Daily and hourly rainfall distribution in space and time – conditions in southern Sweden

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ABSTRACT

Very extreme events occur randomly in space and in time. In this paper daily precipitation from more than 200 stations within a 10 000 km^2 region in the very south of Sweden is analysed. While there is a relation between moderate daily precipitation and annual precipitation, the most extreme events are found to be independent of annual precipitation and also of altitude and distance to the sea. The most extreme events are distributed evenly over the region. Variations of the climate are considered. For three cities daily storms are analysed for a period of 89 years. No trend over time is found of the daily high precipitation. Hourly storms are analysed for four stations within the city of Malmö. The probability of concurrent events is rather high, but there is little correlation between the rain intensities at the different stations during the most intense events.

Key words | concurrent events, error analysis, peaks over threshold, trends

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INTRODUCTION

While it is rather easy to relate annual precipitation to physiographic parameters, and often also to relate mean daily maximum precipitation to such parameters or to the annual precipitation (e.g. Madsen *et al.* 1998), the very extremes seem to occur more randomly. For example the highest daily storm measured in Sweden (Ellesson & Persson 1961) is from Bäckaskog in the northwest of the Skåne Peninsula in the very south of Sweden. The storm depth is more than double that of the second highest storm observed in Skåne. Bäckaskog is where the annual precipitation is the lowest in southern Sweden. In this paper extreme storms in southern Sweden are analysed. Different sets of data are used: long-term daily precipitation from the three cities Malmö, Halmstad and Göteborg, 30 years of daily precipitation from a regional dense network covering an area of 10 000 km^2, and hourly rainfall from stations within the city of Malmö. Spatial distribution and correlation are considered. The peaks over threshold method is used. Different distributions are fitted to station values as well as to regional data. It is expected that storm intensities will increase in a warmer climate. Trends of intensities over almost 100 years are investigated. The objectives are to determine the probability of the most extreme events and see if changes have occurred over time. An objective is also to see if the most extreme events are differently related to main statistics than moderately high rain intensities.

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DATA BASE

The daily precipitation data analysed in this paper are from official SMHI (Swedish Meteorological and Hydrological Institute) stations in the cities Malmö, Halmstad and Göteborg along the southern part of the west coast of Sweden. The data series extend from 1919 to 2007. Data after 1961 are obtained in digitalized form from SMHI, while older data are found from old notes. The observation period is 89 years. The distance between Malmö in the very south and Halmstad is about 150 km. It is another 150 km to Göteborg.

The regional analysis of daily precipitation is based on 30 years of observations (1961–1990) from 230 stations over an area of about 10 000 km^2 in the southernmost county of Sweden, Skåne, see Figure 1. The station net was organized by Hon. Dr Jan Ellesson and SMHI gauges were used.

The hourly storm data are from the city of Malmö. Each observation was carefully analysed. The rain was measured with tipping bucket. The rain depth resolution of the tipping buckets is 0.2 mm. Data from four stations are used. At three of them, the series are almost complete for the last 12 years; at the fourth for almost 30 years. The stations are all within a radius of 2.5 km. The data were used for a study of local variations of hourly storms.

All data sets have been used to determine extreme values. Events exceeding threshold values have been included. The parameters of different frequency distributions have been determined either using the method of moments. The statistical analysis was done for individual stations and also for many stations pooled together. The probability of high rain intensity was related to annual precipitation and altitude.

OBSERVED EXTREME EVENTS

The highest observed daily rainfall in the SMHI official station net for Skåne (the county of southernmost Sweden) is 159 mm (from the town of Båstad south of Halmstad on the northern slope of the ridge Hallandsås in northwest, see Figure 1) from 1936. The Ellesson station net does not extend north of the Hallandsås ridge. South of the Hallandsås ridge the highest official daily storm is just above 100 mm. However, there is an observation reported by Ellesson & Persson (1961), who during a field study in 1960 in an SMHI-gauge measured 237 mm in the north-eastern part of the Skåne peninsula. This is where the annual mean precipitation in Skåne is the lowest, only about 450 mm. In the period 1961 to 1990 the maximum daily rainfall recorded at any of the regional 230 stations in Skåne was 114 mm. The rainfall in the three cities Malmö, Halmstad and Göteborg did not exceed 100 mm during any day in 89 years.

The most intense short-term rain measured in Sweden is from Stockholm and dates back to 1916. In the Höganäs handbook (1975) it is as stated 25 mm in 5 minutes. The largest one-hour storm is from Uppsala north of Stockholm and is 104 mm (Hernebring 2006). The most intense storm in Malmö is from the station called Limhamn. At that station the 10-minute maximum storm depth is 21 mm, the 30 minute depth 33 mm, and the 1 hour storm 43 mm.

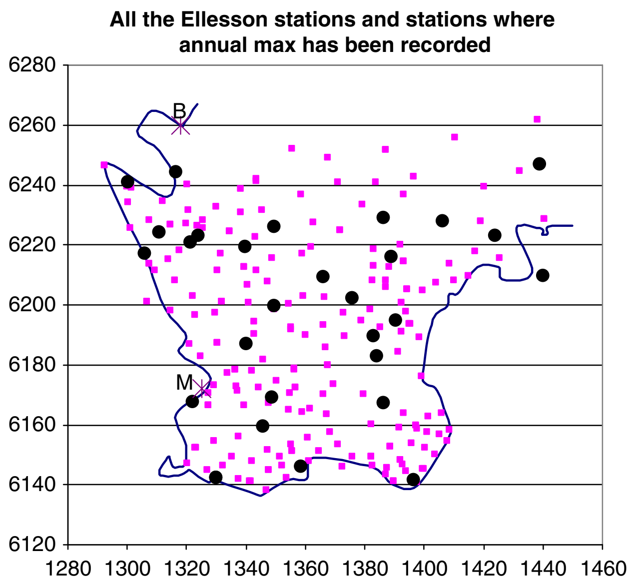

Figure 1 | Location of stations where annual maximum has been observed in a 30-year period (filled circles) and location of all precipitation stations in Skåne (squares). Malmö (M) and Båstad (B) are shown with x. The coordinates gives the scale in km.

SPATIAL DISTRIBUTION OF EXTREME DAILY PRECIPITATION

The Ellesson data of 230 stations for the period 1961 to 1990 were used to analyse the regional distribution of extreme daily rainfall. The rain gauges are distributed over an area of about 10 000 km^2. Skåne is a peninsula, Figure 1, so no station is further away from the sea than 50 km. There are three ridges with altitude up to 200 m within the region. The annual precipitation is more than 800 mm at the high altitudes, but only about 450 mm near the sea in the north-east.

In the period 1961–90 there are eight events of rainfall larger than 100 mm and 10 larger than 80 mm at one or more stations during a day. They are distributed evenly over the whole region. The annual maximum daily precipitation for the 30 years is from 28 different stations, which are shown in Figure 1 together with the full station net. It seems that the very extreme rainfalls are distributed randomly all over the region. It has already been pointed out that the most extreme daily event has been recorded in the north-east of Skåne, where the annual precipitation is the lowest.

Considering the modest extremes, there is a difference between stations with different geographical position. SMHI defines extreme precipitation as 40 mm/day. In Malmö in the very south (Figure 1) at the western coast events larger than 40 mm have occurred 20 times since 1919. The return period for such an event in Malmö is thus close to 4.5 years. On the ridge Linderödsåsen and on its slope towards the eastern coast of Skåne the return period for similar events is two years, as found from observations at all the stations on the ridge over the period 1961 to 1990. The probability for modest extreme events is weakly related to altitude, but more related to geographical position. Rains from the south-east release their water while ascending over the small ridge Linderödsåsen.

It is possible to relate modest daily precipitation to annual precipitation. Madsen *et al.* (1998) have shown a relation between daily precipitation and mean annual precipitation in Denmark. Since there is a relation between altitude and annual precipitation and a relation between altitude and high daily precipitation, there is also such a relation in the region of Skåne. However, there is no relation with the very largest storms. This is illustrated in Figure 2, which shows the number of extreme events at different stations as function of annual precipitation. There is a clear relation for storms exceeding 40 mm/day but not for storms exceeding 50 mm.

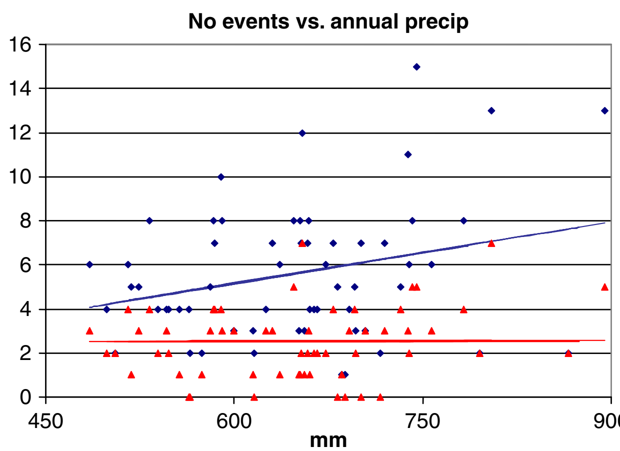

Figure 2 | Number of storms exceeding 40 mm/day as function of annual precipitation (squares and upper line) and number of storms exceeding 50 mm/day (triangles and lower line). Only stations with 28–30 years of records are included.

It was not possible to find a relation between intense daily storms and distance to the sea.

FREQUENCY ANALYSIS – DAILY PRECIPITATION

Instead of using annual maxima to determine the probability of extreme events, all independent observations above a given high threshold value are used, i.e. the peaks over threshold (POT) approach. The theory of the POT method has been developed and described by Rosbjerg and co-workers (e.g. Rosbjerg 1985; Rasmussen & Rosbjerg 1989; Rosbjerg *et al.* 1992) in a series of papers. The POT method was reviewed in depth by Madsen *et al.* (1998). Usually when applying this method the number of annual exceedances is 2–3 or more. In this paper only the very extremes are considered, and therefore the number of annual exceedances is most often less than unity. The parameters of the generalized Pareto distribution were determined with the method of moments. The ranking position is chosen as $(i-a)/(N+b)$, where i is position and N number of included observations with $a = 0.35$ and $b = 0.4$, which is the median plotting, the use of which is motivated by Rosbjerg (1988). Since the threshold level is chosen very high, it may be justified to use a pure exponential exceedances distribution in the POT approach. Then the expression for the *T*-year event, as already shown by Shane & Lynn (1964), is very simple:

$$P = P_{threshold} + m \ln(\lambda T)$$

where λ = number of exceedances per year and m = mean of $(P - P_{threshold})$.

The precipitation has been measured daily at the station Bulltofta in Malmö since 1919. Every event (which amounts to 20) exceeding 40 mm has been used for frequency analysis. The relation between intensity and return period is shown in Figure 3 for two different theoretical distributions. The highest values seem not to belong to the same probability distribution as the values between 40 and 60 mm. The four highest observations are in a narrow range, 73–79 mm. The observed very high values tend to flatten out with increased return periods. However, using the Kolmogorov–Smirnov test the null hypothesis cannot be rejected for any of the distributions. The maximum deviation between the theoretical probabilities and the observations is 0.23.

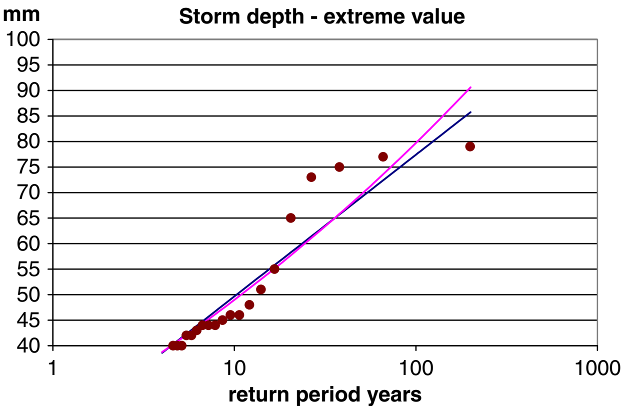

Figure 3 | Observed daily storms exceeding 40 mm in Malmö in the period 1919–2007 and two probability distributions, generalized Pareto (curved, light colour) and exponential (straight line, dark).

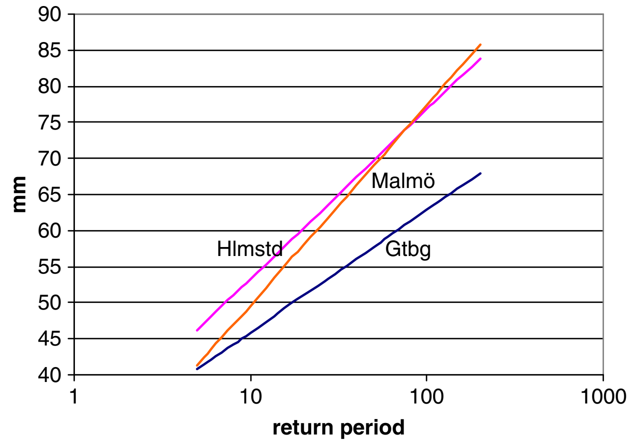

Figure 4 | Probability of extreme daily storm events in Malmö, Halmstad and Göteborg determined from exponential distribution using 89 years of data with the two-year storm as threshold value.

The standard deviation of the T-year event in the case of exponentially distributed exceedances can be determined easily. The approach here follows Rosbjerg (1985):

$$s^2 = \mathrm{m}^2/n^*(1+k^*\ln^2(\lambda T))$$

where s is the standard deviation, T is the return period and λ is the number of exceedances above the given threshold in a year. Rosbjerg (1985) has shown that the ln-term should be multiplied with a correction factor, k, which depends on the number of observations and has also giving a graph for the correction factor. When there are more than 10 observations the correction factor is close to unity. The standard deviation is 9 mm for the 100-year event, 7 mm for the 50-year event and drops to 3 mm for the 10-year event. The 68% confidence interval is then within 68 mm and 86 mm.

The daily rainfalls for the period 1919 to 2007 from Halmstad and Göteborg have been analysed in the same way as those for Malmö. The mean annual maximum rainfall are about the same in the three cities. The frequency of high intensities is, however, much higher in Halmstad than in the other cities, as is seen in Table 1. The frequency of daily rains exceeding 20 mm is 4.4 per year in Halmstad, while such large events occur less than two times per year in the other cities. Still the very extremes of 20–100 year return period are the same for Malmö and Halmstad. The 100 year storms are those obtained from the exponential distribution. The very extreme daily rains are lower in Göteborg than in Malmö and Halmstad. Comparison of the extremes is done in Figure 4. Daily rains of 100 mm have a very long return period as determined from the probability distributions.

The same statistical analysis as for the three cities was performed also for all the stations in the Ellesson precipitation net in the region of Skåne. The results are similar as for the three major cities and even more clear, although the analysis is based only on 30 years of data. The number of storms exceeding 40 mm is related to the annual precipitation, but this is not the case for the very extremes as already shown in Figure 2. The very extremes are randomly distributed. These events are not related to mean rainfall and not related to storms of one-year return period. The observations from and the probability distributions for the station

Table 1 | Precipitation statistics 1919–2007, unit mm, f = frequency events per year

Station	Annual	Max daily	MeanMax	T = 20 y	T = 100 y	f > 20 mm	f > 40 mm
Malmö	600	79	33	57	78	1.8	0.22
Halmstad	750	82	36	58	77	4.4	0.42
Göteborg	700	67	33	50	63	1.8	0.22

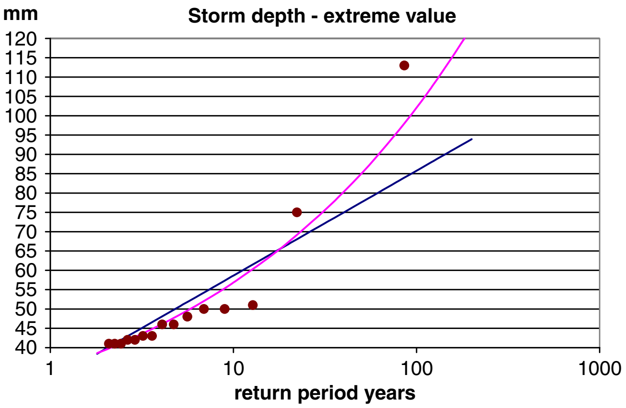

Figure 5 | Return periods of daily rains at Linderöd determined with threshold level 40 mm with 30 years of data. Curved light line, generalized Pareto distribution; straight line, exponential distribution.

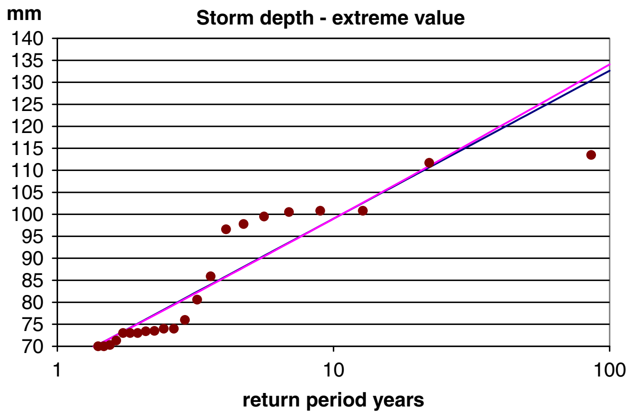

Figure 6 | Return periods for storms to occur somewhere (different each time) within the station net (230 stations in Skåne). The generalized Pareto distribution and the exponential distribution are almost identical. Maximum probability deviation 0.2.

Linderöd, which is the station with the highest observed precipitation and also the highest annual precipitation, are compared in Figure 5 using a threshold of 40 mm/day, which includes 16 observations in 30 years. The maximum deviation between observations and theoretical distributions is 0.23, not allowing rejection of the null hypothesis when performing the Kolmogorov–Smirnov test.

It has been discussed above that the very highest observations may belong to a different distribution than the more modest storms, and that these very extreme events appear in a homogeneous pattern over the region. To allow a much higher threshold than 40 mm, all independent events in the period 1961–90 in the data from the Ellesson station net were considered (many observations from a specific day were considered to belong to the same event, so of two observations from the same day only the highest is included in the analysis). The probability of very high rain intensity to occur at some of the stations in Skåne (any of them and it may be a different station each time) was estimated. With a threshold value of 70 mm/day, 22 intense rainfalls could be included. The mean of the exceedances events is only 81 mm (11 mm above the threshold). The 100-year daily rainfall for occurrence at one place in Skåne is about 135 mm as can be seen in Figure 6.

TRENDS OF DAILY RAINFALL

In large parts of Europe including southern Sweden the annual precipitation has increased slightly over the last 100 years. Climate models show a further increase. These models also show expected increased daily rain intensities, e.g. Räisanen & Joelsson (2001), Jones & Reid (2001). Based on down-scaling from global circulation models Skaugen *et al.* (2003) have computed that extreme daily precipitation should increase by 10–50% in large parts of Norway.

Instead of using models it is more straightforward to analyse observation series. Häggström (2001) has analysed high daily point precipitation in Sweden over the last 80 years. The fraction of stations having daily storms exceeding 40 mm was about 30% in the 1930s and early 1940s, but only 20% in the late 1950s and in the 1960s and 1970s. During the 1980s and 1990s it has been 25% as it also was in the 1920s.

There are studies from Italy, where 200 year data series have been used (Brunetti *et al.* 2000; Cislaghi *et al.* 2005). There is a trend towards less number of rainy days and longer dry periods. The mean precipitation of a rainy day has increased. However, only for the city of Genoa is there an increase of the extreme precipitation. Schmidli & Frei (2005) used 100 years of observations from 104 stations Switzerland. They found an increase of intensive winter storms but not of summer storms. Hundecha & Bardossy (2005) came to the same conclusion for Germany.

Since 1960 according to a study by Osborn *et al.* (2000), high daily rainfalls during winter has increased in Britain, but summer storms have become less intense. The summer rains are still more intense than the winter rains. Also Fowler & Kilsby (2003) have analysed precipitation data for the UK without finding any change of the return period for high daily rainfall. However, they found an increase of the 5 and 10 day precipitation in southern England and a corresponding decrease in Scotland.

Trends of daily precipitation have been investigated for North America. Although the annual precipitation has increased over almost the entire Canada, there is no general trend of changed daily precipitation. However, the number of days with high precipitation has increased in the very north of the country (Kunkel 2003). Kunkel finds an increased daily intensity for the US compared to 1920/30, but not if the investigation is extended to 1880.

It seems that if precipitation series are extended far back there are no clear trends toward changed high daily precipitation in observations series from Europe or North America. However, the very extreme rains can not easily be statistically analysed.

The daily rain series from Malmö, Halmstad and Göteborg from 1919 including 2007 have been used to try to find trends of extreme events. In Figure 7 the annual daily maximum precipitation in Halmstad has been plotted. There is no trend in any direction, nor is there for Malmö or Göteborg, (Bengtsson 2008). Also the moving average has been plotted. From the moving average the trends are visualized for short periods. There is an increase since 1985 of daily extremes in Halmstad, but not over a longer period.

SHORT-TERM RAINFALL

Short-term rainfall of duration hours are briefly included in this study. The intention is to show the spatial correlation between observations within the same city and see how these

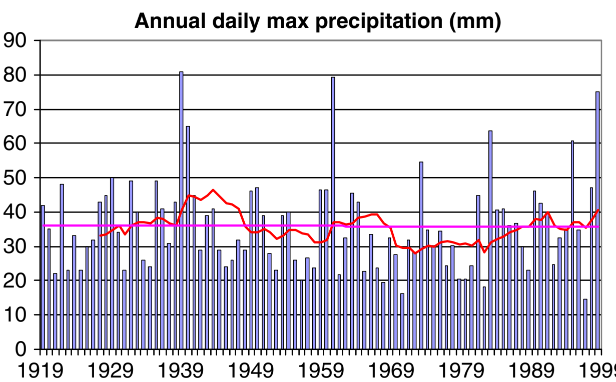

Figure 7 | Annual maximum daily precipitation in Halmstad, 10-year running mean and trend line for the period 1919–2007 (Bengtsson 2008).

are related to the severity of a storm; the correlation may tend to be less for storms of long return period compared to more modest storms and the very extremes tend to be randomly distributed.

Four stations in Malmö have continuous measurements that can be used to investigate extreme precipitation of minute to hour duration: Turbinen with 28 years of data, Limhamn, Augustenborg and Bulltofta all with 12 years of data. All the stations have tipping buckets of 0.2 mm volume. The gauge at Turbinen did not function in July–August 1991 nor in the spring of 1999, but when comparing with the daily observations it is seen that no big storms occurred in this period. Data are missing from all the other stations in the autumn of 1999, also from Bulltofta for the autumn of 2000, and from Augustenborg for the autumn of 2003. These are not periods with very high intensity storms.

The largest hourly storm in Malmö since 1996 occurred in August 2006 at Limhamn. Almost all the daily rainfall (45 mm at Limhamn) was concentrated to 30 minutes (41 mm). At the other stations the storm depth was less than half. However, the mean statistics are not much different for the four stations in Malmö (Table 2). The one- and two-year storms (chosen to be the 11th highest and 5th highest observations) are almost the same at the four stations. The five-year storm is determined from POT-analysis using a threshold of 14 mm, which for all stations corresponds closely to a one-year storm. The five-year storm is almost the same at the four stations. However, as seen when comparing the result of the extreme value analysis for station Turbinen (Figure 8) and station Limhamn (Figure 9), the estimated 100-year storm is much higher for Limhamn, about 50 mm, than for Turbinen, about 38 mm. The 100-year storm determined from the Pareto distribution is similar for Augustenborg, 38 mm, and Bulltofta, 35 mm. Since the derived statistics are the same for all the stations regarding storms of intensity lower than the most extremes, since there are no topographical differences, and since the

Table 2 | Hourly rain depth mm at the stations in Malmö

Bulltofta	60 min	Turbinen	60 min	Limhamn	60 min	Aborg	60 min
max	29	max	38	max	43	max	29
T = 5	26	T = 5	25	T = 5	25	T = 5	24
T = 2	19	T = 2	19	T = 2	19	T = 2	18
T = 1	14.4	T = 1	14.4	T = 1	14.8	T = 1	14.0

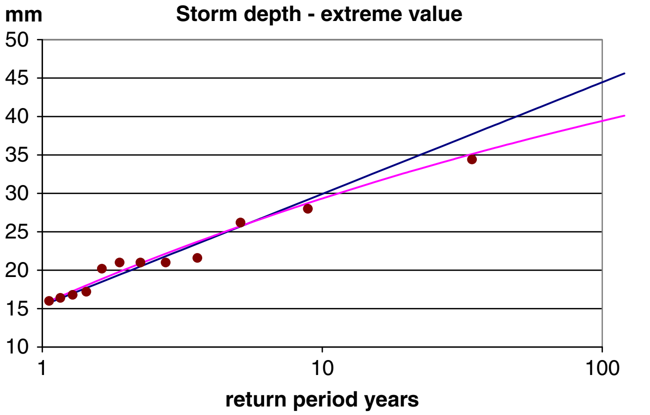

Figure 8 | Return periods of hourly storms at Turbinen, Malmö. Threshold 14 mm, corresponding to the one-year storm. The lower ligther curve is generalized Pareto-distribution and the upper line is exponential distribution.

Table 3 | Number of observations and events at the four stations in the period 1996–2007

Threshold mm	11.0	14.0	17.5
Return period year	0.5	1	2
No observations	85	44	21
No events	49	27	17
No overlap	55	33	12
Mean correlation	0.39	0.16	0

stations are within a few km, it is reasonable to assume that also the most extreme storms at the four stations would have been the same if the observations series were very long. Thus, the small area of Malmö is considered to be homogeneous with respect to rainfall characteristics. Spatial cross-correlation and computation of regional means can then be done in a straightforward way.

The probability of overlapping observation (concurrent observations exceeding threshold level at more than one station) and the cross-correlation between the different stations was determined for different threshold levels. If rain appeared at a second station within three hours after it appeared at a first station, the rain at the two stations was defined to belong to the same event. This allows for a storm to move over both stations within that time. As shown in Table 3, the number of overlapping observations relative to the total observations is high when the threshold level is low. In the table the mean correlation is also shown. The correlation is significant for the 0.5-year return period storms, not for the less frequent storms. The probabilities of concurrent events are shown for threshold level 11 mm/hour (return period about 0.5 year) in Table 4, and for 14 mm/hour (return period 1 year) in Table 5. It is seen from the tables that the probability of an event at a station, when there is an event at another station, is about the same for both threshold levels. It is in the range 0.35–0.6. The highest probabilities for concurrent high storms are between stations Turbinen and Limhamn and Turbinen and Augustenborg. However, when considering these concurrent observations with high probability, the cross-correlation is low. Instead, the only significant correlation is between station Bulltofta and Augustenborg. The correlation is strong 0.8–0.9 being significant at 10% for 0.5-year and one-year return storm. For all other station combinations, the cross correlation drops with increasing rain intensity from being insignificant to close to zero for storms of one-year return period or longer.

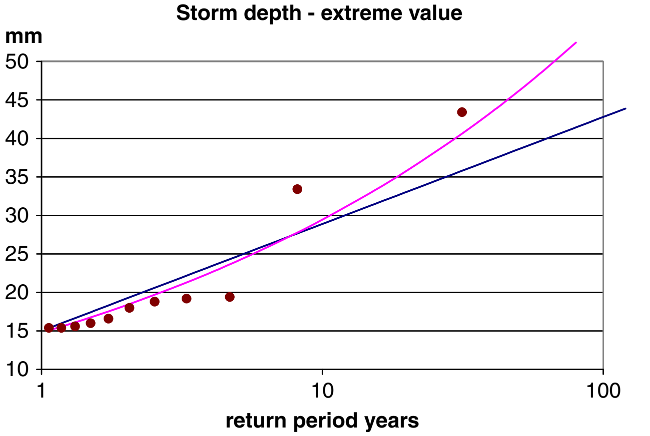

Figure 9 | Return periods of hourly storms at Limhamn, Malmö. Threshold 14 mm, corresponding to the one-year storm. The curved lighter line is generalized Pareto distribution and the lower line is exponential distribution.

Madsen *et al.* (2002) considered regional mean and inter-site correlation to find *T*-year storms for the Copenhagen

Table 4 | Probability of concurrent event hourly storm exceeding 11 mm, if an event occurs at the x-marked station

	B if x	T if x	L if x	A if x
x-Bulltofta		0.35	0.35	0.35
x-Turbinen	0.35		0.60	0.40
x-Limhamn	0.35	0.60		0.35
x-Aborg	0.40	0.60	0.40	

Table 5 | Probability of concurrent event hourly storm exceeding 14 mm, if an event occurs at the x-marked station

	B if x	T if x	L if x	A if x
x-Bulltofta		0.35	0.40	0.50
x-Turbinen	0.35		0.60	0.60
x-Limhamn	0.35	0.60		0.35
x-Aborg	0.50	0.60	0.40	

region. Here a rather crude approach from Roux & Desbordes (1996) based on a similar study in Paris is used. Since it is assumed that the statistics are the same for each individual station, the regional mean is simply the mean of the observations at the four stations giving the 100-year storm as about 41 mm. When determining the confidence interval the variation of the mean must be determined. Roux and Desbordes computed how the effective sample size is reduced, when there are correlation between stations. The reduced effective sample size is

$$n' = n/((1 + 2\, n_{overlap}/n)r)$$

where n is the sample size, $n_{overlap}$ the number of concurrent observations and r the correlation. For the only stations between which there is correlation, Bulltofta and Augustenborg, the total number of observations over the one year return threshold is 19. The number of concurrent observations is only 5, but when these occur the correlation is high, 0.8. The effective number of observations at these two stations reduces from 19 to 13 and the total sample size from 44 to 38.

The standard deviation is estimated as previously for the daily storms but with only the effective number of observations being used. From the standard deviation the confidence at chosen levels is computed. Considering only events in excess of the one-year storms (threshold 14 mm) the confidence interval at the 10% level (5% on each side) is ± 3 mm for return period 5 year, and ± 8 mm for return period 100 year, which is 12% and 20% of the regional mean.

The regional values should be representative for an individual station. It may also be of interest to find the probability of high rainfall somewhere in Malmö, where it rains the most during a certain event. The place may be different from event to event. If only the highest independent observations at all stations are used, the probability of very large storms in one of the stations can be determined, giving an estimate of large storms within a radius of about 2.5 km in Malmö. The hourly storm depth is shown as function of return period in Figure 10. Again the threshold level 14 mm is used, which allows 28 values to be included in the 12-year period. The 100-year storm is then 53 mm, which is close to the storm estimated for the Limhamn station using the generalized Pareto distribution. When the stations are pooled, the Pareto and exponential distributions give the same result also for the very extremes. The 10-year storm to occur somewhere in Malmö is 36 mm, which is considerably higher than for the Limhamn station, 28 mm. The five-year storm is 32 mm. These values, representing storms somewhere in Malmö, are about 30% higher than the regional storms representing specific stations.

A remark should be made concerning the reliability of storm data measured by tipping buckets. The gauges used in the present study are not individually calibrated. The stations are run by the city of Malmö without continuous control of the stations. The gauges used in Malmö have not been calibrated. The rain intensity is simply determined linearly from the number of tippings. However, the tipping intensity is not always linear with the rain intensity. Some rain falls in between the buckets, or the buckets are not completely emptied at each tipping. When using commercial buckets, the volume of the bucket is not exactly as given by the manufacturer. A severe problem with high-resolution rainfall measurements is that debris that has fallen into the funnel of

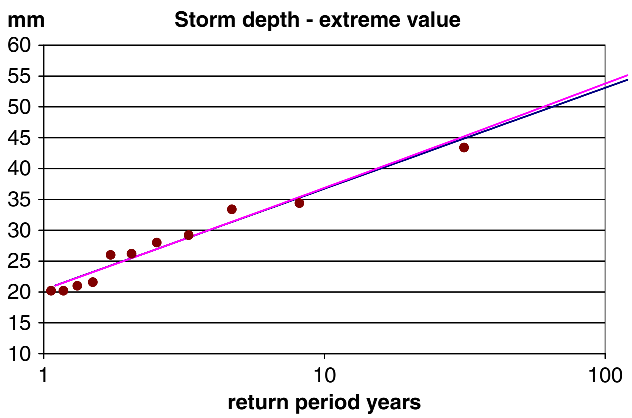

Figure 10 | Return periods for hourly storms to occur somewhere within a 2.5 km radius in Malmö. The Pareto distribution is slightly above the exponential line.

the gauge may disturb the measurements. The rain water does then not fill the buckets at the correct intensity and with the correct timing. Manual check of all data from the Malmö stations was done excluding observations when the 5-minute storm depth was the same as the 60-min storm depth and also excluding observations, when there was no rain at all at any accumulating station in the larger Malmö region.

CONCLUSIONS

The return period of daily rain exceeding 40 mm is 2–5 years at different stations in southern Sweden. The return period can be related to the annual precipitation. However, the most extreme storms seem to occur randomly within the 10 000 km^2 southernmost region of Sweden not being related to physiographic characteristica or mean statistics. Daily storms exceeding 100 mm are very rare with return period exceeding 100 years. There is no trend towards increasing or deceasing very high daily precipitation over the last 90 years along the Swedish west coast. Concerning hourly storms, only few very intense storms have occurred concurrently at stations in Malmö within a 2.5 km radius. For modest storms of 1-year return period the probability of concurrent high rain intensity is 0.35–0.60.

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