Trends in Middle East climate extreme indices from 1950 to 2003

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[1] A climate change workshop for the Middle East brought together scientists and data for the region to produce the first area-wide analysis of climate extremes for the region. This paper reports trends in extreme precipitation and temperature indices that were computed during the workshop and additional indices data that became available after the workshop. Trends in these indices were examined for 1950–2003 at 52 stations covering 15 countries, including Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iran, Iraq, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, and Turkey. Results indicate that there have been statistically significant, spatially coherent trends in temperature indices that are related to temperature increases in the region. Significant, increasing trends have been found in the annual maximum of daily maximum and minimum temperature, the annual minimum of daily maximum and minimum temperature, the number of summer nights, and the number of days where daily temperature has exceeded its 90th percentile. Significant negative trends have been found in the number of days when daily temperature is below its 10th percentile and daily temperature range. Trends in precipitation indices, including the number of days with precipitation, the average precipitation intensity, and maximum daily precipitation events, are weak in general and do not show spatial coherence. The workshop attendees have generously made the indices data available for the international research community.

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1. Introduction

[2] Any change in the frequency or severity of extreme climate events could have profound impacts on nature and society. It is thus very important to analyze extreme events. However, most analyses of long-term global climate changes have focused on changes in mean values. This is largely due to the lack of availability of high quality daily resolution data required for monitoring, detection and attribution of changes in climate extremes. The compilation, provision, and updating of a globally complete and readily available full resolution daily data set is difficult. For example, the global analysis of climate extreme indices by *Frich et al.* [2002] does not cover large areas of land. Data used in that study are very sparse (or there are no data at all) over most of Central and South America, Africa, and southern Asia. In addition, the analyses conducted by different researchers in different countries may not seamlessly merge together to form a global map because the

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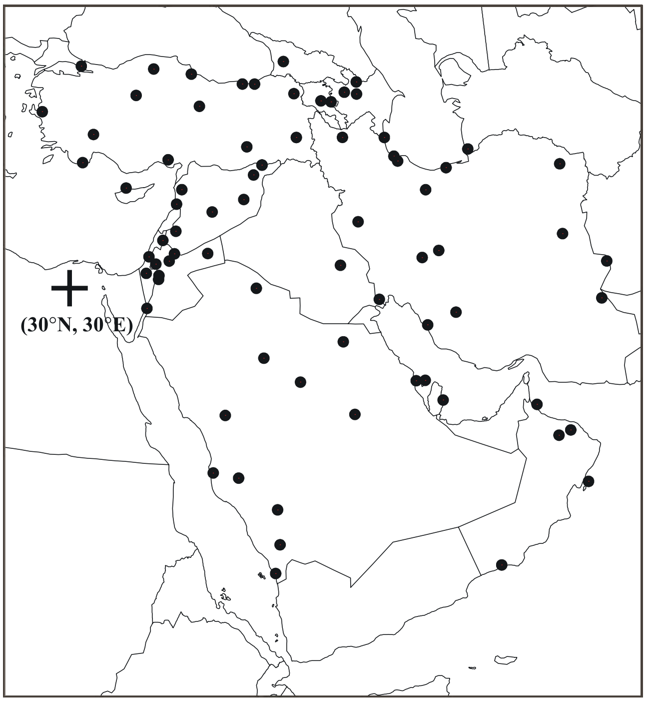

Figure 1. Locations of all stations.

analyses might have been conducted on different indices [e.g., *Bonsal et al.*, 2001] and/or using different methods.

[3] To address this issue and to provide better input to the forthcoming IPCC Fourth Assessment Report, the joint WMO CCl/CLIVAR Expert Team (ET) on Climate Change Detection, Monitoring and Indices (ETCCDMI) has been coordinating an international effort to develop, calculate, and analyze a suite of indices of climate extremes. These indices are calculated by different individuals in different countries and regions, using exactly the same formula. The analyses of those indices can thus fit seamlessly into the global picture [e.g., *Karl et al.*, 1999; *Peterson et al.*, 2002; *Easterling et al.*, 2003]. It is hoped that this effort will result in an improved monitoring of climate extreme change with much broader spatial coverage than currently available. A series of five regional climate change workshops were held in 2004 and early 2005 to analyze changes in extreme climate indices for the regions not studied before [e.g., *Frich et al.*, 2002]. A group of volunteers have organized one of these workshops in Alanya, Turkey, from 4 to 9 October 2004 (S. Sensoy et al., Meeting summary: Workshop on enhancing Middle East climate change monitoring and indices, submitted to *Bulletin of the American Meteorological Society*, 2005, hereinafter referred to as Sensoy et al., submitted manuscript, 2005) to collect, quality control, and analyze data for the Middle East region. The objective of this workshop was to cover the region from Turkey to Iran and from Georgia to the southern tip of the Arabian Peninsula. Twelve scientists from 11 countries in the region participated the workshop. A few countries chose not to participate in the workshop but later contributed data for the postworkshop analysis, including Saudi Arabia, Iraq and Israel. Details about the workshop and a few preliminary findings from the workshop are reported in the work of Sensoy et al. (submitted manuscript, 2005). In this paper, we present more detailed, more careful postworkshop analysis on the trends in the indices of extreme temperature and precipitation in the Middle East. In addition, we also include analyses of station data that only became available after the workshop. The paper is structured as following. Data and methods are described in section 2. The analytical results are presented in section 3. Conclusions and discussion follow in section 4.

2. Data

2.1. Data Sources

[4] Daily precipitation amounts and daily maximum and daily minimum temperatures at 75 stations from 15 countries in the Middle East and adjacent region (referred to as Middle East hereafter), namely Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iran, Iraq, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, Turkey, were available for this analysis. Most of the 52 stations presented in this paper were brought to the workshop by the workshop attendees, with one station from Cyprus supplied by the Hadley Centre and another station supplied by the Iraqi Meteorological Service. Data from these stations were quality controlled, homogeneity tested, and preliminarily analyzed (see below) on site during the workshop (Sensoy et al., submitted manuscript, 2005). After the workshop, daily precipitation for two Oman stations were extended back to 1946 using data archives held at the Climate Research Unit, University of East Anglia (P. Jones, personal communication, 2005). The Saudi Arabia Meteorological Service also provided 12 Saudi stations data after the workshop. These data were very carefully processed by the lead authors during the postworkshop analysis. In addition, data from 12 Iranian stations (some stations were also analyzed during the workshop) have been analyzed at the Atmospheric Science and Meteorological Research Centre of Iran using the same procedures described in this paper. In this case, indices rather than original daily precipitation and temperature data were provided for this analysis. Figure 1 shows the locations of all available stations.

[5] Most Turkish stations have data starting in 1920s or 1930s. However, the majority of the stations do not have observational data until 1950s. Data from several countries, including Armenia, Azerbaijan, Israel, and Saudi Arabia are available only from the mid-1960s or early 1970s. To make the best use of available data and also to provide best spatial coverage, the subsequent trend analysis will cover two periods; 1950 to 2004 and 1970 to 2004.

2.2. Data Quality Control and Homogeneity Testing

[6] The main purpose of this data quality control (QC) procedure is to identify errors usually caused by data processing such as manual keying. The procedure automatically sets a daily precipitation amount to a missing value if it is less than zero, and both daily maximum and minimum temperatures to missing values if daily maximum temperature is less than daily minimum temperature. In these instances daily maximum temperatures were manually removed. The quality control procedure also identifies outliers in daily maximum and minimum temperature.

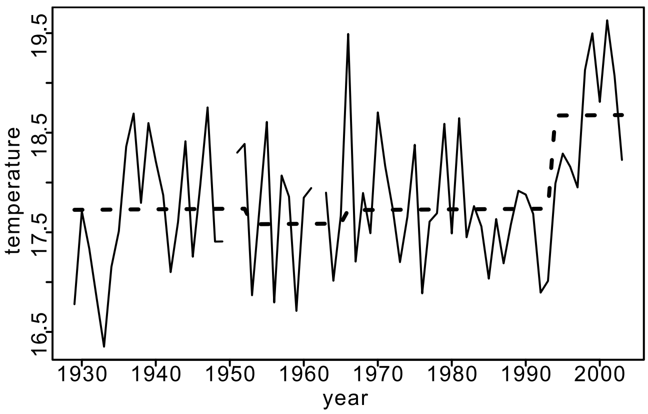

Figure 2. Homogeneity test of annual mean daily maximum temperature (°C) for station Rize (40°31′E, 41°02′N), Turkey. The largest, statistically significant discontinuity around 1993 is verified by the station history metadata, which indicate that the station relocated in 1995.

These are daily values outside a threshold defined by the user. In this study, this threshold is defined as the mean of the value for the day plus or minus four times the standard deviation of the value for the day (std), that is, [*mean* − 4 × *std*, *mean* + 4 × *std*]. Daily temperature values outside of these thresholds are marked as potentially problematic, they are manually checked and corrected on a case by case basis by workshop attendees who are knowledgeable about their own daily data.

[7] Data homogeneity is assessed using an R-based program, RHtest, developed at the Climate Research Branch of Meteorological Service of Canada, and available from the ETCCDMI Web site. This program is capable of identifying multiple step changes at documented or undocumented change points. It is based on a two-phase regression model with a linear trend for the entire base series [*Wang*, 2003]. Detailed discussion about this model can be found in the work of *Wang* [2003].

[8] The data quality control (QC) and homogeneity test procedures identified some apparent problems in the data. Each potential outlier was manually validated using information from the days before and after the event along with expert knowledge about the climate. A QC log file was produced for every station to document each change or acceptance of an outlier with the reasons. The two-phase regression model from *Wang* [2003] was applied to annual mean daily maximum, minimum, and mean temperatures as well as daily temperature range, to identify likely inhomogeneities in the data. Once a possible step change is identified in the annual series, it is also checked against station history meta data records, if available. Figure 2 shows an example where a step change has been detected at the Turkish station Rize. Adjusting daily data to account for step changes is very complex and difficult to do well [*Aguilar et al.*, 2003]. There is only limited success in adjusting daily temperature data [*Vincent et al.*, 2002]. It was thus decided that station data that are deemed inhomogeneous be excluded from the analysis or only the period after the discontinuity used. A total of 52 stations in the region were retained for the subsequent analysis. Station information including names and coordinates, as well as the period of record, are listed in Table 1.

3. The Analyses

3.1. The Indices

[9] The ETCCDMI recommended a total of 27 core indices (Table 2) with primary focuses on extremes to be derived from station daily data. They are a part of a larger list defined by the World Meteorological Organization Working Group on Climate Change Detection [*Folland et al.*, 1999; *Jones et al.*, 1999; *Peterson et al.*, 2001]. Most of the definitions for the indices were presented in the work of *Peterson et al.* [2001], and have been computed for other regions [e.g., *Aguilar et al.*, 2005; *Haylock et al.*, 2005; *Vincent et al.*, 2005; L. Alexander

Table 1. List of Stations

Country	Station Name	Period	Longitude, deg E	Latitude, deg N
Armenia	Martuni	1950–2003	45°18′	40°30′
	Yerevan	1970–2000	44°28′	40°08′
Azerbaijan	Astara	1970–2000	48°53′	38°27′
	Ganga	1970–2000	46°24′	40°42′
	Shaki	1970–2000	47°10′	41°13′
	Yevlakh	1970–2000	47°12′	40°36′
Cyprus	Akrotiri	1957–2003	35°21′	32°59′
Georgia	Samtredia	1936–2000	42°22′	42°11′
Iran	Abadan	1951–2000	48°15′	30°22′
	Babolsar	1951–2000	52°39′	36°43′
	Birjand	1951–2000	59°12′	32°52′
	Bushehr	1951–2000	50°50′	29°58′
	Kerman	1960–2002	56°58′	30°15′
	Kermanshah	1961–1999	40°07′	34°19′
	Ooroomieh	1961–1999	45°05′	37°32′
	Rasht	1956–2000	49°39′	37°12′
	Shahre Kord	1951–2000	50°51′	32°20′
	Shiraz	1951–2000	52°26′	29°33′
	Tabriz	1951–2000	46°17′	38°05′
	Tehran-Mehrabad	1956–1999	51°19′	35°51′
	Zabol	1962–2000	61°29′	31°13′
	Zahedan	1951–2000	60°53′	29°28′
Iraq	Kul-Al-Hai	1950–2000	46°03′	32°10′
Israel	Eilat	1964–1999	34°57′	29°33′
	Harkenaan	1964–1999	35°30′	32°58′
	Jerusalem	1964–1999	35°13′	31°52′
	Nahalhazerim	1967–1999	34°43′	31°16′
Jordan	Mafraq	1959–2004	36°15′	32°22′
	Rawshed	1960–2004	38°12′	32°30′
Oman	Masirah	1946–2003	58°54′	20°40′
	Salalah	1947–2003	54°05′	17°02′
Saudi Arabia	Bisha	1970–2003	42°38′	19°59′
	Dhahran	1970–2003	50°10′	26°16′
	Hail	1970–2003	41°41′	27°26′
	Jeddah Airport	1970–2003	39°11′	21°42′
	Al-Madinah	1970–2003	39°42′	24°33′
	Riyadh	1970–2003	46°44′	24°42′
	Al-Taif	1970–2003	40°33′	21°29′
Syria	Idleb	1975–2003	36°37′	35°56′
	Kamishli	1968–2003	41°13′	37°02′
	Damascus Mezze	1965–1993	36°13′	33°29′
	Palmyra	1965–1993	38°18′	34°33′
	Safita	1965–2003	36°08′	34°49′
Turkey	Adana	1929–2003	35°21′	36°59′
	Ankara	1929–2003	32°53′	39°57′
	Finike	1961–2003	30°09′	36°18′
	Istanbul	1929–2003	29°05′	40°58′
	Izmir	1938–2003	27°10′	38°26′
	Kars	1929–2003	43°06′	40°37′
	Kastamonu	1930–2003	33°47′	41°22′
	Sivas	1930–2003	37°01′	39°45′
	Trabzon	1929–2003	36°18′	41°17′

Table 2. List of 27 ETCCDMI Core Indices

ID	Indicator Name	Definitions	Unit
FD0	frost days	annual count when TN(daily minimum) < 0°C	days
SU25	summer days	annual count when TX(daily maximum) > 25°C	days
ID0	ice days	annual count when TX(daily maximum) < 0°C	days
TR20	tropical nights	annual count when TN(daily minimum) > 20°C	days
GSL	growing season length	annual (Jan.1 – Dec. 31 in NH, July 1 – June 30 in SH) count between first span of at least 6 days with daily mean temperature (TG) > 5°C and first span after 1 July (1 Jan. in SH) of 6 days with TG < 5°C	days
TXx	max Tmax	annual maximum value of daily maximum temp	°C
TNx	max Tmin	annual maximum value of daily minimum temp	°C
TXn	min Tmax	annual minimum value of daily maximum temp	°C
TNn	min Tmin	annual minimum value of daily minimum temp	°C
TN10p	cool nights	Percentage of days when TN < 10th percentile	%
TN90p	warm nights	Percentage of days when TN > 90th percentile	%
TX10p	cool days	Percentage of days when TX < 10th percentile	%
TX90p	warm days	Percentage of days when TX > 90th percentile	%
WSDI	warm spell duration indicator	annual count of days with at least 6 consecutive days when TX > 90th percentile	days
CSDI	cold spell duration indicator	annual count of days with at least 6 consecutive days when TN > 10th percentile	days
DTR	diurnal temperature range	Monthly mean difference between TX and TN	°C
ETR	annual temperature range	difference between maximum TX and minimum TN in the year	°C
RX1day	max 1 day precipitation amount	monthly maximum 1-day precipitation	mm
RX5day	max 5 days precipitation amount	monthly maximum 5-day precipitation	mm
SDII	simple daily intensity index	annual total precipitation divided by the number of wet days (defined as PRCP $\geq$ 1.0 mm) in the year	mm
R10	number of heavy precipitation days	annual count of days when PRCP$\geq$10 mm	days days
R20	number of heavy precipitation days	annual count of days when PRCP$\geq$20 mm	days days
Rnn	number of heavy precipitation days	annual count of days when PRCP $\geq$ nn mm, nn is user defined threshold	days days
CDD	consecutive dry days	maximum number of consecutive days with RR < 1 mm	days
R95p	very wet days	annual total PRCP when RR > 95th percentile	mm
R99p	extremely wet days	annual total PRCP when RR > 99th percentile	mm
PRCPTOT	annual total wet day precipitation	annual total PRCP in wet days (RR $\geq$ 1 mm)	mm

et al., Global observed changes in daily climate extremes of temperature and precipitation, submitted to *Journal of Geophysical Research*, 2005, hereinafter referred to as Alexander et al. submitted manuscript, 2005; A. M. G. Klein Tank et al., Changes in daily temperature and precipitation extremes in central and South Asia, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Klein Tank et al., submitted manuscript, 2005]. We compute these indices using RClimDex, an R-based software package developed at the Climate Research Branch of Meteorological Service of Canada on behalf of the ETCCDMI. This software along with documentation is available at http://cccma.seos.uvic.ca/ETCCDMI. The bootstrap procedure of *Zhang et al.* [2005] has been implemented in RClimDex to ensure that the percentile based temperature indices do not have artificial jumps at the boundaries of the in-base and out-of-base periods. Over a large region (e.g., Saudi Arabia), observational data are only available for the period starting in 1970. As a result, a base period of 1971–2000 has been used when computing percentile based indices to provide the best spatial coverage. Only daily data with sufficiently long records which passed these quality control and homogeneity procedures were used in this analysis.

3.2. Regional Average Series

[10] To provide an overall picture of climate variation in the region, we also computed regional averages for every index. Because of wide range of the climates in the region, the regional averaged indices are computed as the mean of the indices at individual stations relative to their climatology for the period 1971–2000. The majority of the stations that have the data for the early period (1950–1970) are located in the northern portion of the region, as a result, these regional series is less representative for the whole region during the early period.

3.3. Trend Calculation

[11] A linear trend is computed from the indices series using a Kendall's tau based slope estimator due to *Sen* [1968]. This estimator is robust to the effect of outliers in the series. It has been widely used to compute trends in hydrometeorological series [e.g., *Wang and Swail*, 2001; *Zhang et al.*, 2000]. The significance of the trend is determined using Kendall's test because this test does not assume an underlying probability distribution of the data series. There is however a problem associated with the Kendall test in that the result is affected by serial correlation of the series. Specifically, a positive autocorrelation, that is likely the case for most climatological data, in the residual time series will result in more false detection of a significant trend than specified by the significance level [e.g., *von Storch*, 1995; *Zhang and Zwiers*, 2004]. This would make the trends detection unreliable. Because of this, we use an iterative procedure, originally proposed by *Zhang et al.*

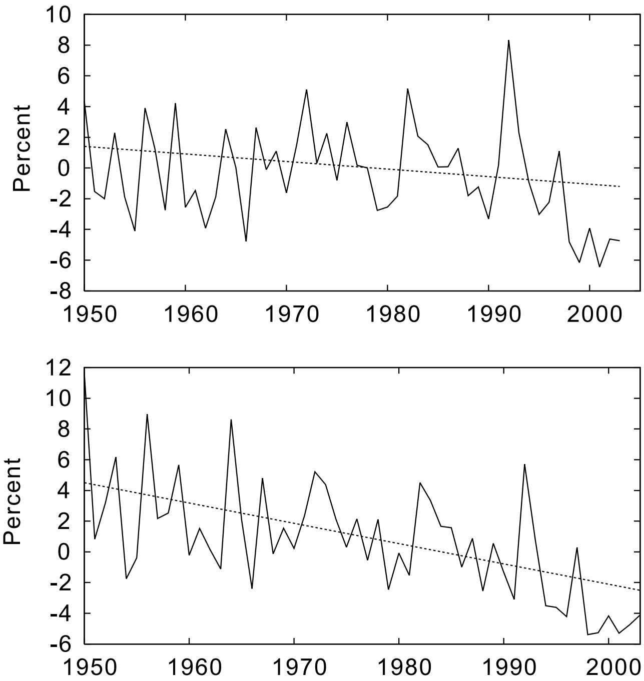

Figure 3. Regionally averaged anomaly series (relative to the mean for 1971–2000) of annual (top) TX10p and (bottom) TN10p. Dashed lines represent linear trends for 1950–2003.

Table 3. Trends per Decade for the Regional Indices of Temperature and Precipitation Extremes[a]

Index	1950–2003	1970–2003
FD0	−0.6 (−1.7, 0.4)	**2.8** (−4.7, −0.7)
SU25	1.0 (−0.03, 2.2)	**3.6** (1.5, 6.0)
ID0	n/a	n/a
TR20	**3.7** (2.5, 4.8)	**6.2** (4.7, 7.9)
GSL	n/a	n/a
TXx	0.07 (−0.07, 0.23)	**0.3** (0.05, 0.55)
TNx	**0.23** (0.13, 0.33)	**0.5** (0.3, 0.7)
TXn	0.2 (−0.03, 0.4)	**0.6** (0.1, 1.2)
TNn	**0.28** (0.01, 0.54)	**0.6** (0.1, 1.2)
TN10p	−**1.3**, (−1.8, −0.8)	−**2.5** (−3.4,−1.6)
TN90p	**1.2** (0.7, 1.7)	**2.6**, (1.6, 3.6)
TX10p	−0.4 (−1.1, 0.2)	−**0.2** (−0.3, −0.09)
TX90p	**0.66** (0.01, 1.4)	**2.4** (1.2, 4.1)
WSDI	0.24 (−0.3, 1.0)	**1.6** (0.4, 1.5)
CSDI	−**0.9** (−1.4, −0.4)	−**1.3** (−2.3, −0.6)
DTR	−**0.12** (−0.17, −0.06)	−0.01 (−0.14, 0.01)
RX1day	0 (−0.07, 0.07)	0 (−0.2, 0.15)
RX5day	0 (−0.09, 0.08)	0 (−0.22, 0.06)
SDII	−0.006 (−0.016, 0.003)	−0.08 (−0.03, −0.02)
R10	−0.03 (−0.12, 0.05)	0 (−0.20, 0.16)
R20	0 (−0.09, 0.04)	0 (−0.22, 0.16)
CDD	−**5.0** (−9.5, −0.4)	3.6 (−5.8, 9.0)
R95p	−0.3 (−5, 4.0)	−6 (−15, 3)
R99p	−1.6 (−4.4, 0.8)	−3.3 (−8.7, 1.5)
PRCPTOT	−0.3 (−9.6, 10.9)	−**24** (−44, −4.5)

[a]The 95% confidence intervals are shown in parentheses. Values for trends significant at the 5% level are shown in boldface.

[2000] and later refined by *Wang and Swail* [2001], to compute the trend and to test the trend significance taking account of a lag-1 autocorrelation effect. Details of the trend estimation and significance testing are explained in the work of *Wang and Swail* [2001, Appendix A]. To take account of missing values, at least 80% of data for the period are required before a trend can be computed. Throughout the paper, we consider a trend as being significant if it is statistically significant at the 5% level.

4. Results

4.1. Trends in Temperature Indices

4.1.1. Percentile-Based Temperature Indices

[12] Figure 3 shows the regional averaged anomalies of annual series of percentage of days when daily maximum or daily minimum temperature is below its 10th percentile (referred to TX10p and TN10p, respectively). A decreasing trend is apparent for both TX10p and TN10p since the 1970s, suggesting a decrease in the number of cold days. The trends are significant (Table 3). Regional anomalies of annual series of percentage of days when daily maximum or daily minimum temperature is above its 90th percentile (referred to TX90p and TN90p, respectively) are plotted in Figure 4. TX90p and TN90p displayed sharp increases in the 1990s contrasting with the more gradual trends in TX10p and TN10p. Trends in both indices are significant (Table 3).

[13] The spatial distribution of trends for both periods, 1950–2003 and 1970–2003, in the annual TX10p and TN10p are shown in Figure 5. For the period 1950–2003, TN10p showed a strong pattern of decreasing trends with only few stations showing increasing trend. The frequency of TN10p events has reduced at about 1% per decade at the majority of stations. For the period 1970–2003, trends become more coherent spatially with more stations showing significant trends in TN10p than in TX10p. In addition, the magnitudes of the trends are also greater. Statistically significant and spatially coherent decreasing trends are

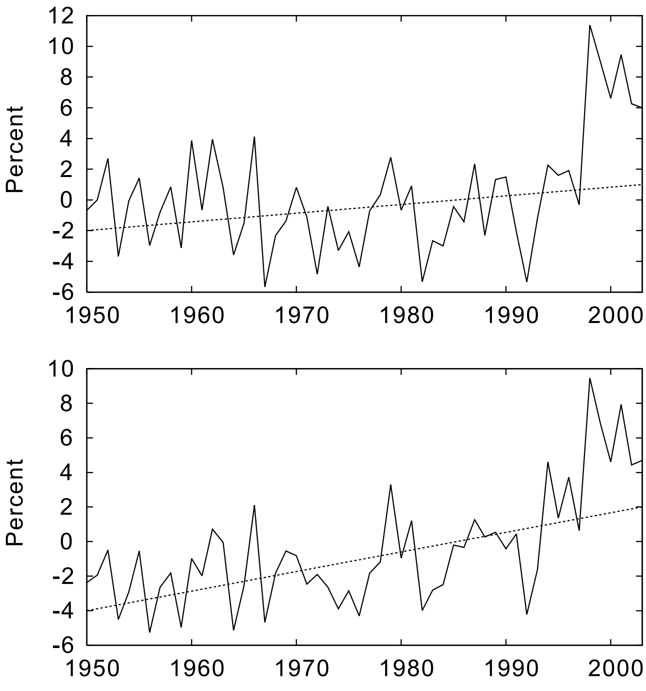

Figure 4. Same as Figure 3 but for (top) TX90p and (bottom) TN90p series.

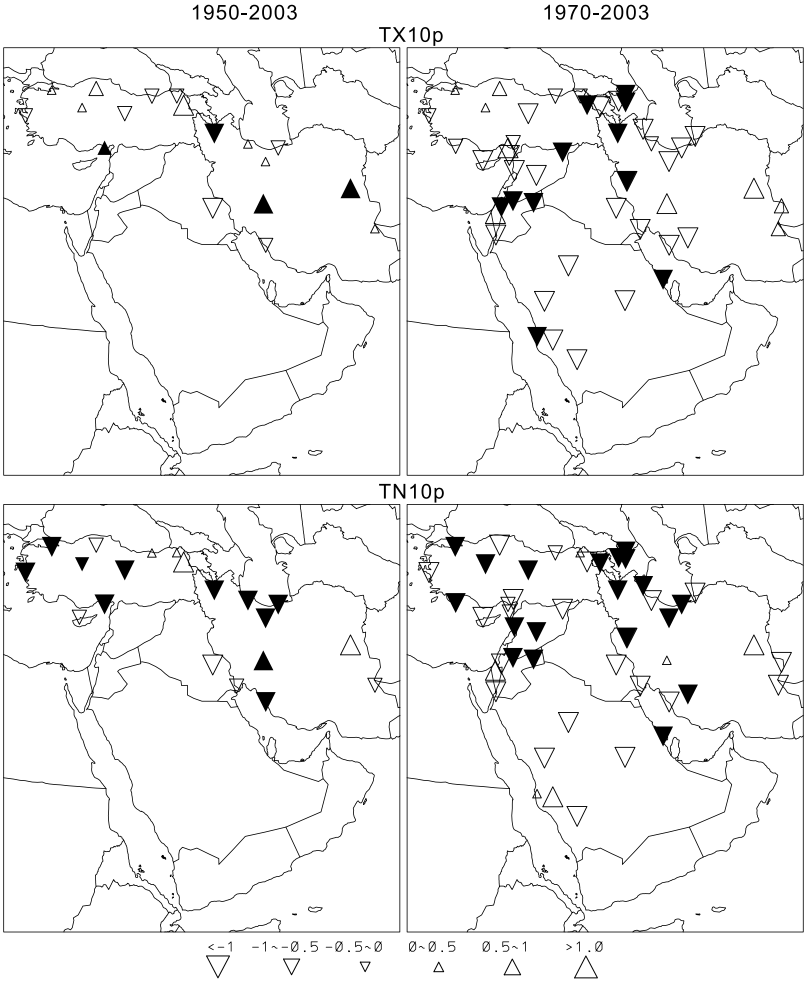

Figure 5. Trend in the annual TX10p and TN10p series for the period 1950–2003 and 1970–2003. Upward triangles represent increasing trends, downward triangles decreasing trends. Different sizes of triangles indicate different magnitudes (shown in the legend) of trend (in percentage per decade). Solid triangles represent trends significant at the 5% level.

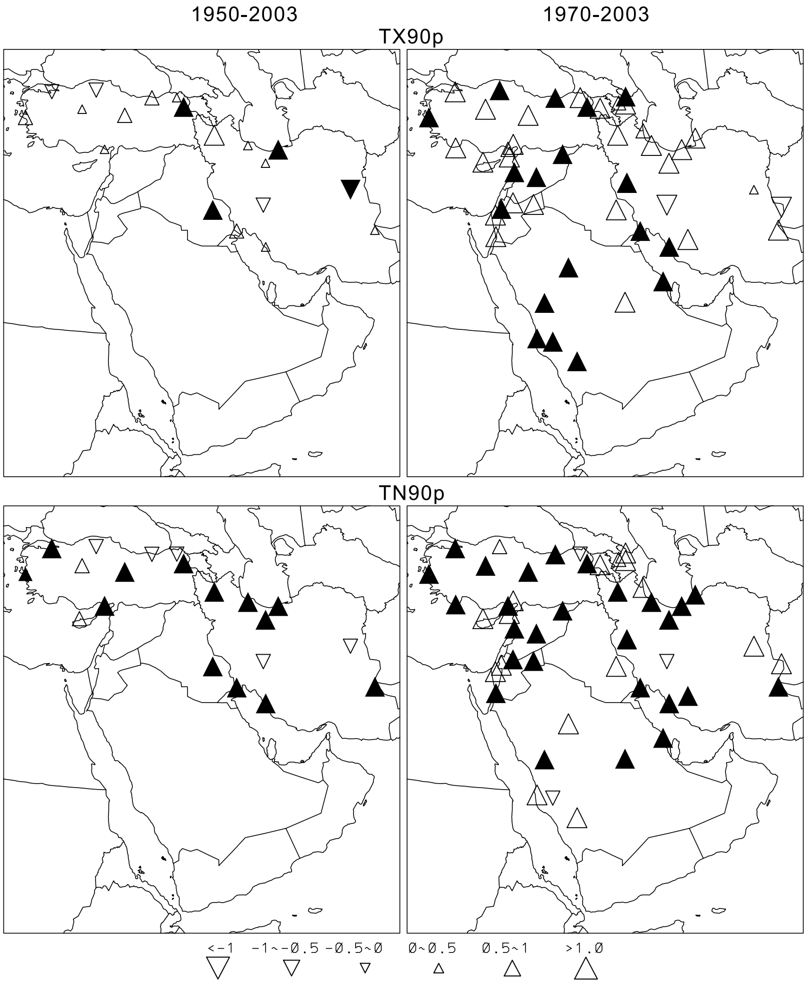

Figure 6. Same as Figure 5, but trends for TX90p and TN90p.

observed in the Northern part of the region. Trends over the south, the desert areas of Saudi Arabia and Iran, are generally not significant. However, this may due to stronger year to year variation in TN10p and TX10p in these regions that makes it harder to detect a significant trend. These spatial patterns compare well with the long-term change in the regional series (Figure 3) in that the strongest decrease has been observed mainly in more recent decades. The maps of trends for TX90p and TN90p (Figure 6) look similar to those of TX10p and TN10p. However, the trends are generally of opposite signs and significant at more stations. An increase in TX90p or in TN90p generally corresponds to a decrease in the maps for TX10p or TN10p.

[14] Trends differ from one season to another, especially in the number of stations experiencing statistically significant trends. Figure 7 shows an example of TN90p for the period 1970–2003. The direction of the trends (decrease or increase) in the seasonal data are generally similar to those observed in the annual data, but summer and autumn usually have more stations with statistically significant trends than winter and spring. The spatial patterns of the TX90p trend are similar to those of the TN90p trend for the same season (not shown), but the number of stations showing a statistically significant trend is smaller for TX90p. Trends in the TN10p and TX10p series are similar to those of TN90p and TX90p, but in opposite direction (not shown). The trends in TN10p are typically stronger than those of TX10p. Significant trends have only been observed in summer for the latter index. The spatial distribution of trends for 1950–2003 are similar to those for the period 1970–2003, with 1950–2003 trends being weaker.

[15] Overall (Table 3), there have been significant increases in the number of warm days, and significant decreases (but at fewer stations) in the number of cold days. The increasing trends in the number of warm days are much stronger than the decreases in the number of cold days. Changes in the frequencies of cold days and warm days do not occur at the same time, i.e., decreases in the number of cold days are more gradual and start in the 1970s, while increases in the number of warm days mainly occurred in the 1990s. More stations observed significant trends in summer than any other seasons. Because the percentage of stations that showed a significant trend could be larger than 60% (for annual series) which is much higher than what one would expect by chance, it may be concluded that trends in some percentile based indices are also significant for the region (field significance).

4.1.2. Annual Maximum and Minimum Values of Daily Temperatures

[16] The areal averages of anomalies for annual maximum and minimum values of daily maximum temperatures (referred to as TXx and TXn respectively) are displayed in

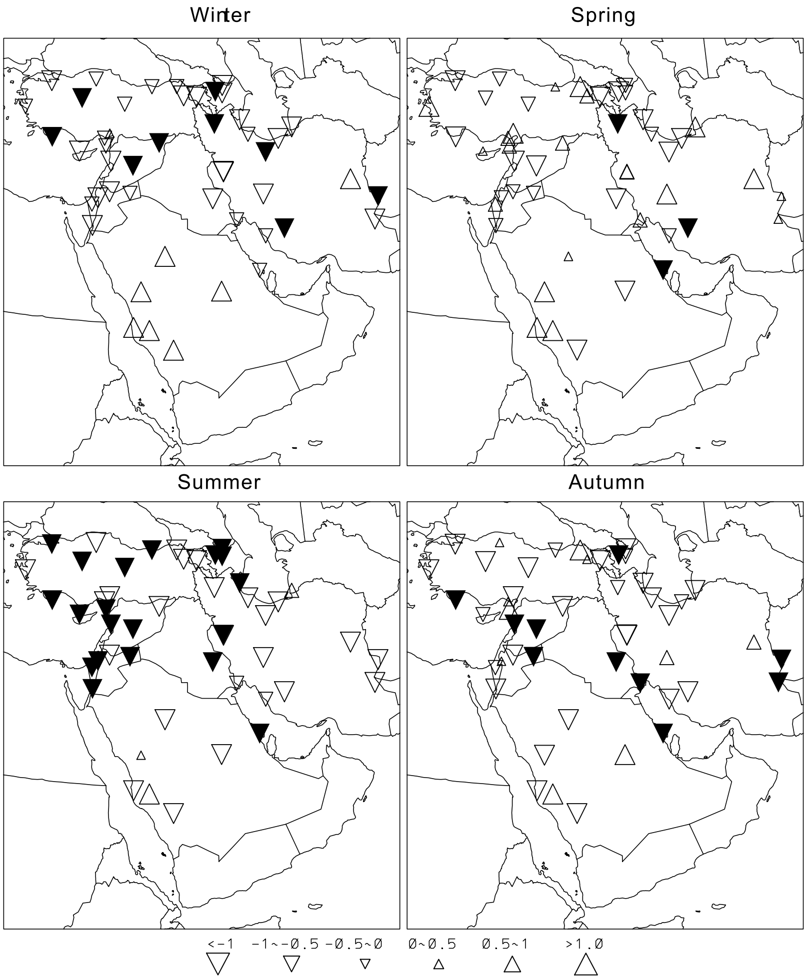

Figure 7. Same as Figure 5, but trends for seasonal TN90p for period 1970–2003.

Figure 8. Neither series shows a significant trend, though values are higher near the end of series. At individual sites, both TXx and TXn show upward but weak trends during both of the two periods 1950–2003 and 1970–2003. Statistically significant trends are found at very few sites (not shown).

[17] The long-term changes in the annual maximum and minimum values of daily minimum temperatures (referred to as TNx and TNn respectively) are similar to those of TXx and TXn (Figure 9), but the trends are stronger. Trend in the areal averaged annual values is also significant (Table 3). Note that the interannual variability in the annual maximum values of daily minimum temperature is considerably smaller than that of annual minimum values, reflecting much smaller variability in the summer (in which annual maximum temperature occurs) than in the winter (in which annual minimum temperature appears). Upward trends in the highest and lowest daily minimum temperatures in the year are significant at many stations, with more significant trends in the summer than in the winter. However, most of the sites showing significant trends are located toward the north of the region (Figure 10). Since trend detection is a signal to noise ratio problem and temperature variability is much higher in winter than in summer, the smaller number of stations with a significant trend in TNn than in TNx does not necessarily indicate that minimum temperature has increased more in summer than in winter. It may simply suggest that it's much harder to detect a significant trend in winter due to higher variability in that season. A high percentage of stations show a significant trend suggesting that the trend for the region as a whole is significant, although perhaps less so in the desert regions.

4.1.3. Other Temperature Indices

[18] A few additional indices have been computed and analyzed for temperature. They include the number of

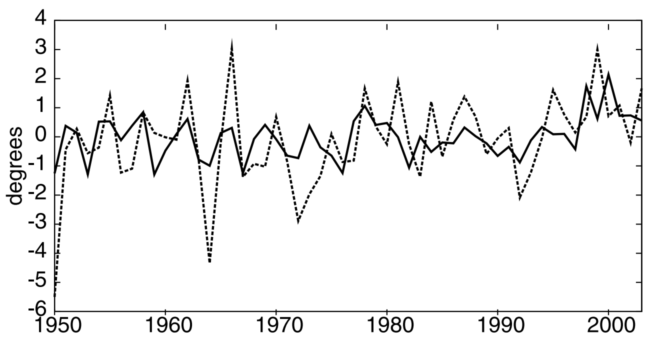

Figure 8. Regional averages of anomalies of annual maximum (solid line) and minimum (dashed line) values of daily maximum temperatures.

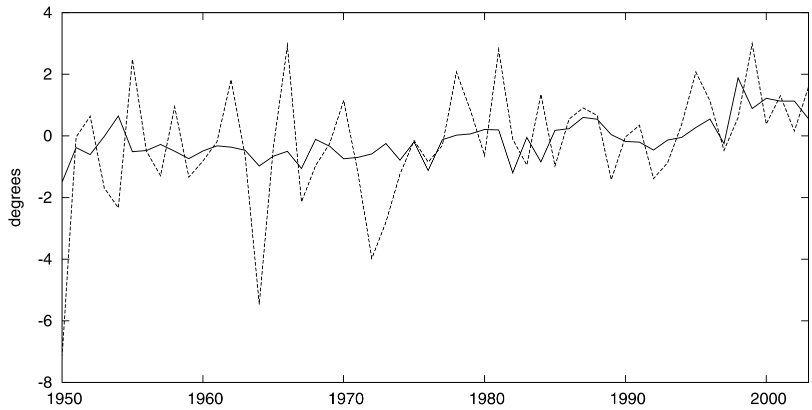

Figure 9. Regional averages of anomalies of annual maximum (solid line) and minimum (dashed line) values of daily minimum temperatures.

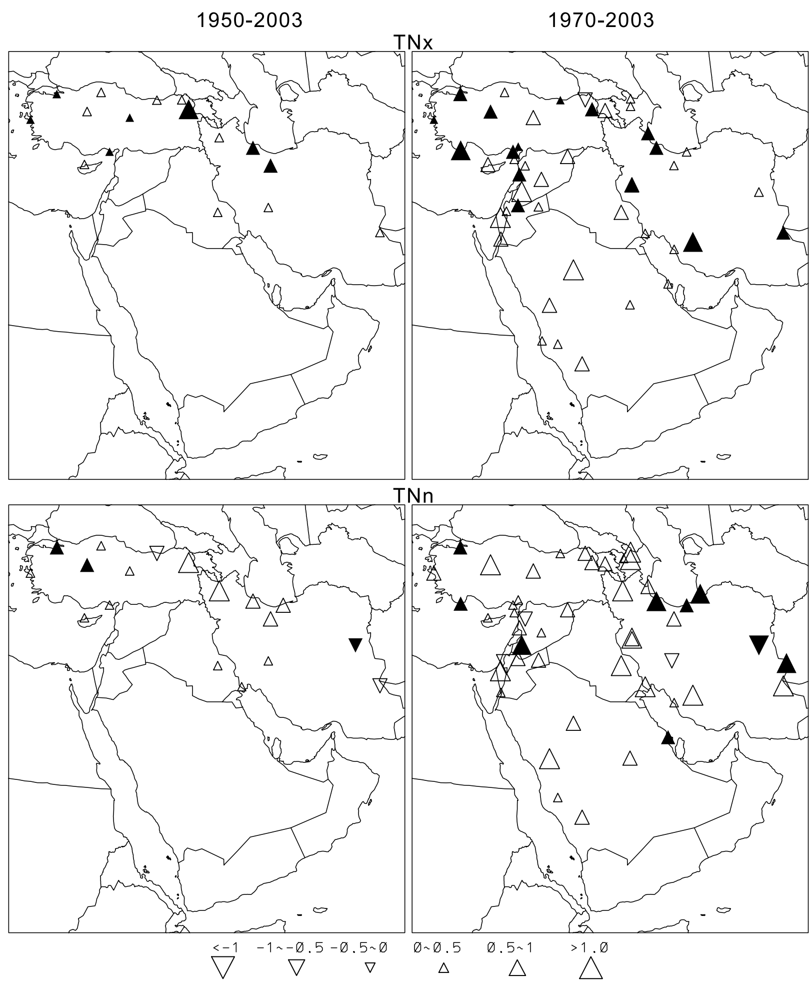

Figure 10. Trend in the annual maximum (TNx) and minimum (TNn) values of daily minimum temperature. Solid triangles represent trend significant at the 5% level. Unit for the legend is °C per decade.

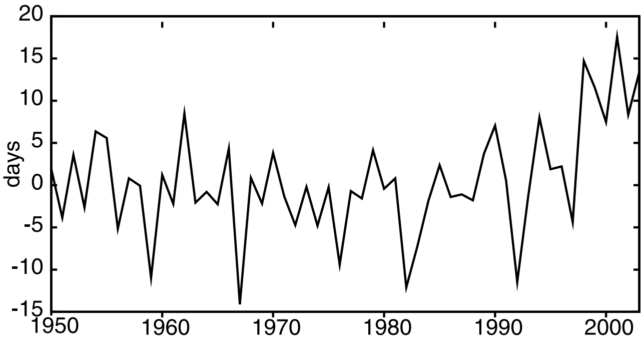

Figure 11. Regional averages of anomalies of number of summer days.

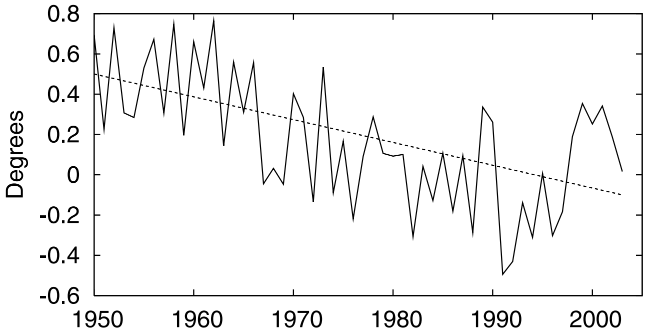

Figure 13. Regional averages of anomalies of daily temperature range. Dashed line represents a linear trend for 1950–2003.

summer days (SU25), the number of frost days (FD), the diurnal temperature range (DTR), the number of tropical nights (TR20), the length of growing season, and the length of cold and warm spells. Time series for regional averaged anomalies for SU25, FD, DTR, and TR20 are displayed in Figures 11–14, respectively. Trends in the regional series are summarized in Table 3. The long term changes of SU25 are very similar to that of TX90p and TN90p in that there is little trend prior 1990, but it has sharply increased during the past one and half decades. These results correspond very well to the findings that most of upward trend in the TX90p and TN90p is attributable to the increase in temperatures during warmer seasons in more recent years. The number of frost days showed little long-term trend, though it has been decreasing since the 1980s. Similar to what has happened in many parts of the world [e.g., *Frich et al.*, 2002], the daily temperature range has significantly decreased in the region (Figure 13). The number of tropical nights has significantly increased (Figure 14, Table 3). Most of the increase in tropical nights has occurred in more recent decades, due to sharp increases in the summer temperatures during the period. Other indices including the length of the growing season, the length of cold and warm spells, and the intra-annual extreme temperature range (ETR), do not exhibit any significant trend (not shown).

4.2. Trends in Precipitation Indices

[19] Precipitation variation is characterized by strong interannual variability without any significant trend in any of the precipitation indices analyzed (Table 3). As an example, regional averages of precipitation anomalies are plotted in Figure 15. Because precipitation climatology varies considerably from one place to another place in the region, the time series of precipitation anomalies shown in Figure 15 are more representative for the wetter region. If precipitation anomalies at individual sites are normalized by relevant climatology, the high values during the 1970s and 1980s shown in Figure 15 would be leveled off (not shown). Figure 16 shows the trend maps for the annual maximum daily precipitation and total precipitation for the two periods. Both show increasing and decreasing trends and lack of spatial coherency and there are very few stations showing a statistically significant trend.

5. Discussion and Conclusions

[20] We have examined trends in 27 indices mainly highlighting changes in extreme temperature and precipitation at 75 stations from 15 countries in the Middle East region for the period 1950–2003. Our study makes important contributions to the climate change research for the region and will also contribute to the IPCC Fourth Assessment Report. The daily precipitation and temperature data that are used to derive the indices in this study have never been available before. In addition, data quality and homogeneity that are of critical importance for assessing climate change are also carefully examined using accepted procedures by experts who are knowledgeable

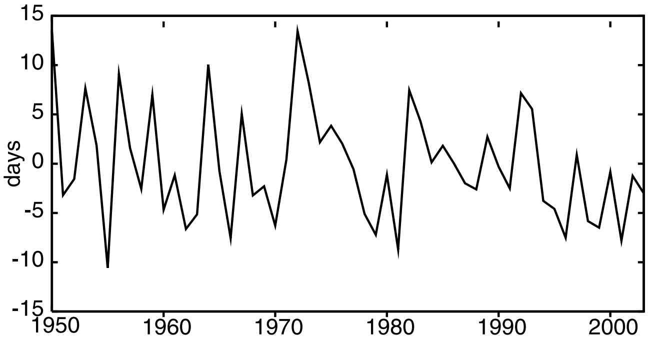

Figure 12. Regional averages of anomalies of number of frost days. Dashed line represents a linear trend for 1950–2003.

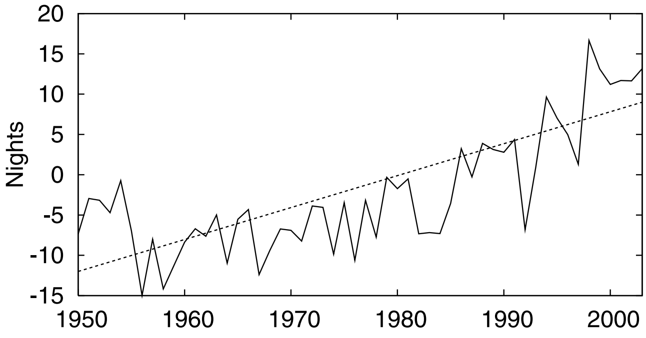

Figure 14. Regional averages of anomalies number of tropical nights. Dashed lines represents a linear trend for 1950–2003.

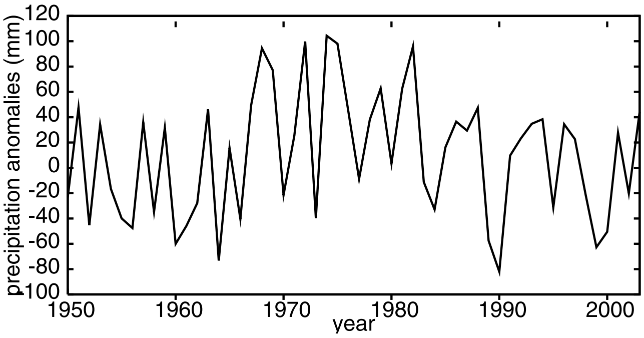

Figure 15. Regional averages of annual precipitation anomalies.

of their local climate and data collection procedures. These exercises would usually not be very feasible for global analysis conducted at large data centers. Data that are potentially problematic due to quality or inhomogeneity have been excluded from the analysis. Thus the conclusions we draw are based on sound techniques and the most reliable data.

[21] The results show statistically significant, and spatially coherent, trends in temperature indices corresponding to a warming trend in the region. It was found that the frequency of warm days has significantly increased while the frequency of cold days has significantly decreased. The reduction in the number of cold days is gradual and started in the 1970s, but the increase in warm days exhibits a sudden increase toward the 1990s. There have been significant increase in the number of summer nights but the daily temperature range has significantly decreased. Trends in precipitation indices, including annual total precipitation, the number of days with precipitation, the average precipitation intensity, and maximum daily precipitation events, are weak and are not very significant in general. Our findings corresponds well with what has been observed in the neighboring regions (e.g., Alexander et al. submitted manuscript, 2005; Klein Tank et al., submitted manuscript, 2005). For example, Klein Tank et al. (submitted manuscript, 2005) showed similar trends in the indices in the central and south Asia. The workshop attendees have generously made the indices data available for the international research community at the ETCCDMI's Web site (http://cccma.seos.uvic.ca/ETCCDMI). This is a significant development in the sharing climate change information. The workshop was a very good beginning for regional cooperation.

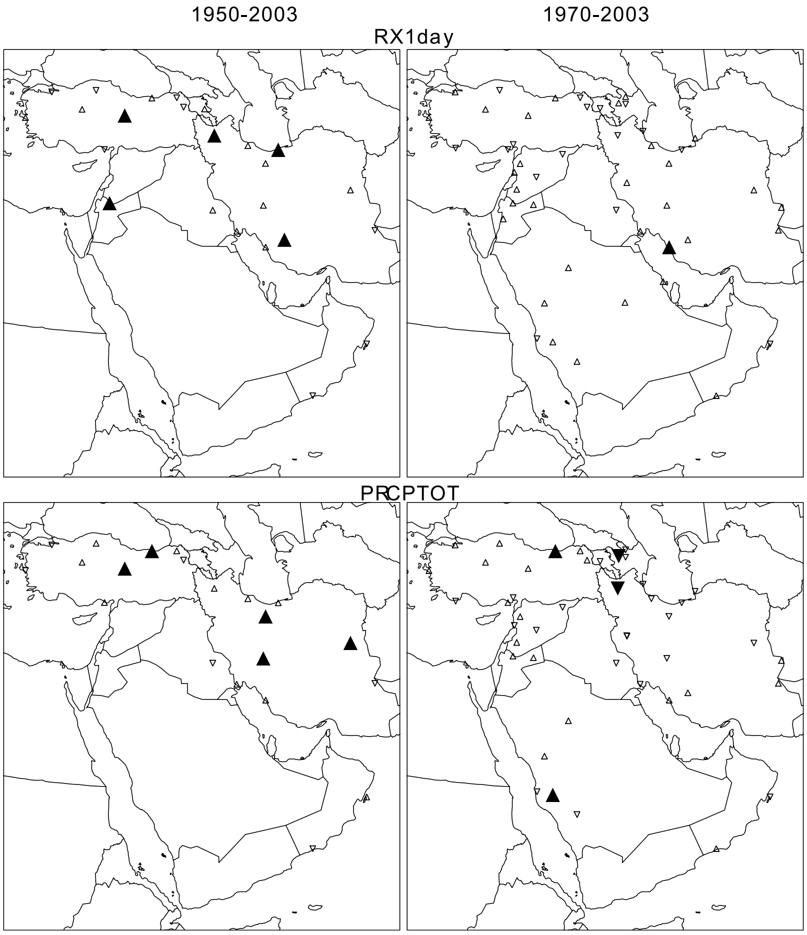

Figure 16. Trend in the annual maximum daily precipitation amount (RX1day) and annual total precipitation (PRCPTOT) for 1950–2003 and 1970–2003. Upward triangles indicate positive trend and downward triangles negative trends. Solid triangles show trends.

[22] **Acknowledgments.** Most of the analyses presented in this paper were conducted during the Workshop on Enhancing Middle East Climate Change Monitoring and Indices. This workshop was coordinated by the joint WMO CCl/CLIVAR Expert Team on Climate Change Detection, Monitoring, and Indices and was organized by a group of volunteers who are also coauthors of this paper. It was financially supported by the U.S. State Department to GCOS in support of the IPCC. The workshop attendees enjoyed and very much appreciated the hospitality provided by the Turkish State Meteorological Service during the workshop. The RHtest program was developed by Xiaolan Wang and Feng Yang of the Meteorological Service of Canada.

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