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Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO

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ABSTRACT: A workshop was held in Casablanca, Morocco, in March 2012, to enhance knowledge of climate extremes and their changes in the Arab region. This workshop initiated intensive data compilation activities of daily observational weather station data from the Arab region. After conducting careful control processes to ensure the quality and homogeneity of the data, climate indices for extreme temperatures and precipitation were calculated.

This study examines the temporal changes in climate extremes in the Arab region with regard to long-term trends and natural variability related to ENSO and NAO. We find consistent warming trends since the middle of the 20th Century across the region. This is evident in the increased frequencies of warm days and warm nights, higher extreme temperature values, fewer cold days and cold nights and shorter cold spell durations. The warming trends seem to be particularly strong since the early 1970s. Changes in precipitation are generally less consistent and characterised by a higher spatial and temporal variability; the trends are generally less significant. However, in the western part of the Arab region, there is a tendency towards wetter conditions. In contrast, in the eastern part, there are more drying trends, although, these are of low significance.

We also find some relationships between climate extremes in the Arab region and certain prominent modes of variability, in particular El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). The relationships of the climate extremes with NAO are stronger, in general, than those with ENSO, and are particularly strong in the western part of the Arab region (closer to the Atlantic Ocean). The relationships with ENSO are found to be more significant towards the eastern part of the area of study.

KEY WORDS climate extremes; climate change; observations; temperature; precipitation; ENSO; NAO

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1. Introduction

Climatic extreme events may have major impacts on society, economy, ecosystems, and on human health; they drive natural and human systems much more than the average climate (Parmesan *et al.*, 2000). This is particularly relevant given the expectation of continuing changes in extremes. Assessing the state of the climate and science, the IPCC (Field *et al.*, 2012) concluded that 'it is likely that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale' and that 'there is medium confidence that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale'. Additionally, Peterson *et al.* (2012) documented how anthropogenic climate change is altering the odds of extreme events occurring. While some of the major extreme events that occurred in 2011 were not unusual in the context of natural variability, there were other events where an anthropogenic signal could be detected.

When monitoring observed changes in climate and, in particular, climate extremes, for many regions (particularly in Africa, South America and parts of Asia) we are still lacking suitable and comparable data (Alexander *et al.*, 2006). To address this and try to fill the data gaps, regional workshops coordinated by the joint World Meteorological Organization (WMO) Commission for Climatology (CCl), Climate Variability and Predictability (CLIVAR), and Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI) are regularly organised in different regions of the world (Peterson and Manton, 2008), mostly in developing countries. The workshops include hands-on sessions where participants assess the time series of daily station observations of maximum and minimum temperature as well as daily precipitation data that they brought with them (once selected and extracted from their national databases), under the guidance of international experts. Hence, the workshops provide several benefits, including capacity-building in terms of training the participants regarding data quality control, homogeneity testing and climate analysis and also in gaining high-quality observational data for climate analysis. This helps to complete our knowledge about how the climate is changing both regionally and globally.

Also, for much of the Arab region, availability of both observational data for research and studies focused on analysis of changes in climate extremes is limited. Although observations from a few stations are available in international archives, such as the Global Historical Climatology Network (GHCN)-Daily dataset (Menne *et al.*, 2012) or the European Climate Assessment and Dataset (Klok and Klein Tank, 2009), many of the records are short or have a large number of missing values. Direct personal contact with local participants, both during and after the ETCCDI climate workshops, allows researchers to verify suspicious values or specific station characteristics.

From 13 March to 16 March 2012, a workshop organised by the United Nations Economic and Social Commission for Western Asia (ESCWA), the League of Arab States (LAS), the Arab Centre for the Studies of Arid Zones and Dry Lands (ACSAD), the Swedish Meteorological and Hydrological Institute (SMHI), the World Meteorological Organization (WMO) and the United Nations International Strategy for Disaster Risk Reduction (UNISDR), on the topic of regional climate in the Arab region, was held in Casablanca, Morocco. Representatives of the meteorological services of all Arab countries were invited, and participants from 17 countries were present at the workshop. The participants were asked to bring long-term daily observational data from their countries to analyse during the workshop, and more stations were analysed afterwards.

The ETCCDI provides standardized software for quality control and calculation of climate indices, such as the RClimDex platform freely available at http://etccdi.pacificclimate.org/software.shtml. The RH-TestV3 program for homogeneity testing temperature and precipitation series is also freely available at the same website. Documentation of the indices calculation software is available in different languages, such as English and French; in preparation for this workshop it was also translated into Arabic.

The Arab region extends from the Maghreb in Northwest Africa to the Arabian Peninsula. While in previous climate assessments (such as IPCC), this region is usually treated as parts of two continents (Africa and Asia), there are a number of common climatic characteristics across the region. Most of the Arab region is located in the northern hemisphere sub-tropics and thus is characterised by semi-arid to arid climate conditions with generally dry and hot summers and mild winters. There are, however, also a number of differences between the Arab sub-regions associated with differing atmospheric circulation and rainfall patterns across the region. The Arab region is also vulnerable to meteorological extreme events. Heavy rain may lead to disastrous flooding, such as the devastating flood in Algier, Algeria, in November 2001 which caused more than 800 deaths, or the extreme rainfall events in Jeddah, Saudi Arabia, in November 2009 and January 2011 (Almazroui, 2011). Drought is also a recurring issue throughout the region (e.g. Al-Qinna *et al.*, 2011; Kaniewski *et al.*, 2012).

There have not been previous Arab region-wide analyses of how the area's climate is changing. One regional study focussed on changes in climate extremes over the Middle East region (Zhang *et al.*, 2005), which forms the eastern part of our investigation area. This investigation reported consistent changes towards more warm and less cold extremes in this region. Precipitation was found to be characterised by strong interannual variability without any significant trend. In addition to this study, there have been some local analyses focussing in more detail on the Arabian Peninsula, for example, AlSarmi and Washington (2011) and Almazroui *et al.* (2012), which also found warming trends in most of the station data. Almazroui *et al.* (2012) showed that the warming during the dry season (June to September) is faster compared to the warming during the wet season (November to April). In contrast, examining four stations in Saudi Arabia since 1961, Alkolibi (2002) found 'no discernible signs of climatic change'. Regional warming trends have also been reported for stations in Libya (El Tantawi, 2005; El Kenawy *et al.*, 2009; El Fadli, 2012), Sudan (Sanhouri, 2011), Djibouti (Ozer and Mahamoud, 2012), and Tunisia (Dahech and Beltrando, 2012). Driouech *et al.* (2010) documented a decrease in precipitation over the period 1958–2000 in the Moulouya watershed in Morocco.

Model simulations of climate extremes in this region during the historical period show similar warming trends over the past century (Sillmann *et al.*, 2013a). These trends continue in multi-model future climate projections (Sillmann *et al.*, 2013b). The signal in extreme precipitation projections is incoherent, however, there is a tendency towards drying. Projections of changes in the nearby Mediterranean region point to a warming trend with more frequent extreme warm events (Giorgi and Lionello, 2008).

This study provides a comprehensive analysis of climate extremes in the entire Arab region, which has not been previously studied as a whole. It is the result of major efforts regarding data collection and data quality control. After a description of the data and methods used in this study (Section 2), we present results regarding observed long-term changes in temperature and precipitation extremes in Section 3. We also investigate internal variability related to teleconnections with large-scale internal variations of the climate system (Section 4). We discuss our results and formulate conclusions in Section 5.

2. Data and methods

To assess changes in extremes, daily station data were used to calculate a suite of 27 indices developed by the ETCCDI (Frich *et al.*, 2002; Peterson, 2005). These internationally coordinated indices continue to undergo refinement (Zhang *et al.*, 2011). These climate extreme indices are calculated based on daily observational data of precipitation totals and daily minimum (i.e. night-time) and maximum (i.e. daytime) temperatures. Daily observations from a number of weather stations in the participating countries were brought to the workshop, and additional data were also retrieved from some countries during the post-workshop analysis. For some countries there were restrictions regarding the sharing of daily observational data. If daily data could not be provided, the country participants performed the complete analysis for all their stations in close discussion with the experts, so that it was possible to share at least the calculated climate indices, based on the quality-controlled daily time series.

Many countries in the Arab region have recently suffered from conflict and war. This has affected the availability of suitable data in parts of the region. For some areas affected by armed conflicts, there are long gaps of up to several years in the available time series, and in some instances older data are also unavailable. For example, for the Palestinian stations of Hebron, Jericho and Nablus, the data are only available to the Palestinian Meteorological Office after 1996; former data are still in Jordanian, Egyptian or British archives, but the Palestinian Meteorological Office experiences difficulties in accessing those data. Similarly, all the stations from Lebanon that were available for this study have long breaks in the 1980s and 1990s, which makes it difficult to assess homogeneity. There is a high probability that the instruments were changed between the periods when observations are available. For this reason, we could not include data from either Palestine or Lebanon in this study. Access to suitable data for Syria, Oman, Yemen, Somalia and Comoros could not be obtained for this study. To avoid gaps in some sub-regions from affecting our results for the whole region, we included some station data for Syria from Zhang *et al.* (2005), which unfortunately end in 2003; an update for the past decade would be desirable if data could be made available.

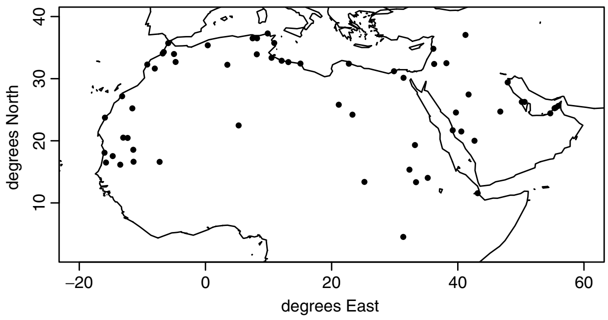

Figure 1. Locations of all stations from which at least 30 years of homogeneous data were available to be included in this study.

In total, more than 100 station time series were collected and analysed during and after the workshop. After careful quality control and testing for homogeneity of each time series, we finally used data from 61 stations for this study. Table 1 provides an overview of the stations used, which are well distributed across the northern parts of Africa, and the Middle East/Arabian Peninsula region (Figure 1).

All ETCCDI workshops use standardised software to quality-control the data, test the time series for homogeneity, and calculate the extreme climate indices. This ensures straightforward comparison of results across different regions of the globe. As a first step, the station time series were subjected to a quality control algorithm, closely following the guidance outlined in Klein Tank *et al.* (2009), to identify suspicious values such as outliers from the seasonal climatological norm, or unreasonable values (e.g. negative precipitation amounts, or minimum temperature higher than maximum temperature). The suspicious values were then corrected or verified by the country participants, based on reviewing entries in their local climate archives and also their expertise of local weather and climate conditions.

Table 1. List of stations included in this study. We only use stations with at least 30 years of homogeneous data. 'T' indicates stations of which only temperature data were used, 'P' indicates stations of which only precipitation data were used.

Country	Station	Latitude	Longitude	Period of homogeneous data
Algeria	Alger Dar-El-Beida	36.41	3.13	1971–2009
Algeria	Annaba	36.5	7.48	1970–2009
Algeria	Ghardaia	32.24	3.48	1964–2009
Algeria	Oran Sennia	35.38	0.36	1971–2009
Algeria	Tamanrasset	22.48	5.26	1950–2009
Bahrain	Bahrain Airport	26.26	50.6	1950–2008
Djibouti	Djibouti	11.57	43.15	1980–2009
Egypt	Cairo Airport	30.13	31.4	1976–2007
Egypt	Alexandria	31.2	29.88	1976–2005
Jordan	Mafraq	32.36	36.25	1964–2011
Jordan	Rwashed	32.5	38.2	1974–2011
Kuwait	Kuwait Intl Airport	29.22	47.96	1981–2011
Libya	Derna	32.4	22.72	1956–2010
Libya	Kufra	24.2	23.3	1979–2010
Libya	Misurata	32.42	15.05	1979–2010
Libya	Tazerbo	25.8	21.13	1963–2002
Libya	Tripoli AP	32.66	13.15	1980–2010
Libya	Zuara	32.88	12.08	1956–2010
Mauritania	Atar	20.51	−13.05	1965–2010
Mauritania	Bir Moghrein	25.23	−11.58	1978–2006
Mauritania	Boutilimit	17.54	−14.7	1969–2010
Mauritania	Ching	20.46	−12.36	1965–2010
Mauritania	Kaedi	16.15	−13.5	1969–2010
Mauritania	Kiffa^{T}	16.62	−11.4	1977–2010
Mauritania	Nema^{T}	16.61	−7.26	1974–2010
Mauritania	Nouakchott	18.08	−16.0	1965–2010
Mauritania	Rosso	16.5	−15.77	1969–2007
Mauritania	Tidjkja	18.55	−11.43	1977–2010
Morocco	Laayoune^{T}	27.17	−13.22	1976–2011
Morocco	Dakhla^{P}	23.72	−15.93	1980–2011
Morocco	Kenitra^{P}	34.3	−6.6	1960–2011
Morocco	Rabat^{T}	34.05	−6.77	1978–2011
Morocco	Fes	33.97	−4.98	1961–2011
Morocco	Safi	32.28	−9.23	1975–2011
Morocco	Midelt	32.68	−4.73	1977–2011
Morocco	Marrakech^{T}	31.62	−8.03	1971–2011
Morocco	Tanger^{T}	35.72	−5.9	1972–2011
Saudi Arabia	Bisha	20	42.64	1977–2010
Saudi Arabia	Dharan	26.27	50.15	1970–2004
Saudi Arabia	Hail	27.45	41.7	1978–2011
Saudi Arabia	Jeddah	21.7	39.2	1981–2011
Saudi Arabia	Madinah	24.55	39.7	1970–2011
Saudi Arabia	Riyadh	24.7	46.74	1970–2010
Saudi Arabia	Taif	21.5	40.55	1977–2010
Sudan	Abudamed	19.32	33.2	1943–2011
Sudan	El Fasher	13.37	25.2	1940–2009
Sudan	Gadaref	14.02	35.24	1943–2009
Sudan	Juba	4.52	31.36	1950–2009
Sudan	Khartoum	15.36	32.33	1945–2009
Sudan	Senar	13.33	33.37	1950–2009
Syria	Safita	34.82	36.12	1965–2003
Syria	Kamishli	37.03	41.22	1968–2003
Tunisia	Bizerte^{T}	37.27	9.87	1972–2009
Tunisia	Jendouba^{T}	36.5	8.17	1973–2009
Tunisia	Mednine^{T}	33.35	10.48	1978–2009
Tunisia	Monastir^{T}	35.75	10.91	1969–2009
Tunisia	Tozeur^{T}	33.93	8.13	1966–2009
UAE	Abu Dhabi	24.43	54.65	1982–2011
UAE	Dubai	25.25	55.33	1975–2011
UAE	Ras Al Khimah	25.62	55.93	1977–2011
UAE	Sharjah	25.33	55.52	1977–2011

After quality control, as a second step, all time series were carefully tested for homogeneity using the RH-TestV3 program (Wang and Feng, 2009). We generally used a penalised maximal F-test (e.g. Wang, 2008a) to identify potential change points in the time series. This procedure was applied to the monthly means of daily maximum and minimum temperatures and to monthly total precipitation amounts; it is based on two-phase regression models for the detection of shifts in individual station time series (Wang, 2008b). Due to the generally large distances between the stations, we could not use testing methods that make use of reference stations. The identified potential change points were then compared with documented changes to the station, to assess whether the changes had been artificially introduced, e.g. by changes in station location or instruments, or whether they may reflect natural shifts in climate. If the identified significant change points occurred concurrently with documented station changes, we assumed the time series to be inhomogeneous and restricted the usage of data to homogeneous time periods (column 5 in Table 1). Many of the time series showed potential change points that had not been documented, particularly around 1983, 1993 and 1998 – all years with strong El-Niño conditions. This suggests that El Niño Southern Oscillation (ENSO) may have had an influence on the local climate conditions in the Arab region. Therefore, the relationship between ENSO and local climate extremes is also investigated in this study (Section 4).

Adjustment for homogeneity is a complex problem (e.g. Domonkos, 2011), related to a number of uncertainties. It is particularly problematic if no nearby homogeneous reference station is available. Therefore, we decided not to adjust data for homogeneity in the context of this study. Instead, for this article, we used only stations that provide at least 30 consecutive years of homogeneous data (Table 1) and discarded inhomogeneous stations or periods. However, as 34 out of the 61 stations used here exhibit inhomogeneities, which limit the length of time series for investigation, it would be desirable for future work to apply a suitable method to correct for inhomogeneities in these data sparse regions. Additional data from about 40 stations have been made available for this study but had to be disregarded because they did not contain any period of 30 years of homogeneous data. Careful adjustment for homogeneity would thus also serve to include more stations in such a study.

As a final step, a set of climate indices, as recommended by the ETCCDI, was calculated for each time series. Most of the indices represent different types of extreme events related to particularly high or low temperature and precipitation values. The indices represent different aspects of extreme climate events, such as intensity, frequency and duration. An overview of the indices calculated is provided in Table 2 (for more detailed information, also refer to Zhang *et al.*, 2011). Some of the indices are calculated relative to certain climatic percentile values. For temperatures, the percentiles are calculated relative to the time of year, i.e. they follow an annual cycle. This means that, for example, a warm percentile extreme, such as TX90p or TN90p as the ETCCDI defines them, is just as likely to occur in winter as in summer. We used 1981–2010 as the base period for calculating the percentile values, as for this period data from most of the stations were available. If more than 25% of data during the base period were missing, no percentile-based indices were calculated.

Linear trends were fitted to the time series using ordinary least squares regression. We present the calculated trends at each station for two periods: (a) for 1981 to present (i.e. as long as the station provides data; see Table 1) when data from all stations are available and (b) for 1966 to present, to show changes over a longer period but still with reasonable spatial coverage derived from a satisfactory number of long-term stations. To gain a more integrated picture on how the climate is changing across the whole region, we also present station average time series. To account for the different time periods covered by each station, first the anomalies from the 1980–2000 common reference period were calculated for each station, and then the different anomaly time series were averaged. Note that this 21-year reference period is slightly different from the 30-year base period used for calculating the percentile values.

To investigate the relationships of the extreme climate indices with large-scale internal variability in the climate system, we calculated correlations with ENSO- and NAO-indices. The Southern Oscillation Index (SOI) was used to represent ENSO and was calculated as the difference in standardized pressure between Tahiti and Darwin (Trenberth, 1984). Indices based on sea-surface temperatures (SSTs) could also have been used for ENSO but these produced similar and slightly weaker correlations than those found using SOI. The Hurrell NAO index (NAOI; NCAR, 2012) was used to examine the NAO relationship with the climate extremes. This index is calculated using the difference in sea level pressure between Lisbon in Portugal and Reykjavik/Stykkisholmur in Iceland. Correlations (Spearman's rank) of these two variability indices with several of the climate extreme indices were calculated for individual stations and area-averages. The climate extremes indices were de-trended before the correlations were calculated. Maps of the resulting correlation coefficients were plotted. Scatter plots of the SOI and NAOI versus the climate extreme indices were also plotted in order to examine for possible asymmetries in the relationships. The correlations were generally stronger for seasonal indices, particularly during the months December to February when both ENSO and NAO are most pronounced, rather than for annual values. We also calculated lag-correlations, but found them to be less significant.

3. Long-term changes in extreme climate indices

3.1. Changes in mean and extreme temperatures

The data provide evidence for significant warming trends throughout the entire Arab region, generally reflected by

Table 2. List of the ETCCDI climate indices. All indices are calculated annually, * denotes indices which are also calculated monthly.

Index		Definition	Unit
	A. Temperature		
	Intensity		
TXn*	Min Tmax	Coldest daily maximum temperature	°C
TNn*	Min Tmin	Coldest daily minimum temperature	°C
TXx*	Max Tmax	Warmest daily maximum temperature	°C
TNx*	Max Tmin	Warmest daily minimum temperature	°C
DTR*	Diurnal temperature range	Mean difference between daily maximum and daily minimum temperature	°C
	Duration		
GSL	Growing season length	Annual number of days between the first occurrence of 6 consecutive days with Tmean > 5 °C and first occurrence of consecutive 6 days with Tmean < 5 °C. For the Northern Hemisphere this is calculated from 1 January to 31 December while for the Southern Hemisphere it is calculated from 1 July to 30 June.	days
CSDI	Cold spell duration indicator	Annual number of days with at least 6 consecutive days when Tmin < 10th percentile	days
WSDI	Warm spell duration indicator	Annual number of days with at least 6 consecutive days when Tmax > 90th percentile	days
	Frequency		
TX10p*	Cool days	Share of days when Tmax < 10th percentile	% of days
TN10p*	Cool nights	Share of days when Tmin < 10th percentile	% of days
TX90p*	Warm days	Share of days when Tmax > 90th percentile	% of days
TN90p*	Warm nights	Share of days when Tmin > 90th percentile	% of days
FD	Frost days	Annual number of days when Tmin < 0 °C	days
ID	Icing days	Annual number of days when Tmax < 0 °C	days
SU	Summer days	Annual number of days when Tmax > 25 °C	days
TR	Tropical nights	Annual number of days when Tmin > 20 °C	days
	B. Precipitation		
	Intensity		
Rx1day*	Max 1-day precipitation	Maximum 1-day precipitation total	mm
Rx5day*	Max 5-day precipitation	Maximum 5-day precipitation total	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (i.e. when precipitation ≥ 1.0 mm)	mm/day
R95p	Annual contribution from very wet days	Annual sum of daily precipitation > 95th percentile	mm
R99p	Annual contribution from extremely wet days	Annual sum of daily precipitation > 99th percentile	mm
PRCPTOT	Annual contribution from wet days	Annual sum of daily precipitation ≥ 1 mm	mm
	Duration		
CWD	Consecutive wet days	Maximum annual number of consecutive wet days (i.e. when precipitation ≥ 1.0 mm)	days
CDD	Consecutive dry days	Maximum annual number of consecutive dry days (i.e. when precipitation < 1.0 mm)	days
	Frequency		
R10mm	Heavy precipitation days	Annual number of days when precipitation ≥ 10 mm	days
R20mm	Very heavy precipitation days	Annual number of days when precipitation ≥ 20 mm	days
Rnnmm	Precipitation above a user-defined threshold	Annual number of days when precipitation ≥ nn mm (nn: user-defined threshold)	days

more and stronger warm extremes and fewer and weaker cold extremes.

The annual averages of daily maximum and minimum temperatures show upward trends for most stations (Figure 2), some of them significantly. The warming trends are generally stronger during the most recent 30 years (since 1981) than for the longer period (since 1966). This is also confirmed by the region-averaged time series, which show that most of the warming has happened since the early 1970s. Averaging the temperature anomalies of all stations reveals significant warming trends for both variables across the Arab region.

Regarding climate extreme indices, the warming trends are most significantly reflected by the frequencies of cool and warm nights and days (Figure 3). These indices count the occurrences of temperatures below the 10th percentile (cool nights/days) and above the 90th percentile (warm nights/days), respectively. They are thus representative of the upper and lower tails of the distribution functions of daytime and night-time temperatures, which have

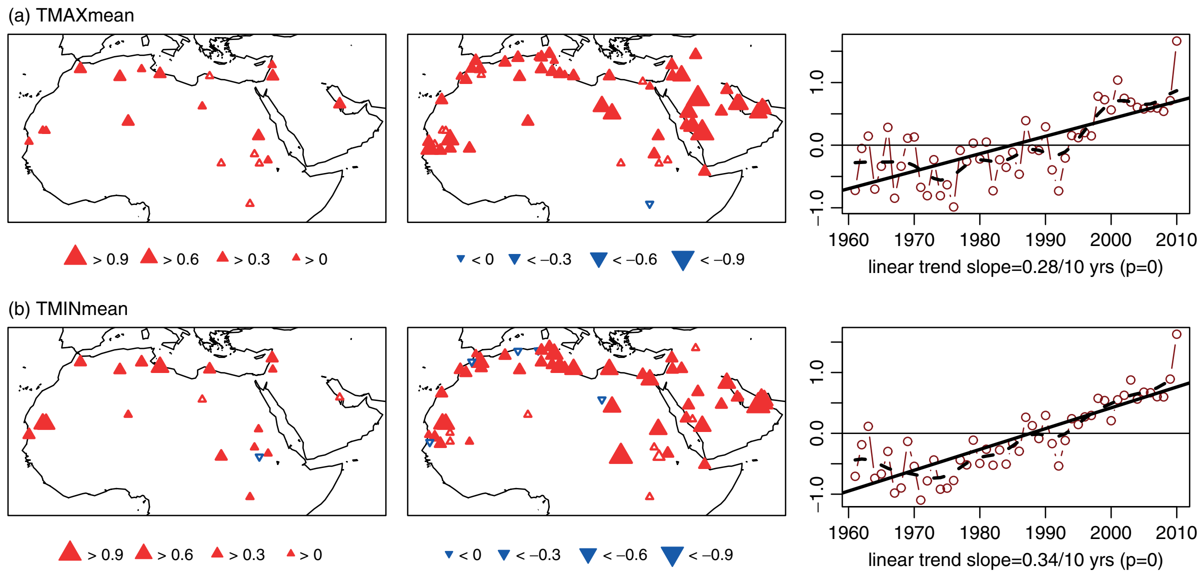

Figure 2. Changes in mean annual TMAX and mean annual TMIN (unit: °C/10 years). Left: linear trends after 1966, middle: linear trends after 1981, right: time series of regional averages of anomalies from the 1980–2000 period. Upward pointing triangles show increasing trends, downward pointing triangles represent decreasing trends. Significant changes ($p \leq 0.05$) are indicated by filled symbols. Red colour coding indicates warming, blue indicates cooling trends.

experienced significant shifts in most regions of the globe (Donat and Alexander, 2012). Consistently, throughout the entire Arab region, we find decreasing numbers of cool nights and cool days and increasing numbers of warm nights and warm days. These changes are significant for most stations at the 5% level, and seem to be somewhat weaker at locations in lower latitudes, such as some Sudanese stations. Again, most of the warming appears to have happened during the past 40 years since the early 1970s. The magnitudes of the negative trends in the cool extremes are, on average, larger than the magnitudes of the positive trends in warm extremes.

The index representing the warmest day of the year shows a tendency towards higher temperatures at most stations (Figure 4(a)). Note that the annual maximum value represents only one value per year at the very upper tail of the distributions, and is therefore based on a much smaller sample, undergoing a higher variability compared to the (more moderate) extremes indices discussed previously. Still, the increases are significant at a number of stations and also tend to be stronger during the most recent 30 years. On average across the region, TXx values have increased by about 1 °C since the 1960s. Similarly, the coldest night of the year (TNn) displays warming trends at the majority of stations (not shown). The regional average of TNn has increased by about 0.5 °C since the 1960s. Changes are also found in the duration of warm and cold spells (Figure 4(b) and (c)). While the warm spell duration index (WSDI) shows some significant increases, strong decreases are found for the cold spell duration index (CSDI).

3.2. Changes in precipitation indices

The occurrence of extreme precipitation is characterised by much stronger temporal and spatial variability than seen in the temperature extremes. Therefore, changes in the precipitation extremes are generally less consistent between the different stations and regions, and the trends are also mostly less significant. A lower signal-to-noise ratio for precipitation in comparison to temperature indices has been found in numerous other studies for other regions around the world (e.g. Frich *et al.*, 2002; Hegerl *et al.*, 2004; Alexander *et al.*, 2006)

On average over the whole Arab region, the 1960s were wetter than any of the more recent decades. So trends starting in the 1960s show drying, while trends starting in the 1970s show no change or perhaps even a slight wetting trend. This is apparent from both the total annual precipitation (PRCPTOT, Figure 5(a)) and also from the frequency of days with more than 10 mm of rainfall (R10mm, Figure 5(b)). While particularly in the western part of the region (Algeria, Morocco, and Mauritania), there is a consistent tendency towards wetter conditions during the past 30 years, for most of the rest of the Arab region the changes in precipitation indices are generally not significant. However, another consistent feature seems to be (mostly non-significant) decreases in both the PRCPTOT and R10mm precipitation indices over much of the Arabian Peninsula.

The number of consecutive dry days (CDD, Figure 5(c)), as a measure for absence of precipitation, also shows trends towards drier conditions. This result is particularly evident in the eastern part of the Arab region; most of the stations in Egypt, Djibouti and on the Arabian Peninsula show upward trends (however mostly non-significant). Given the nature of rainfall in the region, this result suggests that the dry (summer) season is extending in length. Across the rest of the region, i.e. most parts of North Africa, there is no clear pattern in the CDD changes.

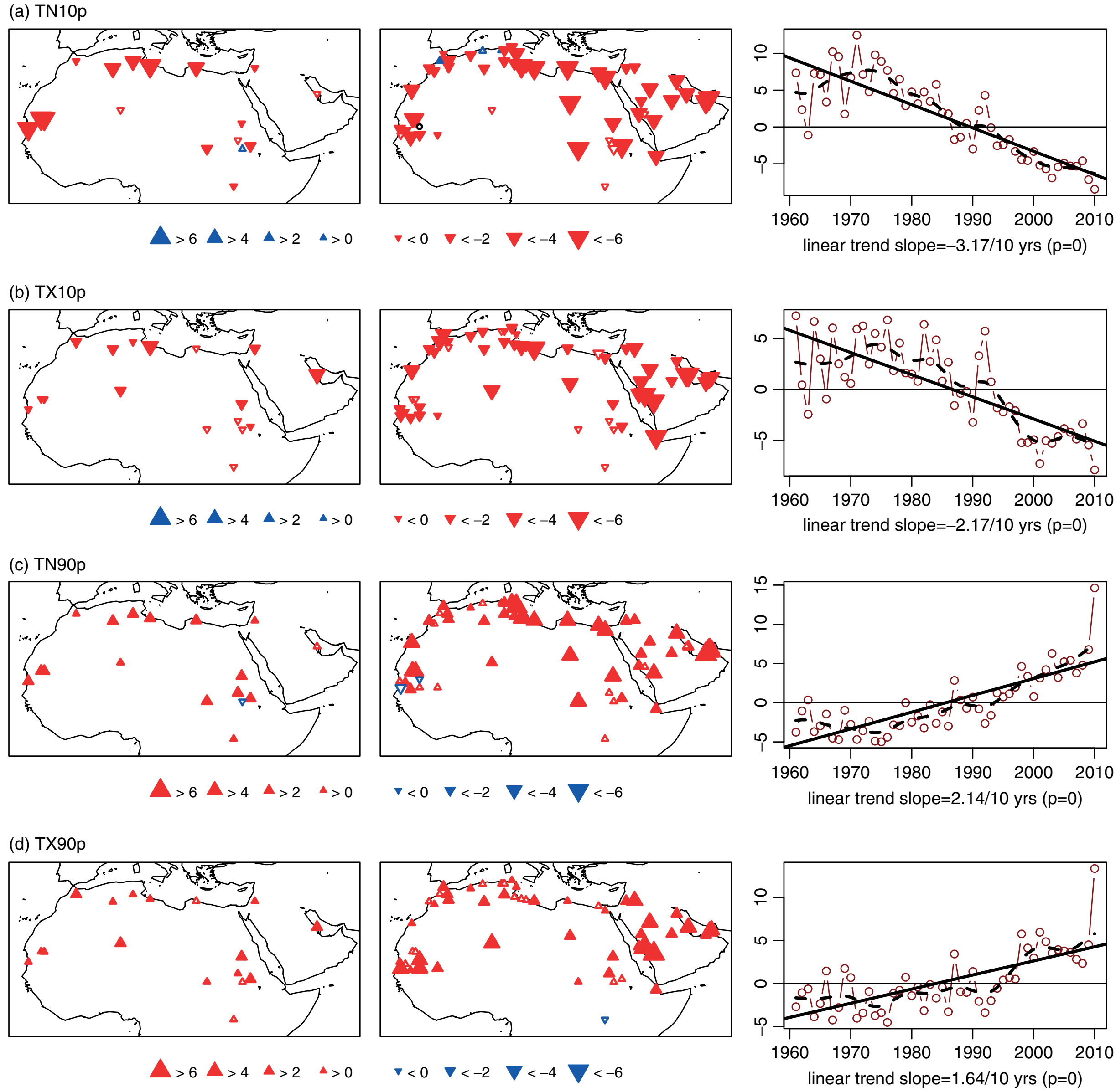

Figure 3. As Figure 2, but for frequency of cool nights (TN10p), cool days (TX10p), warm nights (TN90p), and warm days (TX90p). Upward pointing triangles show increasing trends, downward pointing triangles represent decreasing trends. Significant changes ($p \leq 0.05$) are indicated by filled symbols. Red colour coding indicates warming, blue indicates cooling trends (unit: % of days/10 years).

4. The effect of ENSO- and NAO-related variability on the climate extremes

Some of the stations show significant responses to prominent patterns of internal variability of the climate system. Here, we investigate relationships of the calculated climate extremes indices with indices representing the state of ENSO and NAO. Both variability patterns are most pronounced during the boreal winter, which also leads to the strongest correlation values during this season. Here, we present the results for the seasonal averages during December, January, February (DJF) of both climate extremes and variability indices.

The relationships between ENSO and the climate extremes indices are generally stronger for the temperature indices than for the precipitation indices. In the west of the Arab region, the teleconnection between ENSO and the climate extremes appears to be weak. Although, several stations in Mauritania show significant negative correlations between SOI and mean minimum temperature. In the east of the region there are some stations with significant correlations. The strongest correlation signal is observed with the diurnal temperature range (DTR) index, which combines both daily minimum and maximum temperatures. The rank correlation coefficients between SOI and DTR show significant positive correlations at several sites in the Arabian Peninsula and northeast Africa (Figure 6(a)). In La Niña seasons, the DTR tends to be greater than in El Niño seasons. While mostly positive correlations are found for maximum temperatures, the signal is mixed and generally weaker for minimum temperatures. The physical mechanisms behind

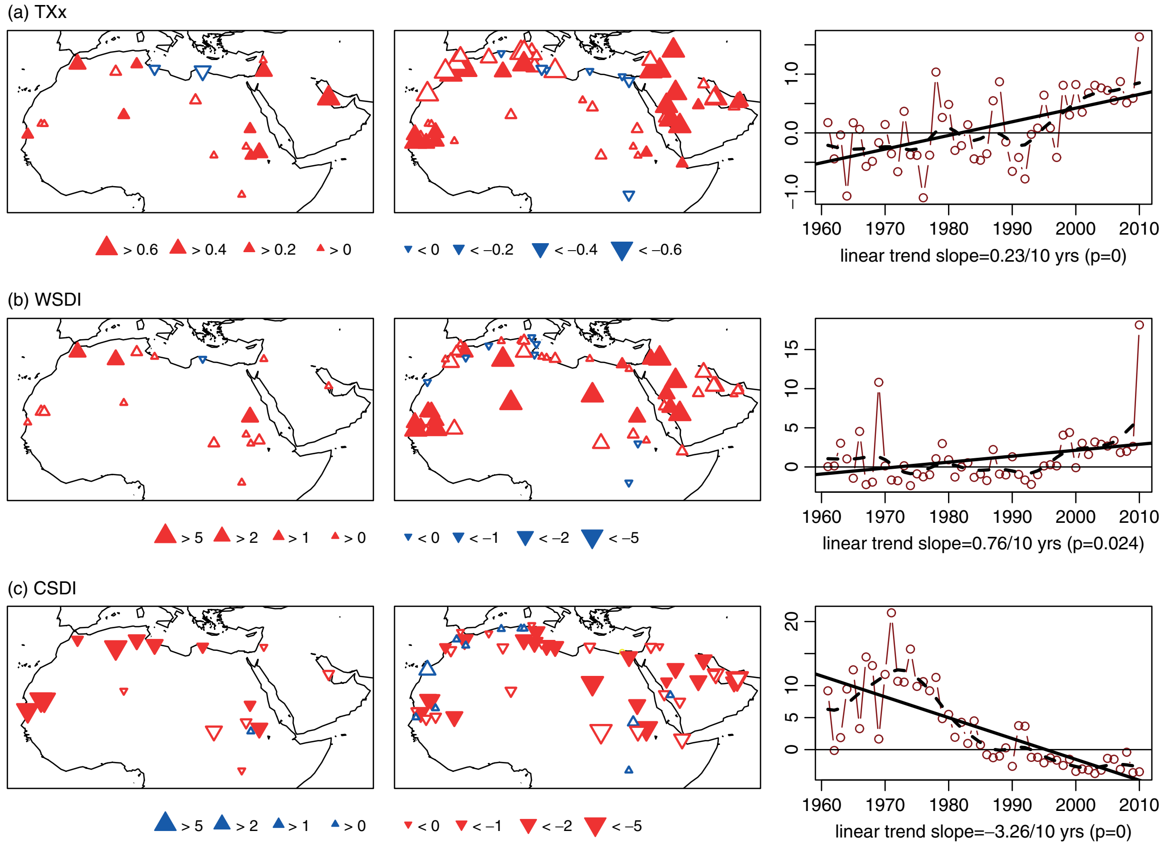

Figure 4. As Figure 2, but for annual maximum temperature (TXx, unit: °C/10 years), warm spell duration index (WSDI, unit: days/10 years) and cold spell duration index (CSDI, unit: days/10 years). Upward pointing triangles show increasing trends, downward pointing triangles represent decreasing trends. Significant changes ($p \leq 0.05$) are indicated by filled symbols. Red colour coding indicates warming, blue indicates cooling trends.

these teleconnections are not studied here but require further investigation.

The relationships between NAO and the climate extremes are found to be stronger than those between ENSO and extremes, particularly in the west of the region. This is to be expected considering the relative proximity of the areas in which these two modes of variability act. NAO negative periods are related to more southerly storm tracks which sometimes affect the north of Africa. The results show that NAO seems to have more of an influence on temperature extremes than precipitation extremes, and that the relationships tend to be stronger with warm extremes than cool extremes. The stations most strongly influenced by the NAO are largely in the west of Africa or on the Mediterranean coastline. The NAOI is negatively correlated with the maximum temperature for the DJF season (TXx) and in northern and western areas of Africa these correlations are mostly significant (Figure 6(b)). This suggests that NAO negative periods are associated with higher maximum temperatures. Area-averages of each index were taken for stations in the western part of the investigation area (i.e. Algeria, Libya, Mauritania, Morocco and Tunisia) and plotted against the NAOI for each season from 1961 to 2010.

The plots of area-averaged TXx and the percentage of time when maximum temperature is above the 90th percentile (TX90P) show that there is an asymmetric relationship between NAO and the extremes indices (Figure 6(c) and (d)): The magnitudes of negative NAO seasons exert a greater influence on these extreme indices than the strength of positive NAO seasons do; the slopes of lines of best fit in both plots are significantly different from zero only for negative NAO seasons. During NAO positive periods, the Atlantic storm track is located more towards the north; therefore, it is unsurprising that the magnitude of positive NAO events has little impact on climate extremes in north-western Africa. Again, further study is required to examine the NAO-extremes teleconnection in this region, but our results would suggest that NAO provides a degree of predictability in temperature extremes in north-western Africa.

5. Summary, discussion and conclusions

We present an analysis of climate extremes in the Arab region, and their changes since the middle of the 20th Century. Daily observational data from weather stations across the Arab region were brought together and subjected to careful assessment for quality and homogeneity, before calculating climate indices representative of different aspects of extreme climatic events. The results give evidence for significant changes in the occurrence of

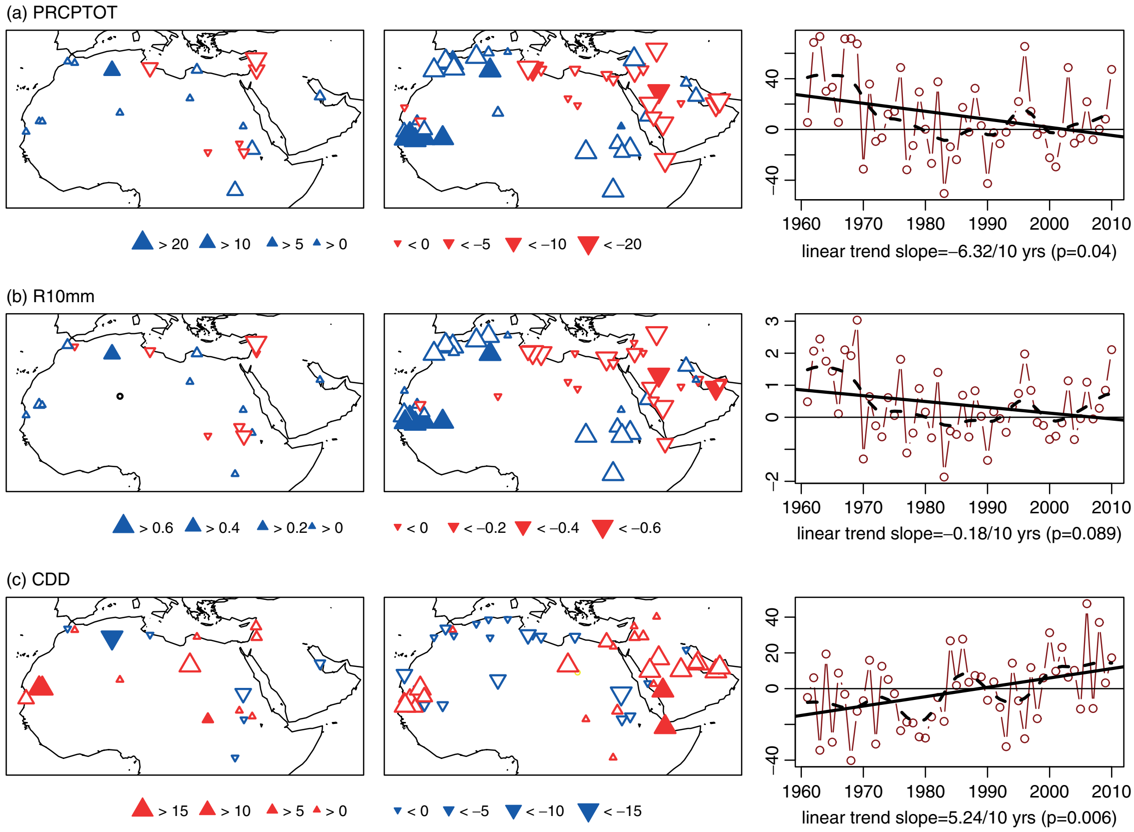

Figure 5. As Figure 2, but for precipitation indices total annual precipitation on wet days (PRCPTOT, unit: mm/10 years), heavy precipitation days (R10mm, unit: days/10 years) and consecutive dry days (CDD, unit: days/10 years). Upward pointing triangles show increasing trends, downward pointing triangles represent decreasing trends. Significant changes ($p \leq 0.05$) are indicated by filled symbols. Red colour coding indicates drying trends, blue indicates trends towards wetter conditions.

climate extremes during the past five decades. There are consistent warming trends across the region, most significantly seen in increasing frequencies of warm days and warm nights, and fewer cool days and cool nights. Significant warming trends are also found in the absolute temperature values. The changes in the precipitation-based indices are generally less significant and spatially inconsistent. Regional time series indicate relatively wet conditions in the 1960s and a shift towards drier conditions in the early 1970s. Therefore, area-average long-term trends since 1960 show a tendency towards drier conditions, but little change is found since the 1970s. Locally, in the western part of the region there seems to be a consistent tendency towards wetter conditions during the past 30 years, whereas in the eastern part there are some consistent drying trends. These observational results are in qualitative agreement with climate modelling studies (e.g. Sillmann *et al.*, 2013a).

We also find relationships between climate extremes in the Arab region and NAO and ENSO. While ENSO has a stronger effect on extremes in the eastern part of the Arab region, NAO has a stronger influence in the western part. For NAO we show that the relationship with climate extremes in much of North Africa is asymmetric in nature: correlations are particularly strong for negative NAO seasons, whereas they are largely non-significant for positive NAO seasons.

The relationship of the climate indices with NAO and ENSO may explain some variability, however, the strong consistent warming trends across the region are the dominant characteristic of change.

On average, the frequency of temperatures below the 10th percentile seems to decrease faster than temperatures above the 90th percentile are becoming more frequent. This points to a narrowing of the temperature distributions. Indeed, Donat and Alexander (2012) documented how (in addition to significant shifts towards warmer conditions) the variance of the temperature distributions has become smaller in the northern hemisphere extra-tropics during the past 60 years, whereas variance has increased in low latitudes.

While the focus of the ETCCDI indices is primarily on climate extremes, some of them do not look very far out into the extreme tails of the distribution. A case could be made that the most environmentally and societally relevant extremes are those major events that have return periods in excess of 20 years. However, if one only has 50 years of data available to analyse, one could not make a reliable assessment of how the frequency of a ~20-year return period extreme were changing as there would only be a few data points for each station. As the focus of the ETCCDI is on climate change detection, the indices calculated are those with return periods in the order of once every 10 days (for temperature). This provides

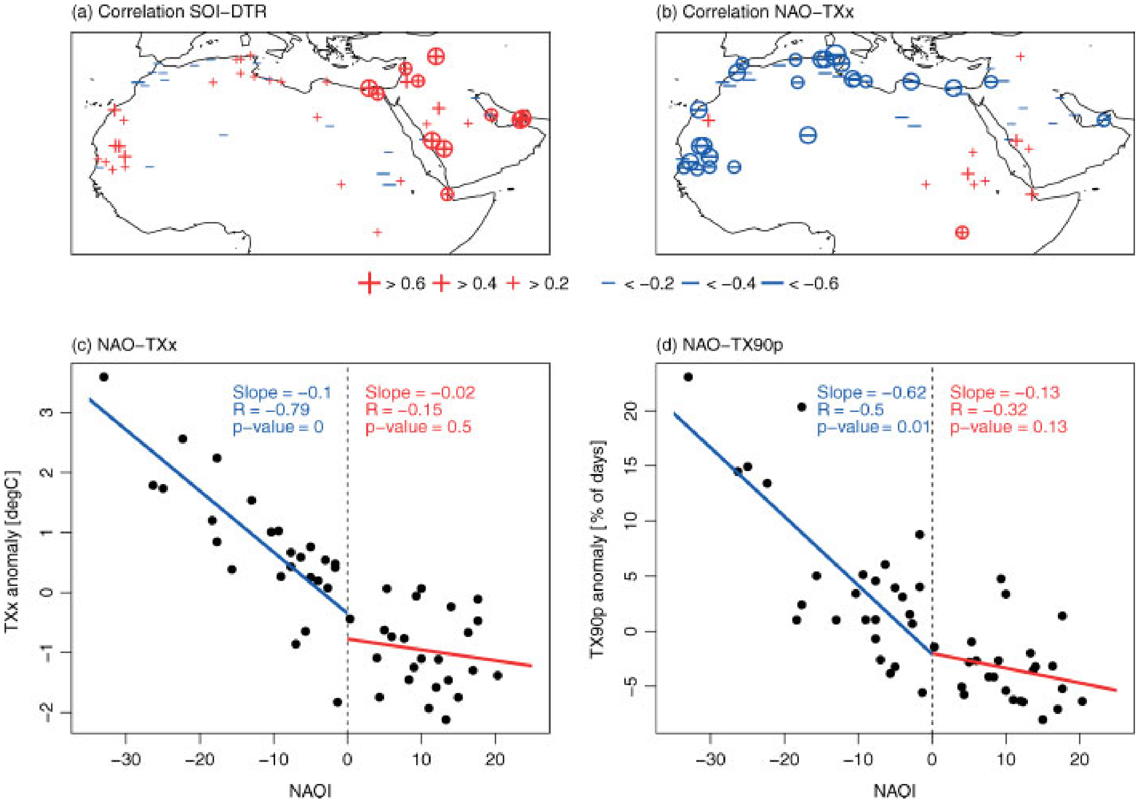

Figure 6. Relationship between chosen extreme indices and ENSO or NAO during boreal winter (DJF). (a) Spearman rank correlation between DTR and the SOI index, (b) correlation between TXx and NAO. + (−) indicate positive (negative) correlations. Significant correlations ($p \leq 0.05$) are marked with a circle. Correlations are calculated for as long as each station provides homogeneous data. (c) Scatter plot for de-trended area-average TXx anomalies during 1961–2010 in the western part of the investigation area (Mauritania, Morocco, Algeria, Tunisia, Libya) and NAO, (d) as (c) but for TX90p.

enough data points to support robust assessments of changes. Furthermore, as shown in Peterson *et al.* (2008), the statistical behaviour (e.g. trend) of these extremes reflects with great accuracy the behaviour of extremes that are four times as rare.

This study fills important gaps in the global picture of how these types of climate extremes are changing. Despite the coordinated international efforts of filling in data sparse areas (see Peterson and Manton, 2008), there are still wide gaps over much of Africa and South America (e.g. Alexander *et al.*, 2006). The data collated for this study may potentially also extend the production of new global data sets of climate extremes (Donat *et al.*, 2013). It also shows the value of regional analysis, cross-border verification of climate change signals, and international collaboration in providing sound climate change information of value to public and private planners at all levels. Indeed, meteorological services in all 14 Arab countries participating in this analysis can use this information as part of their contributions to the Global Framework for Climate Services and as a start to future analyses.

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