP/NCAR, with (*r)* 0.96 at Ajdabyia and 0.91 at Nalute, but slightly lower (*r)* of 0.66 at Hon. Strong positive correlations in the seasonal observations and modelled ERA-Interim temperature data are found, with a (*r)* range between 0.95 (Ajdabyia) in autumn and 0.75 (Nalute) in winter. The mean seasonal observations and modelled ERA-Interim temperature data though all seasons are strongly (positive) correlated, with (*r)* ranges between 0.95 (Ajdabyia) in autumn and 0.75 (Nalute) in winter. This finding is supported by Nastos et al., (2011), who found similar high seasonal correlations *(r)* in minimum and maximum temperature across 26 meteorological stations in Greece (1955–2001).

7.12.2 Precipitation

Observed precipitation data is higher than both NCEP and ERA-Interim data by 10% (Ajdabyia), 34% (Hon) and higher more than at Nalute. The temporal patterns in annual precipitation in the observed and reanalysis NCEP/NCAR data are in reasonable agreement, with slightly closer capture of the observed patters in the ERA-Interim reanalysis dataset relative to the NCEP/NCAR. This is comparable to the good agreement found by Janowiak et al. (1998) in large scale features when comparing monthly precipitation from NCEP–NCAR reanalysis and the GPCP rain gauge–satellite dataset over the period 1988–1995, with rather poor agreement in some regional areas.

The NCEP/NCAR annual precipitation reanalysis shows negative trends (- 0.126 mm a^{-1}) at Hon and (-0.169 mm a^{-1}) Nalute. Negative trends in annual precipitation series are found in both of the observational and modelled of ERA-interim data at the three stations. The rates in observed trend are generally higher compared to modelled NCEP/NCAR data (1948-2010); a similar pattern is found in the ERA-interim dataset with higher trends compared to the observed at Ajdabyia and Hon.

The trend patterns of the reanalysis ERA-Interim seasonal precipitations are characterized by relatively lower compared to the observation data at the three stations. The trends of observational and reanalysis NCEP/NCAR precipitation data is almost agreement in annual and some seasons. The observational and reanalysis NCEP/NCAR precipitation data showed significant differences (confidence level 95%) in annual precipitation at Ajdabyia and Nalute, while significant differences in autumn at the three stations and at Hon and Nalute in spring and winter.

Strong positively correlations in annual precipitation are found at Ajdabyia between the observations and NCEP/NCAR reanalysis data with a correlation coefficient (*r)* of 0.63 at Nalute, with a similar relationship identified between the observed and ERA-Interim reanalysis (*r)* of 0.76. Strong positive correlated series are found at Ajdabyia during for all seasons between the observations and both modelled NCEP/NCAR and ERA-Interim data, with a correlation coefficient (*r)* ranges between 0.49 (spring) and 0.69 (winter) against the NCEP/NCAR data 0.59 (autumn) against the modelled data in autumn. Strongly positively correlated is found at Nalute during all mean seasons between the observations and modelled.

7.13 SUMMARY

Libya is a country with considerable climatic variability, from the Sahara to coastline, and from the internal mountainous uplands to the Green Mountains along the NE coast. The reanalysis of the NCEP–NCAR and ERA-Interim gridded data should only be applied when taking into consideration the aforementioned limitations, which could not be represented properly by the reanalysis model (e.g. Nalute, located on 621 m a.m.s.l), with the differences between the two reanalysis data sets attributed to topographical factors such topography and land–sea distribution, which is not represented properly by the reanalysis model. The main findings of this Chapter are:

This thesis shows that, there is a generally good agreement in mean average temperature is found between the observed and ERA-Interim and NCEP/NCAR reanalysis datasets; with differences between the observed and reanalysis ERA-interim dataset averaging 0.53 °C and 0.66 °C with the NCEP/NCAR dataset. Significant increases are identified in annual and seasonal mean average temperature when comparing the observed and NCEP/NCAR and ERA-Interim reanalysis datasets. Strong positively correlation is identified between the observed and reanalysis NCEP/NCAR annual temperature. The ERA-Interim temperature data is characterized by considerable higher values compared to those generated by the NCEP/NCAR reanalysis, a result of the shorter period used within the ERA-Interim reanalysis (1979-2010).

According to the precipitation analysis, the observed total precipitation across Libya is characterized by being higher relative to each of the NCEP/NCAR and ERA-Interim reanalysis datasets by 10-34%; it could be attributed to the Libyan topographic features not being correctly represented by the reanalysis model. The reanalysis ERA-Interim precipitation dataset are in slightly higher agreement with observation compared to the NCEP/NCAR data, the reanalysis ERA-Interim designed for shorter period 1979-2010. Negative trends in precipitation are found in the observed and both reanalysis dataset, with good agreement to between the observation data and the reanalysis NCEP/NCAR.

The reanalysis NCEP/NCAR and ERA-Interim data provides stronger correlations to observed temperature than observed precipitation, with the ERA-Interim reanalysis providing higher values compared to the observed and NCEP/NCAR reanalysis. The analyses indicates good agreement between both sets of reanalysis NCEP/NCAR and ERA-Interim data in comparison to the observed mean average temperature, with significant increases in all observation and reanalysis data. Therefore, these findings could be used to compensate the modelled data for the missing observation data through a comprehensive study includes most of meteorological stations across Libya.

Chapter 8

CONCLUSION

This chapter reviews the aim, objectives and principal findings of the thesis providing an explanation of the key results and significant findings. The implications for future climate and further study are also considered.

In this thesis, analysis of variability in temperature (for 18 synoptic station; Table 4.1), precipitation (for 28 meteorological stations; Table 5.1), potential and actual evapotranspiration (for 16 synoptic stations; Table 6.1) and other climatic data; relative humidity, surface wind speed, sunshine duration and atmospheric pressure (for 16 meteorological stations; Table 6.1) was undertaken. The data used consisted of daily (1956-2010, 55 years), monthly (1945-2010, 65 years) and annual (1961-2010, 50 years) data. Data availability varied between stations, temperature and precipitation data are available for 1945 for all the 18 synoptic stations, while precipitation data is available from 1931 for a few stations. Daily data is available for 18 synoptic stations for temperature and precipitation (1956-2010), with data available until 2010 at all synoptic stations. Data availability for the other climatic parameters (relative humidity, surface wind speed, atmospheric air pressure, sun-shine duration) is limited prior for 1961, but good datasets are available after this date for all 16 synoptic stations. The reanalysis data sets NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010) for temperature and precipitation data grids covering the three stations: Ajdabyia, Hon and Nalute across Libya were considered.

8.1 SUMMARY AND DISCUSSION OF CLIMATIC PARAMETERS

8.1.1 Temperature

In this thesis, temperature has been analysed over almost all of Libya from data from all available stations across Libya. Variability of maximum, minimum and mean average temperature as well as the extremes of temperature has been studied across Libya for the period 1945-2010. To examine the long-term changes and trends of temperature in Libya, a number of graphical, trend analysis, measures of association and statistical trend detection methods are applied (Chapter 3). No clear relationships exist between rate of temperature changes and population growth for the cities studied across Libya based on the results in this thesis.

The results of temperature analysis for the 66 years (1945-2010) revealed significant increases in maximum, minimum and mean average temperature across Libya. There is a significant annual rate of change in maximum temperature (0.017 °Ca-1), with a particularly strong warming that began in the mid-1980s and rapid increases at double the previous rate (0.034 °Ca-1) during the last 33 years (1978-2010; Table 4.4). The significant increases in maximum temperature identified across Libya (1945-2010), are comparable with rates of global (Alexander et al., 2006; IPCC, 2007), regional (Ben-Gai et al., 1999) and local warming (Aesawy and Hasanean, 1998; El-Tantawi, 2005), which are affected by a number of natural factors and/or human activities and land use (e.g. Ben-Gai et al., 1999; El-Tantawi, 2005).

Based on the findings in this thesis, minimum temperature has rapidly increased at an average rate of 0.032 °C a-1 (1945-2010), with a much higher rate (0.051 °Ca-1) during the last 33 years (1978-2010). This is considerably faster than the IPCC (2007) global mean temperature increase of 0.74 °C ± 0.18 °C over the last 100 years. Comparable findings were found in Libya by El-Tantawi, (2005) (1946-2000) and El Kenawy et al., (2009) (1951-1999), but with lower rates of increasing minimum temperature.

Analysis using 66 years (1945-2010) of mean average temperature data has shown significant increases (0.024 °Ca-1), with a doubling of the warming rate (0.048 °Ca-1) for the last 33 years (1978-2010; Table 4.11); as a result of rapid increases in annual minimum temperature bringing the overall mean value up. This finding conflicts with that of El-Kenawy et al. (2012), who showed that most increases in mean average temperature in north-eastern Spain during the period 1920-2006 resulted from the increase in maximum temperature.

Analysis of annual minimum and maximum temperature using the 33 years (1978-2010) showed that, minimum temperature warming is characterised as more rapid compared to the maximum temperature. Therefore, the rate of increases in minimum night temperature is high compared to the increase in maximum day temperature, these findings are supported by El-Tantawi (2005), who indicated that, minimum temperatures rose at more than twice the rate of maximum temperatures across Libya during the period 1946-2000. Decreasing and no change in temperature parameters (maximum, minimum and mean average) are found during the first 33 years (1945-1977) across Libya. These findings are similar to El-Tantawi (2005), who found some negative trends in mean, minimum and maximum temperatures at most Libyan stations during the period 1946-1975. However, Philandras et al. (2008) identified cooling trends since the early 1960s until the mid-1970s across Greece. In contrast, Domroes and Eltantawi (2005), found negative trends in maximum temperature were observed across Egypt for the recent period, 1971–2000

Examination of annual average temperature for the two study periods (1945-1977 and 1978-2009) identified statistically significant (95% confidence level) increases, with the later period 1978-2009 warmer at all stations. This corroborates the concerns of rapid global warming and its impacts in this region. These results are consistent with previous regional and local research (e.g. Aesawy and Hasanean 1998; Ben-Gai 1999; El-Tantawi 2005; El-Kenawy et al., 2009), which showed a significant increases in temperature for different regions across the Mediterranean basin.

Seasonal temperature data indicates that rapid increases in maximum temperature took place in autumn, summer and spring, with the most rapid warming observed in summer and autumn. Minimum temperature increases averaging 0.035 °Ca-1, with mean seasonal averages in minimum temperature characterised as having higher rates of increase compared to maximum temperature, with the highest rates of increase in the warm season (April-September). These trends in maximum, minimum and mean average temperature are in general agreement with global, regional and local temperature trends since the late nineteenth century, which show the most rapid increase since the mid-1970s (IPCC, 2007; Hansen et al., 2013). The results of extreme temperature identified significant increasing trend in extreme cold temperature in monthly minimum value of daily minimum temperature (TNn) at all stations. A mixture of decreases and increases in maximum extreme temperature trends in monthly maximum value of daily maximum temperature (TXx) are also found.

8.1.1.1 Causes of increases temperature

Changes in the state of the climate system can occur due to natural reasons; external (e.g. variation in the solar out puts and suns pots) and/or internal (e.g. atmospheric compositions, atmospheric-oceanic oscillations and volcanic activity) actions. Houghton et al., (2001) suggested that natural climate forcing probably increased during the first half of the 20th century; reconstructions of climate during the 20th century indicate that the direct effect of variations in solar forcing over the last 10 decades was about 20-25% of the observed change, with the rest resulting from increases in greenhouse gases. Pidwirny (2004) suggested that 1% change of solar output constant caused a change in equilibrium temperature of about 0.6 °C. Jones et al. (2001) showed that the relationship between global annual temperature and sunspot number data over the 20th century is varied with changes in temperature higher during the first half of the 20th century (1901-1950) relative to the second half (1951-2000).

The interannual variability of temperature in the North Africa region is complex and controlled by many factors (Balas et al., 2007). The Pacific El Nino-Southern

Oscillation (ENSO) and North Atlantic Oscillation (NAO) phenomena play a role in interannual temperature variability in many regions through the world (e.g. Philander, 1990; Hurrell, 1995). Significant effects are observed on the anomaly variability patterns of precipitation over the arid and semiarid regions of North Africa by the North Atlantic Oscillation (NAO), while the El-Nino of the Southern Oscillation (ENSO) significantly affecting the variability over some regions in North Africa (Djomou et al., 2013).

Temperature variability can be associated to variations in large-scale atmospheric patterns represented by Eastern Atlantic and the Western Mediterranean Oscillations, resulting from increases in atmospheric circulation and anticyclone conditions in recent decades, which seem to play a significant role in explaining spatial and temporal variability of temperatures in the Mediterranean basin. Therefore, regional and local temperature trends can be strongly influenced by regional variability and changes in the climate system. In addition, It is believed that the volcanic eruptions can be responsible for changes (fall) in global annual average temperature by less than 1.0 °C (Pidwirny, 2004); this may explain why 1992 and 1993 were the coldest years in the 1990s with mean annual temperature in Libya potentially affected by the eruption of Mount Pinatubo .

Overgrazing in semi-arid areas leads to increased rates of albedo (as the fraction of the solar energy; shortwave radiation, reflected from the earth back into space), which have a greater irradiative heat loss than adjacent vegetated areas, by reflecting more sunlight compared to the crops, grasses and trees (Barry, 1977) that leads to changes in climate, which may influence climatic parameters (temperature, precipitation and evaporation).

According to the Technical Centre of Environmental Protection (TCEP, 1998), about half million ha were cleared during the period 1980-2000 in different regions across Libya (principally around Tripoli, Musratah Al-Jabal and Al-Akhdar) for seasonally irrigated plantations. Regional urbanization and industrialization are believed to be more influential on regional temperature than the global warming from 1951-2000

(Chung, et al., 2004). In Libya, the effects of urban heat islands on temperature and precipitation are very weak.

Latitude, altitude and land–sea distribution are the main physical and geographical factors controlling temperature and they seem to play a noticeable role to explaining variability of temperature in Libya (Al-Jadide, 1985; Emgailee 1995; Lama 1996; Ageena 2002; Ageena et al. 2012, 2013).

The changing composition of the atmosphere, including greenhouse gases and aerosol content, is a major internal forcing mechanism of climate change. The amounts of aerosols in the atmosphere produced by human activities are able to change the climate through changing the chemical and microphysical properties of clouds which absorb solar and infrared radiation. Total emissions of carbon dioxide ($CO_{2)}$ have sharply increased in Libya from 1960-2009, particularly during the last 30 years (1980-2010), with an increase from 693 tons in 1960 to 83,214,246 tons in 1980 and to 133,452,660 tons in 2009; a probable function of the expanding petrochemical and oil production in the country over the period. A positive (high) correlation is found between emissions of CO_2 and mean annual temperatures for the different regions, with values ranging from 0.36 to 0.84, with six cases exceeding 0.50; with some of the most rapid increases for sites in close proximity to large oil fields and exports centres, e.g. Ajdabyia, Zwarah, and Sabha.

The present study has revealed a number of results; the following are considered the main:

1. No clear evidence the relationships between population's effects and temperature in the most populated cites, where 40% of Libya's people resided, with the total population of Tripoli (1,065,405), Benghazi (670,797) and Musratah (550,980).
2. Warming could be attributed to changing desertification during the last 20 years, with more clear at Al-Jfarah plan and Green mountain regions
3. The relationship between mean annual temperatures and cloud cover are negative at most of coastal stations; with the exception of Tripoli Airport and Binina.

4. Increasing emissions of CO_2 since the early 1970s have had a pronounced effect on temperature increases at all stations across Libya (1960-2009).

8.1.2 Precipitation

The results of the study of variability in temporal and spatial precipitation in Libya are presented in Chapter 5, for the period 1945-2010. The data are analysed using a number of graphical, trend analysis, measures of association and statistical trend detection methods for sites across Libya. The results are comparable with the previous studies over the last half of the 20th century which examined spatial and temporal variability in local and regional (Mediterranean and North Africa) precipitation. In general, precipitation decreases sharply in a southward direction from the coast to the inland region, with a more gradual gradient west to east across Libya outside of the coastal region, with the Green Mountains in the northeast receiving some of the highest levels of precipitation in Libya; with about 50% of the years (1961-2010) receiving annual precipitation of 100-300 mm, whereas about 90% of the years at inland stations (Sahara) receive <50 mm.

Northern Libya is frequently affected by low pressure (depressions) associated with a branch of the westerly jet stream (Emgalee, 1995; Zikree 1998). These depressions are more frequent in winter, with only 28% of the total annual depressions resulting in effective precipitation over Libya (Libyan National Meteorological Centre, 2000).

Changes in seasonal precipitation trends across Libya has been identified, with negative autumn average trends (-0.241 mm S^{-1}), positive winter (0.435 mm S^{-1}) and spring (0.049 mm S^{-1}) average trends. As a consequence, seasonal and annual precipitation trends in Libya seem to be strongly affected by local factors including topography and land use, where the coastal region is mainly affected by Mediterranean convection processes, with the exception of central coast region.

Changes in seasonal precipitation trends during the last 66 years (1945-2010) expose well pronounced monthly, seasonal and annual patterns, with an increasing tendency in precipitation during the last 33 years (1978-2010). Increasing trends in annual precipitation have been found at 69% of stations across Libya (average trend rate of 0.166 mm a^{-1}) for the 66 years (1945-2010), with an average higher trend (1.437 mm a^{-1}) during the first 33 years (1945-1977). A decreasing trend (average rate -1.703 mm a^{-1}) has been identified at about 65% of the stations across Libya, with a more rapid average rate of -2.126 mm a^{-1} at about 80% of the coastal stations for the last 33 years (1978-2010), with significant decreases at some stations. Changing trends has been found in seasonal precipitation (1945-2010), with positive trends (average rate of 0.435 mm a^{-1}) at 67% of stations in winter and a negative trend during spring at 60% of stations (-0.241 mm a^{-1}). These finding are supported by El-Tantawi, (2005) who identified positive trends in annual precipitation during the period 1946-2000, with a negative trends at most stations from 1976-2000.

The examination of changes in the frequency of precipitation events and intensity of precipitation per event indicates mixed trends in number of rainy days and intensity of precipitation with no significant trends in extreme precipitation found. A positive trend in consecutive dry days (0.014 $d.a^{-1}$) and corresponding negative trend in consecutive wet days (-0.027 $d.a^{-1}$) are identified.

8.1.2.1 Potential causes of variability in Libyan precipitation

Global precipitation has increased significantly by approximately 2% during the 20th century (Folland et al., 2001), which is supported by Mosmann et al. (2004); Xu et al. (2005); Yu et al. (2006) who identified rates of increase between 7% and 12% for the areas 30–85° N latitude and by about 2% for the areas in 0–55° S. On the other hand, a pattern of continuous aridity since the late 1960s has been observed over the western parts of North Africa and South of the Sahara since the 1980s, which includes a large area of Libya (Folland, et al., 2001).

Precipitation is generally characterised by high temporal and spatial variability, which can partly be explained by changes in atmospheric circulation (Luterbacher and Xoplaki, 2003) and it is expected to affect fluctuations in the hydrological cycle, including increases/decreases in precipitation, geographical distribution of precipitation and droughts. Relationships between precipitation indices for the different stations in North Africa (Morocco, Algeria, Tunisia, Libya and Egypt) and large scale atmospheric circulation patterns including the North Atlantic Oscillation (NAO), Western Mediterranean Oscillation (WEMO), Mediterranean Oscillation (MO) and El Nino Southern Oscillation (ENSO) have been studied by Tramblay et al., (2013), who identified decreases in precipitation totals and wet days, with an increase in the duration of dry periods. Moreover, Meddi et al. (2010) identified a decrease in total annual precipitation in northwest Algeria after 1970 and related this to the El Nino Southern Oscillation (ENSO) index. These findings are supported by El Hamly et al. (1998) and Knippertz et al. (2003) as they observed an increase in dry years after 1970 in Morocco and identified a relationship with positive NAO phases.

The relationship between North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), Southern Oscillation Index (SOI) and local precipitation are well studied (e.g. Philander, 1990; Hurrell, 1995; Jones et al., 1997; Houghton et al., 2001; Mc-Carthy et al., 2001; El-Kenawy 2005; Djomou et al., 2013). In general, changes of ENSO in recent decades are replicated in precipitation variations throughout the world, particularly over the tropics and sub-tropics regions (Houghton et al., 2001). McCarthy, et al. (2001) suggested that the NAO is the most responsible factor for inter-annual fluctuation in precipitation over the Northern Africa, while in Libya, a weak positive relationship between annual precipitation and NAO index has been identified by Al-Kenawy (2005), with high correlations for a few cities across Libya. In comparison, weakly negative links between SOI and annual and seasonal precipitation has been found at three cities in Libya by El-Kenawy (2005). Changes of temperature and its effect on air masses-movements and air pressure circulation are one of the important impacts on changes in global precipitation (Ritter, 2003).

The present study has revealed a number of results; the following are considered the main:

1. No clear relationship exists between total annual precipitation and global CO_2 increases, in Libya. This is attributed to the presence of many factors

affecting precipitation (e.g. longitude, distance from the sea, ocean currents, vegetation).

2. No clear links between precipitation and temperature across Libya are identified, with a mixture of negative and positive correlations, with significant (95% confidence level) negative correlations only found at a small number of stations.

8.1.3 Evapotranspiration

In Chapter 6 the variability of potential and actual evapotranspiration in Libya during the last 50 years (1961-2010) was examined. Additional climatic parameters including relative humidity, surface wind speed, sun-shine duration and atmospheric pressure were considered. The main finding is that annual potential evapotranspiration, based on the Thornthwaite Penman- Monteith ($PET_{T\text{-}W}$) showed increasing trend (average rate of 2.818 mm a^{-1}) across Libya (1961-2010); with 63% of stations showing a significant increase (95% confidence level). This increase in $PET_{T\text{-}W}$ is mainly a consequence of significant increases in temperature across Libya, as identified in Chapter 4.

The main findings of annual potential evapotranspiration, based on Penman-Monteith ($PET_{P\text{-}M}$), variation in Libya indicated mixed changes, with decreasing trends in potential evapotranspiration (average rate -4.191 mm a^{-1}), which is equivalent of more than 200 mm a^{-1}, with the actual evapotranspiration characterised with a much lower trend (average rate of -0.774 mm a^{-1}) compared to the potential evapotranspiration over the last 50 years (1961-2010). These results are relatively comparable with previous studies (e.g. IPCC, 2007; Chaouche et al., 2010) over the last half of the 20th century, which have identified comparable changes and trends in evapotranspiration across the Mediterranean region and North Africa.

The temporal patterns of the $PET_{T\text{-}W}$ and $PET_{P\text{-}M}$ data are in good agreement for the coastal region and reasonable agreement but with higher values for the inland region, a result of the greater influence of weather variability on $PET_{P\text{-}M}$ compared to $PET_{T\text{-}W}$. The averaged potential evapotranspiration values varied greatly across Libya, ranging from 826.3 (Shahat) to 3026.3 mm a^{-1} (Sabha) for PET_{T-W} and PET_{P-M} respectively. Generally, trends follow a north - south gradient, reflecting the weather parameters that affect rates of evaporation. The inland region is characterized by higher values compared to the coastal region, with the highest values of both PET_{T-W} and PET_{P-M} found in the southern inland Sahara region, while the lowest estimates were in coastal and more mountainous areas (e.g. Shahat and Nalute).

8.1.3.1 Causes of variability of evapotranspiration

Evapotranspiration is an important climatic parameter controlling surface energy exchange and is controlled by changes in climatic parameters. Global warming may generate more evaporation as a result of higher surface temperatures, which may also alter precipitation patterns; though future changes to relative humidity, surface wind speed, sun-shine duration and atmospheric pressure could also affect future rates of evaporation across Libya.

There is a positive strong correlation between annual and seasonal maximum temperature and potential evapotranspiration across the coastal region, where potential evapotranspiration is less affected by maximum temperature than in the inland region. However, changes in potential evapotranspiration (PET_{P-M}) in particular, could be result from changes in other climatic parameters and/or topography and land use.

The highest annual correlations (positive) are found between potential evapotranspiration and surface wind speed in the inland region of Libya, where there is a huge expanse and no natural or artificial windbreaks, with high wind speeds recorded (76 knots at Tazerbou recorded in March 1986). A strong inverse relationship is found between annual and seasonal relative humidity and potential evapotranspiration across the coastal region, while the inland region is less affected by relative humidity, which explains the poor correlation coefficient. A higher degree of responsiveness for the inland PET_{P-M} to the change in meteorological variables than coastal PET_{P-M} of surface wind speed, sun-shine duration and atmospheric pressure are observed.

The present study has revealed a number of results; the following are considered the main:

1. Potential evapotranspiration is characterized by higher affected by maximum temperature compared to the minimum and mean average temperature.
2. Potential evapotranspiration at coastal region is characterized by higher affected by relative humidity, where the inland region is characterized by higher affected by wind speed and sun-shine duration.

8.1.4 Other climatic parameters

A mix of annual positive and negative changes in meteorological parameters are observed for the period 1961-2010, with more prevailing positive trends in relative humidity (0.037% a^{-1}), atmospheric pressure (0.028 hp a^{-1}) and sun-shine duration (0.012 h d^{-1}), but with a negative trend in annual surface wind speed (-0.0065 m s^{-1}), averaged for all stations across Libya. These changes in meteorological parameters could be presented by local changes in topography, land use, altitude and respect to the vegetation and plant distribution, so would require further examination with detailed site information.

8.1.5 Reanalysis

Changes and trends in the observed and modelled temperature and precipitation data for the three stations: Ajdabyia, Hon and Nalute; as well as comparison and relationships between the reanalysis and station data sets are made.

The analyses indicates good agreement between both sets of reanalysis NCEP/NCAR and ERA-Interim data in comparison to the observed mean average temperature, with significant increases in all observation and reanalysis data. The findings are comparable with previous studies over the last half of the 20th century (e.g. Flocas et al., 2005; Mooney et al., 2010) which have studied changes and trends in temperature at global and region levels, the findings of this thesis identify that the observed temperature data and NCEP/NCAR reanalysis are lower compared to the ERA-

Interim reanalysis data. This result could be attributed to the shorter period of the ERA-Interim (1979-2010) data compared to the NCEP/NCAR (1948-2010) data, and to topographical factors, (e.g. Nalute located at 621 m a.m.s.l), which could not be represented properly by the reanalysis models.

8.2 IMPLICATIONS OF FUTURE CLIMATE CHANGE

This section examines the possible effects of climate change on broader aspects of Libyan society and the environment. Libya is particularly vulnerable to climatic changes as it is a rapidly developing country (IPCC, 2007) with large sections of the population reliant on agriculture.

8.2.1 Implications of change in climate on the human health

Many of the consequences of changes in climatic parameters such as temperature and precipitation on human health have been evaluated by scientists (e.g. IPCC, 2001and 2007; Climate Change Science Program, 2008; National Institute of Health, 2010; Portier et al., 2010; Christine et al., 2013). A warmer earth and fluctuations in precipitation could lead to the spread of diseases such as malaria and dengue, an increase in heat-related mortality and more deaths resulting from extreme weather events; with 0.2% of annual global mortality attributed to climate change (Lacetera et al, 2013).

According to estimates by the World Health Organization (WHO) and Brown (2007), since 2000 about 160,000 deaths annually throughout the world result from warming, with the number of lives lost expected to double to ~300,000 a^{-1} by 2020. With the largest proportion of deaths occurring in developing countries, which are characterised by significant levels of exposure to environmental factors and low levels of adaptation to climate change compared to the developed countries. In 2003 approximately 35,000 people died across Europe as a result of heat waves (UNEP, 2004; Marc, 2005; Campbell, 2009). Recent research on the implications of climate change on environmental variables relevant to the human life identifies that countries in northern Africa are particularly susceptible to heat-related impacts (Habib and

Ghanawi, 2010), with an enormous impact on health in West Africa (Madeleine et al., 2004). There is considerable evidence that infectious diseases such as malaria will increase, with more than 2.4 million people killed a year by Malaria in Africa alone (Morse, 2003). The IPCC notes that globally heat waves are expected to rise in severity, frequency, and duration in the coming decades, with north African countries particularly susceptible (Habib and Ghanawi, 2010).

Warming, heat waves and extreme heat are more likely to impact populations as cases of heat stroke and dehydration are the most common cause of weather-related deaths as people are less prepared for excessive temperature, particularly in the summer, with certain groups in society particularly vulnerable. Those with medical conditions are particularly vulnerable with approximately one million Libyan people suffering from diabetes (Libyan Association for Diabetes and Endocrinology, 2006) of which, ~32% of the total population are <16years old (General Directorate of Documentation and Information 2006). Habib and Ghanawi (2010) showed that the prevalence of Blastocystosis (Heterokonts), on patients in Libya may be related to the hot and dry weather conditions.

8.2.2 Implications of change in climate on environmental variables

Climate change will have the greatest effect on the agricultural sector (e.g. Water for Agriculture and Energy in Africa, 2008; Kafle and Bruins, 2009; Schilling et al., 2012), as a result of warming and significant temporal and spatial changes in precipitation, which will increase rates of water loss through evapotranspiration. According to the World Bank Group (2011), an increase of 1°C in temperature is predicted to produce changes in precipitation of between 5-10% and increases in the amount of precipitation received during the heaviest precipitation events by 3-10%. Climate change is already causing the growing season to start earlier, lengthening the growing season leading to earlier flowering (Menzel and Fabian 1999; Hogda et al., 2013) especially in warm and moderate countries and regions, such as the region around Gharyan at Jabal Nafusa in western Libya and in Al-Jabal Al-Akhdar in eastern Libya. Changes in the frequency, length and timing of heat waves in the agricultural region such as the Benghazi plains will affect agricultural yields and increase the number and variety of insects (McMichael et al., 2003; IPCC, 2007).

Precipitation is important in Libya for agricultural purposes with ~99% of the total agricultural area in Libya, particularly in the north region, irrigated using groundwater from northern aquifers, which are recharged by precipitation. Changes in frequency, length, amount and number of precipitation days have significant effects on agricultural yields and change the growing season. Increased temperatures and decreased precipitation will lead to an increased rate of evapotranspiration, which will result in a greater demand for ground water for agricultural processes, a resource currently over exploited. Decreases in precipitation could put freshwater resources at risk, water scarcity is endemic and changes in the water balance would have substantial implications for agriculture and population, increased desertification and associated socio-economic impacts. The issues of water shortage and decrease groundwater represent the greatest threat to Libya (Alghariani, 2007).

Flooding is one of the most important climate change risks to human life in both rainy regions and regions that rarely have significant precipitation, particularly in the large metropolitan area where floods destroy homes and leave thousands of people homeless. Frequently, thousands of people living around Wadi Al-Mjanin are forced to leave their homes because of flooding as a result of unexpected precipitation (e.g.1975-1976, 1980-1981 and 1986-1987). Moreover, flooding can cause overflows from sewage treatment plants and impact on human health reducing the availability of fresh water and food. As extreme precipitation events are expected to become more intense in the future, these events are likely lead to more risk.

Increasing temperature and changes to the other climatic parameters may also result in increases in the frequency of Saharan dust storms. The frequency of sand storms increased during the period 1965-1997 in north-western Libya (Kredegh, 2002), a period and region in which this study has identified increased temperatures and reduced precipitation. Saharan dust can significantly impact the environment and human activities, so if climatic processes are increasing the availability of dust by degrading/hindering soil formation and vegetation cover this could result in significant changes in marginal desert surfaces and cause further environmental, health and economic problems.

8.3 RECOMMENDATIONS FOR FUTURE STUDY

The work presented here can be used to support future climate studies that aim to examine climate variability focusing on the climatic parameters or regions in Libya, and provide valuable data concerning broader changes affecting North Africa. 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 effects on society still require further investigation. The proposed areas for further investigation identified below, develop on the main themes and findings identified within the early sections of this chapter, and the thesis overall, these are:

i. To raise the efficiency and performance of Libyan meteorological stations, particularly, synoptic stations through improvements to data completeness, standard of stations and operating procedures, regular training provision to operational station meteorologists and calibration of instruments across Libya to international standards (e.g. WMO). Whilst these aspects are outside the remit of this thesis, the funding of the research by a Libyan scholarship and expertise of the researcher (15 years expertise as an operational and agricultural climate analyst and subsequently as a forecast meteorologist) coupled with the amount of time in the early thesis spent on data management and quality checking suggest that these issues require addressing.

ii. A review of the meteorological station distribution across Libya is required, with an increase in the number of stations, particularly in urban areas and distribution of rain gauges. A broader review of precipitation measurement and performance across Libya is required

iii. Current climatic changes in precipitation, temperature (min, max and mean) and evaporation will have significant implications for the agricultural sector, and more broadly on water resources. These changes may compound current long-term water resource issues relating to water availability and use of fossil waters in Libya.

iv. The initial review of the reanalysis data for Libya shows good relationships for temperature, but some of the data for precipitation requires improvement, this study only considered two parameters for three sites in three different regions using two models, further studies should examine a larger number of parameters/sites/models within the regions, to provide a more detailed review of the climate reanalysis for Libya.

v. Examination of the impacts of climatic changes identified in this thesis on broader areas of society (e.g. human health) requires further analysis. Little data is currently available on the significance of rapid changes in minimum summer temperature (for example) on human health. Whilst similar increasing trends and patterns are identified in other regions of the Mediterranean (often at lower rates of change), little work has explored the significance of these changes in Libya, a country already near the human comfort index threshold (Willett and Sherwood, 2011).

8.4 REVIEW OF AIMS AND OBJECTIVES

Variability of temporal and spatial climatic parameters: temperature, precipitation, evapotranspiration and other parameters across Libya have been analysed to successfully address the six objectives of this thesis, these are reviewed below:

1.) To digitise and scrutinise all daily/monthly temperature and precipitation data for 18 synoptic stations and monthly precipitation data for 10 meteorological stations across Libya for the last 66 years (1945-2010). Data for 16 synoptic stations of relative humidity, surface wind speed, sun shine duration and atmospheric pressure for the last 50 years (1961-2010) also included.

The documented data were initially digitized and inspected and daily, monthly and annual data series for the different parameters produced, extensive assessment of the initial data was undertaken, this represented a significant part of the first year's work in the PhD.

2.) To identify temporal fluctuations, patterns and trends in temperature, across Libya based on (a) annual data, (b) seasonal data, (c) monthly data, and (d) daily data; and to identify and examine any spatial changes within the data. Extremes in temperature across Libya also analysed.

Significant warming occurred during the last 33-years (1978-2010), relative to the previous 33-year period (1945-1977), with trends in maximum (0.034 °Ca-1), minimum (0.032 °Ca-1) and mean average temperature (0.21 °Ca-1) across Libya. The spatial and temporal distributions of various changes in temperature are detailed in Chapter 4, the most notable change being the rapid increase in minimum temperature over the later period (Ageena et al., 2012), with significant but more subtle changes in maximum temperature (Ageena et al., 2013).

3.) To identify temporal fluctuations, patterns, and trends in precipitation, across Libya based on (a) annual data, (b) seasonal data, (c) monthly data, and (d) daily data; and to identify and examine any spatial changes within the data. Temporal fluctuations, patterns, and trends Number of precipitation days, intensity of precipitation and extremes in precipitation across Libya also analysed.

A mixture of increasing and decreasing trends in precipitation are found across Libya during the period 1945-2010, with considerable regional variation in the different timeframes/parameters examined.

4.) To identify temporal fluctuations and patterns in potential and actual evapotranspiration and compare between Penman-Monteith and Thornthwaite potential evapotranspiration across Libya based on (a) annual data, (b) seasonal *data, (c) and monthly data. Relationships between potential evapotranspiration and climatic parameters also considered during the last 50 years 1961-2010.*

Significant increases in potential and actual evapotranspiration across Libya during the period 1961-2010 are identified at all temporal scales; see Chapter 6 for a detailed discussion of the role of other climatic variables on evapotranspiration rates.

5.) To identify temporal fluctuations and patterns in climatic parameters; surface wind speed, relative humidity, sun shine duration and atmospheric pressure on annual data for the last 50years (1961-2010).

Positive trends in relative humidity, atmospheric pressure and sun-shine duration compared to negative prevailing trends in wind speed are the principal finding.

6.) To analysis modelled NCEP/NCAR (1948-2010) and ERA-Interim (1979-2010) temperature and precipitation data at three stations. Comparison of the observational dataset with the reanalysis NCEP/NCAR and ERA-Interim- is also considered.

The reanalysis NCEP/NCAR and ERA-Interim data provides stronger correlations to observed temperature than observed precipitation, with the ERA-Interim reanalysis providing higher values compared to the observed and NCEP/NCAR reanalysis.

8.5 CONCLUSION

1. In general, minimum (Ageena et al., 2012), maximum and mean temperatures (Ageena et al., 2013) have increased significantly over the last 66 years, with seasonal variation being detected mainly from 1980s, with considerable increases in minimum temperature over the last 33 years.

2. Precipitation trends in Libya seem to be strongly affected by local factors (topography and land use), whereas the northern precipitation is mainly affected by low pressure areas (depressions) across the Mediterranean basin associated with a branch of the westerly jet stream.

3. In general, potential evapotranspiration (PET_{P-M}) measured using the Penman Monteith method indicated higher values than potential evapotranspiration (PET_{T-W}) using the Thornthwaite method, with the inland stations characterized by higher rates of evaporation compared to the coastal stations, as a result of potential evapotranspiration at coastal stations being more influenced by weather parameters.

4. ERA and NCEP/NCAR reanalysis data show reasonable agreement for temperature, but less confidence must be placed in the reanalysis of precipitation.

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APPENDICES

Appendix 1.1

Ageena I, Macdonald N, Morse A. (2013), Variability of minimum temperature across Libya (1945-2009), *International Journal of Climatology,* 33: 641-653 (DOI: 10.1002/joc.3452)

Appendix 2.1

Ageena I, Macdonald N., Morse A. (2014), Temporal and spatial variation of maximum and climatic temperature across Libya (1945-2009), *Theoretical and Applied Climatology,* xx: xxx-xxx, DOI 10.1007/s00704-013-1012-z

Appendix: 3.1: The Anderson-Darling formula

The Anderson-Darling formula is a statistical test of whether or not a climatic dataset of temperature and rainfall comes from normal distribution and to compare how well a data set fits different distributions (Gentle, 2003).

Arrange the observations x_1, x_2 ...., *xn in* the sample issued from x in sending order *i.e.,* $x_1 < x_2 \ldots < x_n$

$AD = \sum_{i=1}^{n} \frac{1-2i}{n} \{\ln (F_0[Z_{(i)}]) + \ln (1-F_0[Z_{(n+1-i)}])\} - n;$ ....

Where,

F_0 is the assumed (Normal) distribution with the assumed estimated Parameters (μ, σ);

Z (i) is the i^{th} sorted, standardized, sample value;

Where;

n is the sample size;

ln is the natural logarithm

i runs from 1 to n.

Two hypotheses for the Anderson-Darling test for the normal distribution are given below:

H_0: The data follows the normal distribution

H_1: The data do not follow the normal distribution

Reject the null hypothesis ($H_{0:}$ data are normally distributed),

If: Anderson-Darling (AD) test statistic is greater than critical value (cv).

The rejection rule is: $AD > CV = 0.752/ (1+0.75/n + 2.25/n^2)$.

Appendix: 3.2: Normalized and percentiles

The absolute value of this anomaly time series was also tested to identify changes in interannual precipitation. The absolute value of this anomaly time series of is also tested for trends to identify changes in annual rainfall, actual evapotranspiration and aridity index during the period 1945-2010 (Ramos 2001; Fernandes et al., 2007; Luis et al., 2009 Rainfall). Thus the

$$Yij = (Pa * 100) / Pn$$

Where:

Yij *is* the normalized variable

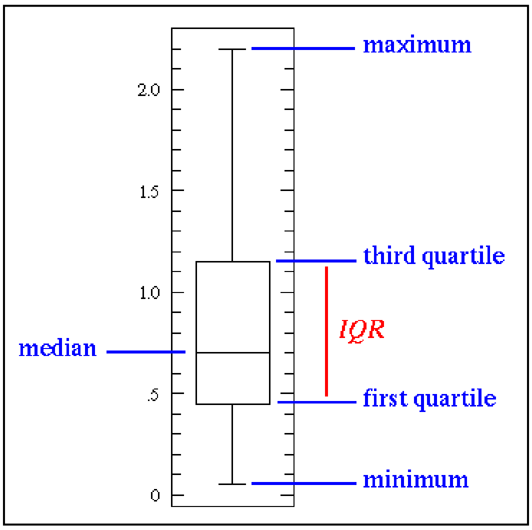
Pa, the actual rainfall at stations i during year j

Pn is the period study years average rainfall at station i

Appendix: 3.3: Box plots

A box plot descriptive diagram is applied to clarify spatial variability of annual rainfall for the period 1945-2010.

The box plot diagram presents five sample statistics, the maximum, the minimum, the lower quartile (first quartile -25%), and the median (50%) and the upper quartile (third quartile –75%).



The box is a rectangle which is closes the middle of the sample, with the ends at the first quartile (bottom) and third quartile (top) of the boxes.

Appendix: 3.4: Pearson Product-Moment

Pearson Product-Moment Correlation Coefficient The (*r)* correlation is a linear correlation necessary to find the degree of the association of two sets of variables, x and y, to obtain the value of *r* from ungrouped data. Strength and direction of line relationships between observational mean average temperature and modelled NCEP/NCAR-1948-2010 and ERA-Interim-1979-2010 data for the three selected meteorological stations have been determined. the formula is as follows (Guilford 1973).

Pearson Product-Moment Correlation Coefficient (*r*)

$$r = \frac{N\sum XY-(\sum X)(\sum Y)}{\sqrt{[N\sum X^2-(\sum X)^2]}\sqrt{[N\sum YX^2-(\sum Y)^2]}}$$

Where,

X and *Y,* is the sample Pearson correlation coefficient,

N, are a number of samples

Appendix: 3.5: Spearman’s rank

Nonparametric Spearman’s rank correlations coefficient (*rho*) test was applied to indicate the significant relationships between annual total evapotranspiration and climatic parameter; maximum and minimum temperature, precipitation, relative humidity, surface wind speed, sun shine duration and atmospheric air pressure. Strength and direction of line relationships between observational precipitation and modelled NCEP/NCAR-1948-2010 and ERA-Interim-1979-2010 data for the three selected meteorological stations have been determined.

$$Rho = \frac{1-6\sum(di)^2]}{[\, n\,(n^2-1)]}$$

Where,

n is a number of samples,

di is the difference between the ranks of *Xi* and *Xi'*

Appendix: 3.6: Critical Values of the Pearson Product-Moment test

df = n - 2	Level of significant for two tailed Test			df = n - 2	Level of significant for two tailed Test		
	0.1	0.05	0.01		0.1	0.05	0.01
1	0.988	0.997	1.000	21	0.352	0.413	0.526
2	0.900	0.950	0.990	22	0.344	0.404	0.515
3	0.805	0.878	0.959	23	0.337	0.396	0.505
4	0.729	0.811	0.917	24	0.330	0.388	0.496
5	0.669	0.754	0.874	25	0.323	0.381	0.487
6	0.643	0.707	0.834	26	0.317	0.374	0.479
7	0.582	0.666	0.798	27	0.311	0.367	0.471
8	0.549	0.632	0.765	28	0.306	0.361	0.463
9	0.521	0.602	0.735	29	0.301	0.355	0.456
10	0.497	0.576	0.708	30	0.296	0.349	0.449
11	0.476	0.553	0.684	35	0.275	0.325	0.418
12	0.458	0.532	0.661	40	0.257	0.304	0.393
13	0.441	0.514	0.641	45	0.243	0.288	0.372
14	0.426	0.497	0.623	50	0.231	0.273	0.354
15	0.412	0.482	0.606	60	0.211	0.250	0.325
16	0.400	0.468	0.590	70	0.195	0.232	0.303
17	0.389	0.456	0.575	80	0.183	0.217	0.283
18	0.378	0.444	0.561	90	0.173	0.205	0.267
19	0.369	0.433	0.549	100	0.164	0.195	0.254
20	0.360	0.423	0.537				

Appendix: 3.7: Regression equation

The simple linear regression equation is established, a, b for regression coefficient can be estimated by the least square method. The statistical of the linear regression coefficient is estimated using t-test statistic (Jun et al., 2012).

$$Y = a + bX,$$

Where:

X is the explanatory variable
Y is the dependent variable.
The slope of the line is b, and a is the intercept (the value of y when $x = 0$)

Appendix: 3.8: t-test

To calculate a value of t-test based on state the research hypothesis and null hypothesis (Thomas 2000; Shenbin et al., 2006; Kirono et al., 2009; Jun et al., 2012)

a) State the research hypothesis; where the t-test will be a two-tailed test for significant, the mean average data of two periods of time are equal

H0: µ1 = µ2

b) State the null hypothesis;

The mean average data of two periods of time are different: H0: µ1 ≠ µ2

c) Select the level of alpha, where the selected a value for this thesis $p = 0.05$.

The statistical t-test is most commonly applied when the test statistic would follow a normal distribution if the value of a scaling term in the test statistic were known.

To calculate a value of t-test:

$$t = \frac{x_1{}' - x'_2}{\sqrt{\frac{s_1{}^2}{n_1} + \frac{s_2{}^2}{n_2}}}$$

Where,

X_1’ = mean of sample 1 and X_2 = mean of sample 2

n_1 = number of data in sample 1,

n_2 = number of data in sample 2

$s_1{}^2$ = variance of sample 1 = $\frac{\Sigma(x_1 - x_1\prime)^2}{n_1}$ and,

$s_2{}^2$ = variance of sample 2 = $\frac{\Sigma(x_2 - x_2\prime)^2}{n_1}$

Appendix: 3.9: Mann–Kendall test

This software uses the non-parametric Mann–Kendall test Mann (1945; Mitchell et al., 1966; Kendal, 1970; Sneyers, 1999), which can be used to analyses trends in annual maximum, minimum, and climatic temperature data for 1945-2009. The Mann-Kendall trends (Q) are computed according to the Sen’s slope. Positive (negative) values indicate an increase (decrease) in concentration over time, with the strength of trend is proportional to the magnitude of the M-K (Salmi et al., 2002).

$$S = \sum_{i=1}^{n=1} \sum_{j=i+1}^{n} sgn\ (xj - xi)$$

Where,

Xi and *xj* are the annual values in years *i* and *j, j* > *k,* respectively, and

E(S) =0Var(S) = $\frac{[\, n\,(n-1)\,(2n+5) - \sum_{i=1}^{n} ti \;\; i(i-1)(2i+5)]}{18}$

Where:

ti denotes the number of tied values of extent i,

For the n greater than 10, the test statistic is,

$$\text{Z.MK} = \begin{cases} \frac{S-1}{\sqrt{Var\,(S)}}\, for\ S > 0 \\ 0 \qquad for\ s\ = 0 \\ \frac{S+1}{\sqrt{Var\,(S)}} for\ S < 0 \end{cases}$$

A positive Z value indicates an upward, where negative indicates downward trend. The statistical significances levels are (*** = 0.001 level of significance, ** = 0.01 level of significance, * = 0.05 level of significance, + = 0.1 level of significance), where the blank cell, is > 0.1, which means there is a 10% probability that making a mistake with rejecting HO of no trend, with the alternative hypothesis, H1, where there is an trend; increasing or decreasing monotonic.

Appendix: 3.10: Sen's slop value

To derive an estimate of the slop Q, following form;

$$Q = \frac{\text{Xi'}-\text{Xi}}{\text{j}-\text{k}} \quad \text{, i = 1, 2 ... N, j > k}$$

Appendix: 3.11: Mann-Whitney U-test

The two-tailed hypotheses being test with the Mann-Whitney U-test (Gravetter, 2008) are as follows;

$$\text{U1} + \text{U}_2 = R1 - \frac{n(n1+1)}{2} + R_2 - \frac{n^{2(n^2+1)}}{2}$$

For independent samples designs; use instead of uncorrelated t-test if data is either in the form of ranks or obviously non-normal or there is an obvious different in the variance of the two groups, to do the procedure follow these (for large number of data):

Rank data (taking both groups together) giving ranks 1 to the lowest score, and so on Fined the sum of the ranks for the smaller sample- A in the example opposite-) if both samples are the same size, find the sum of ranks of samples A). Call this T

Find $U = \mathrm{N_a}\, N_\beta + \frac{N_\mathrm{a}\,(N_\mathrm{a}+1)}{2} - T$

Where:

N_a is the number of scores in the smaller sample (or if both samples are same size, the sample whose ranks were totalled to find (T)

The standard deviation of U can be found as

$$\mathrm{SD_v} = \frac{\sqrt{Na\; Nb\;(\,N+Nb+1)}}{12}$$

$$Z = \frac{U - \frac{N_\mathrm{a} N_\mathrm{a}}{2}}{SDv} * V$$

V. Look up the s of U and U' in table attached. There is a significant difference if the observed value is equal to or less than the table value.

The two-tailed hypotheses being test with the Mann-Whitney U-test are as follows;

H0 (Null-hypothesis): there is no difference between the two periods of climatic data on average.

HA (Alterative hypothesis): there is difference between the two periods of climatic data on average.

Appendix: 3.12

Example determinations of PET with mean monthly data using Penman-Monteith formula. Given monthly average climatic data of March 2000 of Tripoli Airport Penman-Monteith evapotranspiration for in March 2000,

$$\frac{0.408\,\Delta\,(Rn-G)+\gamma\,\frac{900}{T+273}\,u_2\,(e\text{ş}-e_{\mathrm{a}})}{\Delta+\gamma\,(1+0.34\,u_2)}$$

Where,

PET	reference crop evapotranspiration (mm/d),
Rn	net radiation at crop surface (MJ/ m²d),
G	soil heat flux (MJ/ m²d),
T	average temperature (°C),
U_2	wind speed measured at 2m height (m/s),
Δ	slope vapour deficit (kPa),
γ	psychometric constant (kPa °C),
$(e_a - e_x)$	vapour pressure deficit (kPa),
900	conversion factor

Weather parameter	Values and unites
Monthly daily maximum temperature (T.max)	24.1°C
Monthly daily minimum temperature (T.min)	7.7 °C
Monthly daily dry bulb temperature	15.7 °C
Monthly daily wet bulb temperature	12.3 °C
Monthly daily vapour pressure (ea)	12.0 kPa/°C
Monthly daily wind speed (u2)	3.135 m/s
Monthly daily mean relative humidity RH	70%
Monthly daily maximum relative humidity RH	100%
Monthly daily minimum relative humidity RH	16%
Monthly sunshine duration (h/day)	9.3 hours/day
Mean monthly temperature (T. Month i - For April)	19.7 °C
Mean monthly temperature (T. month, i-1(For March)	15.9 °C

Steps calculation of penman evapotranspiration

Step 1: Mean daily temperature

T mean = (T max + T min)/2

= (24.1 +7.7)/2 =15.9 °C

Step 2: Slope of saturation vapour pressure curve (Δ)

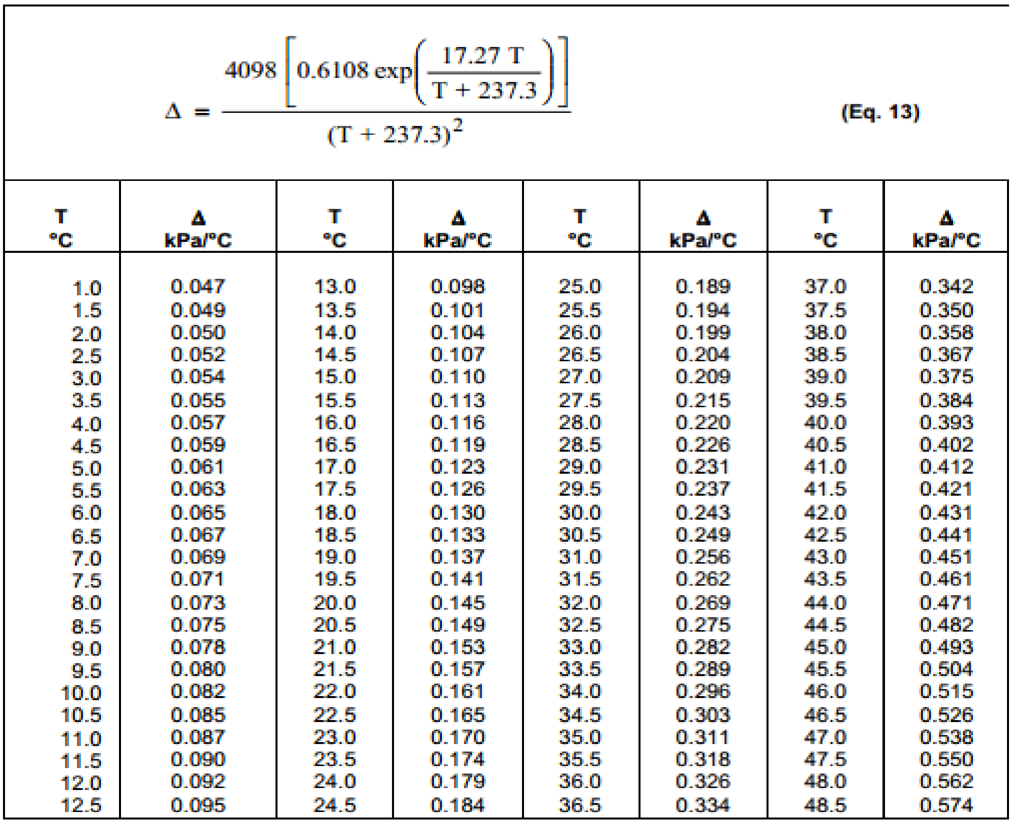
Δ = Estimated by table 6.3 or used the following the equation

$$\Delta = \frac{4098\ [0.6108 \exp \frac{(17.27\ T)}{(T+273.3)}}{(T+273.2)^2}$$

$$\Delta = \frac{4098\ [0.6108 \exp \frac{(17.27*15.9)}{(15.9+273.3)}}{(15.9+273.2)^2}$$

= 0.127 kPa/°C

Table 3.2: Slope of vapour pressure curve (Δ) for different temperatures (T)



$$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27\ T}{T+237.3}\right)\right]}{(T+237.3)^2} \qquad \textbf{(Eq. 13)}$$

T °C	Δ kPa/°C	T °C	Δ kPa/°C	T °C	Δ kPa/°C	T °C	Δ kPa/°C
1.0	0.047	13.0	0.098	25.0	0.189	37.0	0.342
1.5	0.049	13.5	0.101	25.5	0.194	37.5	0.350
2.0	0.050	14.0	0.104	26.0	0.199	38.0	0.358
2.5	0.052	14.5	0.107	26.5	0.204	38.5	0.367
3.0	0.054	15.0	0.110	27.0	0.209	39.0	0.375
3.5	0.055	15.5	0.113	27.5	0.215	39.5	0.384
4.0	0.057	16.0	0.116	28.0	0.220	40.0	0.393
4.5	0.059	16.5	0.119	28.5	0.226	40.5	0.402
5.0	0.061	17.0	0.123	29.0	0.231	41.0	0.412
5.5	0.063	17.5	0.126	29.5	0.237	41.5	0.421
6.0	0.065	18.0	0.130	30.0	0.243	42.0	0.431
6.5	0.067	18.5	0.133	30.5	0.249	42.5	0.441
7.0	0.069	19.0	0.137	31.0	0.256	43.0	0.451
7.5	0.071	19.5	0.141	31.5	0.262	43.5	0.461
8.0	0.073	20.0	0.145	32.0	0.269	44.0	0.471
8.5	0.075	20.5	0.149	32.5	0.275	44.5	0.482
9.0	0.078	21.0	0.153	33.0	0.282	45.0	0.493
9.5	0.080	21.5	0.157	33.5	0.289	45.5	0.504
10.0	0.082	22.0	0.161	34.0	0.296	46.0	0.515
10.5	0.085	22.5	0.165	34.5	0.303	46.5	0.526
11.0	0.087	23.0	0.170	35.0	0.311	47.0	0.538
11.5	0.090	23.5	0.174	35.5	0.318	47.5	0.550
12.0	0.092	24.0	0.179	36.0	0.326	48.0	0.562
12.5	0.095	24.5	0.184	36.5	0.334	48.5	0.574

Step 3: Atmospheric pressure

(P) = 101.3 * 101.3 * (293-0.0065 * Z)/293]$^{5.26}$

P = 101.3 * (293-0.0065 * 81)/293]$^{5.26}$

= 100.3 kPa

Psychometric constant (γ) = ($c_{p\ P}$) / (ε λ)

Where,

γ = psychometric constant [kPa °C^{-1}],

P= atmospheric pressure [kPa],

λ= latent heat of vaporization, 2.45 [MJ kg $^{-1}$],

c_p = specific heat at constant pressure, 1.013 $^{-3}$ [MJ kg $^{-1}$ °C^{-1}] and

ε = ratio molecular weight of water vapour/dry air = 0.622.

= (1.013^{-3} *100.1) / (0.622*2.45)

= 0.0665[kPa °C $^{-1}$],

(1+0.34u_2)

= 1+0.34*3.135

= 2.066

Δ / [Δ+ γ (1+0.34u_2)]
= 0.127/[0.127+ 0.0665 (2.066)]

= 0.481

[900 / (T. Mean +273)] * u2

[900 / (15.9 +273)] * 3.135

= 9.766

γ / [Δ+ γ (1+0.34u_2)]

= 0.0665 / (0.127+0.0665*2.066)

= 0.084

Step 4: Vapour pressure deficit

T max = 24.1 °C

e° (T max) = 0.611 exp (17.27 *24.1/24.1+273.3)

= 2.475 kPa

T min = 24.1 °C

e° (T min) = 0.611 exp (17.27 *7.7/7.7+273.3)

= 0.618 kPa

Saturation v.p (e_s) = [e° (T max) + e° (T min)]/2
= [2.475 + 0.618]/2

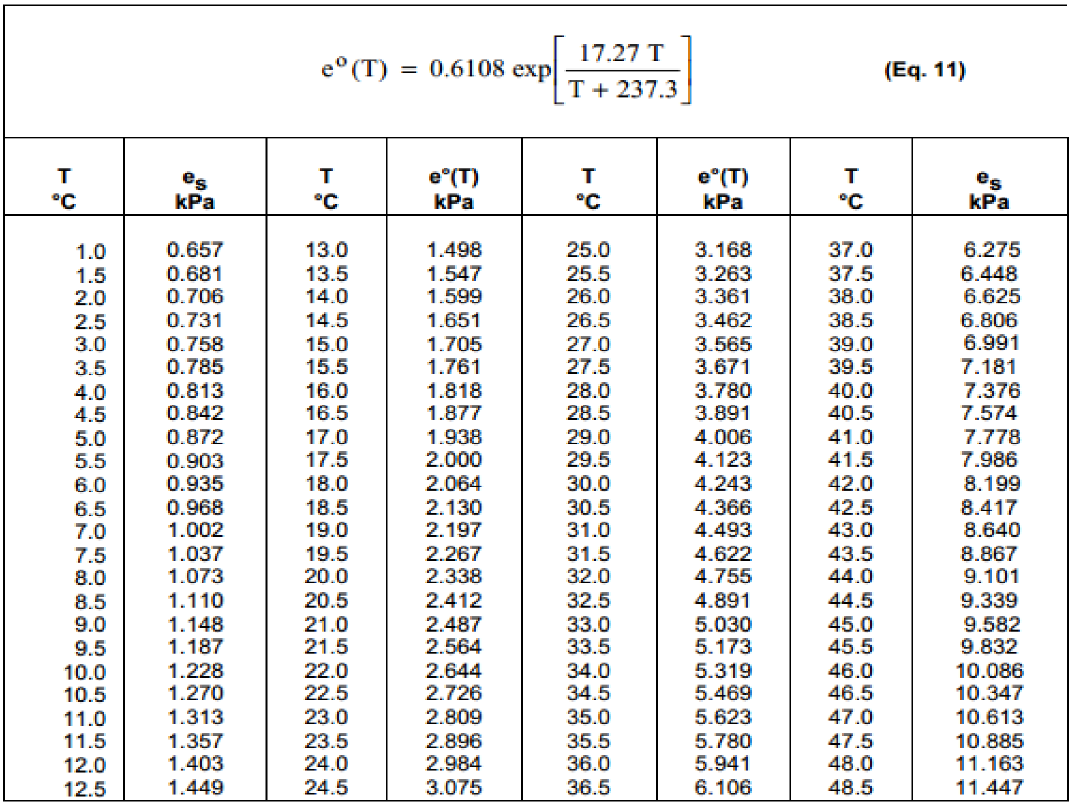
= 1.547 kPa

Actual v.p (e_a) = RH/100 [e° (T max) + e° (T min)]/2
= 70/100 [2.475 + 0.618]/2

= 1.083 kPa

Vapour pressure deficit = es – ea
= 1.547-1.083 =0.464 kPa

Table 3.3: Saturation vapour pressure (e_o (T)) for different temperatures (T)



$$e^{o}(T) = 0.6108 \exp\left[\frac{17.27\,T}{T + 237.3}\right]$$ **(Eq. 11)**

T °C	**e_s kPa**	**T °C**	**e°(T) kPa**	**T °C**	**e°(T) kPa**	**T °C**	**e_s kPa**
1.0	0.657	13.0	1.498	25.0	3.168	37.0	6.275
1.5	0.681	13.5	1.547	25.5	3.263	37.5	6.448
2.0	0.706	14.0	1.599	26.0	3.361	38.0	6.625
2.5	0.731	14.5	1.651	26.5	3.462	38.5	6.806
3.0	0.758	15.0	1.705	27.0	3.565	39.0	6.991
3.5	0.785	15.5	1.761	27.5	3.671	39.5	7.181
4.0	0.813	16.0	1.818	28.0	3.780	40.0	7.376
4.5	0.842	16.5	1.877	28.5	3.891	40.5	7.574
5.0	0.872	17.0	1.938	29.0	4.006	41.0	7.778
5.5	0.903	17.5	2.000	29.5	4.123	41.5	7.986
6.0	0.935	18.0	2.064	30.0	4.243	42.0	8.199
6.5	0.968	18.5	2.130	30.5	4.366	42.5	8.417
7.0	1.002	19.0	2.197	31.0	4.493	43.0	8.640
7.5	1.037	19.5	2.267	31.5	4.622	43.5	8.867
8.0	1.073	20.0	2.338	32.0	4.755	44.0	9.101
8.5	1.110	20.5	2.412	32.5	4.891	44.5	9.339
9.0	1.148	21.0	2.487	33.0	5.030	45.0	9.582
9.5	1.187	21.5	2.564	33.5	5.173	45.5	9.832
10.0	1.228	22.0	2.644	34.0	5.319	46.0	10.086
10.5	1.270	22.5	2.726	34.5	5.469	46.5	10.347
11.0	1.313	23.0	2.809	35.0	5.623	47.0	10.613
11.5	1.357	23.5	2.896	35.5	5.780	47.5	10.885
12.0	1.403	24.0	2.984	36.0	5.941	48.0	11.163
12.5	1.449	24.5	3.075	36.5	6.106	48.5	11.447

Step 5: Radiation

Number of the day in the year (J) is estimated based on table 6.4

J for the 15th March = 75

Latitude =32.48 = (32+40/60) =32.66
Extraterrestrial radiation (Ra),
$24*60/\pi \, G_{sc} \, dr \, [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega s)]$

Solar constant (G_{sc}) = 0.0820 [MJ m^{-2} min^{-1}]
Inverse relative distance earth-sun

$(dr) = 1+0.033\cos [(2\pi/365)\, J]$

$= 1+0.033\cos [(2*3.14/365) *75]$

=1.009

Solar declination

$(\delta) = 0.409\ \mathit{sin}\ [(2\pi/365)^{*}\ J\ -1.39]$

$\delta = 0.409\mathit{sin}\ [(2^{*}3.14/365)^{*}75\ -1.39]$

$= -0.0406$ rad

Latitude $(\varphi) = \pi/180$

$= 3.14/180$

$=0.0174$

Sunset hour angle
$(\omega_s) = \mathit{arcos}\ [\tan(\varphi) * \tan(\delta)]$
$= \mathit{arcos}\ [\tan(0.0174) * \tan(-0.0406)]$

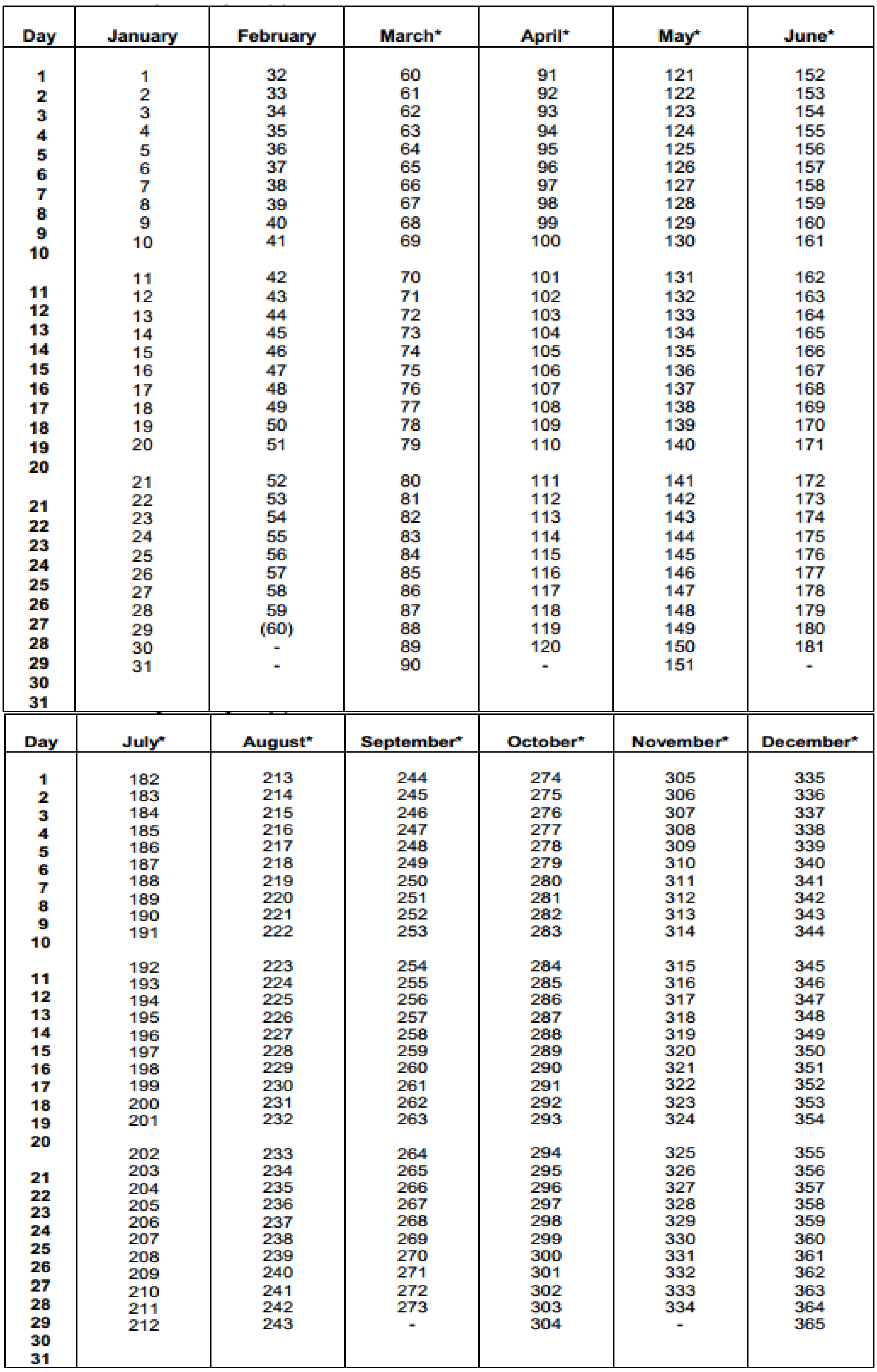
$= 1.572$ rad

$Ra= 24^{*}60/\pi\ G_{sc}\ dr\ [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega s)]$

$=24^{*}60/3.14^{*}0.082^{*}1.009[1.572^{*}0.0174^{*}-0.0406+0.999^{*}0.999^{*}0.0999$

$= 37.864$ MJ $m^{-2}\ d^{-1}$

Table: Number of the day in the year (J)



Day	January	February	March*	April*	May*	June*
1	1	32	60	91	121	152
2	2	33	61	92	122	153
3	3	34	62	93	123	154
4	4	35	63	94	124	155
5	5	36	64	95	125	156
6	6	37	65	96	126	157
7	7	38	66	97	127	158
8	8	39	67	98	128	159
9	9	40	68	99	129	160
10	10	41	69	100	130	161
11	11	42	70	101	131	162
12	12	43	71	102	132	163
13	13	44	72	103	133	164
14	14	45	73	104	134	165
15	15	46	74	105	135	166
16	16	47	75	106	136	167
17	17	48	76	107	137	168
18	18	49	77	108	138	169
19	19	50	78	109	139	170
20	20	51	79	110	140	171
21	21	52	80	111	141	172
22	22	53	81	112	142	173
23	23	54	82	113	143	174
24	24	55	83	114	144	175
25	25	56	84	115	145	176
26	26	57	85	116	146	177
27	27	58	86	117	147	178
28	28	59	87	118	148	179
29	29	(60)	88	119	149	180
30	30	-	89	120	150	181
31	31	-	90	-	151	-

Day	July*	August*	September*	October*	November*	December*
1	182	213	244	274	305	335
2	183	214	245	275	306	336
3	184	215	246	276	307	337
4	185	216	247	277	308	338
5	186	217	248	278	309	339
6	187	218	249	279	310	340
7	188	219	250	280	311	341
8	189	220	251	281	312	342
9	190	221	252	282	313	343
10	191	222	253	283	314	344
11	192	223	254	284	315	345
12	193	224	255	285	316	346
13	194	225	256	286	317	347
14	195	226	257	287	318	348
15	196	227	258	288	319	349
16	197	228	259	289	320	350
17	198	229	260	290	321	351
18	199	230	261	291	322	352
19	200	231	262	292	323	353
20	201	232	263	293	324	354
21	202	233	264	294	325	355
22	203	234	265	295	326	356
23	204	235	266	296	327	357
24	205	236	267	297	328	358
25	206	237	268	298	329	359
26	207	238	269	299	330	360
27	208	239	270	300	331	361
28	209	240	271	301	332	362
29	210	241	272	302	333	363
30	211	242	273	303	334	364
31	212	243	-	304	-	365

Day length (N) = (24/ π) * ωs

= (24/3.14)* 1.572

= 12.02

Relative sunshine fraction = sun shine duration (n)/ day length (N)

= 9.3/12.02

= 0.774

Solar or shortwave radiation
$(R_s) = (a_s + b_s * n/N) * Ra$
= (0.25+0.50*0.774) * 37.864

= 24.119 MJ m^{-2} d^{-1}

Clear-sky solar radiation

$(R_{SO}) = (0.75 * 2*10^{-5}) * R_a$

= (0.75 *2*10^{-5}) * 37.864

= 28.459 MJ m^{-2} d^{-1}

Net solar or shortwave radiation

$(R_{sn}) = (1-\alpha) * R_s$

Where, α is albedo =0.23

= (1-0.23) * 24.119

=18.572 MJ m^{-2} d^{-1}

Stefan-Boltzmann law at different temperatures (T) Based on Table

$\sigma T.max\ K^4 = 38.23$ MJ m^{-2} d^{-1}

$\sigma T.min\ K^4 = 30.42$ MJ m^{-2} d^{-1}

$(\sigma T.max\ K^4 + \sigma T.min\ K^4)/2$

= (38.23+30.42)/2

= 34.325 MJ m^{-2} d^{-1}

Net long wave radiation

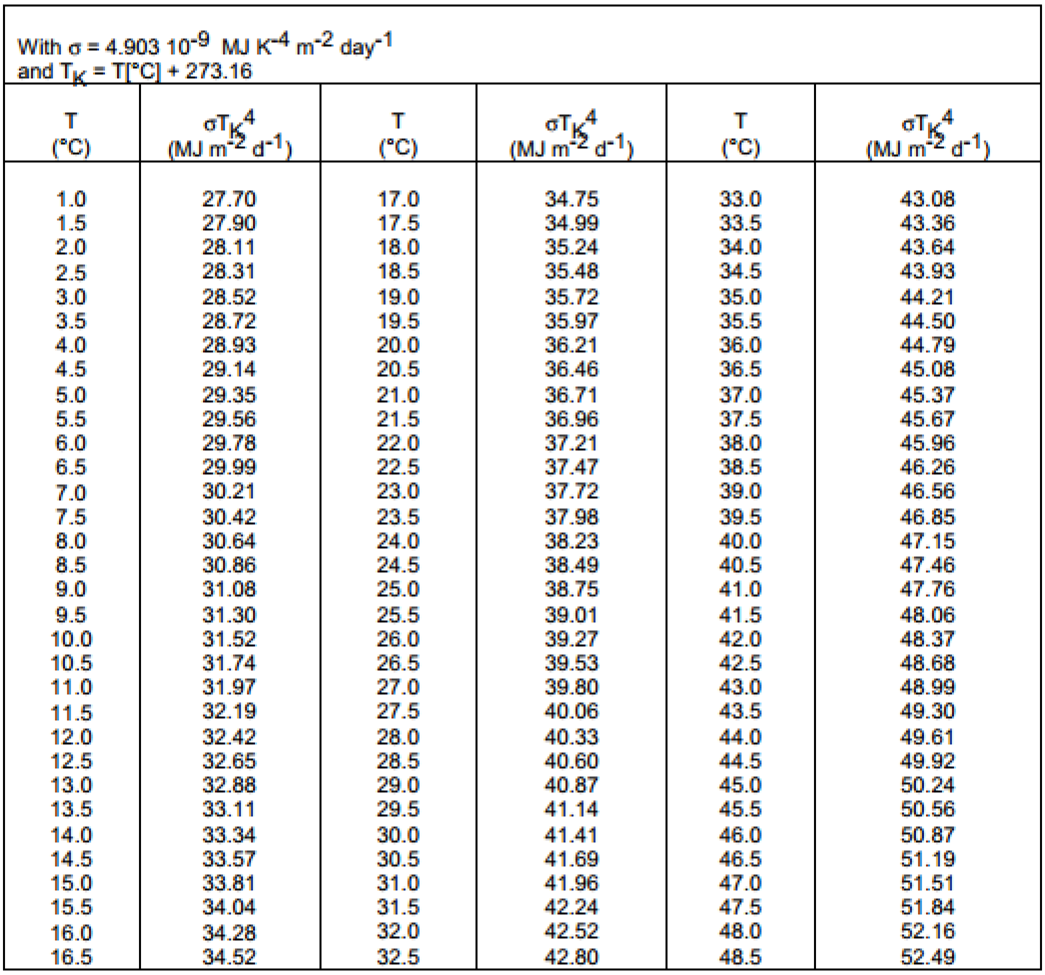
$R_{nl} = [(\sigma T.\max K^4 + \sigma T.\min K^4)/2](0.34-0.14\sqrt{ea})\ [1.35 *(R_s/R_{so})-0.35]$

= (34.325) (0.34-0.14√1.0829) (1.35*(24.119/28.459) -0.35

= 34.325 * 0.194 * 0.794

=5.287 MJ m^{-2} d^{-1}

Table: σTK4 (Stefan-Boltzmann law) at different temperatures (T)



With $\sigma = 4.903\ 10^{-9}$ MJ K^{-4} m^{-2} day^{-1}
and $T_K = T[°C] + 273.16$

T (°C)	σT_K^4 (MJ m^{-2} d^{-1})	T (°C)	σT_K^4 (MJ m^{-2} d^{-1})	T (°C)	σT_K^4 (MJ m^{-2} d^{-1})
1.0	27.70	17.0	34.75	33.0	43.08
1.5	27.90	17.5	34.99	33.5	43.36
2.0	28.11	18.0	35.24	34.0	43.64
2.5	28.31	18.5	35.48	34.5	43.93
3.0	28.52	19.0	35.72	35.0	44.21
3.5	28.72	19.5	35.97	35.5	44.50
4.0	28.93	20.0	36.21	36.0	44.79
4.5	29.14	20.5	36.46	36.5	45.08
5.0	29.35	21.0	36.71	37.0	45.37
5.5	29.56	21.5	36.96	37.5	45.67
6.0	29.78	22.0	37.21	38.0	45.96
6.5	29.99	22.5	37.47	38.5	46.26
7.0	30.21	23.0	37.72	39.0	46.56
7.5	30.42	23.5	37.98	39.5	46.85
8.0	30.64	24.0	38.23	40.0	47.15
8.5	30.86	24.5	38.49	40.5	47.46
9.0	31.08	25.0	38.75	41.0	47.76
9.5	31.30	25.5	39.01	41.5	48.06
10.0	31.52	26.0	39.27	42.0	48.37
10.5	31.74	26.5	39.53	42.5	48.68
11.0	31.97	27.0	39.80	43.0	48.99
11.5	32.19	27.5	40.06	43.5	49.30
12.0	32.42	28.0	40.33	44.0	49.61
12.5	32.65	28.5	40.60	44.5	49.92
13.0	32.88	29.0	40.87	45.0	50.24
13.5	33.11	29.5	41.14	45.5	50.56
14.0	33.34	30.0	41.41	46.0	50.87
14.5	33.57	30.5	41.69	46.5	51.19
15.0	33.81	31.0	41.96	47.0	51.51
15.5	34.04	31.5	42.24	47.5	51.84
16.0	34.28	32.0	42.52	48.0	52.16
16.5	34.52	32.5	42.80	48.5	52.49

The net radiation $R_n = R_{ns} - Rnl$

= 18.75-5.283

= 13.469 MJ m^{-2} d^{-1}

Soil heat flux (G) = 0.14 ($T_{\text{month i}} - T_{\text{month i-1}}$)

= 0.14 (15.9-10.7)

= 0.728 MJ m^{-2} d^{-1}

(Rn –G) = 13.469-0.728

= 12.741 MJ m^{-2} d^{-1}

0.408 (Rn –G)
= 0.408(12.741)
= 5.198 mm d^{-1}

Grass reference evapotranspiration

0.408 (Rn-G) = 5.198

$\Delta/[\Delta+\gamma(1+0.34u2)]= 0.481$

5.198 *0.481 = 2.500 mm d^{-1}

900u2/(T+273) = 9.766

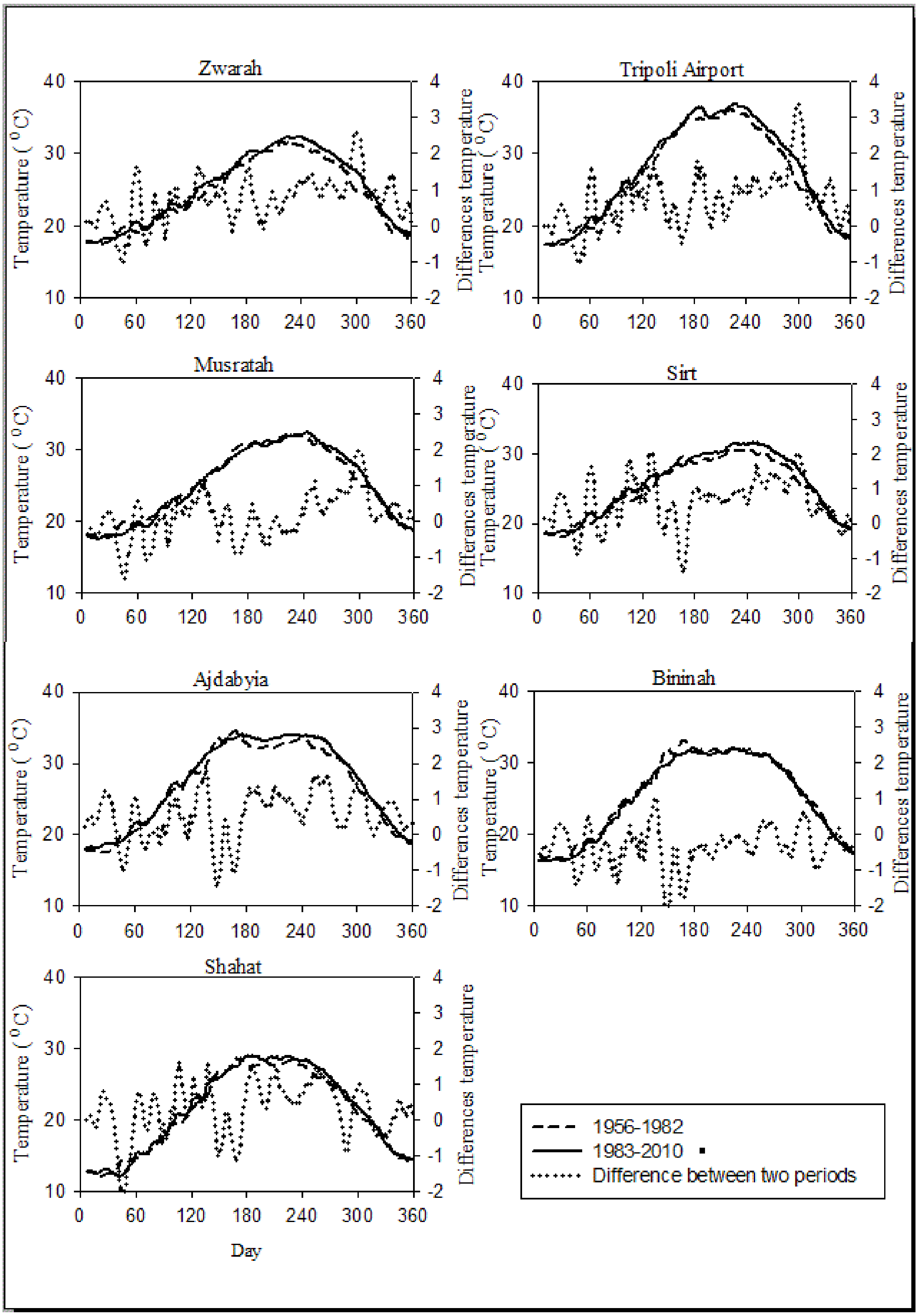
(es-ea) = 0.464

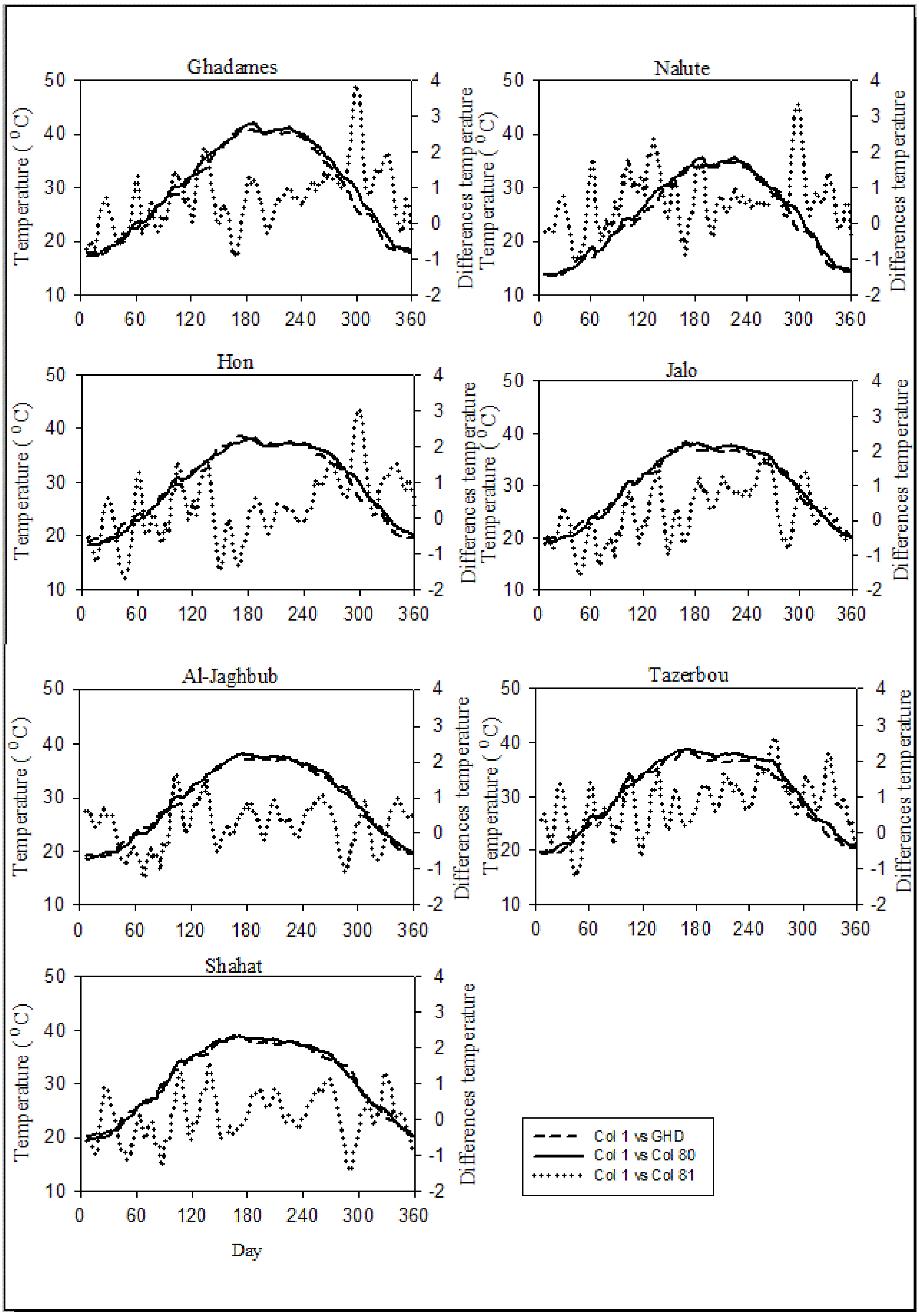
$\gamma/[\Delta+\gamma(1+0.34u2)] = 0.084$

9.766 *0.464*0.084 = 0.381 mm d^{-1}

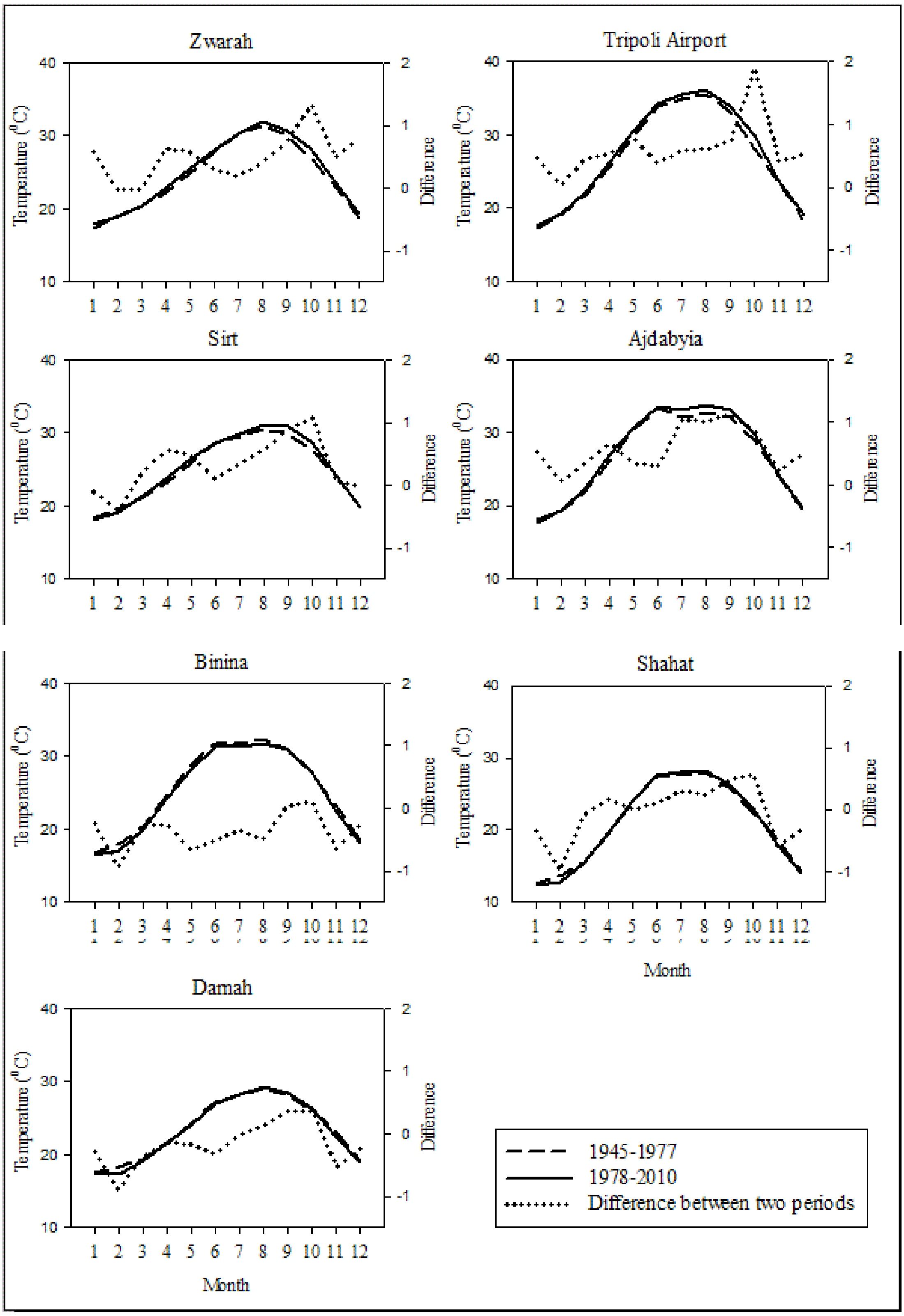
PET_{PM} = 2.500 +0.381 mm d^{-1} = 2.881 mm d^{-1}

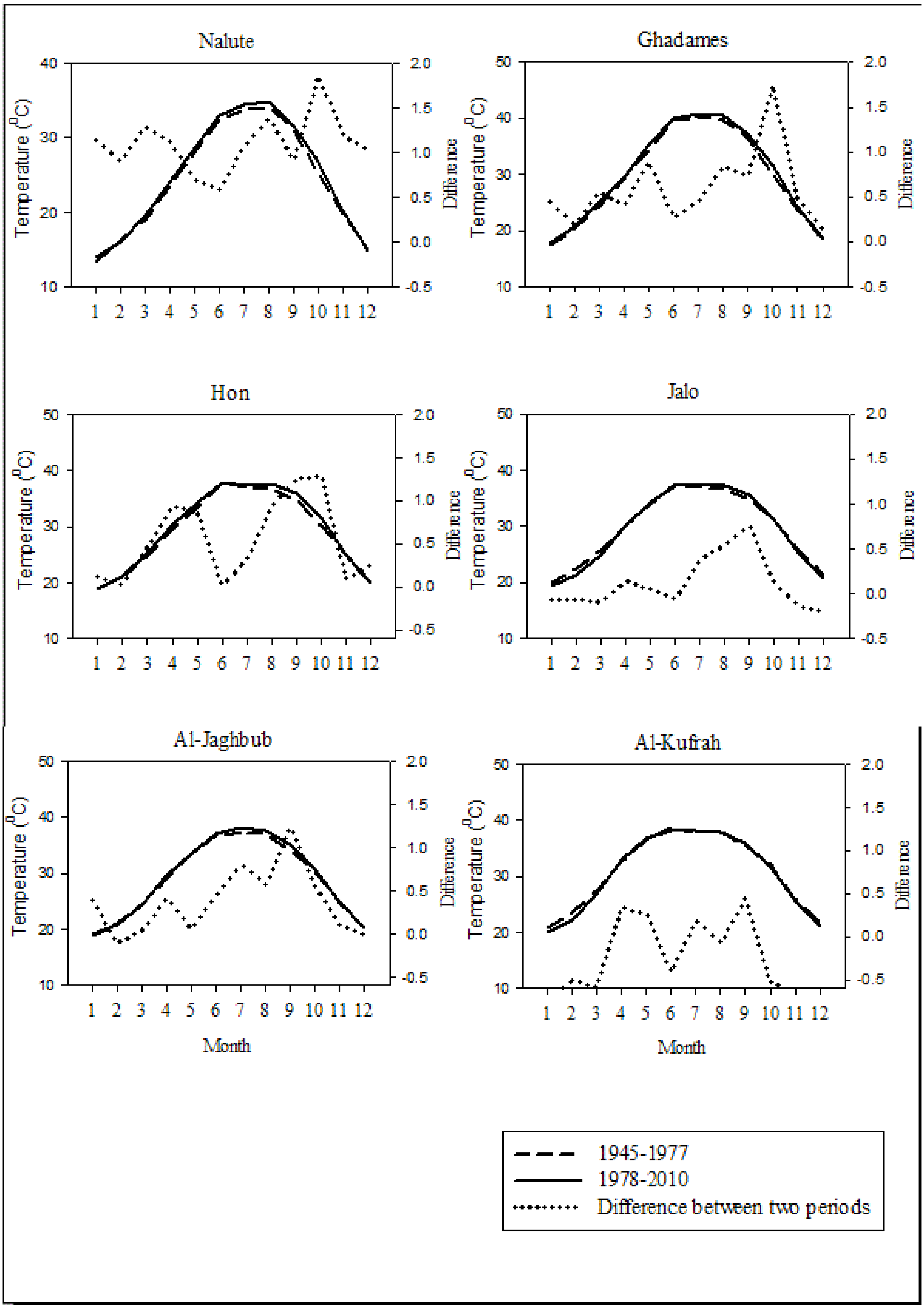
Appendix 4.1: Annual means 11-day moving averages of the mean daily maximum temperature for the two periods 1956-1982 and 1983-2010



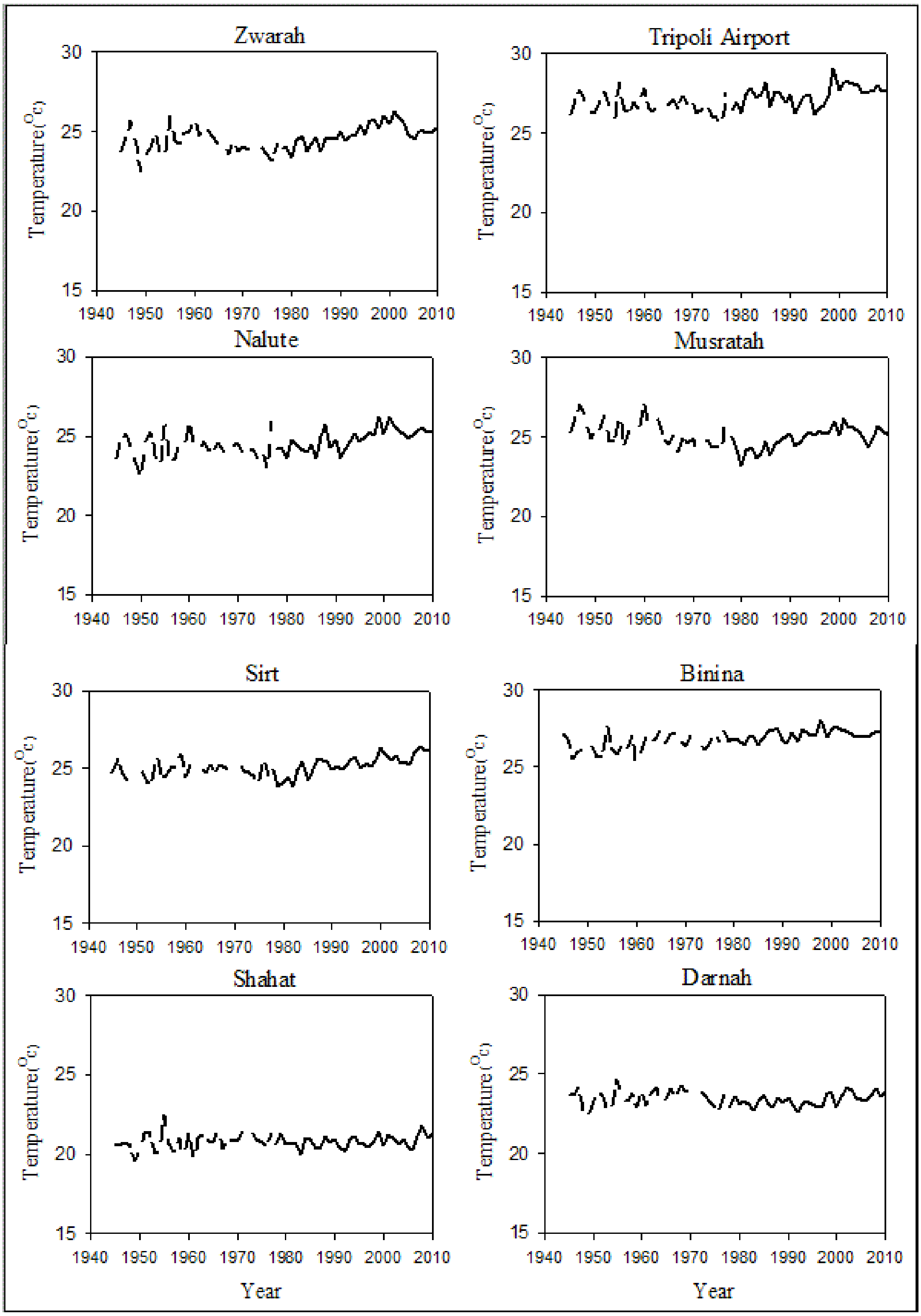

Ghadames
Nalute
Hon
Jalo
Al-Jaghbub
Tazerbou
Shahat
Temperature (°C)
Differences temperature
Day
50
40
30
20
10
4
3
2
1
0
-1
-2
0
60
120
180
240
300
360
Col 1 vs GHD
Col 1 vs Col 80
Col 1 vs Col 81

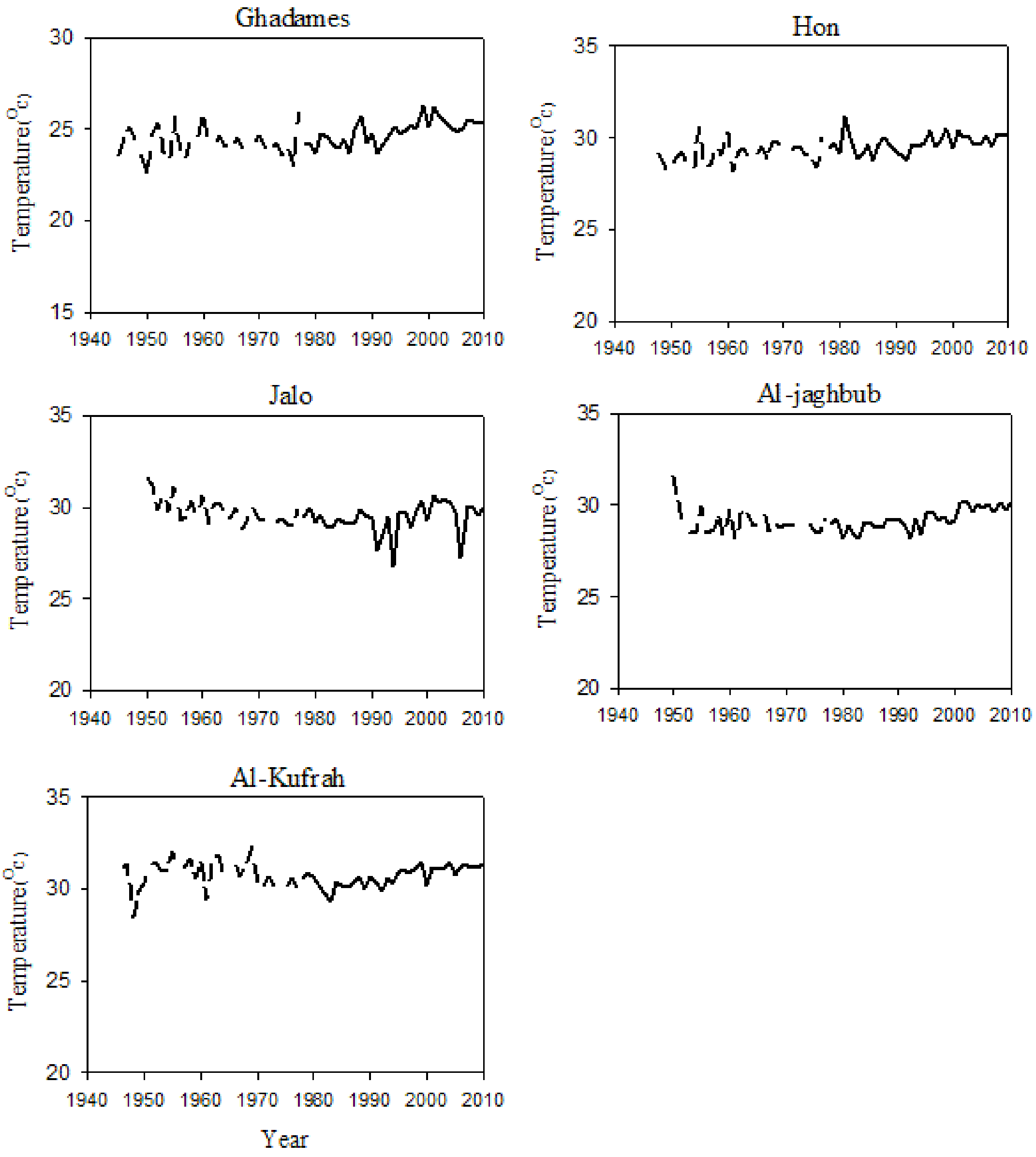
Appendix 4.2: Mean monthly maximum temperature for the two periods 1945-1977 and 1978-2010



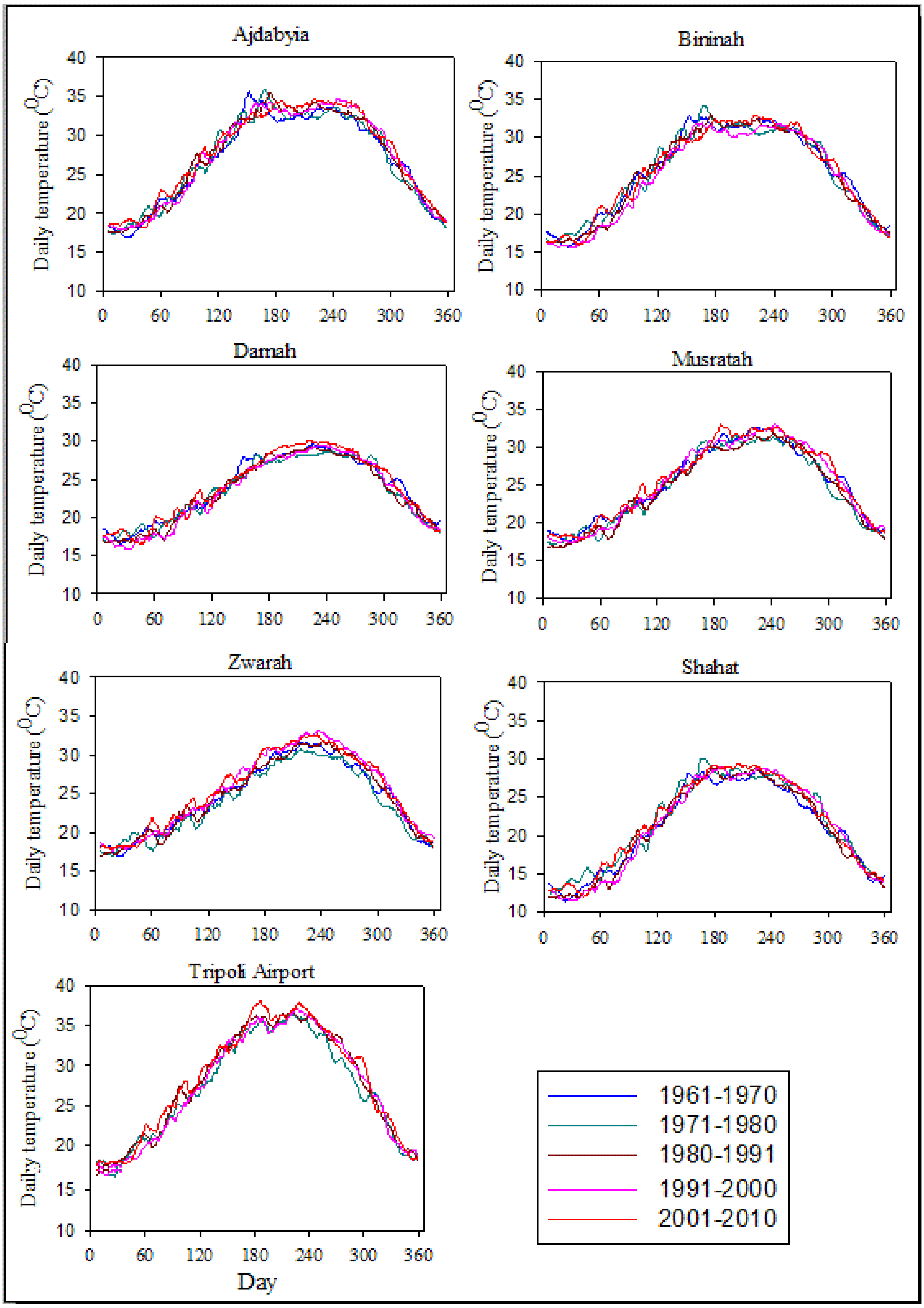

Nalute
Ghadames
Hon
Jalo
Al-Jaghbub
Al-Kufrah
Temperature (°C)
Difference
Month
10
20
30
40
50
-0.5
0.0
0.5
1.0
1.5
2.0
1 2 3 4 5 6 7 8 9 10 11 12
1945-1977
1978-2010
Difference between two periods

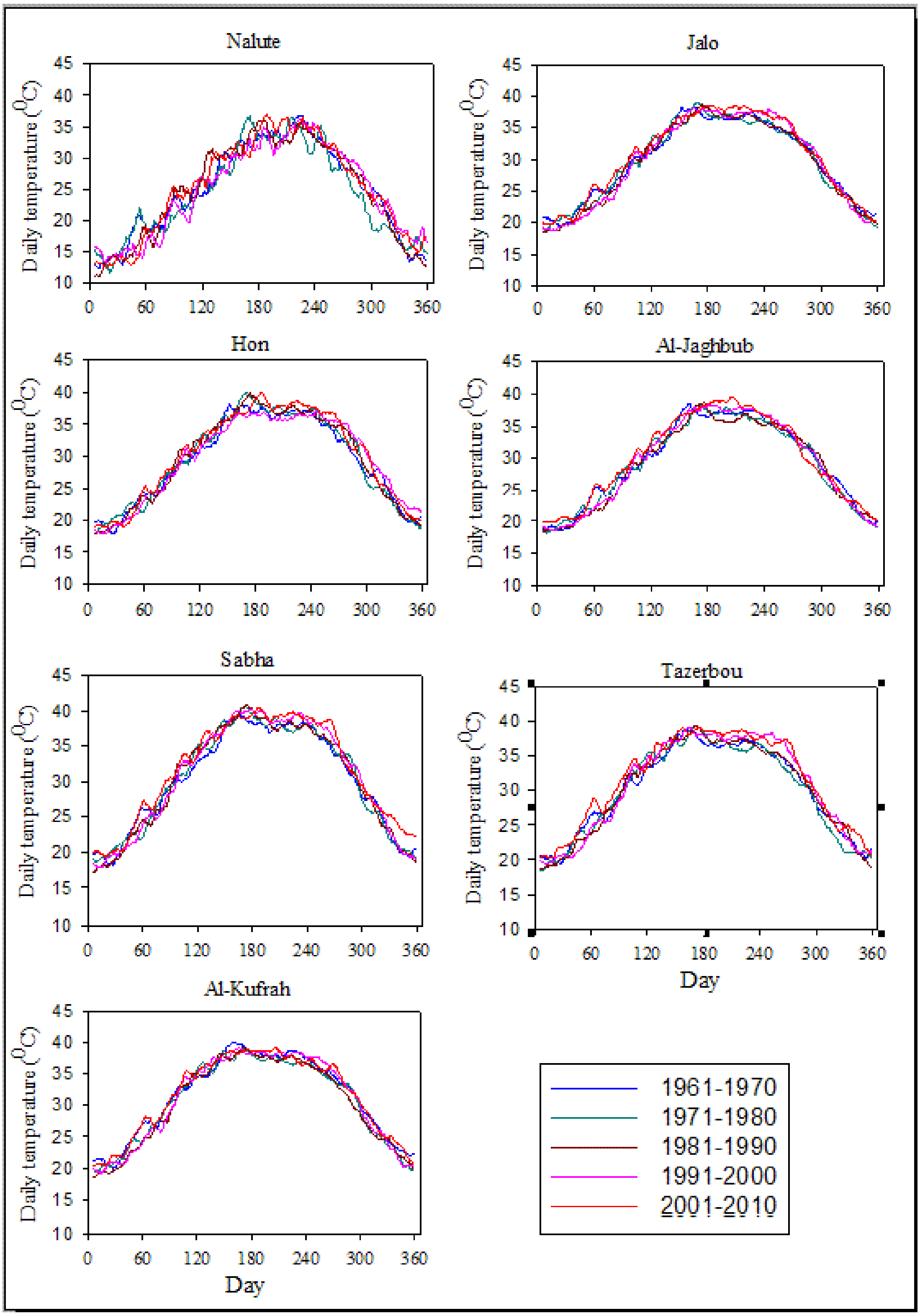
Appendix 4.3: Annual means maximum temperature for the two periods 1945-1977 and 1978-2010



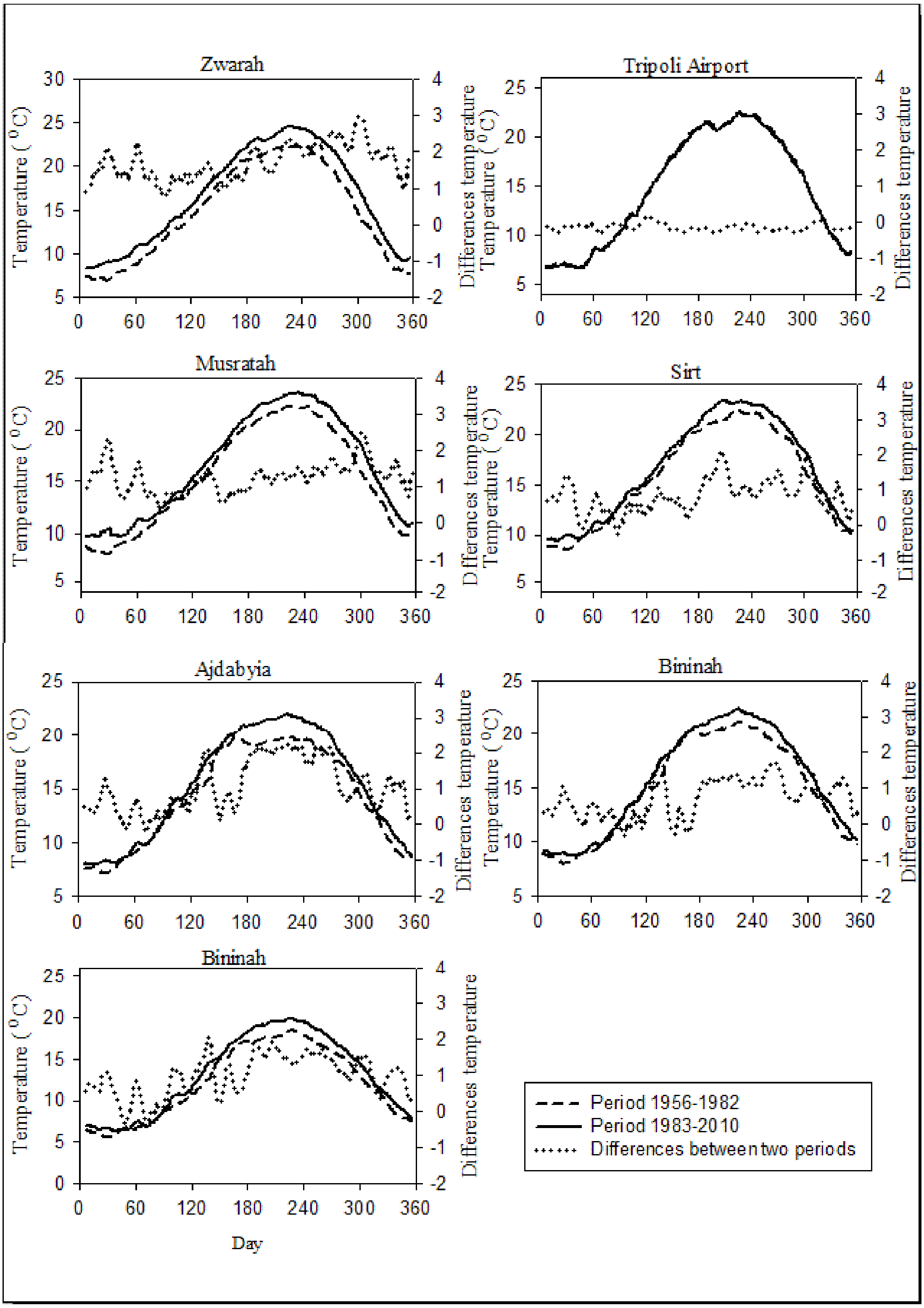

Ghadames
Temperature(°c)
30
25
20
15
1940 1950 1960 1970 1980 1990 2000 2010
Hon
Temperature(°c)
35
30
25
20
1940 1950 1960 1970 1980 1990 2000 2010
Jalo
Temperature(°c)
35
30
25
20
1940 1950 1960 1970 1980 1990 2000 2010
Al-jaghbub
Temperature(°c)
35
30
25
20
1940 1950 1960 1970 1980 1990 2000 2010
Al-Kufrah
Temperature(°c)
35
30
25
20
1940 1950 1960 1970 1980 1990 2000 2010
Year

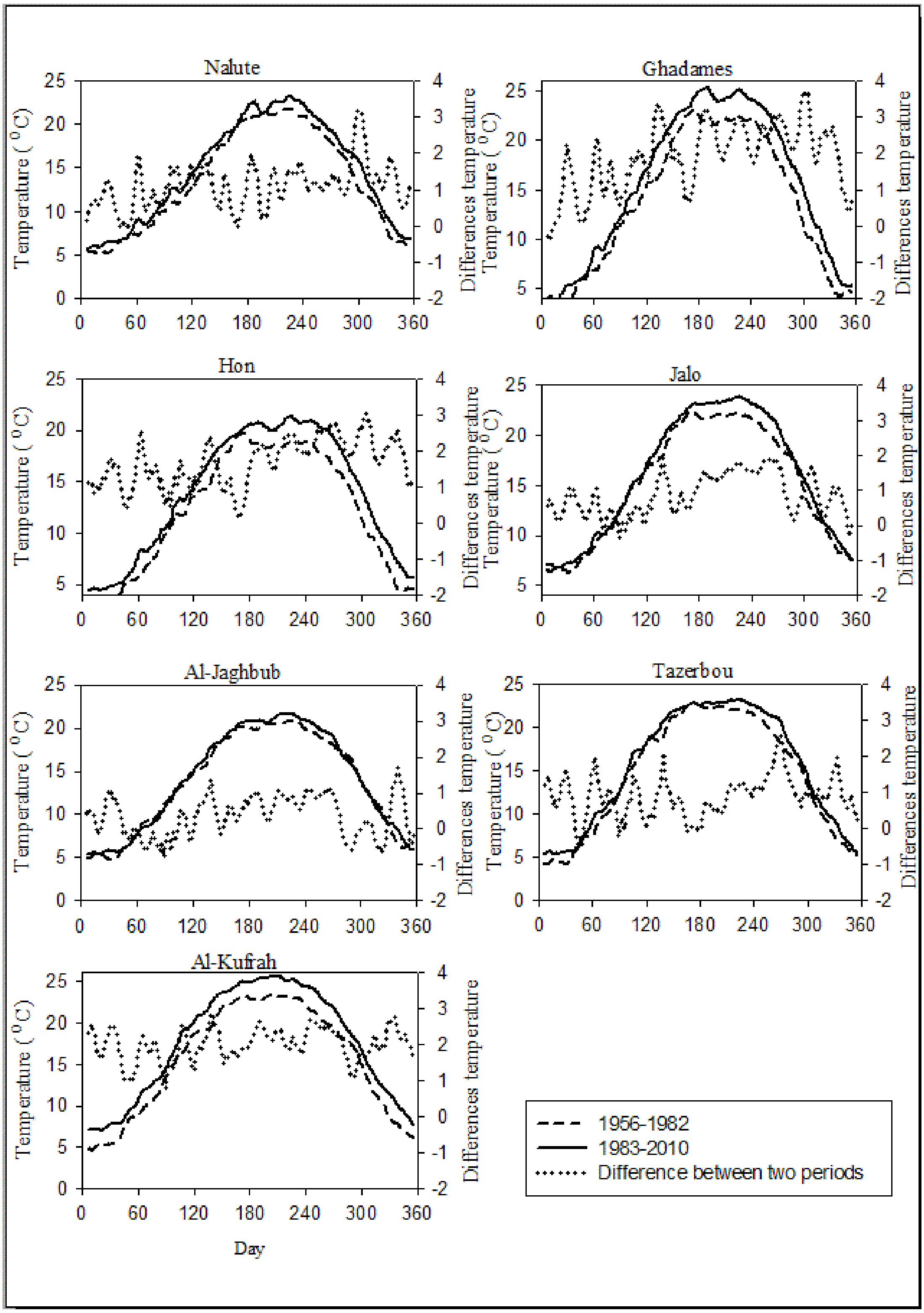
Appendix 4.4: Decadal mean of 11-day moving average of the mean daily maximum temperature during the period 1961-2010 over near decadal windows



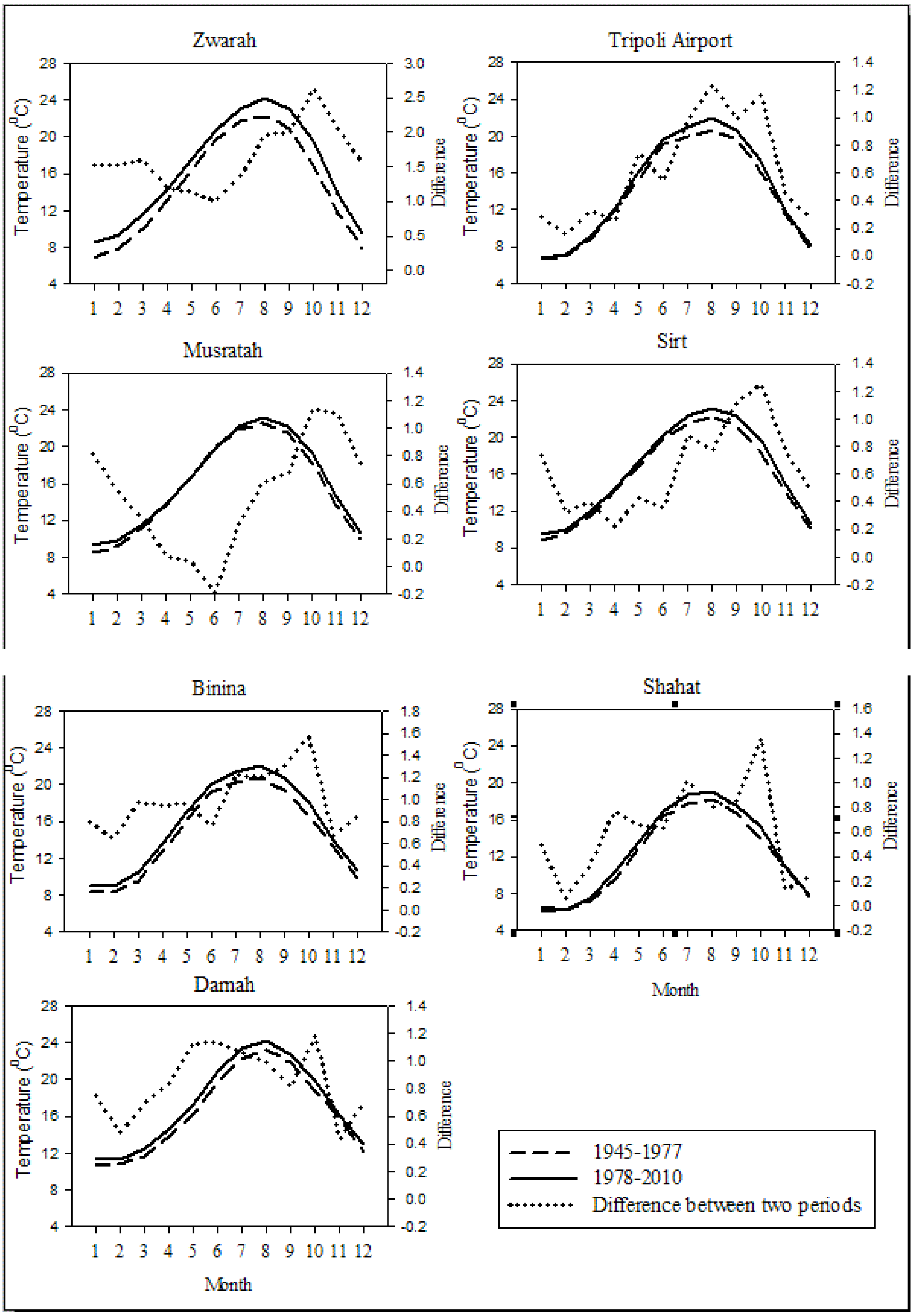

Nalute
Jalo
Hon
Al-Jaghbub
Sabha
Tazerbou
Al-Kufrah
Daily temperature (⁰C)
45
40
35
30
25
20
15
10
0
60
120
180
240
300
360
Day
1961-1970
1971-1980
1981-1990
1991-2000
2001-2010

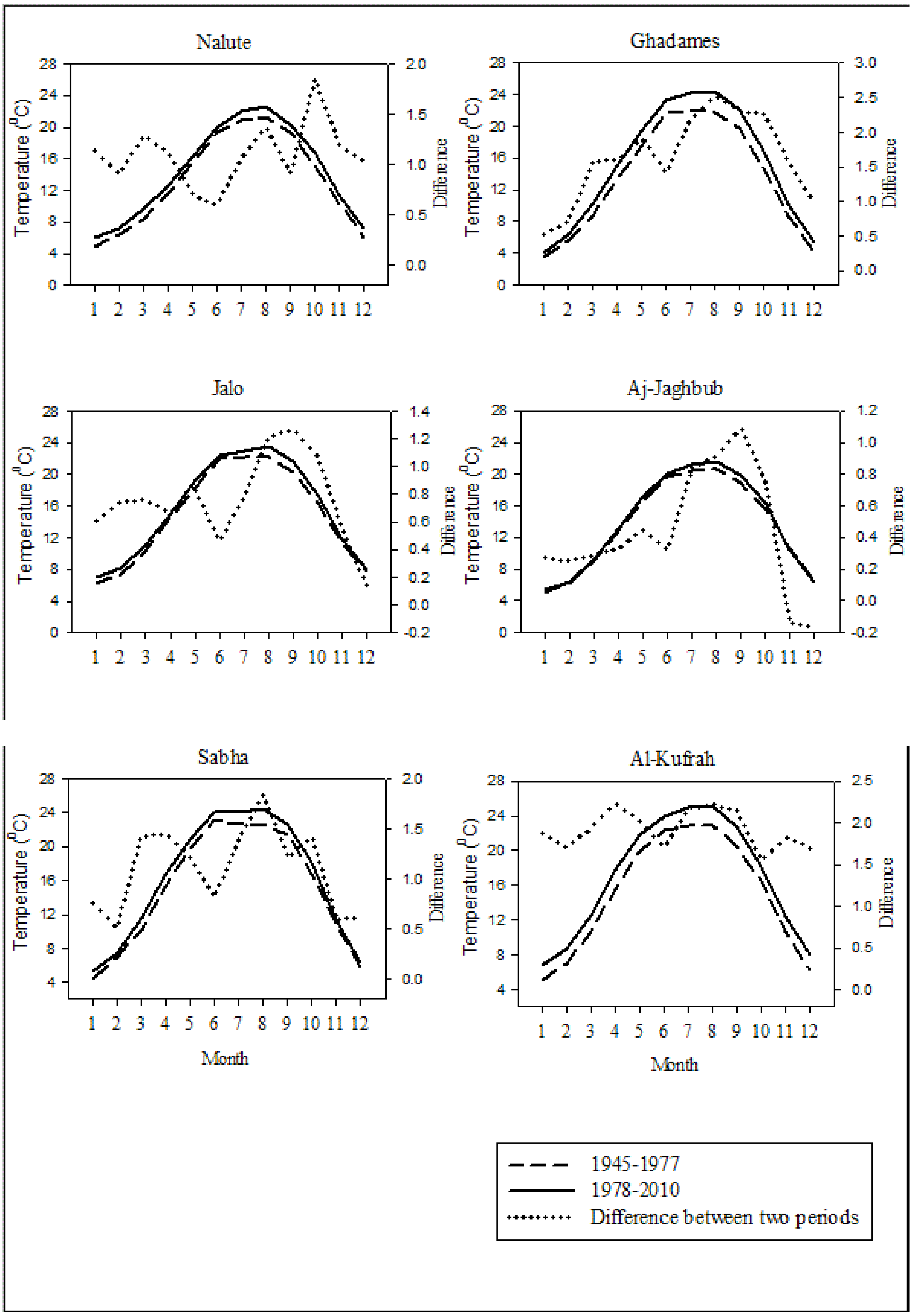
Appendix 4.5: Annual means 11-day moving averages of the mean daily minimum temperature for the two periods 1956-1982 and 1983-2010.



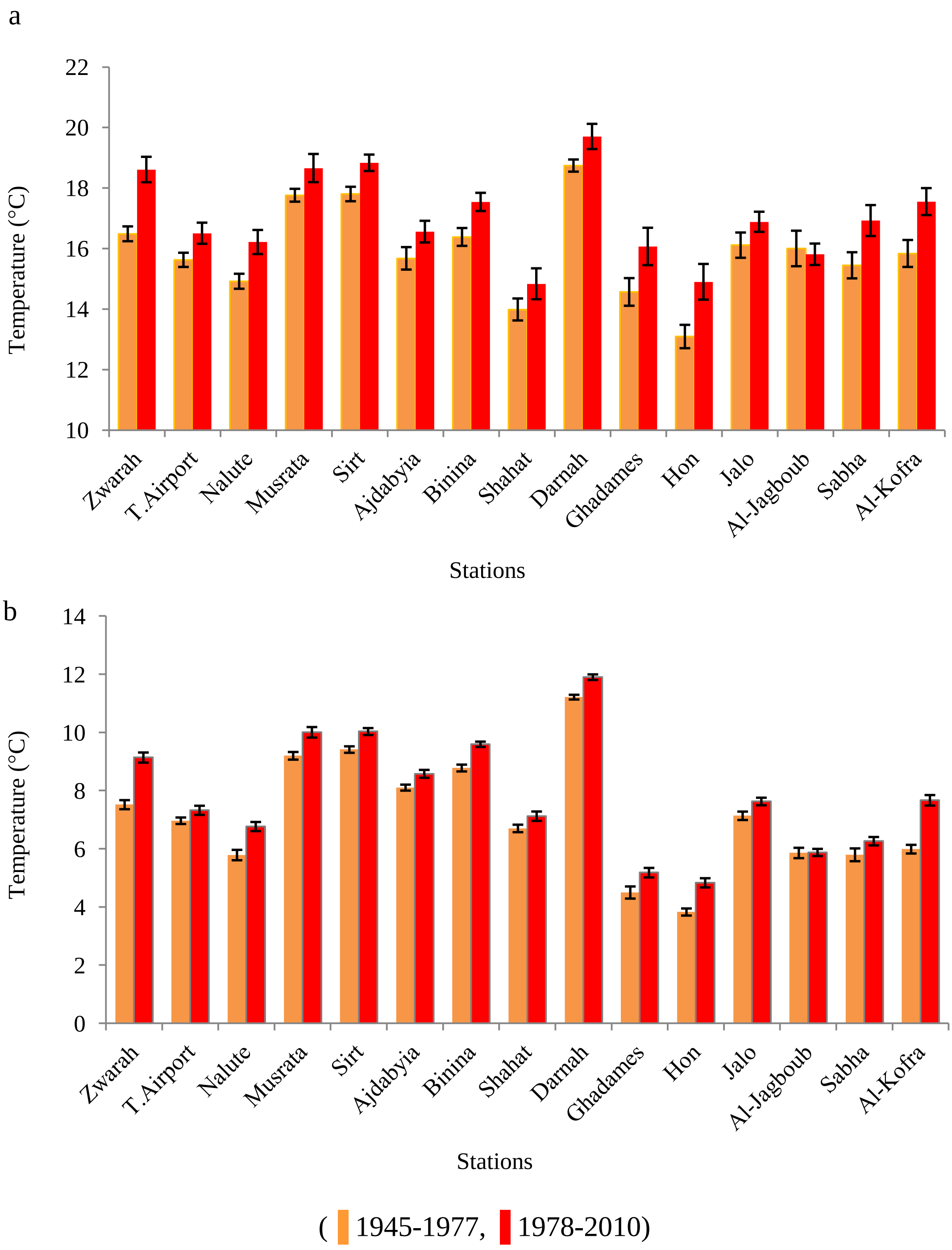

Nalute
Ghadames
Hon
Jalo
Al-Jaghbub
Tazerbou
Al-Kufrah
Temperature (^{0}C)
Differences temperature
Day
0
60
120
180
240
300
360
0
5
10
15
20
25
-2
-1
0
1
2
3
4
1956-1982
1983-2010
Difference between two periods

Appendix 4.6: Mean monthly minimum temperature for the two periods 1945-1977 and 1978-2010.

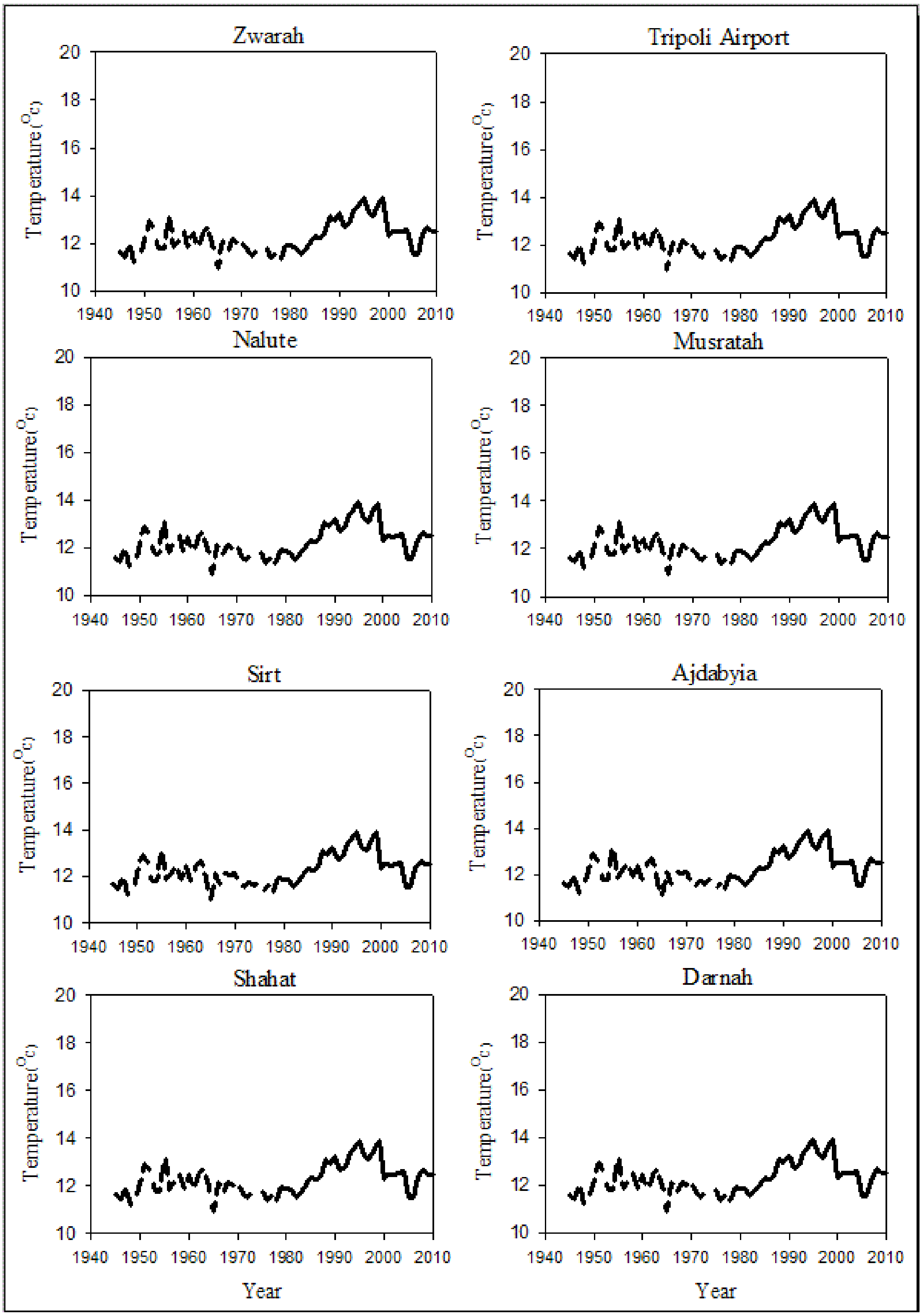


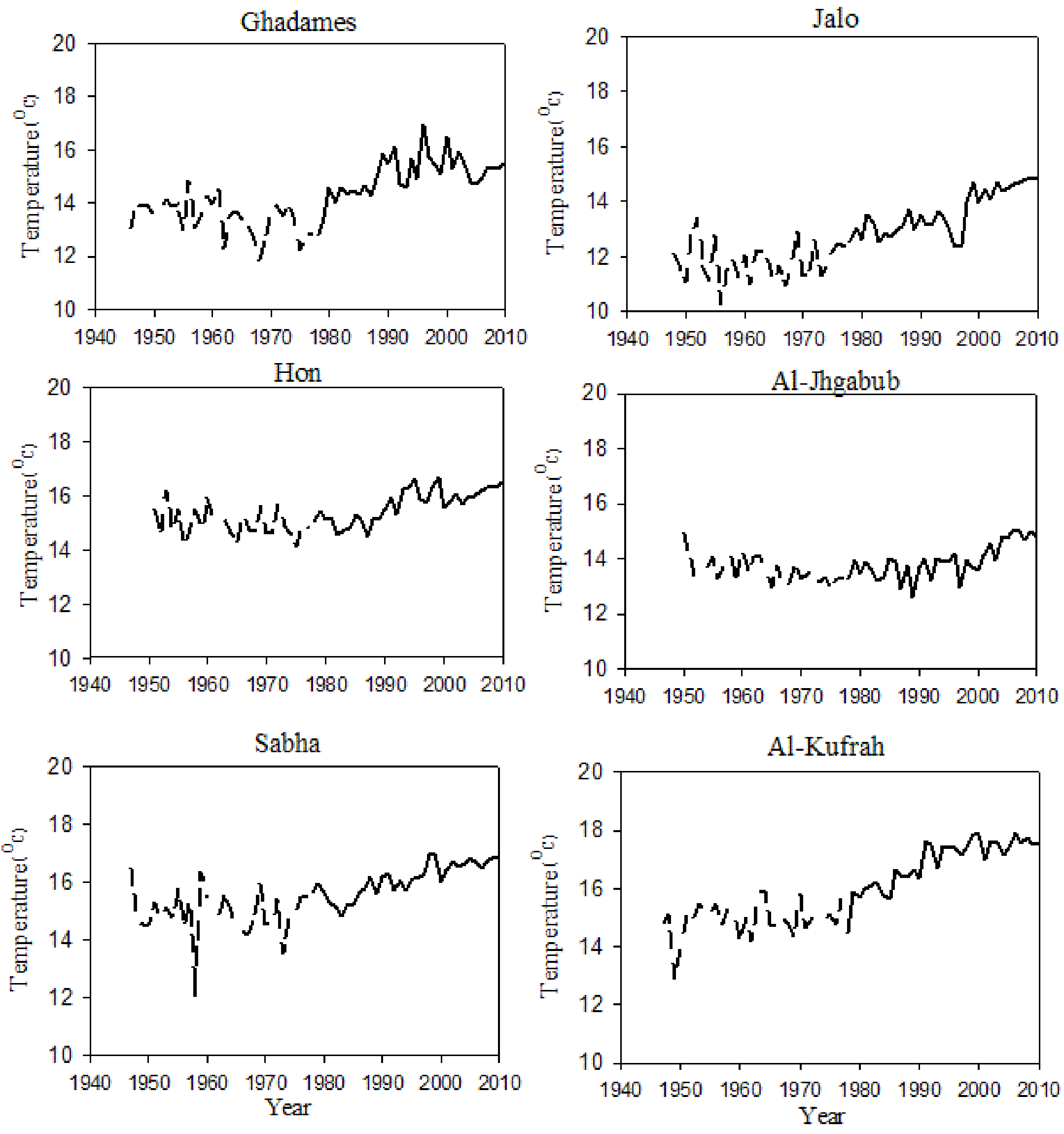

Nalute
Ghadames
Jalo
Aj-Jaghbub
Sabha
Al-Kufrah
Temperature (°C)
Difference
Month
1 2 3 4 5 6 7 8 9 10 11 12
0 4 8 12 16 20 24 28
1945-1977
1978-2010
Difference between two periods

Appendix 4.7: Mean minimum temperature for the two periods 1945-1977 and 1978-2009, at a) autumn, with error bars representing two standard errors (95.4% confidence level; and b) winter, with error bars representing three standard errors (68.2% confidence level).

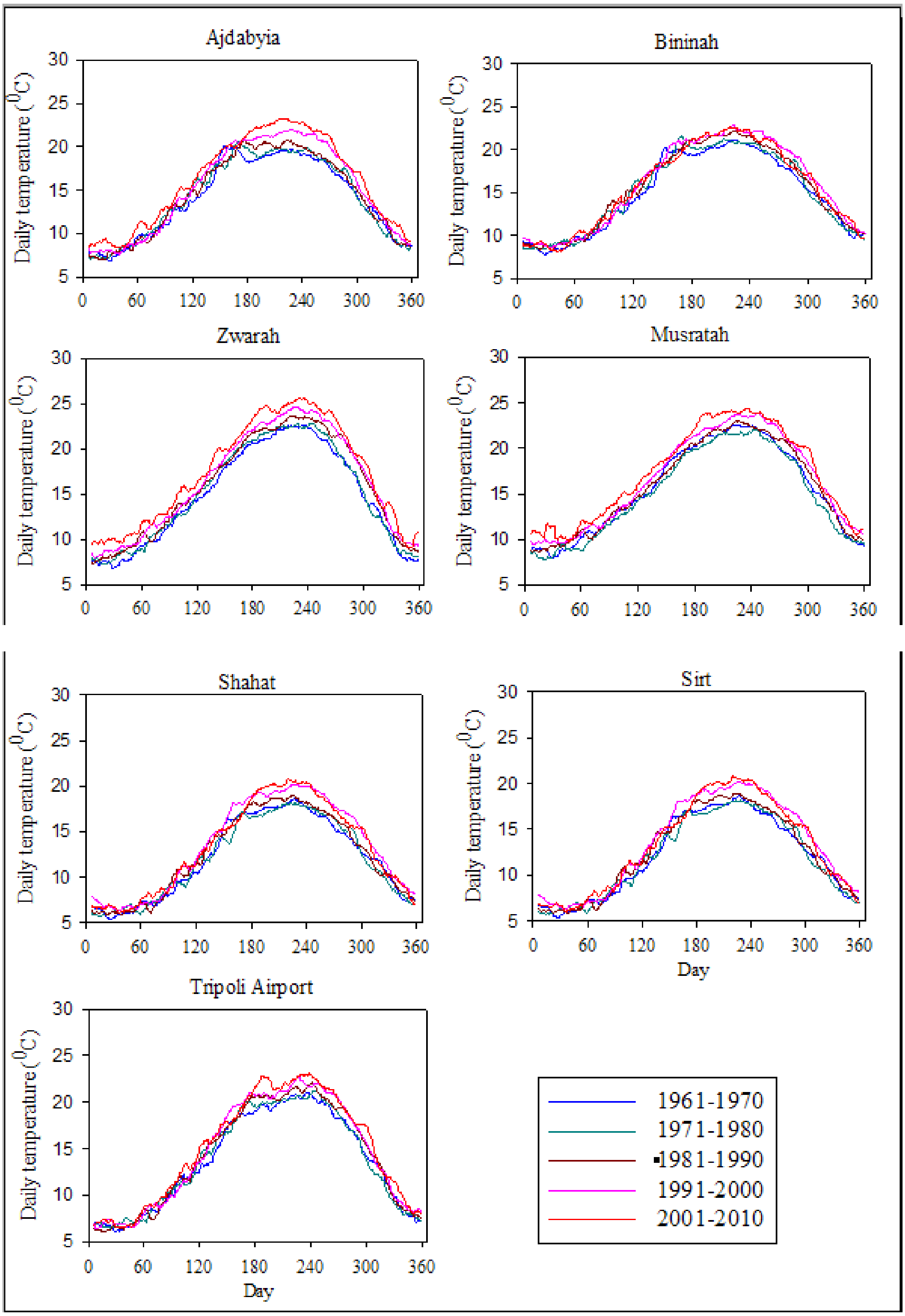


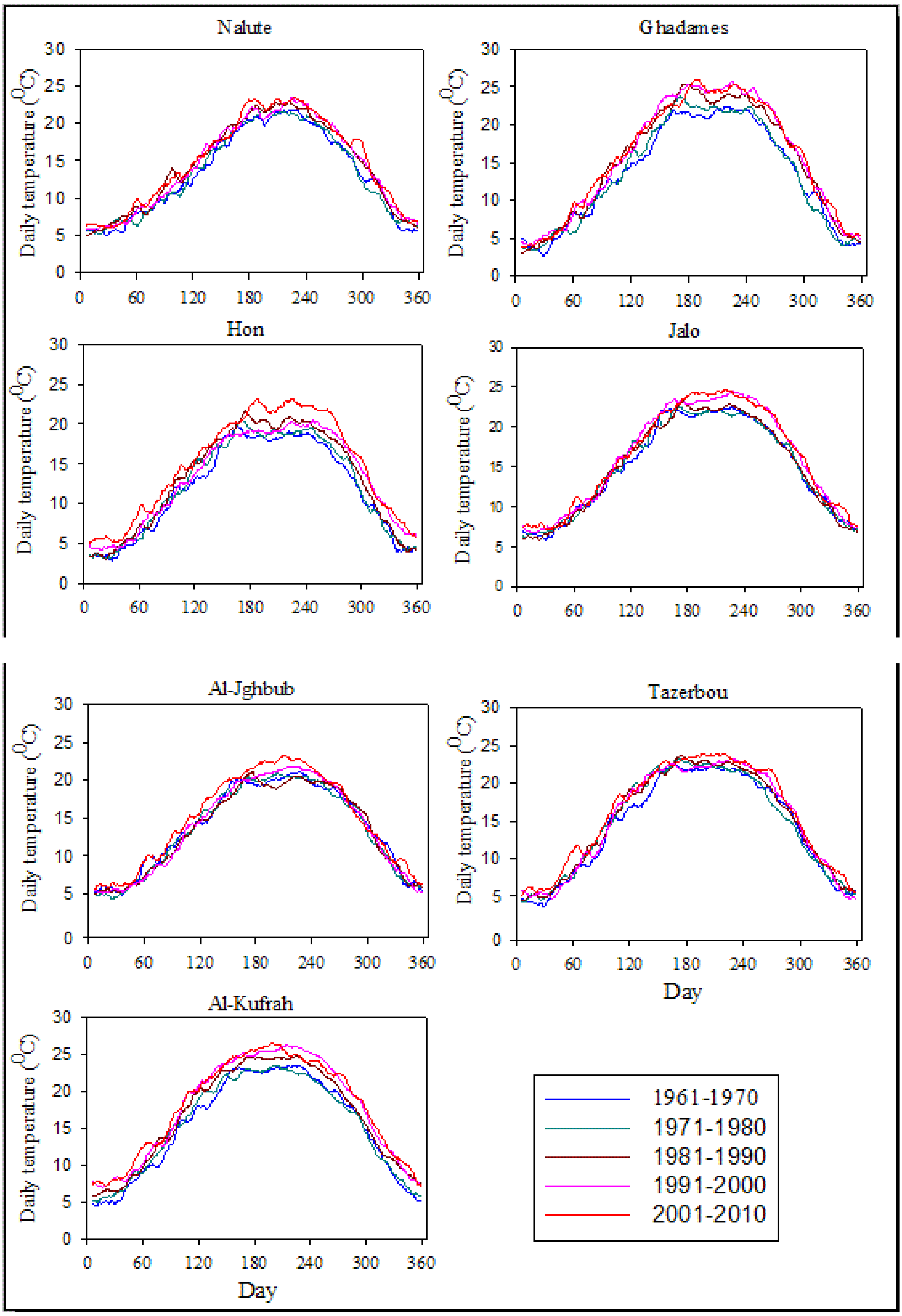
Appendix 4.8: Annual mean minimum temperature for two periods 1945-1977 and 1978-2010



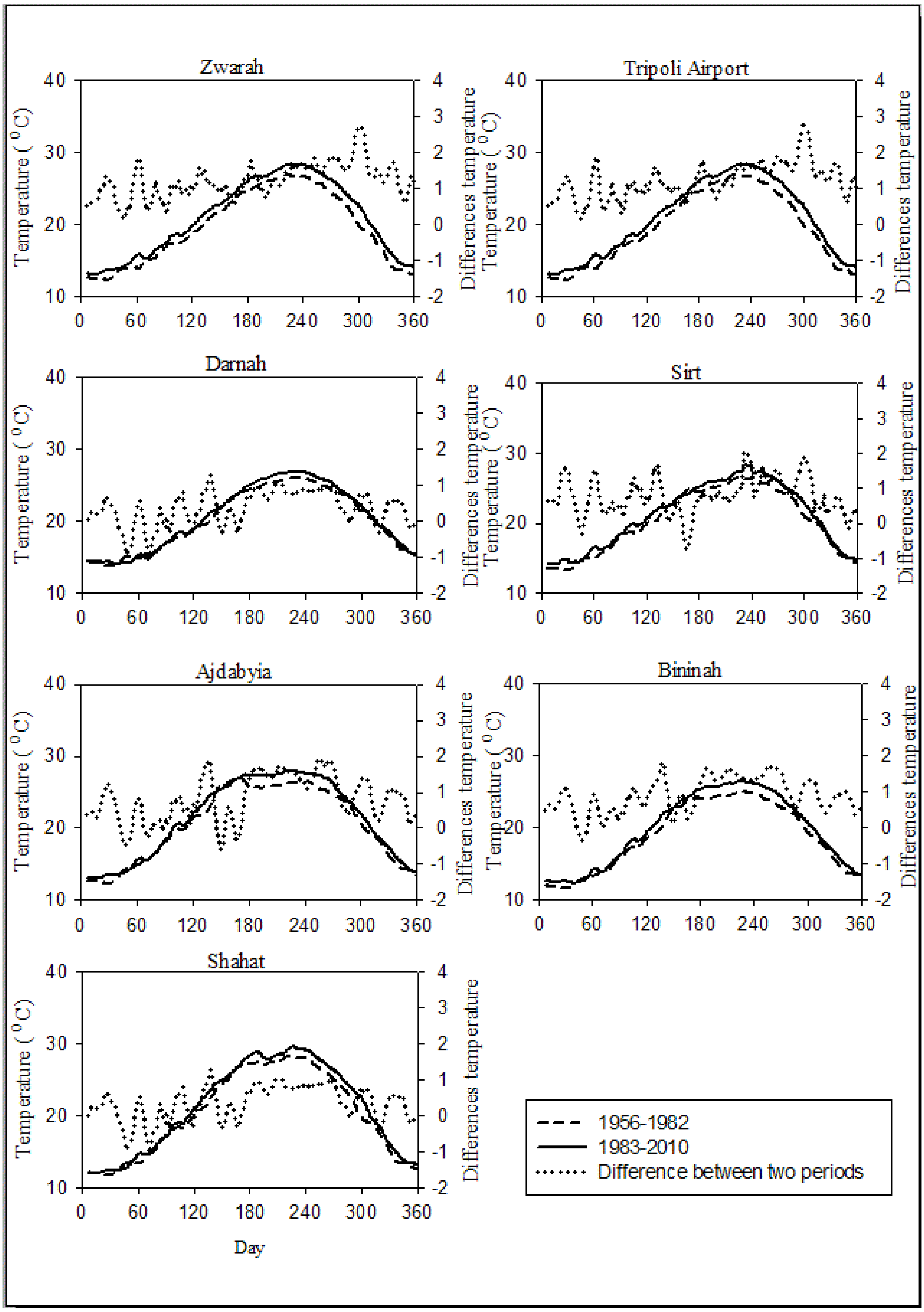

Ghadames
Jalo
Hon
Al-Jhgabub
Sabha
Al-Kufrah
Temperature(^{0}c)
20
18
16
14
12
10
1940
1950
1960
1970
1980
1990
2000
2010
Year

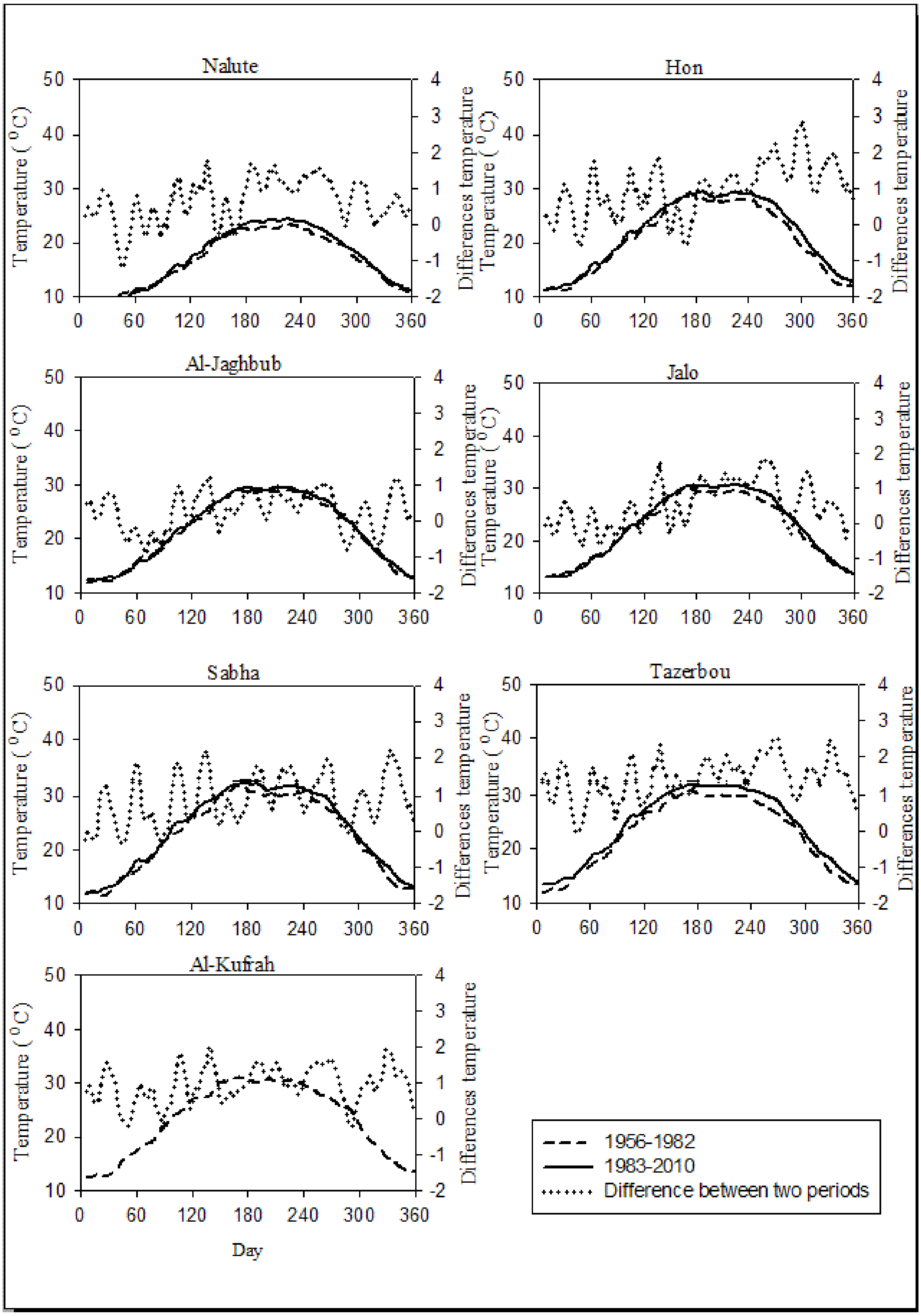
Appendix 4.9: Decadal mean of 11 day moving averages of the mean daily minimum temperature over near decadal windows for the period 1961-2009, with the curves from a separate decadal block.



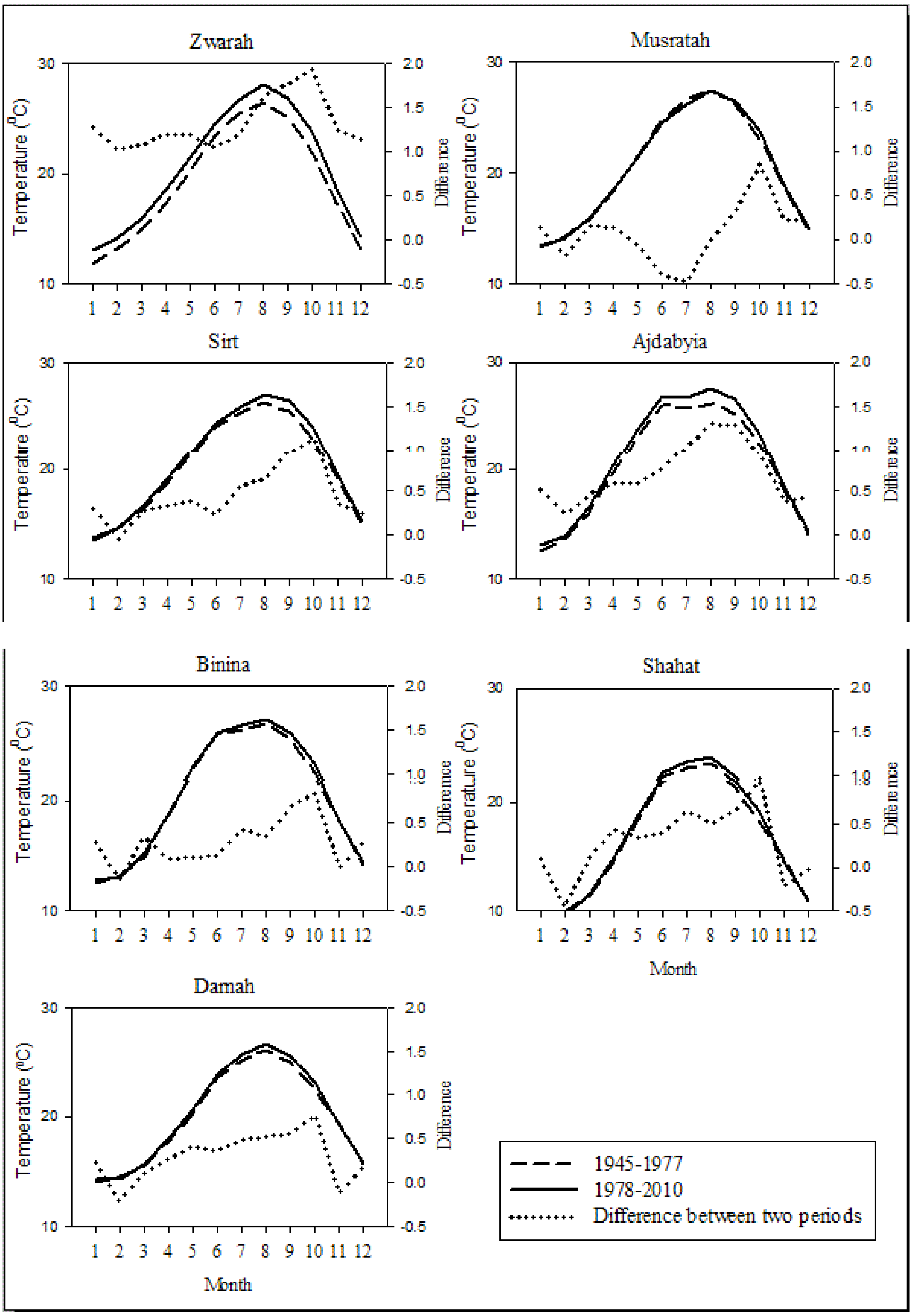

Nalute
Ghadames
Hon
Jalo
Al-Jghbub
Tazerbou
Al-Kufrah
Daily temperature (⁰C)
Day
0
5
10
15
20
25
30
60
120
180
240
300
360
1961-1970
1971-1980
1981-1990
1991-2000
2001-2010

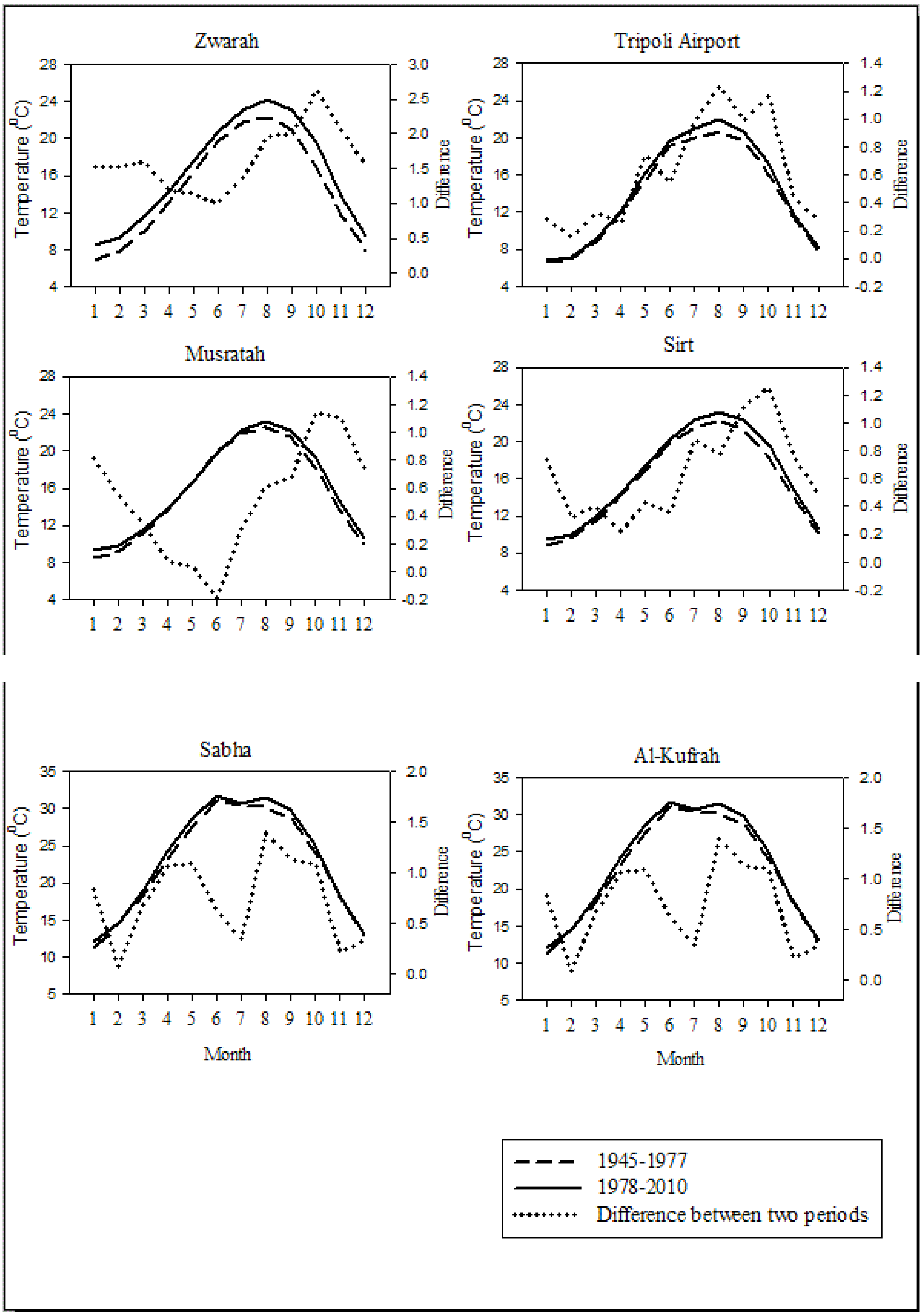
Appendix 4.10: Annual means 11-day moving averages of the mean daily average temperature for the two periods 1956-1982 and 1983-2010.



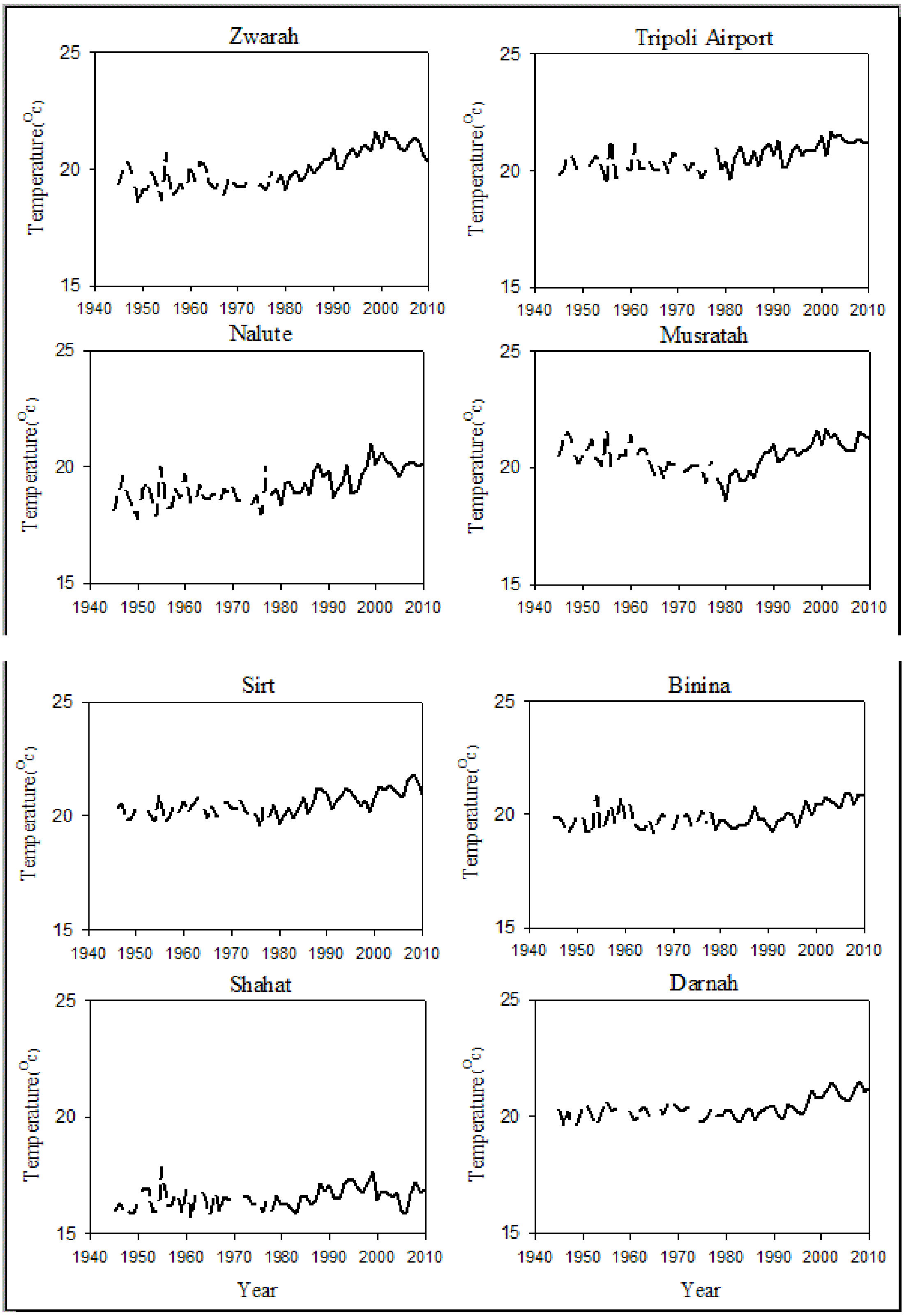

Nalute
Hon
Al-Jaghbub
Jalo
Sabha
Tazerbou
Al-Kufrah
Temperature (⁰C)
Differences temperature
Day
0
60
120
180
240
300
360
10
20
30
40
50
-2
-1
0
1
2
3
4
1956-1982
1983-2010
Difference between two periods

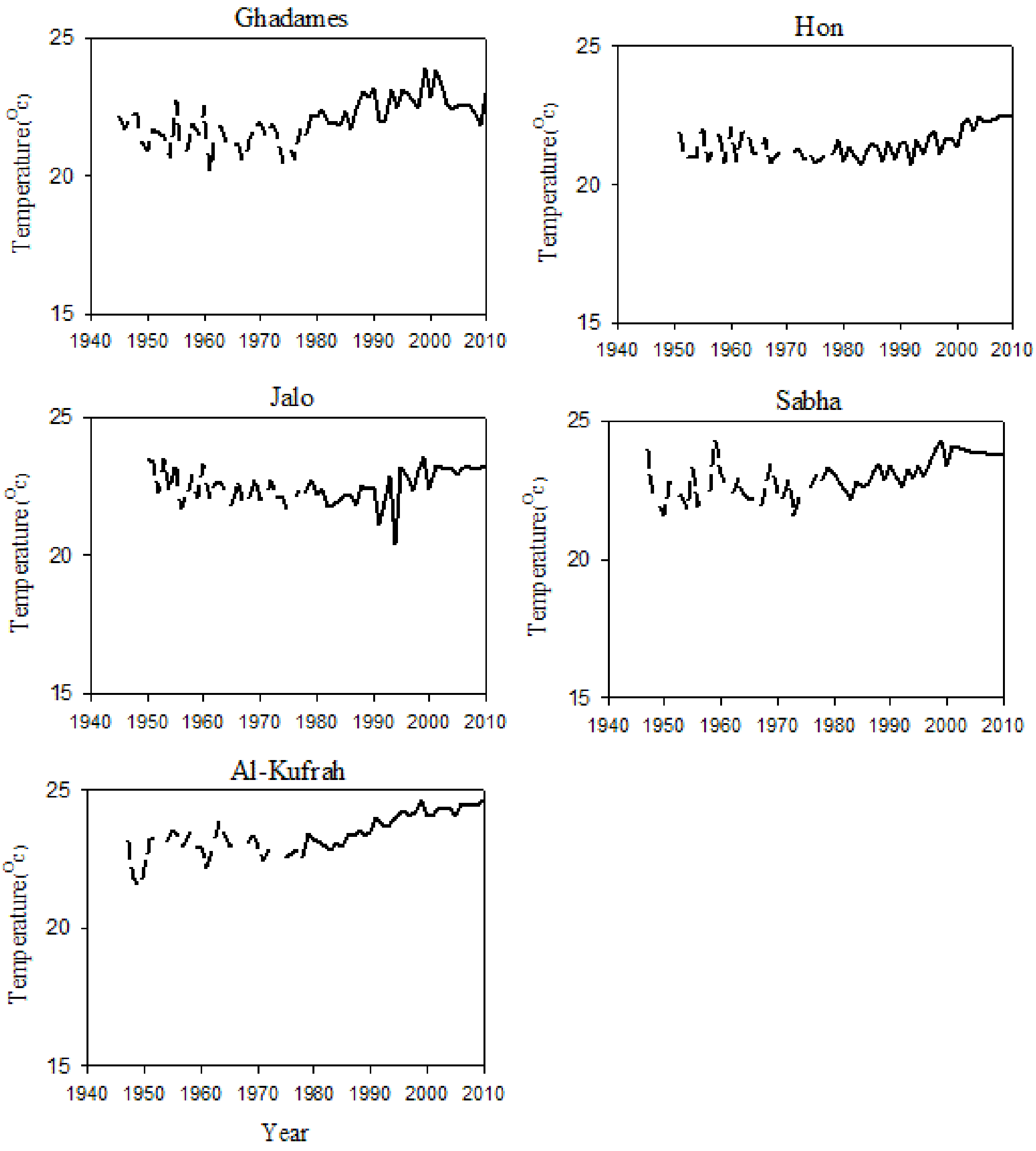
Appendix 4.11: Mean monthly average temperature for the two periods 1945-1977 and 1978-2010.



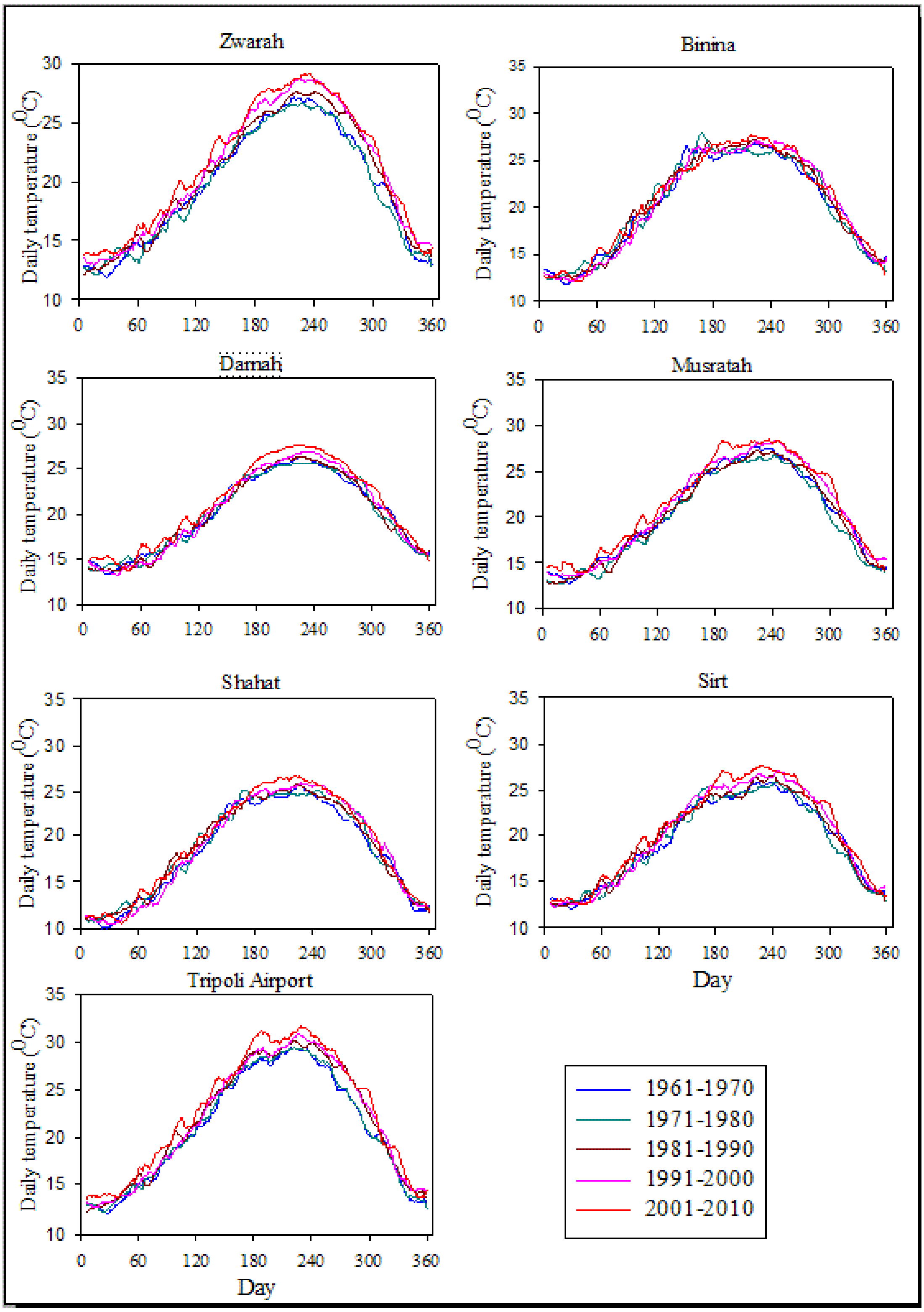

Zwarah
Tripoli Airport
Musratah
Sirt
Sabha
Al-Kufrah
Temperature (0C)
Difference
Month
1 2 3 4 5 6 7 8 9 10 11 12
4 8 12 16 20 24 28
0.0 0.5 1.0 1.5 2.0 2.5 3.0
-0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
5 10 15 20 25 30 35
0.0 0.5 1.0 1.5 2.0
1945-1977
1978-2010
Difference between two periods

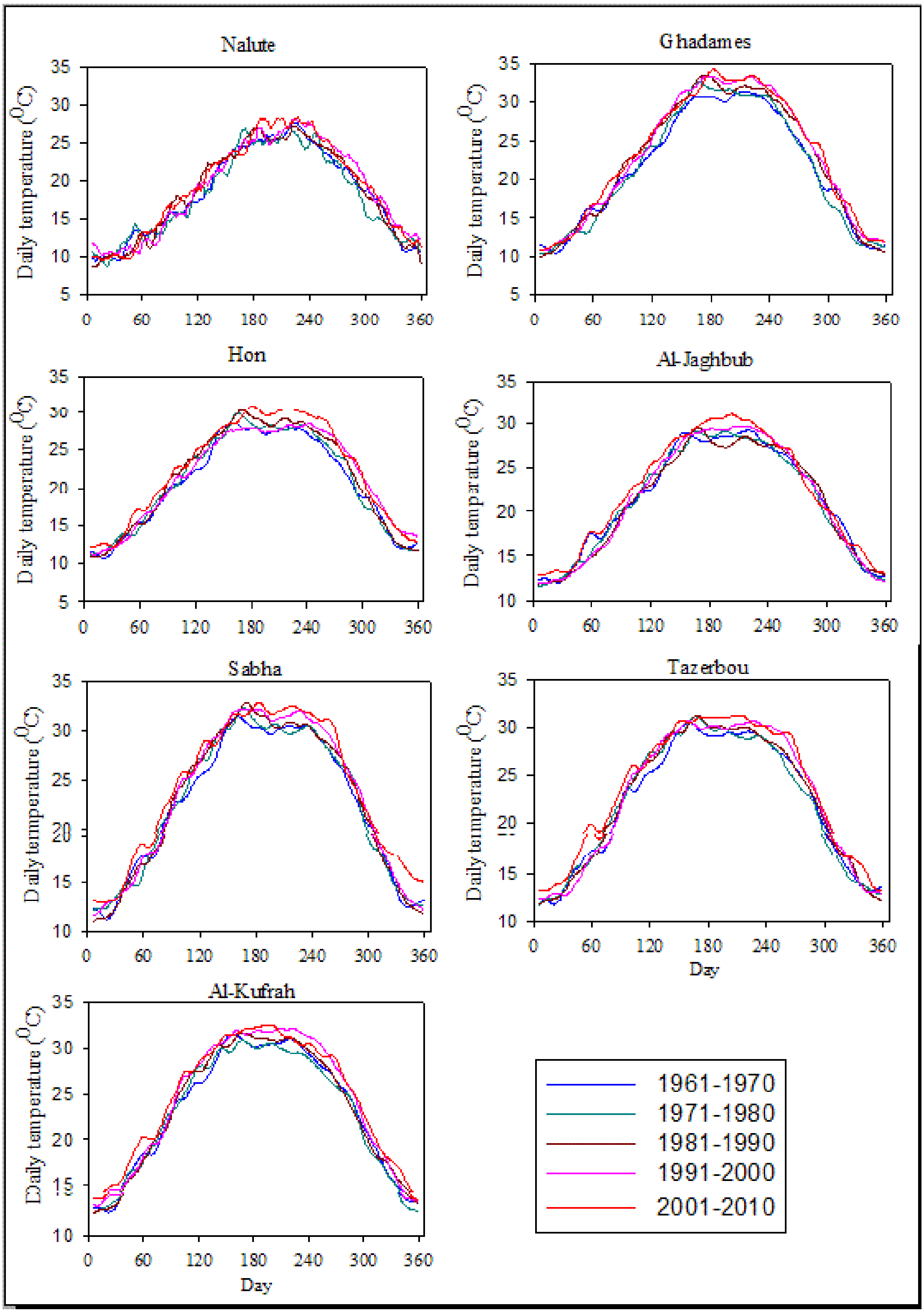
Appendix 4.12: Annual mean average temperature for the two periods 1945-1977 and 1978-2010.



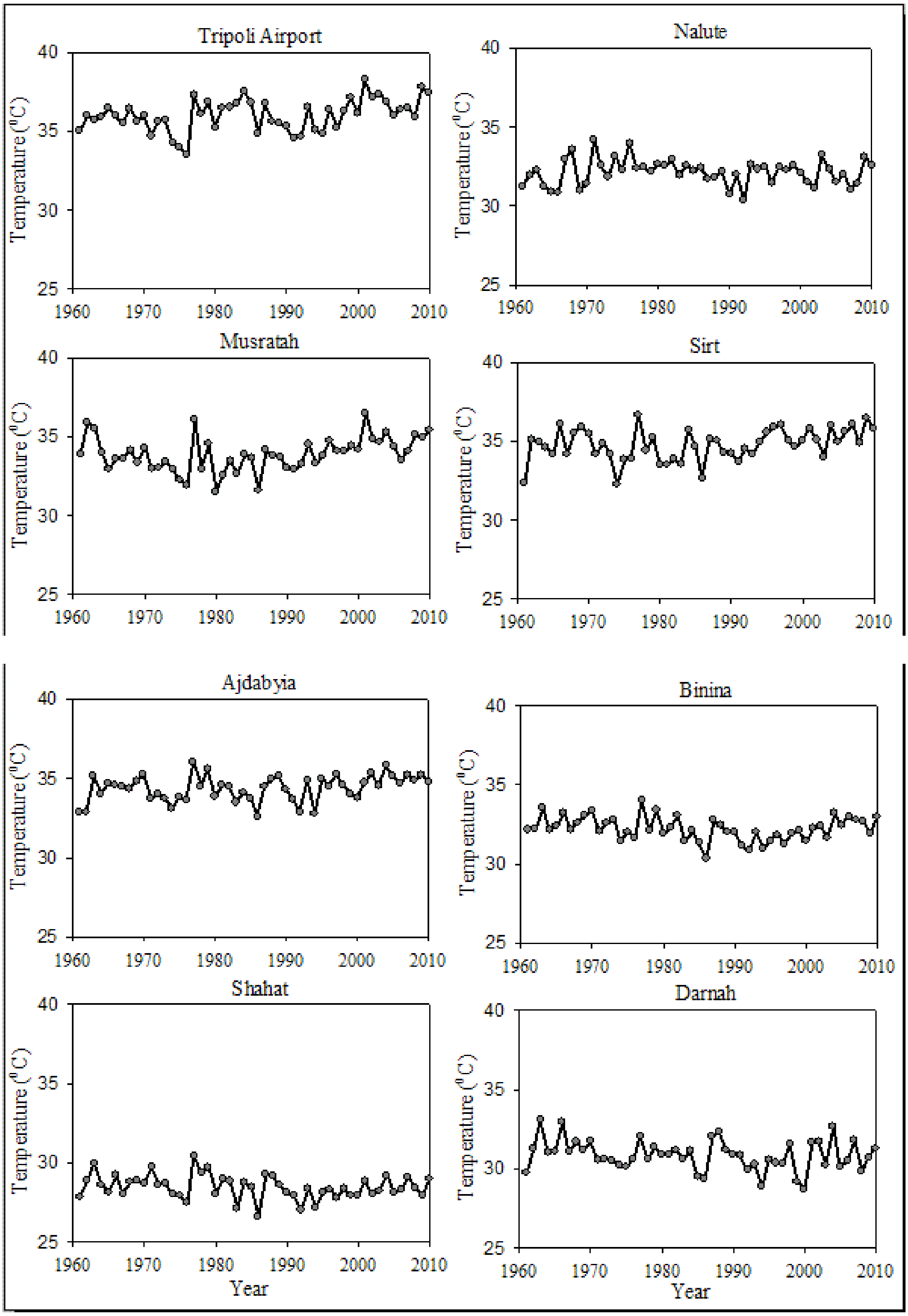

Ghadames
Hon
Jalo
Sabha
Al-Kufrah
Temperature(°c)
25
20
15
1940
1950
1960
1970
1980
1990
2000
2010
Year

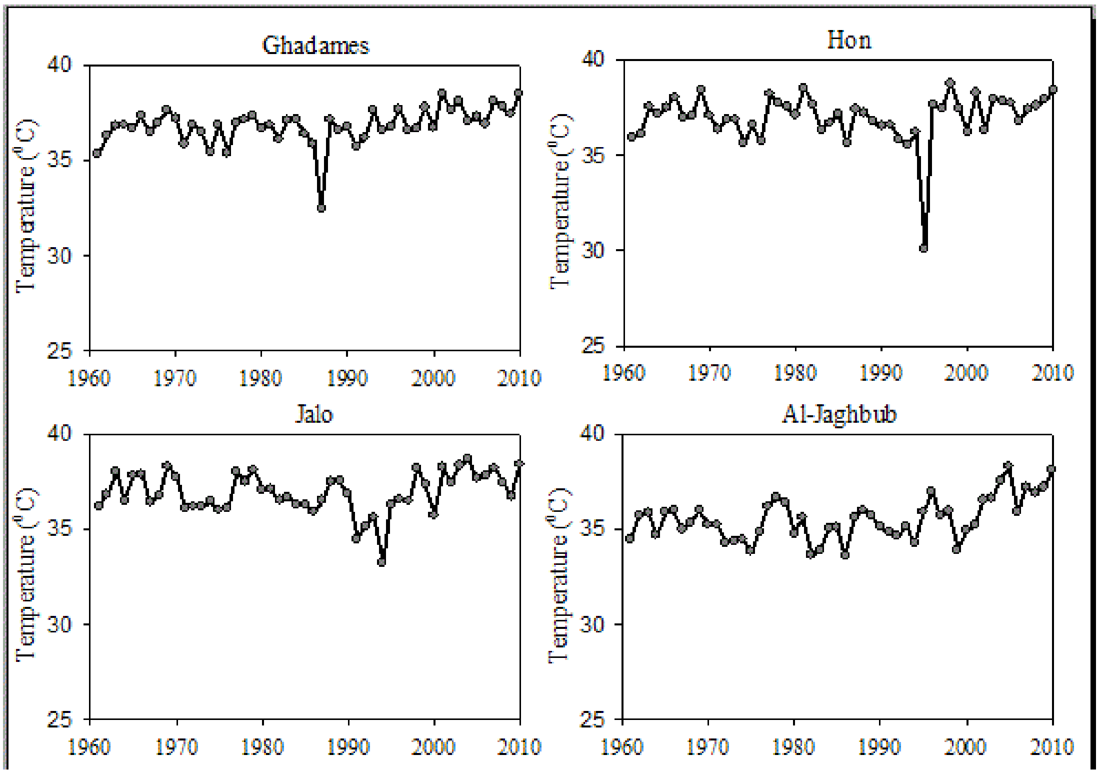
Appendix 4.13: Decadal mean of 11-day moving averages of the mean daily average temperature over near decadal windows for the period 1961-2010, with the curves for each separate decadal block.

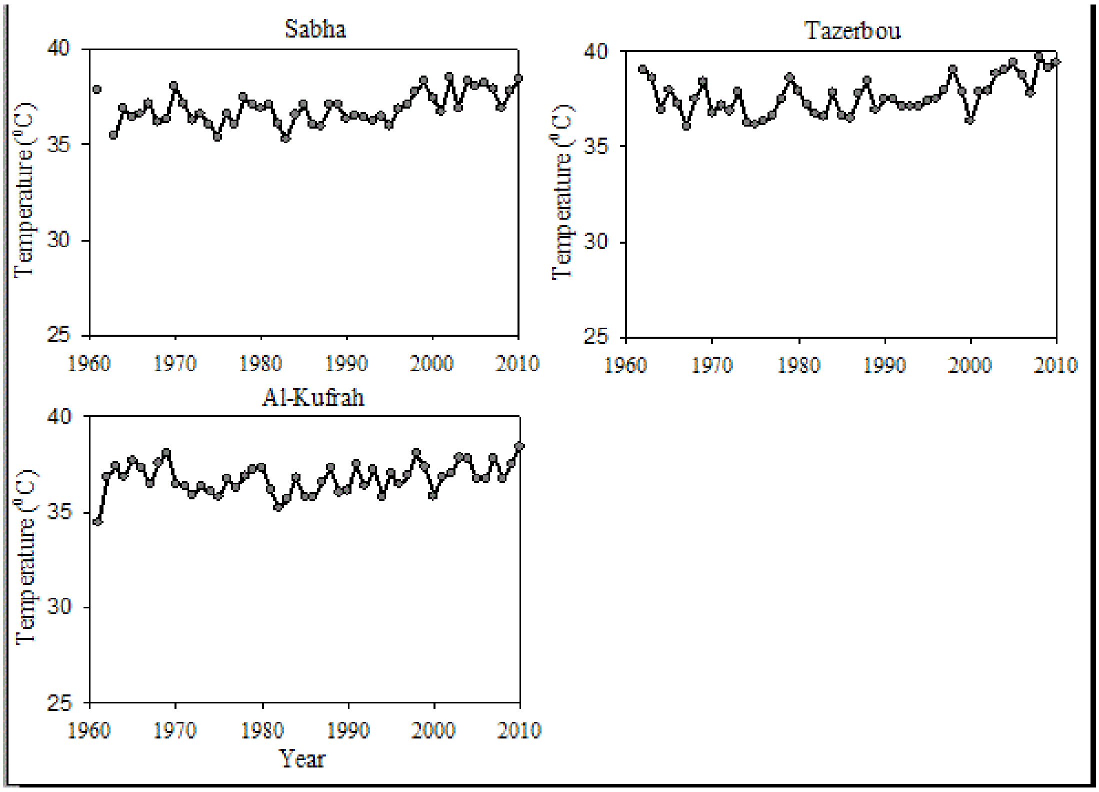



Nalute
Ghadames
Hon
Al-Jaghbub
Sabha
Tazerbou
Al-Kufrah
Daily temperature (0C)
Day
35
30
25
20
15
10
5
0
60
120
180
240
300
360
1961-1970
1971-1980
1981-1990
1991-2000
2001-2010

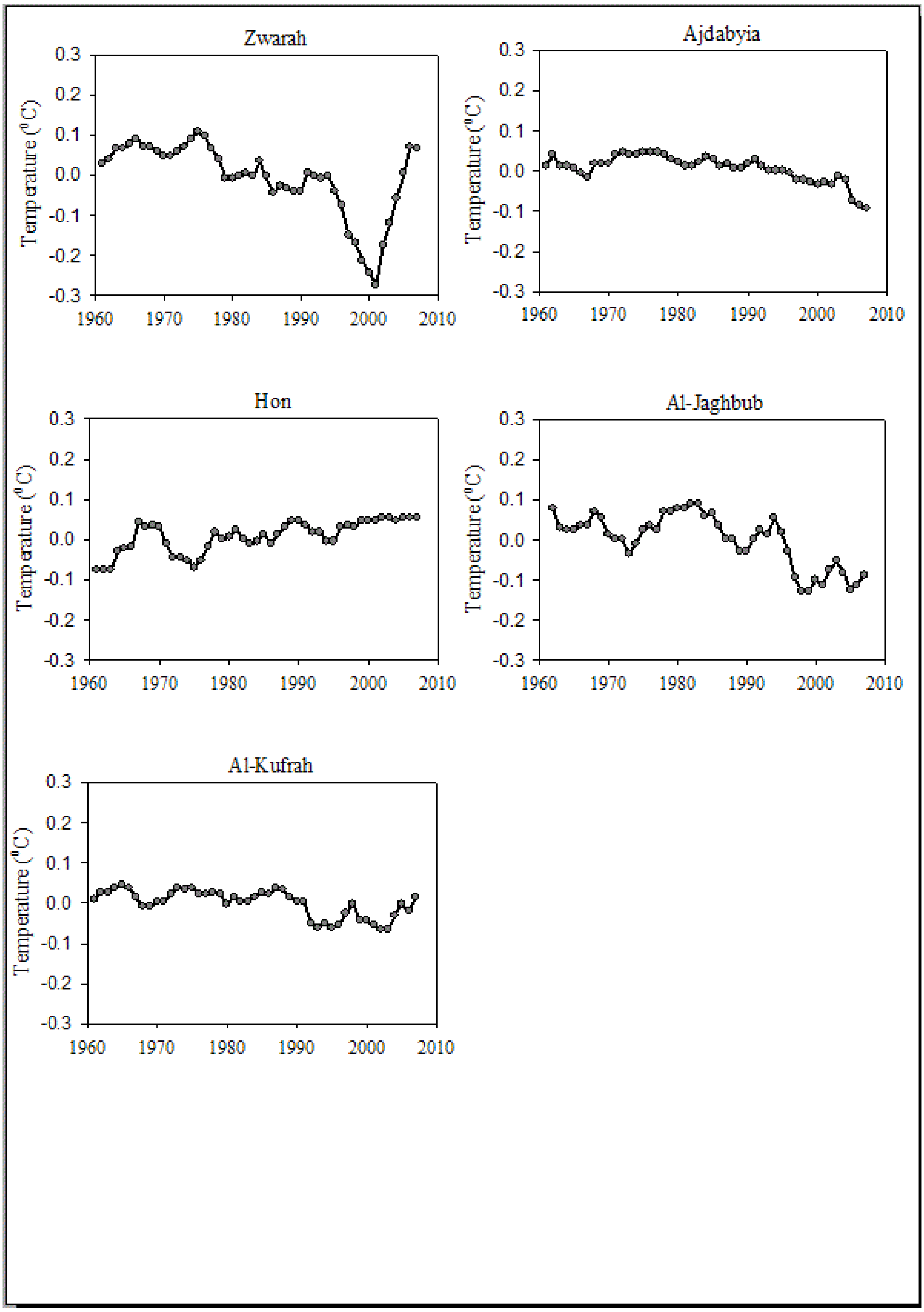
Appendix 4.14a: Regional annual anomalies series during 1961-2010 for warmest day (TXx).



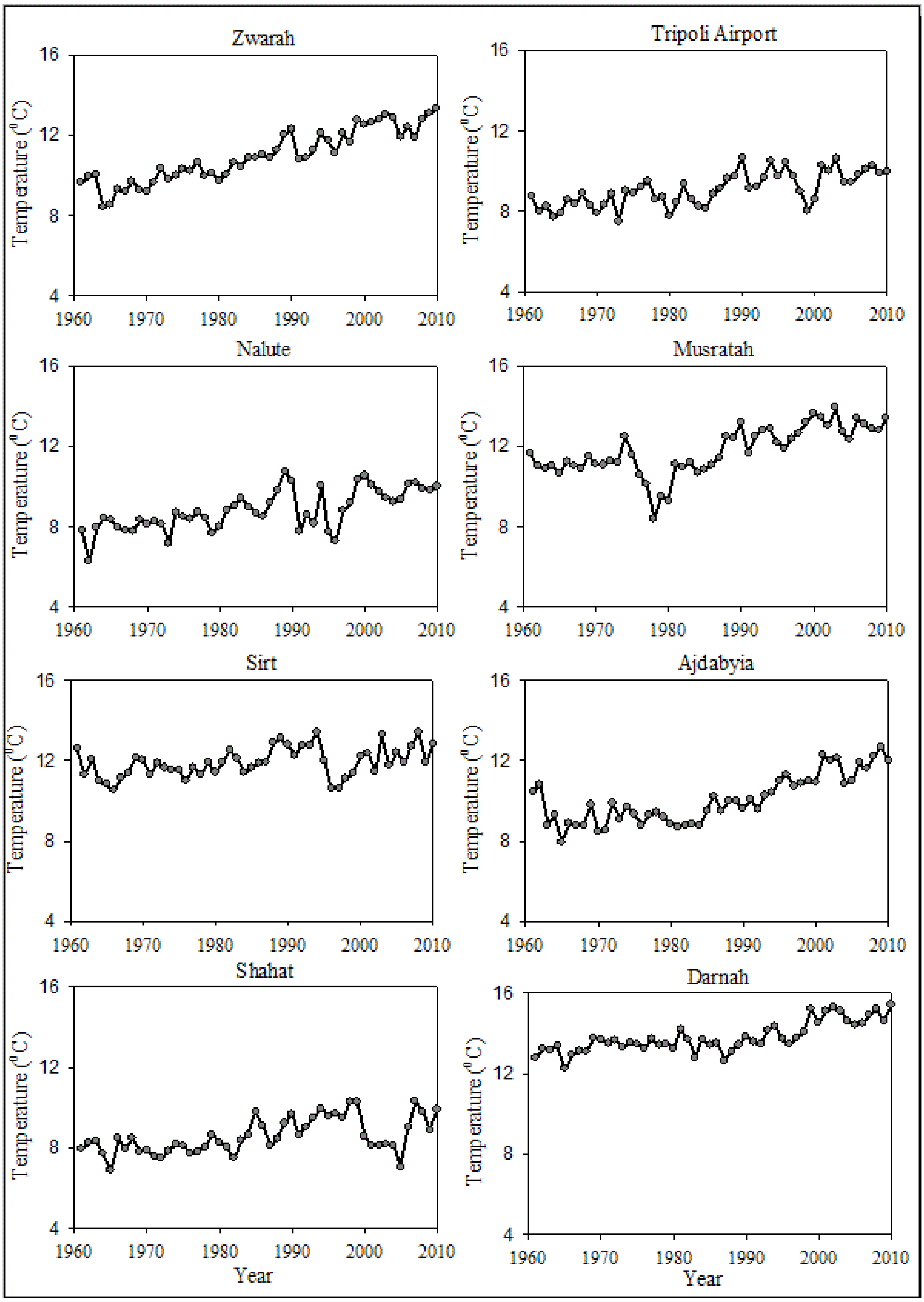

Ghadames
Hon
Jalo
Al-Jaghbub
Temperature (°C)
40
35
30
25
1960
1970
1980
1990
2000
2010

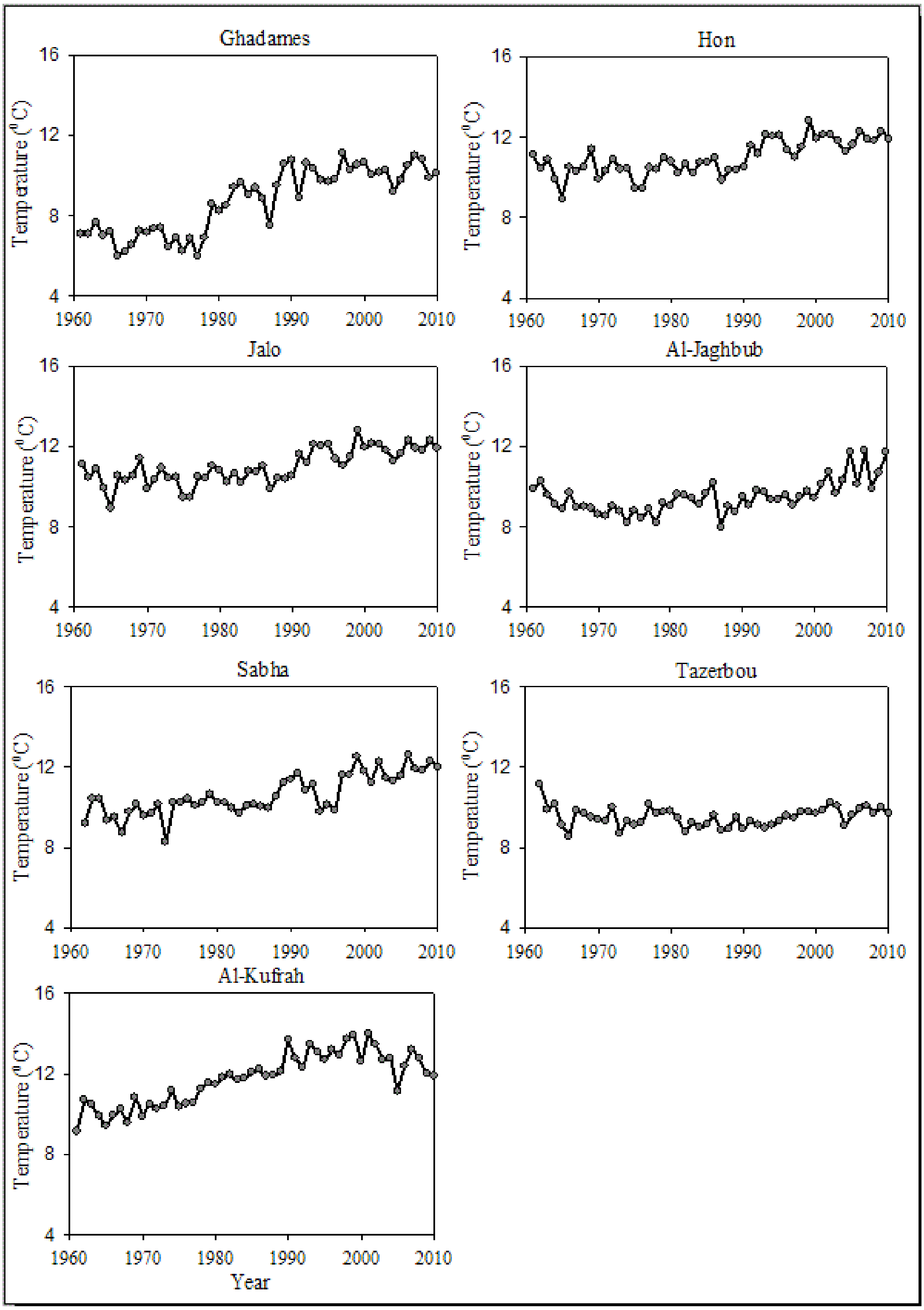

Sabha
Tazerbou
Al-Kufrah
Temperature (°C)
40
35
30
25
1960
1970
1980
1990
2000
2010
Year

Appendix 4.14b: Regional annual anomalies series during 1961-2010 for warmest nights (TN90).

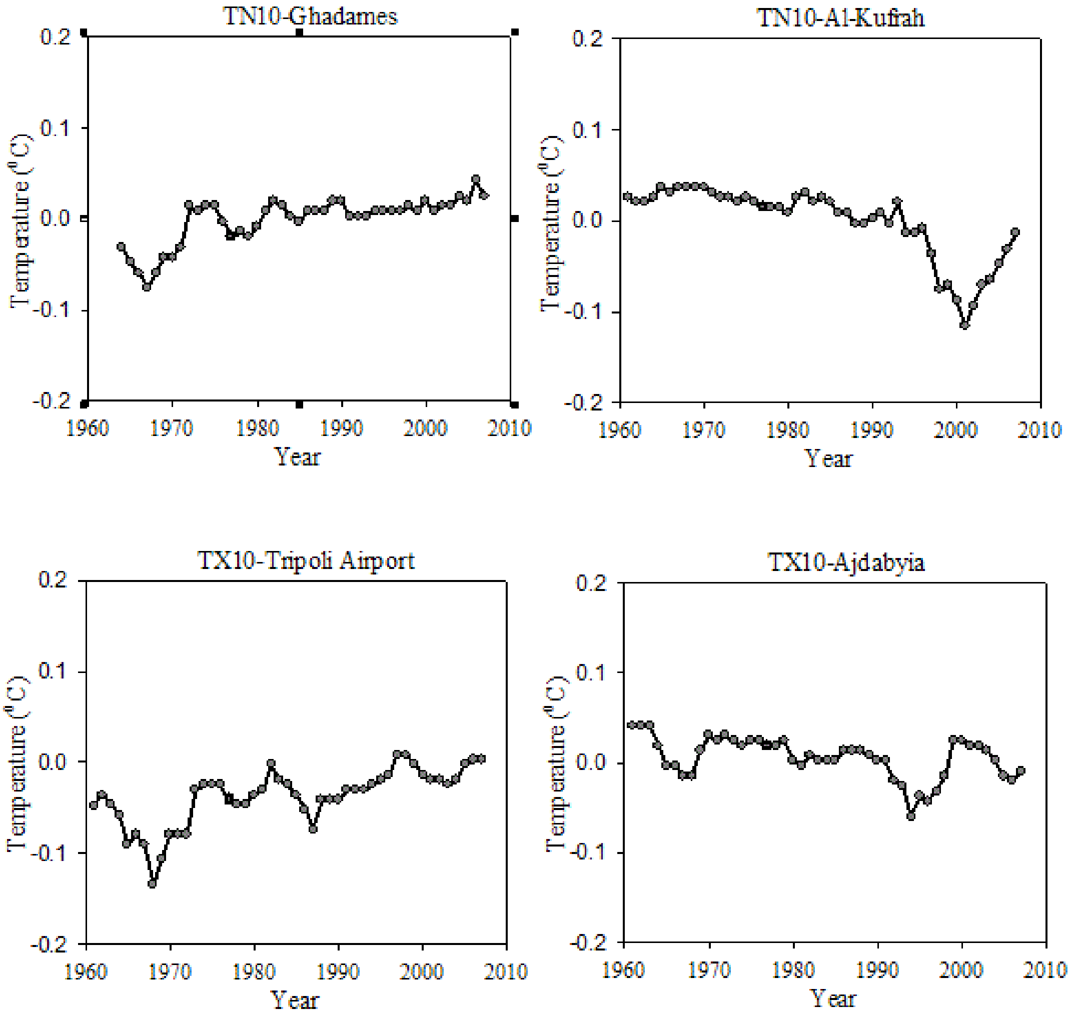


Appendix 4.15a: Regional annual anomalies series during 1961-2010 for coldest night (TNn)

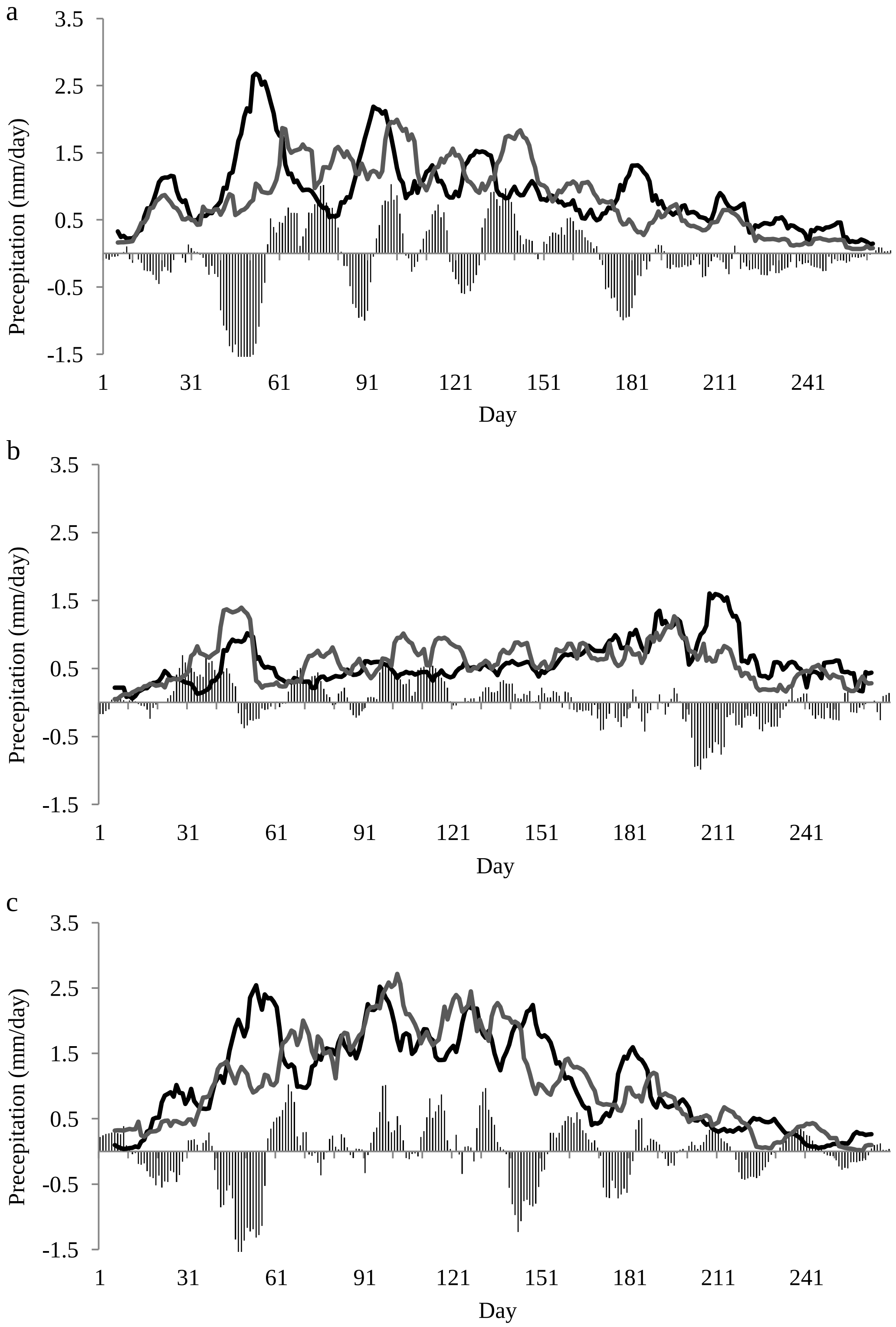


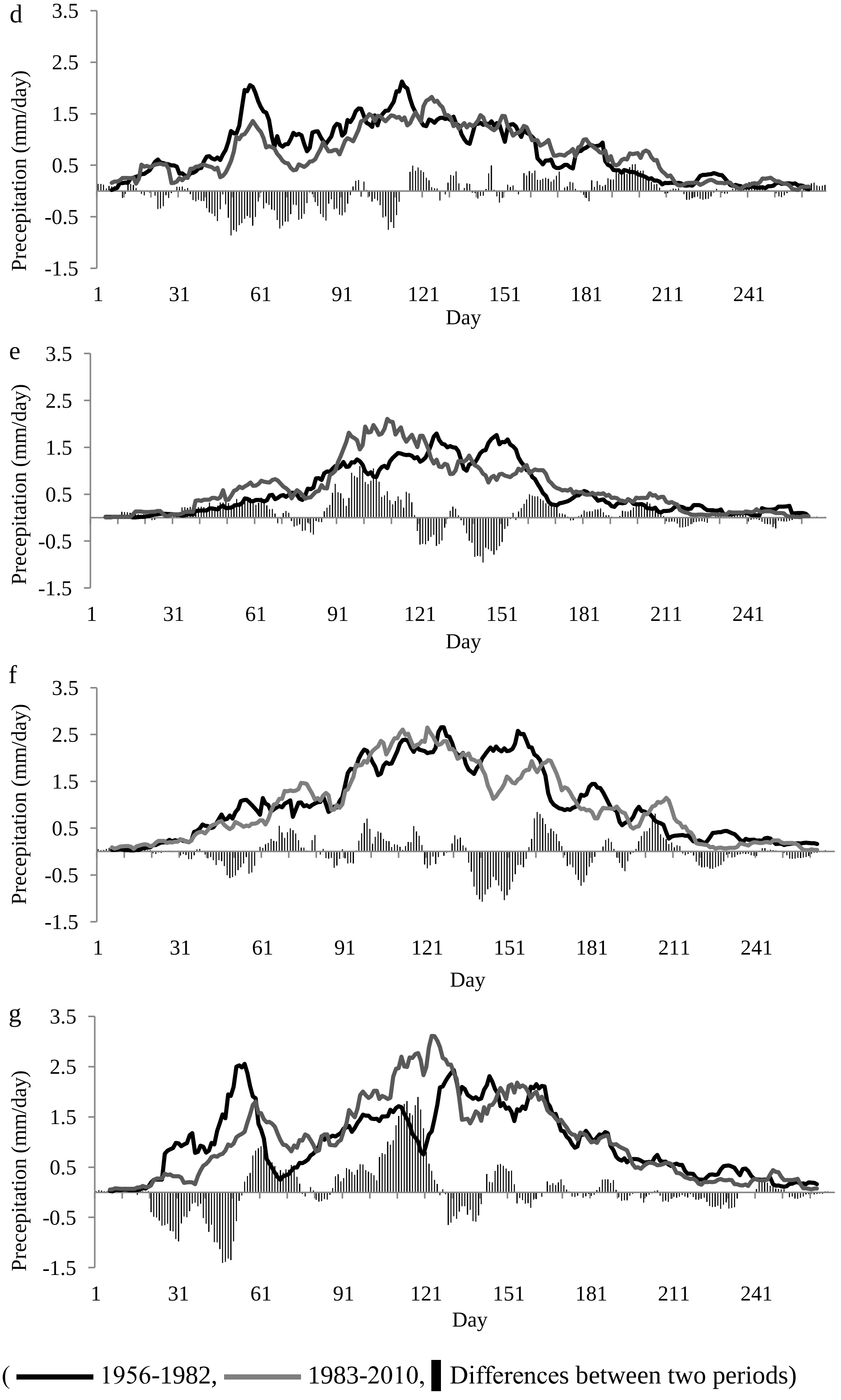

Ghadames
Hon
Jalo
Al-Jaghbub
Sabha
Tazerbou
Al-Kufrah
Temperature (^{0}C)
16
12
8
4
1960
1970
1980
1990
2000
2010
Year

Appendix 4.15b: Regional annual anomalies series during 1961-2010 for cold nights (TN10) and cold days (TX10).

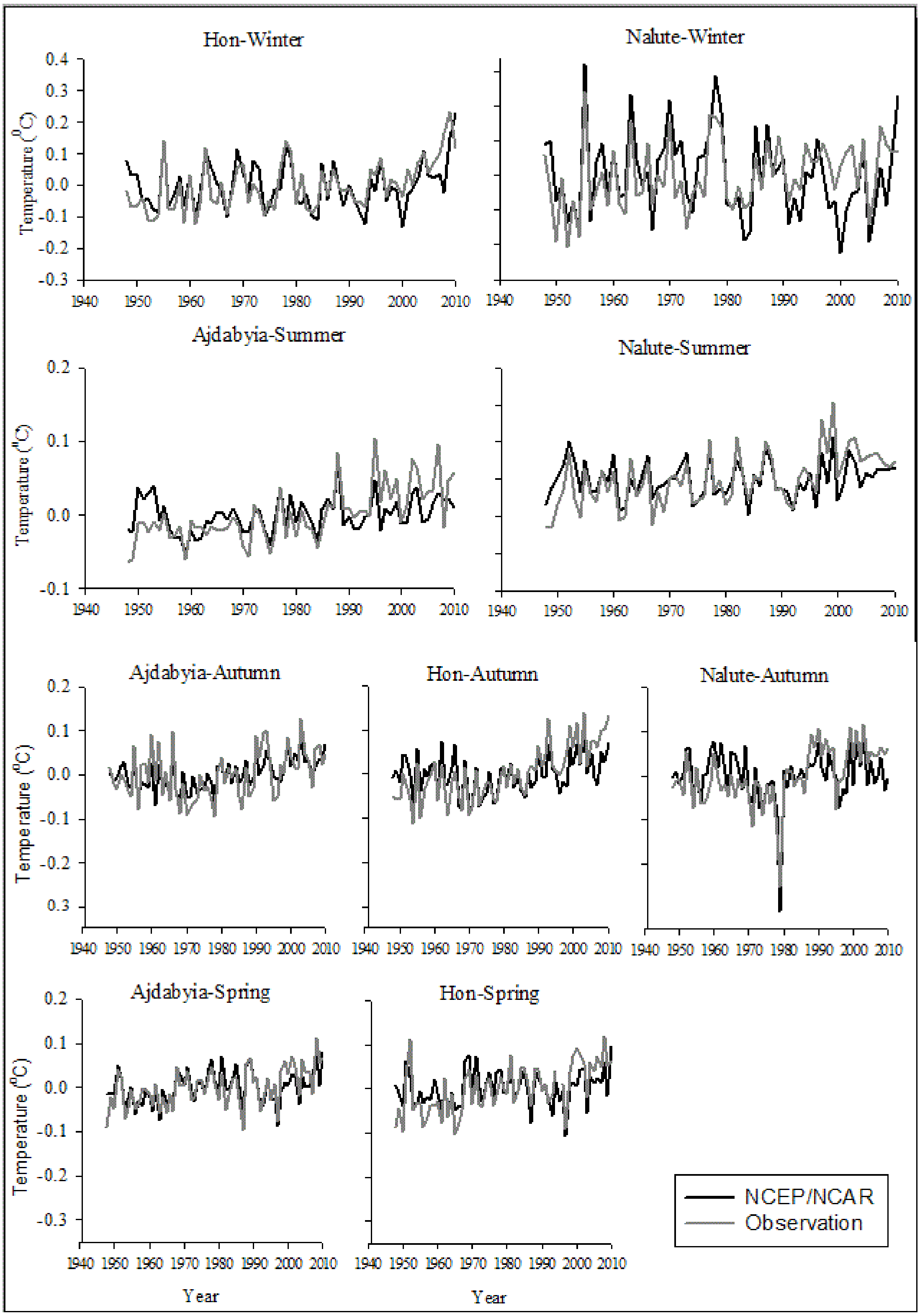


Appendix 5.1: An 11 day, moving mean daily precipitation variation with differences between two periods (1956-1982 and 1983-2010) at; a) Zwarah; b) Nalute; c) Musratah; d) Sirt; e) Ajdabyia; f) Binina and, g) Darnah

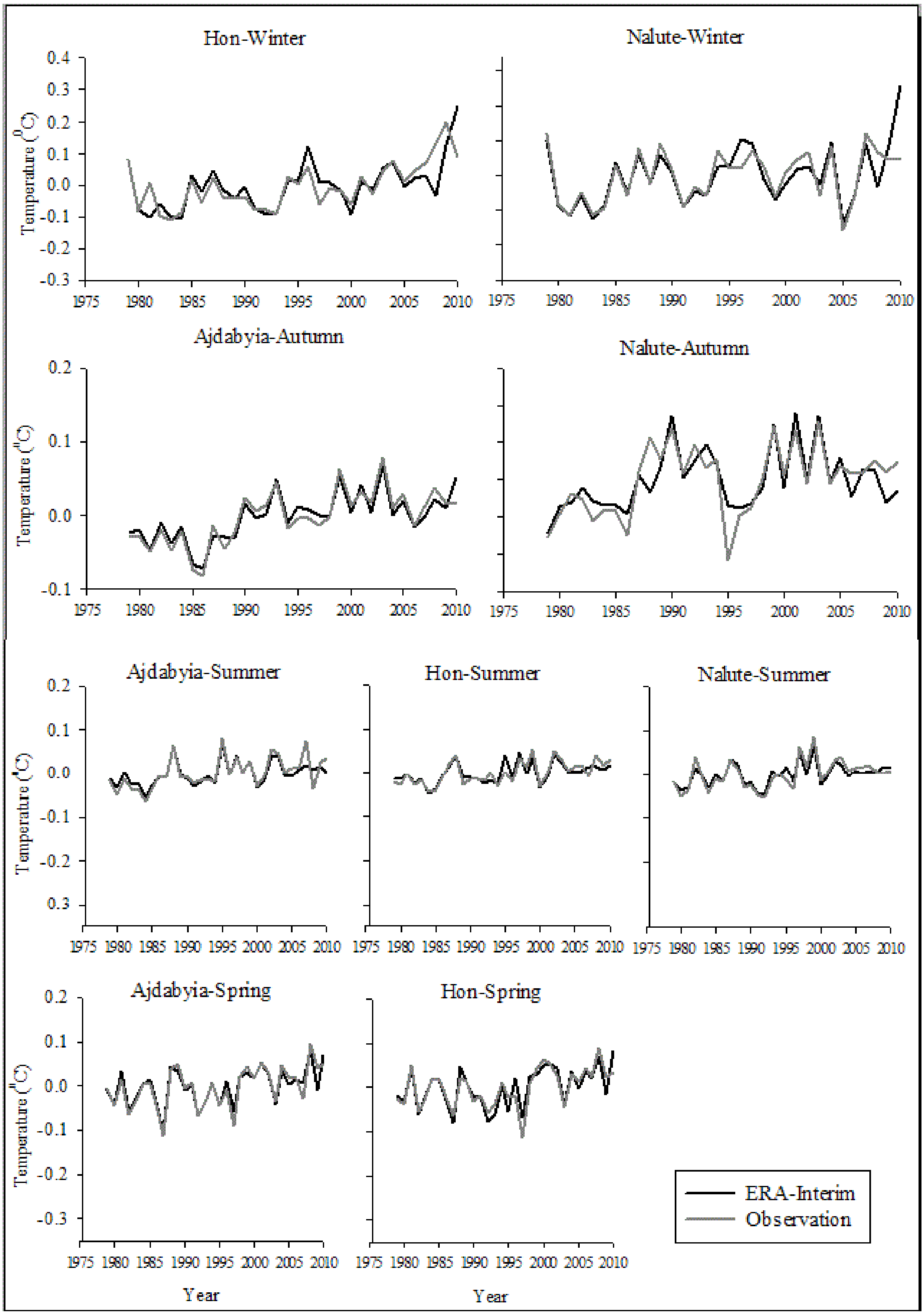



d
e
f
g
Precepitation (mm/day)
3.5
2.5
1.5
0.5
-0.5
-1.5
1
31
61
91
121
151
181
211
241
Day
(1956-1982, 1983-2010, ▌Differences between two periods)

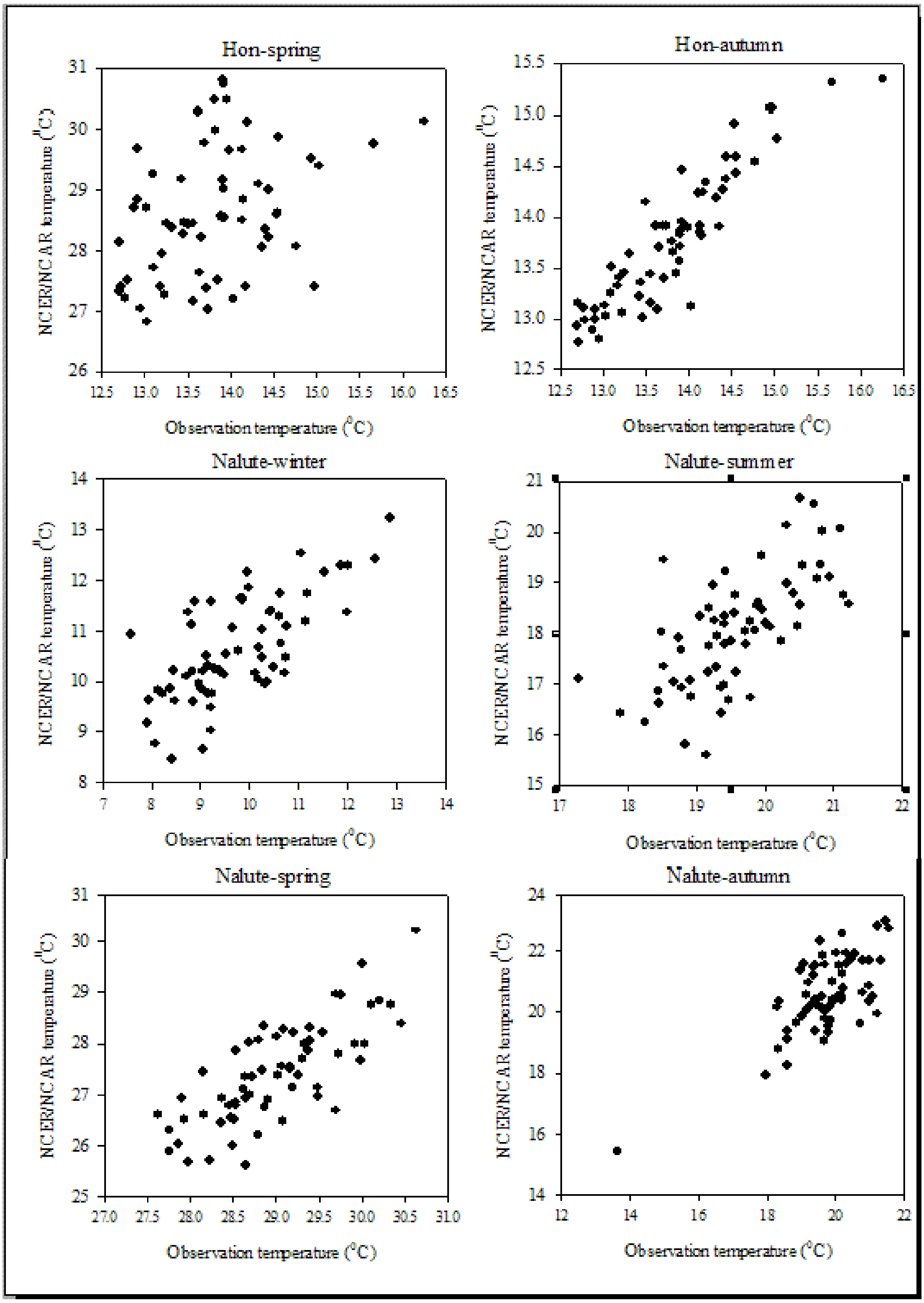
Appendix 7.1: Normalised seasonal mean average temperature anomalies of observation and NCEP/NCAR modelled data

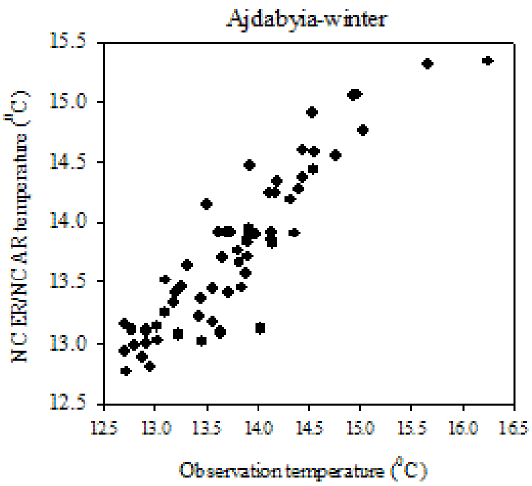


Appendix 7.2: Normalised seasonal mean average temperature anomalies of observation and ERA-Interim.

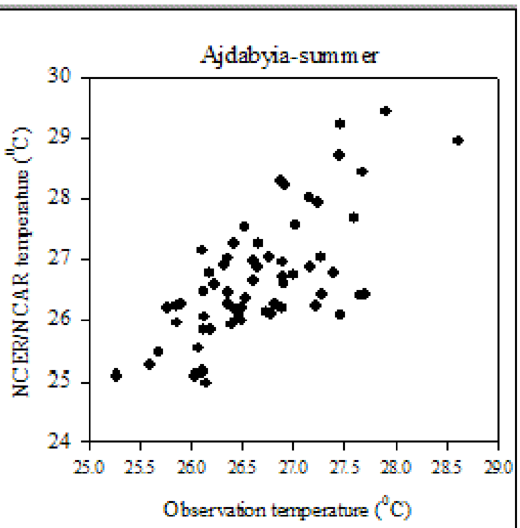


Appendix 7.3a: The seasonal observations mean average temperatures as function of a) NCEP/NCAR the three stations: Ajdabyia, Hon and Nalute.

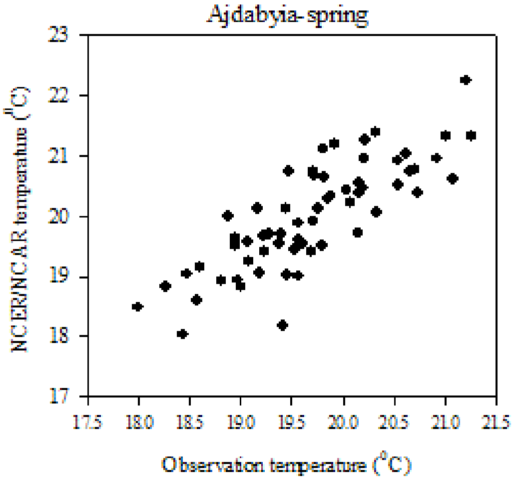




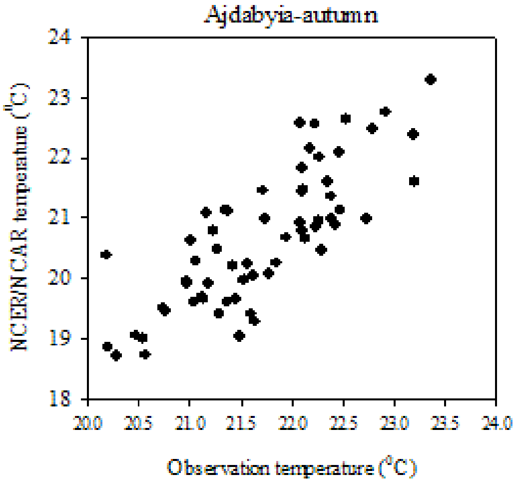
Ajdabyia-winter



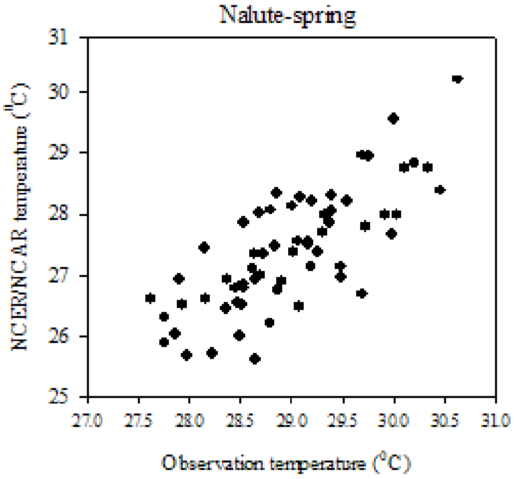
Ajdabyia-summer



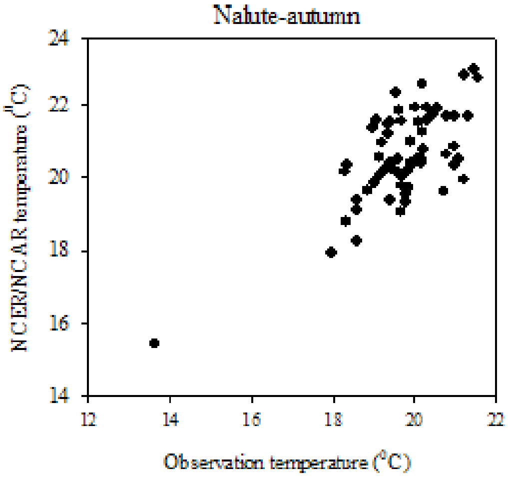
Ajdabyia-spring



Ajdabyia-autumn

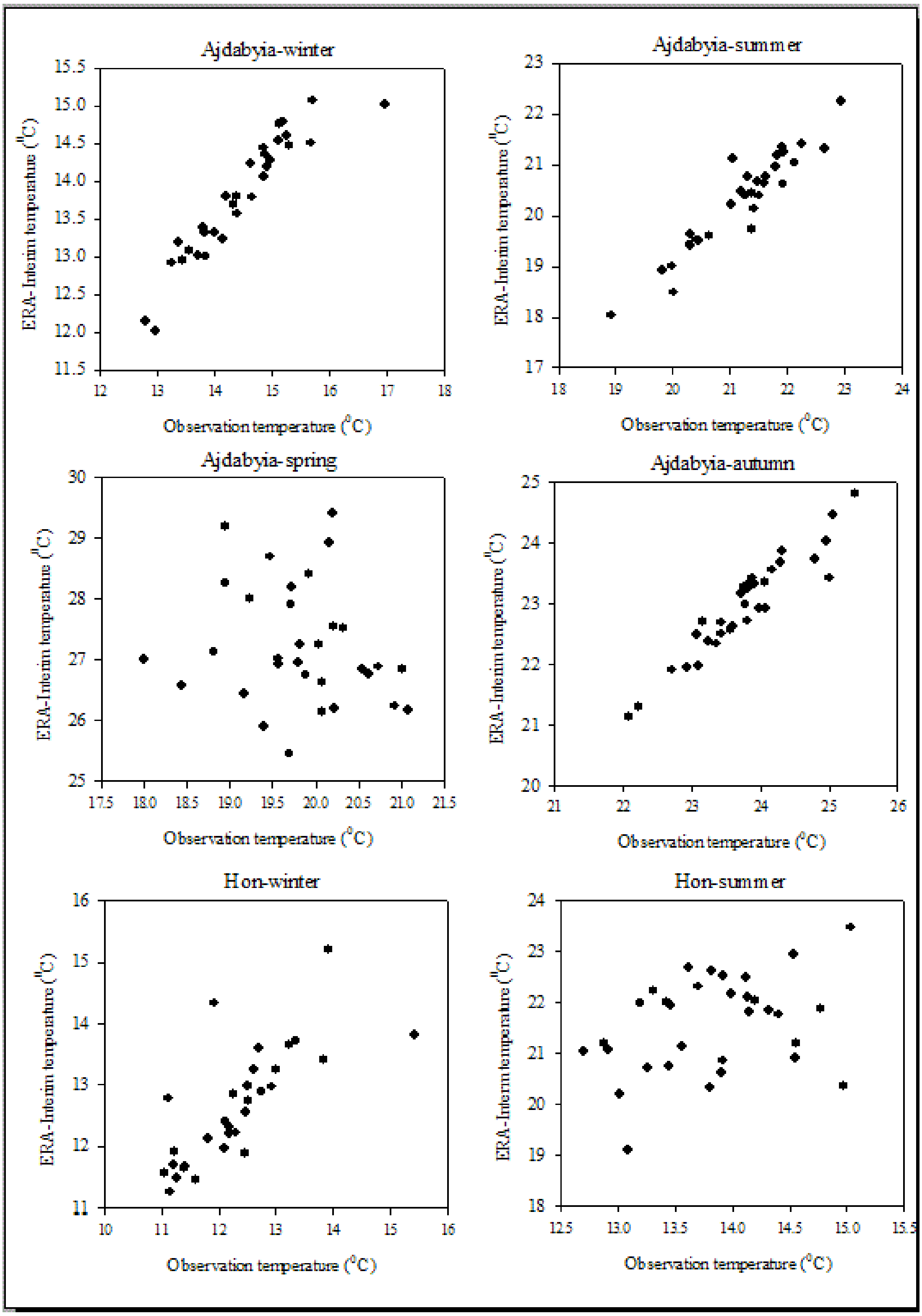


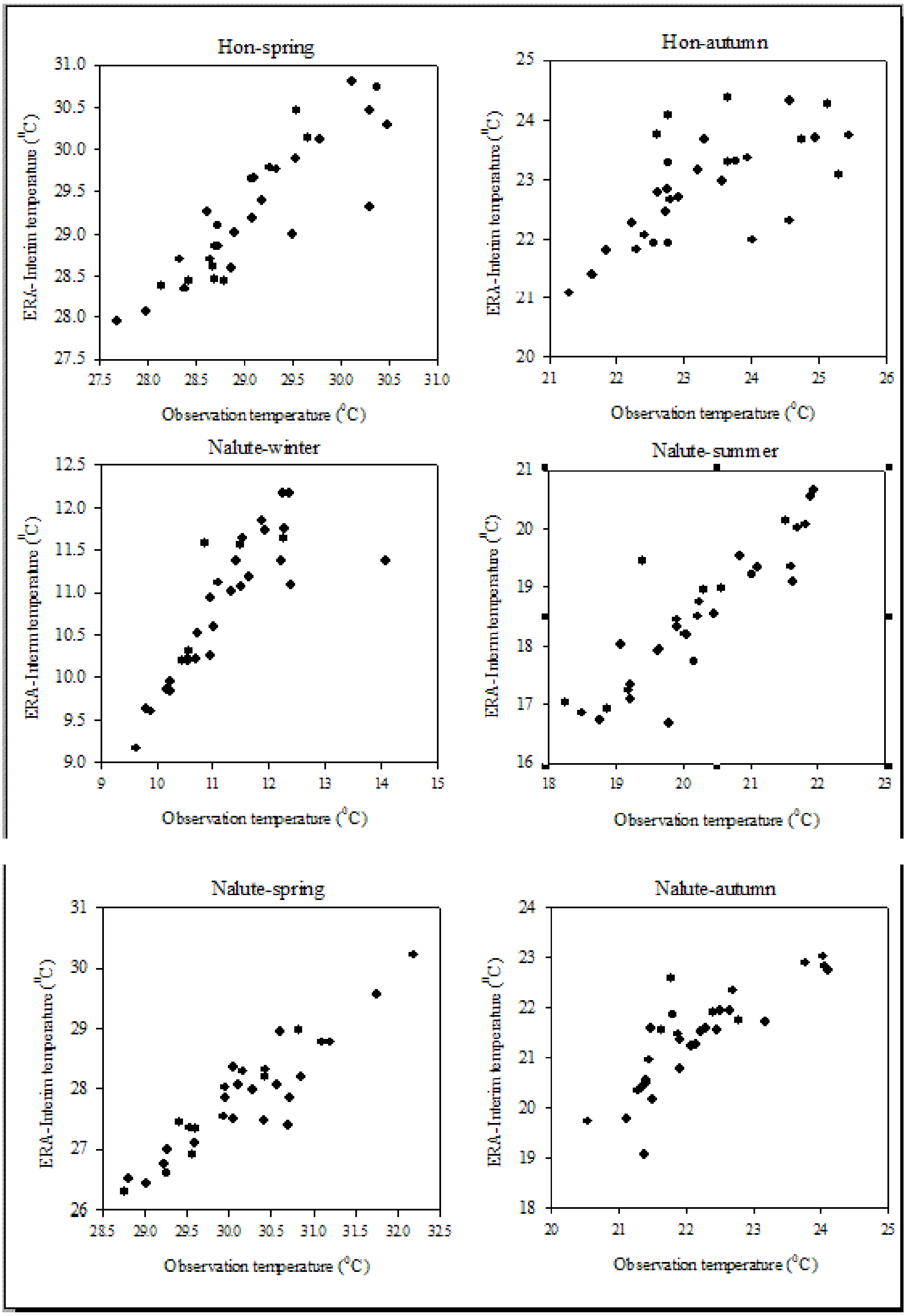
Nalute-spring



Nalute-autumn

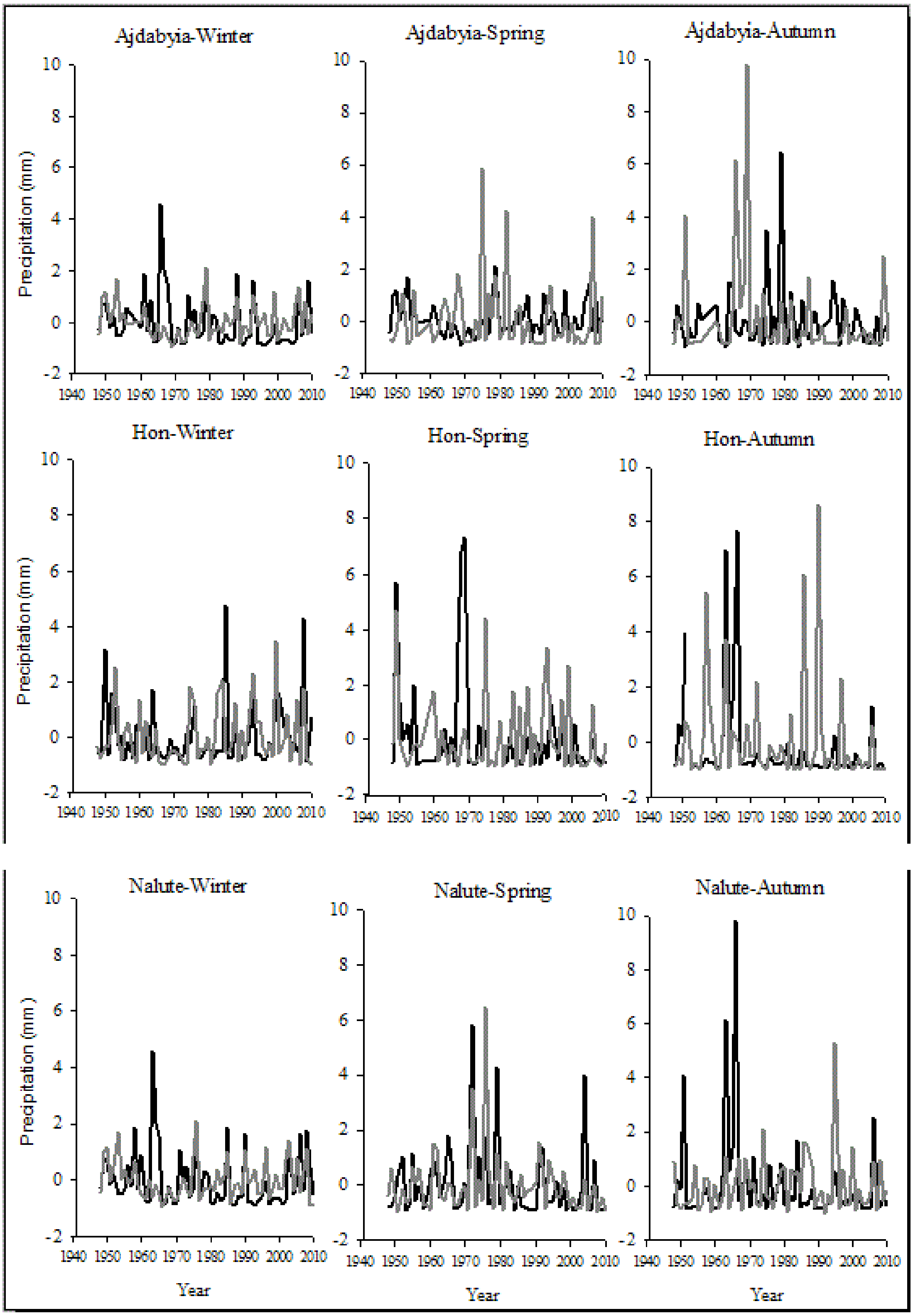
Appendix 7.3b: The seasonal observations mean average temperatures as function of a) ERA-Interim the three stations: Ajdabyia, Hon and Nalute.




Hon-spring
ERA-Interim temperature (0C)
31.0
30.5
30.0
29.5
29.0
28.5
28.0
27.5
27.5
28.0
28.5
29.0
29.5
30.0
30.5
31.0
Observation temperature (0C)
Hon-autumn
ERA-Interim temperature (0C)
25
24
23
22
21
20
21
22
23
24
25
26
Observation temperature (0C)
Nalute-winter
ERA-Interim temperature (0C)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
9
10
11
12
13
14
15
Observation temperature (0C)
Nalute-summer
ERA-Interim temperature (0C)
21
20
19
18
17
16
18
19
20
21
22
23
Observation temperature (0C)
Nalute-spring
ERA-Interim temperature (0C)
31
30
29
28
27
26
28.5
29.0
29.5
30.0
30.5
31.0
31.5
32.0
32.5
Observation temperature (0C)
Nalute-autumn
ERA-Interim temperature (0C)
24
23
22
21
20
19
18
20
21
22
23
24
25
Observation temperature (0C)

Appendix 7.4a: Normalised seasonal precipitation anomalies of observation and NCEP/NCAR data at the three stations for the period 1979-2010

(▬ Observation, ▬ NCEP/NCAR data)



Appendix 7.4b: Normalised seasonal precipitation anomalies of observation and ERA- Interim data at the three stations for spring and autumn (1979-2010).