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Trends in extreme precipitation and return values in Norway 1900-2004

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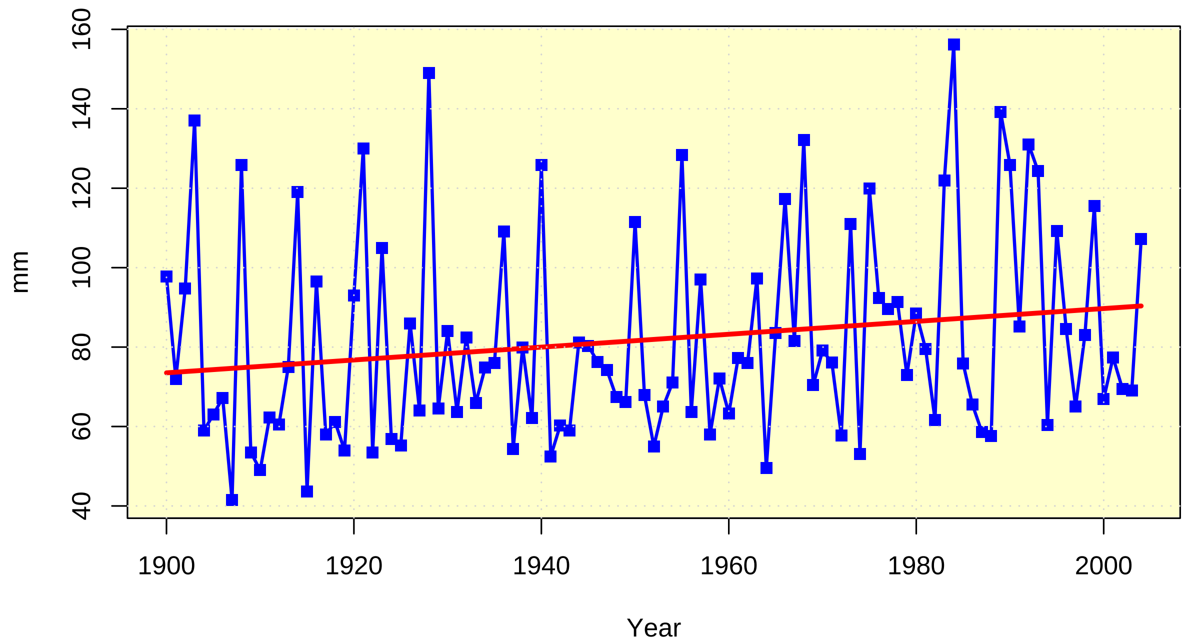

Maximum 1-day precipitation during the last century at Lysebotn, South Western Norway.

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Abstract

Trends and frequencies of extreme precipitation have been studied for long observation series in Norway. The annual maximum 1-day precipitation shows an increasing tendency during the 20th century, although significant trends were found only at four locations. The frequency of extreme precipitation values was highest in the 1920's - 1930's and in the 1980's – 1990's. The occurrence of the most extreme events seems to have decreased during the 20th century, whereas the number of slightly smaller precipitation events has increased in the same period.

Design values used for flood predictions and dam constructions were investigated for possible changes during the last decades. A 5% increase in the 5-years return period value was found on a regional scale in the south western and the northernmost regions of Norway since the standard normal period 1961-1990. In the remaining Norwegian regions the picture was more scattered with both increases and decreases. Large local and regional gradients exist in both annual and 1-day maximum precipitation. These gradients are also reflected in the absolute and relative changes in the return values.

Keywords
Precipitation, extremes, trends, Norway, 20th century

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1 Introduction

An increase in the annual precipitation has been observed during the last century at higher northern latitudes (Hulme, 1995; Dai et al.,1997; Folland, et al., 2001). Studies of Norwegian precipitation series indicate an increase in annual and partly in seasonal precipitation also in Norway (Hanssen-Bauer 2005; Hanssen-Bauer and Førland, 1998). Hanssen-Bauer (2005) found that the annual precipitation had increased between 3% and 21% for various parts of Norway during the period 1895-2004.

In the latest IPCC-report Folland et al. (2001) concluded that over the latter half of the 20th century it is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events reported by the available observing stations in the mid- and high-latitudes of the Northern Hemisphere. In a study of trends in maximum 1-day precipitation in the Nordic region, Førland et al. (1998) found a maximum in the 1930s and a tendency of increasing maximum values during the 1980s and 1990s.

Estimates of extreme precipitation is one of the basic parameters for the runoff calculations in the Norwegian ”Directions for Flood Estimation” (NVE, 2002). The methodology used for estimating return period values for extreme precipitation in Norway is described in Førland (1992).

The capacities of existing Norwegian dam constructions and river regulations are dimensioned and evaluated against estimates of extreme floods and precipitation based on long series of observations. A key issue is whether these estimates are still valid, or whether the climate development during the recent global warming urges a revision of the present return period values.

The aim of this study is therefore to investigate if the maximum 1-day precipitation has changed during the last century and to investigate if the design values, used in dam constructions, would be different if calculated on the last 30 years of observations compared to those of the standard normal period, 1961-1990.

2 Methods and data

2.1 Return values and PMP

In Norway a modified version (Førland and Kristoffersen, 1989; Førland, 1992; Alexandersson et al 2001) of the British M5-method (NERC, 1975) is used for estimation of extreme precipitation values with long return periods. The basic value for the estimations in Norway is the 24h precipitation with a return period of 5 years, M5, cf. eqs. (2.1) and (2.2). In a Nordic comparison (Alexandersson et al., 2001) it was found that the General Extreme Value (GEV) and M5-methods gave reasonable estimates also for the most extreme values.

The Gumbel equation (2.1) (WMO, 1981) was used to calculate extreme precipitation with return period, T, up to 5 years.

$$X(T) = Xmean - \frac{\sqrt{6}}{\pi} * \left(0.577 + \ln\left(-\ln\frac{T-1}{T}\right)\right) * Xstdev \qquad (2.1)$$

For return periods larger than 5 years, the equation (2.2) was used (Agersten, 2002)

$$\begin{aligned} &X(T) = M5 * \exp\left(C * \left(\ln(T-0.5) - 1.5\right)\right) \\ &\quad C = 0.165 + 0.0236 * \ln(M5) && 2 < M5 \le 10 && (mm) \\ &\quad C = 0.219 && 10 < M5 \le 15 && (mm) \\ &\quad C = 0.300 - 0.0294 * \ln(M5) && 15 < M5 \le 25 && (mm) \\ &\quad C = 0.3584 - 0.0473 * \ln(M5) && 25 < M5 \le 350 && (mm) \\ &\quad C = 0.167 - 0.0145 * \ln(M5) && 350 < M5 \le 1000 && (mm) \end{aligned} \qquad (2.2)$$

where M5 = X(T=5years) (from eq. 2.1).

Probable maximum precipitation, PMP, is the extreme precipitation with infinite return period, T=∞. The PMP value can be estimated using (2.2) with the following T values (Førland, 1987)

$$\begin{aligned} &T = 36000 && (year) && M5 \le 45 && (mm) \\ &T = 47829 - 262.9 * M5 && (year) && 45 < M5 \le 125 && (mm) \\ &T = 22503 - 62.4 * M5 && (year) && 125 < M5 \le 200 && (mm) \\ &T = 10000 && (year) && 200 < M5 && (mm) \end{aligned}$$

The observed precipitation values used in the calculations of the PMP is given for a fixed time period (06 – 06 UTC). However, the design value of precipitation used in flood prediction is given for a **n** hours period. The precipitation for an arbitrary 24 hours period is 'normally' higher than for the fixed 24 hours period. Thus, the M5 value for the fixed one-day period need to be multiplied by a 'one-day to 24-hours factor', in order to achieve the design value. In this study a conversion factor of 1.13 is used, which is an average value based on continuous precipitation measurements (WMO, 1974).

2.2 Trend analyses

Trend lines were calculated fitting a linear model, using the method of least squares, to each of the time series of annual maximum 1-day precipitation. The non-parametric Mann-Kendall test was applied for investigating the significance of the trends. The test can be used without knowing the exact distribution of the time series, and its test statistics t is defined by

$$t = \sum_{i=1}^{n} n_i \tag{2.3}$$

where n is the number of elements and n_i is the number of smaller elements preceding element x_i (i = 1,2,..,n) (Sneyers, 1990). The test statistics is close to normally distributed under the hypotheses of randomness for n > 10 (Sneyers, 1995). The expectation value, E(t), and variance, Var(t), of the test statistics are given by

$$E(t) = \frac{n(n-1)}{4} \tag{2.4}$$

$$Var(t) = \frac{n(n-1)(2n+5)}{72} \tag{2.5}$$

The standardised distribution of the test statistic is

$$u(t) = \frac{t - E(t)}{\sqrt{Var(t)}} \tag{2.6}$$

The time series were successively tested by adding one by one year reapplying the test for each year added. Using graphical presentation of the standardised test statistic, the development of trends in the series was easily traced. It has been proved valuable to also apply the test backward, starting with the last year, (Demarèe, 1991). The test were therefore ran both forward and backward.

2.3 Extreme precipitation events

The return values (i.e. M5 and PMP) are calculated on time series of the maximum 1-day precipitation event each year. If several events with precipitation close to the maximum value occur during a year, this will not be reflected in the return values. In order to investigate if the climate has become more extreme, we have studied the regional occurrences of large precipitation events. The occurrences of precipitation events exceeding a) the M5 value and b) 80% of the M5 value were calculated on annual and 5-years basis for each station. M5 values for fixed 1-day periods calculated on the whole time series were used. Average frequencies of extreme precipitation were calculated for groups of stations in different regions (see Table 1).

3 Results and discussion

3.1 Changes in design values from 1961-90 to 1975-2004

Design values were investigated for 211 stations, representing the different precipitation regions in Norway, Figure 1 and Table 1. The regions reflect areas where long term trends and decadal scale variability of standardised precipitation are quite uniform (Hanssen-Bauer and Førland, 1998). In southern Norway a relatively dense network of precipitation stations exist, Figure 1. Each of the climate regions is covered by several stations. However, the vast majority of the stations are located below the timber line. Only a few stations represent the mountain areas and only up to 950 m a.s.l. Further north the network is coarser with few stations within each region. The coverage of the northernmost counties is especially poor.

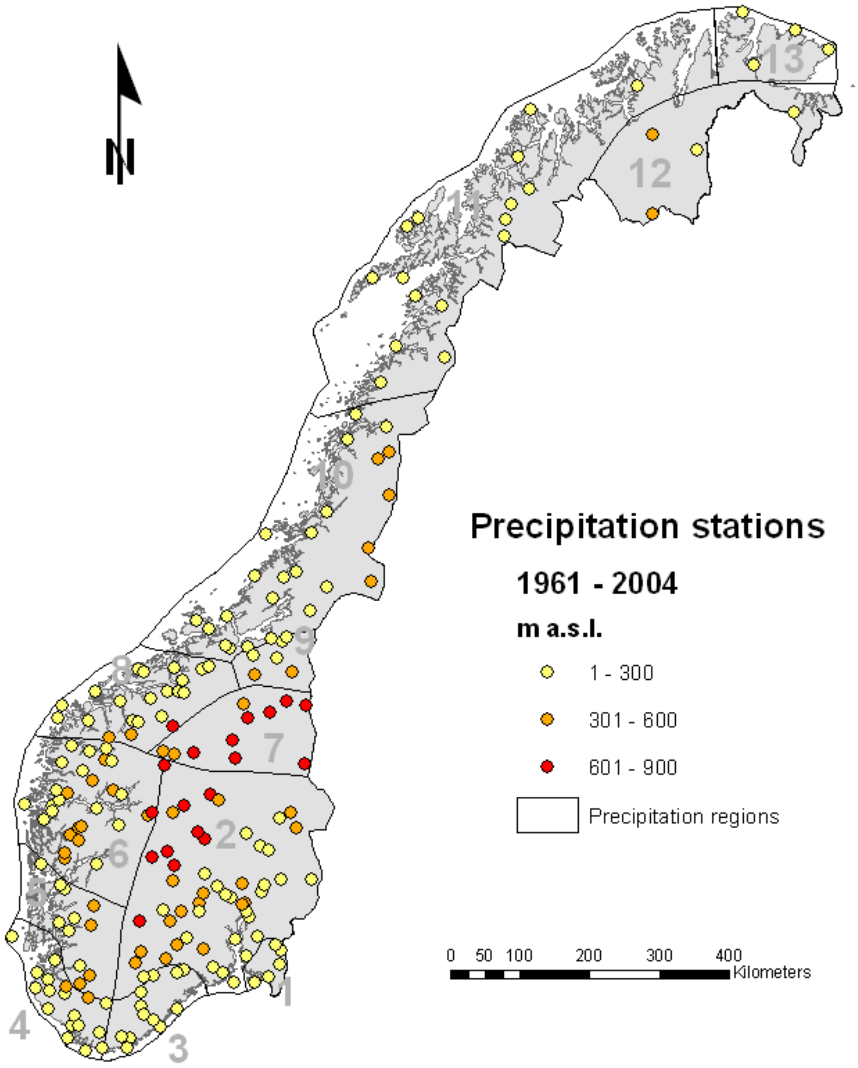

Figure 1 Map of precipitation regions and precipitation stations with observations in the period 1961 – 2004. The colors indicate the altitudes of the stations.

Table 1 Overview of the precipitation regions, groups of regions and stations within each region.

Precipitation region	Region group	Number of stations		Station altitudes (m a.s.l.)
		1900 – 2004	1961 - 2004	
1	South East (SE)	2	5	8 – 182
2	South East (SE)	8	52	6 – 954
3	South East (SE)	2	12	4 – 252
4	South West (SW)	2	18	4 – 348
5	South West (SW)	3	11	5 – 582
6	South West (SW)	5	28	3 – 806
7	Central (C)	3	11	372 – 830
8	Central (C)	1	20	4 – 621
9	Central (C)	1	6	33 – 330
10	North (N)	2	24	10 – 498
11	North (N)	4	16	3 – 230
12	North (N)	2	4	44 – 389
13	North (N)	0	4	8 – 14

Five years return period values (M5) and probable maximum precipitation (PMP) were calculated on the observed 1-day precipitation series for the period 1975-2004 and compared to those of the recent standard normal period 1961-1900.

Large local and regional gradients exist for maximum 1-day precipitation as well as annual precipitation in Norway. This is reflected in the M5 and PMP values which range from 25 to 160 mm and from 160 to 450 mm, respectively. Figure 2 shows the geographical distribution of the M5 and PMP values. In the inland of the south eastern and central regions, and in the north western regions, large areas with relatively uniform distribution are found. These areas are also characterized by relatively small precipitation values. On the western coast, both in the south and in the north, the distribution is more scattered and large gradients exist within short distances. The highest design values are in coastal regions in Western Norway and in Nordland county.

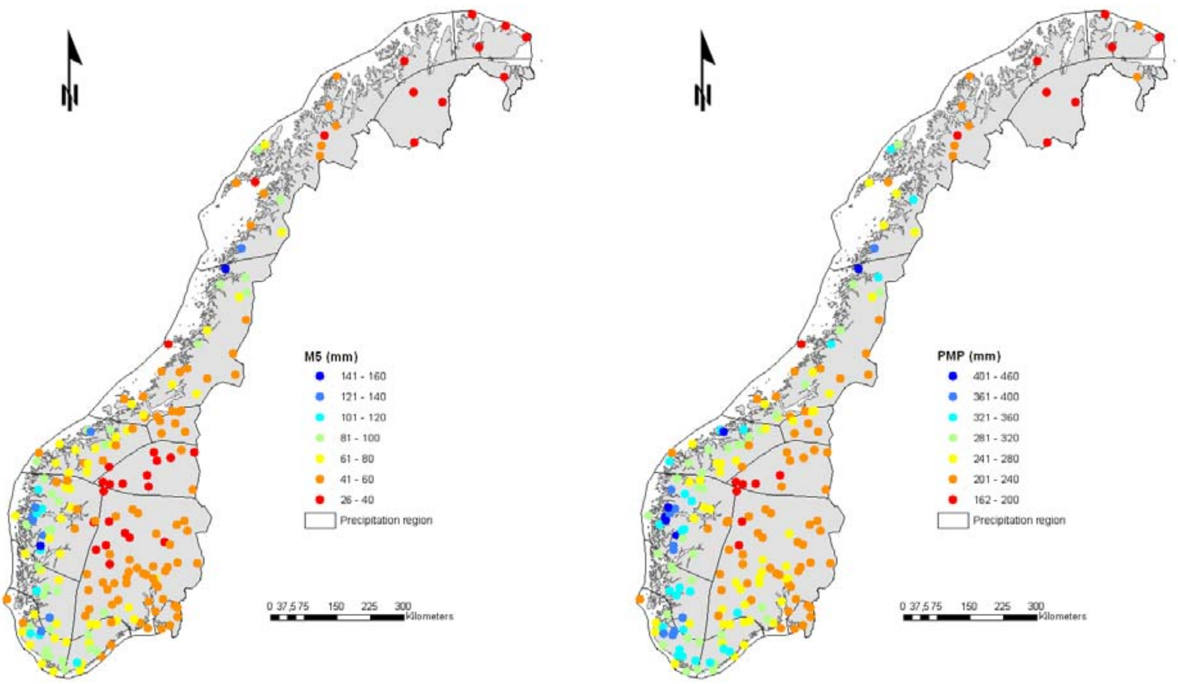

Figure 2 M5 and PMP values for the recent normal period (1961-1990).

The changes in M5, from the standard normal period 1961-90 to the most recent 30-years period (1975-2004), ranges from -16% to +23 %, Table 2 and Figure 3. At half of the stations the change is within +/- 5%. Similar to the M5 values itself, the changes in M5 show large variations within short geographical distances. A scattered picture with both large increases and large decreases in M5 is seen in northern Norway. In region 13, the M5 has increased whereas the north western coastal areas show a tendency towards decreasing M5. However, the stations are sparsely distributed and the results should be interpreted with caution. The regional median values (Table 2) show a general increase in M5, up to 5%, in the south-western part of Norway (region 4-6) and the western part of the central regions (region 8). In the inland of the central regions (region 9-10) the changes span over a wide range, with a weak dominance towards decreased M5. The northern part (inland) of region 1 shows a general increase in M5, similar to that of the south-western regions, whereas the changes in M5 are apparently random distributed in the southern part of the south-eastern regions. The change in PMP, Figure 4, shows a similar pattern in that of M5, although with slightly smaller ratios.

Table 2 Regional change in the M5 and PMP values. Median, minimum and maximum of the ratio between the last 30 years period (1975-2004) and the standard normal period (1961-1990) are listed.

Region number	Number of stations	M5 ratio 7504/6190			PMP ratio 7504/6190		
		Median	Minimum	Maximum	Median	Minimum	Maximum
1	5	0.98	0.96	1.02	0.99	0.98	1.01
2	52	1.04	0.89	1.20	1.02	0.94	1.12
3	12	1.02	0.95	1.23	1.02	0.97	1.13
4	18	1.02	0.95	1.12	1.01	0.97	1.07
5	11	1.05	0.99	1.08	1.03	0.99	1.05
6	28	1.05	0.97	1.17	1.03	0.99	1.09
7	11	1.00	0.87	1.15	1.01	0.93	1.08
8	20	1.03	0.97	1.17	1.02	0.99	1.11
9	6	0.99	0.96	1.13	1.00	0.98	1.08
10	24	0.99	0.84	1.12	1.00	0.90	1.07
11	16	1.01	0.85	1.14	1.00	0.91	1.08
12	4	0.97	0.92	1.03	0.99	0.96	1.02
13	4	1.09	1.05	1.12	1.06	1.03	1.07

The absolute change of the M5 an PMP values ranges from -15 to +16 mm (M5) and from -29 to 33 (PMP), respectively. The largest increases are seen in south western Norway and the largest decreases in north western Norway, Figure 5 and Figure 6.

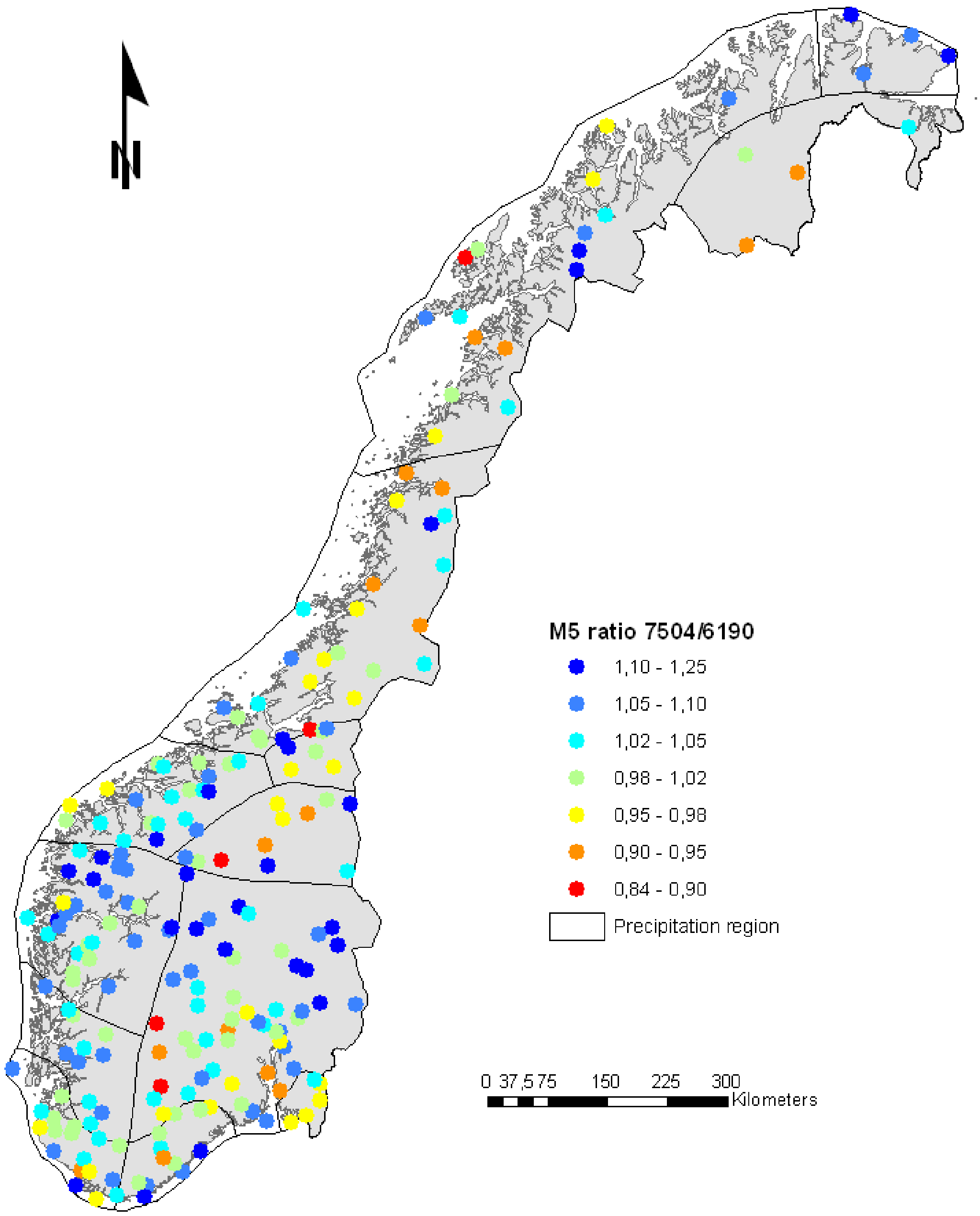

Figure 3 Relative change in the M5 values from the 1961-1990 period to the 1975-2004 period.

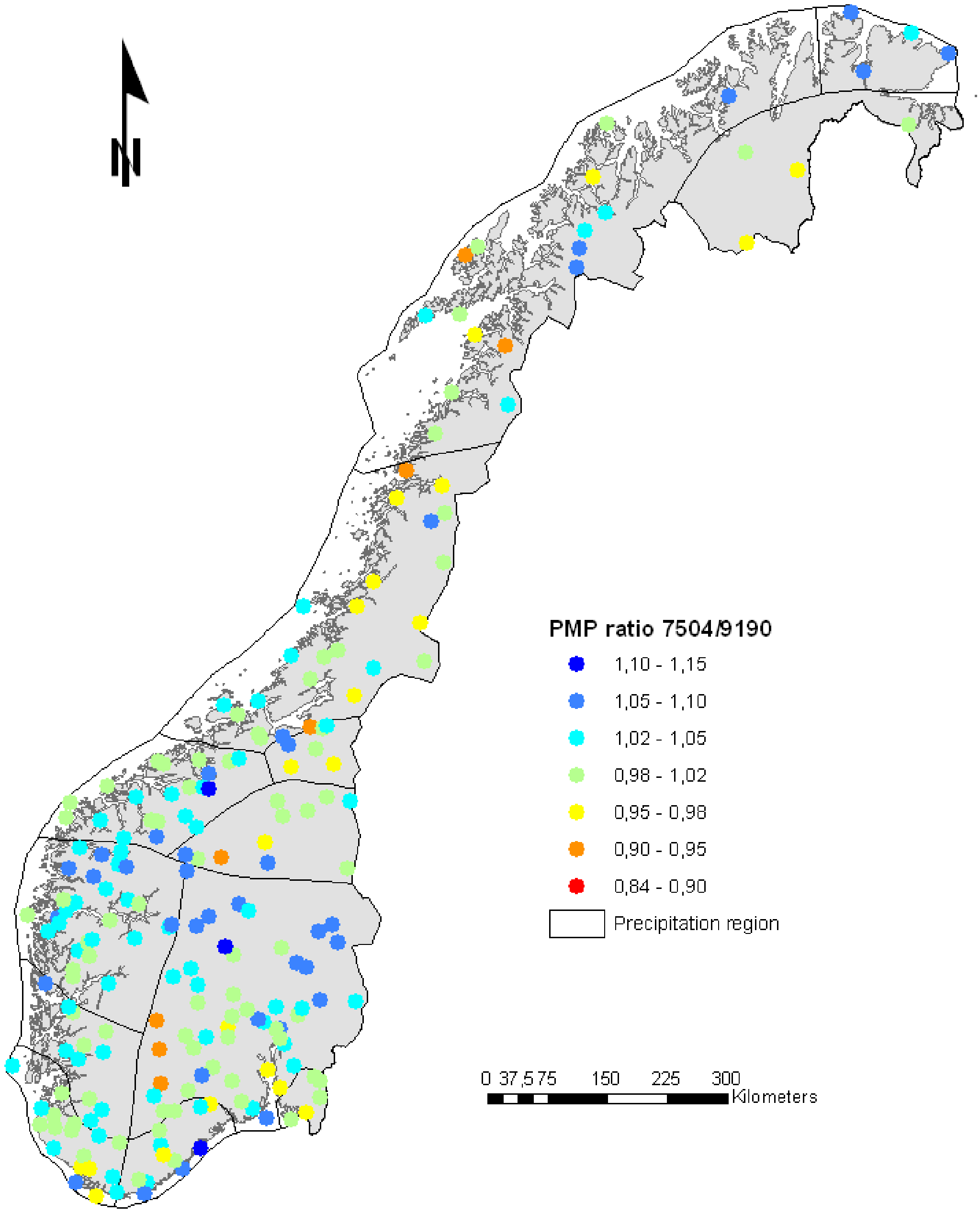

Figure 4 Relative change in the PMP values from the 1961-1990 period to the 1975-2004 period.

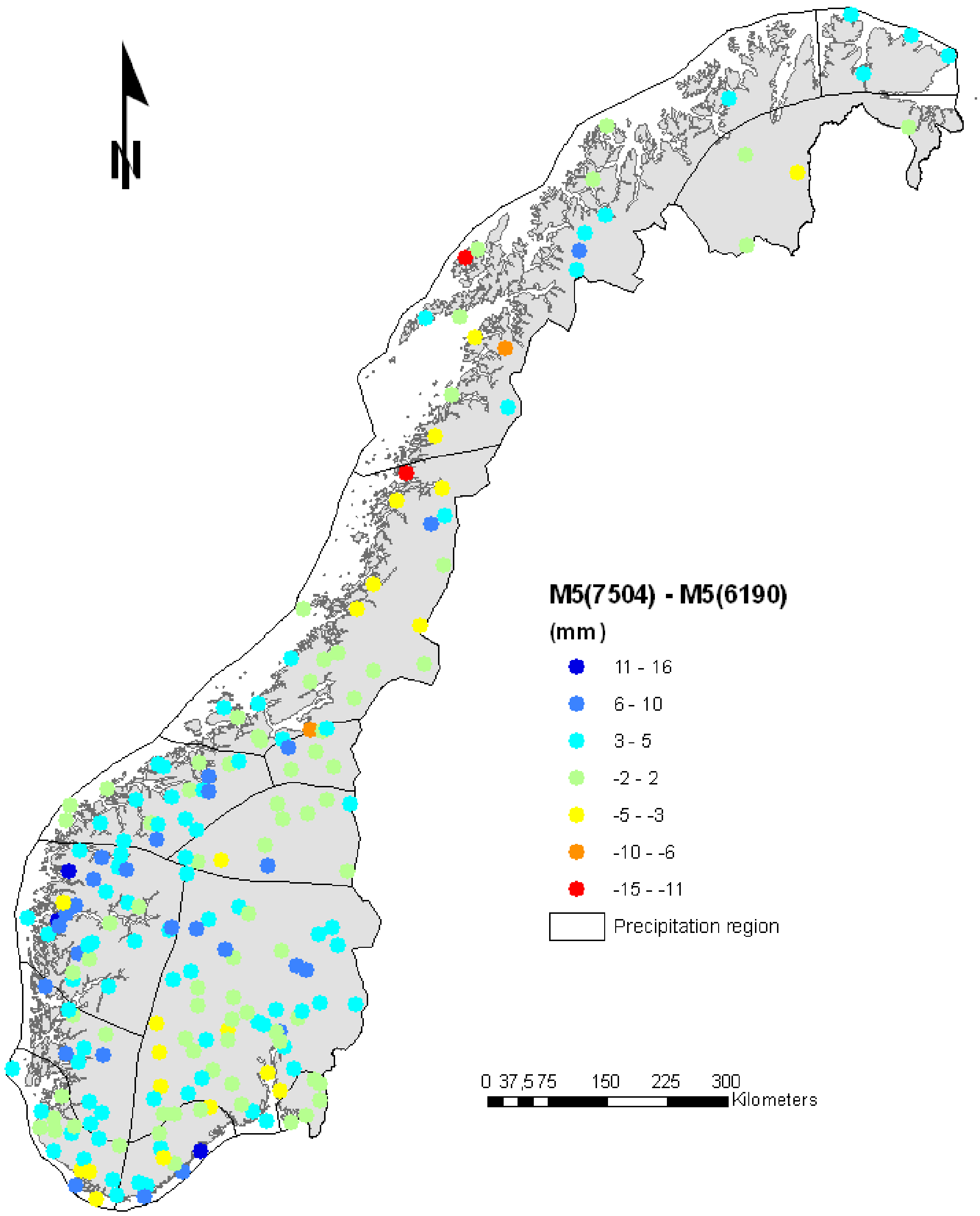

Figure 5 Change in M5 values (mm) from the 1961-1990 period to the 1975-2004 period.

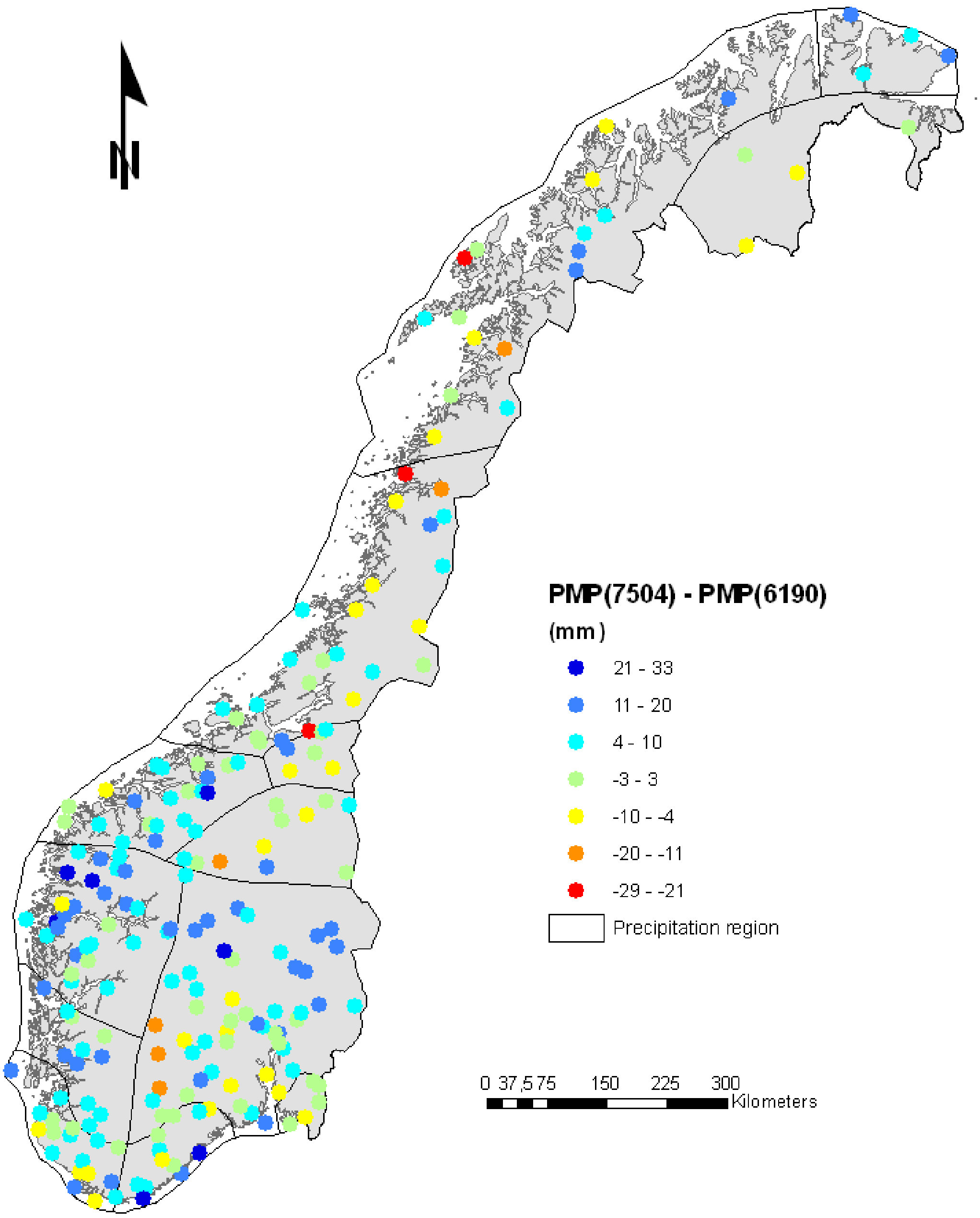

Figure 6 Change in PMP values (mm) from the 1961-1990 period to the 1975-2004 period.

3.2 Long term variations of M5 values

Changes in the extreme precipitation and return period values were analysed for the last century. Long term precipitation series from 33 stations, Table 3 and Figure 7, with daily observations since 1900 were selected for the study. In addition two stations with observations from 1931 were included in order to achieve a better representation of the northern part of Norway. A few stations in northern Norway are lacking values for some months during the 2nd world war. For some of the other stations the data series covers a slightly shorter period. Except for that, most of the series consist of complete records. The precipitation series are spread over the Norwegian mainland, representing different climate regions. Most of the stations are located below the timber line. Thus, the alpine areas are poorly represented.

M5 values were calculated on moving 30 years periods and compared to the $M5_{6190}$ (the M5 value of the recent normal period, 1961-1990). Trend analyses of the maximum 1-day precipitation were conducted and the occurrences of extreme precipitation events were analysed.

Table 3 Stations with long term precipitation series used in this study.
R: Region number, StNum: Station number, Name: Station name, Period: Period of daily observations available in digital form.

R	StNum	Name	UTM zone 33 N		Altitude	Period
			East (m)	West (m)	(m a.s.l.)	
1	1230	HALDEN	293324	6559288	8	1882 - 2005
1	1650	STRØMSFOSS SLUSE	309876	6578316	113	1883 - 2005
2	5350	NORD-ODAL	310449	6699653	147	1896 - 2005
2	6550	ØRBEKKEDALEN	332074	6772015	513	1897 - 2005
2	12520	NES PÅ HEDMARK	280092	6746340	205	1901 - 2005
2	18500	BJØRNHOLT I NORDMARKA	259887	6664930	360	1883 - 2005
2	25640	GEILO	125162	6730140	841	1896 - 2005
2	27800	HEDRUM	212729	6572692	31	1896 - 2005
2	31900	TUDDAL	152336	6639433	464	1896 - 2005
2	34900	POSTMYR I DRANGEDAL	145442	6586110	464	1896 - 2005
3	38450	HEREFOSS	113207	6505462	85	1896 - 2005
3	39220	MESTAD I ODDERNES	82784	6474729	151	1900 - 2005
4	44480	SØYLAND I GJESDAL	-21687	6540066	263	1903 - 2005
4	44800	SVILAND	-23374	6555438	230	1896 - 2005
5	42890	SKREÅDALEN	22381	6549799	474	1896 - 2005
5	45350	LYSEBOTN	21826	6576347	9	1896 - 2005
5	46450	RØLDAL	42460	6660694	393	1903 - 2005
6	50350	SAMNANGER	295	6737748	370	1901 - 2005
6	51470	BULKEN	21022	6755428	323	1896 - 2005
6	53070	VIK I SOGN III	46583	6800132	65	1895 - 2005
6	54600	MARISTOVA	125135	6794947	806	1896 - 2005
6	55550	HAFSLO	82110	6820413	246	1896 - 2005
7	9100	FOLLDAL	241900	6898143	709	1896 - 2005
7	10100	OS I ØSTERDAL	295274	6938055	788	1896 - 2005
7	15660	SKJÅK	141706	6882108	432	1896 - 2005
8	58960	HORNINDAL	63627	6902684	340	1896 - 2005
9	68330	LIEN I SELBU	304747	7014790	255	1896 - 2005
10	72100	NAMDALSEID	315895	7130466	86	1896 - 2005
10	73800	TUNNSJØ	435916	7173942	376	1907 - 2005
11	81900	SULITJELMA	546446	7446810	142	1896 - 2005
11	83500	KRÅKMO	541640	7520122	76	1896 - 2005
11	86850	BARKESTAD	492015	7634007	3	1897 - 2005
11	90450	TROMSØ	652342	7732168	100	1931 - 2005
12	97250	KARASJOK - LATENJARGA	909023	7741604	129	1931 - 2005
12	99450	BJØRNSUND	1085168	7777198	28	1896 - 2002

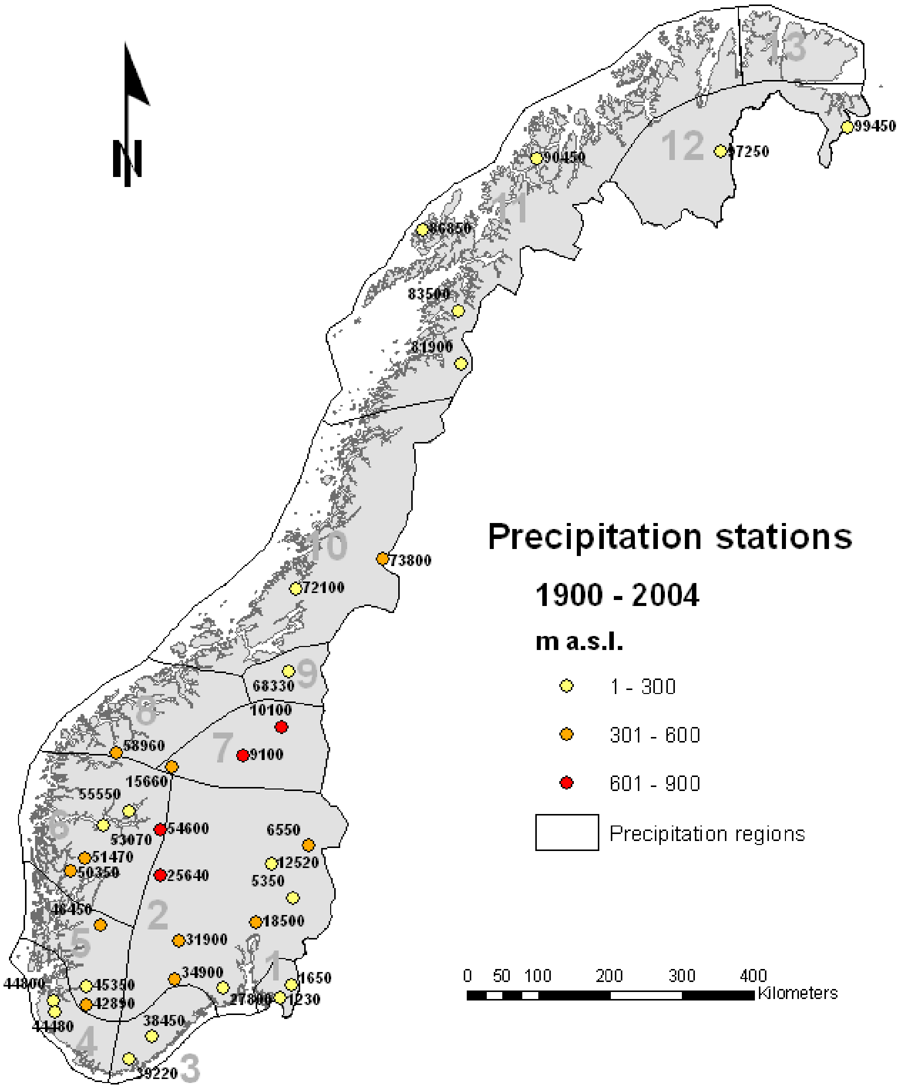

Figure 7 Map of the stations with long precipitation series (1900 – 2004). The colors indicate the altitudes of the stations.

The moving 30-years M5 values show large deviations, up to 35 % at 86850 Barkestad, from the recent M5 value (M5 for the normal period 1961-1990), Figure 8 and Appendix A1. At some stations the recent M5 value is close to maximum in the studied period and for other stations approximately at minimum. A local maximum in the periods ending around 1940 – 1960 and a tendency of increasing M5 values during the last 10-15 years is seen for many of the stations. The PMP values show a pattern almost identical to that of the M5 values, although with lover percentages. Large fluctuations in the M5 and PMP values are also observed at stations where no significant long term trend is found in the maximum precipitation.

a) b)

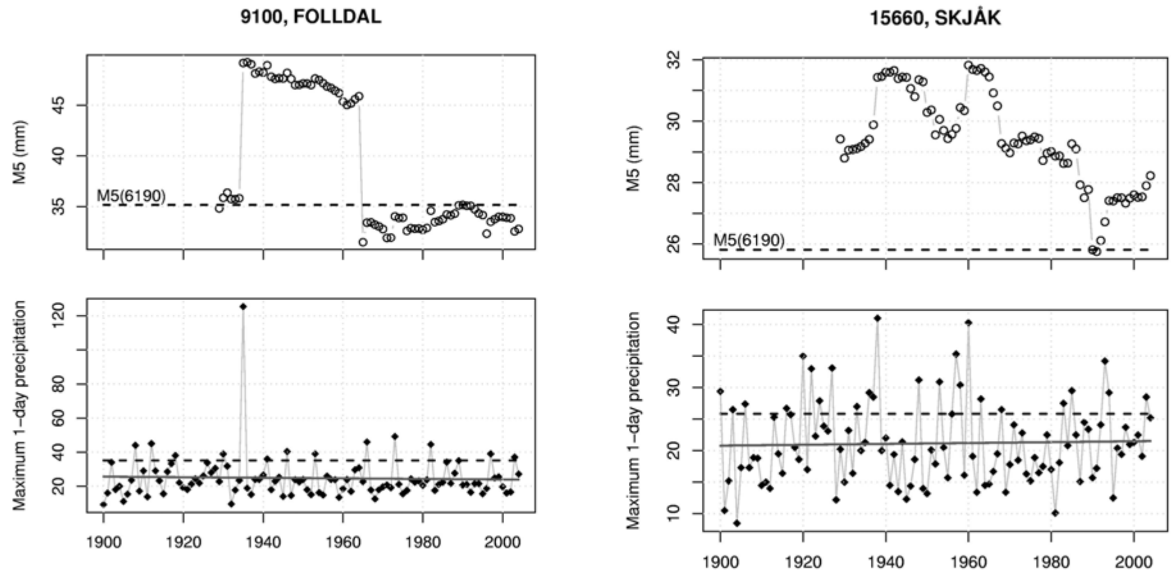

Figure 8 Example on the influence on M5 of (a) one single extreme 1-day precipitation event and (b) a change in frequency and magnitude of extreme maximum 1-day precipitations when no trend exists.

The M5 graph for 9100 Folldal, Figure 8a, gives an indication of the sensitivity in the calculations. One single very extreme precipitation event (‘outlier’), in an otherwise rather homogeneous series of maximum precipitation, causes an increase in M5 value of approximately 40%. Because the M5 values are estimated from 30 years of observations, this increase is seen over the same period of time. Similar influences of single extreme precipitation events are seen at several of the other stations too. A natural question is if the observation is real. In this case, the meteorological observer has made a note in the protocol (freely translated into English): “A heavy thunderstorm passed over Folldal on June 27th 1935. 100 mm rain fell between 16:05 to 17:35. The ‘Folldal værks’ power station was set on fire by a lightning stroke and pretty much damaged.”

An interesting case is observed at 15660 Skjåk, Figure 8b. The frequency of extremely high maximum precipitation (maximum precipitation above $M5_{6190}$) has decreased resulting in lower M5 values during the last decade than earlier. Simultaneously a small, although insignificant, increase in maximum precipitation has occurred.

Both these examples indicate that the Gumbel equation, used to calculate the M5 values, is sensitive to occurrences of very extreme events and that ‘outliers’ may dominate the average annual maximum. Using longer observation series will reduce the influence of single events, giving more robust estimates of the return values. Therefore, in the basic methodology for estimation of extreme precipitation in Norway, the M5-values for short time periods were adjusted to be valid for the whole 20th century (Førland, 1987). Local outliers were smoothed by analysing the ratio between M5 and the annual normal precipitation (Førland, 1987, 1992).

3.3 Trend in maximum 1-day precipitation

Maximum observed 1-day precipitation ranges from 41 mm at 15660 Skjåk to 195 mm at 50350 Samnanger, Figure 9a and Table 4. In general, the highest maxima are found in the southern, western and north western regions. There are also large local and regional gradients in the mean annual maximum 1-day precipitation, Figure 9b, ranging from 21 mm at 15660 Skjåk to 108 mm at 50350 Samnanger.

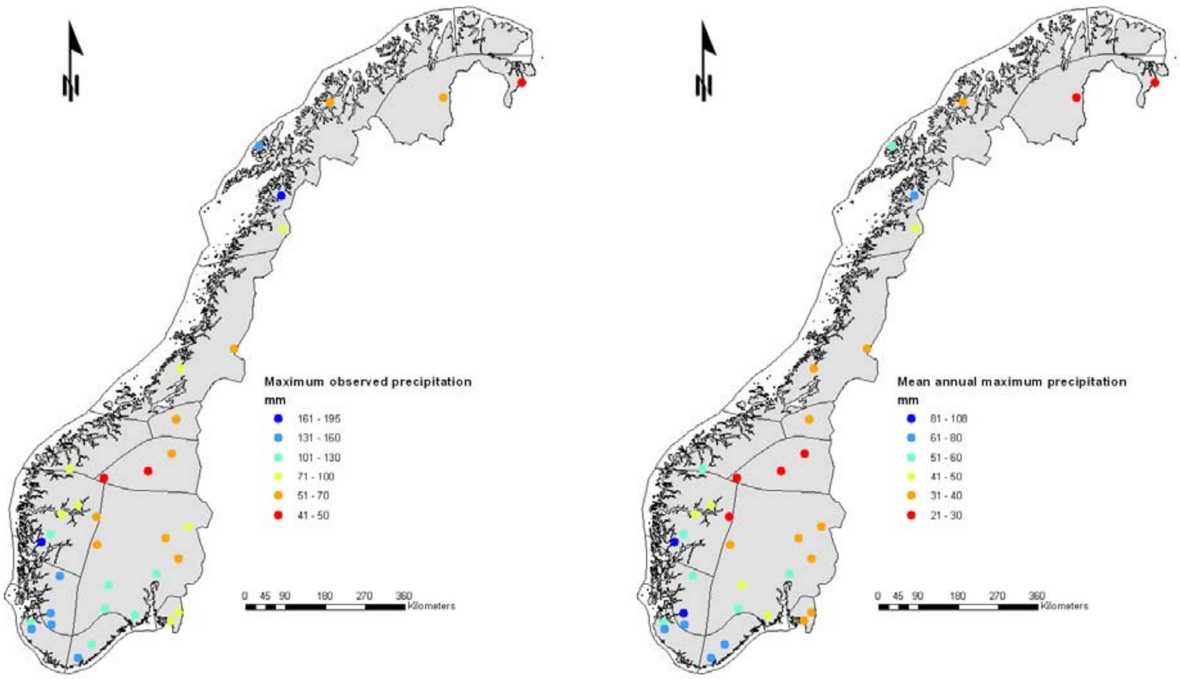

Figure 9 Absolute maximum and mean annual maximum1-day precipitation at the studied locations.

Trend analyses of the maximum 1-day precipitation indicate an increase since 1900 for two thirds of the stations. The change is moderate for most of the stations and the trend is significant at 5 % level at only four stations, Table 4 and Figure 10. No clear relation between increase in maximum precipitation and precipitation regions was found. The largest increase in the maximum precipitation is in the south-eastern part of Norway. However, stations with no trend or negative trend, although insignificant, are also present in this area.

Table 4 Statistics and trends of the annual maximum 1-day precipitation.
Linear trends are given as mm per decade and in % of the 1961-90 value per decade.

R	StNum	Annual maximum 1-day precipitation					Trends		Level of Signifi-cance
		Min	Max	Median	Mean (1900-2004)	Mean (1961-1990)	mm per decade	% of mean (1961-1990)	
1	1230	20	73	34	37	37	0.07	0.2	not sign.
1	1650	20	79	34	36	37	-0.02	-0.1	not sign.
2	5350	19	69	33	35	33	-0.02	-0.1	not sign.
2	6550	20	74	35	38	36	0.31	0.9	not sign.
2	12520	14	65	28	31	27	0.22	0.8	not sign.
2	18500	28	104	50	51	50	0.24	0.5	not sign.
2	25640	19	59	30	31	31	0.04	0.1	not sign.
2	27800	29	111	47	50	49	-0.32	-0.7	not sign.
2	31900	21	121	41	43	41	-0.54	-1.3	not sign.
2	34900	24	121	54	58	62	0.99	1.6	not sign.
3	38450	28	116	61	65	68	0.06	0.1	not sign.
3	39220	36	151	67	70	73	0.91	1.3	not sign.
4	44480	44	158	69	74	77	-0.12	-0.2	not sign.
4	44800	35	129	56	59	63	0.57	0.9	not sign.
5	42890	37	141	66	69	73	1.66	2.3	1%
5	45350	42	156	76	82	89	1.62	1.8	5%
5	46450	29	132	53	56	56	0.23	0.4	not sign.
6	50350	66	195	109	108	107	-0.25	-0.2	not sign.
6	51470	37	104	54	56	56	-0.07	-0.1	not sign.
6	53070	20	73	40	42	47	0.85	1.8	5%
6	54600	11	60	26	29	30	1.42	4.7	1%
6	55550	22	72	40	41	41	0.23	0.6	not sign.
7	9100	9	126	22	25	25	-0.17	-0.7	not sign.
7	10100	13	58	25	27	28	-0.11	-0.4	not sign.
7	15660	9	41	20	21	19	0.07	0.4	not sign.
8	58960	37	96	55	56	56	0.51	0.9	not sign.
9	68330	20	63	32	33	32	-0.08	-0.2	not sign.
10	72100	22	79	38	40	41	0.24	0.6	not sign.
10	73800	15	62	30	31	33	0.44	1.3	not sign.
11	81900	23	85	43	46	48	0.28	0.6	not sign.
11	83500	27	172	61	65	68	-0.52	-0.8	not sign.
11	86850	28	136	47	53	61	0.31	0.5	not sign.
11	90450	20	64	30	32	32	0.12	0.4	not sign.
12	97250	11	51	23	23	25	0.70	2.8	not sign.
12	99450	11	46	23	24	27	0.42	1.5	not sign.

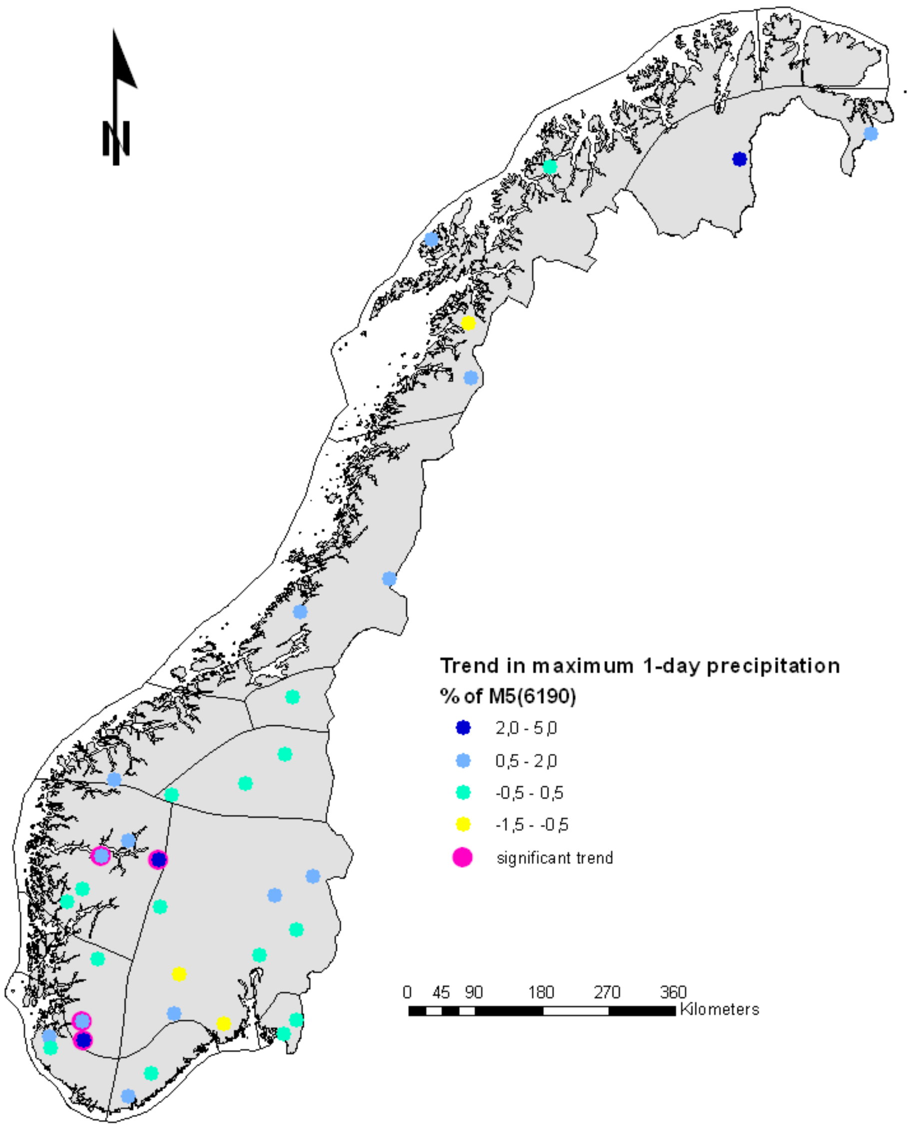

Figure 10 Trend in the annual maximum of observed 1-day precipitation in the period 1900 – 2004.

3.4 Occurrence of extreme precipitation.

The result of the frequency analyses of extreme 1-day precipitation events are shown in Figure 11. The highest frequencies are found in the 1920s and the 1930s, and, for the south western and central regions, in the 1980s and the 1990s (Figure 11, column 1). This is in accordance with Førland et al (1998) who found a maximum frequency of 'extraordinary precipitation events' in Fennoscandia in the 1930s and in the 1980s and 1990s. The frequency of precipitation events ≥ M5(1-day) (M5 for fixed 1-day period) shows a clear decrease in the south eastern regions. In the other regions the changes are minor. The change in frequencies becomes more visible when accumulated over discrete five years periods (Figure 11, column 2). Weak tendencies of decreasing frequencies are seen in the south western and northern regions whereas a weak increase is seen in the central regions. The picture changes when the threshold is decreased to 80% of the M5(1-day) value. Then a general increase in the frequencies is seen in all regions (Figure 11, column 3), although rather weak except for the south western regions. This indicates that the frequency of large extremes has decreased but that the frequency of slightly smaller precipitation events has increased.

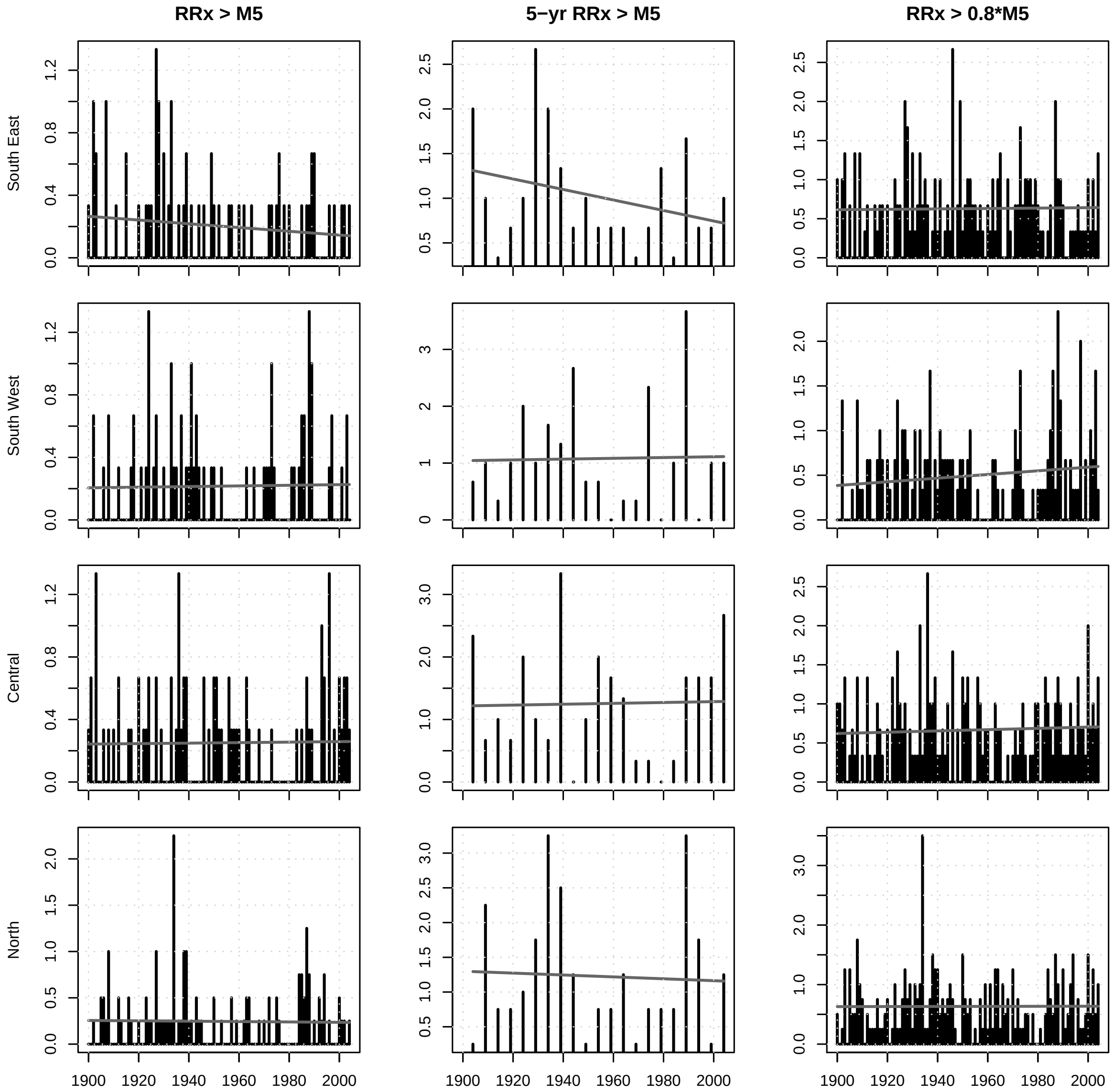

Figure 11 Extreme 1-day precipitation events per station.
Column 1: Annual number of events ≥ M5(1-day), Column 2: as column 1, but accumulated over five years, Column 3: Annual number of events ≥ 0.8*M5(1-day).

4 Summary and conclusions

Changes in extreme precipitation and its influence on the design values, used in flood prognoses and dam constructions, have been studied. Comparison of the periods 1975-2004 and 1961-90 shows a general increase in the five year return period value (M5(24 hr)) in the south western regions. The increase is up 5 % on a regional scale. A similar increase is seen in the northernmost region. However, the result for that region is based on very few stations. In the other regions the changes are more scattered with both increases and decreases. The probable maximum precipitation (PMP(24hr)) shows a similar change, although with slightly smaller percentages.

Extreme value statistics for periods of 30 years are strongly influenced by 'outliers'. In a stable climate, the estimations of return period values should therefore be based on as long series as possible.

The long term trends during the 20th century of annual maximum 1-day precipitation show an increasing tendency at 2/3 of the stations. However, only four stations have a significant trend at 5% level. These four are all located in the south western part of Norway. No systematic correlation between the trends and geographic location was found.

High frequencies of extreme precipitations events (precipitation greater than the M5(1-day)) were found in the 1920s – 1930s and in the south western and central regions in the 1980s – 1990s. A clear decrease in the occurrence of extreme precipitations during the last century was found in the south eastern regions. In the other regions the changes were minor. However, the occurrences of slightly less extreme events seem to have increased. Frequencies of precipitation events larger than 80 % of the M5(1-day) values show an increasing tendency in all regions. The increase is strongest in the south western regions.

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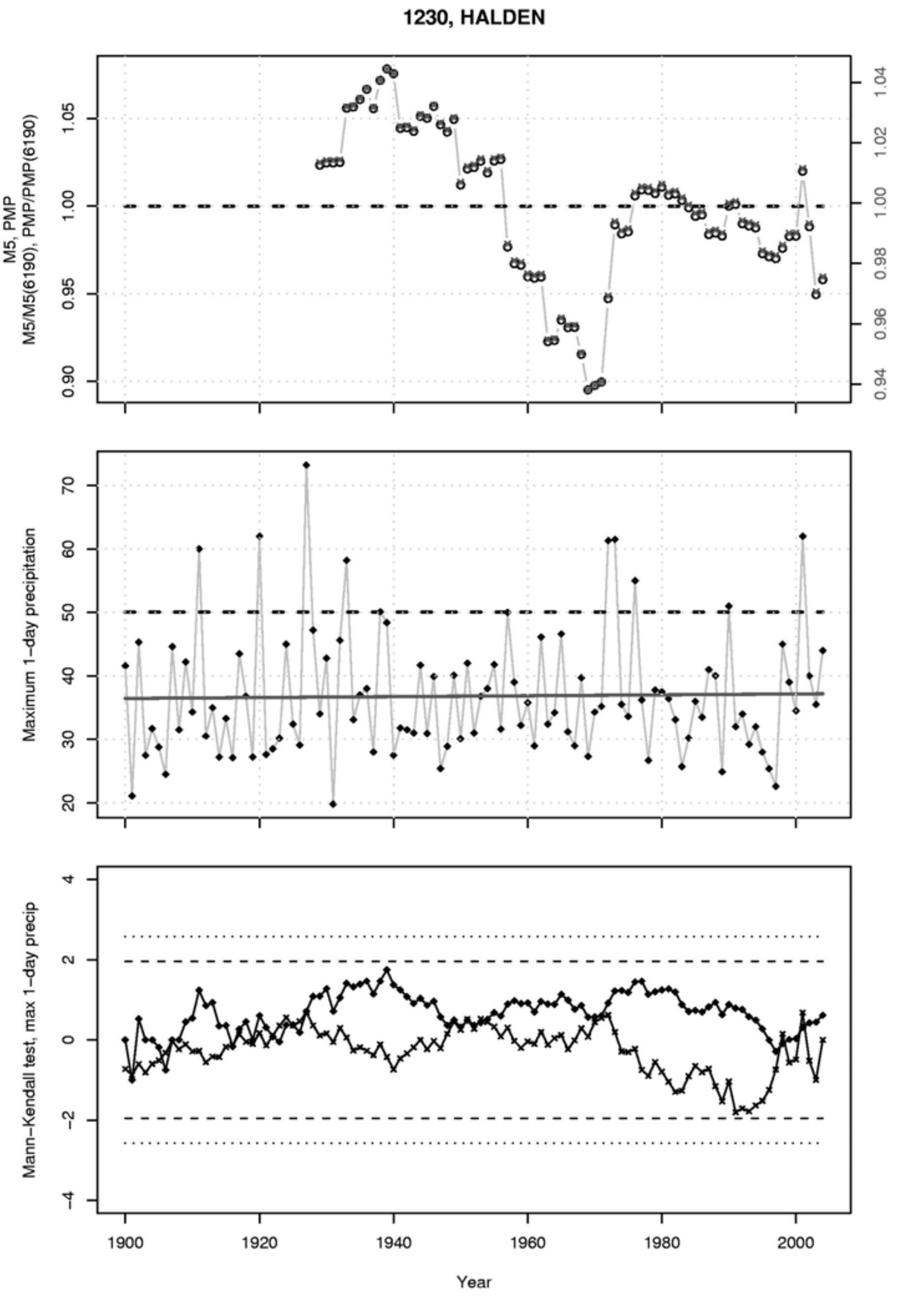
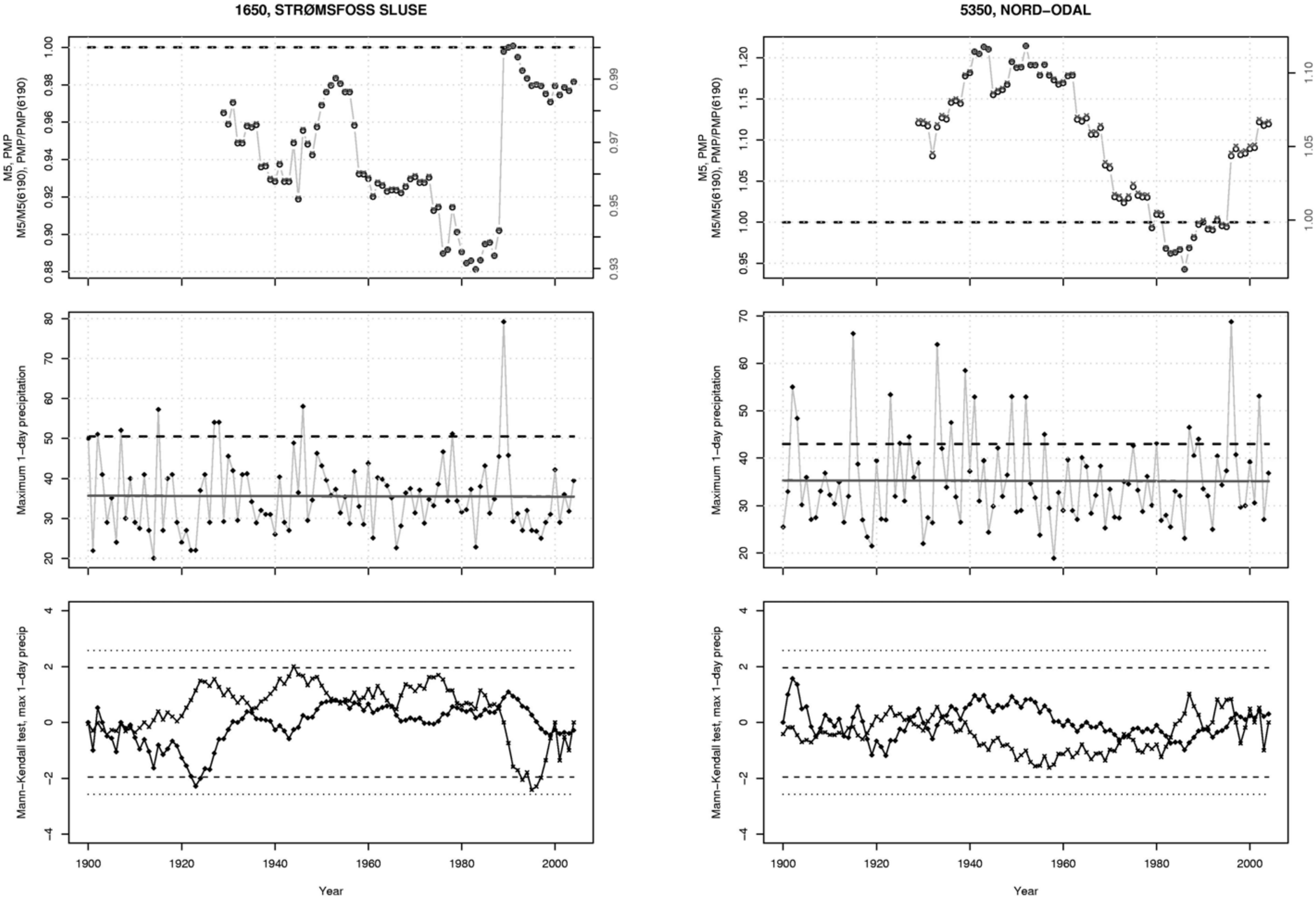
6 Appendix

Moving M5 and PMP values calculated on the long term precipitation series are shown in panel one in the following figures, one for each station. The values are plotted on the last year of the 30 years time span they are calculated from. The y-axes show the relative M5 (left) and PMP (right) values, respectively.

Annual maximum 1-day precipitation is show in the second panel. The solid grey line (▬▬) shows the least square linear trend through the data set. A dashed line (▬ ▬) indicates the recent M5 value. In the third panel the forward (─♦─) and backward (─×─) test statistics of the Mann-Kendall trend test is shown. The significance levels of 1% and 5% are plotted with dotted (· · · ·) and dashed (− −) lines, respectively.

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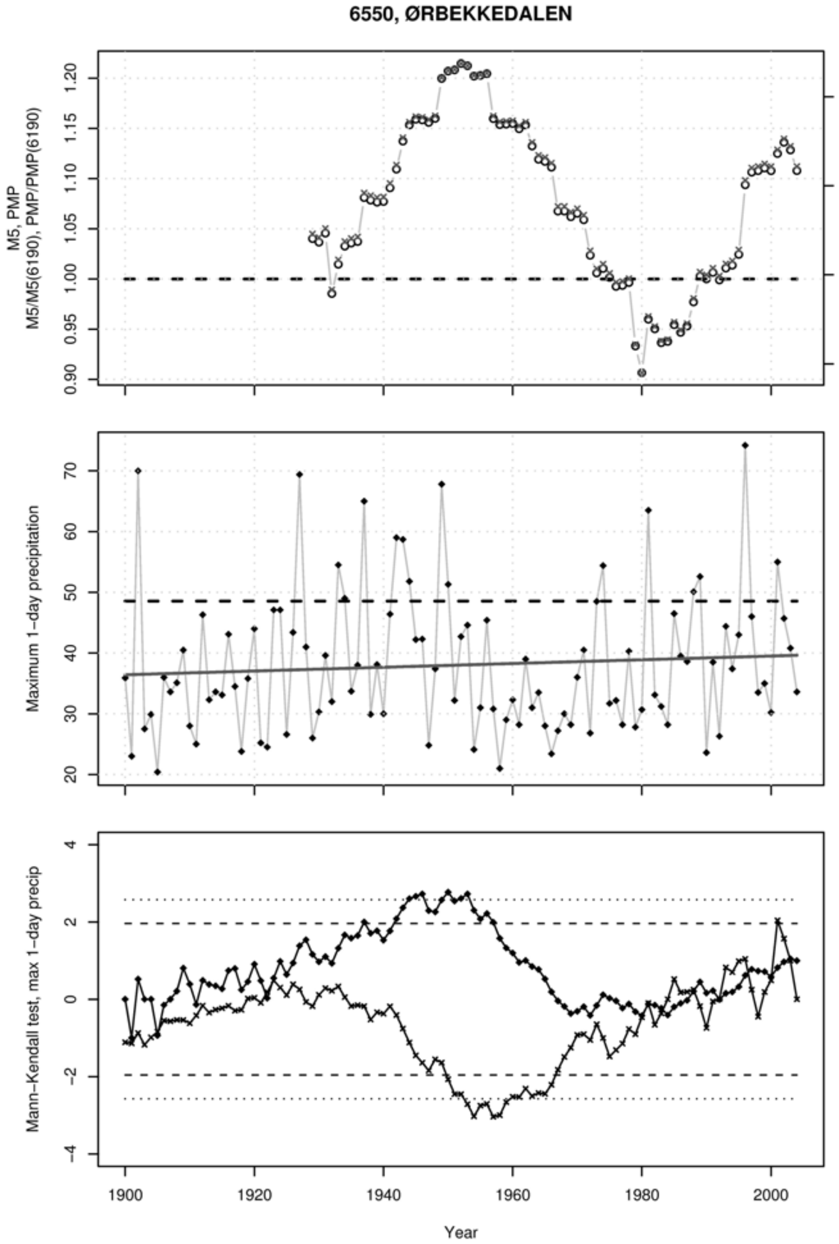
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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M5, PMP
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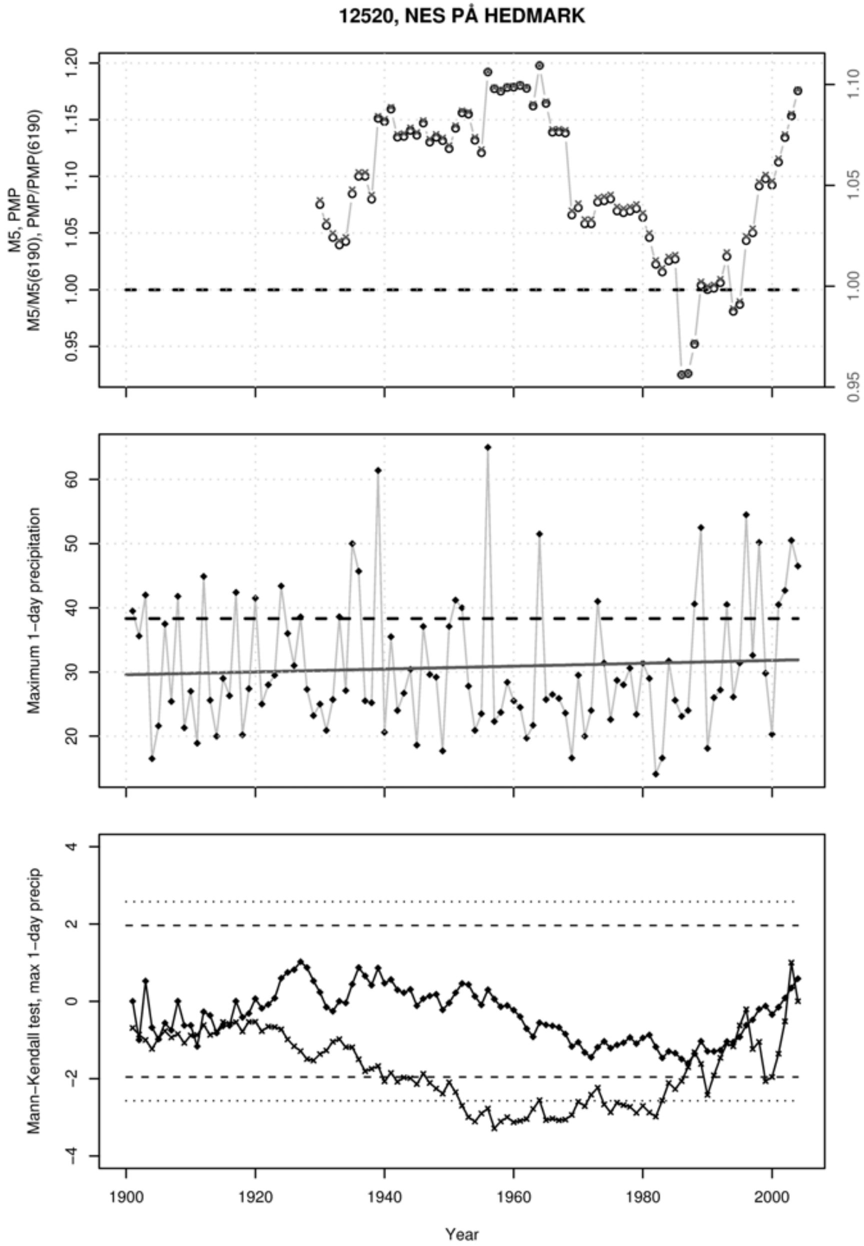
Maximum 1-day precipitation
Mann-Kendall test, max 1-day precip
Year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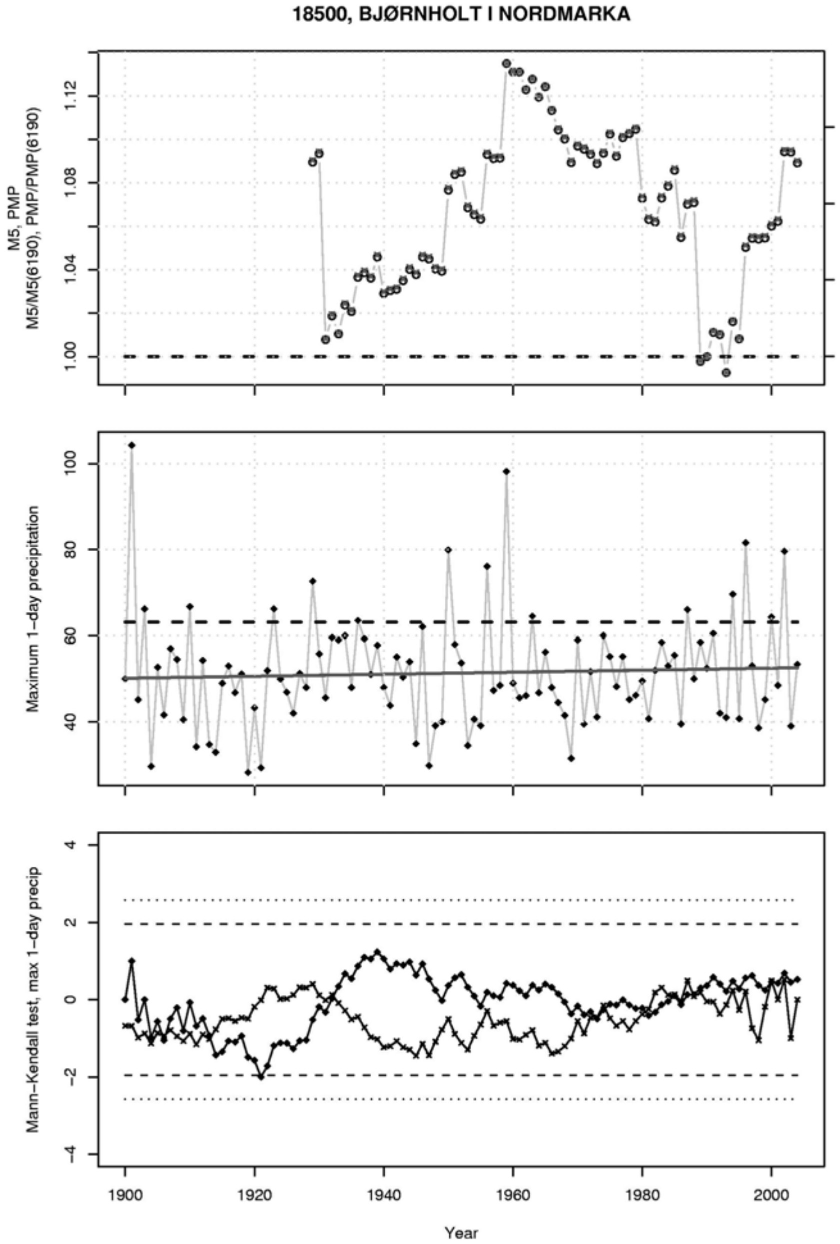
Maximum 1-day precipitation
Mann-Kendall test, max 1-day precip
Year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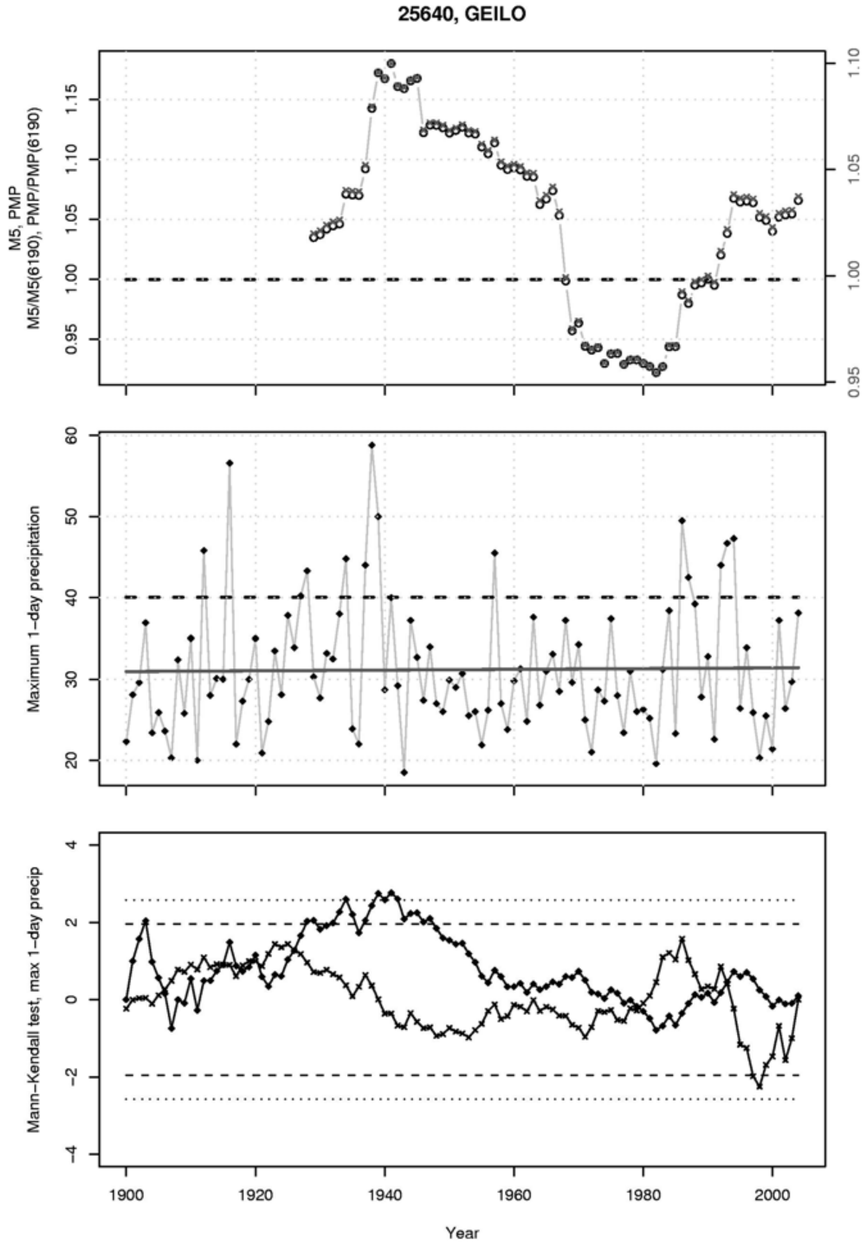
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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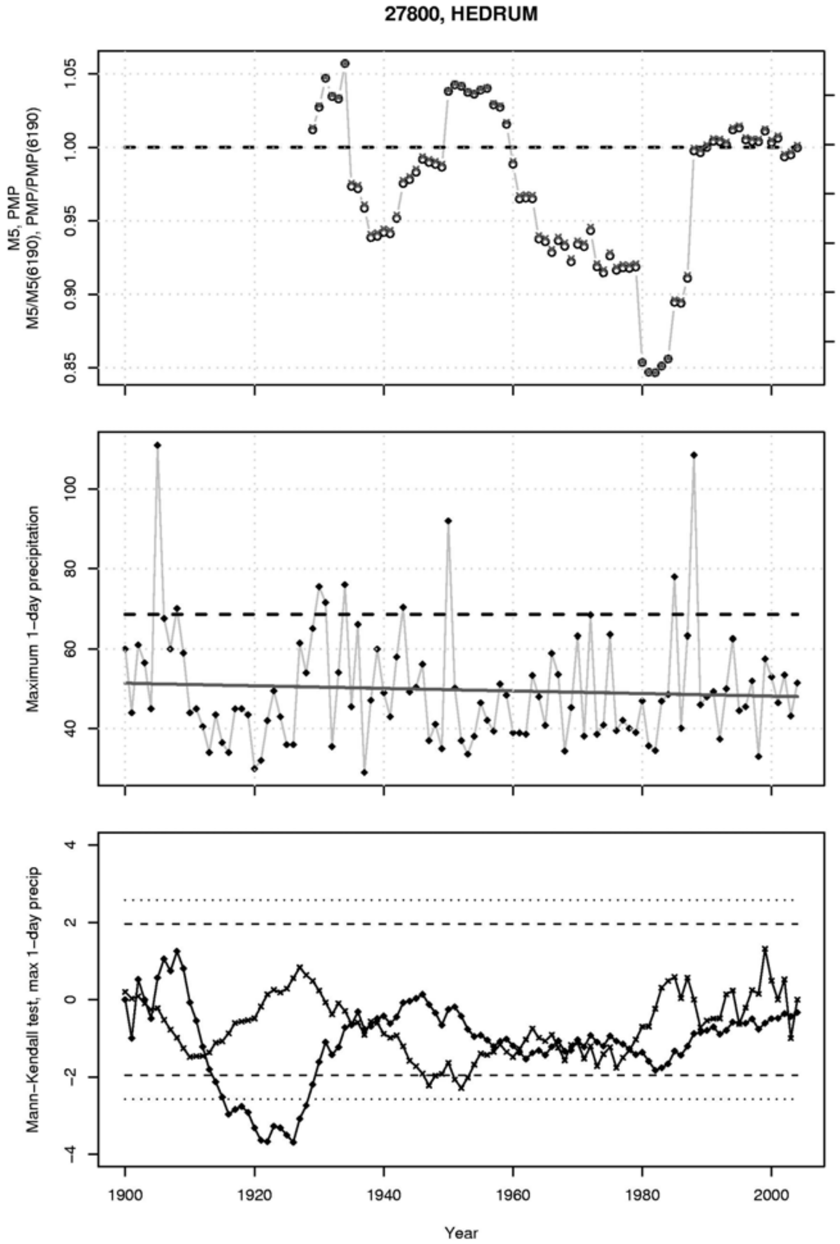
Mann−Kendall test, max 1−day precip
Year



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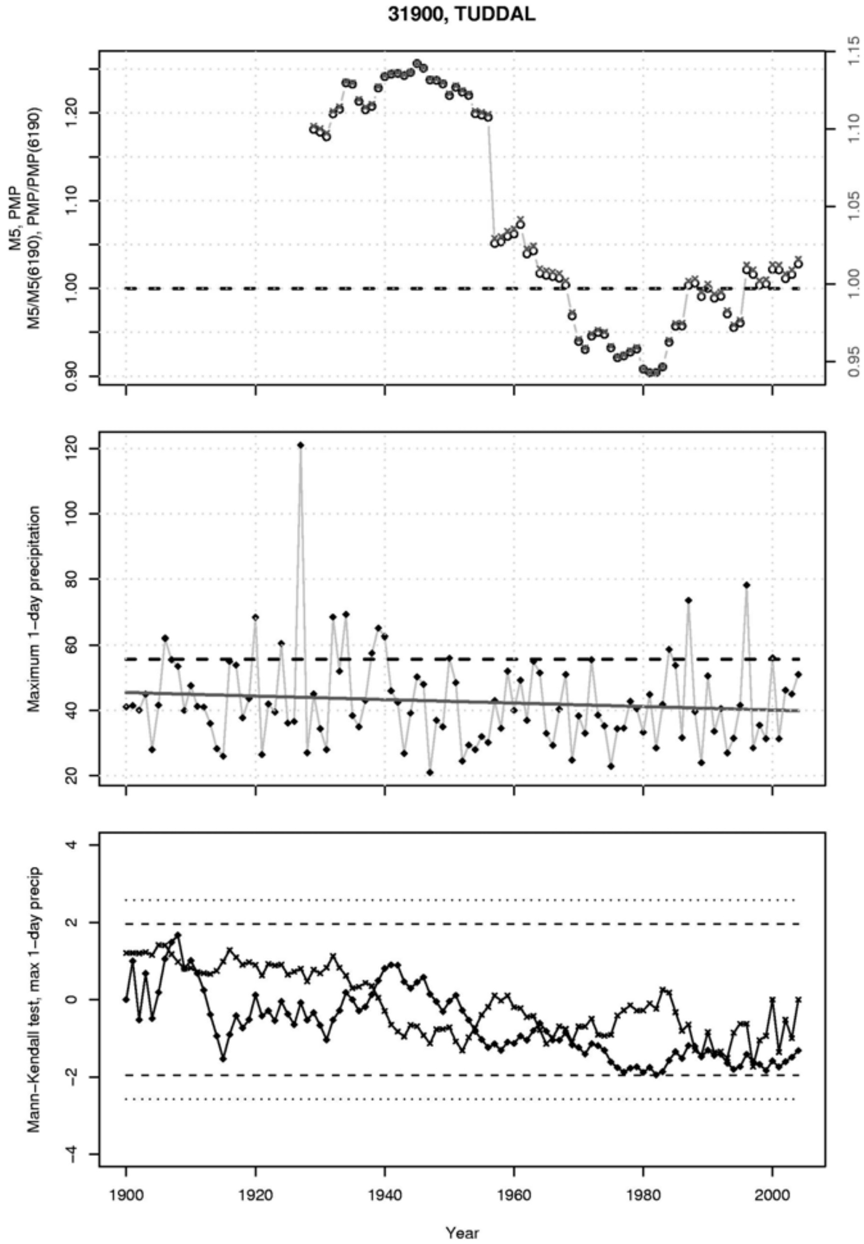
Maximum 1-day precipitation
Mann-Kendall test, max 1-day precip
Year



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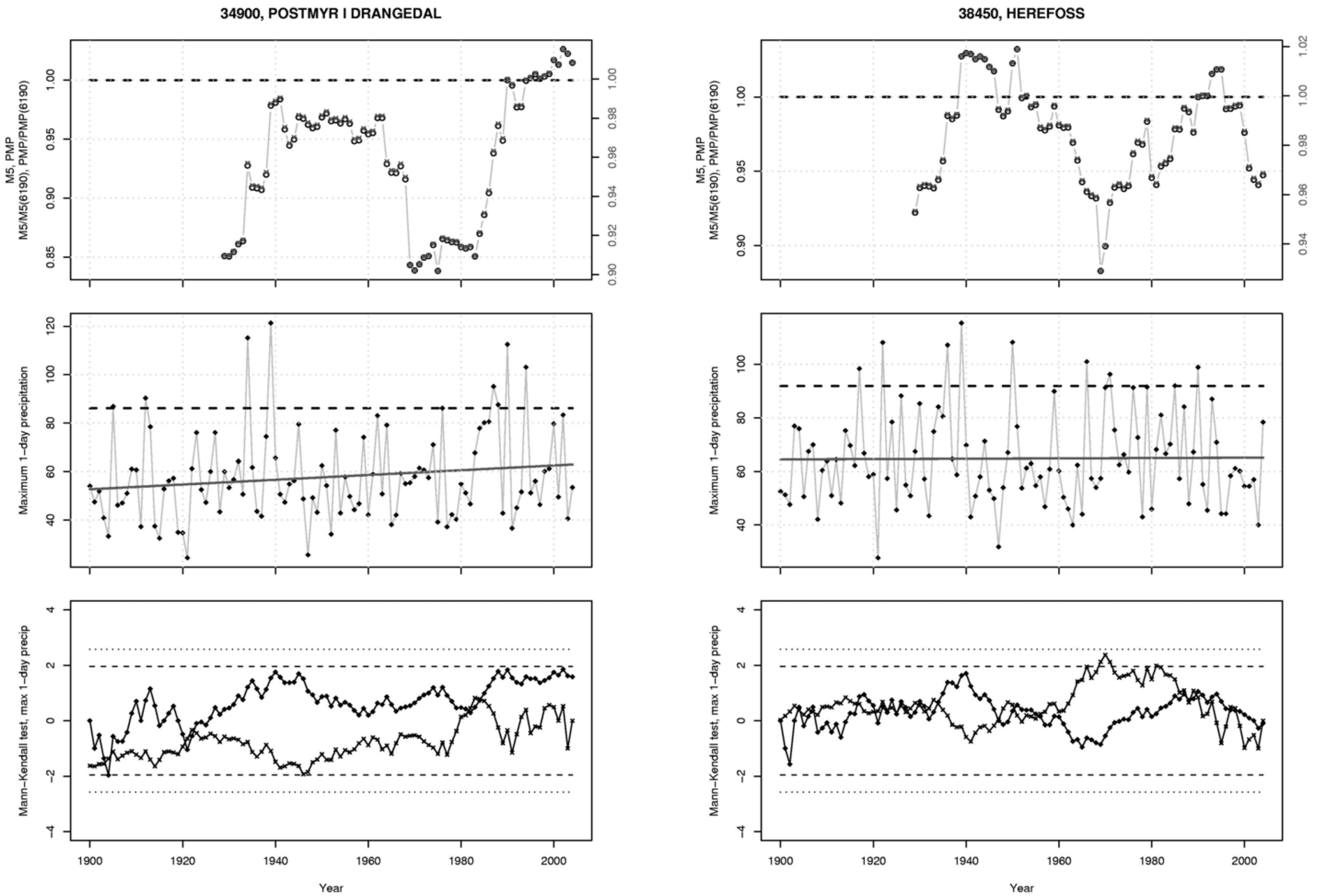
Maximum 1-day precipitation
Mann-Kendall test, max 1-day precip
Year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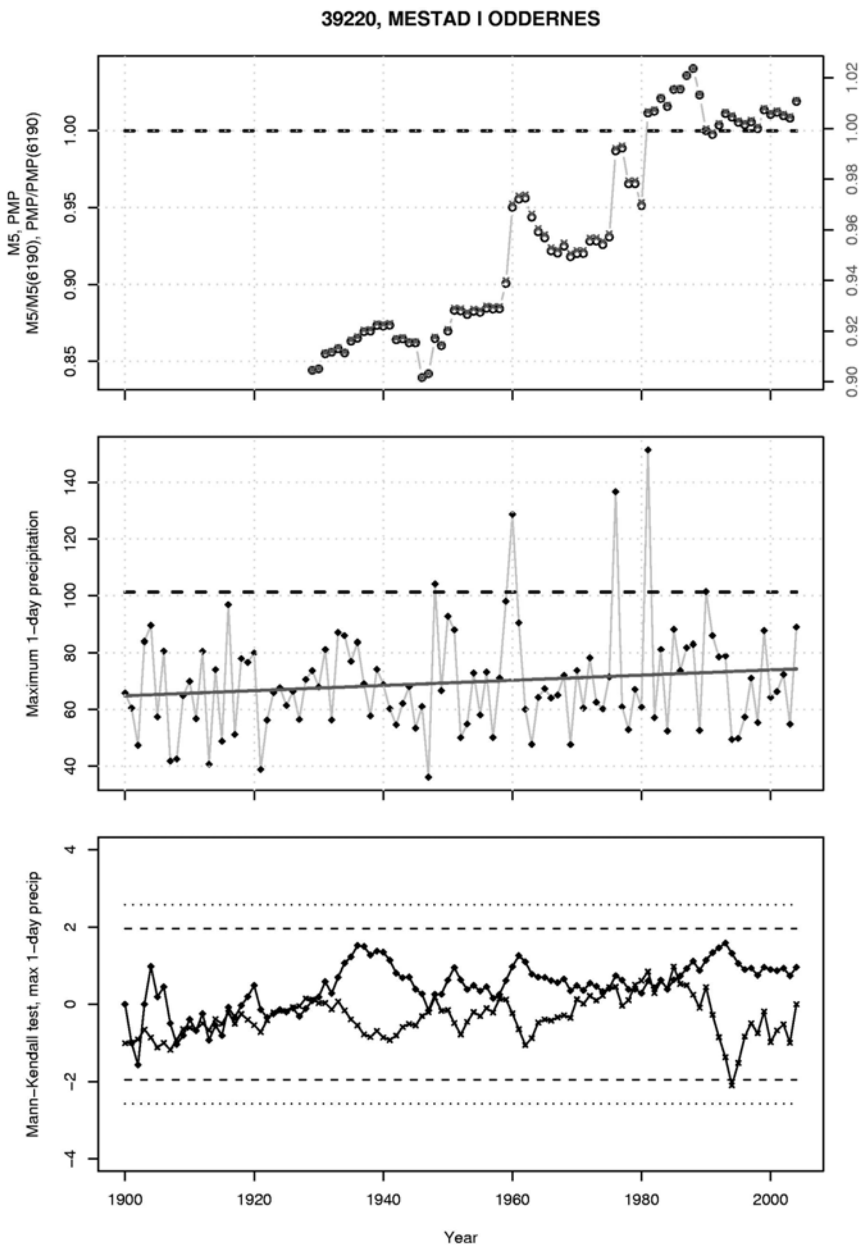
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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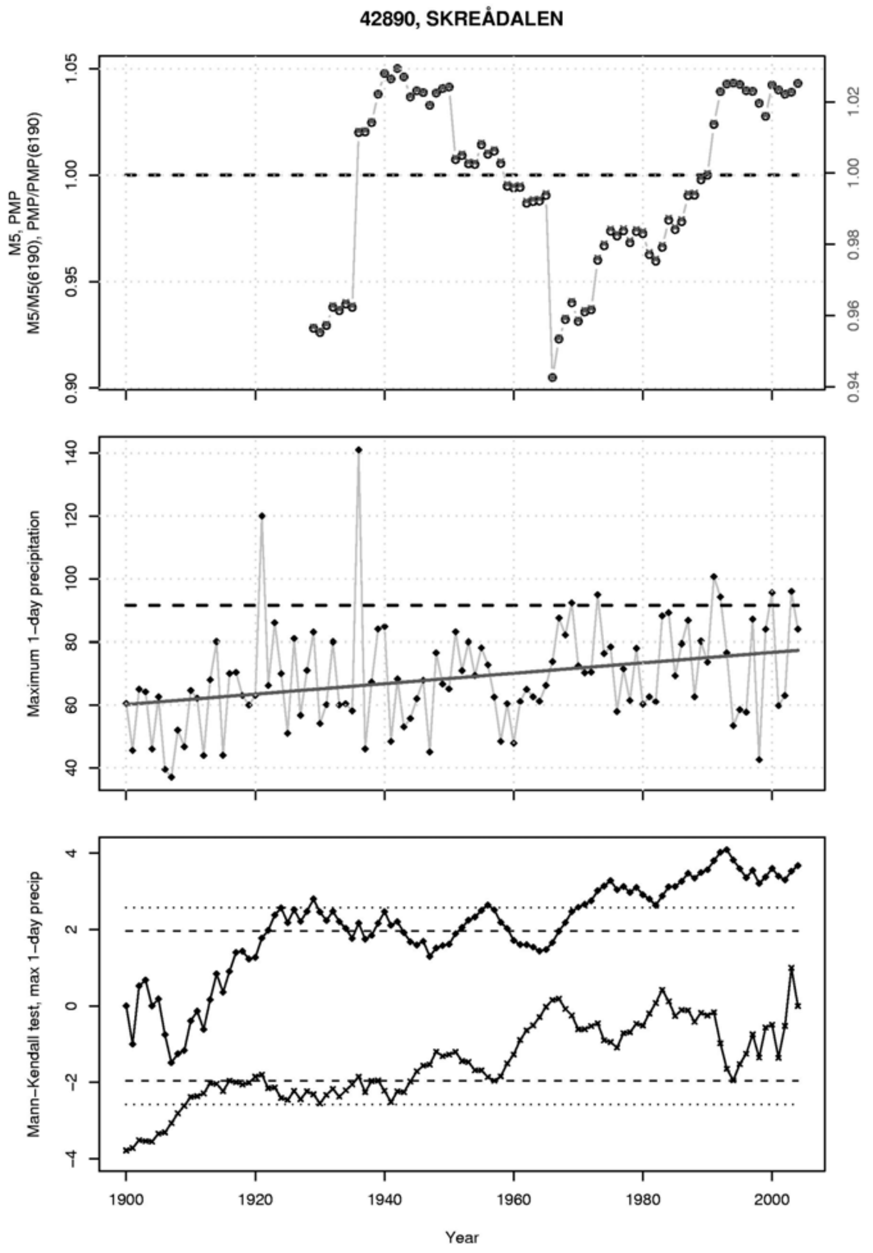
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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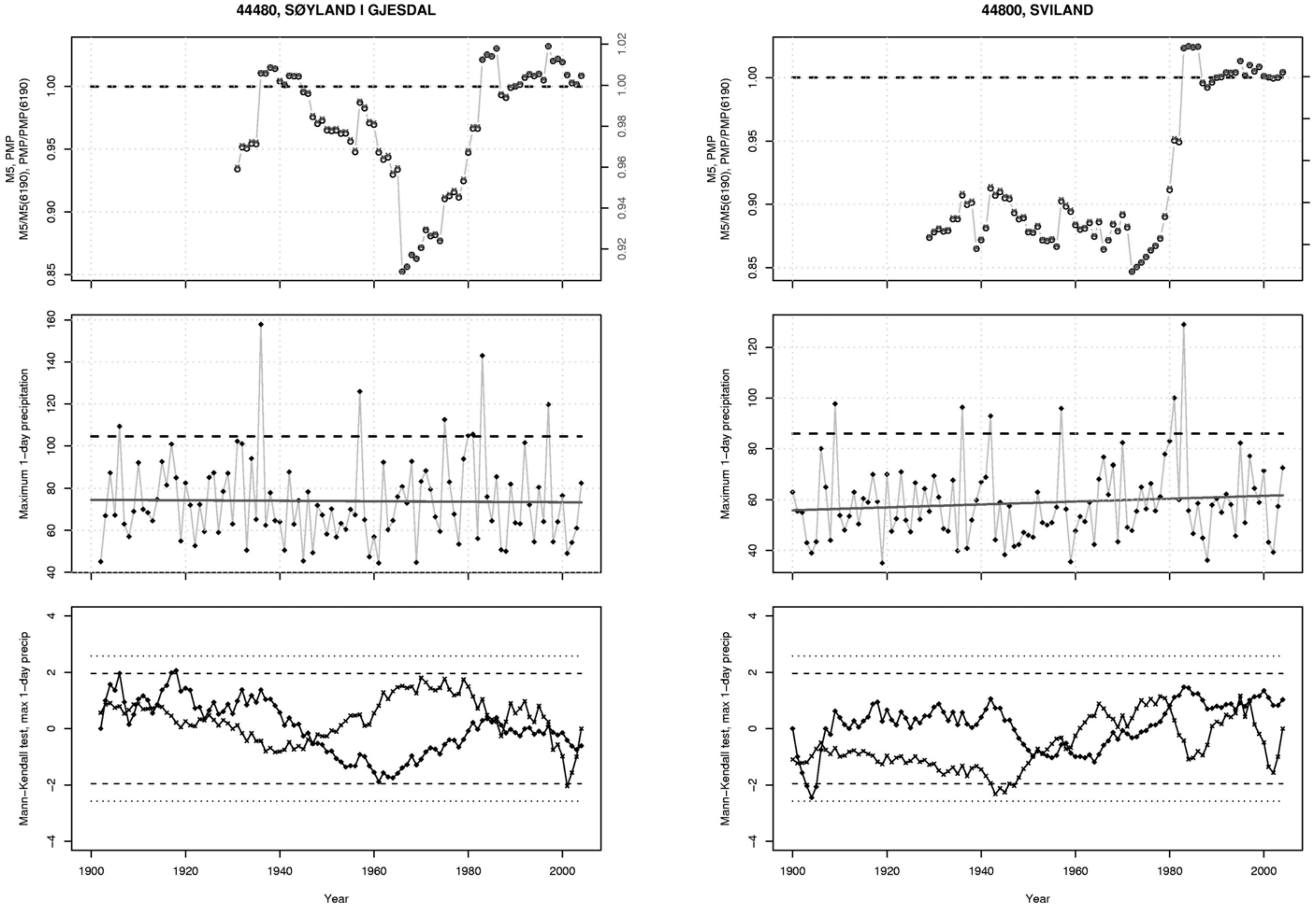
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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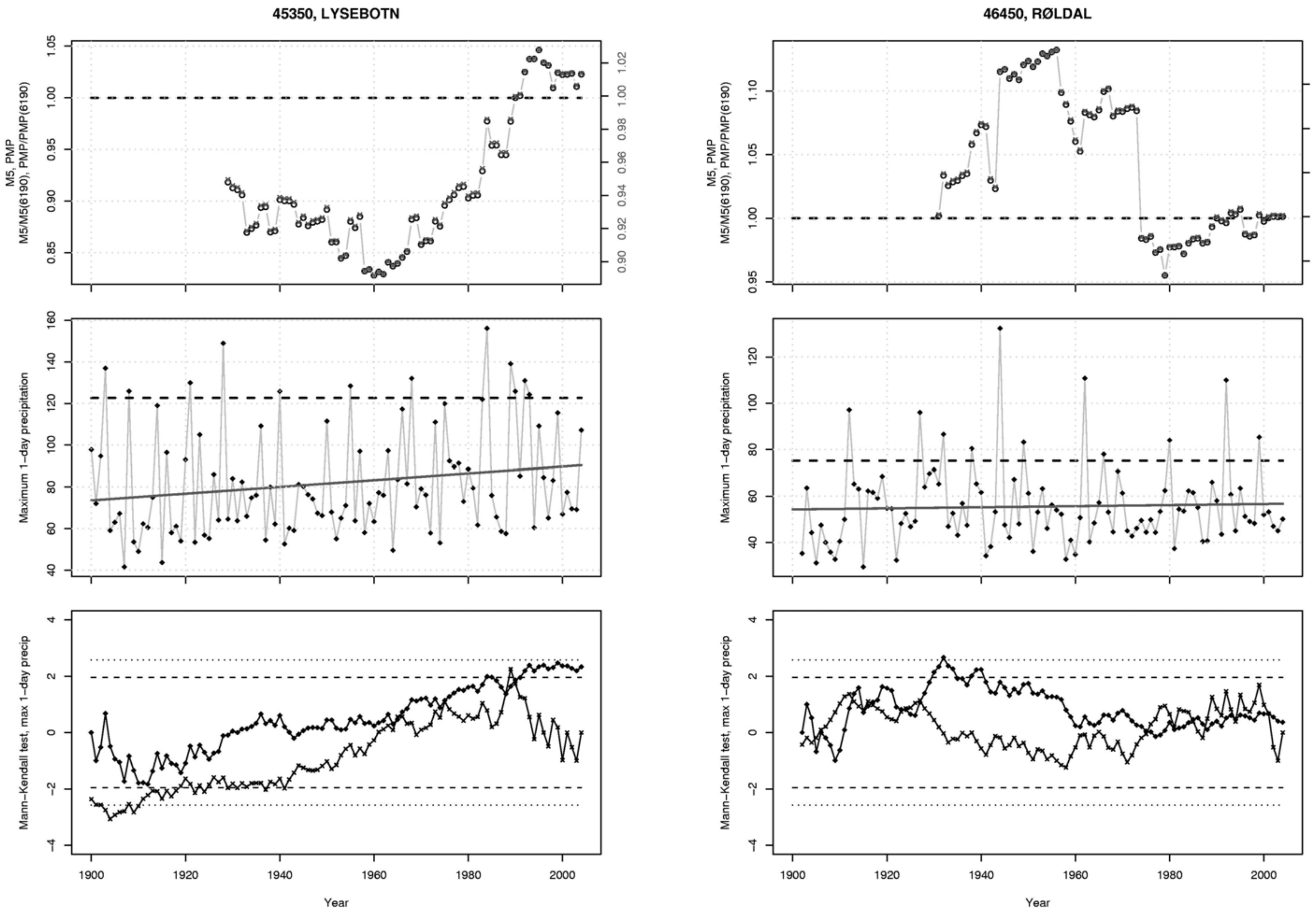
Year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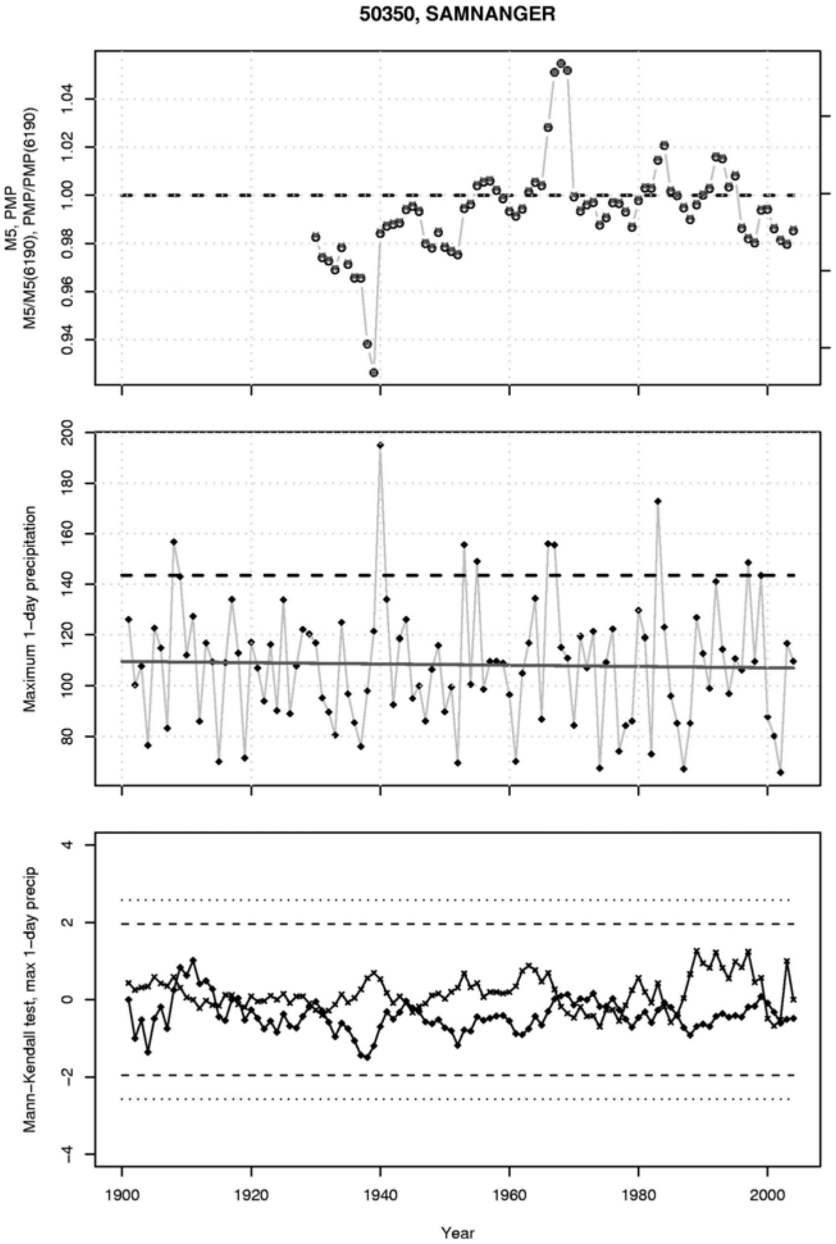
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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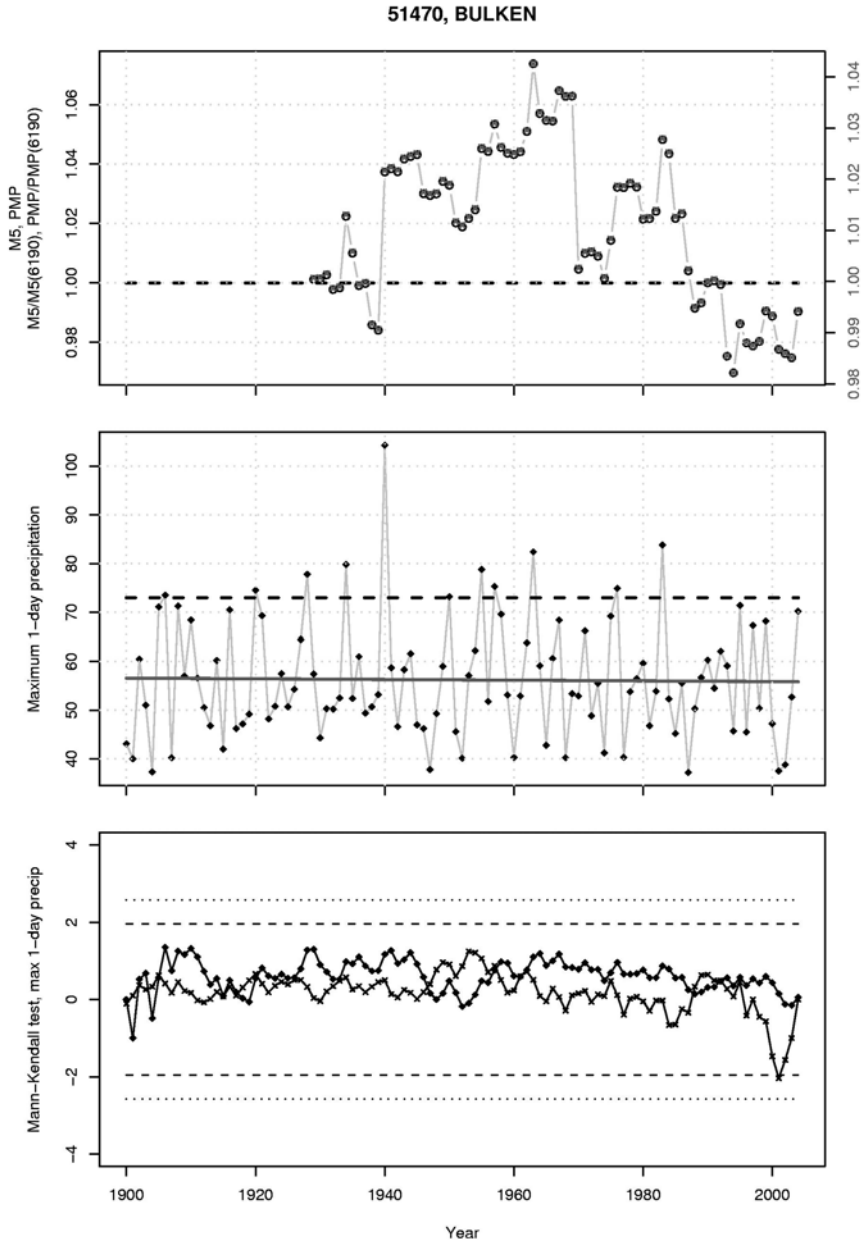
Maximum 1-day precipitation
Mann–Kendall test, max 1-day precip
Year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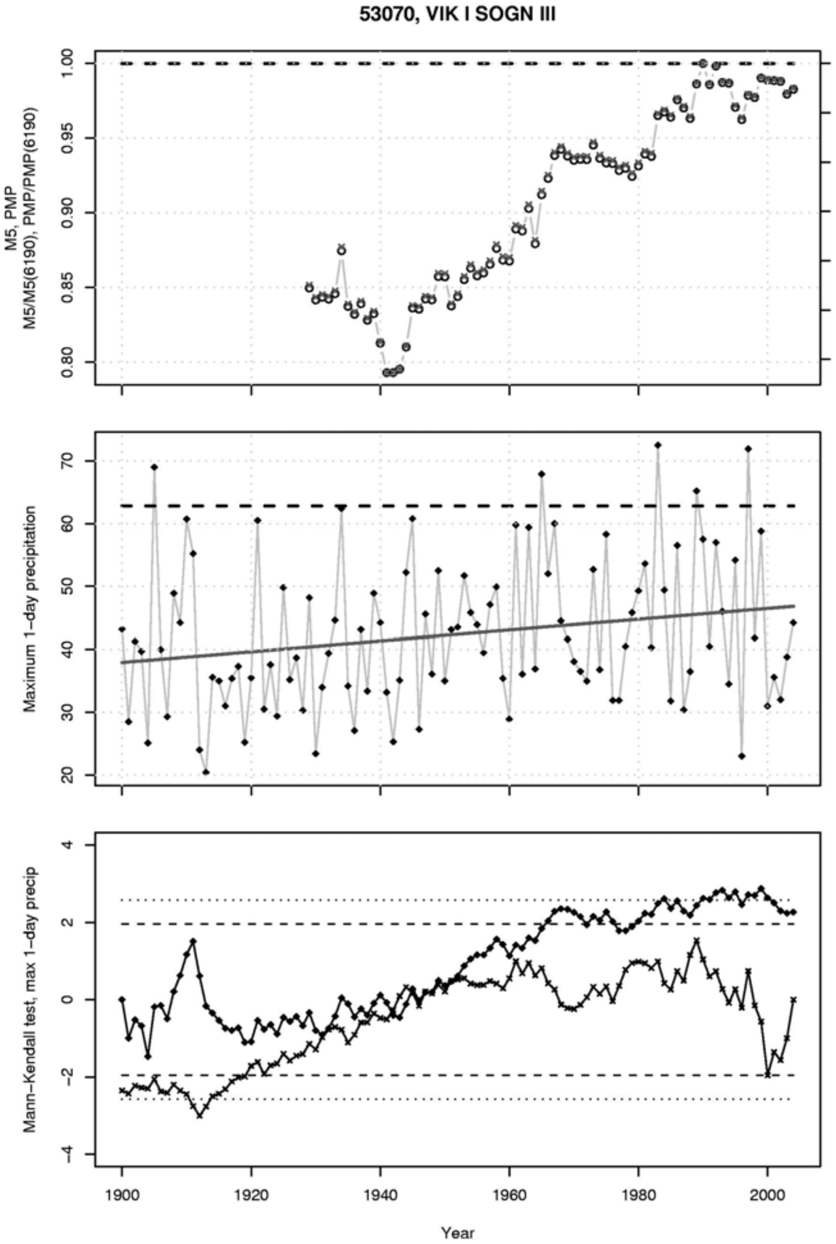
Maximum 1-day precipitation
Mann–Kendall test, max 1-day precip
Year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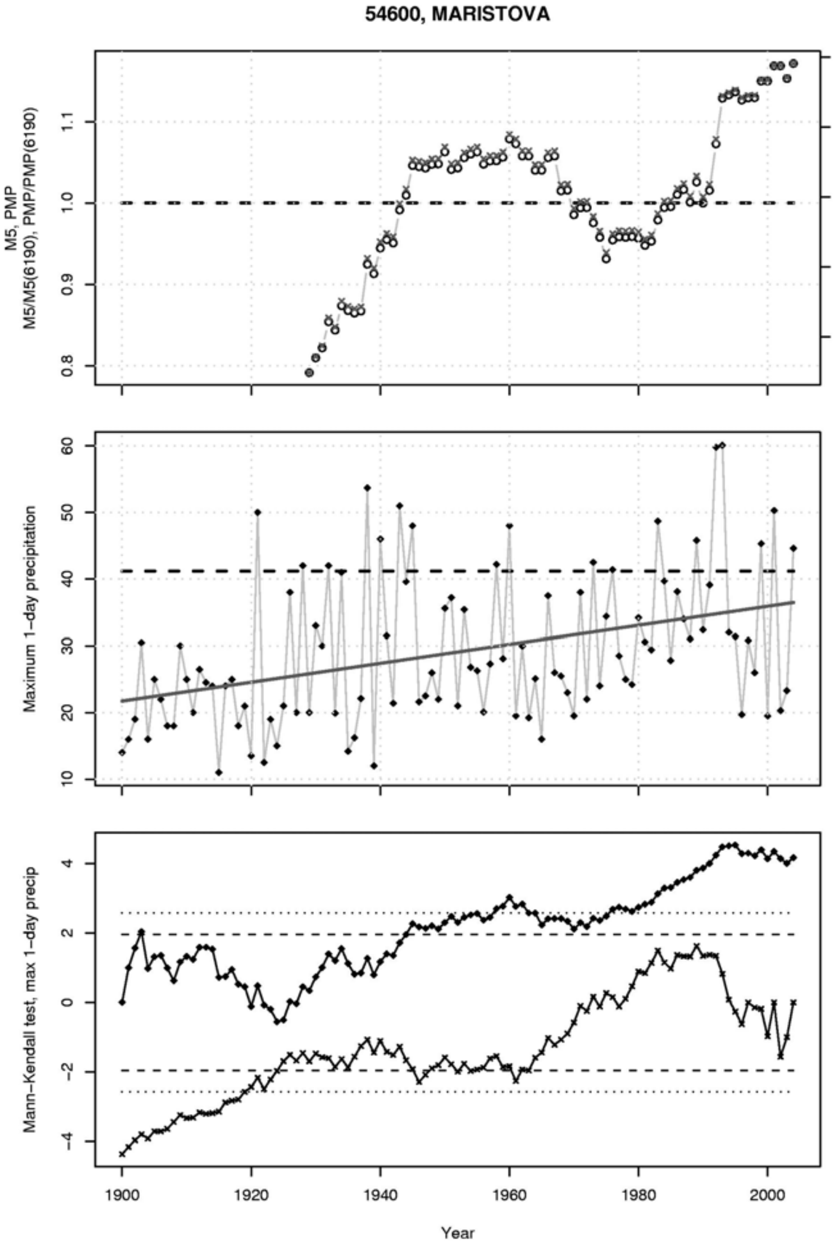
Mann-Kendall test, max 1-day precip
Year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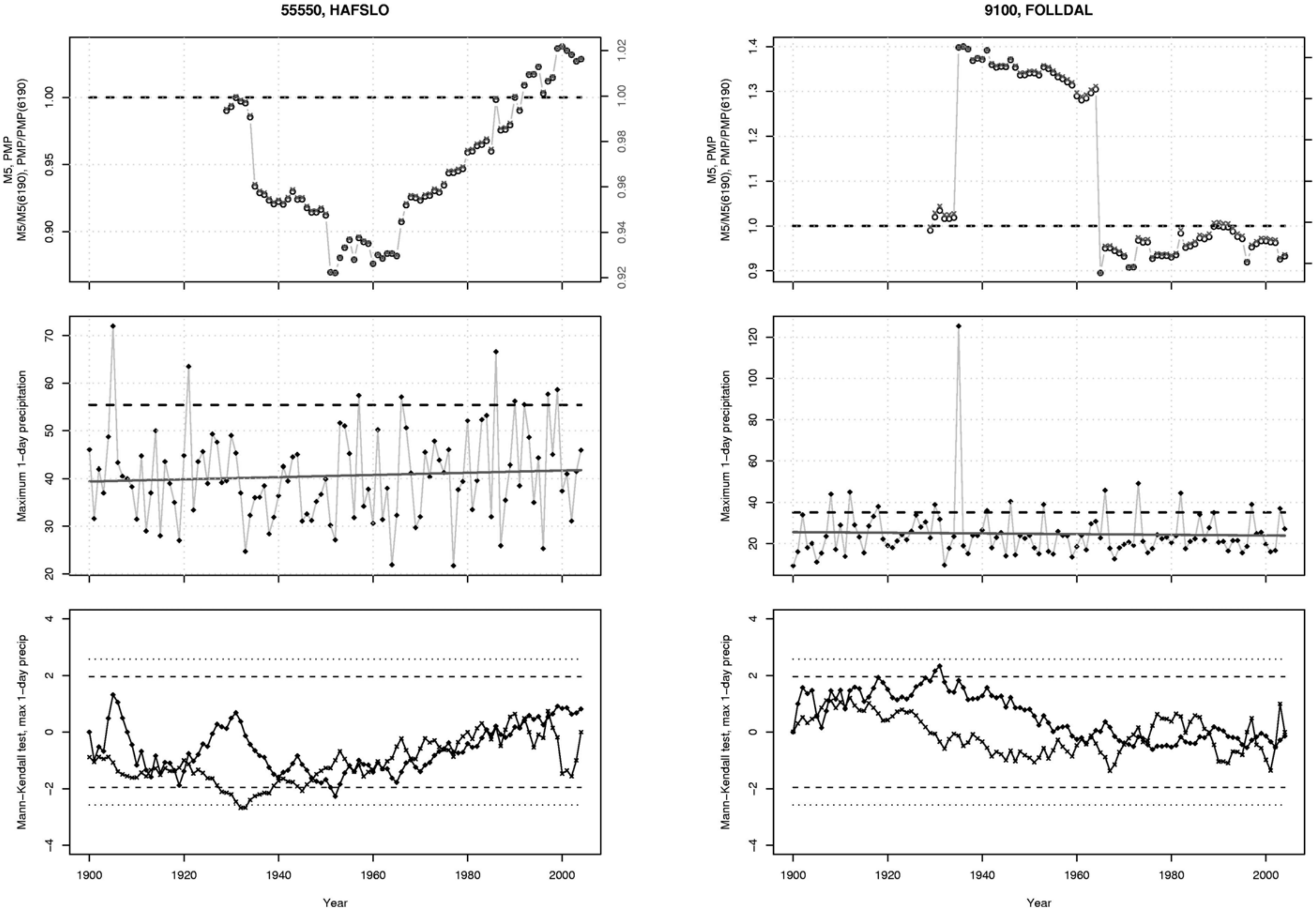
Mann-Kendall test, max 1-day precip
Year



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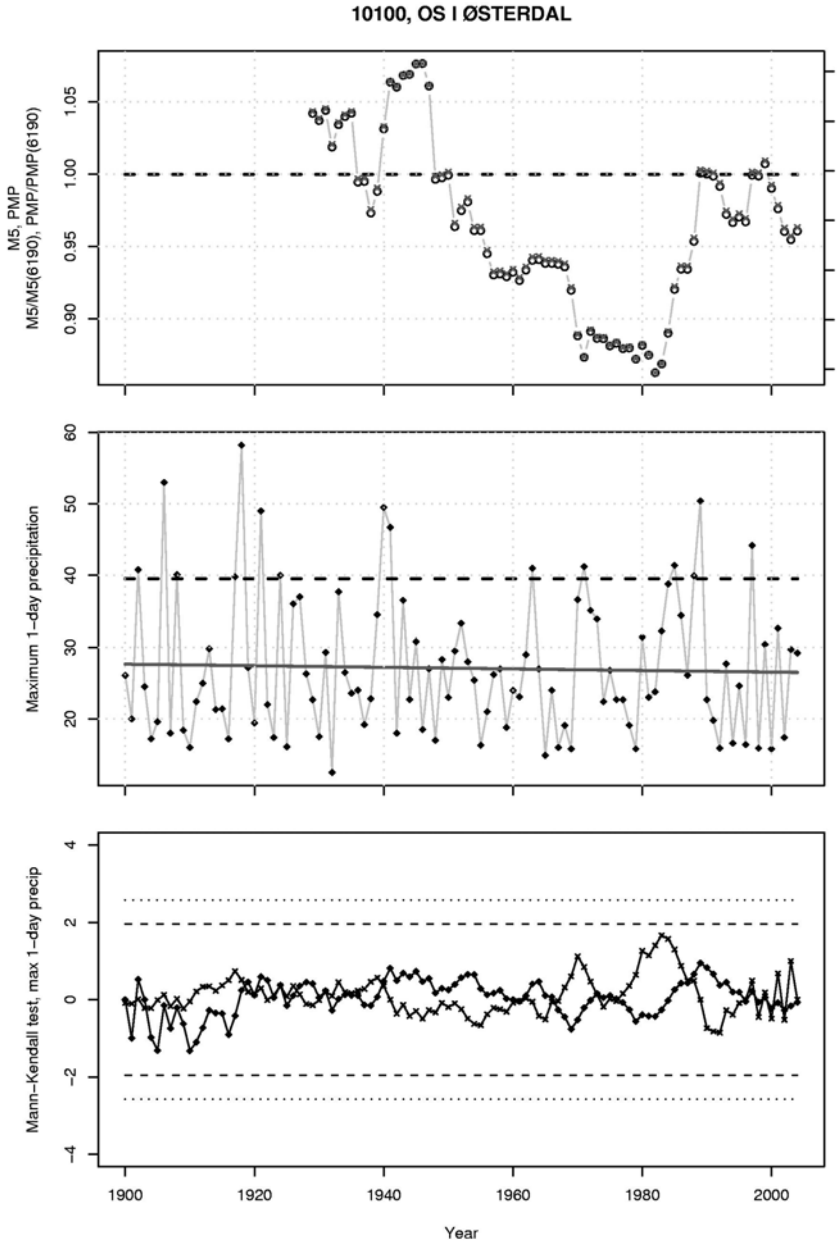
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year



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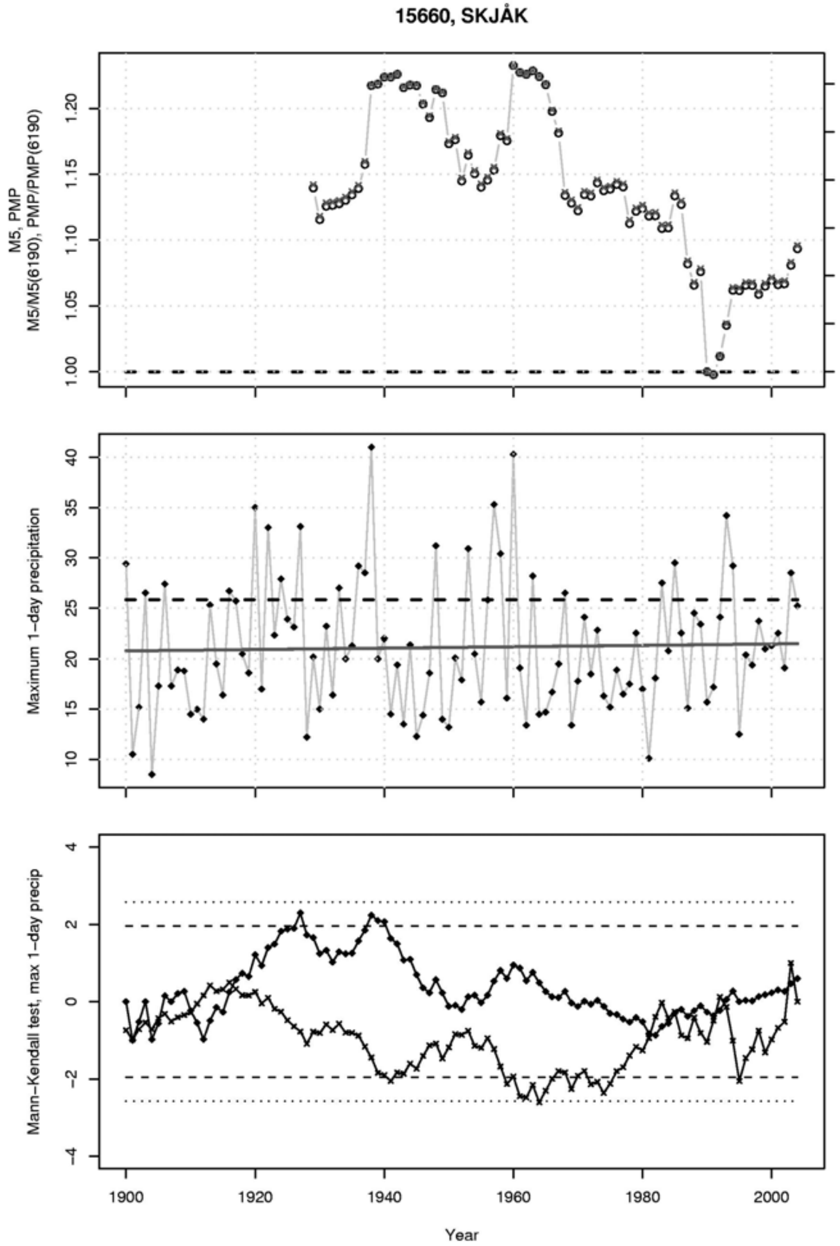
Maximum 1–day precipitation
Mann–Kendall test, max 1–day precip
Year



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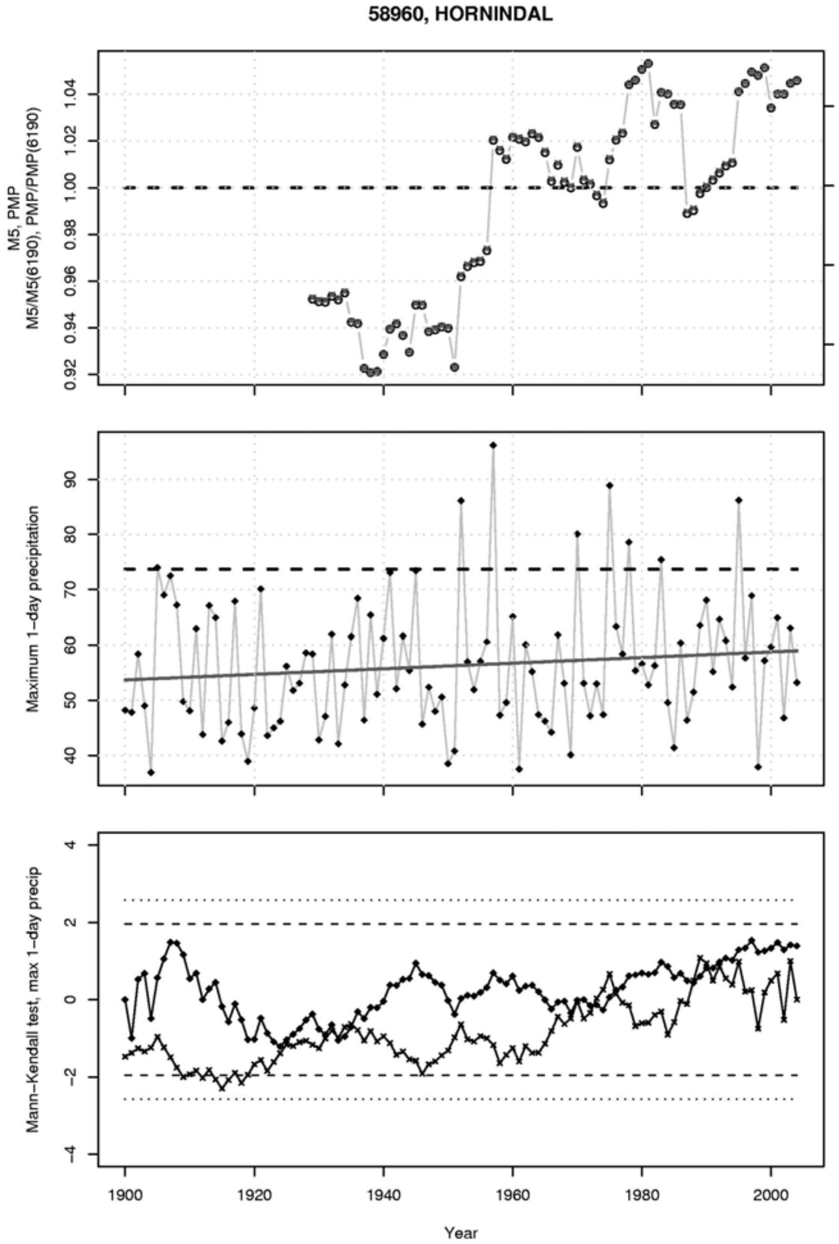
Mann–Kendall test, max 1–day precip
Year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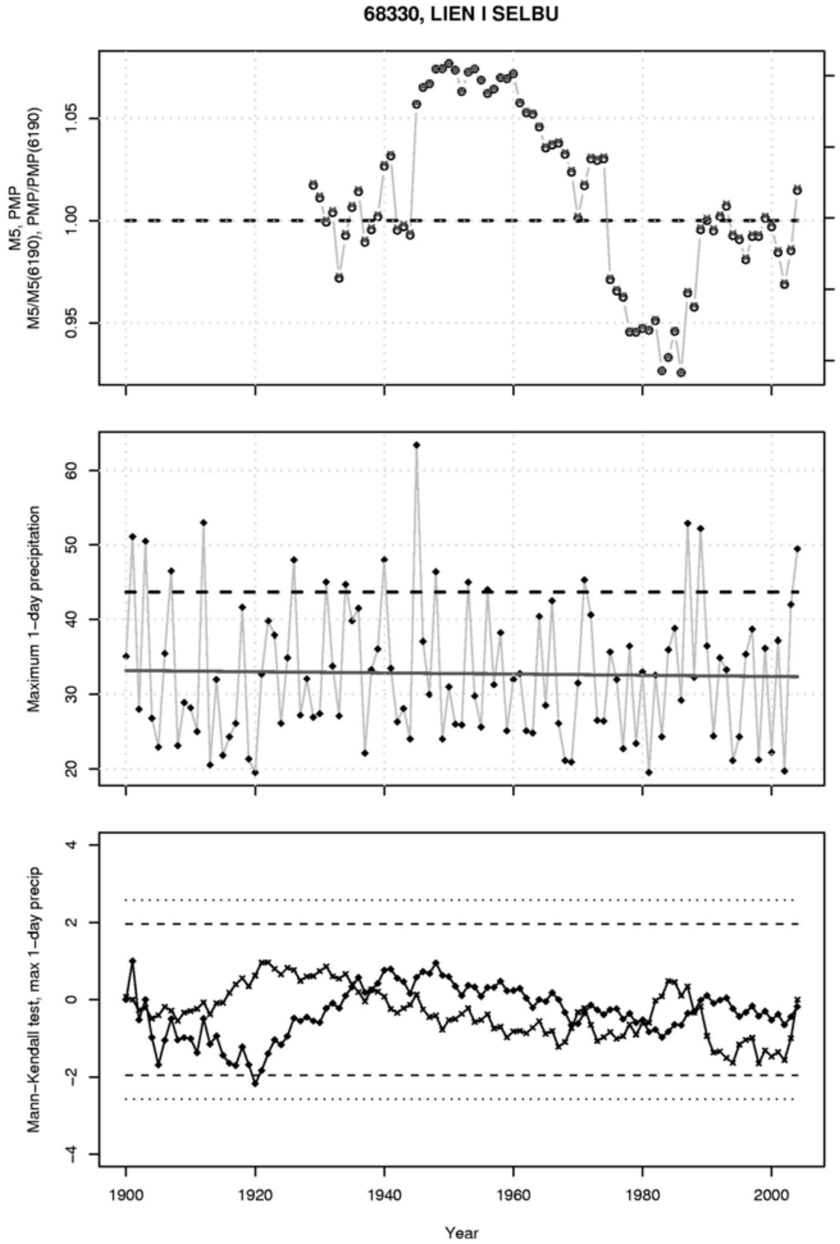
Mann-Kendall test, max 1-day precip
Year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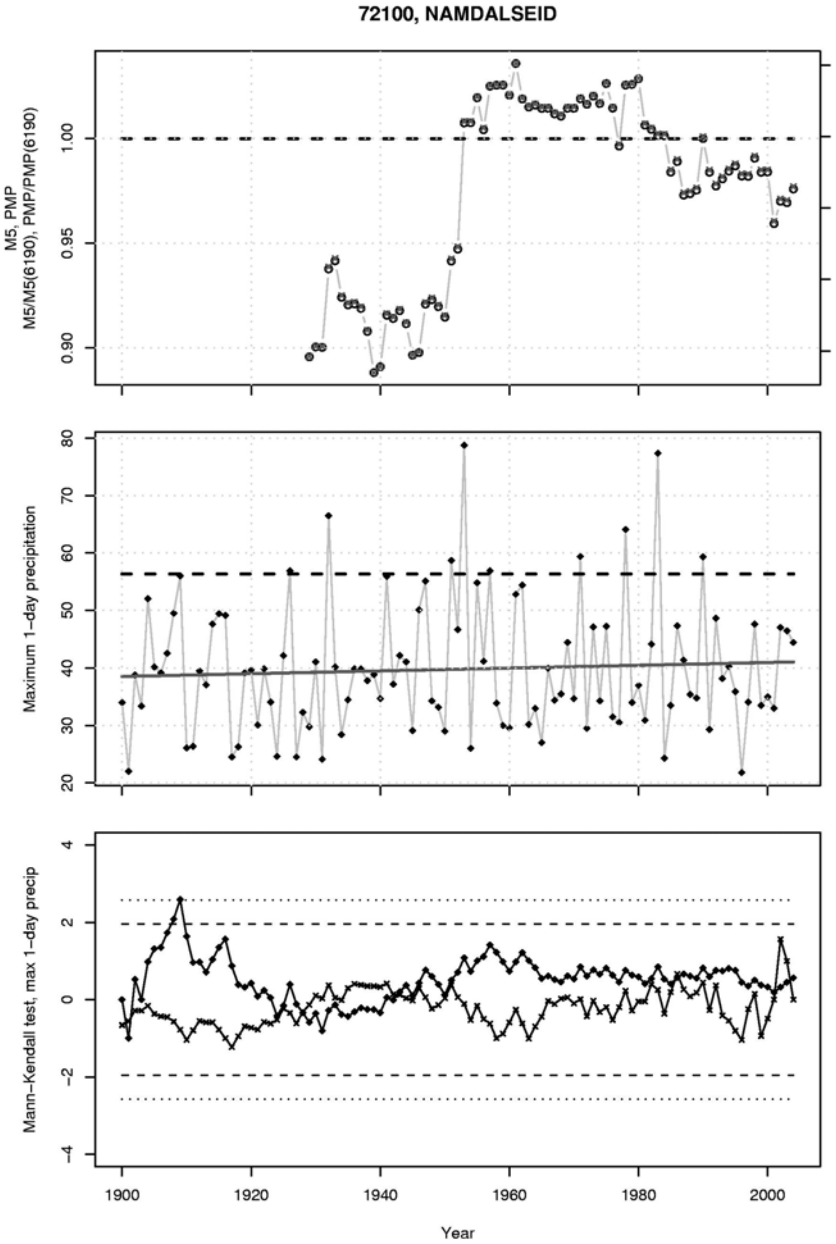
Year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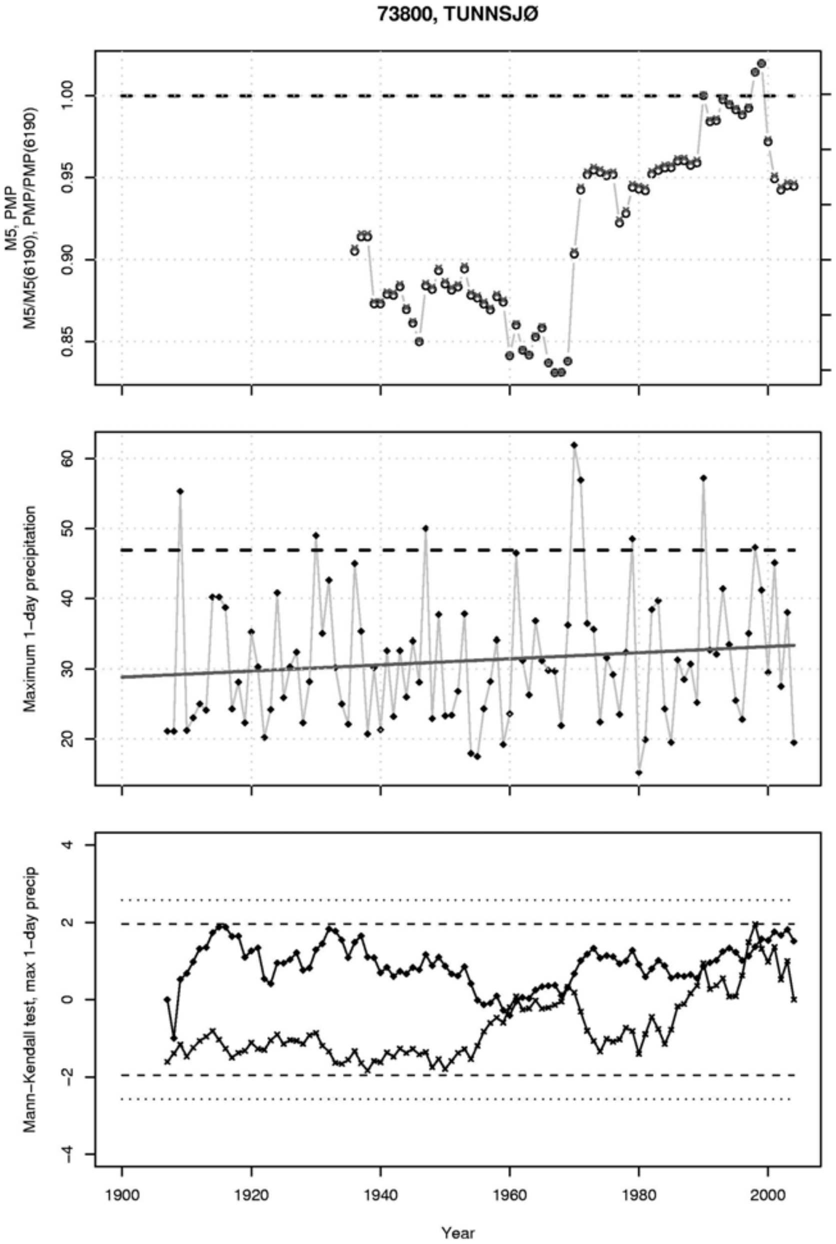
Mann−Kendall test, max 1−day precip
Year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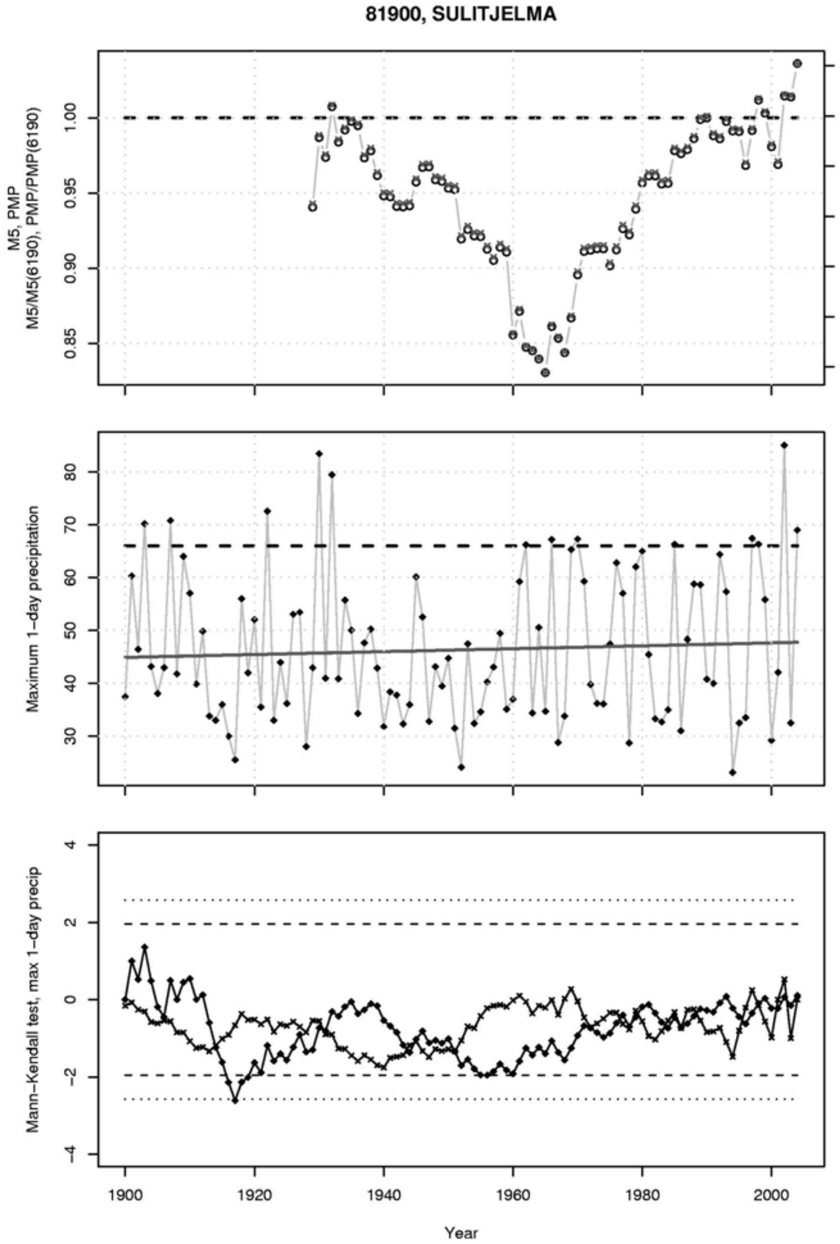
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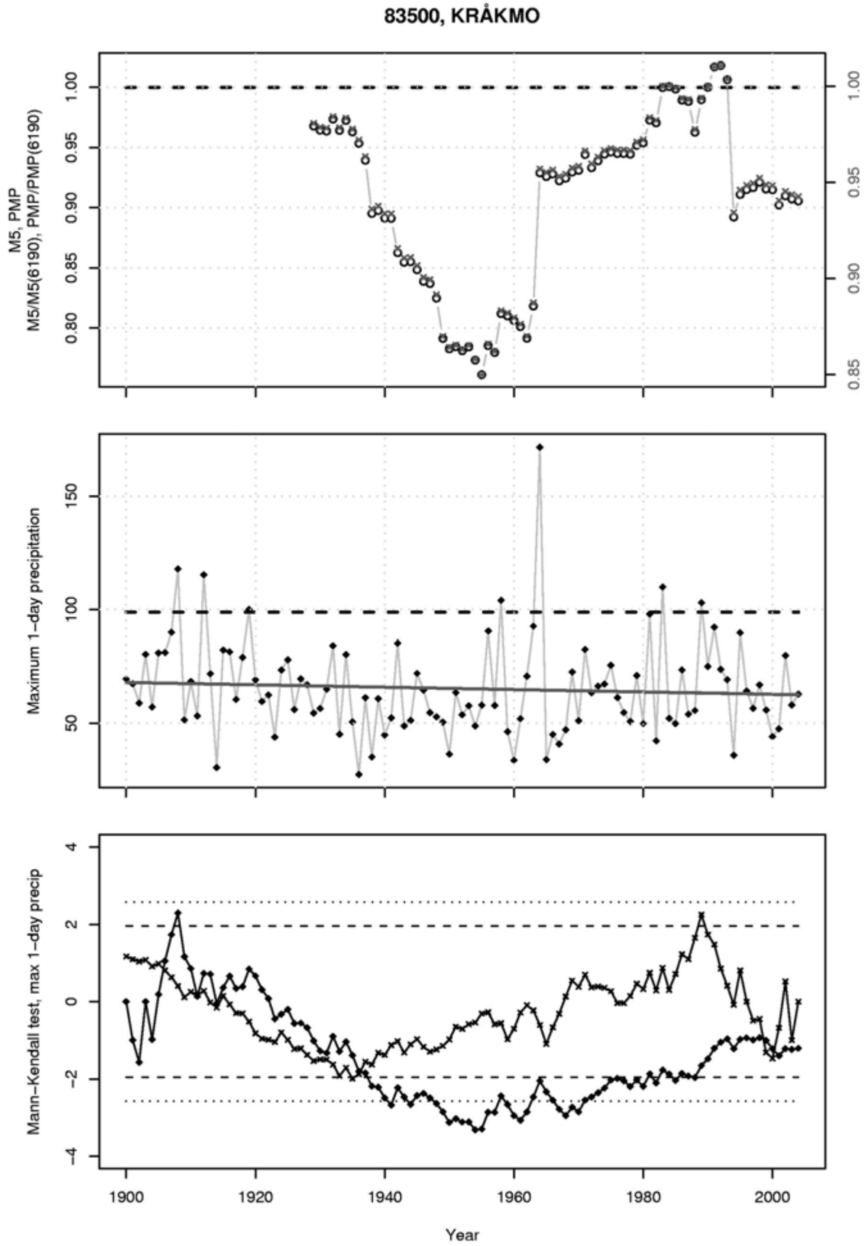
Mann-Kendall test, max 1-day precip
Year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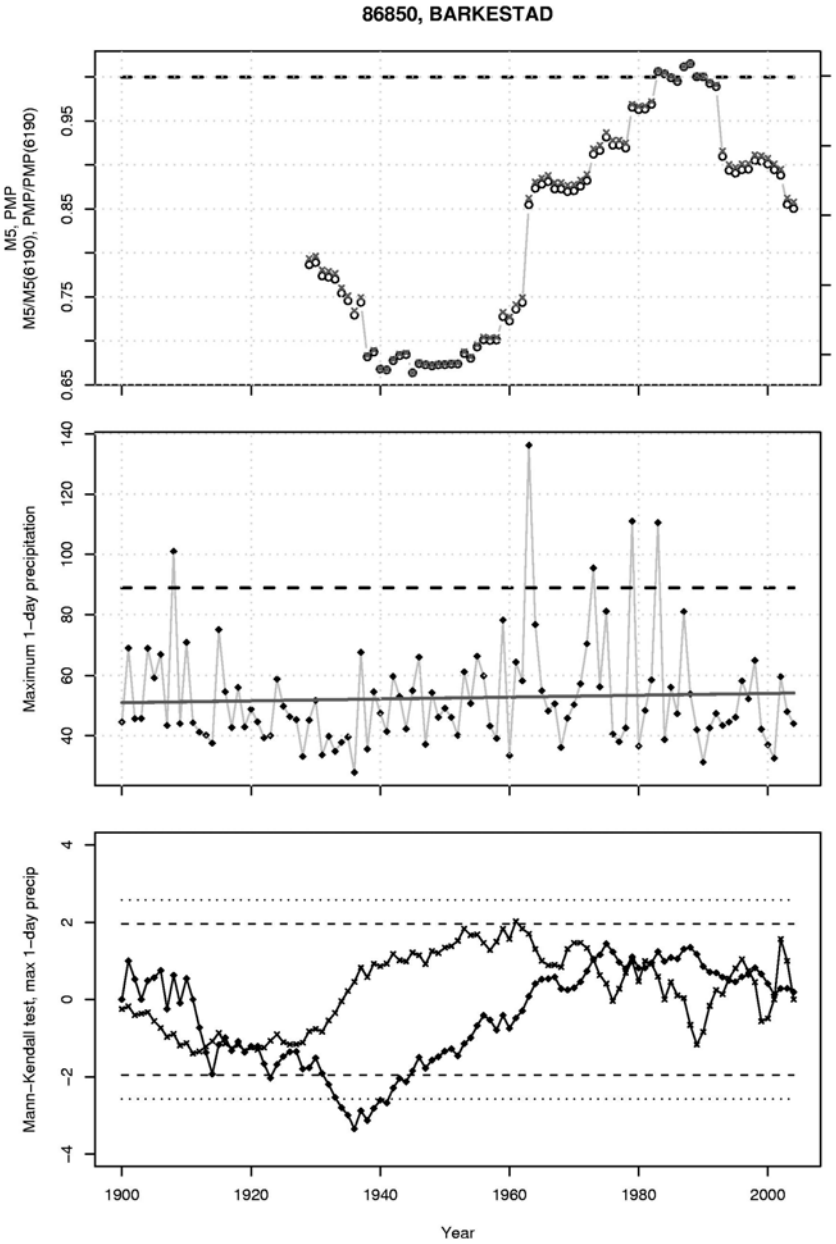
Year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Maximum 1−day precipitation
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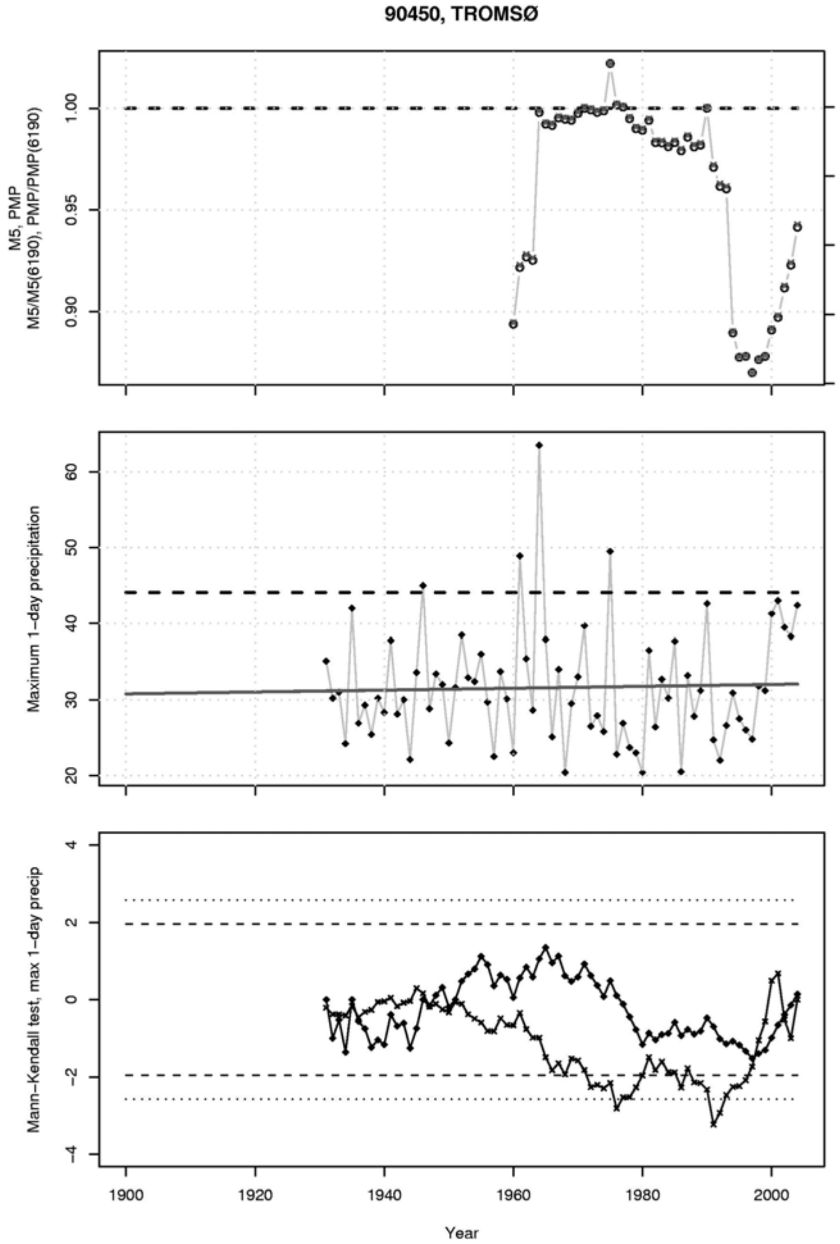
Year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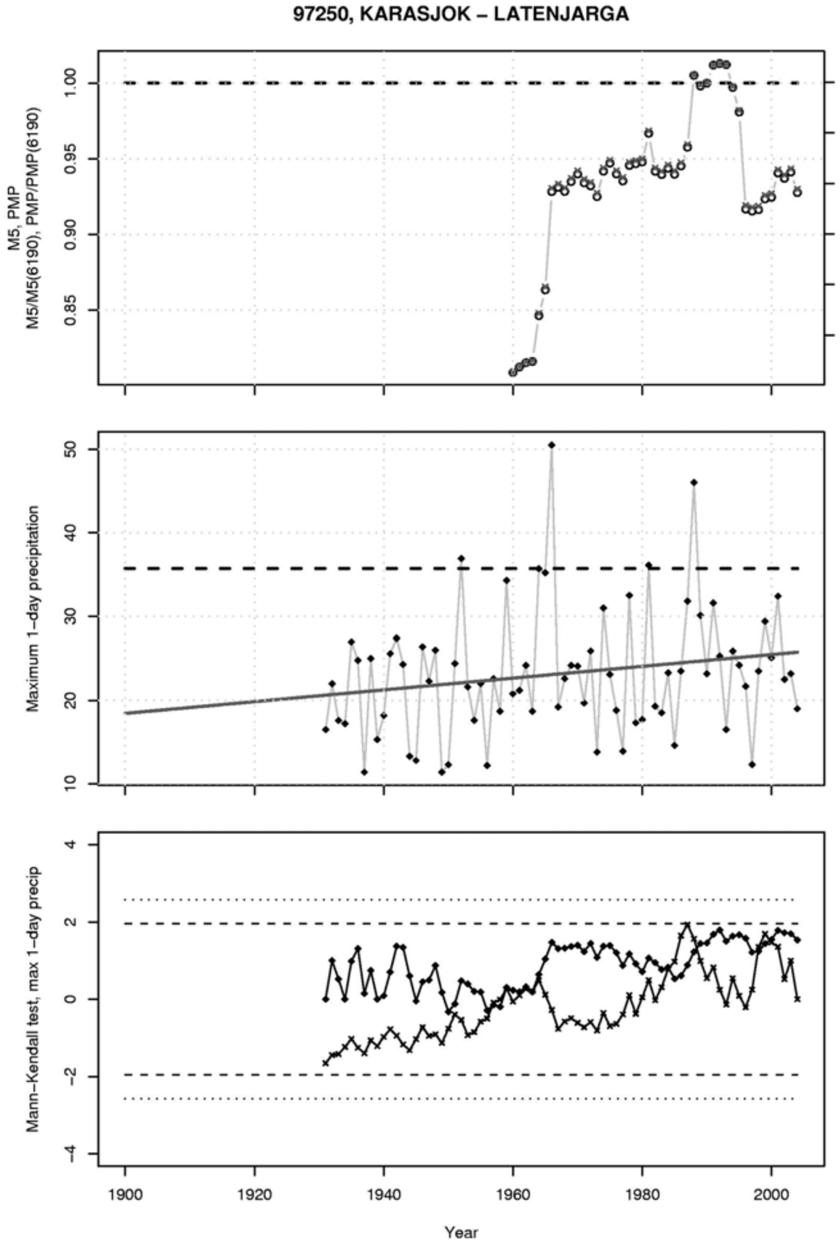
Maximum 1−day precipitation
Mann−Kendall test, max 1−day precip
Year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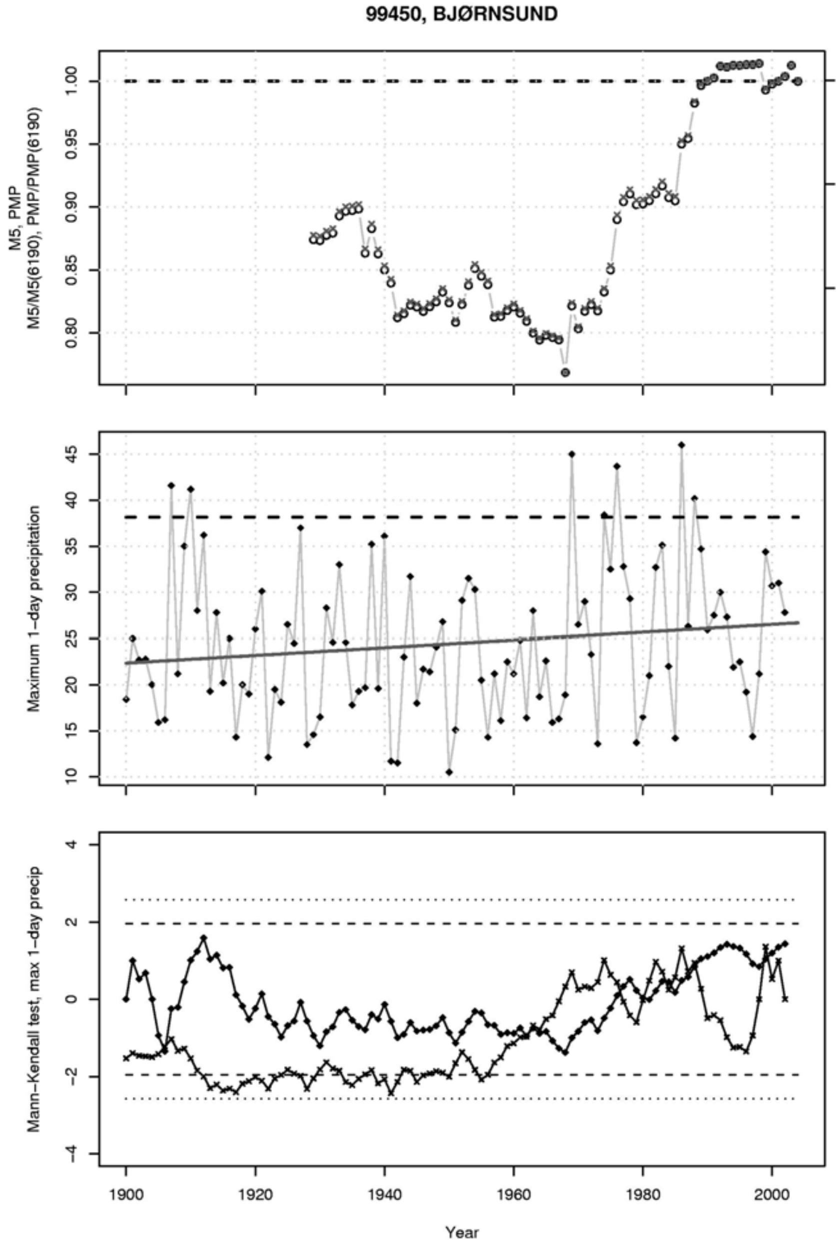
Maximum 1-day precipitation
Mann-Kendall test, max 1-day precip
Year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Maximum 1-day precipitation
Mann-Kendall test, max 1-day precip
Year