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Trends in European precipitation extremes over 1951–2010

E. J. M. van den Besselaar,* A. M. G. Klein Tank and T. A. Buishand
Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

ABSTRACT: Significant trends in precipitation extremes over Europe since the middle of the 20th century have been found in earlier studies. Most of these studies are based on descriptive indices of moderate extremes that occur on average a few times per year. Here we have analyzed rarer precipitation events which occur on average once in 5, 10 and 20 years in the 1950s and 1960s using extreme value theory. We have focused on the 1-d and 5-d precipitation amounts in Northern and Southern Europe in all four seasons. Changes over the time period 1951–2010 are studied by considering five consecutive 20-year time intervals with 10-year overlap. Despite considerable decadal variability, our results indicate that 5-, 10- and 20-year events of 1-d and 5-d precipitation for the first 20-year period generally became more common during this 60-year period. For all regions, seasons and return periods, the median reduction in return period between the first and last 20-year periods is ∼21% with variations between a decrease of ∼2% and ∼58%. Copyright © 2012 Royal Meteorological Society

KEY WORDS Europe; precipitation extremes; station observations; GEV distribution

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1. Introduction

In recent years, there have been many flooding events in Europe, including large scale events in Poland during spring 2010, Germany and France in May 2008, Ukraine and Romania in July 2008, and United Kingdom in summer 2007 (for a description of such large scale events see http://www.ecad.eu/events/selectevents.php), and numerous flash floods like the recent one in Genoa (Italy) in November 2011. Quite often these flooding events are associated with extreme precipitation giving rise to the question whether precipitation has become more extreme in recent years compared to previous decades. To answer this question, information about current and recent trends in precipitation extremes is needed. According to Christensen *et al*. (2007), the odds may have shifted to make some extremes more likely under present-day warming conditions than in an unchanging climate.

A growing number of studies indicate the presence of significant positive trends in precipitation extremes in Europe during recent decades (e.g. Klein Tank and Können, 2003; Moberg *et al*., 2006; Alexander *et al*., 2006; Zolina *et al*., 2009). These results for the whole of Europe are generally based on descriptive indices of extremes which occur on average once (or several times) each year (or season) such as those defined by the Expert Team on Climate Change Detection and Indices (ETCCDI; see http://www.clivar.org/organization/etccdi/etccdi.php). Examples are the maximum 1-d precipitation amount per year or the number of days with precipitation over 20 mm. Extreme value theory complements these descriptive indices, by providing a way to evaluate the intensity and frequency of rarer extremes. Trends in rarer extremes are difficult to detect, because by definition only a few of these events can be found in the observational series.

Most studies on observed changes in rare extremes in Europe have focussed on specific areas, such as Fennoscandia (Groisman *et al*., 2005), the United Kingdom (Fowler and Kilsby, 2003) or the French Mediterranean region (Pujol *et al*., 2007). In this study, we focus on rare precipitation extremes at meteorological stations over the whole European area.

We examine the daily precipitation series from the European Climate Assessment and Dataset (ECA&D, http://www.ecad.eu) project (Klein Tank *et al*., 2002; Klok and Klein Tank, 2008). Figure 1 shows the precipitation stations used in the analysis. For each station, the linear trend (estimated using ordinary least squares) in the total precipitation amount over the period 1951–2010 is given for winter (December, January, February) and summer (June, July, August). Northern Europe (above 48°N, approximately region NEU from Giorgi and Francisco (2000)) shows a wetting trend in winter while Southern Europe (below 48°N, approximately region MED from Giorgi and Francisco (2000)) shows an indication towards drying. The average trends and the percentage of stations with significant trends at the 10% level (using Student's t-test per station) for each region and season are given in Table I. The average trends for Northern Europe in winter, spring and autumn are much larger and of opposite sign (positive) than the average

* Correspondence to: E. J. M. van den Besselaar, Royal Netherlands Meteorological Institute (KNMI), PO Box 201, 3730 AE De Bilt, The Netherlands. E–mail: besselaar@knmi.nl

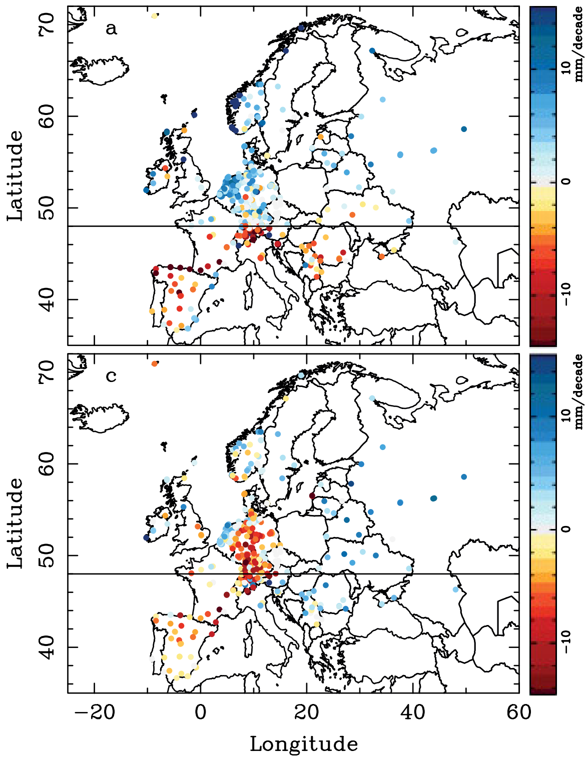

Figure 1. Trend in total precipitation amount in winter (top) and summer (bottom) over the period 1951–2010. The horizontal solid line shows the position of 48°N. Shown are the locations used in this study.

Table I. Average trend (mm/decade) over 1951–2010 in total precipitation amount in Northern and Southern Europe for the 4 seasons (DJF: winter, MAM: spring, JJA: summer, SON: autumn). The percentages of stations with a significant trend at the 10% level are shown in parentheses.

	DJF	MAM	JJA	SON
North	5.08 (28%)	4.05 (26%)	−0.99 (11%)	4.86 (21%)
South	−5.33 (30%)	−0.53 (16%)	−2.03 (13%)	3.17 (16%)

trend in summer. In Southern Europe the average trends in winter, spring and summer are negative and in autumn positive. Winter and autumn have the largest trends.

Here, we investigate if the seasonal maximum 1-d and 5-d precipitation amounts (hereafter RX1day and RX5day, respectively) over Northern and Southern Europe show similar signs of trend as those in the total amounts. RX1day events are indicative of extreme showers which are important for flash floods on local scales. RX5day events are indicative of wet periods which may result in high water levels in larger scale river basins. For the calculation of RX5day all possible 5 d periods within the season of interest are considered, i.e. day 1–5, day 2–6, and so on (ECA&D Project Team 2012).

Section 2 describes the method used in this study. The results are given in Section 3 and we end with a discussion and conclusion in Section 4.

2. Methods

From the daily series in ECA&D, we calculated the winter, spring, summer and autumn RX1day and RX5day for each station. The maximum amounts for a particular season were only determined if there were at least 85 d with valid data present for that season. We selected only those stations that have complete series of 60 values, so one for each year (or season) in the period 1951–2010 (December 1950–November 2010). Also, only stations with series for both RX1day and RX5day were retained. This selection resulted in 478 stations, 367 of which are located in Northern Europe and 111 in Southern Europe (Figure 1). Note that the stations are not evenly distributed, the density is high in some western European countries and low in eastern ones.

We used a regional generalized extreme value (GEV) distribution to describe the distribution of the seasonal maxima in the 20-year periods 1951–1970, 1961–1980, 1971–1990, 1981–2000 and 1991–2010, assuming that the precipitation climate is constant during each of these periods. The parameters of the GEV distribution were estimated for each 20-year period using the first three sample L-moments l_1 (= average), l_2 and l_3 of the seasonal maxima at each station in the region (i.e. Northern or Southern Europe). The scaled sample L-moments l_3/l_1 and l_2/l_1 were averaged over the region to obtain regional estimates of the GEV shape parameter θ and the ratio $\gamma = \sigma/\mu$ of the GEV scale parameter σ and location parameter μ (Stedinger *et al*., 1993). The 48°N parallel rather well separates the stations in the northern part of Europe with relatively low values of γ from those with relatively high values of γ in the southern part. This ratio also shows a larger spatial variation in Southern Europe than in Northern Europe. For the location parameter of the regional GEV distribution, we took the regional average of the estimated location parameters for the individual stations as derived from the at-site mean seasonal maximum, and the regional estimates of θ and γ.

We used the bootstrap method to obtain confidence intervals for the GEV parameters and return periods. To preserve spatial dependence, the maxima at the different stations in a certain year were resampled simultaneously (e.g. Faulkner and Jones, 1999). We formed a bootstrap sample of 60 years by first drawing randomly 10 years from the period 1951–1960 with replacement, then ten years from the period 1961–1970 and so on. The maxima for the resampled years 1–20 were used for the first period, those for the resampled years 11–30 for the second period and so on. This ensures that the bootstrap sample includes the same 10-year overlap between 20-year periods. The regional GEV parameters were then estimated in the same way as for the original data set. We repeated this process 1000 times. The percentile method (e.g. Efron, 1982, Mudelsee, 2010) was used to obtain equi-tailed 90% confidence intervals. Strictly speaking, the term confidence interval is in fact not correct for the presented intervals for the return period, since these

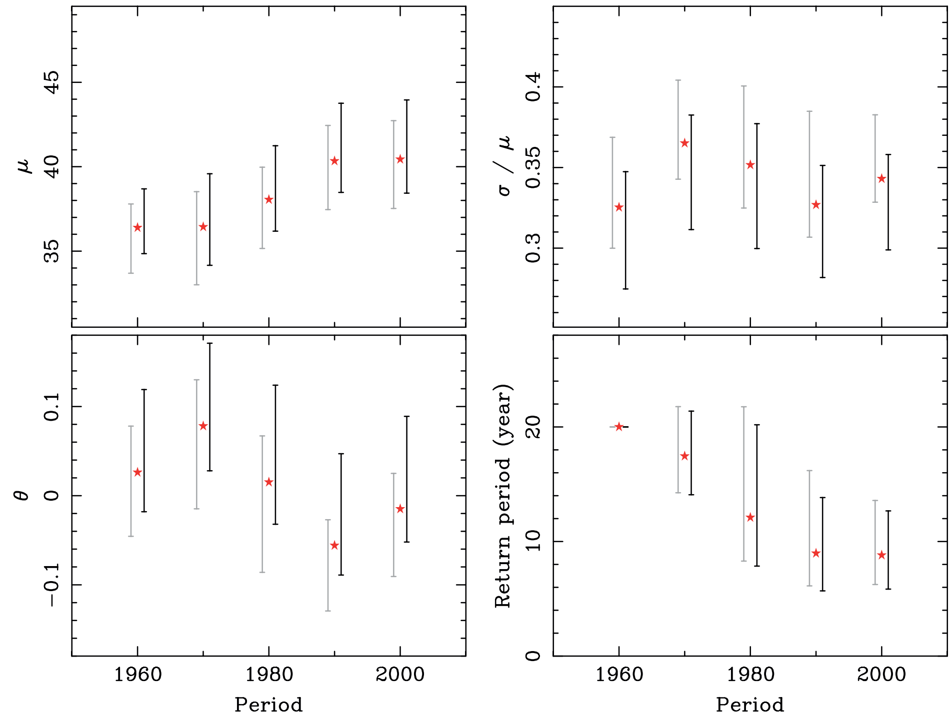

Figure 2. Change in GEV parameters μ, σ/μ and θ, and the change in return period of the 20-year events in 1951–1970 for RX5day in winter in Northern Europe. Grey: bias corrected 90% bootstrap confidence intervals. Black: 90% bootstrap percentile confidence intervals. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

intervals refer to the return period of an estimated return level for the period 1951–1970 in more recent years instead of the return period of a given event in these years (see below).

As an illustration, Figure 2 presents the parameters of the regional GEV distribution for winter RX5day in Northern Europe. The figure further shows how the return period of the 20-year event for the period 1951–1970 (as derived from the fitted regional GEV distribution for that period) varies over the other 20-year periods. To obtain this information, the precipitation amount corresponding to the 20-year return period in 1951–1970 was taken and for that amount the return periods for the other time periods were determined. The stars and intervals in the figure for the year 1960 were derived from data over the period 1951–1970, for the year 1970 from data over the period 1961–1980 and so on. The return period decreases over time, which implies that the 20-year event has increased. This increase is mainly due to the increase of the GEV location parameter. The 90% confidence intervals for the two most recent 20-year periods 1981–2000 and 1991–2010 fall below the 20-year return period. This implies that for more than 95% of the bootstrap samples the return period of the 20-year event in 1951–1970 is less than 20 years in these two periods, indicating strong statistical evidence of a decrease in return period in recent decades. The bootstrap percentile confidence intervals in Figure 2 are compared with the bootstrap bias-corrected percentile confidence intervals (Efron, 1982). In the latter, the endpoints of the confidence interval are adjusted if the median of the bootstrap estimates of the quantity of interest differs from the estimate from the original data. For the three GEV parameters, there are marked differences between the percentile and bias-corrected percentile confidence intervals, which may be attributed to biases resulting from the small sample size of 20 values for each station. Averaging of the sample L-moment ratios as recommended by Hosking and Wallis (1997) rather than the sample L-moments scaled by the sample mean generally leads to larger biases, *cf* Sveinsson *et al*. (2001). For the 20-year return period there is, however, little difference between the percentile and bias-corrected percentile confidence intervals.

The bias-corrected and accelerated percentile method (e.g. Efron, 1987; Mudelsee, 2010) provided similar confidence intervals as the bias-corrected percentile intervals in almost all cases (not shown). This may be ascribed to the low skewness of the regional parameter estimates due to the spatial averaging. Resampling blocks of two years as recommended by Alexander *et al*. (2006) did not result in wider confidence intervals than resampling of individual years (not shown).

In the remainder of this article we consider only the return periods for which we give the equi-tailed 90% bootstrap percentile confidence intervals.

3. Results

Before studying the trends in the return period, the adequacy of the fit of the regional GEV distribution was

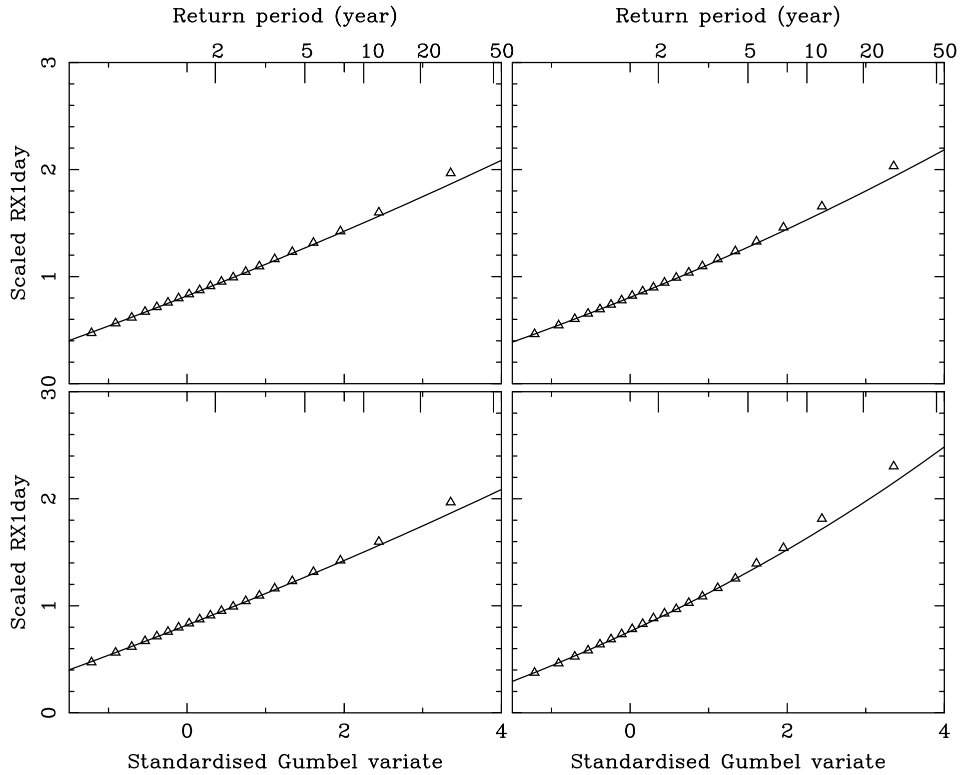

Figure 3. Gumbel plots of the scaled RX1day values during the period 1951–1970 for Northern Europe (top) and Southern Europe (bottom) in winter (left) and summer (right). The solid lines represent the return levels of the scaled seasonal maxima according to the fitted regional GEV distribution.

verified by producing Gumbel plots of the scaled seasonal maxima. A selection of four of these plots are presented in Figure 3. To obtain these plots the seasonal maxima were first divided by their mean for the 20-year period of interest. These scaled seasonal maxima were then ranked in increasing order for each station, and subsequently the values for each rank were averaged over all stations in the region (Northern or Southern Europe). The average ranked values are plotted against the standardised Gumbel variate. Figure 3 shows that these ranked values are generally close to the curve for the regional GEV distribution. Only for RX1day in summer in Southern Europe, the regional GEV distribution tends to underestimate the upper tail of the distribution slightly. This tendency is also found for the RX1day summer maxima in Southern Europe for the other 20-year periods, and for the RX5day summer maxima in Southern Europe. Other departures from the GEV distribution were not found.

Regarding the trends in the return periods, we focus here on the 5-, 10- and 20-year events for the first 20-year period (1951–1970). Figures 4–7 show the changes for RX1day and RX5day for Northern and Southern Europe in winter, spring, summer and autumn, respectively. No confidence interval is presented for the first time period as this value was fixed to 5, 10 or 20 years for the original data as well as for each of the bootstrap samples. Table II gives the relative changes in return period between the first and last 20-year periods.

The changes in the return periods presented here depend on the season and region. For the RX1day and RX5day extremes in Northern Europe in winter (Figure 4) and spring (Figure 5) there is an overall decreasing trend in return periods which is indicative of increasing precipitation extremes. The trend is most pronounced in RX5day in Northern Europe in spring. Twenty-year events in 1951–1970 in this case become ∼8-year events in 1991–2010. For Southern Europe in winter, the 20-year events in 1951–1970 stay more or less 20-year events in later periods. In spring, Southern Europe shows a small decrease in the return periods in the last 20 years.

For summer (Figure 6) and, to a lesser extent, autumn (Figure 7), the time evolution is more irregular. In Northern Europe both RX1day and RX5day show first an increase in return periods (indicative of a tendency towards lower extremes) followed by a decrease (indicative of a tendency towards higher extremes). The return period in the last time period for Northern Europe is not as low as for winter and spring, although the trend in total precipitation amount in autumn is about the same as that for winter and spring (Table I). Southern Europe shows first a small decrease in return period for both RX1day and RX5day in summer and autumn before levelling off (no change in extremes).

The identified changes in return period are somewhat dependent on how rare the considered extremes are. The relative changes between 1951–1970 and 1991–2010 for the 20-year return period are generally larger than those

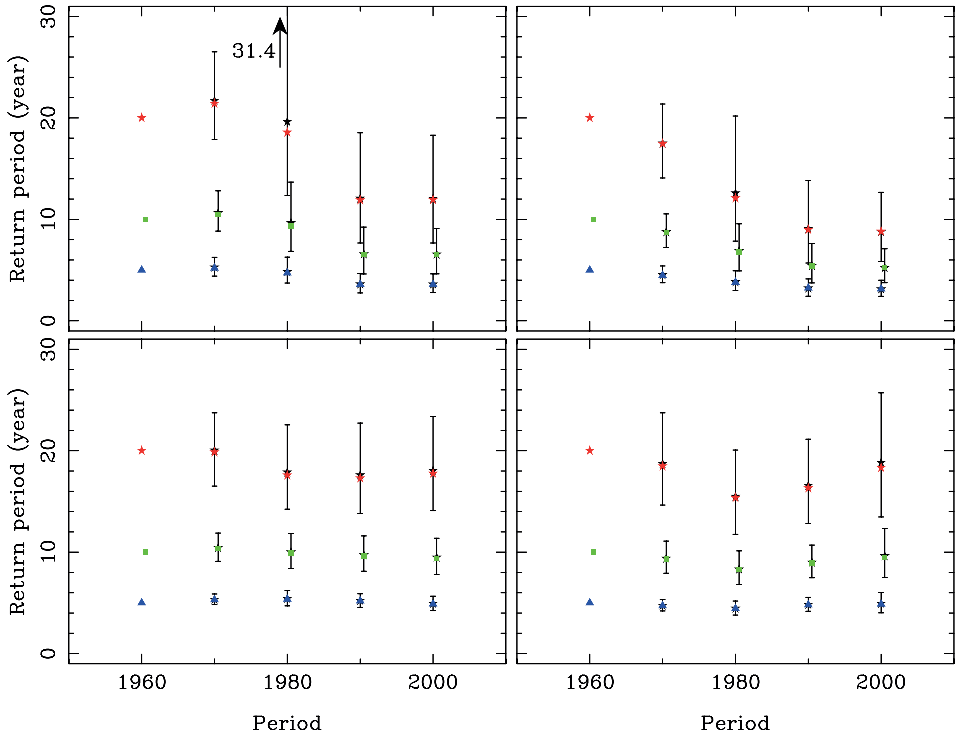

Figure 4. Changes in return period from 1951–1970 to 1991–2010 for events occurring once in 5 (blue triangles), 10 (green squares) or 20 years (red stars) in the first period for Northern Europe (top) and Southern Europe (bottom) in winter. Black: 5–95% range of the bootstrap samples including the mean; left: RX1day; right: RX5day. The values for 10-year events are slightly shifted for clarity. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

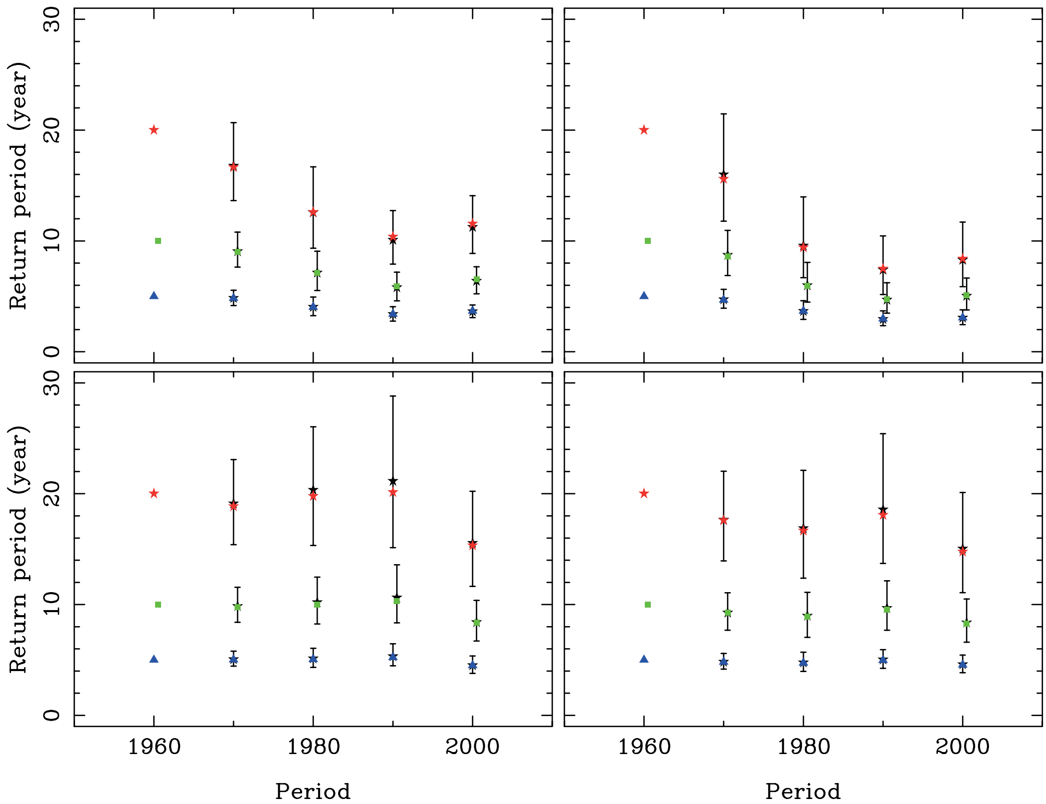

Figure 5. Changes in return period from 1951–1970 to 1991–2010 for events occurring once in 5 (blue triangles), 10 (green squares) or 20 years (red stars) in the first period for Northern Europe (top) and Southern Europe (bottom) in spring. Black: 5–95% range of the bootstrap samples including the mean; left: RX1day; right: RX5day. The values for 10-year events are slightly shifted for clarity. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

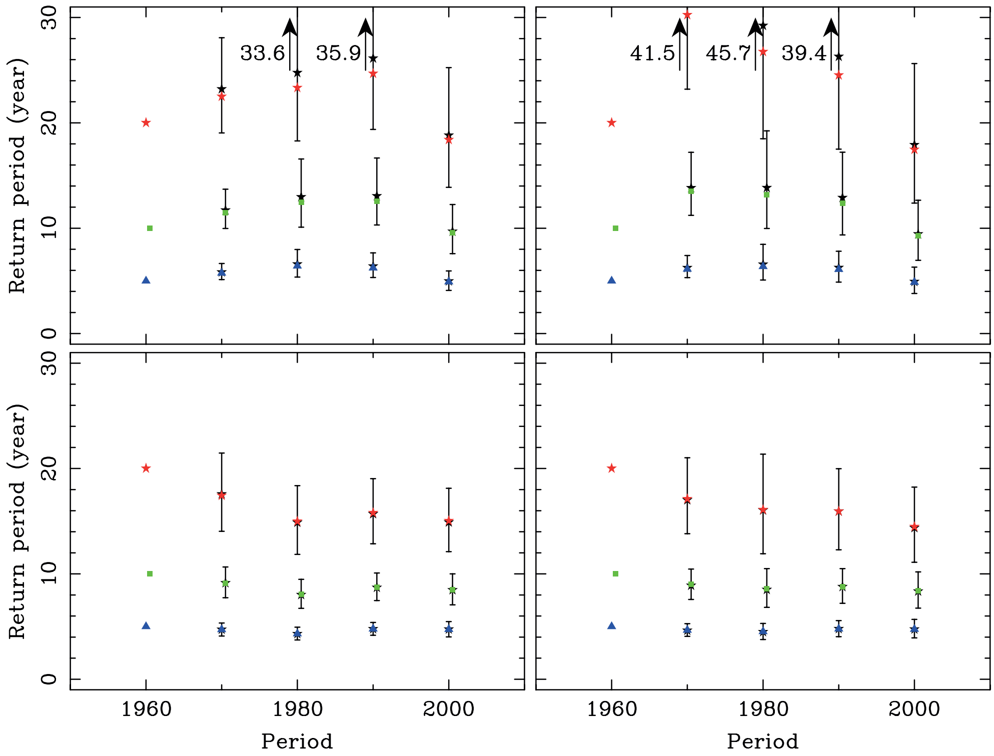

Figure 6. Changes in return period from 1951–1970 to 1991–2010 for events occurring once in 5 (blue triangles), 10 (green squares) or 20 years (red stars) in the first period for Northern Europe (top) and Southern Europe (bottom) in summer. Black: 5–95% range of the bootstrap samples including the mean; left: RX1day; right: RX5day. The values for 10-year events are slightly shifted for clarity. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

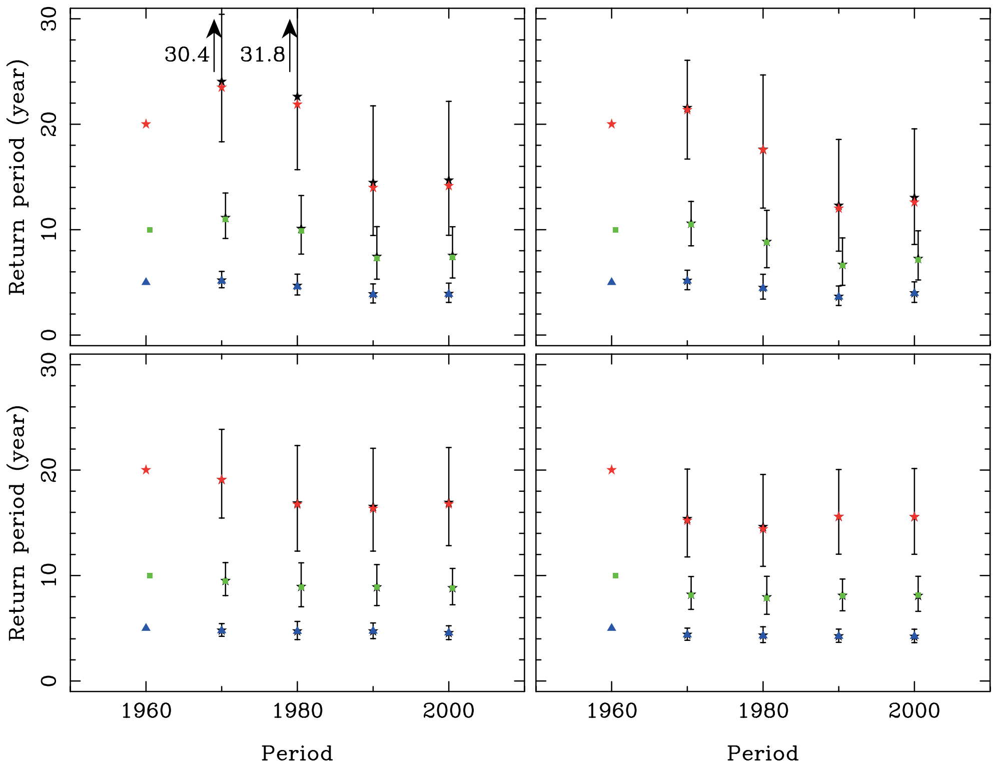

Figure 7. Changes in return period from 1951–1970 to 1991–2010 for events occurring once in 5 (blue triangles), 10 (green squares) or 20 years (red stars) in the first period for Northern Europe (top) and Southern Europe (bottom) in autumn. Black: 5–95% range of the bootstrap samples including the mean; left: RX1day; right: RX5day. The values for 10-year events are slightly shifted for clarity. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table II. Relative changes (in %) in return period between 1951–1970 and 1991–2010 for events occurring once in 5, 10 or 20 years in the first period. The results are given for Northern and Southern Europe, RX1day and RX5day, and for winter (DJF), spring (MAM), summer (JJA) and autumn (SON). The approximate return periods in 1991–2010 for the events are given in parentheses.

	RX1day				RX5day			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
	5-Year events				5-Year events			
North	−28.1 (3.6)	−26.3 (3.7)	−1.6 (4.9)	−22.4 (3.9)	−37.3 (3.1)	−38.4 (3.1)	−2.5 (4.9)	−20.9 (4.0)
South	−2.1 (4.9)	−9.9 (4.5)	−5.3 (4.7)	−8.6 (4.6)	−2.3 (4.9)	−8.8 (4.6)	−5.1 (4.7)	−15.3 (4.2)
	10-Year events				10-Year events			
North	−34.6 (6.5)	−34.8 (6.5)	−4.5 (9.6)	−26.1 (7.4)	−47.4 (5.3)	−49.2 (5.1)	−7.0 (9.3)	−28.6 (7.1)
South	−6.1 (9.4)	−16.5 (8.4)	−15.0 (8.5)	−11.8 (8.8)	−5.3 (9.5)	−17.2 (8.3)	−16.2 (8.4)	−18.8 (8.1)
	20-Year events				20-Year events			
North	−40.4 (11.9)	−42.3 (11.6)	−8.1 (18.4)	−29.3 (14.1)	−56.0 (8.8)	−58.0 (8.4)	−12.7 (17.5)	−37.1 (12.6)
South	−11.3 (17.8)	−23.4 (15.3)	−24.9 (15.0)	−16.2 (16.8)	−8.4 (18.3)	−26.2 (14.8)	−27.6 (14.5)	−22.2 (15.6)

for the 5-year return period. For example, for RX5day in spring in Northern Europe, the return period of the 20-year events in 1951–1970 decrease by ∼58% in 1991–2010, while the return period of the 5-year events decrease by ∼38%. For all regions, seasons and return periods, the median reduction in return period between the first and last 20-year periods is ∼21% with variations between an decrease of ∼2% and a decrease of ∼58% (Table II).

4. Discussion and conclusion

In this article we have analyzed up to 20-year extremes of maximum 1-d and 5-d precipitation amounts in all four seasons for Northern and Southern Europe. In Northern Europe, the picture for the changes in extreme precipitation is approximately the same as that for the trend in total precipitation amount. In Southern Europe the 20-year RX1day and RX5day events stay about the same in winter, but become slightly wetter in other seasons, although the regional trend in total precipitation amount in winter and summer indicates drying. The general tendency towards higher precipitation extremes is consistent with the trends in more common events identified using the descriptive indices of extremes which occur on average several times per year (Klein Tank and Können, 2003; Moberg *et al*., 2006). Trenberth *et al*. (2007) concluded that the number of heavy precipitation events (e.g. 95th percentile) increased within many land regions, even in regions with a reduction in total precipitation amounts. The increase of heavy precipitation events is also consistent with theory of a warming climate (Allen and Ingram, 2002) and observed significant increasing amounts of water vapour in the atmosphere (Willett *et al*., 2008).

This study shows results for Northern Europe and Southern Europe as a whole. Therefore subregional and local differences in trends are not picked up, although other studies show that these exist. Examples are Łupikasza *et al*. (2010) who observed that the trends in moderate precipitation extremes in Southern Poland differed from those in central-eastern Germany, and Kyselý (2009) who found differences in trends between the western and eastern parts of the Czech Republic.

Groisman *et al*. (2005) have studied total precipitation and frequency of intense precipitation in several regions of the world, including the Fennoscandia region where they had access to much more station data than we have available in ECA&D. They found a significant increase in the annual totals and in the frequency of very heavy annual and summer precipitation events. We did not study annual trends, but our results for Northern Europe for summer differ from those by Groisman *et al*. (2005).

For annual 5-d and 10-d precipitation amounts in the UK, Fowler and Kilsby (2003) have found that the 50-year event during 1961–1990 has become an 8-, 11- and 25-year event in East, South and North Scotland, respectively, during the 1990s. In Northern England the average recurrence interval has also halved. This is in line with our results for Northern Europe where 20-year events in 1951–1970 have a probability of occurring more often in later time periods.

Studying local differences in precipitation extremes over Europe and attributing the identified changes to natural or anthropogenic forcing factors (as in, e.g. Min *et al*., 2009) could be the subject of a future study. Linking the RX1day and RX5day precipitation extremes to atmospheric flow patterns as, e.g. by Maraun *et al*. (2011) offers the possibility to determine the contribution of long-term variations in the air flow patterns to the observed increases in RX1day and RX5day over Northern Europe in winter and spring. This may provide an answer to the question whether these increases are associated with the reported shift in the storm tracks (Pfahl and Wernli, 2012), or to similar questions.

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