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Changes in daily temperature and precipitation extremes in central and south Asia

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[1] Changes in indices of climate extremes are studied on the basis of daily series of temperature and precipitation observations from 116 meteorological stations in central and south Asia. Averaged over all stations, the indices of temperature extremes indicate warming of both the cold tail and the warm tail of the distributions of daily minimum and maximum temperature between 1961 and 2000. For precipitation, most regional indices of wet extremes show little change in this period as a result of low spatial trend coherence with mixed positive and negative station trends. Relative to the changes in the total amounts, there is a slight indication of disproportionate changes in the precipitation extremes. Stations with near-complete data for the longer period of 1901–2000 suggest that the recent trends in extremes of minimum temperature are consistent with long-term trends, whereas the recent trends in extremes of maximum temperature are part of multidecadal climate variability.

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1. Introduction

[2] Climate extremes are receiving increased attention, because the impacts of climate change are felt most strongly through changes in the extremes. Yet, global pictures of changes in extremes [*Frich et al.*, 2002] typically show large areas with sparse data coverage or none at all. One such area includes parts of central and south Asia where no long-term digital daily data (necessary for the analysis of extremes) are readily available internationally. Only a few national studies on extremes exist. *Yan et al.* [2002] found a gradual reduction of the number of cold days in China over the 20th century and an increase in the number of warm days only since 1961. For the same country, *Liu et al.* [2005] found that the increased frequency of heavy precipitation events contributed 95% of the total increase of precipitation over the period 1960–2000. The increase in total precipitation was 2% over that time period. For India, *Roy and Balling* [2004] found that about two thirds of all the studied time series (1910–2000) exhibit increasing trends in the indices of precipitation extremes and that there are coherent regions with increases and decreases.

[3] The present study reports on the outcomes of a workshop held in Pune, India (14–19 February 2005), which brought together a unique daily data set for the whole region of central and south Asia. The objective was to investigate the changes in some of the recently defined [*Peterson et al.*, 2001] indices of temperature and precipitation extremes. The workshop was coordinated by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI), which was jointly established by the WMO Commission for Climatology and the Research Programme on Climate Variability and Predictability (CLIVAR). It is the last in a series of regional workshops dedicated to climate extremes with the intention to fill in missing areas on the world map. The concept of this series

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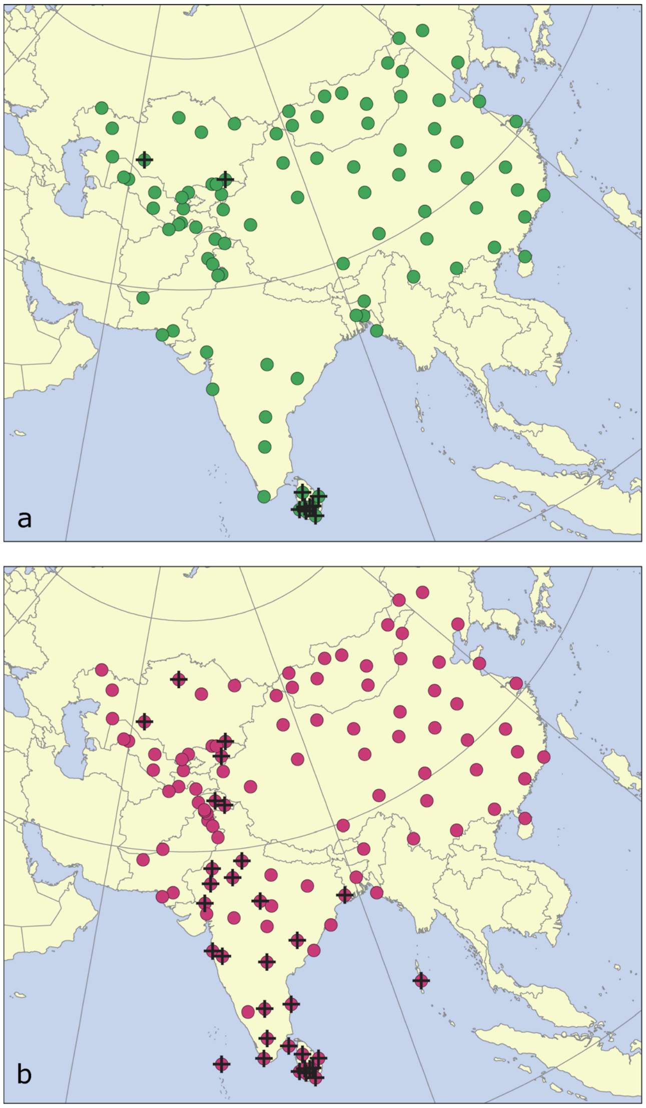

Figure 1. Stations used in this study for (a) temperature and (b) precipitation with data spanning the period 1961–2000 (dots) or 1901–2000 (dots with crosses).

of workshops is explained by *Peterson* [2005]. The workshops are modeled after the Asia Pacific Network workshops [*Manton et al.*, 2000]. Results for other regions of the world are reported by *New et al.* [2006], *Vincent et al.* [2005], *Haylock et al.* [2006], *Zhang et al.* [2005a], and *Aguilar et al.* [2005].

[4] In the present study, the changes in extremes over central and south Asia are analyzed for the period 1961–2000. They are placed in the long-term perspective of the period 1901–2000 as far as data availability allows. Only annually specified indices are considered; no separation was made to season or month.

2. Data

[5] Daily time series of temperature (minimum and maximum) and precipitation for a total of 159 stations from 13 countries were brought to the workshop. Of this data set, 94 (116) stations are selected for studying the changes in temperature (precipitation) extremes in the period 1961–2000 (Figure 1). For a subset of 9 (32) stations the changes for the longer period 1901–2000 are investigated (Figure 1). The selection criteria are based on a combination of tests for data length, completeness, quality, and homogeneity (see *Aguilar et al.* [2005] for details). Station series with more than 20% missing observations from 1961–2000 are excluded from the analysis as are years with less than 361 observation days. Station series with indications of discontinuities of nonclimatic origin in the period of analysis have been used only from after the time of the last discontinuity. For 23 of the 29 series with discontinuities the reason is unclear; for the other 6 series the inhomogeneities could be related to known dates of station relocations or changes in exposure, but adjustment was not attempted.

3. Method and Indices of Extremes

[6] Twelve indices of temperature and precipitation extremes have been selected from the list of indices for surface data recommended by the ETCCDMI [see *Peterson et al.*, 2001]. The selected indices (Table 1) are relevant to the climate in the region and refer to modest cold, warm and wet extremes with a return period of ≤1 year. This ensures

Table 1. Definitions of the Indices of Cold and Warm Temperature Extremes and the Indices of Wet Precipitation Extremes Used in This Study[a]

Index	Description	Definition
		Temperature Extremes
TN10, days TX10, days	cold nights cold days	Number of days in a year with temperature below a site- and calendar day–specific threshold value, calculated as the calendar day 10th percentile of the daily temperature distribution in the 1961–1990 baseline period.
TN90, days TX90, days	warm nights warm days	Number of days in a year with temperature above a site- and calendar day–specific threshold value, calculated as the calendar day 90th percentile of the daily temperature distribution in the 1961–1990 baseline period.
TNn, °C TXx, °C	coldest night warmest day	The temperature extremes, i.e., lowest minimum temperature and highest maximum temperature, in a year.
		Precipitation Extremes
RX1day, mm RX5day, mm	highest 1 and 5 day precip. am.	Annual maximum precipitation sums for 1 day intervals and 5 day intervals.
R10mm, days R20mm, days	heavy and very heavy precipitation days	Number of days per year with precipitation amount ≥10 mm and ≥20 mm.
R95, mm R99, mm	precip. on very and extremely wet days	Precipitation amount per year above a site-specific threshold value for very and extremely wet days, calculated as the 95th and 99th percentile of the distribution of daily precipitation amounts on days with 1 mm or more precipitation in the 1961–1990 baseline period.

[a]After *Peterson et al.* [2001].

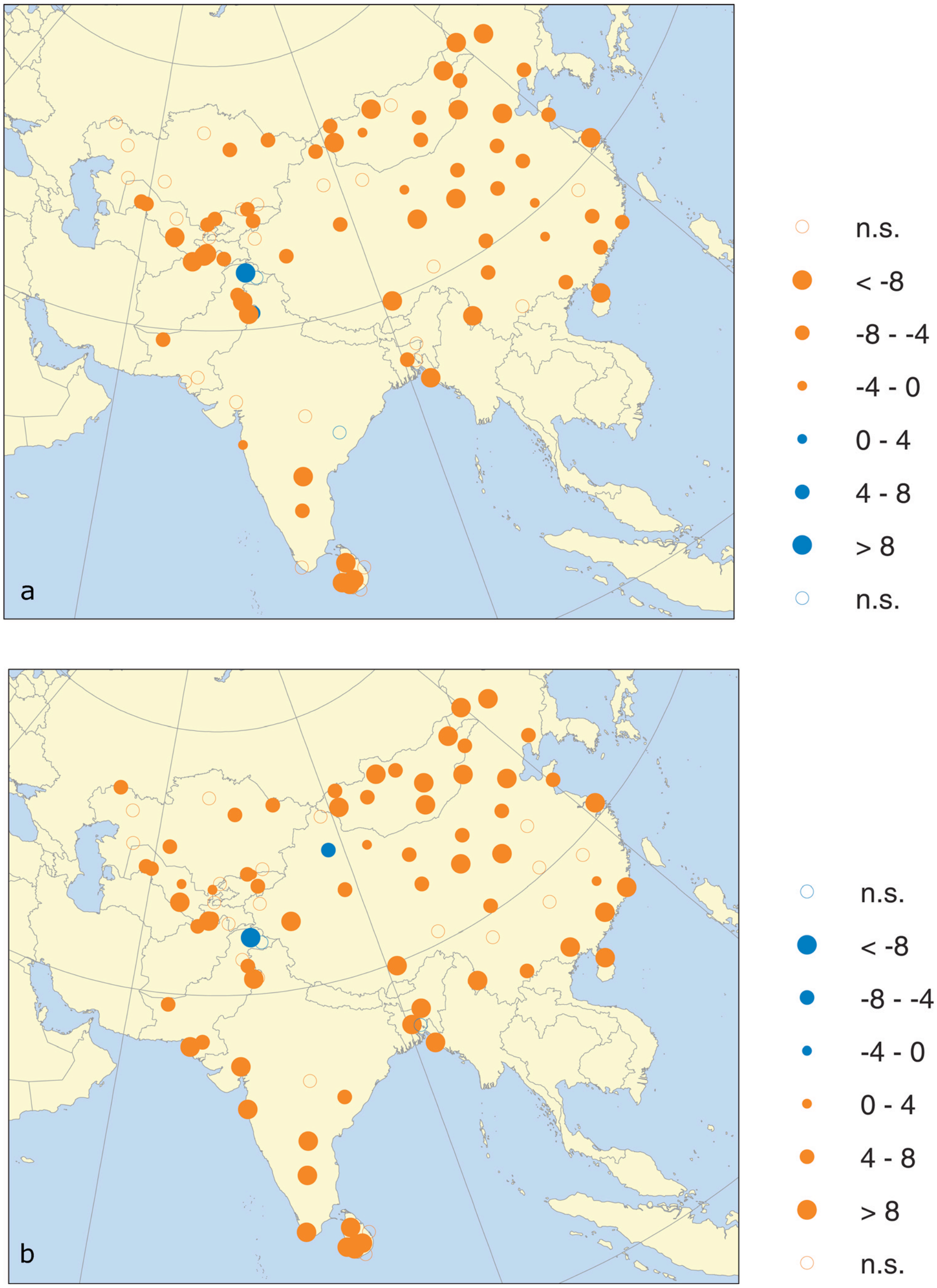

Figure 2. Trends per decade for (a) cold nights TN10 and (b) warm nights TN90 for the period 1961–2000. The dots are scaled according to the magnitude of the trend. Color coding is applied: red corresponds to warming trends and blue to cooling trends.

that the number of events is sufficiently large to allow for meaningful trend analysis in series of duration of 40–100 years. The indices are calculated using the RClimDex software package developed at the Meteorological Service of Canada (available from http://cccma.seos.uvic.ca/ETCCDMI/index.shtml). The period 1961–1990 was chosen as the base period for the indices that represent counts of days crossing climatological percentile thresholds at a station. The bootstrap procedure of *Zhang et al.* [2005b] 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. For temperature, the percentiles are calculated from 5 day windows centered on each calendar day. Calendar day–specific thresholds account for the mean annual temperature cycle. For precipitation, the percentiles are calculated directly from the sample of all wet days in the 30 yr series (1961–1990).

[7] Trends in the indices of temperature and precipitation extremes are calculated by ordinary least squares fits. Trend significance is tested using a student's *t* test. Apart from the trends for individual stations, trends are also calculated for the region as a whole. The regional temperature (precipitation) trends are obtained from regional average indices

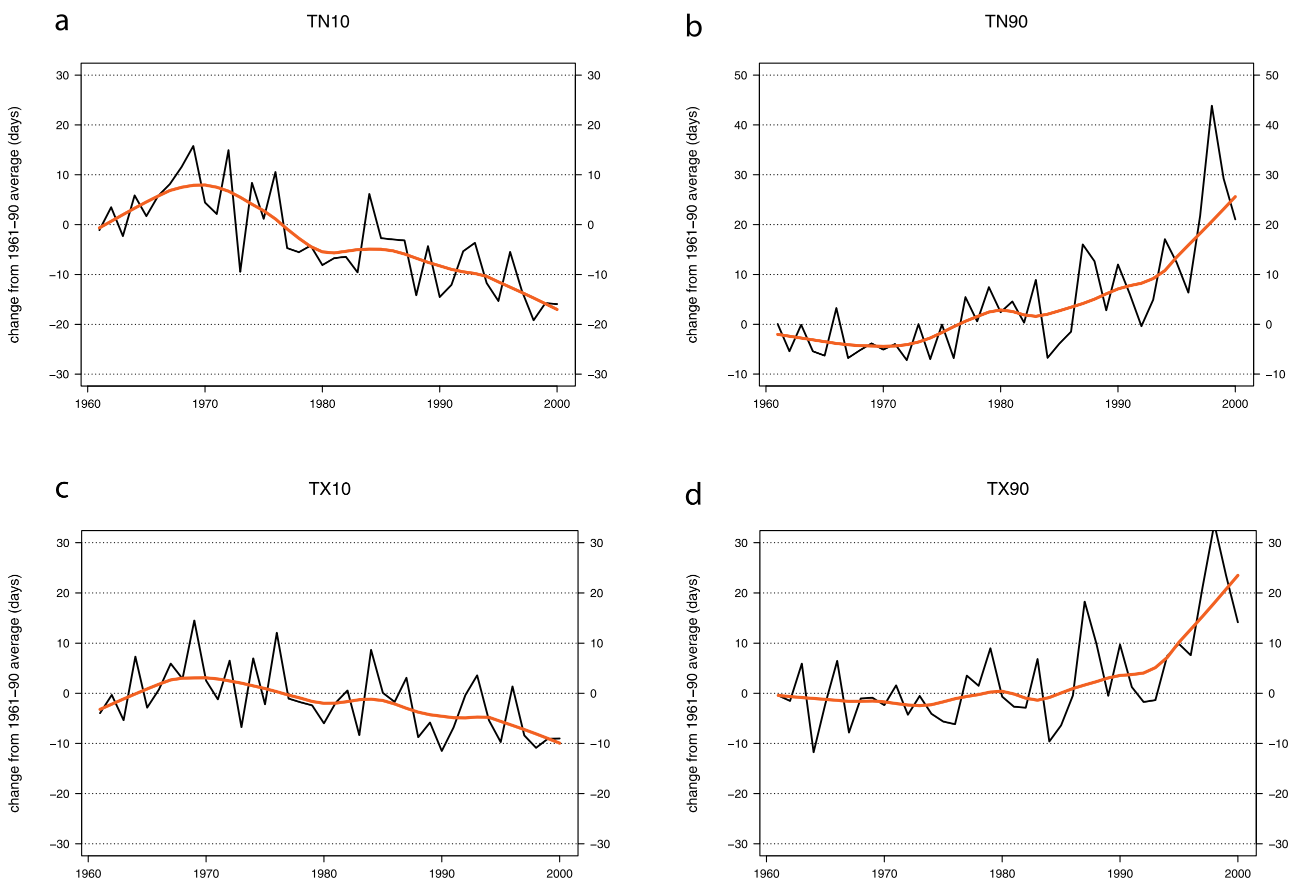

Figure 3. Regional series for the indices of (a) cold nights TN10, (b) warm nights TN90, (c) cold days TX10, and (d) warm days TX90. The red line is based on the lowess smoother [*Cleveland*, 1979].

series calculated as the arithmetic average of the annual indices values at all 94 (116) stations for 1961–2000 or 9 (32) stations for 1901–2000. When calculating the regional trends, years in the regional average indices series for which less than 75% of the stations had valid values were omitted.

[8] We compare the trends in the cold temperature extremes with the trends in the warm temperature extremes to investigate whether the observed warming in the region [*Jones and Moberg*, 2003] is accompanied by warming of both tails of the temperature distribution. The trends in the wet extremes are compared with the trends in the total amounts to see whether precipitation has become more intense in recent years.

4. Observed Changes

4.1. Period 1961–2000

[9] The 1961–2000 trends for the annual number of cold nights (TN10) and warm nights (TN90) are shown in Figure 2. About 70% of the stations have statistically significant (5% level) decreases in TN10 and increases in TN90, reflecting the general warming in the region. For the same nighttime indices, the time series of regional averages are presented in Figures 3a and 3b. The plots show that these nighttime extremes change considerably with time in the region. The trend results are given in Table 2. As expected when a Gaussian shaped temperature distribution shifts toward higher temperatures [see *Klein Tank and Können*, 2003], the trend in the count index for the warm tail TN90 (6.86 days/decade) is larger than the opposite trend in the count index for the cold tail TN10 (−5.70 days/decade).

[10] The daytime trends TX10 and TX90 (Figures 3c and 3d) have the same sign as their nighttime counterparts TN10

Table 2. Trends per Decade (With 95% Confidence Intervals in Parentheses) for the Regional Indices of Temperature and Precipitation Extremes[a]

Index	Units per Decade	1961–2000	1901–2000[b]
TN10	days	**−5.70** (−7.38 to −4.02)	**−5.08** (−5.90 to −4.26)
TX10	days	**−2.60** (−4.14 to −1.06)	**−1.75** (−2.83 to −0.67)
TN90	days	**6.86** (4.74–8.98)	**4.31 (3.47–5.15)**
TX90	days	**4.72** (2.62–6.82)	2.55 (1.35–3.75)
TNn	°C	**0.73** (0.45–1.01)	0.22 (0.14–0.30)
TXx	°C	**0.17** (0.07–0.27)	**0.08** (0.04–0.12)
RX1day	mm	1.02 (−0.20–2.24)	0.46 (−0.18–1.10)
RX5day	mm	1.26 (−0.76–3.28)	0.97 (−0.21–2.15)
R10mm	days	0.11 (−0.23–0.45)	0.08 (−0.10–0.26)
R20mm	days	0.10 (−0.12–0.32)	0.08 (−0.04–0.20)
R95	mm	**6.46** (0.72–12.20)	2.85 (−0.59–6.29)
R99	mm	3.01 (−0.19–6.21)	0.43 (−1.75–2.61)
DTR	°C	**−0.12** (−0.16 to −0.08)	**−0.03** (−0.05 to −0.01)
RR	mm	6.87 (−8.41–22.15)	**7.81** (0.37–15.25)
R95/RR	%	**0.55** (0.11–0.99)	0.11 (−0.21–0.43)
R99/RR	%	0.28 (−0.08–0.64)	−0.01 (−0.25–0.23)

[a]Values for trends significant at the 5% level (*t* test) are set bold face. The bottom rows give the trends for the diurnal temperature range (DTR), total precipitation (RR), and the ratios R95/RR and R99/RR.

[b]Based on the subset of nine temperature or 32 precipitation stations (see Figure 1).

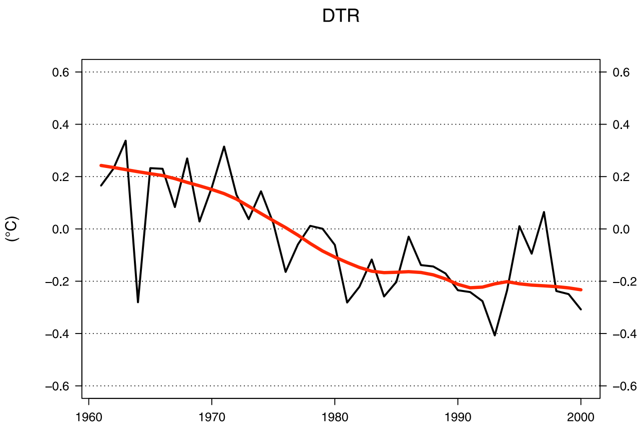

Figure 4. Regional series of the diurnal temperature range DTR. The red line is as in Figure 3.

and TN90, but are markedly smaller (−2.60 days/decade for TX10 and 4.72 days/decade for TX90). This smaller warming of daytime versus nighttime extremes is consistent with the observed decrease in diurnal temperature range (DTR) shown in Figure 4 (−0.12°C/decade). The other regional indices of lowest minimum and highest maximum temperature in the year (TNn and TXx) show trends that also correspond with the general warming (Table 2).

[11] In contrast to the temperature extremes, the significance of changes in precipitation extremes for 1961–2000 is low. No coherent trends are seen in any subregion. The map of station trends (Figure 5) illustrates this for the 5 day maximum precipitation amount (RX5day). The observed RX5day trends have mixed positive and negative sign in all of the region. Only 16% of the station trends are significant at the 5% level. The other indices of precipitation extremes show irregular station trend patterns as well. Consequently, no statistically significant trends in most of the regional indices of precipitation extremes are detected (Table 2). Only the increase in the amounts on very wet days (above the 95th percentile) in the region is significant at the 5% level (6.46%/decade). Further in the tail of the precipitation distribution, no significant increase could be detected for the amounts on extremely wet days (above the 99th percentile). Figures 6a and 6b present the regional series of the ratio between the precipitation amount on very and extremely wet days, respectively, and total precipitation. The contribution of very wet days (above the 95th percentile) to the total amounts varies between 19%–28% and increases slightly over time. The trend in this ratio is 0.55%/decade (significant at the 5% level (see Table 2)). The contribution of extremely wet days (above the 99th percentile) to the total amounts varies between 4%–10%, but here the trend (0.28%/decade) is not significant at the 5% level.

[12] For temperature as well as precipitation, the regional trends for 1961–2000 based on the subset of stations that is used for calculating the trends in the longer period are within 25% of the regional trends based on the whole data set in Table 2.

4.2. Period 1901–2000

[13] The results for the longer period of 1901–2000 are shown in Figure 7. Analysis suggests that the recent decrease in TN10 and increase in TN90 in the region (Figure 3) is part of a long-term trend in these indices of cold and warm nighttime extremes, which persists over the whole century. For TX10 and TX90 the situation is different, because the recent decrease in TX10 and increase in TX90 are part of longer-term variations with opposite trends in these indices of cold and warm daytime extremes in the first half of the century. Thus TX10 and TX90 are recovering from the levels observed early in the century. This

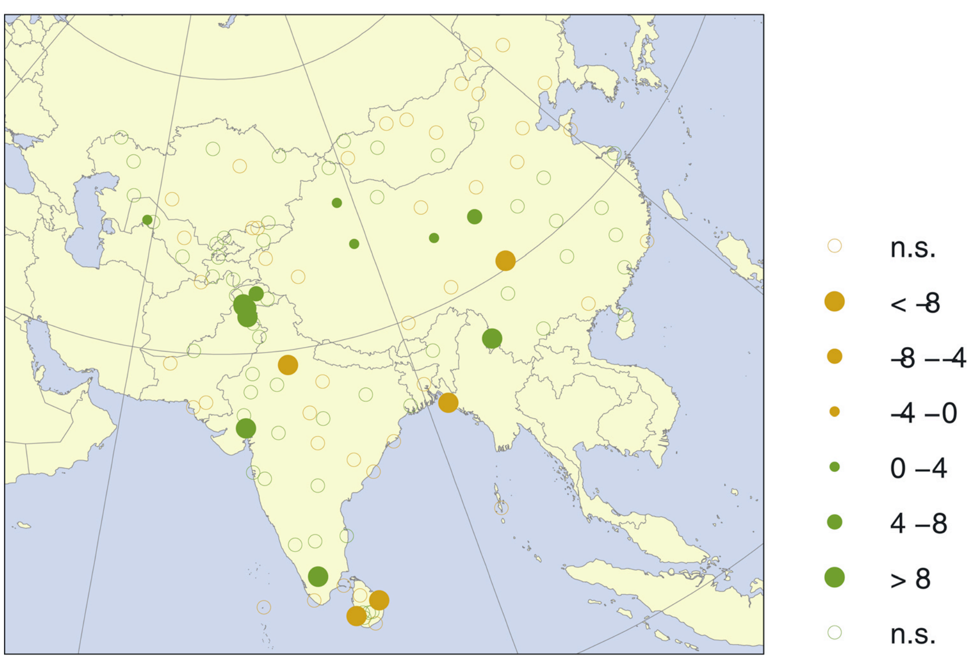

Figure 5. Trends per decade for the annual maximum of 5 day precipitation amounts RX5day for the period 1961–2000. The dots are scaled according to the magnitude of the trend. Color coding is applied: green corresponds to increasing trends and yellow corresponds to drying trends.

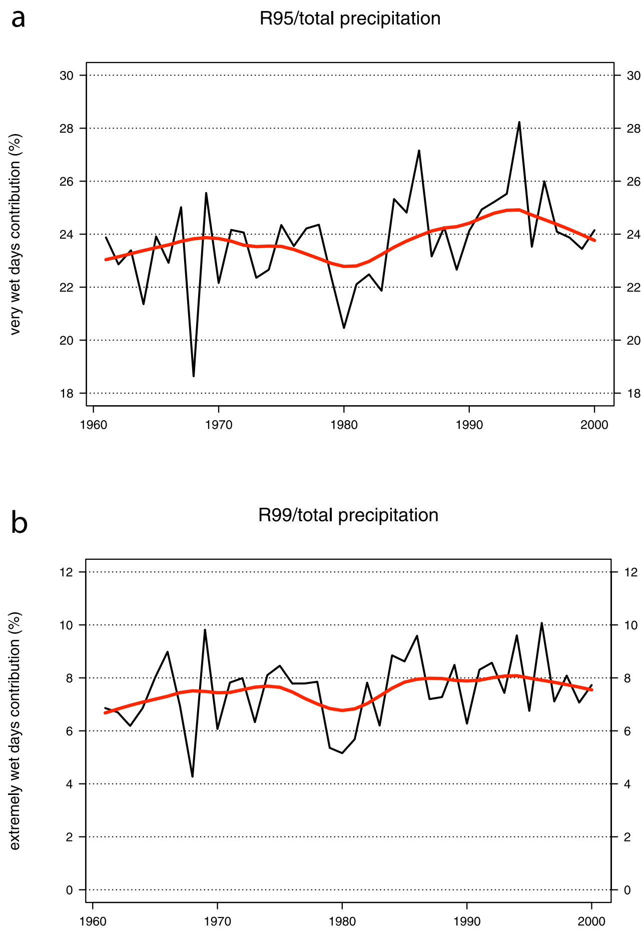

Figure 6. Regional series (a) for the ratio between the index of precipitation falling on very wet days (R95) and total precipitation and (b) for the ratio between the index of precipitation falling on extremely wet days (R99) and total precipitation. The red line is as in Figure 3.

behavior affects the linear trends over the whole century (Table 2). No significant trends in the indices of precipitation extremes are detected for the period 1901–2000 (Table 2). Only the increase in total precipitation RR (7.81 mm/decade) is significant at the 5% level.

5. Discussion

[14] Comparison of the 1961–2000 trends with the changes over the longer period 1901–2000 illustrates that linear trends need to be interpreted with care, as they may not be a good representation of the actual change in a variable. The observed trends may indeed be part of long-term trends, which is the case for TN10 and TN90. They may also be part of slow climate fluctuations, which is the case for TX10 and TX90. Further detailed analyses are necessary to provide the reason for the different long-term change of the minimum and maximum temperature extremes. This includes using more advanced statistical estimates of trends and their significance (e.g., applying the nonparametric Mann-Kendall rank test), which may change the magnitude of the trends presented in Table 2. However, a robustness test (not shown) in which the present results are compared with those obtained by discarding outliers near the ends of the indices series suggests that the conclusions will not change.

[15] In contrast to the temperature extremes, no robust signal of changes in precipitation extremes is observed either for the short or long period. The only index with a significant (5% level) positive trend for the short period is R95, the precipitation amount on very wet days. The ratio R95/total precipitation also increases significantly (5% level). Therefore relative to the changes in total amounts, there is a slight indication of disproportionately large changes in the extremes. Although the precipitation indices are calculated on an annual basis, they will be dominated by the precipitation in the wet season, particularly in the monsoon area. From an impact point of view, indices that represent the start and end of the wet season may be more appropriate in that area than the ones studied here.

[16] Changes in climate at the regional scale are largely the result of variability in large-scale atmospheric circulation patterns. This means that the observed trends can partly be understood by studying the correlation with accompanying changes in large-scale atmospheric circulation. For instance, *Archer and Fowler* [2004] identified a significant positive correlation between precipitation in the upper Indus basin and the North Atlantic Oscillation index. To what extent the trends of the present study are related with atmospheric circulation changes needs to be addressed in future studies.

[17] In any time series, changes in routine observing practices may have introduced inhomogeneities of non-climatic origin that severely affect the extremes. Even though each time series has been carefully scrutinized, the results for individual stations may be affected by inhomogeneities in the underlying series that were not detected. Therefore robust conclusions are only drawn from tendencies over large areas and regional average trends.

[18] Because of the irregular spatial distribution of stations over the region, areas with a higher density of stations are overrepresented in the regional indices. Therefore sophisticated area weighting methods, which were not applied in this study, might alter the results somewhat. On the basis of the experience in similar studies [e.g., *Klein Tank and Können*, 2003], we estimate that the trends in our regional indices series would agree within 10% with trends in area-weighed indices series. Global-scale analyses of these indices are presented by *Alexander et al.* [2006].

[19] No use is made of statistical extreme value theory to analyze the changes in extremes. Instead, simple indices are calculated that describe various characteristics of extremes, including frequency, amplitude and persistence. The indices are easy to understand but only represent a limited number of all possible statistical characteristics of extremes. Projecting the indices on more formal measures of extremes that are common in extreme value theory will likely provide additional insight into the possibilities for improved indices definitions. Such an activity has recently been started under the umbrella of the ETCCDMI [*Zwiers et al.*, 2003].

6. Conclusions

[20] With the help of standardized descriptive indices, a better understanding of observed changes in temperature and precipitation extremes is gained for central and south

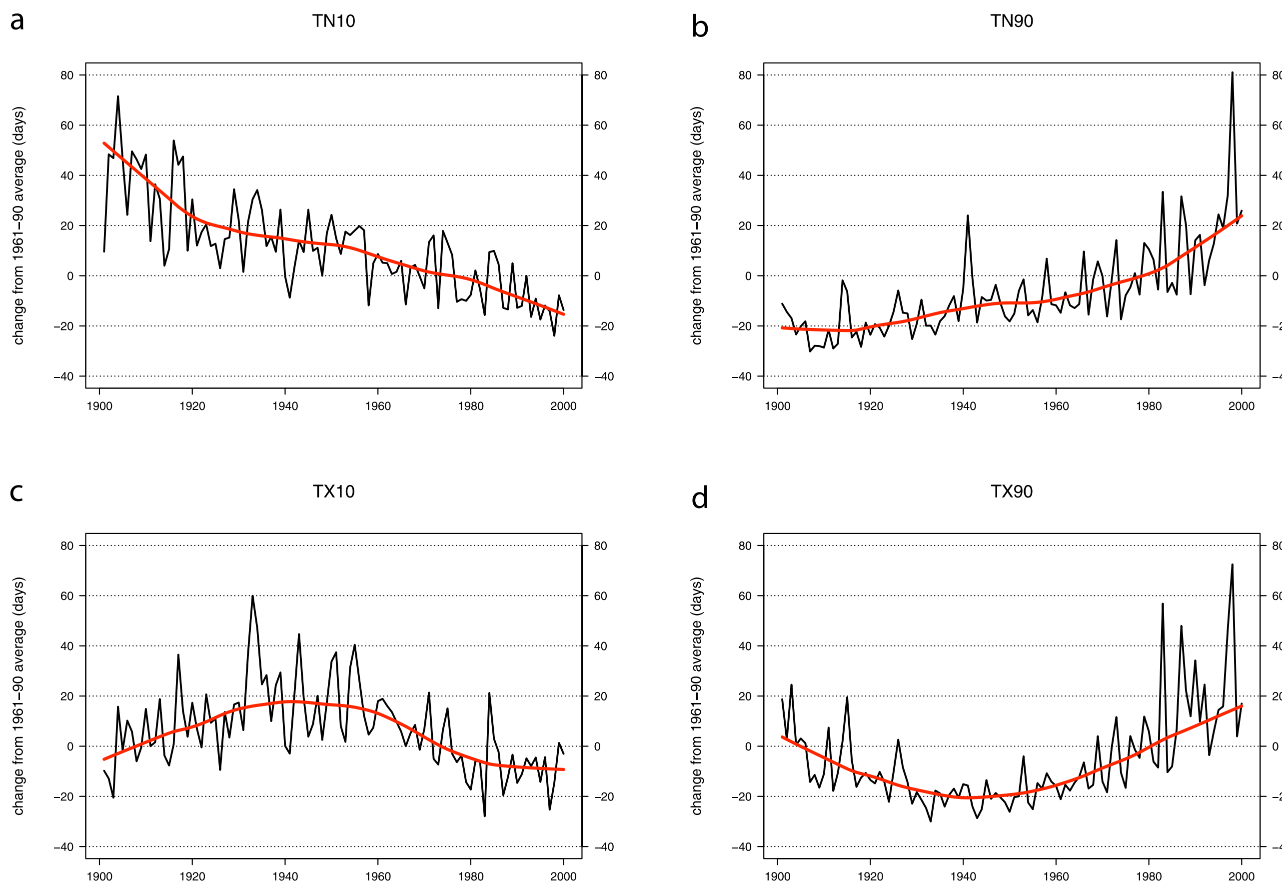

Figure 7. As in Figure 3, but now for the period 1901–2000 based on the subset of stations for which long data series are available (see Figure 1).

Asia. In addition to trends over 1961–2000, longer time series for a limited number of stations are used to place the 40 year changes in extremes in a longer-term perspective.

[21] At 70% of the stations, statistically significant increases in the percentage of warm nights/days and decreases in the percentage of cold nights/days are observed for the period 1961–2000. The maps of station trends for the temperature indices show spatially uniform patterns, even though the climate varies across the region. All temperature extremes show regional trends that agree with the average warming in the region. In line with the observed decrease in the DTR, the (daytime) trends in maximum temperature extremes are smaller than the (nighttime) trends in minimum temperature extremes.

[22] No consistent pattern of changes in precipitation extremes could be detected for the majority of precipitation indices. The only significant (5% level) regional trend in extreme precipitation indices is the increase in the amount on very wet days. Also, the increase in the contribution of very wet days to the total amounts between 1961 and 2000 is significant at the 5% level, implying disproportionate changes of the precipitation extremes.

[23] The small subset of stations with data for the longer period of 1901–2000 shows that the recent trends in extremes of minimum temperature are consistent with long-term trends. However, the recent trends in extremes of maximum temperature are opposite to the trends observed in the first half of the 20th century.

[24] The Pune workshop had a major capacity building aspect, which has helped foster a greater appreciation of the importance of long-term in situ daily data for analysis of climate variability and change. The workshops helped reach Global Climate Observing System (GCOS) goals for data preservation and exchange [*Global Climate Observing System*, 2003] (available at http://www.wmo.ch/web/gcos/Second_Adequacy_Report.pdf). The derived indices series are publicly available for 10 of the 13 countries (from http://cccma.seos.uvic.ca/ETCCCDMI), enabling other scientists to undertake a variety of climate studies hitherto impossible. Most importantly, the derived indices series feed into the global analysis of *Alexander et al.* [2006]. By using an internationally coordinated exact formula for each index, the present analyses for central and south Asia fit together seamlessly with analyses in the other regions where similar workshops have been held. As a result, the Intergovernmental Panel on Climate Change (IPCC) will now for the first time be able to assess changes in extremes for large regions of the world where indices results were previously unavailable [*Folland et al.*, 2001].

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