Trends in Indices of Daily Temperature and Precipitation Extremes in Europe, 1946–99

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ABSTRACT

Trends in indices of climate extremes are studied on the basis of daily series of temperature and precipitation observations from more than 100 meteorological stations in Europe. The period is 1946–99, a warming episode. Averaged over all stations, the indices of temperature extremes indicate ‘‘symmetric’’ warming of the cold and warm tails of the distributions of daily minimum and maximum temperature in this period. However, ‘‘asymmetry’’ is found for the trends if the period is split into two subperiods. For the 1946–75 subperiod, an episode of slight cooling, the annual number of warm extremes decreases, but the annual number of cold extremes does not increase. This implies a reduction in temperature variability. For the 1976–99 subperiod, an episode of pronounced warming, the annual number of warm extremes increases 2 times faster than expected from the corresponding decrease in the number of cold extremes. This implies an increase in temperature variability, which is mainly due to stagnation in the warming of the cold extremes.

For precipitation, all Europe-average indices of wet extremes increase in the 1946–99 period, although the spatial coherence of the trends is low. At stations where the annual amount increases, the index that represents the fraction of the annual amount due to very wet days gives a signal of disproportionate large changes in the extremes. At stations with a decreasing annual amount, there is no such amplified response of the extremes.

The indices of temperature and precipitation extremes in this study were selected from the list of climate change indices recommended by the World Meteorological Organization–Commission for Climatology (WMO–CCL) and the Research Programme on Climate Variability and Predictability (CLIVAR). The selected indices are expressions of events with return periods of 5–60 days. This means that the annual number of events is sufficiently large to allow for meaningful trend analysis in ~50 yr time series. Although the selected indices refer to events that may be called ‘‘soft’’ climate extremes, these indices have clear impact relevance.

1. Introduction

Surface air temperatures in most European regions have increased during the twentieth century (Houghton et al. 2001). In line with the characteristics of global temperature rise (Jones et al. 1999b; Karl et al. 2000), the European rate of change has been highest in the last quarter of the century (Klein Tank et al. 2002). The warming is projected to continue and is likely to be accompanied by changes in extreme weather and climate events (Houghton et al. 2001). Yet, little is known quantitatively about the nature of these changes. In this context, it is relevant to learn how the past warming affected the occurrence of temperature extremes, or whether the past warming was accompanied by detectable changes in precipitation extremes. Studies on these issues are receiving increased attention in the last few years (Easterling et al. 2000; Meehl et al. 2000).

Although changes in extreme temperature and precipitation events have been analyzed for individual European countries and stations (see, e.g., Forland et al. 1998; Tuomenvirta et al. 2000; Moberg et al. 2000; Brunetti et al. 2000; Osborn et al. 2000; Yan et al. 2002), a coherent picture for Europe as a whole is lacking. The main reason is the limited spatial coverage of the high time-resolution European datasets used in such studies. The second reason is that until recently no accepted standardization existed in the definitions of climate extremes, which has made it difficult to compare the results of different studies. This situation has changed now. The objective of the present study is to investigate the trends in some of the recently defined (Peterson et al. 2001) indices of temperature and precipitation extremes using the European Climate Assessment (ECA) daily dataset (Klein Tank et al. 2002).

The indices of temperature and precipitation extremes considered in the present study were selected

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from the list of indices for surface data recommended by the joint working group on climate change detection of the World Meteorological Organization–Commission for Climatology (WMO–CCL) and the Research Programme on Climate Variability and Predictability (CLIVAR; Peterson et al. 2001). The selected indices refer to extremes with return period typically on the order of weeks, rather than to once-in-a-lifetime events. This choice ensures that the annual number of extremes is sufficiently high to allow for meaningful trend analysis in series of ~50 yr length and therefore in the series of the ECA dataset.

About half of the indices considered in the present study are expressions of anomalies relative to local climatology in the standard-normal period 1961–90, enabling comparisons between stations in different countries and regions. Using this type of indices, we compared trends in Europe-average cold temperature extremes with trends in Europe-average warm temperature extremes to investigate whether they suggest equal warming in both tails of the temperature distributions. For precipitation, we compared trends in extreme precipitation with trends in total amount to investigate whether extremes contributed disproportionately to overall wetting or drying. Some preliminary results of our study have been included in Frich et al. (2002; see also Houghton et al. 2001), who provides trend estimates for temperature and precipitation extremes in about half the global land areas.

Section 2 describes the criteria for station selection from the daily ECA dataset and section 3 the selection of indices from the Peterson et al. (2001) list. The procedures for estimating trend values for Europe-average indices, comparing cold to warm extremes, and comparing precipitation extremes to total amount are outlined in section 4. Section 5 presents the observed trends for temperature and precipitation. In section 6 the results are discussed. Section 7 summarizes the conclusions.

2. Analysis period and data selection

The ECA dataset (Klein Tank et al. 2002) comprises the period 1901–99, but the data coverage of Europe in the first part of the century is not adequate for our purpose. This restricts the period of analysis to 1946–99 (and its subperiods 1946–75 and 1976–99), for which 195 daily temperature series and 202 daily precipitation series are available in ECA (status February 2003). Not all of these ECA series were used in the present study. First, the time series that received the lowest ranking in our homogeneity test (Wijngaard et al. 2003) were excluded from the analysis, except for some series that were retained based on the metadata support and recommendations provided by the participants in the ECA project. Second, series with more than 20% missing or incomplete years in the analysis period or one of its subperiods were excluded from the analyses. The criterion applied for incompleteness is less than 361 observation days per year. Such a strict criterion is needed because some indices are critically dependent on the serial completeness of the data.

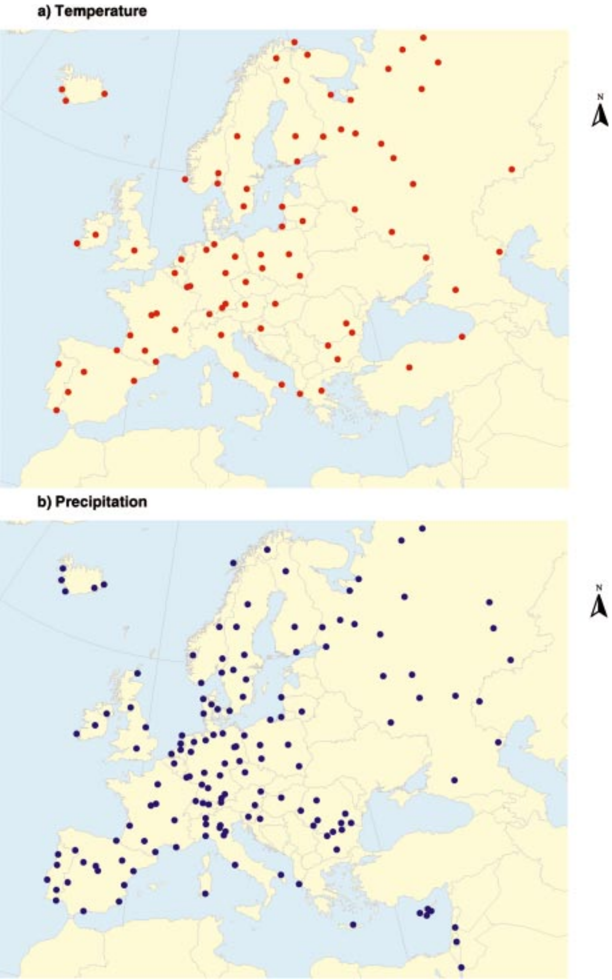


FIG. 1. ECA stations with daily time series of (a) temperature and (b) precipitation used in this study.

A total of 86 daily temperature series and 151 daily precipitation series from the ECA dataset survived all selection criteria. Only these station series (Fig. 1) were used in the present study to calculate the indices.

Apart from trends for each individual ECA station, trends were also calculated for Europe as a whole. The European trends were obtained from Europe-average indices series calculated as the arithmetic average of the annual indices values at all 86 temperature stations or 151 precipitation stations. Annual values in the Europe-average indices series based on less than 75% of the stations were omitted when calculating the European trends.

Because of the nonuniform spatial distribution of ECA stations over Europe, areas with a higher density of stations are overrepresented in the Europe average.

Proper area weighing methods would include gridding of time series. Such methods are not applied in this study. Based on the comparison for mean temperature in Klein Tank et al. (2002), we estimate that the trends in our Europe-average indices series would agree within 10% with trends in area-weighed indices series.

3. Indices of climate extremes

From the internationally agreed WMO–CCL/CLIVAR list of over 50 climate change indices available online at http://www.knmi.nl/samenw/eca (Peterson et al. 2001; see also Folland et al. 1999; Nicholls and Murray 1999; Jones et al. 1999a), we selected a set of 13 indices of climate extremes. Of this set, six indices refer to temperature and seven to precipitation (Table 1). Although the definitions allow for seasonal or monthly breakdown, subannual specification is not considered here. The indices selected in the present study are expressed in annual values Y_j, $j = 1, \ldots, N$ with the index j referring to the year and N the length of the period covered by the station series. The temperature indices describe cold extremes as well as warm extremes. The precipitation indices describe wet extremes only. Most of the indices are defined in terms of counts of days crossing thresholds, either absolute (fixed) thresholds or percentile (variable) thresholds. These day-count indices refer to annual numbers of exceedences X_j, $j = 1, \ldots, N$.

Annual day-count indices based on percentile thresholds are expressions of anomalies relative to the local climate. Consequently, the value of the thresholds is site specific. Such indices allow for spatial comparisons, because they sample the same part of the temperature and precipitation (probability density) distributions at each station. Annual day-count indices based on absolute thresholds are less suitable for spatial comparisons of extremes than those based on percentile thresholds. The reason is that, over an area as large as the European continent, annual day-count indices based on absolute thresholds may sample very different parts of the temperature and precipitation distributions. This implies that in another climate regime, the variability in such indices readily stems from another season. For instance, year-to-year variability in frost-day counts (days with minimum temperature $< 0°C$) relates to the variability in the spring and autumn temperatures for the northern part of Europe, whereas in the southern part of Europe annual variability in frost-day counts is determined by winter temperature variability (Heino et al. 1999). Likewise, the threshold of 25°C in the definition of summer days (days with maximum temperature $> 25°C$) samples variations in summer temperatures in the north and variations in spring and autumn temperatures in the south.

In the present study, the values of the percentile thresholds were determined empirically from the observed station series in the climatological standard-normal period 1961–90. This was done as follows. For precipitation, the percentiles were calculated straightforward from the sample of all wet days in the series. For temperature, the percentiles were calculated from 5-day windows centered on each calendar day to account for the mean annual cycle. This yields a total sample size of 30 yr $\times$ 5 days $=$ 150 for each calendar day. The procedure ensures that extreme temperature events, in terms of crossings of percentile thresholds, can occur with equal probability throughout the year. The same property holds for extreme precipitation events, because it was verified that the seasonal dependency in the chosen precipitation percentiles (Table 1) and in the occurrence of wet days can be neglected.

Percentile thresholds were also used by Jones et al. (1999a) and Horton et al. (2001) for determining the frequencies of temperature extremes. Contrary to our approach, their method accounts parametrically rather than empirically for the annual cycle of thresholds. As argued by Yan et al. (2002), the effect on the indices in Table 1 of using either empirical methods for percentile calculations or parametric methods relying on distributions is small.

The index R95%tot, that is, the fraction of annual precipitation amount due to very wet days, has been introduced in our study to explore the supposed amplified response of the extreme precipitation events relative to the change in total amount (Groisman et al. 1999; see also Houghton et al. 2001). Indices like R95%tot are suitable to analyze such changes in the tail of the precipitation distribution, as they implicitly take into account the trends in the total amount. Similar to the indices used by Osborn et al. (2000), but unlike many other indices of precipitation extremes (Haylock and Nicholls 2000), the R95%tot index is not sensitive to changes in the number of wet days.

Table 2 lists the climatological values of the 13 temperature and precipitation indices over the baseline period 1961–90 for five station series from different areas of Europe and for the Europe-average series. For the day-count indices, the corresponding mean return period T_{ret} is given by

$$T_{\text{ret}} = 365/\overline{X} \tag{1}$$

if T_{ret} is expressed in days and the climatological value $\overline{X}$ of X_j in number of days per year. Table 2 shows that the 13 indices highlight extremes with T_{ret} roughly between 5 and 60 days. For the temperature indices based on the 10th- and 90th-percentile thresholds, a constant mean return period of 10 days is found throughout the table, as a direct consequence of the definitions. On the other hand, the values of the precipitation indices that are based on the 75th- and 95th-percentile thresholds are not constant in the table. The reason is that for precipitation the percentile thresholds were determined from the distribution of the daily precipitation amounts at wet days only, rather than all days. Accordingly, the mean return periods of R75% and R95% are 4 and 20

TABLE 1. Definitions of the indices of cold and warm temperature extremes and the indices of precipitation extremes used in this study. The abbreviations and definitions follow the standardization of the CCL/CLIVAR Working Group on Climate Change Detection (Peterson et al. 2001). See also online at http://www.knmi.nl/samenw/eca. In the present study only annually specified indices are considered; no separations are made to season or month.

Extreme indices		
	Indices of cold temperature extremes	
FD	Frost days (absolute threshold)	Number of days (per year/season/month) with minimum temperature below 0°C. Let $TN_{i,j}$ be the daily min temperature at day *i* in period *j*. Then counted are the days with $TN_{i,j} < 0°C$.
TN10%	Cold nights (percentile threshold)	Number of days (per year/season/month) 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 1961–90 baseline period.
TX10%	Cold days (percentile threshold)	TN10% refers to low daily min temperature events (cold nights) and TX10% to low daily max temperature events (cold days). Let $TN_{i,j}$ be the daily min temperature at day *i* in period *j* and let $TN_{i,k}10$ be the 10th percentile for calendar day *k* calculated for a 5-day window centered on each calendar day in the 1961–90 period. Then counted are the days with $TN_{i,j} < TN_{i,k}10$. The cold days are calculated analogously from the daily max temperatures.
	Indices of warm temperature extremes	
SU	Summer days (absolute threshold)	Number of days (per year/season/month) with max temperature above 25°C. Let $TX_{i,j}$ be the daily max temperature at day *i* in period *j*. Then counted are the days with $TX_{i,j} > 25°C$.
TN90%	Warm nights (percentile threshold)	Number of days (per year/season/month) 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 1961–90 baseline period.
TX90%	Warm days (percentile threshold)	TN90% refers to high daily min temperature events (warm nights) and TX90% to high daily max temperature events (warm days). Let $TN_{i,j}$ be the daily min temperature at day *i* of period *j* and let $TN_{i,k}90$ be the 90th percentile for calendar day *k* calculated for a 5-day window centered on each calendar day in the 1961–90 period. Then counted are the days with $TN_{i,j} > TN_{i,k}90$. The warm days are calculated analogously from the daily max temperatures.
	Indices of precipitation extremes	
RX1day	Highest 1-day precipitation amount (absolute extreme)	Maximum (annual/seasonal/monthly) precipitation sums for 1-day intervals (RX1day) and 5-day intervals (RX5day).
RX5day	Highest 5-day precipitation amount (absolute extreme)	Let $R_{i,j}$ be the daily precipitation amount for day *i* in period *j*. Then maximum 1-day values for period j are $\mathrm{RX1day}_j = \max(R_{i,j})$. Let $R_{i,j}5$ be the precipitation amount for the consecutive 5-day interval *i*, *i*-1, *i*-2, *i*-3, *i*-4 in period j. Then maximum 5-day values for period *j* are $\mathrm{RX5day}_j = \max(R_{i,j}5)$.
R10mm	Heavy precipitation days (absolute threshold)	Number of days (per year/season/month) with precipitation amount ≥10 mm (R10mm) and ≥20 mm (R20mm).
R20mm	Very heavy precipitation days (absolute threshold)	Let $R_{i,j}$ be the daily precipitation amount for day *i* in period *j*. Then counted are the days with $R_{i,j} \geq 10$ mm or $R_{i,j} \geq 20$ mm.
R75%	Moderate wet days (percentile threshold)	Number of days (per year/season/month) with precipitation amount above a site-specific threshold value for moderate and very wet days, calculated as the 75th (R75%) and 95th (R95%) percentile of the distribution of daily precipitation amounts at days with 1 mm or more precipitation in the 1961–90 baseline period.
R95%	Very wet days (percentile threshold)	Let $R_{w,j}$ be the daily precipitation amount at wet days *w* (precipitation ≥1 mm) in period *j* and let $R_{w,n}75$ be the 75th percentile of precipitation at wet days in the 1961–90 baseline period. Then counted are the moderate wet days with $R_{w,j} > R_{w,n}75$. The very wet days are calculated likewise.
R95%tot	Precipitation fraction due to very wet days (percentile threshold)	Fraction of (annual/seasonal/monthly) precipitation amount due to very wet days (R95% days). Let R_j be the sum of daily precipitation amount for period *j* and let $R_{w,j}$ be the daily precipitation amount at wet day *w* (precipitation ≥1 mm) in period *j* and $R_{w,n}95$ the 95th percentile of precipitation at wet days in the 1961–90 baseline period. Then $\mathrm{R95\%tot}_j$ is determined as the sum of $R_{w,j}$ at days with $R_{w,j} > R_{w,n}95$ divided by R_j.

TABLE 2. Mean indices values over the 1961–90 baseline period for five stations from different areas of Europe and for the Europe-average series. For the day-count indices, the corresponding mean return period (in days) is also given. RX1day and RX5day are in mm and R95%tot is in % of total annual precipitation. The bottom rows give the averages of mean temperature, diurnal temperature range, annual precipitation amount, and annual number of wet days.

	Reykjavik (Iceland)	Elatma (Russia)	De Bilt (Netherlands)	Salamanca (Spain)	Larissa (Greece)	Europe average
Indices of temperature extremes*						
FD	123 (3)	162 (2)	66 (6)	71 (5)	42 (9)	67 (5)
TN10%	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)
TX10%	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)
SU	0 (—)	39 (12)	18 (30)	91 (4)	143 (3)	64 (6)
TN90%	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)
TX90%	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)	36 (10)
Indices of precipitation extremes*						
R10mm	19 (20)	14 (28)	22 (19)	10 (40)	11 (35)	21 (18)
R20mm	3 (171)	3 (177)	5 (102)	2 (218)	3 (141)	7 (55)
R75%	37 (10)	27 (14)	33 (12)	17 (23)	14 (28)	26 (14)
R95%	7 (56)	6 (83)	7 (66)	3 (134)	3 (176)	5 (71)
RX1day	31 mm	35 mm	33 mm	30 mm	53 mm	44 mm
RX5day	59 mm	57 mm	64 mm	52 mm	74 mm	77 mm
R95%tot	18%	20%	18%	20%	24%	20%
Annual mean temperature	4.4°C	4.3°C	9.4°C	11.7°C	15.7°C	7.6°C
Diurnal temperature range	5.1°C	8.5°C	8.0°C	12.4°C	12.7°C	7.7°C
Annual precipitation amount	799 mm	613 mm	820 mm	391 mm	419 mm	741 mm
Annual number of wet days	148	110	134	69	57	103

* The indices defined in terms of counts of days crossing thresholds are expressed in annual number of days.

wet days, respectively. But since the number of wet days is always lower than 365 and is station dependent, mean return periods of 4 and 20 wet days translate into higher and station-dependent mean return periods if expressed in all (wet + dry) days.

The climatological values in Table 2 are valid for the standard-normal period 1961–90. Another baseline period would have resulted in different numbers for all indices, except for the temperature indices that are based on percentile thresholds. However, the trends in all indices are to a first approximation unaffected by the choice of the baseline period. This was verified by comparing the trend results obtained from the 1931–60 period with the results obtained from the 1961–90 period.

4. Trend estimation and evaluation

Trends in an index of temperature and precipitation extremes Y_j were calculated by a simple least squares fit of the model:

$$Y_j = a + 0.1bj + e_j \qquad j = 1, \ldots, N, \tag{2}$$

where Y_j is the value of the index at year j and e_j is a disturbance term (residual) with mean zero. The regression coefficient b gives the change per decade. Trend significance was tested using a Student's t test. As recommended by Nicholls (2001), not only the test results at the 5% significance level are presented but also the results at the 25% level. For the European trends, 95% confidence intervals were also calculated. The trend calculations were performed for two consecutive subperiods (1946–75 and 1976–99) as well as for the entire 54-yr period 1946–99. It should be noted that the simple weighted average of the trends for the two subperiods is not necessarily the same as the trend for the entire period. The reason is that the trend for the entire period is also affected by the average values of the indices in the two subperiods.

The probability of detecting trends in time series depends on the trend magnitude, the record length, and the statistical properties of the variable of interest—in particular, the variance. For uninterrupted event-count records X_j with independence between successive events, and with the use of Eq. (1), a simple expression can be derived for the signal-to-noise ratio (appendix):

$$C \equiv \frac{b}{\sigma_{\hat{b}}} \approx \frac{1}{10\sqrt{12}} \frac{b}{\overline{X}} \left(\frac{T_{\mathrm{ret}}}{365}\right)^{-1/2} N^{3/2}. \tag{3}$$

Here the factor 10 arises because we choose to express $1/\overline{X}$ and the series length N in years, but b in an increase per decade [Eq. (2)]; the factor 365 is because T_{ret} is in days [Eq. (1)].

The relative trend $b_q/\overline{X}$ that can be detected at a given significance level (e.g., 5%) with a probability of q%, follows from

$$\frac{b_q}{\overline{X}} = C_q \frac{\sigma_{\hat{b}}}{\overline{X}} \approx 10\sqrt{12}C_q \left(\frac{T_{\mathrm{ret}}}{365}\right)^{1/2} N^{-3/2} \tag{4}$$

with C_q the value of C that is required to find a significant trend in q% of the cases for the given level (Buis-

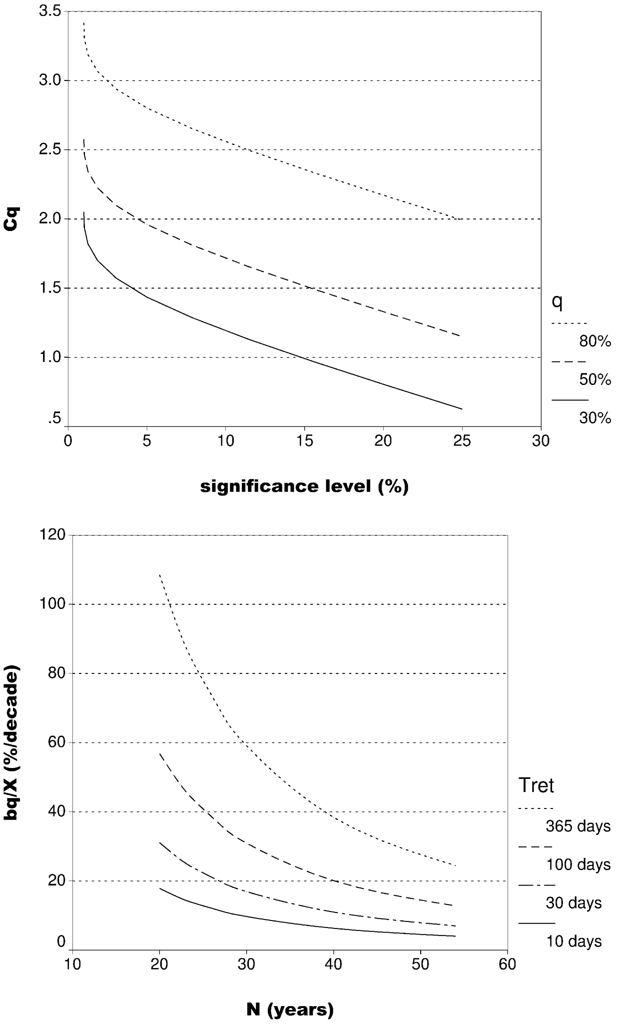


FIG. 2. (a) Dependence of signal-to-noise ratio C_q on the significance level for detection probability 30%, 50%, and 80%. (b) Relation between the relative trend $b_q/\overline{X}$ required for 80% detection probability (significance level 5%) and series length N, for extreme events with average return period T_{ret} = 10, 30, 100, and 365 days, according to Eq. (4). Here, $\overline{X}$ is the climatological value in a baseline period. As independence between successive extremes is assumed, the required trends represent lower estimates.

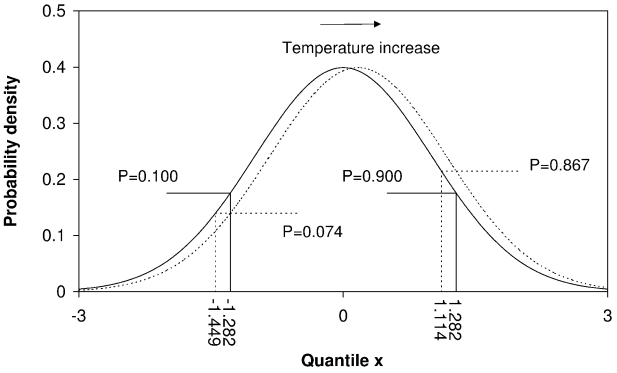


FIG. 3. Effect of a change only in the mean and not in the variance of a Gaussian temperature distribution for the percentile-based temperature indices. The percentile-based indices TN10%, TX10%, TN90%, and TX90% have a value of 36 in a period with unchanging climate. Given the cumulative distribution function $P(x)$ of a Gaussian distribution (with mean 0 and standard deviation 1), a negative 1976–99 trend per decade in TN10% (or TX10%) of, for instance, 4 implies a decrease in probability from $P(x) = 0.100$ in 1976 at the beginning of this 24-yr period to $P(x) = 0.100 - (2.4 \times 2/365) = 0.074$ in 1999 at the end of the period. Inverting $P(x)$ gives that x changes from -1.282 [because $P(x \leq 1.282) = 0.100$] to -1.449 [because $P(x \leq -1.449) = 0.074$]. Assuming a change only in the mean and not in the variance or skewness, the entire distribution must be shifted by $-1.449 - -1.282 = -0.167$. The expected corresponding location change of x for TN90% (or TX90%) is then from $x = 1.282$ [because $P(x \leq -1.282) = 0.900$] to $x = 1.282 - 0.167 = 1.114$. In terms of probability, this gives a change from $P(x) = 0.900$ to $P(x \leq 1.114) = 0.867$. Over the 24-yr period, the expected trend per decade in TN90% (or TX90%), which is denoted TN90%(expect) [or TX90%(expect)] in Table 3, is then $0.033 \times 365/2.4 = 4.95$.

hand et al. 1988). The dependence of C_q on the detection probability and significance level is shown in Fig. 2a.

Figure 2b shows $b_q/\overline{X}$ for $q = 80\%$ as a function of N for various return periods T_{ret} (significance level 5%). As $b_q/\overline{X}$ is proportional to $T_{\text{ret}}^{1/2}$, equal detection probability at the given significance level for events with a return period of 365 days instead of 10 days would require a trend that is 6 times larger. As the required trend value is proportional to $N^{-3/2}$, a 3 times larger trend is needed in a 24-yr record than in a 54-yr record to reach the same detection probability. Note that the trend values in Eq. (4) should be regarded as lower estimates, because of the presence of serial correlation in the event-count records. This leads to a higher standard deviation of the least squares trend estimate (fewer independent extreme events). The values from Eq. (4) and Fig. 2a correspond well with those in the simulation experiment of Frei and Schär (2001), provided that the relative trend in the entire series is less than 50%.

Taking the average over a number of station series S leads to improved trend detectability due to decreased variability in an average series. If there is no spatial correlation between the station series, Eq. (4) can be rewritten as

$$\frac{b_q}{\overline{X}} \approx 10\sqrt{12}C_q\left(\frac{T_{\text{ret}}}{365}\right)^{1/2} N^{-3/2}S^{-1/2}. \tag{5}$$

As the required trend value is proportional to $S^{-1/2}$, averaging over 86 (151) temperature (precipitation) series in Europe, as in the present study, would reduce the required trend value to reach the same detection probability by a factor of 9 (12). Note that for the temperature indices in particular, the actual reduction in the detectable trend is smaller than indicated by Eq. (5) because of spatial correlation.

In a second step of the analysis of temperature extremes, we investigated to what extent the trends in the percentile-based Europe-average temperature indices can be understood by a shift in the daily temperature distribution without a change in variance or skewness.

The procedure illustrated in Fig. 3 was followed. From the observed European trends in the cold extremes TN10% and TX10%, the expected values of the European trends in the corresponding warm extremes were calculated assuming a Gaussian distribution of the daily temperature anomalies. These expected trends, denoted TN90%(expect) and TX90%(expect), were then compared with the observed values for TN90% and TX90%. If the expected and observed trends agree, then the cold and warm tail changed in a ''symmetric'' way, whereas disagreement is indicative of ''asymmetric'' change resulting from a change in variance or skewness. The comparison is sound, since it was verified that the distribution of temperature anomalies is near Gaussian in the domains considered here ($<$30th and $>$70th percentile). If the comparison suggests asymmetry, it was investigated from which tail the effect mainly originates given the observed change in the median accompanying the observed trends in the cold and warm extremes.

In a second step of the analysis of precipitation extremes, we investigated to what extent the increase or decrease in the annual amount can be attributed to an increase or decrease in the number of very wet days R95% or the amount that falls at these days. The sign of the station trends for the annual amount were compared with the sign of the trends in the R95%tot index for the fraction of the annual amount due to very wet days. At stations where the annual amount increases, positive R95%tot trends are indicative of a disproportionate large contribution of the extremes to this wetting. On the other hand, at stations where the annual amount decreases, positive R95%tot trends indicate that the very wet days are less affected than the other wet days. Negative R95%tot trends indicate a smaller than proportional contribution of very wet days to wetting or drying.

5. Results

a. Trends in temperature extremes

Figure 4 shows that the 1946–99 trends in the indices frost days (FD) and summer days (SU) both indicate warming. For FD, the warming trend is significant at the 5% (25%) level for 39 (59) out of 86 stations; for SU, this is the case for 16 (42) stations. Cooling trends significant at the 5% (25%) level are not apparent (apparent for 6 stations) for FD, but for SU there are 4 (14) stations with significant cooling trends, concentrated in southeastern Europe. The trend per decade in the Europe-average annual number of frost days is -1.7; for summer days this trend is 0.8. Consequently, averaged over Europe, there are 9.2 fewer frost days and 4.3 more summer days in the year 1999 than in the year 1946.

The 1946–99 station trends in the annual number of cold nights TN10% and warm nights TN90% also indicate warming (Figs. 5a,b), as do the corresponding indices of maximum temperature: cold days TX10% and warm days TX90% (not shown). The spatial coherence in the trend patterns is higher for the two indices of cold extremes TN10% and TX10% than for the two indices of warm extremes TN90% and TX90%. Despite the dominating warming trend, local cooling trends are found for TN90%, particularly over Iceland and southeastern Europe. These cooling trends mainly emerge from the summer months (April–September) and are also apparent in TX10% and TX90% (not shown). The high 1976–99 warming trend over Europe (0.43°C decade^{-1} compared with 0.11°C decade^{-1} for the entire 1946–99 period) results in larger trends in the indices of temperature extremes for that subperiod, see Figs. 5c,d. The spatial coherence in the trend pattern of the number of warm nights TN90% is markedly enhanced, although the unspecified upper bound of the highest warming interval in the map overemphasizes the effect somewhat. In the 1976–99 period, no station saw a cooling trend in TN90%.

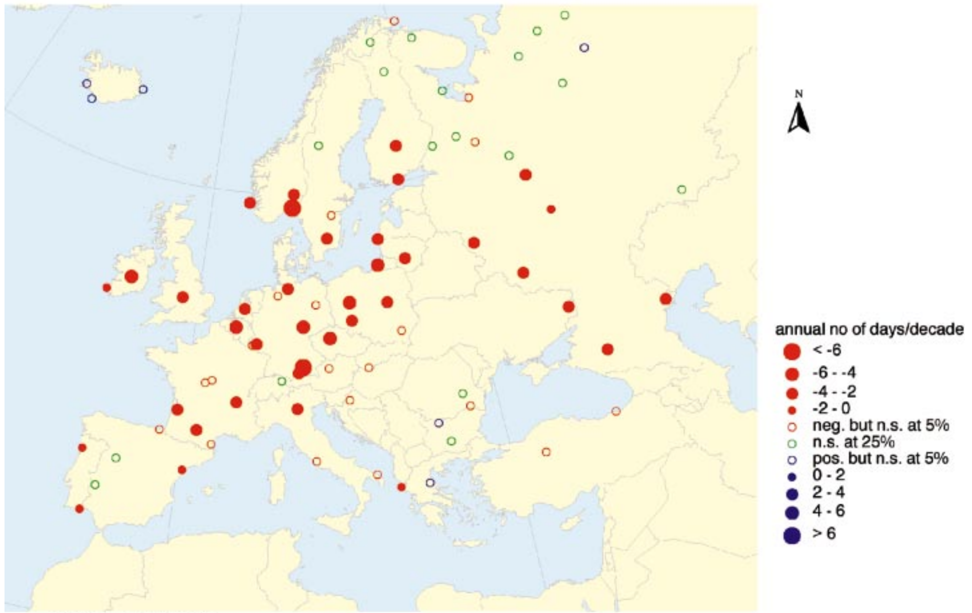
Table 3 gives the European trends in the four percentile-based indices of temperature extremes. For the full period 1946–99, all trends indicate warming, although the TX10% warming is not significant at the 5% level. For the subperiods, this significance level is harder to reach due to the shorter series [see Eq. (4)]. Nevertheless, the warming trends for the indices TN10%, TN90%, and TX90% are significant at the 5% level in the 1976–99 subperiod. The trend per decade for TN90% of 11.3 implies almost a doubling of the annual number of warm nights from the climatological value 36 in 1976 (see Table 2) to 63 in 1999. This translates into a change in return period from 10 to 6 days. For the 1946–75 subperiod of average cooling (by 0.03°C decade^{-1}; not significant at the 5% level), the trends in the warm extremes also indicate cooling. On the other hand, the number of cold extremes decreases, which is indicative of warming. This decrease is only significant at the 25% level and not at the 5% level.

For the 1946–99 warming period, Table 3 shows larger warming trends in the nighttime indices TN10% and TN90% than in the daytime indices TX10% and TX90%, which is in agreement with the observed negative trend in the mean diurnal temperature range (-0.04°C decade^{-1}). For the 1976–99 subperiod of pronounced warming, the almost equal warming trends in the nighttime indices and daytime indices suggest that there is no negative trend in the mean diurnal temperature range. The observed trend in the mean diurnal temperature range is indeed positive (0.03°C decade^{-1}), although not significant at the 5% level.

b. Comparison of trends in cold and warm extremes

The last column of Table 3 includes the expected European trends in the warm extremes TN90%(expect) and TX90%(expect) as calculated from the observed trends in the cold extremes TN10% and TX10% according to the scheme of Fig. 3. For the 1946–99 period, these expected warming trends compare well with the observed

a) FD, 1946-1999



b) SU, 1946-1999

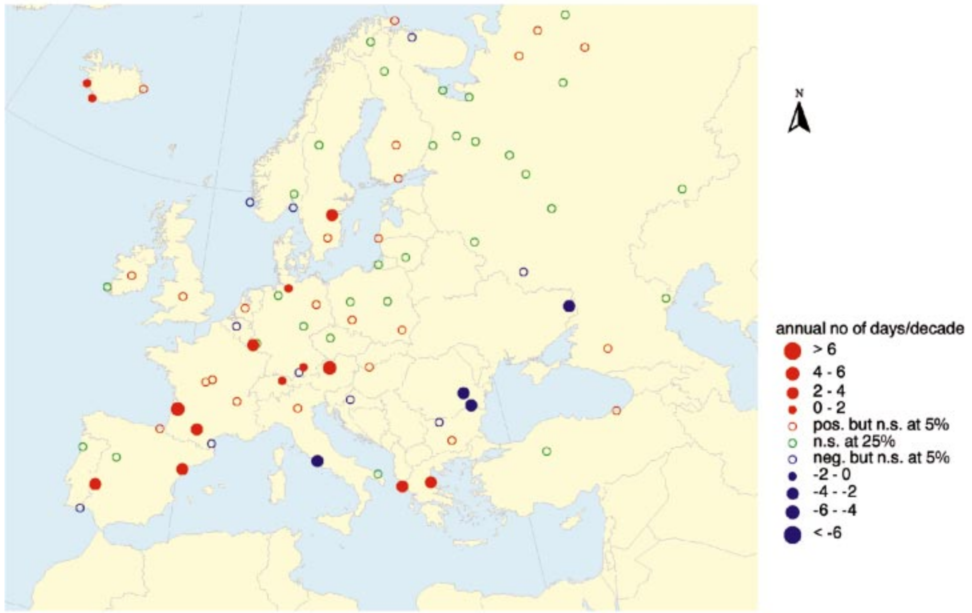
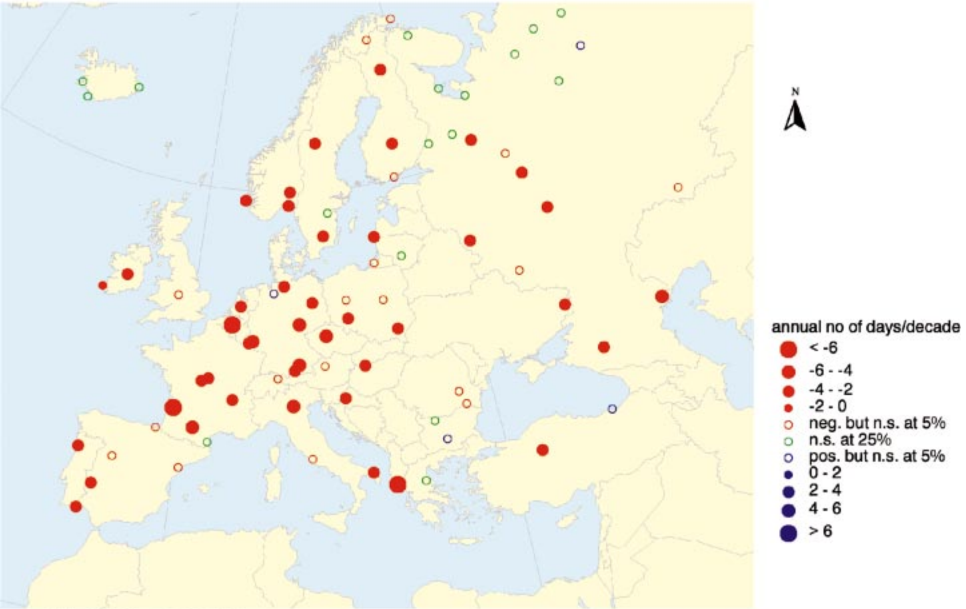


FIG. 4. Trends per decade in the annual number of (a) frost days (FD) and (b) summer days (SU) for the period 1946–99. Dots are scaled according to the magnitude of the trend. For trends significant at the 25% level, but not at the 5% level (Student's *t* test), the sign of the trend is indicated (open circles). Color coding is applied: red corresponds to warming trends (fewer frost days viz. more summer days), blue to cooling trends (more frost days viz. fewer summer days). Green is used for trends that are not significant at the 25% level.

trends TN90% and TX90%. However, for each of the two subperiods, the expected trends in the warm extremes differ significantly from the observed trends. For the 1946–75 subperiod, being an episode of cooling, the cold extremes TN10% and TX10%, and therefore the expected warm extremes TN90%(expect) and TX90%(expect) snow a warming trend. The sign of the expected trends disagrees with that of the observed trends in the warm extremes, which indicate cooling. For the 1976–99 subperiod, when Europe clearly warmed, the expected trends in the warm extremes are about half the observed values.

This result implies that for the two subperiods asym-

a) TN10%, 1946-1999



b) TN90%, 1946-1999

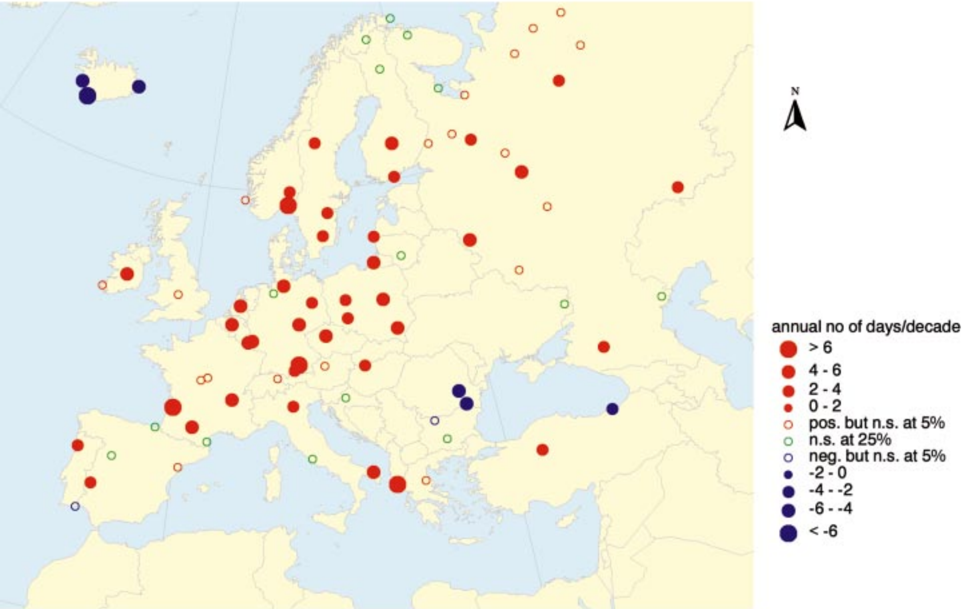


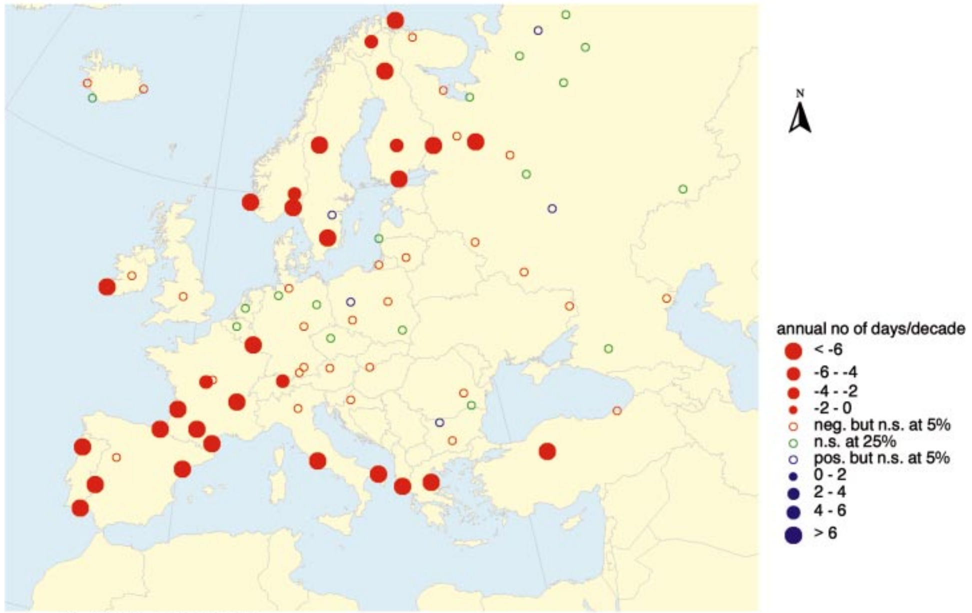
FIG. 5. Trends per decade in the annual number of (a), (c) cold nights TN10% and (b), (d) warm nights TN90% for the periods (a), (b) 1946–99 and (c), (d) 1976–99. Red corresponds to warming trends (fewer cold nights viz. more warm nights), blue to cooling trends (more cold nights viz. fewer warm nights). The open circles are as described in Fig. 4.

metric temperature change can be detected, whereas for the entire period asymmetry is undetectable. Asymmetry leads to a narrowing of the temperature distributions for the cooling subperiod and to a widening of the temperature distributions for the warming subperiod. Comparison with the trend in the median indicates that the asymmetry can mainly be attributed to the fact that the warming trends in TN10% and TX10% lag behind.

c. Trends in precipitation extremes

Figure 6 shows that a positive station trend in the indices of moderate wet days R75% and very wet days R95% dominates in the 1946–99 period. A positive trend is seen mostly at stations where the annual amount increases (Fig. 7). Vice versa, a negative trend does occur mostly at stations in drying areas.

c) TN10%, 1976-1999



d) TN90%, 1976-1999

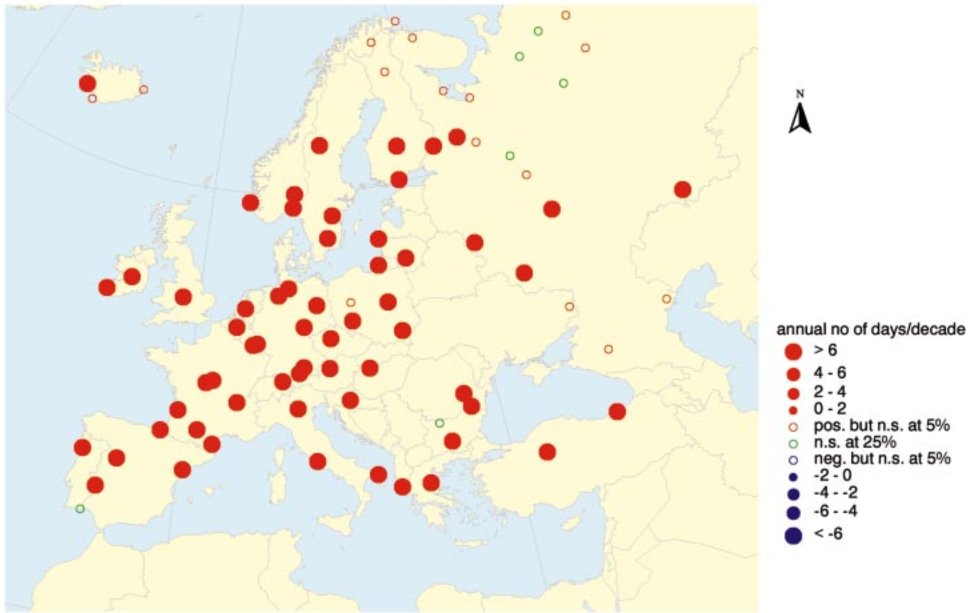


FIG. 5. (*Continued*)

For R75%, R95%, and the other indices of precipitation extremes, the spatial coherence is much lower than for the indices of temperature extremes. Even at short distances (~500 km), positive and negative trends in extreme precipitation are found at stations scattered all over Europe. The usually large local gradients in heavy precipitation events are among the possible explanations for the noisy spatial pattern. Table 4 shows that, averaged over Europe, six out of seven indices of precipitation extremes significantly increase between 1946 and 1999. Increases (though in most cases only significant at the 25% level) are also found in the 1946–75 and 1976–99 subperiods, with the exception of the highest 1-day precipitation amount RX1day that slightly decreases.

Figure 8 shows the 1946–99 station trends in the R95%tot index that defines extreme precipitation relative to the total amount. The trend pattern of R95%tot resembles closely the trend pattern of R95% in Fig. 6.

Table 5 shows that from the 35 (73) stations for which the increase in the annual amount is significant at the 5% (25%) level, 11 (46) stations also have a significant increase in R95%tot. No station with a decrease in the

Table 3. European warming trends per decade (with 95% confidence intervals in parentheses) in the percentile-based indices of cold and warm extremes for the periods 1946–99, 1946–75, and 1976–99. Values for obs trends significant at the 5% level (*t* test) are set bold face. Expected trends in warm extremes *TN90%(expect)* and *TX90%(expect)* are calculated from the obs trends in the corresponding cold extremes, assuming Gaussian temperature distributions and no change in variance or skewness (see Fig. 3). Expected trends in warm extremes that differ at the 5% level (*t* test) from the observed values are marked with *. Note that the climatological values of the annual day-count indices are 36 (see Table 2). The observed European trends in mean temperature and diurnal temperature range are given in the headers.

Cold extremes decrease Annual number of days decade^{-1}		Warm extremes increase Annual number of days decade^{-1}			
European trends 1946–99					
Increase per decade in mean temperature: **0.11** (0.01–0.22)°C					
Increase per decade in diurnal temperature range: **−0.04** (−0.07–−0.01)°C					
TN10%	**2.1** (0.7–3.6)	TN90%	**2.5** (0.9–4.2)	TN90%(expect)	*2.8*
TX10%	1.3 (−0.6–3.1)	TX90%	**2.1** (0.3–3.9)	TX90%(expect)	*1.5*
European trends 1946–75					
Increase per decade in mean temperature: −0.03 (−0.31–0.24)°C					
Increase per decade in diurnal temperature range: −0.03 (−0.11–0.05)°C					
TN10%	2.0 (−2.0–6.1)	TN90%	−2.3 (−5.4–0.7)	TN90%(expect)	*2.3**
TX10%	2.1 (−2.8–7.0)	TX90%	−2.1 (−5.8–1.6)	TX90%(expect)	*2.4**
European trends 1976–99					
Increase per decade in mean temperature: **0.43** (0.09–0.77)°C					
Increase per decade in diurnal temperature range: 0.03 (−0.05–0.12)°C					
TN10%	**4.2** (0.2–8.2)	TN90%	**11.3** (6.6–16.1)	TN90%(expect)	*5.3**
TX10%	4.3 (−1.2–9.9)	TX90%	**10.9** (5.7–16.0)	TX90%(expect)	*5.5**

annual amount significant at the 5% level shows a change in R95%tot significant at the 5% level. This means that a signal of a disproportionate large change in the extremes relative to the total amount is present, but this signal is only apparent in wetting areas. In drying areas, no signal is found.

6. Discussion

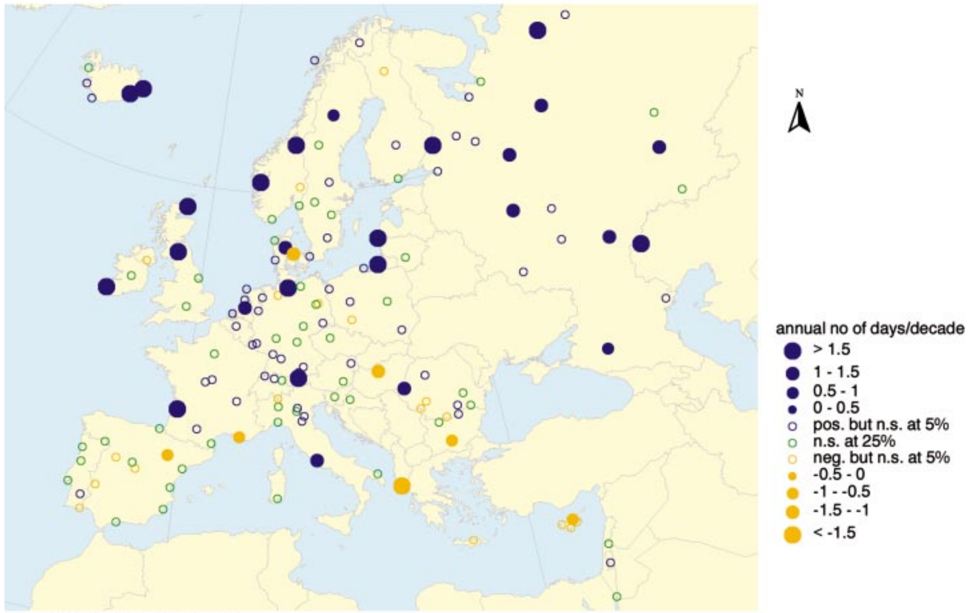
a. Symmetric and asymmetric warming of extremes

The analysis of daily observations shows that the European 1946–99 trends in the annual number of cold and warm temperature extremes do not contradict the assumption of shifted temperature distributions with no change in the parameters other than the mean. This symmetric warming of the cold and warm tails of the temperature distributions implies unchanged temperature variance. However, for the two subperiods, the temperature changes were accompanied by asymmetric rather than symmetric changes in temperature extremes. For the slightly cooling 1946–75 subperiod, the indices of warm extremes TN90% and TX90% show trends that are opposite to what is expected from the observed trends in the corresponding indices of cold extremes TN10% and TX10%. This asymmetry implies a narrowing of the distributions of both minimum and maximum temperature and therefore a lower temperature variance. For the warming 1976–99 subperiod, the indices of warm extremes TN90% and TX90% show considerably larger trends than expected from the observed trends in the corresponding indices of cold extremes TN10% and TX10%, implying a widening of the distributions of minimum and maximum temperature and therefore higher temperature variance.

Our results in Fig. 5 indicate that the temperature rise in the central England series in recent decades is basically associated with an increase in warm extremes, rather than with a reduction in cold extremes. This is in agreement with earlier studies of Yan et al. (2002), Horton et al. (2001) and Fig. 3 of Jones et al. (1999a), although the latter authors drew the opposite conclusion from that figure. The central England result matches the result of the majority of other stations in Europe, including the additional seven stations in Yan et al. (2002), as Table 3 shows that after 1976, the European trends in the indices of warm extremes TN90% and TX90% contribute much more strongly to the warming than the European trends in the indices of cold extremes TN10% and TX10%. Accordingly, Klein Tank et al. (2002) found that the recent warming over Europe in the winter half of the year was accompanied by an *increase* rather than a decrease in the number of cold days that are part of spells of at least five consecutive cold days.

The question remains why the recent warming is occurring asymmetrically and why this asymmetry is not apparent in the long period. As cold/warm extremes are associated with specific atmospheric circulation patterns over Europe, the change in airflow may be the driving force. Cold extremes in winter are often associated with airflow from the snow-covered continent and in summer from the Atlantic Ocean. It is reasonable to assume that cold extremes are less sensitive to large-scale warming than warm extremes, because of the latent heat of snow and the thermal inertia of water. In such a warming scenario, small changes in the frequency of atmospheric

a) R75%, 1946-1999



b) R95%, 1946-1999

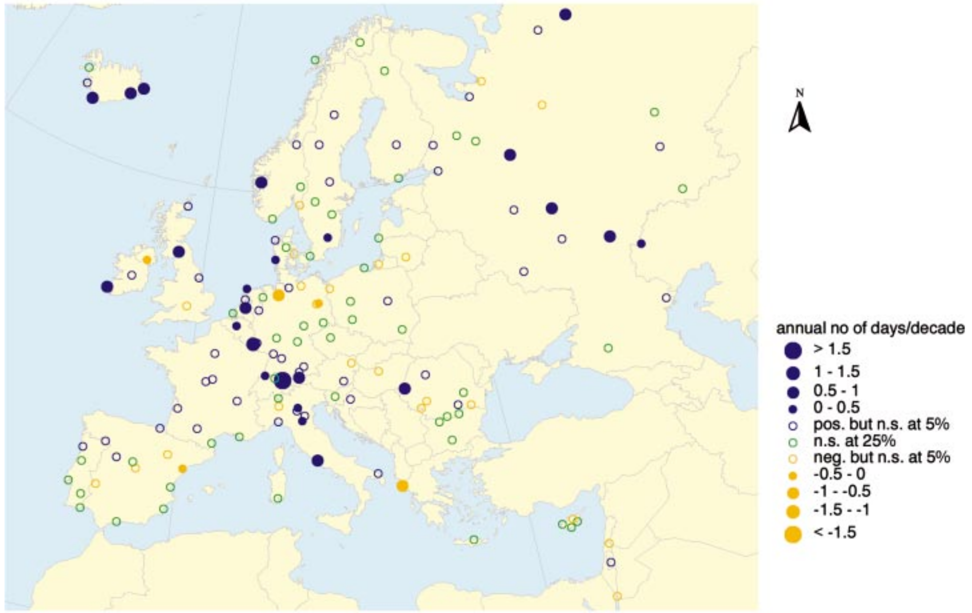


FIG. 6. Trends per decade in the annual number of (a) moderate wet days R75% and (b) very wet days R95% for the period 1946–99. Blue corresponds to wetter conditions, yellow to dryer conditions. The open circles are as described in Fig. 4.

circulation patterns may be capable of stabilizing or increasing the number of cold extremes. The fact that the asymmetry of the subperiods is obscured in the long period may then be due to averaging of two opposite tendencies. Some of the possible changes in atmospheric circulation patterns over the second half of the twentieth century that affect the temperature extremes are well documented, like the changes in the North Atlantic Oscillation (NAO). A systematic study of the relation between circulation changes and (seasonal) changes in cold/warm extremes is needed for a better understanding of the causes for asymmetric temperature change.

b. Amplified response of precipitation extremes

The positive European trends in the indices of wet extremes support the Houghton et al. (2001) statement that ‘‘it is likely that there has been a statistically sig-

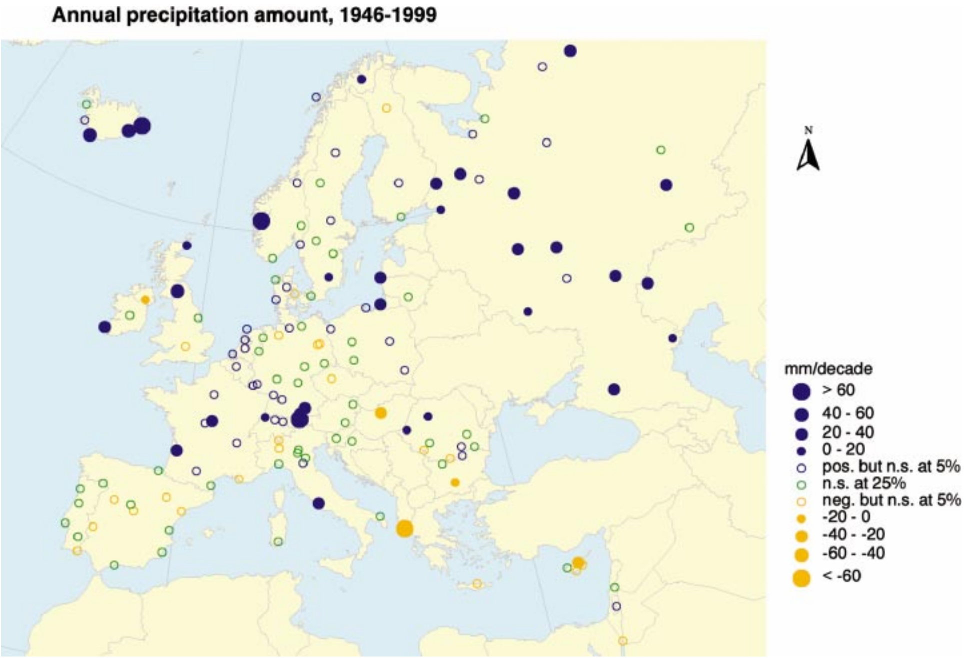


FIG. 7. Trends per decade in the annual precipitation amount for the period 1946–99. Blue corresponds to wetter conditions, yellow to dryer conditions. The open circles are as described in Fig. 4.

nificant increase in the amount of heavy and extreme precipitation events when averaged across the mid and high latitudes.'' According to the hypothesis of Groisman et al. (1999; see also Houghton et al. 2001), there should be an amplified response of the extreme precipitation events relative to the change in total amount. The R95%tot trends as tabulated in Table 5 show that at about one- (two)- third(s) of the ECA stations with an increase in the annual amount significant at the 5% (25%) level, the trend in the amount falling on very wet

TABLE 4. European trends per decade (with 95% confidence intervals in brackets) in the indices of extreme precipitation for the periods 1946–99, 1946–75, and 1976–99. Values significant at the 5% level (*t* test) are set bold face. The observed European trends in annual precipitation amount and annual number of wet days are given in the headers. As in Table 2, the day-count indices (R75%, R95%, R10mm, and R20mm) are expressed in annual number of days.

Percentile-threshold indices Increase per decade		Absolute-threshold indices Increase per decade	
European trends 1946–99 Increase per decade in annual precipitation amount: **7.6** (0.7–14.5) mm Increase per decade in annual number of wet days: 0.4 (−0.5–1.3)			
R75%	**0.4** (0.1–0.7)	R10mm	**0.3** (0.1–0.5)
R95%	**0.2** (0.1–0.2)	R20mm	**0.1** (0.0–0.2)
R95%tot	**0.3** (0.1–0.5)%	RX1day	0.2 (−0.1–0.5) mm
		RX5day	**0.6** (0.0–1.2) mm
European trends 1946–75 Increase per decade in annual precipitation amount: 14.0 (−5.0–32.9) mm Increase per decade in annual number of wet days: 1.3 (−1.1–3.8)			
R75%	0.5 (−0.3–1.4)	R10mm	0.5 (−0.2–1.1)
R95%	0.1 (−0.1–0.3)	R20mm	**0.2** (0.0–0.5)
R95%tot	0.1 (−0.4–0.6)%	RX1day	−0.1 (−1.0–0.7) mm
		RX5day	0.5 (−1.0–2.0) mm
European trends 1976–99 Increase per decade in annual precipitation amount: −1.0 (−19.9–18.0) mm Increase per decade in annual number of wet days: −1.6 (−4.2–1.0)			
R75%	0.4 (−0.4–1.3)	R10mm	0.3 (−0.3–0.9)
R95%	**0.3** (0.1–0.6)	R20mm	0.1 (−0.1–0.4)
R95%tot	**0.8** (0.1–1.5)%	RX1day	−0.2 (−1.2–0.9) mm
		RX5day	0.9 (−1.1–2.9) mm

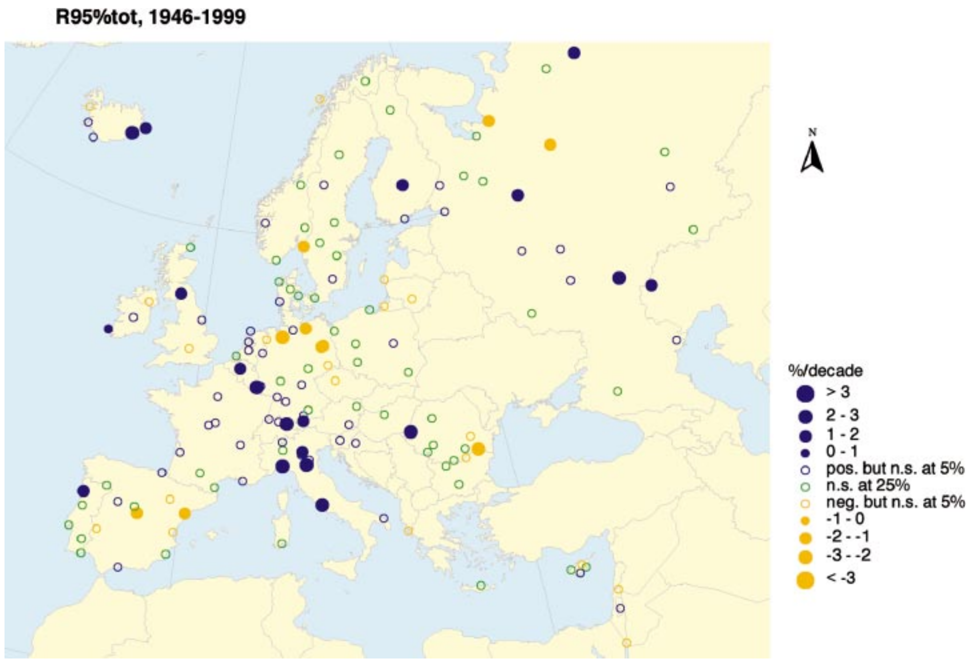


FIG. 8. Trends per decade in the fraction of annual precipitation amount due to very wet days R95%tot for the period 1946–99. Blue corresponds to larger fractions, yellow to smaller fractions. The open circles are as described in Fig. 4.

days is significantly higher. Remarkably, at the ECA stations with a decrease in the annual amount, no negative trends in R95%tot are found. Although only 26% (66%) of the stations show a change in the annual amount significant at the 5% (25%) level, in wetting areas the observations support the notion of an amplified response of the extreme events compared with the annual amount. In drying areas, such an amplified response is not found. Future investigations of the relation between atmospheric circulation and R95%tot may clarify to what extent circulation changes (e.g., related to the NAO) contributed to the observed trends.

c. *Relevance of selected indices for impact studies and climate change studies*

Values of absolute extremes, like the highest 5-day precipitation amount (RX5day) in a year, can often be related with extreme events that affect human society and the natural environment. Indices based on the count of days crossing certain fixed thresholds (e.g., the 0°C threshold as used in the frost days index FD) can also be related to observed impacts, in particular if the thresholds refer to values of physical, hydrological, or biological significance. Indices based on the count of days crossing percentile thresholds are less suitable for direct impact comparisons (Bonsal et al. 2001), but they may provide useful indirect information relevant to impact studies. For instance, the same value for the index very wet days R95% often refers to larger amounts in wet climates than dry climates. The accompanying impacts are likely to differ accordingly. Yet, in every climate regime, nature and man have adapted to the local pattern of climate variability closely and local infrastructure is designed to withstand local extremes. Trends in the R95% index are thus relevant for comparing, for instance, the changes in demands on drainage and sewerage systems at different locations in Europe. Likewise, the trends in TX10% and TX90% are relevant for comparing changes in heating and cooling demands. Changes in percentile-based indices do not necessarily translate to changes in absolute extremes (Zhang et al. 2001).

For climate-change detection studies, indices based on percentile thresholds have a clear advantage, as they can be used to compare the changes in the same parts of the temperature and precipitation distributions Europe-wide. Our results suggest that the percentile thresholds in the selected day-count indices are adequate for

TABLE 5. Contingency table showing the joint distribution of station trends in annual precipitation amount and station trends in fraction of annual precipitation amount due to very wet days R95%tot for the period 1946–99. Categories are: positive trend (+), negative trend (−), and not significant (n.s.) at the 5% level (and 25% level in brackets).

	R95%tot +	R95%tot −	R95%tot n.s.
Annual precipitation amount +	11 (46)	0 (6)	24 (21)
Annual precipitation amount −	0 (4)	0 (13)	5 (10)
Annual precipitation amount n.s.	8 (17)	10 (10)	93 (24)

detection of trends in extremes in the ~50 yr study period 1946–99. On average, more than half of the station trends is significant for the 5% level, and significant Europe-average trends could be detected for all but one of the temperature and precipitation indices. For the 24-yr subperiod 1976–99, significant Europe-average trends could be detected for three out of four temperature indices, even though this requires roughly a 3 times larger trend compared to the 54-yr period. The strong dependence of the detection probability of trends on the series length once again stresses the need for long-term climatic time series with daily resolution.

Due to the small (5–60 day) return periods of the events described by the selected day-count indices, they do not focus on situations that are rare enough to cause serious damage, like severe heat waves or large-scale flooding. In this respect the indices refer to ‘‘soft’’ climate extremes. However, statistical analysis of trends in very extreme temperature and precipitation events (‘‘hard’’ climate extremes with a return period of at least a decade) is not feasible, because of too few events in the short series. For instance, for extremes with return period of 365 days instead of 10 days, 6 times larger percentage trends are required to achieve equal detection probability. On the other hand, trend analysis of soft climate extremes may be considered as empirical support for estimation of trends in hard climate extremes.

Time series with a typical length on the order of ~50 yr are also generated by (regional) climate model simulations. This restricts the extremes that can be subject to trend analysis in these simulations to the same soft climate extremes as in our observational series. Projections of changes in extremes by these models are then also limited to soft climate extremes. Analysis of hard climate extremes with return periods exceeding decades requires long-term ensemble simulations. Validation of the behavior of the selected indices in any model against the results of our empirical study would support the credibility of the model projections.

Folland et al. (2000) proposed that WMO regularly distributes to all nations a consistently analyzed and internationally agreed set of environmental extremes indices. The WMO–CCL/CLIVAR-recommended temperature and precipitation indices used in this European study proved to be good candidates. The indices are applicable to a wide variety of climates and clearly demonstrate how trends in the frequency of cold temperature extremes differ from trends in the frequency of warm temperature extremes and how temperature and precipitation extremes relate to changes in mean climate.

7. Conclusions

- The selected indices of daily temperature and precipitation extremes in Europe show pronounced trends within the 1946–99 period.
- Europe-average trends in mean temperature are accompanied by ‘‘asymmetric’’ rather than ‘‘symmetric’’ changes in temperature extremes for two consecutive periods: 1946–75 and 1976–99.
- The pronounced warming between 1976 and 1999 is primarily associated with an increase in warm extremes rather than with a decrease in cold extremes.
- No such asymmetric change in the cold and warm tails of the temperature distributions is seen from the indices trends for the entire 1946–99 warming period.
- At stations where the annual precipitation amount between 1946 and 1999 increases, the index for the fraction of the annual amount due to very wet days gives a signal of disproportionate large changes in the precipitation extremes.

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APPENDIX

The Variance of the Estimated Regression Coefficient in Event-Count Records

For an uninterrupted record, the variance of the least-squares estimate $\hat{b}$ of the regression coefficient b in the model

$$Y_j = a + bj + e_j \qquad j = 1, \ldots, N \tag{A1}$$

is given by

$$\sigma^2_{\hat{b}} = \frac{\sum_{j=1}^{N} [(j - \bar{j})^2 \operatorname{var} e_j]}{\left[\sum_{j=1}^{N} (j - \bar{j})^2\right]^2}, \tag{A2}$$

where $\bar{j} = ½(N + 1)$ is the average of the year index j. This expression can easily be simplified in the case that var e_j is constant (e.g., Lettenmaier 1976; Kendall et al. 1983, section 45.23):

$$\sigma^2_{\hat{b}} = \frac{12 \operatorname{var} e_j}{N(N^2 - 1)} \approx \frac{12 \operatorname{var} e_j}{N^3}. \tag{A3}$$

For event-count records the error variance depends, however, on the underlying trend. If the successive events are independent, then the X_js have approximately a Poisson distribution with mean $a + bj$. Since the variance of a Poisson variable is equal to its mean, we have to substitute $a + bj$ for var e_j into Eq. (A2), giving

$$\sigma_{\hat{b}}^2 = \frac{a + b\bar{j}}{\sum_{j=1}^{N} (j - \bar{j})^2} + \frac{b \sum_{j=1}^{N} (j - \bar{j})^3}{\left[\sum_{j=1}^{N} (j - \bar{j})^2\right]^2}. \qquad \text{(A4)}$$

Because

$$\sum_{j=1}^{N} (j - \bar{j})^2 = \frac{1}{12}N(N^2 - 1) \approx \frac{1}{12}N^3$$

$$\sum_{j=1}^{N} (j - \bar{j})^3 = 0$$

and $\overline{X}$ is the least squares estimate of $a + b\bar{j}$, Eq. (A2) reduces to

$$\sigma_{\hat{b}}^2 \approx \frac{12\overline{X}}{N^3}. \qquad \text{(A5)}$$

Consequently, in the model

$$Y_j = a + 0.1bj + e_j \qquad j = 1, \ldots, N \qquad \text{(A6)}$$

that we apply in section 4 [Eq. (2)]:

$$\sigma_{\hat{b}}^2 \approx \frac{1200\overline{X}}{N^3}. \qquad \text{(A7)}$$

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