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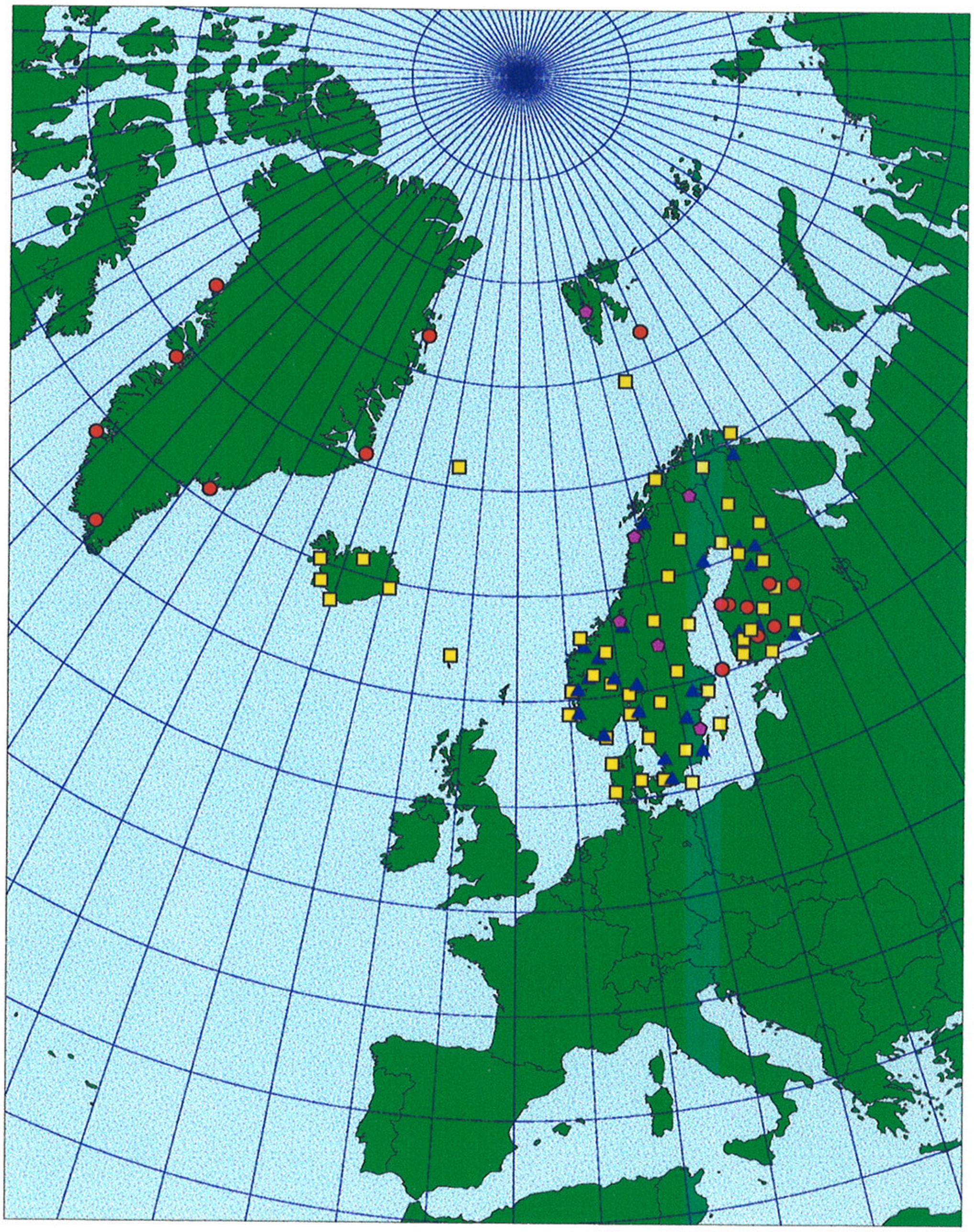
REWARD: - Relating Extreme Weather to Atmospheric circulation using a Regionalised Dataset

Trends in maximum 1-day precipitation in the Nordic region

Eirik J. Førland, Hans Alexandersson, Achim Drebs, Inger Hanssen-Bauer, Haldo Vedin and Ole Einar Tveito



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Trends in maximum 1-day precipitation in the Nordic region

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PROJECT CONTRACTORS

Nordic Council of Ministers (Contract FS/HFj/X-93001)
National Meteorological Institutes in Denmark, Finland[1], Iceland, Norway[2] & Sweden[3]

Abstract

Within the NMR-project REWARD (Relating Extreme Weather to Atmospheric circulation using a Regionalised Dataset) the Nordic meteorological institutes collaborated in establishing and analysing a comprehensive long-term data set of climatic extremes from Denmark, Faeroe Islands, Finland, Greenland, Iceland, Norway and Sweden.

Analysis of the 85 REWARD series of maximum 1-day precipitation (Rx), demonstrated that the Nordic countries comprise a complex region for extreme 1-day precipitation amounts,- both concerning geographical distribution of absolute values, seasons for extreme Rx-values, for long-term trends and for weather situations favourable for high Rx-values. While some Nordic stations have observed Rx-values exceeding 200 mm/day, several stations with 100-year long records never have experienced 1-day rainfalls exceeding 50 mm/day.

Although it is concluded that the annual series of Rx from single stations are no ideal indicators for revealing trends in extreme 1-day rainfall, is was found that for all Nordic countries there is a maximum in the 1930s and a tendency of increasing Rx values during the latest two decades. The decades with maximum frequencies of extraordinary rainfall coincides with decades with high regional summer temperatures. For western Norway, there was no local maximum in the 1930's. In this area the two latest decades have evidently had the highest number of extraordinary rainfall events. During this period, western Norway has experienced a substantial increase in orographic precipitation during autumn, winter and spring.

By using a multiple linear regression model, it was found that the Rx-values show significant correlations with circulation characteristics, especially for stations influenced by orographic precipitation enhancement.

SIGNATURE

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FOREWORD

The lack of data and need for analyses of climatic extremes were recognised by Nordic climatologists, and as a continuation of the EC/NMR-project «North Atlantic Climatological dataset, NACD» (Dahlström et al.,1995; Frich et al., 1996) the Nordic meteorological institutes suggested a major effort to establish and analyse a comprehensive dataset of climatic extremes (Førland et al., 1996b). The original plans for the suggested Nordic project were not fully approved, but a revised project was during 1996-1997 partly financed by the Nordic Council of Ministers (NMR, Contract FS/HFj/X-93001) and partly by own funding by the national meteorological institutes. The project was named *REWARD* - ***Relating Extreme Weather to Atmospheric circulation using a Regionalised Dataset.***

The main objectives of the REWARD-project were:

- *Establish a Nordic dataset of climatic extremes*
- *Analyse trends in extreme temperatures (maximum and minimum temperature, diurnal temperature range (DTR))*
- *Analyse trends in maximum 1-day precipitation*
- *Study relations between atmospheric circulation and extreme climatic events*
- *Evaluate appropriate extreme value distributions for Nordic series of climatic extremes*
- *Work out a first edition of a Nordic Atlas of climatic extremes*

The following scientists have contributed to the REWARD-project (national project leaders are underlined):

The Danish Meteorological Institute (DMI): Povl Frich, Torben Schmith
The Finnish Meteorological Institute (FMI): Achim Drebs, Raino Heino, Jaakko Helminen Heikki Tuomenvirta,
The Icelandic Meteorological Office (VI): Trausti Jónsson, Þóranna Pálsdóttir, Þórður Arason
The Norwegian Meteorological Institute (DNMI): Eirik Førland, Inger Hanssen-Bauer, Per Øyvind Nordli, Ole Einar Tveito
The Swedish Meteorological and Hydrological Institute (SMHI): Hans Alexandersson, Bengt Dahlström, Carla Karlström, Haldo Vedin

The REWARD-project was co-ordinated by Eirik J. Førland, DNMI

CONTENTS

Foreword

1. Introduction

During the last century there has been well-documented global and regional changes in annual and seasonal values of both temperature and precipitation (Nicholls et al., 1996). The mean global surface temperature has increased by about 0.3 to 0.6 C since the late 19th century (Horton & Parker, 1997). For precipitation, the best evidence available suggests that there has been a small positive (1 %) global trend over land during the 20th century (Nicholls et al., 1996). Based on zonally averaged precipitation series for 1900-1992 for land areas north of 50 °N, Hulme (1995) estimated that the annual precipitation had increased by approximately 10%, and that this increase mainly took place after 1940. Førland et al (1996a) documented that in parts of northern Europe the annual normal precipitation is more than 10% higher for the present normal period (1961-90) than for the previous (1931-60). In northern Europe there are small differences between the 1961-90 and 1931-60 precipitation normals during summer, while the normal values have increased substantially during autumn, winter and especially spring (Førland et al., 1996a).

Heavy 1-day precipitation plays a crucial role in the flooding conditions for small watersheds and especially in urban areas. To evaluate the hydrological consequences of the enhanced annual and seasonal precipitation, it is important to know whether there is a similar increase in precipitation extremes. Even small changes in the mean climate or climate variability can produce relatively large changes in the frequency of extreme events; a small change in the variability has a stronger effect than a similar change in the mean (Kattenberg et al., 1996). Groisman et al (1998) have e.g. shown that a 7% increase in mean summer precipitation in western Norway may lead to an increase of 12% in the frequency of heavy daily rainfalls.

Up to now, the majority of climate change investigations has been dealing with average climate and little is known of whether the precipitation increase in parts of northern Europe is caused by increase in number of precipitation days or increased daily precipitation intensity, or a combination of both these features. In the Second Assessment Report of IPCC, Nicholls et.al (1996) stated that the few studies available indicated that in some areas there were evidence of increase in the intensity of extreme rainfall events, but that no clear large-scale pattern had emerged. Attention was called to that the available data and analyses were poor and not comprehensive. This lack of information concerning climatic extremes also complicates the use of model projections to assess the likelihood of future changes in extremes and variability. However, several models indicate an increase in the precipitation intensity, suggesting a possibility for more extreme rainfall events (Kattenberg et al.,1996)

The lack of data and need for analyses of climatic extremes were earlier recognised also by Nordic climatologists. In the joint Nordic project **REWARD** *(Relating Extreme Weather to Atmospheric circulation using a Regionalised Dataset*, Førland et al.,1996b), the main objectives were to establish and analyse a Nordic dataset of climatic extremes. In the REWARD-project, special focus is put upon whether the observed global warming has caused any increase of extreme climatic events in the Nordic area. Trends in Nordic series of daily minimum and maximum temperatures are analysed by Tuomenvirta et al. (1998). The present report deals with maximum 1-day precipitation, *Rx*. In section 2 the REWARD dataset is presented, section 3 gives a survey of observed Rx in the Nordic countries. Weather situations generating large Rx are described in section 4, and long-term variations in Rx is described in sections 5-7.

2. Data

In the Nordic countries, just a few complete long-term climatological series of daily data are available in digital form for the period before ca. 1955. However, paper copies of monthly summaries (incl. Rx) were available. For selected stations, these summaries were digitised, partly within the framework of REWARD and partly during the NACD-project (Frich et al., 1996). Totally 85 long-term series of Rx were made available during the REWARD-project (cf. Table 2.1 and Appendix 1).

Table 2.1. Frequencies of maximum 1-day rainfall at the REWARD stations ***(Period: 1880-1996)***

	Maximum 1-day precipitation (mm)							No. of stations	REWARD MAX (mm)	NATIONAL MAX (mm)
	<50	50-75	75-100	100-125	125-150	150-175	175-200			
DENMARK	0	2	3	0	0	0	0	5	94	169
FAEROES	0	0	1	0	0	0	0	1	77	-
FINLAND	1	9	7	1	0	0	0	18	118	198
GREENLAND	1	3	0	1	1	1	0	7	169	-
ICELAND	0	2	1	0	1	1	0	5	156	243
NORWAY	4	13	5	3	1	2	1	29	195	230
SWEDEN	1	11	6	1	0	0	1	20	187	198*
TOTAL	7	40	23	6	3	4	2	85		

*) Unofficial value: Sweden: 276 mm (in August-97, see sections 3.1 and 4)

The geographical distribution (Figure 2.1.) shows that the stations cover most parts of the Nordic region. The majority of the series is more than 100 years long (Figure 2.2). (A complete survey of the series is given in Appendix A). For a few series, especially in Finland and northern Norway during the 2nd World War,- values for some months are missing. However most of the series consist of complete records.

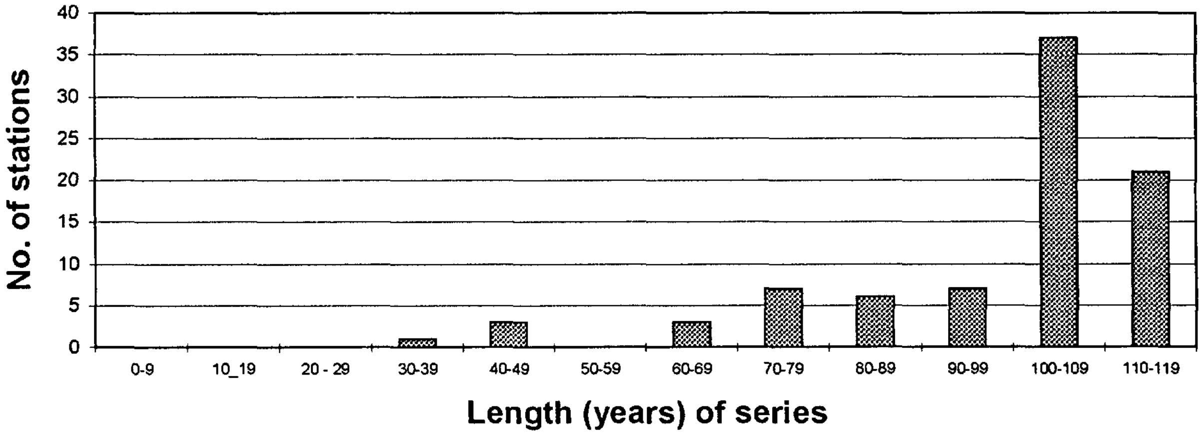


Figure 2.2 Length of REWARD series of maximum 1-day precipitation

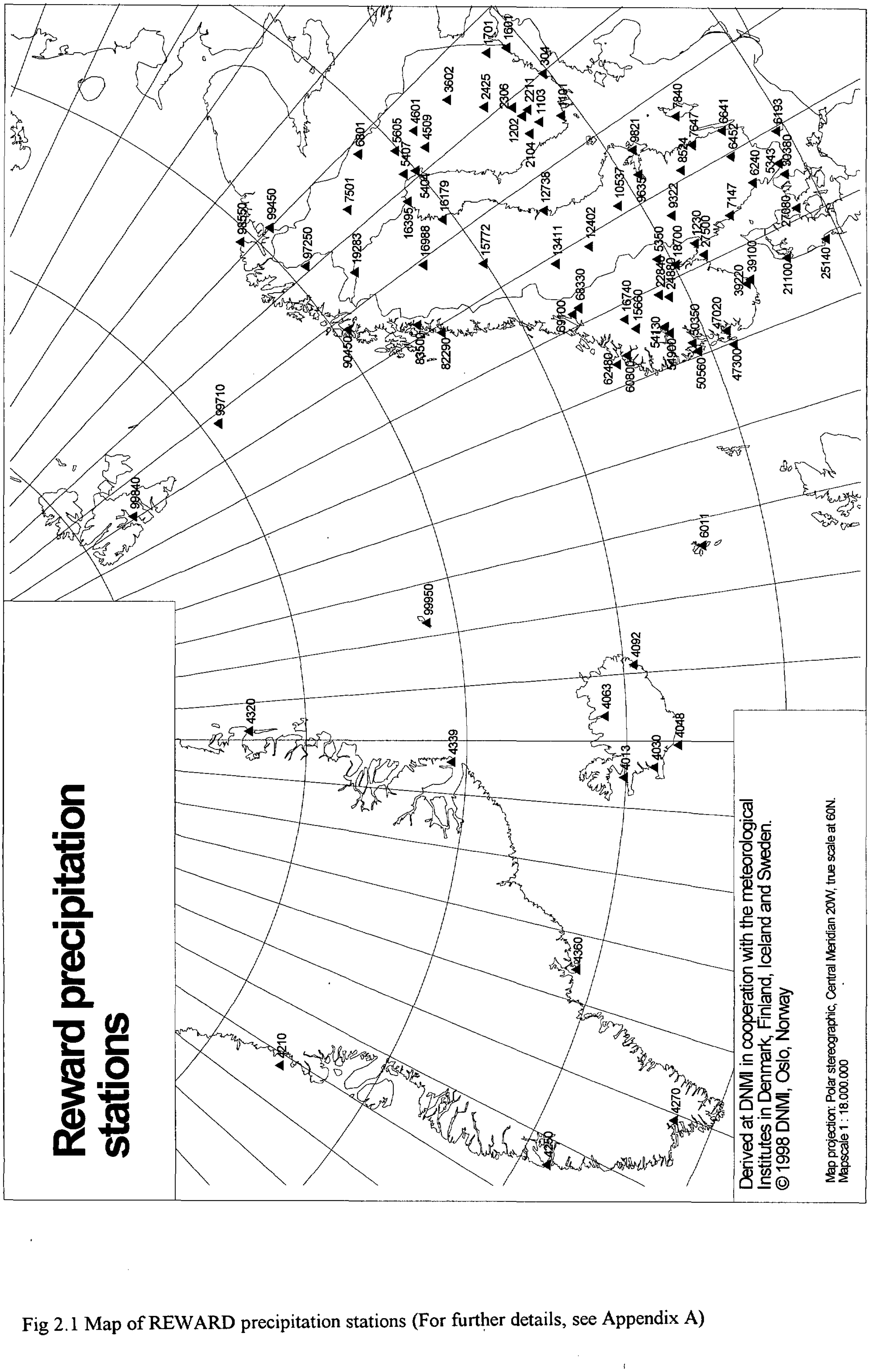


Fig 2.1 Map of REWARD precipitation stations (For further details, see Appendix A)

For some of the stations, inhomogeneities were found in the series of annual precipitation (Frich et al., 1996). As there are no obvious ways of adjusting inhomogeneities in series of daily precipitation, some supplementary series found homogeneous on annual basis were selected in Finland and Norway. These stations were primarily selected in the neighbourhood of the original stations, and accordingly there appear pairs of stations in Finland and southern Norway in Figure 2.1. A detailed description of the REWARD-dataset is given by Drebs et al., 1998.

To evaluate real trends in precipitation, it is essential that the precipitation series are homogeneous. However, most long-term precipitation series are influenced by inhomogeneities. In a comprehensive study of 165 Norwegian long-term series of annual precipitation, Hanssen-Bauer & Førland (1994) found inhomogeneities in about 70% of the series. The range of adjustment factors for annual precipitation were 0.81 to 1.23. Table 2.2 gives a survey of the main reasons for inhomogeneities.

Table 2.2 Reasons for inhomogeneities in series of annual precipitation at 165 Norwegian stations

Reason for inhomogeneity	Relative frequency (%)	Mean adjustment factor
Relocation	47	1.01
Changes in environment	18	1.05
Installation of windshields	9	1.13
New observer	3	1.08
Other known reasons	3	0.95
Reason unknown	21	1.01

Inhomogeneities caused by changes in environment and installation of wind shield are mainly due to changes in the wind exposure of the gauge, and the consequent change in the catch deficiency of the gauge. As the catch deficiency is rather small for high intensity rainfall (Førland et al., 1996c), the adjustment factor for these kinds of inhomogeneities probably are substantially smaller for Rx than for the mean annual precipitation.

In addition to inhomogeneity problems, recorded precipitation extremes may be influenced by reading or measuring errors. A general problem with extremes is to decide whether the reading is true or false. In weather situations with heavy showers, the strong local gradients make it difficult to decide whether a suspiciously high precipitation value is true or due to a misreading. Even sabotage may occur, e.g. as a result of practical jokes adding water or other liquids to the gauges. Also the sampling interval may be erroneous. It happens that the observer «forgets» to read the gauge on a daily basis, and the recorded value may thus be accumulated during several days. Most of these erroneous values will be detected and corrected during the regular quality control at the national meteorological institutes, but in some cases it is difficult to judge between the «true» or «false» alternatives.

Even technical problems may influence the daily precipitation extremes. For Norway the traditional gauge has a capacity of just 230 mm. In the case of the national maximum 1-day value of 229.6 mm (Table 2.1), the gauge was actually overtopped.

In addition to the regular quality control at the NMSs, the REWARD dataset was carefully scrutinised within the project. Possible digitising errors were examined, and a special emphasis was laid on the documentation of outliers. As no adequate homogeneity testing procedures exist for series of maximum daily rainfall, the metadata for annual series were used to evaluate the quality of the series. Most of the REWARD stations are also included in the NACD and Frich et al.(1996) have presented metadata for the annual precipitation series. This metadata survey includes year(s) for inhomogeneities, reasons for inhomogenities, and adjustment factors for inhomogeneities.

3. Maximum 1-day precipitation in the Nordic countries

3.1. Absolute maximum

The highest values of 1-day precipitation for each station in the REWARD-dataset are presented in Figure 3.2, and the absolute highest national values are given in Table 2.1.The maximum observed Rx at the REWARD stations (Table 2.1, Figure 3.2) varies from 41 mm at 15660 Skjåk to 195 mm at 50350 Samnanger (Skjåk is situated just 200 km NE of Samnanger, at the leeward side of the Norwegian mountain range, cfr. Figure 2.1).

In large parts of the Nordic area, the highest recorded 1-day rainfall is in the interval 50-100 mm. Higher values are generally found on the southern and western coast of Norway, and in southern parts of Iceland, while in Arctic areas and northern continental parts of Finland, Norway and Sweden 1-day rainfall larger than 50 mm rarely occur.

The maximum national recordings are 200-250 mm/day in both Finland, Iceland, Norway and Sweden. However, during August 1997 an unofficial value of 276 mm/day was reported in Sweden, and the maximum 1-day precipitation in this event was estimated to be well above 300 mm (Alexandersson et al., 1997, see also section 4).

The large regional differences in range and magnitude of Rx is illustrated in Figure 3.1. The highest ever recorded Rx at e.g. Skjåk and Helsinki are smaller than the lowest annual Rx at Samnanger. Note also the large difference in range of Rx at e.g. Narsarsuaq and Teigarhorn vs. e.g. Skjåk and Helsinki. A comprehensive survey of maximum 1-day precipitation for the Nordic countries is given by Tveito et al. (1998).

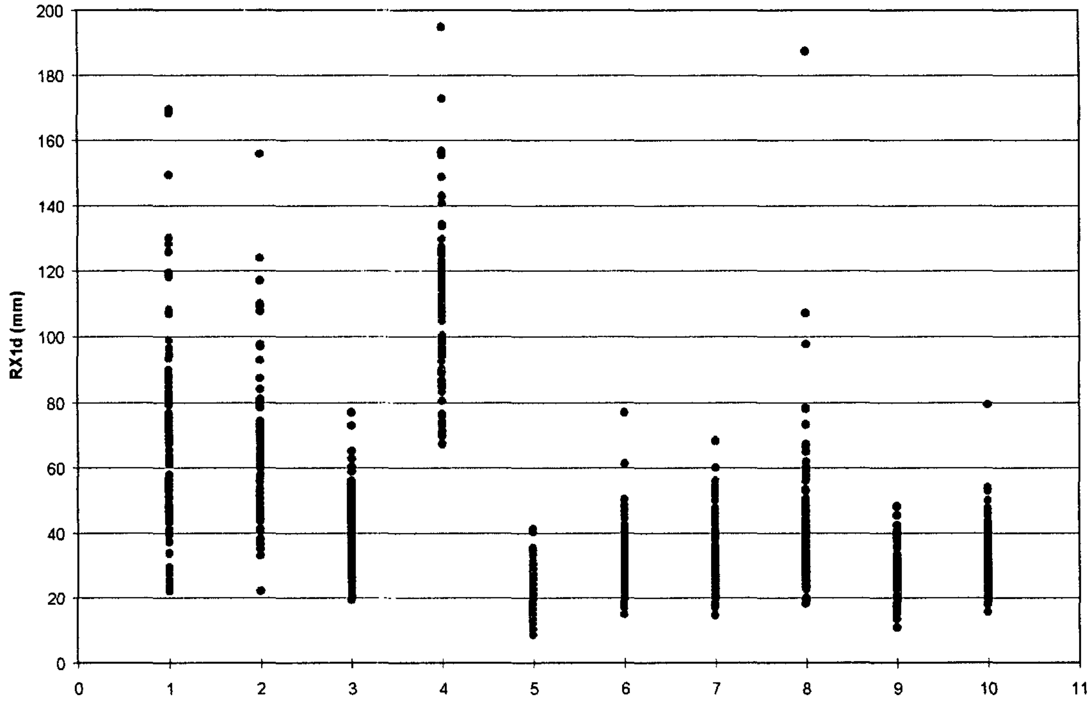


Figure 3.1 Distribution of maximum 1-day precipitation at some selected REWARD-stations
1= 4270 Narsarsuaq (GR), 2= 4092 Teigarhorn (IC), 3=6011 Torshavn (FA), 4= 50350 Samnanger (NO), 5= 15660 Skjåk (NO), 6= 30380 Copenhagen (DK), 7=9821 Stockholm (SW), 8= 12738 Härnösand (SW), 9=0304 Helsinki (FI), 10= 7501 Sodankylä (FI)

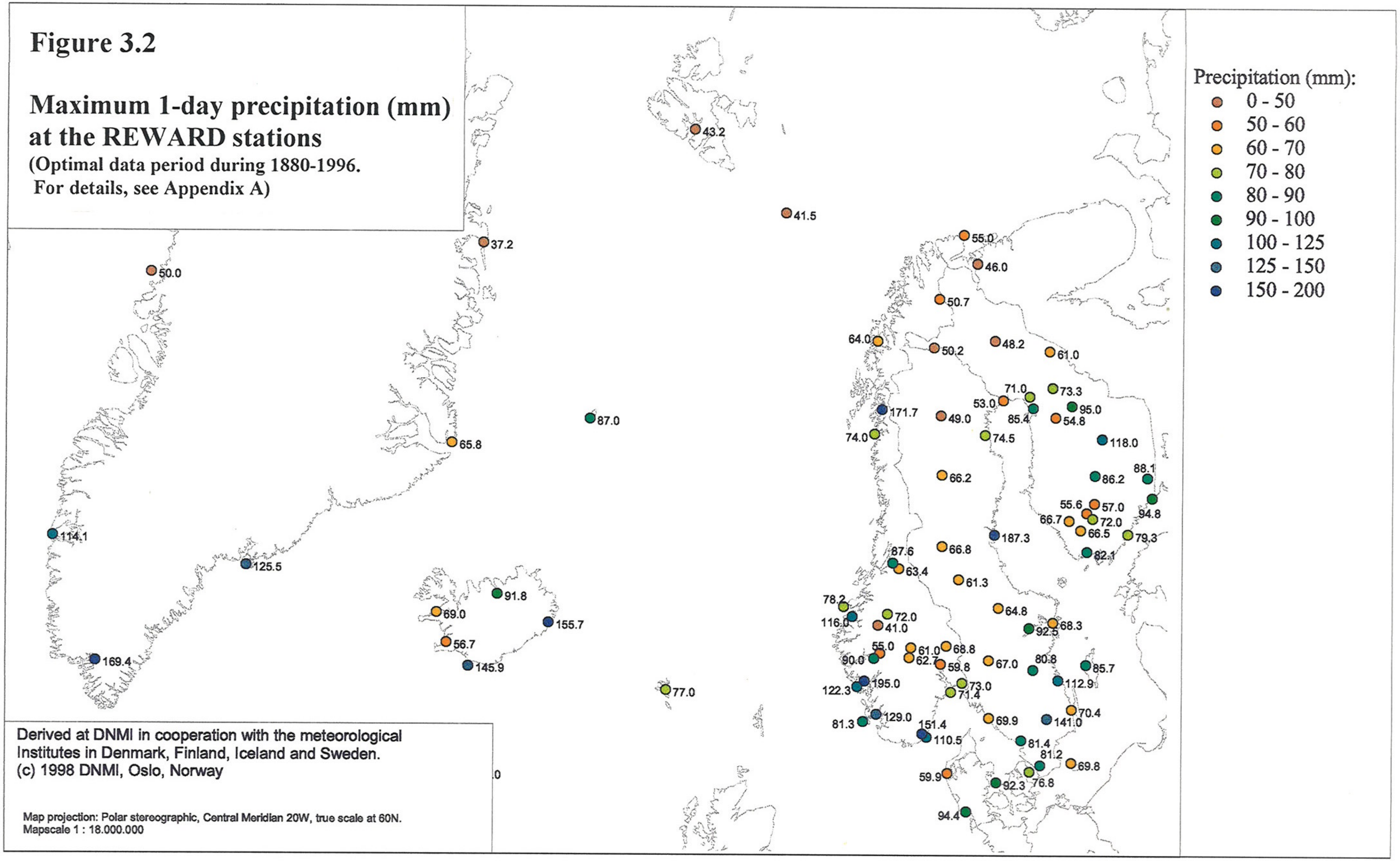


Figure 3.2

Maximum 1-day precipitation (mm) at the REWARD stations
(Optimal data period during 1880-1996.
For details, see Appendix A)

Derived at DNMI in cooperation with the meteorological
Institutes in Denmark, Finland, Iceland and Sweden.
(c) 1998 DNMI, Oslo, Norway

Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

3.2. Mean annual maximum 1-day precipitation

In major parts of the Nordic region, the geographical distribution of mean annual maximum 1 day precipitation is rather uniform (Figure 3.3). In Finland all stations have mean Rx in the interval 26 to 35 mm, in Denmark between 30 and 32 mm and in Sweden between 24 and 36 except for Härnösand with 42 mm. In Greenland, Iceland and Norway however, there are large local and regional gradients, and the scattered REWARD stations are unable to reproduce the real complex geographical distribution. In Norway the highest and lowest mean Rx are 21 and 108 mm, in Iceland 25 and 62 mm. The lowest mean values (~15 mm) are found at the Arctic stations 4320 Danmarkshavn in Greenland and 99840 Svalbard Airport at Spitsbergen. However, the contrasts in Greenland are large: The station 4270 Narsarsuaq has the 2nd highest mean Rx value (69 mm) in the REWARD dataset

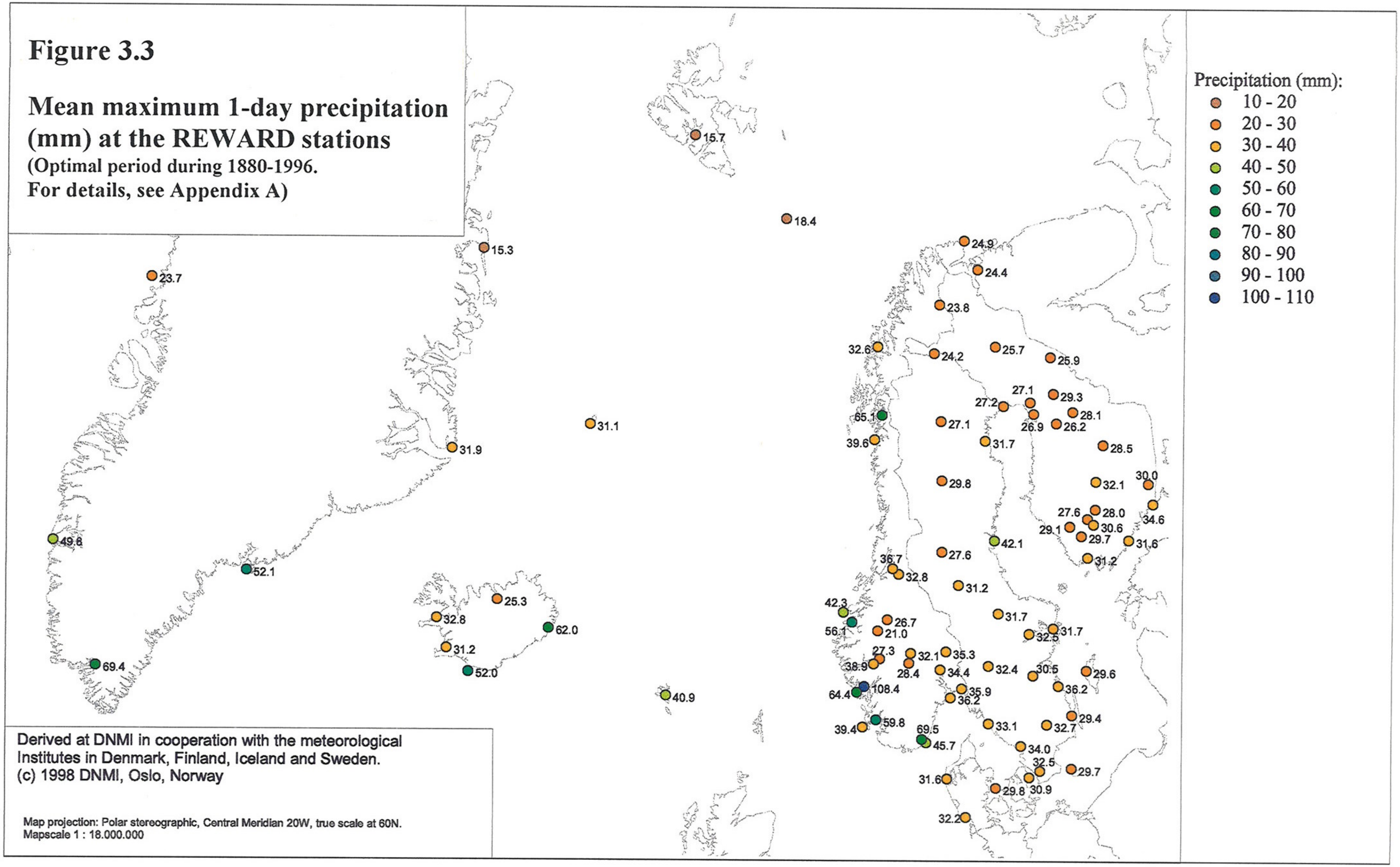
The Faeroe Islands are represented by just one station, 6011 Tórshavn with a mean Rx value of 41 mm. Because of strong orographic precipitation enhancement, there are large local gradients at the Faeroes; the mean annual precipitation increases from 1000 mm/year at the coast, to more than 3000 mm/yr in the mountain areas (Davidsen et al., 1994). In the mountain areas at the Faeroes and also in orographic influenced areas in Iceland, there probably are areas with mean Rx-values exceeding 100 mm.

Even though most of the REWARD Rx series consist of more than 100 years of data, the mean values are influenced by «outliers» (cf. Figure 3.1); causing a skew frequency distribution. Thus, at more than 70% of the stations the mean value is more than 5% higher than the median, and at 3 stations even more than 15% higher. There are large year-to-year variations in Rx, causing quite large standard deviations. At almost all stations in Finland, Sweden and Denmark, Northern Iceland and Norway the standard deviation (std) is between 7 and 13 mm. Exceptions are Härnösand in eastern Sweden, (std=20.5 mm) and stations in southern Iceland and western coastal areas of Norway (std up to 22 mm). The largest standard deviation in the REWARD dataset (29 mm) is at the greenlandic station 4270 Narsarsuaq.

Figure 3.3

Mean maximum 1-day precipitation (mm) at the REWARD stations

**(Optimal period during 1880-1996.
For details, see Appendix A)**



Derived at DNMI in cooperation with the meteorological Institutes in Denmark, Finland, Iceland and Sweden.
(c) 1998 DNMI, Oslo, Norway

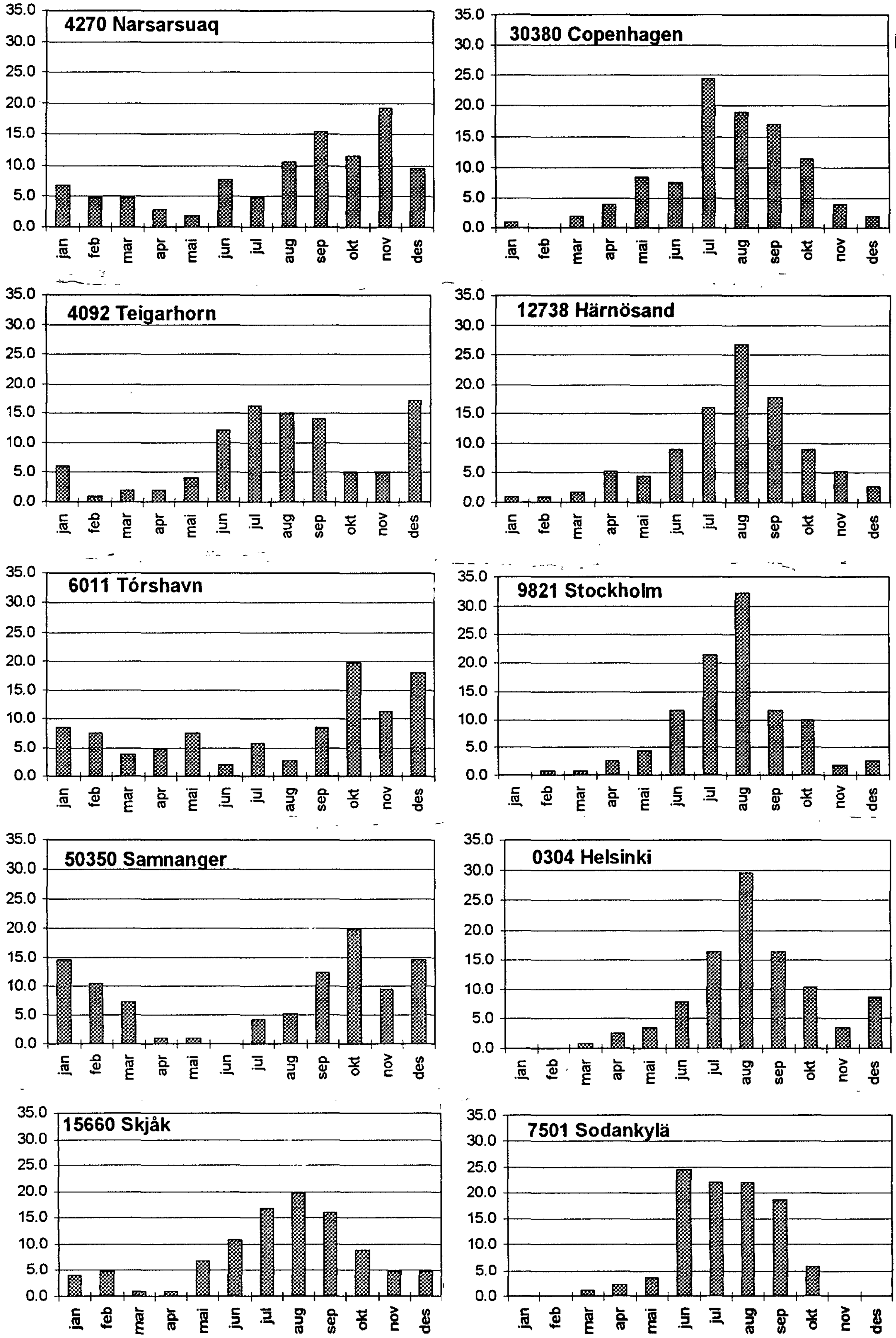
Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

3.3. Seasonal values of maximum 1-day precipitation

Table 3.1 shows that in all Nordic countries, the highest national Rx-values have occurred during summer and autumn. In eastern parts of the Nordic region, most of the highest annual 1-day precipitation values are recorded during the summer or early autumn (Figure 3.4). At the western stations (4270,4092,6011,50350) represented in Figure 3.4, the occurrence of the highest annual Rx is more evenly distributed throughout the year. At 7501 Sodankylä in northern Finland none of the annual Rx-values have occurred during November to February, while at 50350 Samnanger in Western-Norway nearly 50% of the annual Rx values have occurred during these winter months.

Table 3.1 Highest seasonal values (mm) of maximum 1-day precipitation in the REWARD dataset

		SPRING		SUMMER		AUTUMN		WINTER		ANNUAL	
	No of st.	Max	St.no	Max.	St.no	Max.	St.no.	Max.	St. no.	Max.	St. no.
Denmark	5	44.5	6193	94.4	25140	61.2	30380	43.6	6193	94.4	25140
Faeroes	1	53.0	6011	55.1	6011	77.0	6011	72.8	6011	77.0	6011
Finland	17	47.1	1601	118.0	3602	94.8	1601	45.0	1701	118.0	3602
Iceland	5	117.1	4092	155.7	4092	145.9	4048	117.1	4092	155.7	4092
Norway	29	172.8	50350	143.0	50350	195.0	50350	172.8	50350	195.0	50350
Sweden	20	78.0	12738	187.3	12738	83.7	7647	55.9	6452	187.3	12738



4270 Narsarsuaq

30380 Copenhagen

4092 Teigarhorn

12738 Härnösand

6011 Tórshavn

9821 Stockholm

50350 Samnanger

0304 Helsinki

15660 Skjåk

7501 Sodankylä

Fig. 3.4. Monthly frequencies (%) of occurrence of annual maximum 1-day precipitation

3.4. Return period values of maximum 1-day precipitation

3.4.1 Extreme value distributions

For impact evaluations, information on probable values of climatic extremes and estimation of recurrence periods related to extreme weather events are of considerable interest. The determination of design values is of large practical value, e.g. for dam safety and flood protection. Also for various climate impact studies there is a need for risk assessment.

For extreme events, a special family of frequency distributions are adapted, called extreme value distributions (EVD's). For maximum precipitation estimations, the EVD type I (also known as Gumbel 1) distributions is recommended (WMO, 1981). The distribution for annual maximum series is defined as:

$$F(x) = P(X < x) = e^{-e^{-\alpha(x-\beta)}} \qquad [3.1]$$

where $\alpha=1.281/\rho_x$ and $\beta=\mu_x-0.45\rho_x$. μ_x and ρ_x is the population mean and standard deviation respectively. *F(x)* is the frequency distribution, while P(X<x) means the probability for an annual maximum value X less than x. A simplified version of [3.1] gives the value M_T, which is the value exceeded in average every T'th year :

$$M_T = x - \frac{\sqrt{6}}{\Pi}\left(0.577 + \ln\left\{-\ln\left[\frac{T-1}{T}\right]\right\}\right) \cdot s_x \qquad [3.2]$$

3.4.2 Return period values (5 and 100 years) of Rx for the Nordic countries

By using the Gumbel distribution (eq. 3.2) it is possible to estimate values to be exceeded in average every T'th year. In this report estimates (MT) with return periods T=5 and T=100 years are shown.

Figure 3.5 shows that the 5 year return period value of Rx is between 25 and 50 mm in major parts of the Nordic region. Exceptions are stations in southern and western Norway and southern Iceland. The lowest M5-values are found at the northernmost stations and on the leeward side of the Norwegian mountain range. The highest value (125 mm) is found at 50350 Samnanger in western Norway.

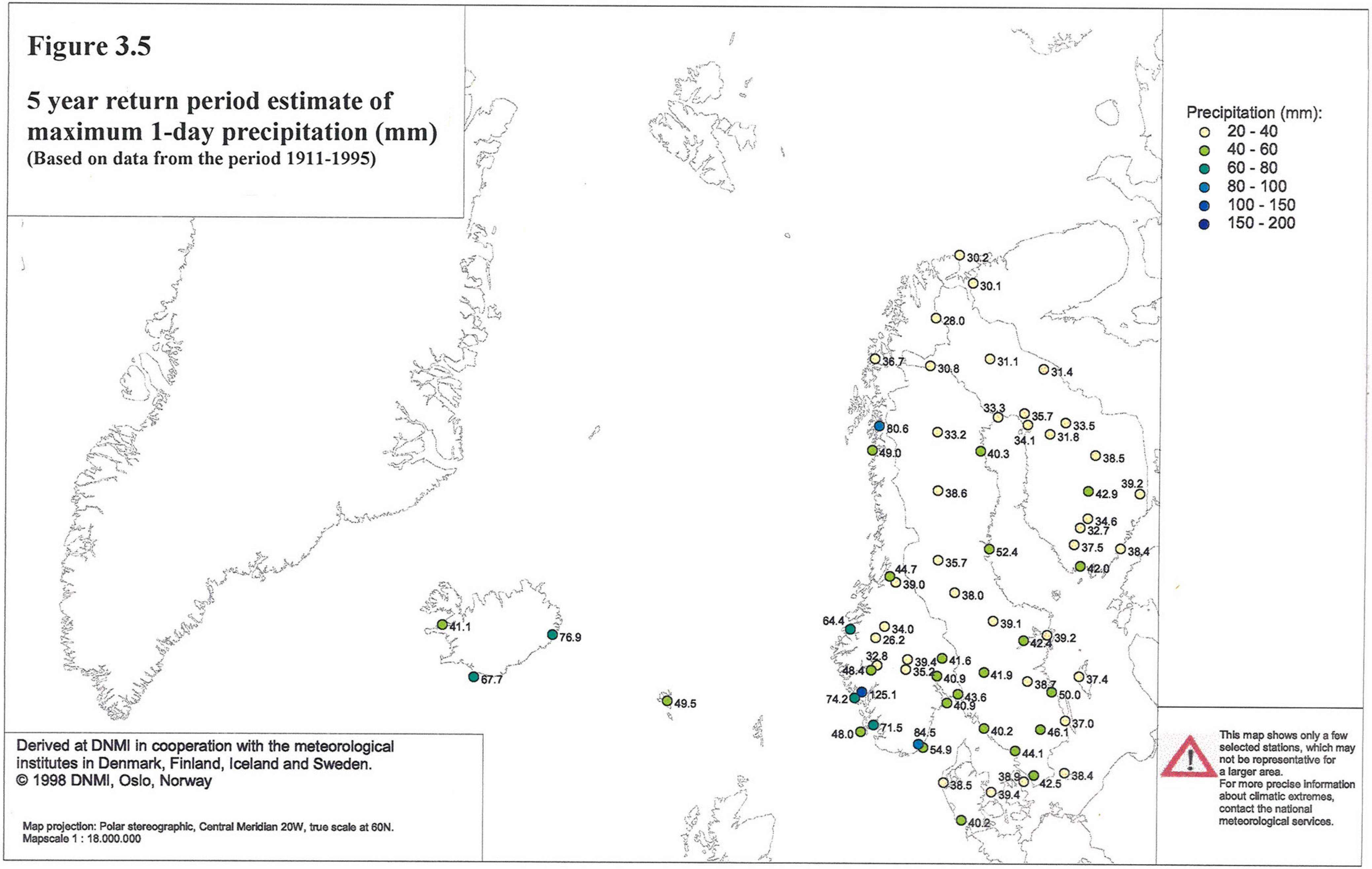
In Norway the 5 year return period value is used both as a criteria for «extraordinary rainfall» (see also chapter 7) and as a basic value for estimating 1000 year and PMP (Probable Maximum Precipitation) values for flood handling and dam design (Førland & Kristofferssen, 1989, Førland, 1992).

The 100-year recurrence value (Figure 3.6) is between 50 and 75 mm in large parts of the area. Exceptions are a few stations in eastern parts of Sweden, and stations in southern and western Norway and southern Iceland, with M100 values larger than 100 mm. The lowest M100 values are as for M5 found at the northernmost Arctic stations, and at the leeward side of the Norwegian mountains.

Figure 3.5

5 year return period estimate of maximum 1-day precipitation (mm)

(Based on data from the period 1911-1995)



Derived at DNMI in cooperation with the meteorological institutes in Denmark, Finland, Iceland and Sweden.

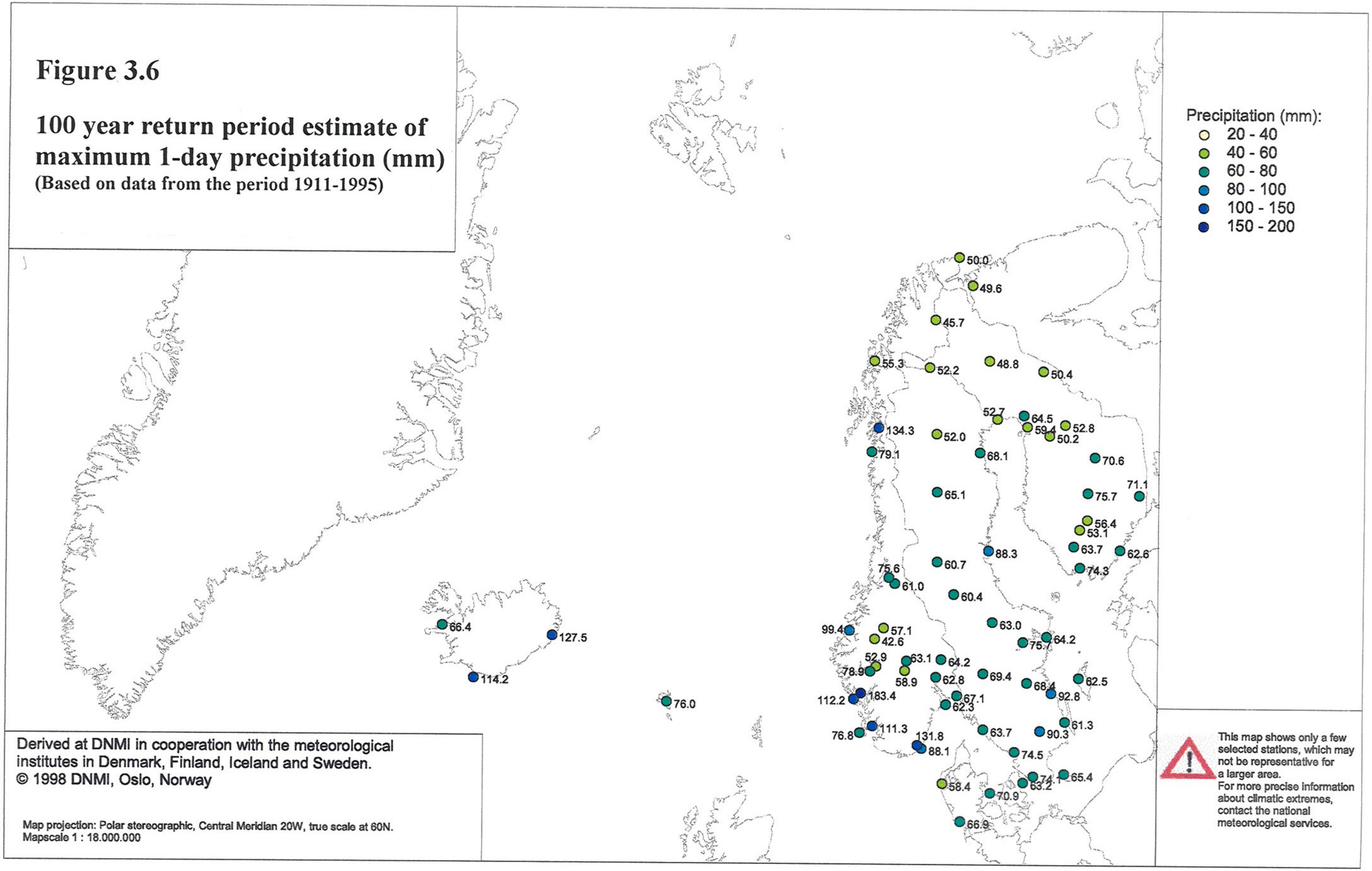
Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

This map shows only a few selected stations, which may not be representative for a larger area.
For more precise information about climatic extremes, contact the national meteorological services.

Figure 3.6

100 year return period estimate of maximum 1-day precipitation (mm)

(Based on data from the period 1911-1995)



This map shows only a few selected stations, which may not be representative for a larger area.
For more precise information about climatic extremes, contact the national meteorological services.

Derived at DNMI in cooperation with the meteorological institutes in Denmark, Finland, Iceland and Sweden.
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Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

3.4.3 Stability of M5 values

The Gumbel distribution was applied on different parts of the REWARD-series. The calculations were performed on running means with period length 20, 30, 40 and 50 years. Figure 3.7 shows that for series of e.g. 30 years length, 70% of the M5 values differed more than ±15% from the M5 value based on the complete century-long series. Even for series of 50 years length, 4% of the M5-estimates differed more than 15% from the long-term M5-value. This emphasises that one should be cautious by basing estimates of return period values on short dataseries. Even the length of the climatic standard normal periods (30 years) is too short to ensure reliable estimates.

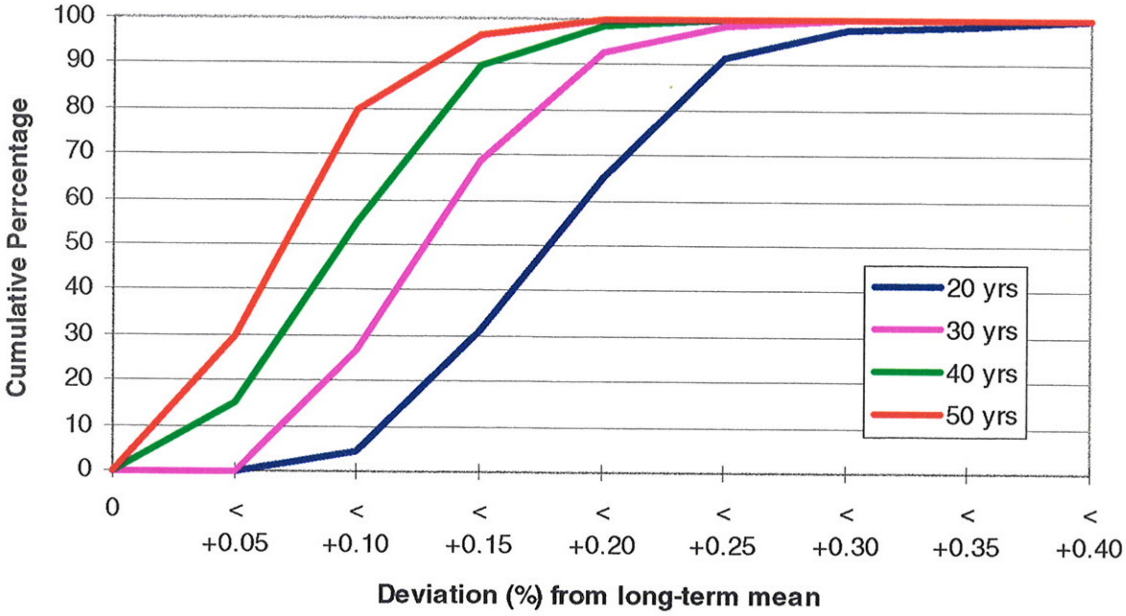


Figure 3.7 Deviations of M5 values based on different sampling periods (20-50 years) from M5-values based on century long series.

3.4.4 Long-term trends in estimates of M5

In section 3.4.3. it was shown that even return period values based on 30 year long series, could deviate substantially from estimates based on century long series. This is illustrated in Figure 3.8, displaying examples of time series of M5-estimates from selected REWARD-stations. The series are displayed both as absolute values (upper panel) and normalised by dividing with the estimate for the normal period 1961-90. The largest variations are found at 4270 Narsarsuaq (GR) and 12738 Härnösand (SW), where the M5-estimate for some 30-year periods were more than 40% higher than the estimate based on data from the standard normal period 1961-90.

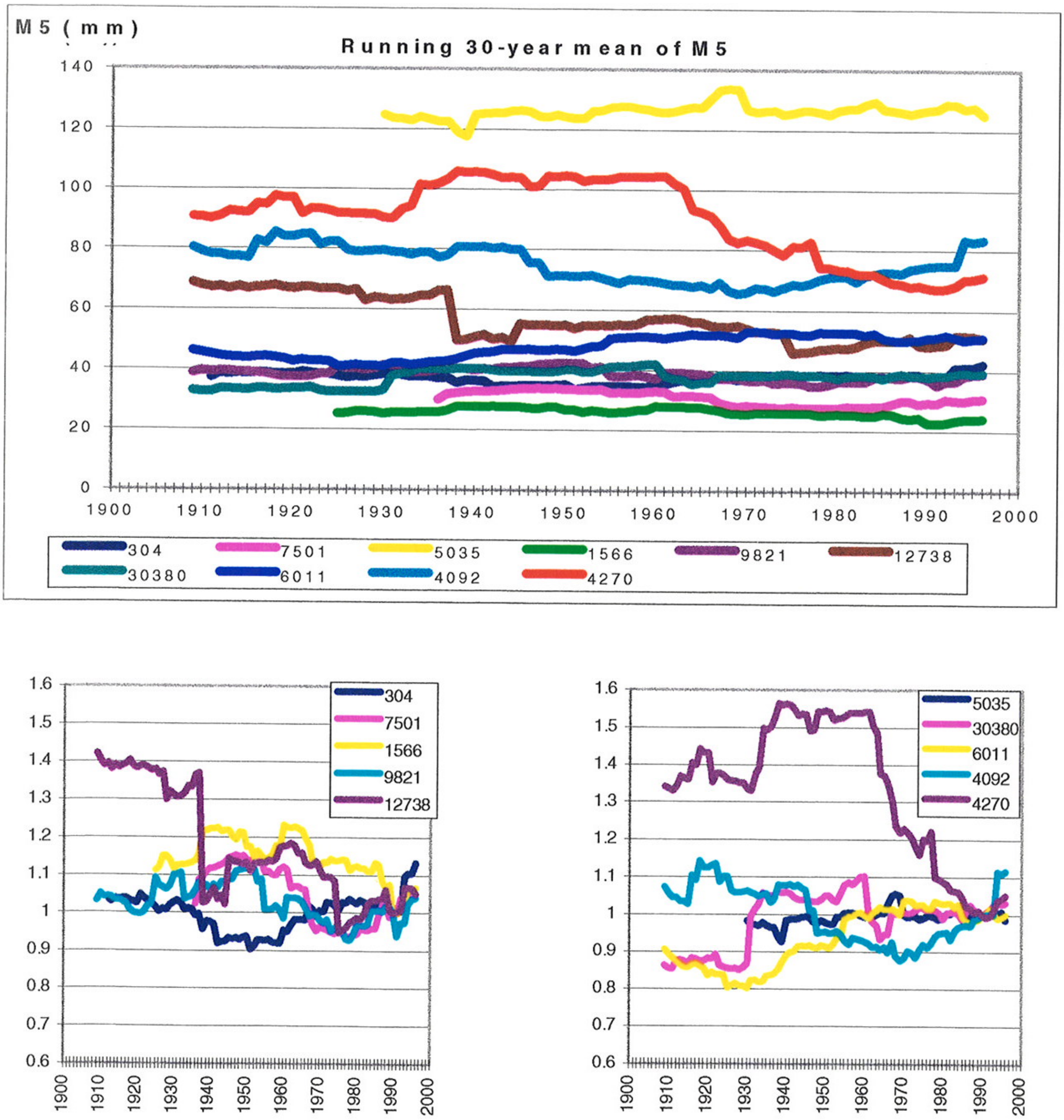


Figure 3.8 Estimates of M5 for running 30-years periods

The estimates are shown both as absolute values (upper panel) and as deviations (ratios) from estimates based on data for the standard normal period 1961-90 (lower panel). Stations: 4270=Narsarsuaq (GR), 4092= Teigarhorn (IC), 6011= Torshavn (FA), 5035= Samnanger (NO), 1566= Skjåk (NO), 30380= Copenhagen (DK), 9821= Stockholm (SW), 12738=Härnösand (SW), 304=Helsinki (FI), 7501= Sodankylä (FI)

4. Connections between heavy 1-day precipitation and atmospheric circulation

4.1 Weather situations generating large 1-day precipitation in Fennoscandia

The intense and lasting lifting, necessary to generate the most extreme 1-day precipitation amounts, may be obtained by any of the three main atmospheric processes creating precipitation within the Nordic area, i.e. lifting in connection with fronts, within convective cells and induced by orography.

Frontal precipitation, related to disturbances moving along the front-line between warm and moist air over Russia and considerably colder air over western Europe, may occasionally during summer and autumn create widespread and extremely large 1-day precipitation over Denmark, Finland and also over Norway and Sweden east of the main water divide. A classic event of this type occurred 21 - 22 July 1789, when south-eastern Norway was hit by devastating rains (Østmo, 1985). Approximately the same area received 100 - 160 mm 30 August - 1 September 1938 (Figure 4.1). During another case, 6 August 1967, large areas in western Finland and north-eastern Sweden got equally high amounts during less than 24 hours (Figure 4.2).

Convective precipitation not related to fronts seldom generates heavy precipitation over large areas although the intensity may locally be extremely high for durations up to one or a few hours. Convection associated with quasi-stationary fronts may however during summer and early spring produce enormous quantities of rain as convective cells move along the front. A recent example of such a case is the one at Fulufjället in Sweden, close to the Norwegian border at the south-eastern outskirts of the Scandinavian mountain range. At the 30 - 31 August 1997 (Figure 4.3) it was raining cats and dogs: The highest measured «unofficial» 1-day value was 273 mm, and a small area probably got more than 400 mm rain during 24 hours. (Aleandersson et al., 1997). This type of extreme precipitation may occur at any place in the Nordic area, but is less common in Iceland and the coastal districts of Norway.

Orographic precipitation dominates in Norway and Sweden to the west of the main water divide and in most parts of Iceland. As comparatively strong winds are essential, orographic precipitation is almost always associated with lows and thus also with fronts, although they may be fairly weak and not a direct part of the precipitation creating process. In contrast to the two above mentioned other processes, that create extreme 1-day precipitation amounts, heavy orographic precipitation is most common in autumn and winter, when lows and lasting strong winds are most frequent. A typical example of extreme orographic precipitation occurred in south-western Norway 25 - 27 November 1940 (Figure 4.4).

In several cases extreme precipitation is generated by a mix of these processes. Thus frontal precipitation is often enhanced by friction differences between land and sea. In situations with onshore or coast parallel wind, when the lower pressure is situated over the sea, this often creates marked precipitation maxima along the coast. This effect is most pronounced at the fairly steep coast in central Sweden between 62 and 63 °N; the area around Härnösand.

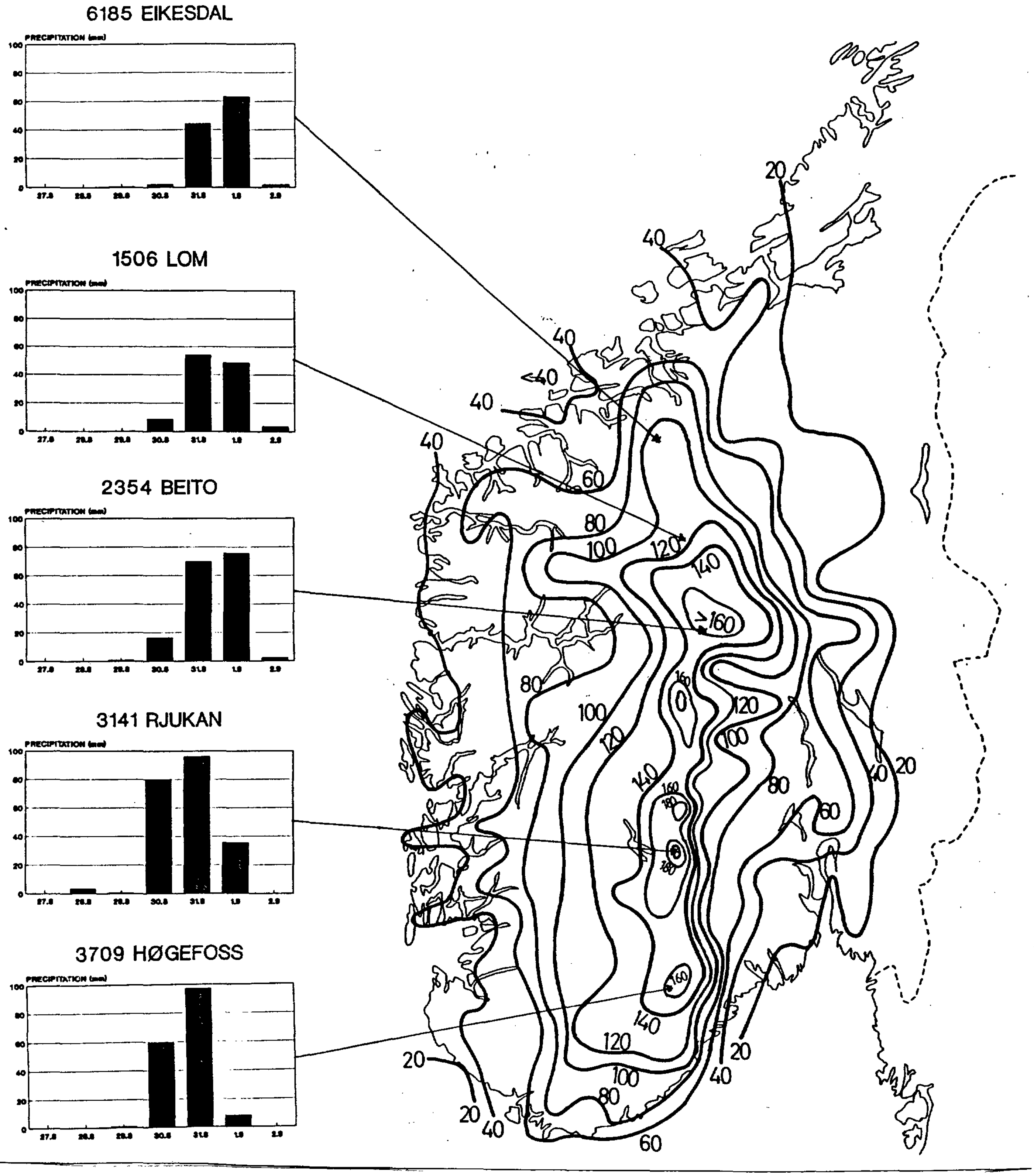


Fig. 4.1a Precipitation (mm) during the 3-day period 29.08 - 01.09.1938

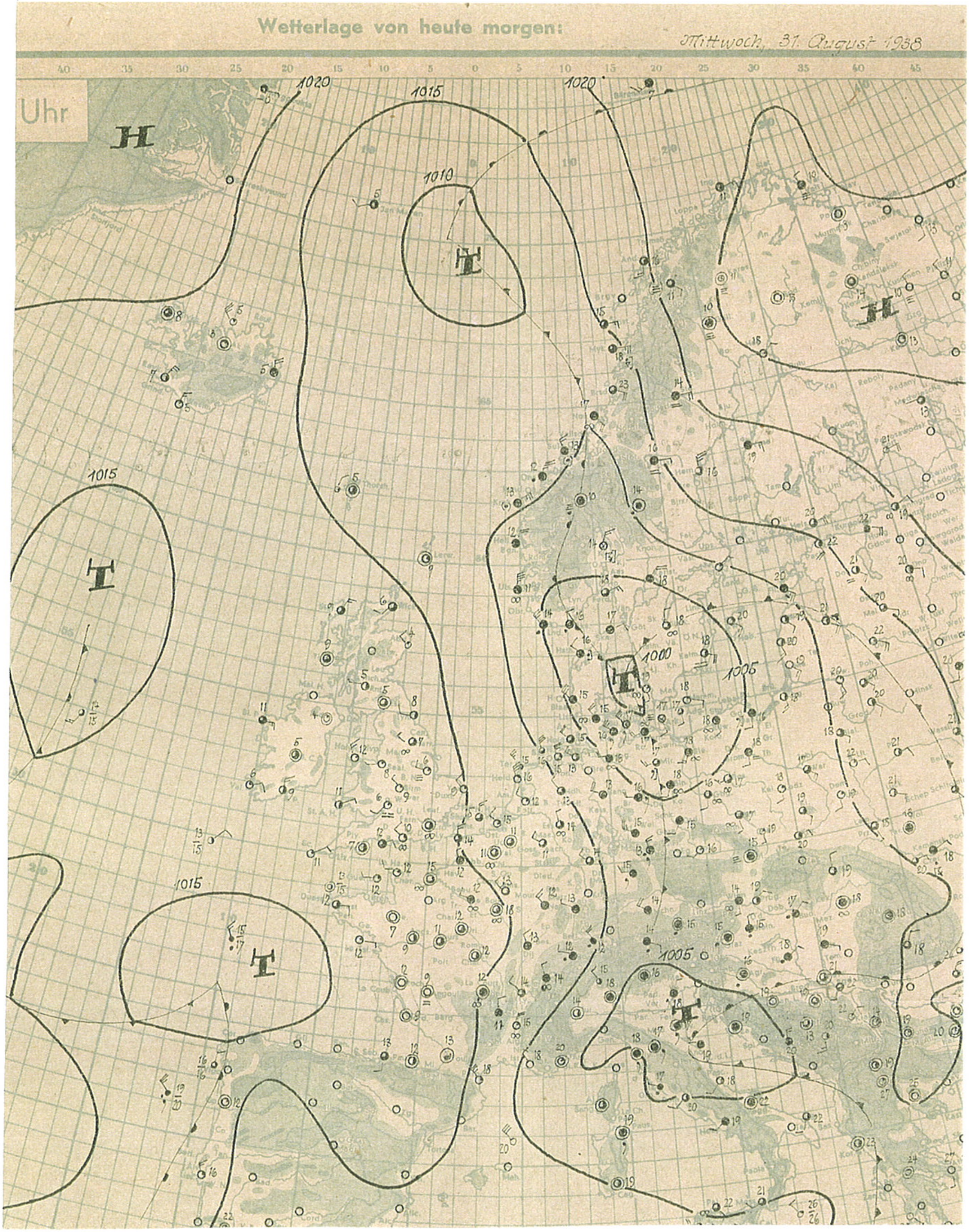


Fig. 4.1b Weather situation 31.08.1938 at 07 UTC
(From Täglicher Wetterbericht, Deutscher Reichswetterdienst, Deutsche Seewarte, Hamburg)

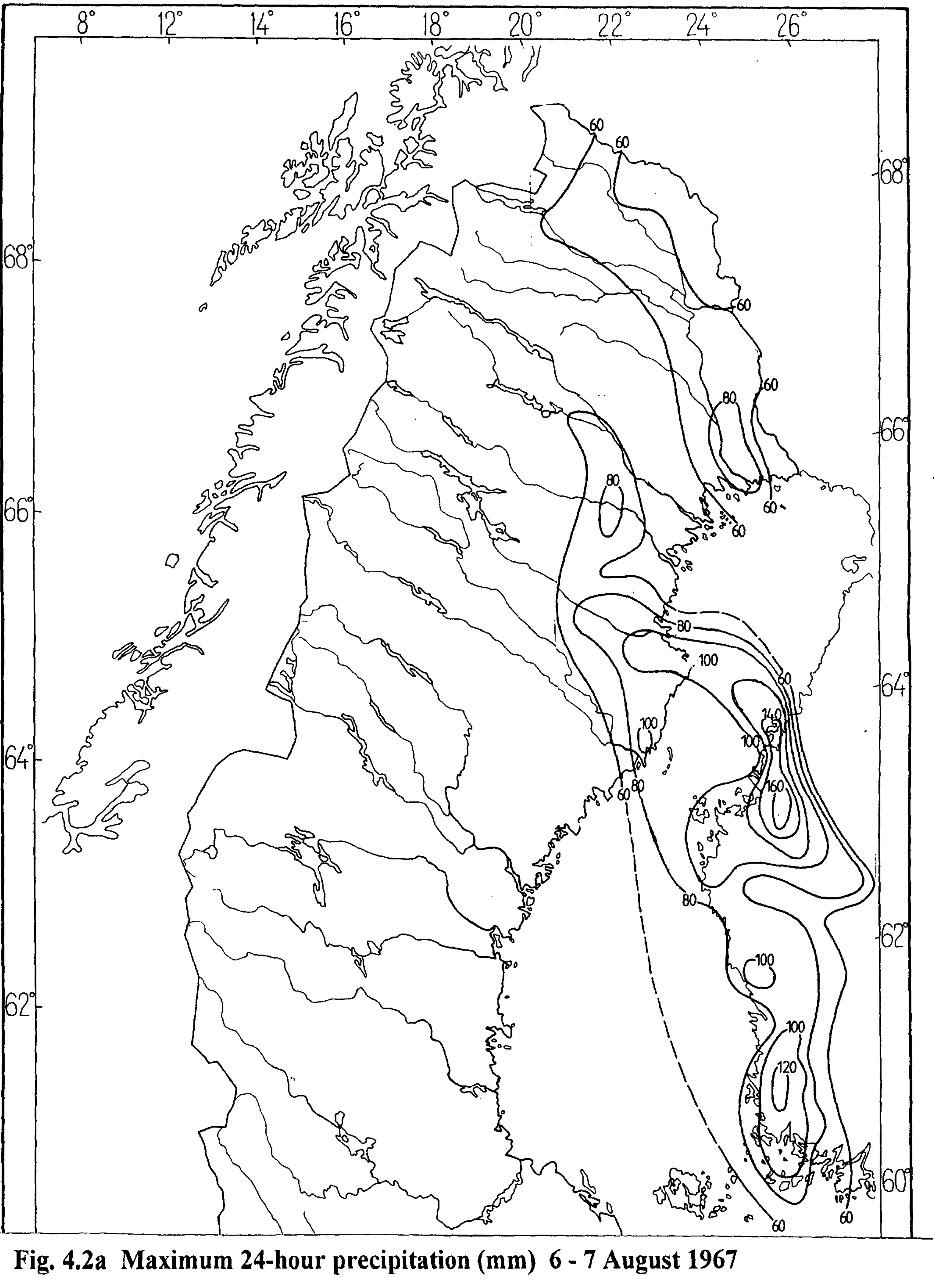


Fig. 4.2a Maximum 24-hour precipitation (mm) 6 - 7 August 1967

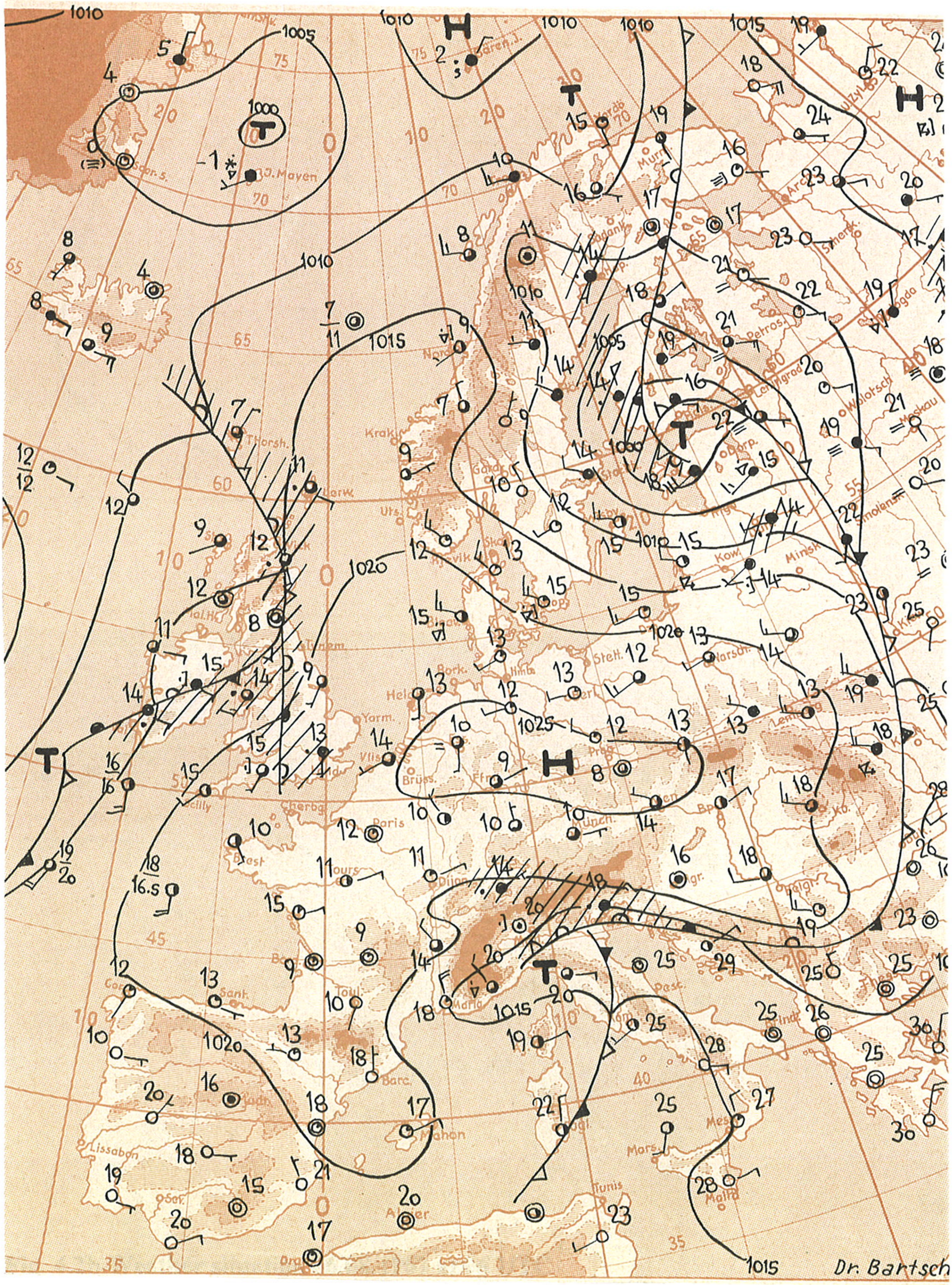


Fig. 4.2b Weather situation 06.08.1967 at 06 UTC

(From Täglicher Wetterbericht, Deutscher Wetterdienst, Offenbach)

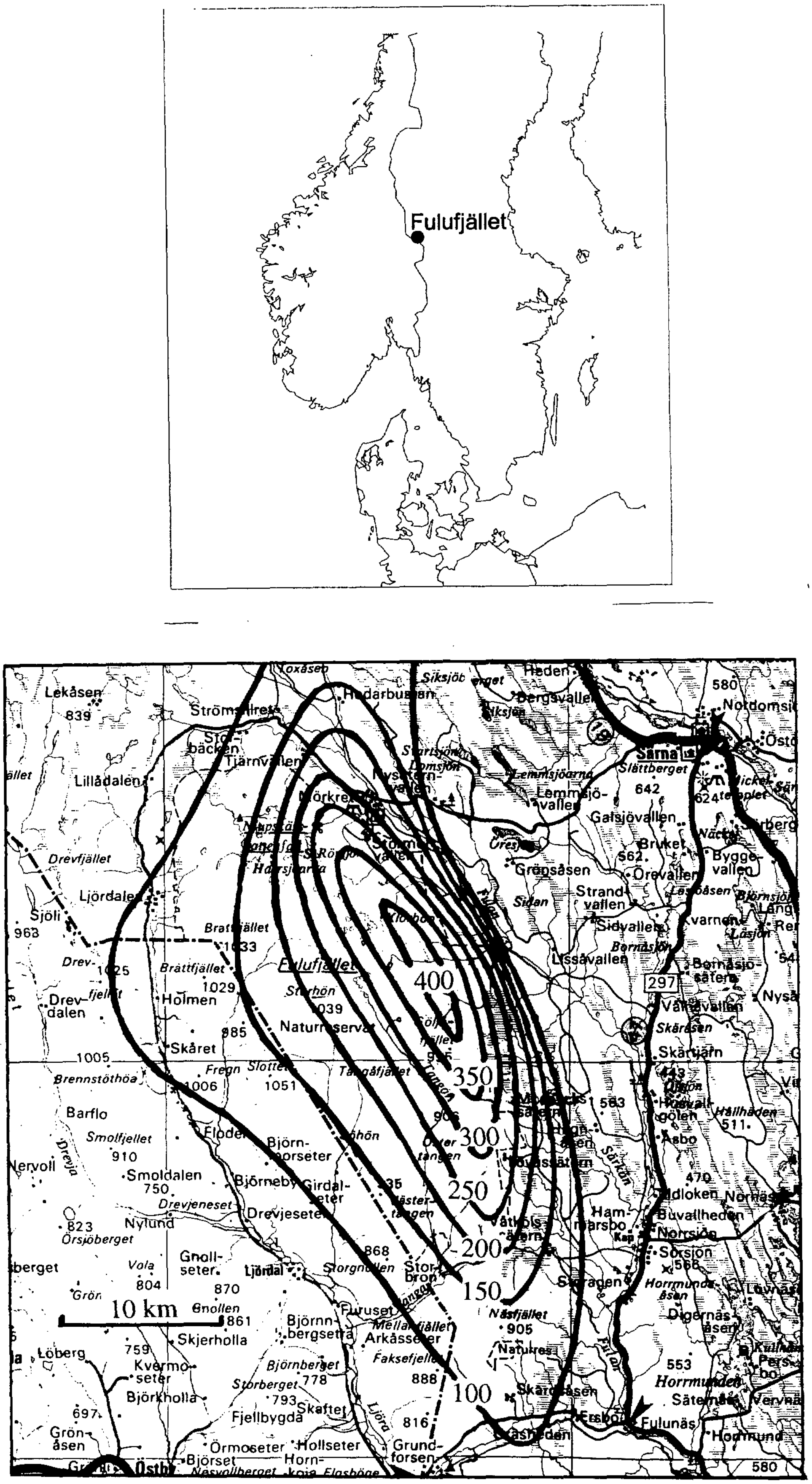


Fig. 4.3a Estimated maximum 24-hour precipitation (mm) at mount Fulufjället during 30. - 31. August 1997

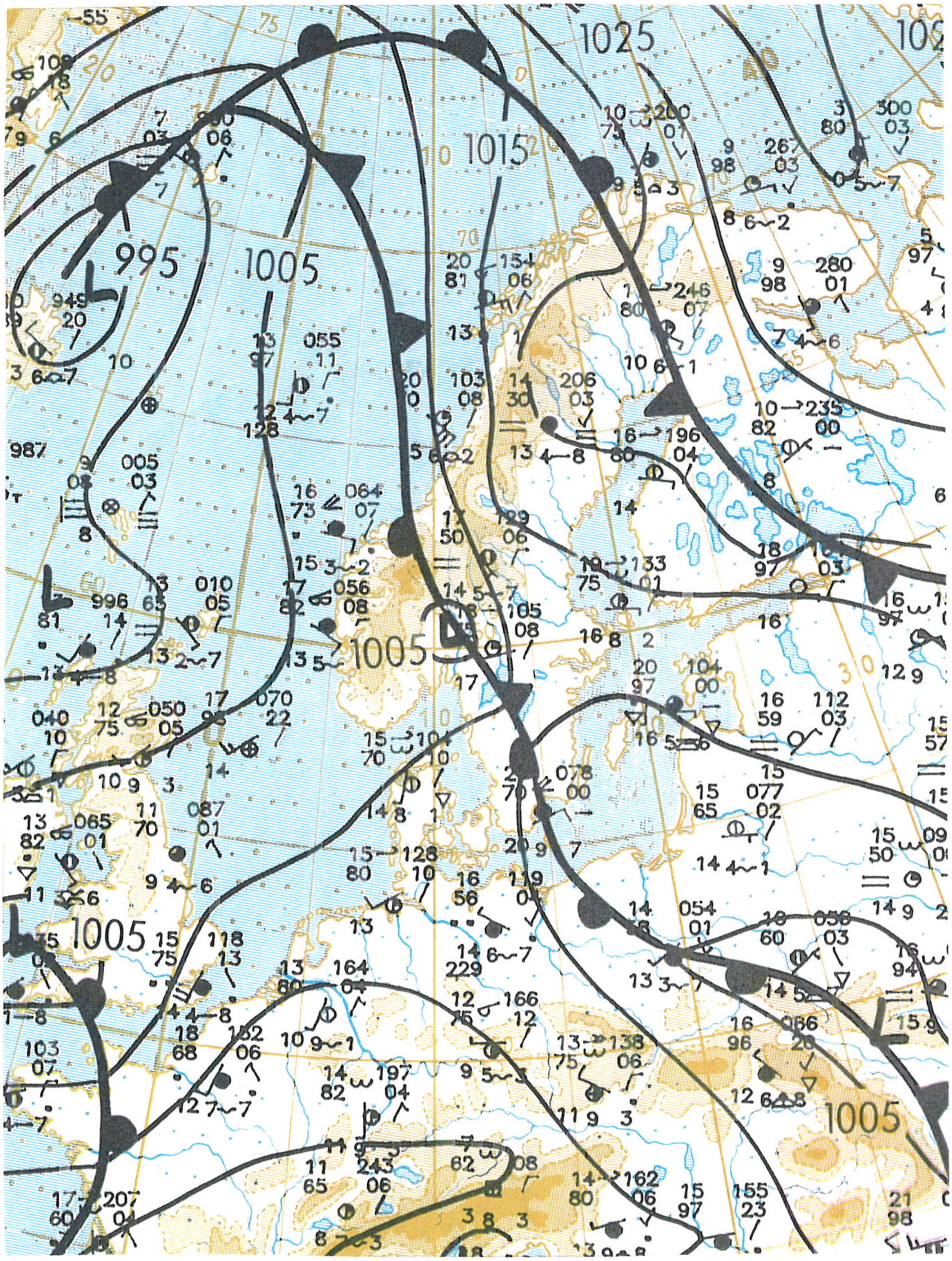


Fig. 4.3b Weather situation 30.08.1997 at 00 UTC

(From Europäischer Wetterbericht, Deutscher Wetterdienst, Offenbach)

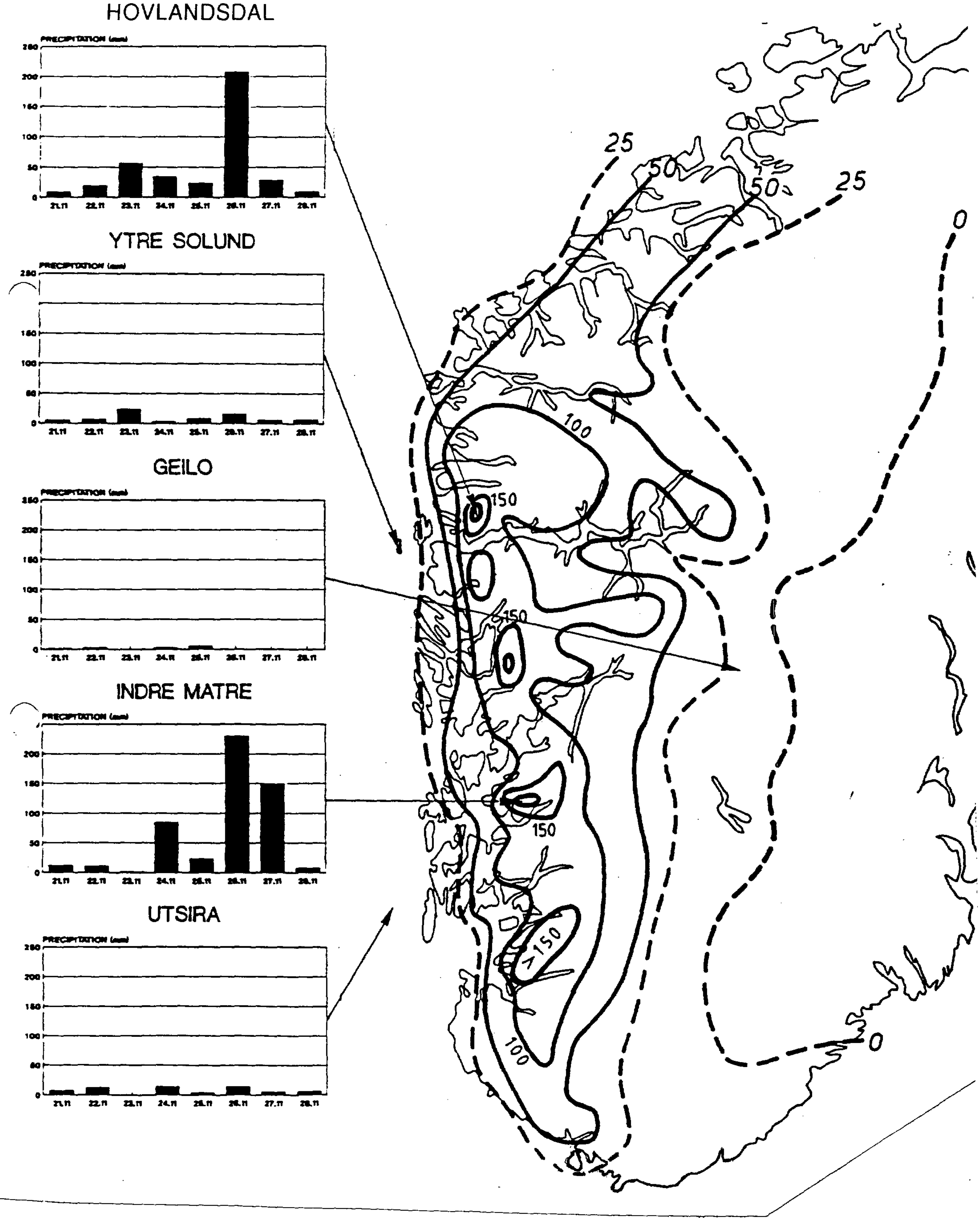


Fig. 4.4a 1-day precipitation (mm) 25.11 - 26.11.1940

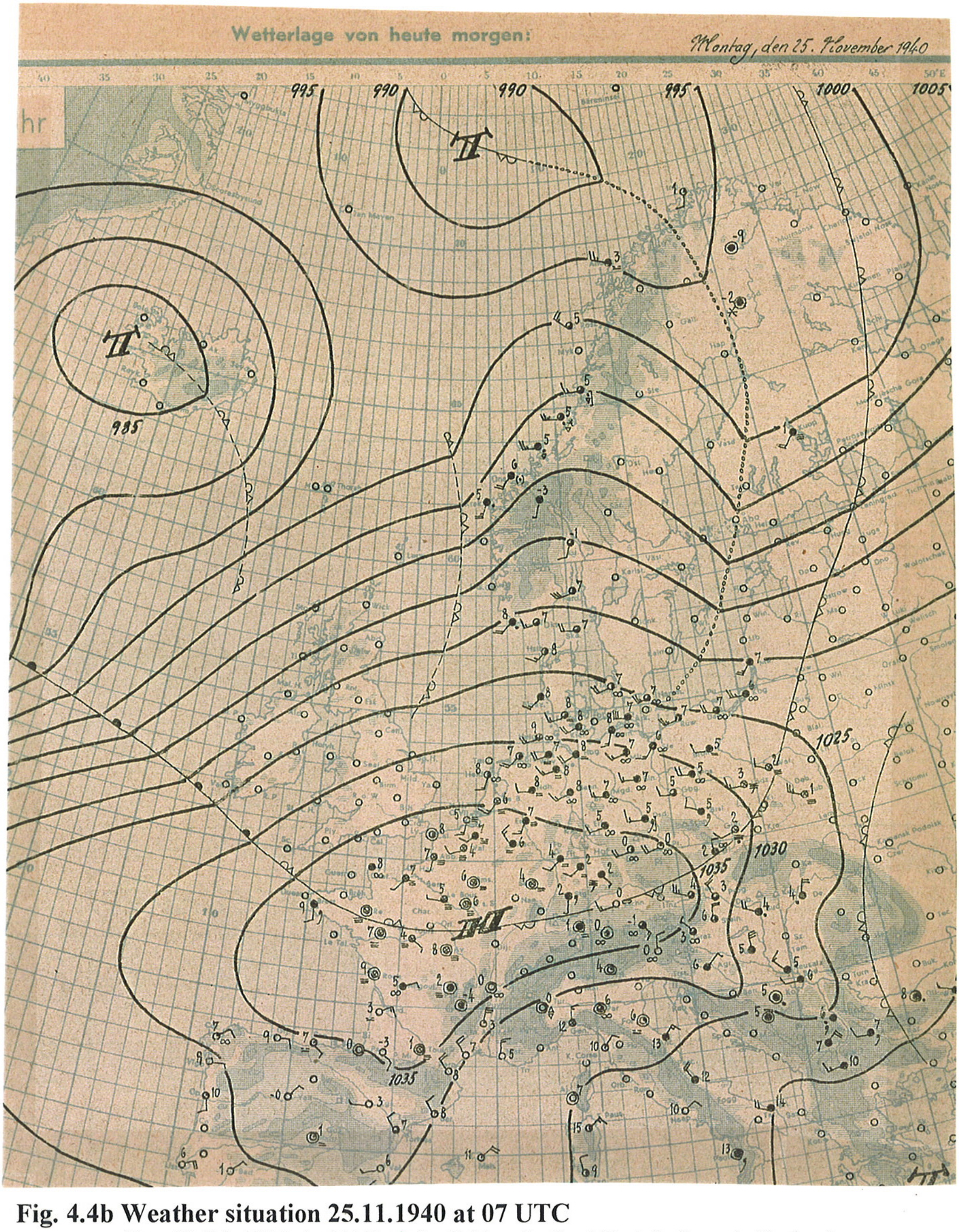


Fig. 4.4b Weather situation 25.11.1940 at 07 UTC

(From Täglicher Wetterbericht, Deutscher Reichswetterdienst, Deutsche Seewarte, Hamburg)

4.2 Regression model linking Rx to atmospheric circulation.

To what extent can the extreme 1-day precipitation amounts, Rx, be explained by circulation characteristics? This was examined for a small number of stations by using four predictors:

Ug: Zonal geostrophic wind component.
Vg: Meridional geostrophic wind component.
P: Pressure at mean sea level.
Tm: Monthly mean temperature.

The first three predictors were obtained from the WASA data set (Schmith et al., 1997, Alexandersson et al., 1998) which consists of three observations per day of air pressure reduced to mean sea level from around 20 stations in northern Europe. Ug and Vg are calculated using the three nearest pressure stations forming a triangle over the REWARD station that is examined. The afternoon observation, nowadays performed at 18 UTC, was used to describe the circulation during the time (06-06 next day) during which the Rx value is measured. The distance between stations with pressure was typically 150-250 km for Fennoscandia. This causes some smoothing and underestimation compared with true geostrophic winds.

Mean temperature for the whole month was taken from the NACD data set (Frich el al, 1996) as no daily data on temperature was available for the whole period and for all stations. Then a multiple linear model was used:

$$RX - \overline{RX} = a(Ug - \overline{Ug}) + b(Vg - \overline{Vg}) + c(P - \overline{P}) + d(Tm - \overline{Tm}) \qquad [4.1]$$

Note that no intercept term arises when the model is written as deviations from mean values. Note also that the data set used just comprises the maximum value for each month so we do not at all cover the more complete variety of data that e.g. one value per day would give. We are instead dealing with a **conditional** data set. But even if it is just maxima we are using it is quite common that a whole month just experience very modest rains so many values will really be small.

Nine stations (see Figure 4.5 and Table 4.1) are chosen to illustrate how well this model works on Rx-data from stations with very different terrain features, distances from coast etc. To make the data sets used in regressions larger, we have made the analysis on a seasonal basis. For each calendar season we then have three values per year. This is reasonable when the three months not are too different concerning Rx and the relations to the predictors.

The correlation coefficients (ρ) in Table 4.1 are really not very high although they are significantly different from zero on the 5% level with a simple approximate test. With n values (around 300 here) an approximative value on the standard deviation of ρ is given by:

$$\sigma_{\rho} \approx \sqrt{(1-\rho^2)/(n-2)} \qquad [4.2]$$

With n=300, the lowest significant value on the 5% level (assumption on normal distribution) becomes as low as 0.1. This is, however, mainly a consequence of the large number of values and a visual inspection (cf. Figure 4.6) clearly unveil how poor the model works in cases with so low ρ-values. Even for the highest correlations, just 30% of the variance is explained by the model in eq. (4.1).

Table 4.1: Correlation coefficients (ρ) between observed values and values calculated from the multiple linear regression model.

Station	Winter	Spring	Summer	Autumn
83500 Kråkmo (Norway)	0.40	0.29	0.16	0.15
16395 Haparanda (Sweden)	0.36	0.24	0.17	0.43
5407 Yli-Ii (Finland)	0.29	0.35	0.19	0.38
15772 Stensele (Sweden)	0.37	0.38	0.36	0.46
5605 Pudasjärvi (Finland)	0.39	0.41	0.13	0.38
50350 Samnanger (Norway)	0.55	0.48	0.49	0.31
39220 Mestad (Norway)	0.51	0.24	0.30	0.27
7840 Visby (Sweden)	0.26	0.34	0.30	0.40
6452 Växjö (Sweden)	0.43	0.28	0.27	0.41

Highest correlations are found for stations where the orographic influence is largest and then it is naturally mainly strong onshore winds that favour large extreme values. At e.g. 50350 Samnanger and 39220 Mestad, westerly resp. southerly winds give the highest correlation For many of the other stations the absolute pressure is the most valuable predictor. Table 4.2-4.5 shows the influence of the four predictors

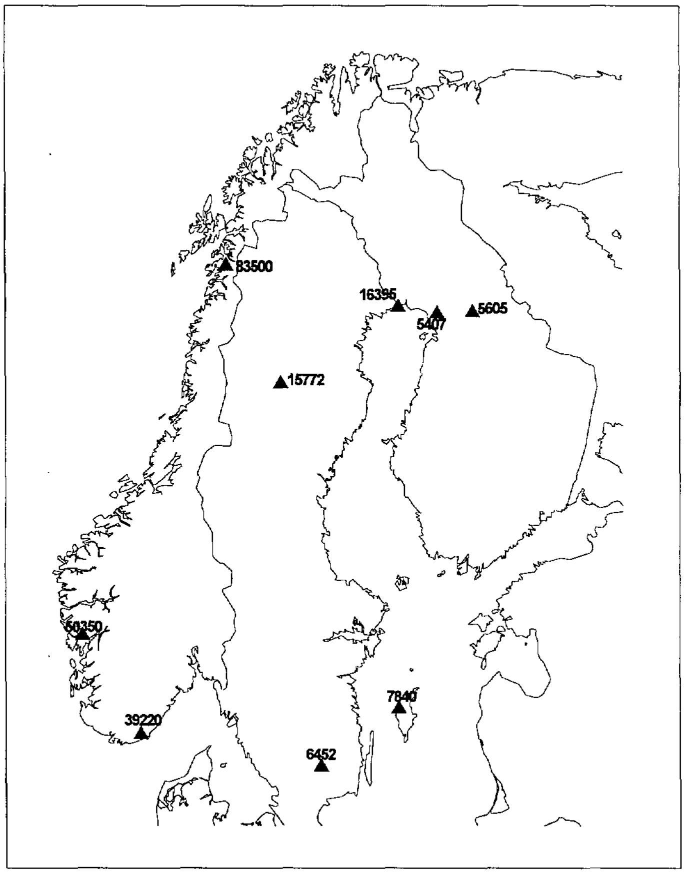


Figure 4.5 Map of the stations used in the regression model

Table 4.2: Regression coefficients (a) for the zonal wind component.
Bold types indicate that the value is significant at the 5% level.

Station	Winter	Spring	Summer	Autumn
Kråkmo	**0.76**	**0.52**	0.16	**0.46**
Haparanda	-0.02	-0.04	-0.11	-0.04
Yli-Ii	0.01	-0.00	0.20	0.05
Stensele	**-0.09**	**-0.14**	**-0.55**	**-0.29**
Pudasjärvi	-0.05	**-0.09**	-0.18	-0.10
Samnanger	**1.08**	**2.07**	**2.63**	**1.36**
Mestad	-0.10	-0.06	-0.10	-0.20
Visby	-0.00	**-0.12**	**-0.22**	**-0.21**
Växjö	0.00	-0.07	**-0.29**	**-0.08**

Table 4.3: Regression coefficients (b) for the meridional wind component.
Bold types indicate that the value is significant at the 5% level.

Station	Winter	Spring	Summer	Autumn
Kråkmo	-0.07	0.25	**-1.61**	-0.18
Haparanda	**0.19**	0.05	0.10	**0.13**
Yli-Ii	**0.08**	-0.04	-0.15	**0.13**
Stensele	**0.11**	0.01	0.05	0.08
Pudasjärvi	0.03	-0.01	-0.12	-0.01
Samnanger	**-0.74**	**-0.45**	**-1.15**	**-0.56**
Mestad	**0.57**	**0.36**	**0.65**	**0.44**
Visby	0.01	**-0.13**	**-0.41**	-0.06
Växjö	0.04	-0.05	**-0.37**	-0.07

Table 4.4: Regression coefficients (c) for surface air pressure.
Bold types indicate that the value is significant at the 5% level.

Station	Winter	Spring	Summer	Autumn
Kråkmo	0.12	**-0.22**	**-0.27**	-0.02
Haparanda	**-0.07**	**-0.10**	**-0.27**	**-0.18**
Yli-Ii	**-0.04**	**-0.08**	**-0.22**	**-0.12**
Stensele	-0.02	-0.05	-0.15	**-0.08**
Pudasjärvi	**-0.06**	**-0.06**	-0.06	-0.08
Samnanger	0.03	-0.25	**-0.44**	0.00
Mestad	**-0.20**	**-0.28**	**-0.38**	**-0.35**
Visby	**-0.10**	**-0.12**	**-0.27**	**-0.22**
Växjö	**-0.12**	**-0.10**	**-0.39**	**-0.19**

Table 4.5: Regression coefficients (d) for monthly mean temperature.
Bold types indicate that the value is significant at the 5% level.

Station	Winter	Spring	Summer	Autumn
Kråkmo	**1.43**	-0.42	0.29	-0.03
Haparanda	**0.22**	**0.22**	0.10	0.53
Yli-Ii	**0.14**	**0.37**	0.39	**0.42**
Stensele	**0.09**	**0.32**	**1.17**	**0.48**
Pudasjärvi	**0.22**	**0.41**	0.36	**0.49**
Samnanger	**4.29**	**-0.78**	-0.27	0.76
Mestad	**2.53**	-0.08	0.11	**0.67**
Visby	0.01	0.17	0.49	**0.34**
Växjö	**0.53**	**0.46**	0.95	**0.58**

The four plots in Figure 4.6 illustrate the performance of the regression model. Each plot shows calculated values at the x-axis and observations at the y-axis. Ideally the values should linger around the 1:1-line but most often the difficulties in finding good predictors cause the calculated values to be too concentrated close to a climatological mean value. Inflating has been used to restore the variance to the same level as the observations. Inflating restores the standard deviation of the calculated predictand values (σ_c) to the original standard deviation of the observations (σ_o) by multiplying the anomalies by a factor σ_o/σ_c. Then some negative values appear but they are of course non-sensical here so they have been set to zero on the plots.

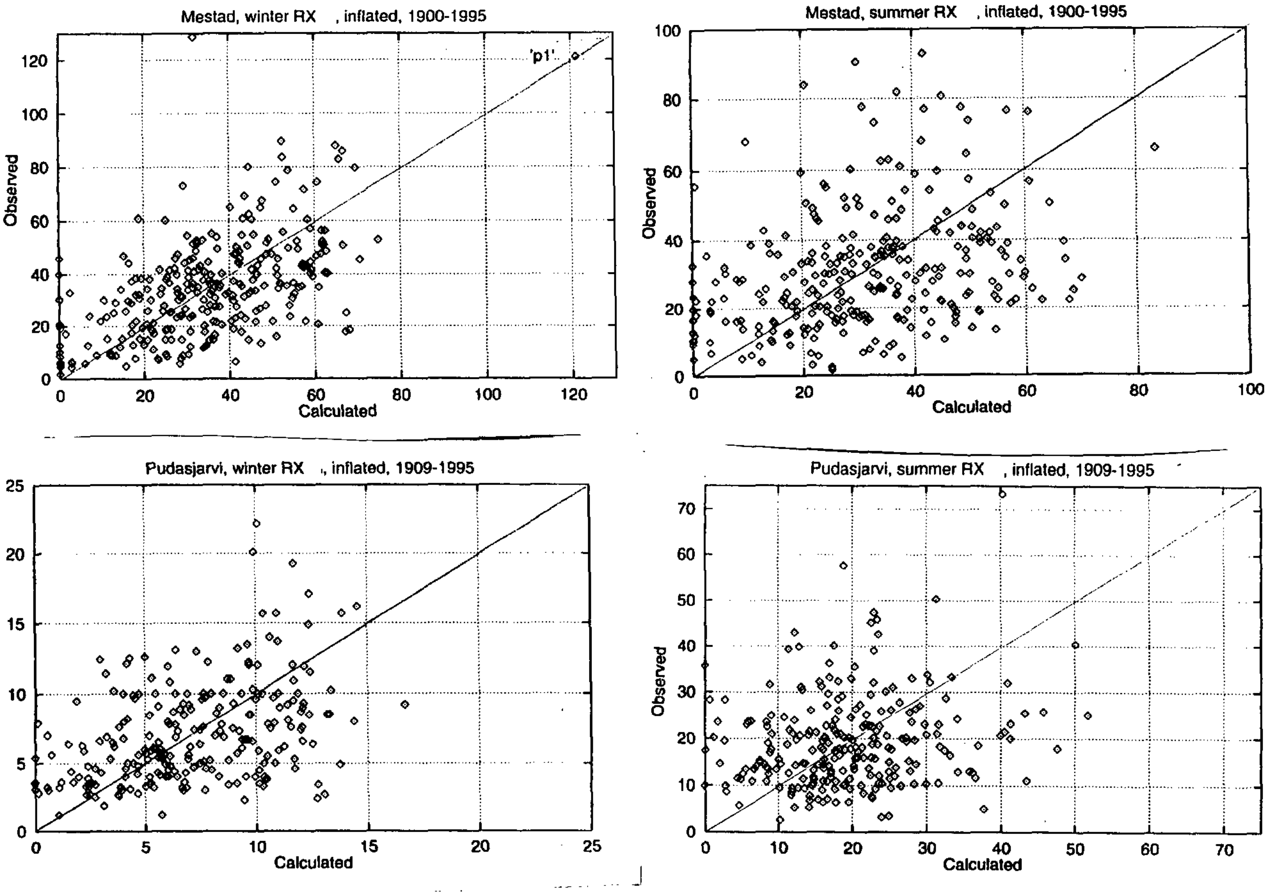


Figure 4.6. Calculated versus observed summer and winter Rx-values for 39220 Mestad and 5605 Pudasjärvi.

Figure 4.6a may be used as an interpretation of the results from the model. This figure shows the winter Rx-values (one value for each of the months Dec, Jan, Feb, 1900-1995) for 39220 Mestad in southern Norway. The triangle used to estimate gesotrophic winds for Mestad was Bergen-Göteborg-Nordby (Jutland). The correlation coefficient is reasonably high, 0.51 (see Table 4.1). Table 4.2-4.5 show that the significant predictors are Vg (positive: Southerly winds favour high Rx), Tm (positive: Mild winter months are favourable for high Rx) and, to a lesser extent, Pa (negative: Low pressure favours high Rx).

Mestad is situated close to the southern coast of Norway, with steep terrain features favouring reasonable relations between the chosen predictors and the extreme one day precipitation. But also precipitation at stations in flatter terrain and not close to coasts can, to some extent, be desribed by this model. Then the dominant predictor is often the absolute pressure which of course predicts higher amounts when the pressure is lower. It is also often better correspondance in autumn and winter than in summer when convective precipitation contributes much to the maxima.

The stations at or fairly close to the uppermost Bothnian Bay (16395 Haparanda, 5407 Yli-Ii and 5605 Pudasjärvi) support each other well. Generally the maxima at these stations are favoured by southerly winds (in autumn and winter), low pressure and warm months.

At the station 15772 Stensele, east of the Scandinavian fells, the Rx-values are strongly dominated by easterly winds and warm months, especially warm summer months.

Station 6452 Växjö in the inner of southern Sweden is somewhat favoured by northeasterly winds, clearly favoured by low pressure and high monthly mean temperatures. This is a bit strange as northeasterly winds and warm weather rarely coexist. But a generally warm month, with just an occasional period of colder weather in connection with a low pressure system just to the southeast of Växjö, seems indeed to be a month favourable for a heavy downpour.

The westerly exposed stations 83500 Kråkmo and 50350 Samnanger are (together with Stensele) the only stations that show only modest dependence from the absolute pressure. Apparently heavy rains can fall not very close to cyclones, for example in warm sectors far south of the centres. In winter large rainfall maxima at Samnanger are favoured by warm months and strong winds from westnorthwest. In spring and summer it is instead favoured by cooler months.

The significant influence from the mean monthly temperature can be considered a bit fictitious, at least for the transitional seasons. This is so because the mean temperature for all spring months taken together almost always is higher than individual March months and lower than May months.

We have found that the Rx-data show significant correlations with circulation characteristics. However, the value of the multiple linear regression model that has been used is quite limited, showing that the complexity of the mechanisms creating daily rainfall maxima is far beyond this simple model. The model has some success especially where strong winds from specific directions favour large precipitation amounts. The model also often gains from the simple fact that low atmospheric pressure is connected to rainfall.

5. Ratio between mean annual maximum 1 day-precipitation for different time periods

5.1 Ratios of Rx for the last two standard normal periods (1961-90)/(1931-60)

The annual precipitation during the standard normal period 1961-90 is higher than during the previous normal period (1931-60) over large parts of the Nordic countries (Førland et al.,1996a). The most pronounced increase (5-15%) is found in western parts of Denmark, Sweden and Norway, and in northern parts of Iceland, Finland and Norway. This general increase is in good accordance with global precipitation series presented by Hulme (1995), by which it can be deduced that the annual precipitation in the northern hemisphere north of 50 °N has increased by 7% between the last two normal periods. However, in some areas on the leeward side of the Norwegian mountains and in eastern parts of Sweden, there was a minor decrease in normal values.

To study regional patterns of changes in 30 year mean values of Rx, the ratios between Rx for the two latest normal periods are displayed in Figure 5.1. The mean Rx is highest during the recent normal period in southern Norway, eastern parts of Sweden, northern areas of Fennoscandia, and southern Iceland. In some of these areas, the mean Rx for 1961-90 is more than 10% higher than for 1931-60. But it should be noted that in some of these areas the mean Rx-value is low (cf. Figure 3.3) and accordingly a difference of a few millimetres may lead to a large percentage difference. However, there is no dominating tendency of increase in Rx in the region: Major areas of Fennoscandia has experienced a decrease in mean Rx-values since the last (1931-60) normal period.

The map of changes in annual precipitation (RR) is inserted in Figure 5.1. A direct comparison of the two maps in Figure 5.1 is difficult, as the inserted map is based on a dense network of more than 1000 stations, while the Rx map is just based on the 85 REWARD stations. Anyhow, there are several similar features in the maps: *Increase* in both RR and Rx in western Norway, southern border areas between Norway and Sweden, in northern Fennoscandia and eastern Finland, and *decrease* on the leeward side of the Norwegian mountains and in southeastern Sweden. But there are also areas where the trends in RR and Rx apparently are opposite.

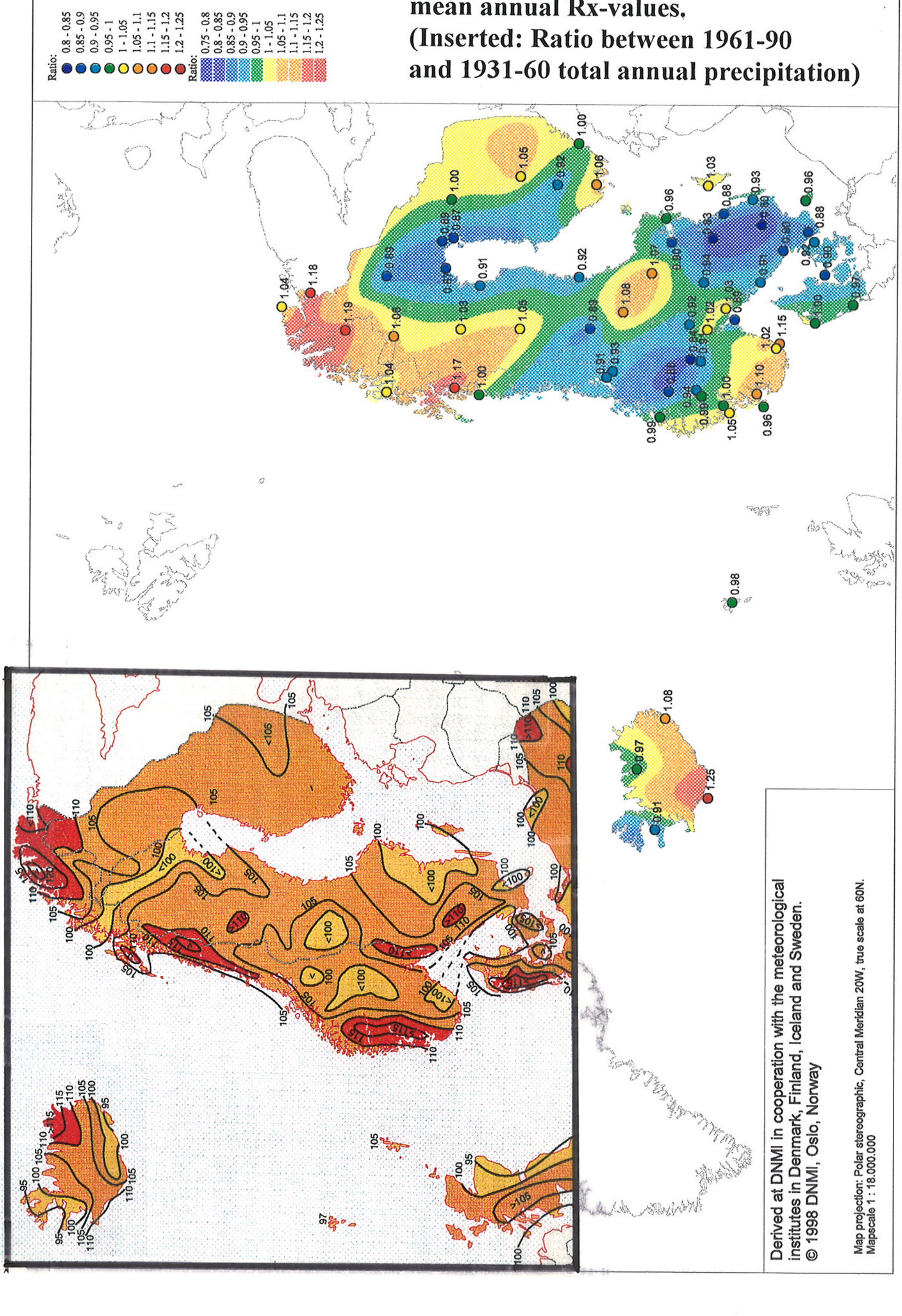
5.2 Ratios of Rx between the periods 1961-90 and 1890-1996.

Values for the standard normal periods are often used as climatological reference values. It is therefore important to know how representative the normal period values are compared to long-term mean values. Figure 5.2 shows the ratio between the mean Rx for the recent standard normal period (1961-90) and the mean Rx value for the complete REWARD datsets, i.e. for the period 1890-1996. (Some stations have somewhat shorter series, cf. Appendix A).

Figure 5.2 indicates that the Rx mean values for the normal period 1961-90 are quite representative for this century. In most parts of the Nordic region, there is less than ± 5% deviation in mean values of Rx for the normal period and the century long mean values. Exceptions are areas on the eastern side of the Norwegian mountains, areas in southeastern Sweden and northeast of the Gulf of Bothnia where the mean values of Rx for the normal period is 5-10% lower than the centennial mean values. Areas with 5-10 % higher values are found in northern parts of Fennoscandia, eastern Finland and southern Iceland.

Figure 5.1

Ratio between 1961-90 and 1931-60 mean annual Rx-values.
(Inserted: Ratio between 1961-90 and 1931-60 total annual precipitation)

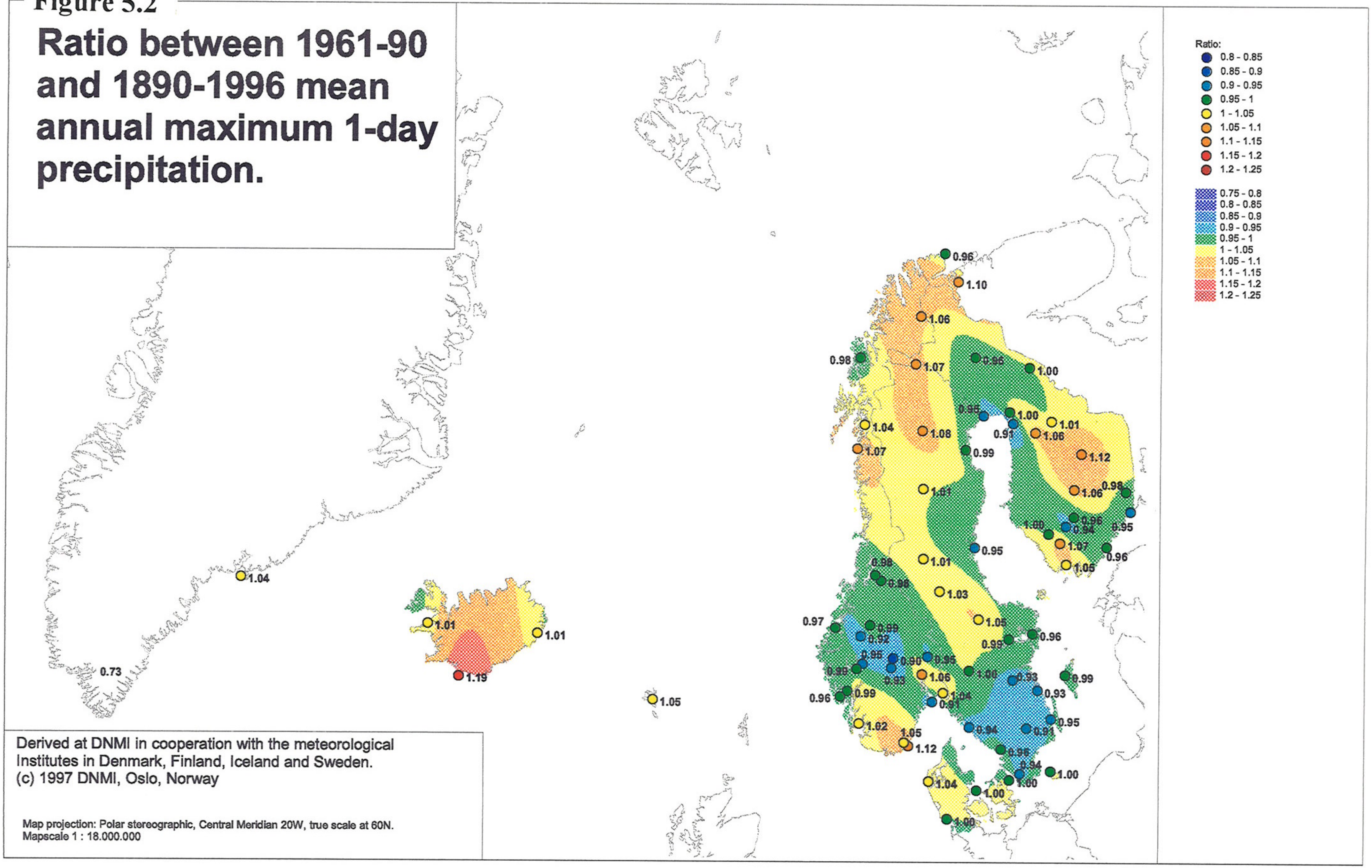


Derived at DNMI in cooperation with the meteorological institutes in Denmark, Finland, Iceland and Sweden.
© 1998 DNMI, Oslo, Norway

Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

Figure 5.2

Ratio between 1961-90 and 1890-1996 mean annual maximum 1-day precipitation.



Derived at DNMI in cooperation with the meteorological Institutes in Denmark, Finland, Iceland and Sweden.
(c) 1997 DNMI, Oslo, Norway

Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

5.3 Ratios of Rx between the periods 1982-1996 and 1890-1996.

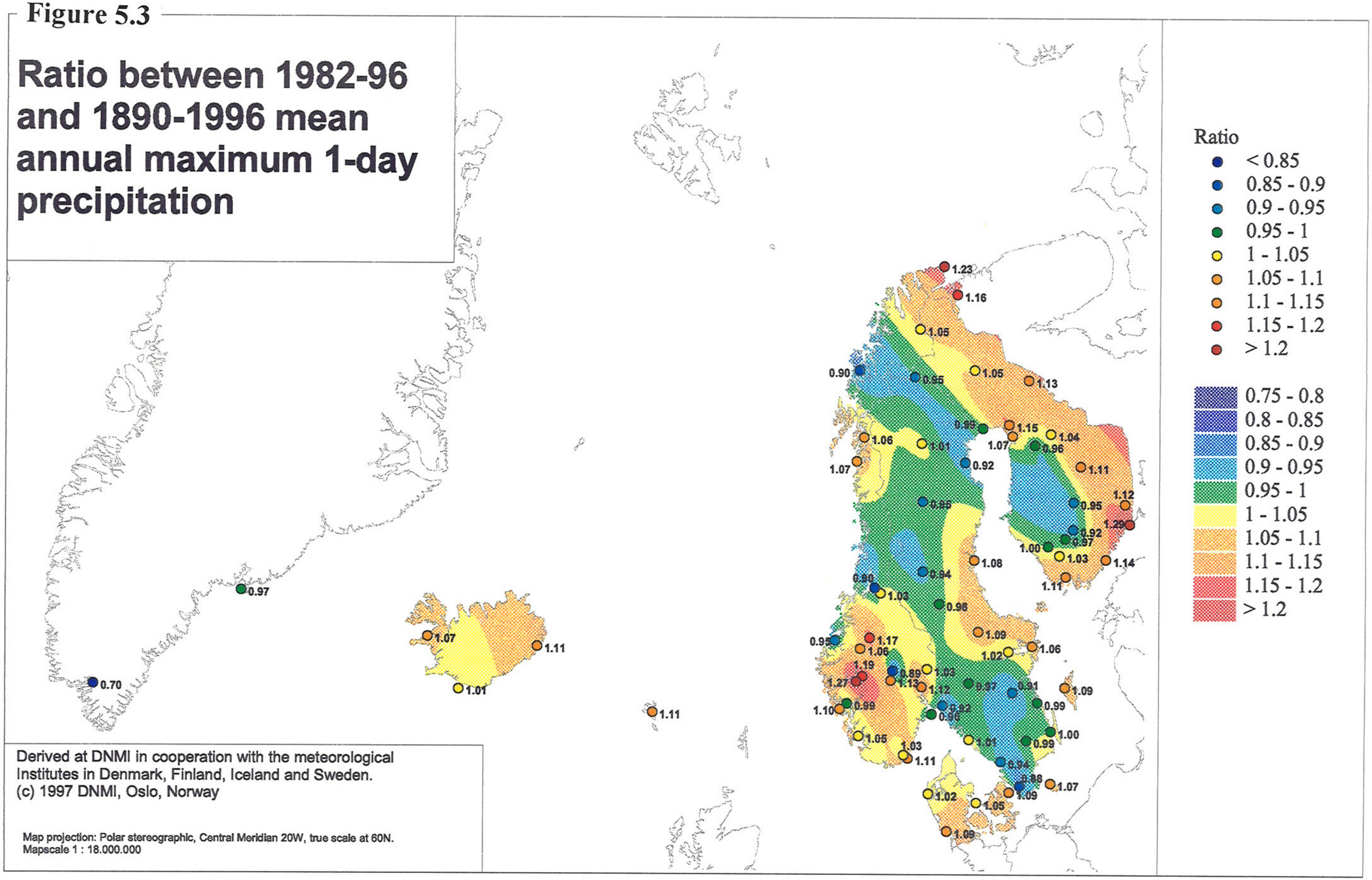
During the last 15 years, there has been a substantial increase in annual precipitation in western parts of Fennoscandia (Førland et al., 1996a). Figure 5.3 shows that the mean Rx values are 5-15% higher than the long-term mean values (1890-1996) for large parts of Denmark, southern Norway, Finland and Iceland.

But as for figs. 5.1 and 5.2, there are no uniform trend patterns for the entire Nordic area; central Norway and major parts of Sweden have lower Rx mean values for the last 15 years than for the century long series.

Because of the large standard deviations (cf. section 3.2), none of the differences in mean values are statistically significant at the 95% level.

Figure 5.3

Ratio between 1982-96 and 1890-1996 mean annual maximum 1-day precipitation



Derived at DNMI in cooperation with the meteorological Institutes in Denmark, Finland, Iceland and Sweden.

Map projection: Polar stereographic, Central Meridian 20W, true scale at 60N.
Mapscale 1 : 18.000.000

6. Trends in maximum 1-day precipitation.

For the contiguous USA, Karl & Knight (1997) found that since 1910 the annual precipitation had increased by about 10%. This increase had arisen for two reasons. First an increase in the frequency of days with precipitation. Second, an increase in intensity was also significantly contributing (nearly half) to the precipitation increase.

To study whether there are any long-term trends in the REWARD series of maximum 1-day precipitation, the series were smoothed by a lowpass filter (FILT2) implying Gaussian weighting. The standard deviation of the Gaussian distribution was set to 9 years. Because of the large differences in precipitation levels, it was difficult to compare the absolute series. The series are therefore normalised by dividing by the mean value of Rx for the standard normal period 1961-90. This way of normalisation instead of the traditional standardising is chosen of two reasons. Firstly it is possible to apply the CTA-technique (Hanssen-Bauer et al., 1997) to convert regional relative curves to absolute values by combination of normalised curves and the 1961-90 map in Figure 3.2. Secondly, the common standardising technique has a drawback on series of Rx as the standard deviation is very vulnerable to outliers. Thus the amplitudes in standardised series of Rx may be suppressed at stations with outliers.

The trend curves displayed in Figure 6.1 indicate that there are no evident national trend patterns. However it is possible to use the CTA-technique on the filtered national series (Figure 6.2). For all the Nordic countries there is a maximum in the 1930's and a tendency of increasing Rx values during the last part of the series. For Denmark the standard deviation of the filtered trend curve in Figure 6.2 is less than 0.05; for the other countries the standard deviations are largely between 0.05 and 0.10. The Mann-Kendall test was used to test the significance of the Fennoscandian trends during the period 1900-1996. Denmark was the only country with a significant trend (positive) on the 5% level for the whole period. For Finland there is a significant positive trend from 1974. For Sweden the trend up to the 1940's was positive. For Norway there is a positive trend (5% level) from 1920, and on the 1% level since 1961. However, because of the diverging individual national curves (Figure 6.1) one should be careful in drawing conclusions from the «national» curves in Figure 6.2.

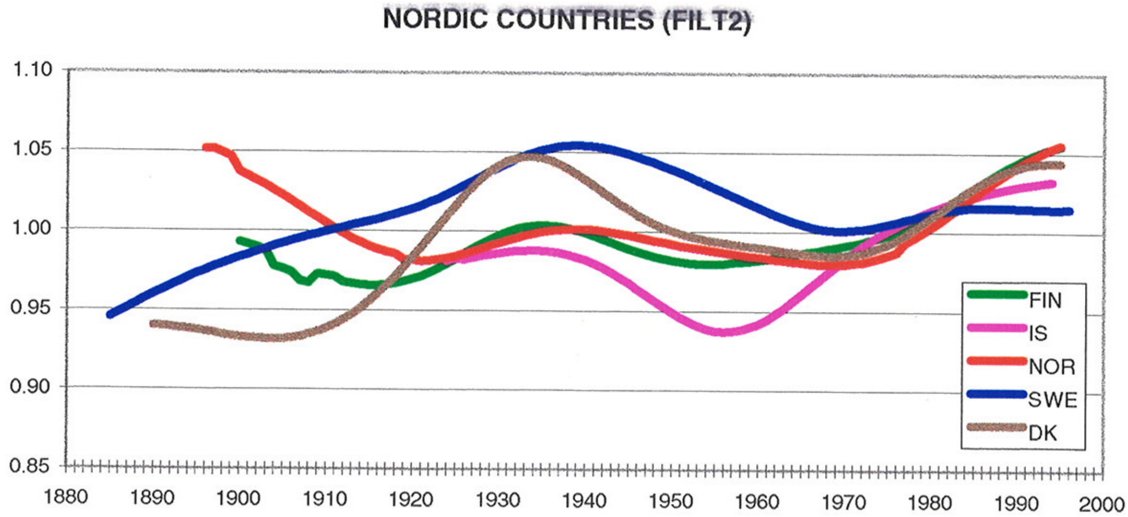
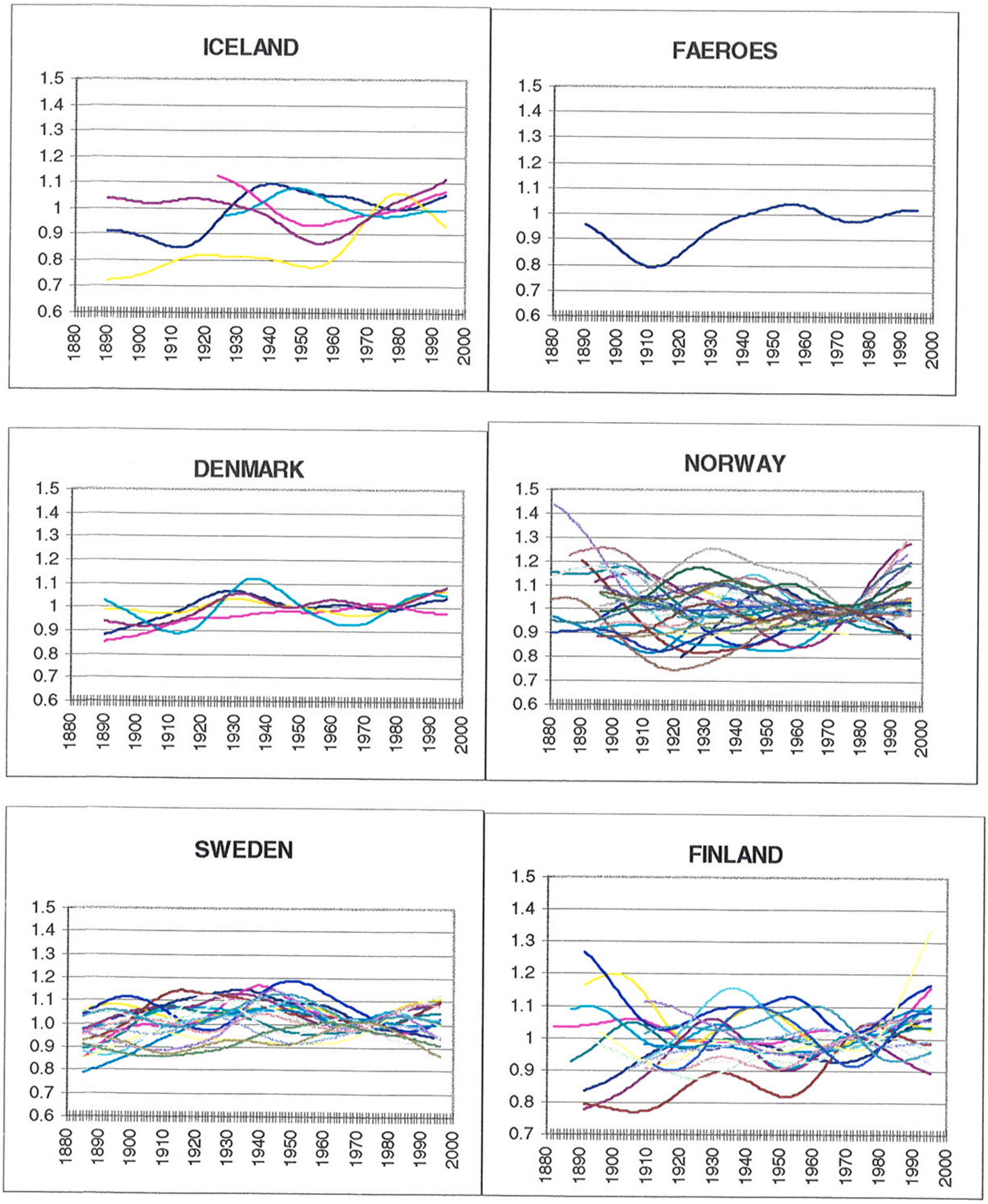


Figure 6.2 Average national trend curves of maximum 1-day precipitation.
The series are anomalies from the 1961-90 average, and are smoothed by a Gaussian filter (std=9 years)

The reason for the diverging trend curves in Figure 6.1 and the large standard deviations for the national curves in Figure 6.2, may be that there are different trend evolutions in different part of the Nordic countries. To study trend curves for smaller regions, neighbouring stations in selected areas were scrutinised. For Finland areas around 1202 Tampere and 5404 Oulu were chosen. Also one area around 9821 Stockholm (SWEDEN 1) and one in the bordering area between Denmark and Sweden (E.DEN & S.SW) were selected.


ICELAND

FAEROES

DENMARK

NORWAY

SWEDEN

FINLAND

Figure 6.1 Trend curves of individual national Rx-series in the REWARD dataset.
The series are normalised, and smoothed by a Gaussian filter (std = 9 years)

For Norway the CTA-technique has earlier been used on annual precipitation series, and it was found that the country could be divided into five regions with distinct different long-term trends (Hanssen-Bauer et al., 1997). Two of these regions for Norway were also selected. Figure 6.3 shows the normalised Rx trend curves for the stations in these six areas. Within these smaller areas there are similarities between some of the filtered series, but still large differences between neighbouring stations emerge. Even trend curves for neighbouring stations may show distinct different trend patterns.

For Sweden all cases since 1926 when areal precipitation have exceeded 90 mm over an area of 1000 square kilometers during a period of 24 hours have been documented (Vedin et al., 1988). An updated version of the distribution over time (Figure 6.4) shows some concentration of cases to certain years, but no evident trend.

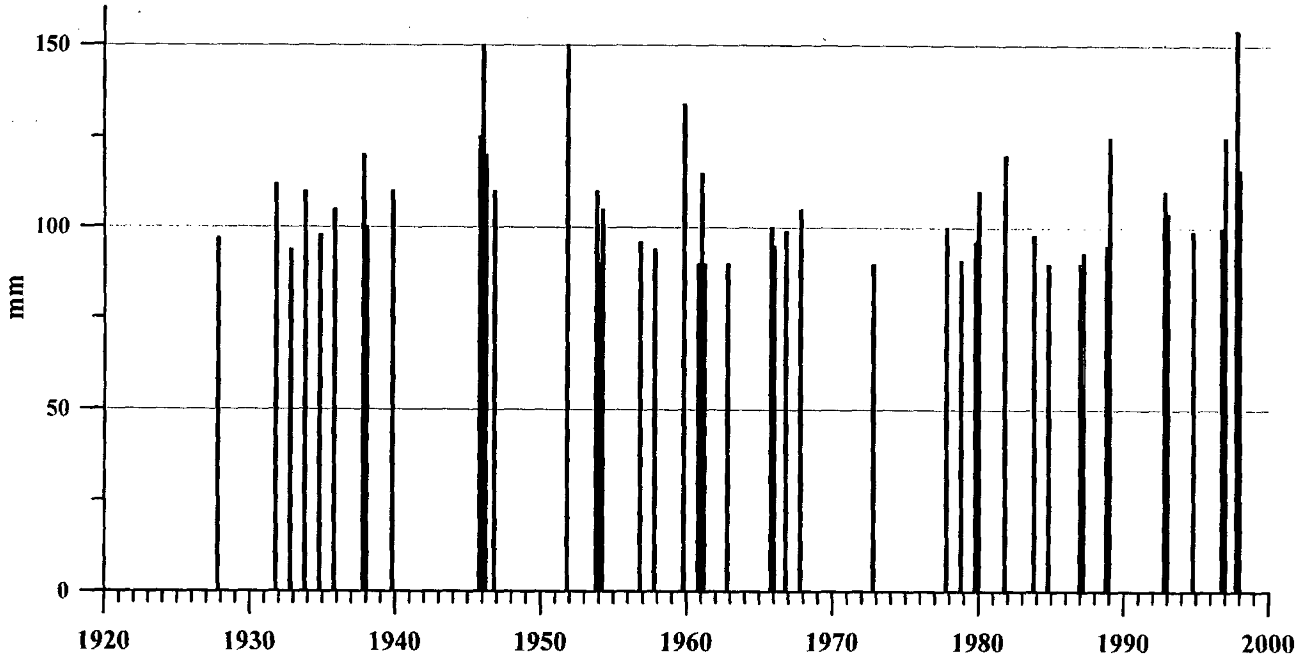


Figure 6.4 Distribution of Swedish cases with areal precipitation greater than 90 mm over 1000 sqkm during 24 hours

Also Heino et al. (1998) found that in large parts of Central and North Europe, there were no major trends in Rx, and no changes in the year-to-year variability. The only station with a statistically documented (rising) trend was the mountain station at Zugspitze in Germany. Also at Swiss stations slightly increasing trends were found, but these were not statistically significant.

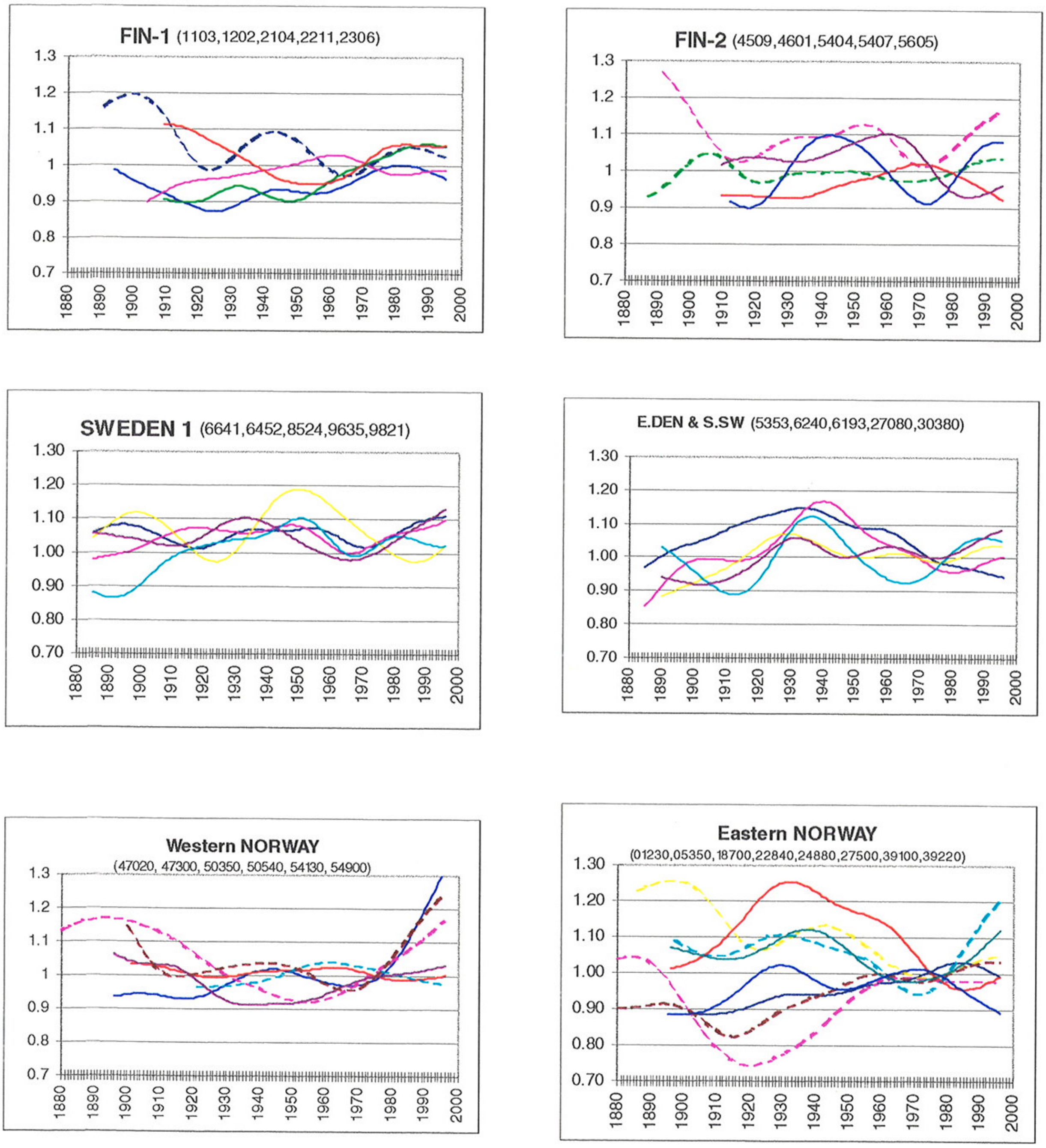


Figure 6.3 Trend curves of individual Rx-series in different Nordic regions (station numbers in brackets).
The series are normalised, and smoothed by a Gaussian filter (std = 9 years)

However, there are several quite different reasons contributing to that annual series of Rx from single stations are no ideal indicators for revealing trends in extreme 1-day rainfall.

- There are usually large local precipitation gradients in heavy rainfall events. Thus, even for secular series, some stations may have experienced several «accidental hits» of heavy rainfall, whereas neighbouring stations have no such «hits» of precipitation at all. These local «accidental hits» may be caused either by slow-moving frontal systems, by local quasi-stationary convective cells, or by local orographic rainfall enhancement.

- Rx-values are very vulnerable regarding misreadings and erroneous sampling intervals, e.g. the reading may represent rainfall from a longer period than 24 hours. Most of these erroneous values are corrected by the NMSs quality control systems, but in some cases it is difficult to judge whether an observation is true or false.

- Trend analysis is impeded by outliers. E.g. smoothed trend curves may be influenced by one «accidental» outlier for several years.

- Series of Rx may be influenced by inhomogeneities. It is difficult to detect and adjust for inhomogeneities in Rx-series (see section 2)

- An extreme 24-hour rainfall event may be split into two parts by the regular observing hours. Thus even with significant trends in extreme 24 hour precipitation, the trend in Rx may be influenced by a number of «accidental hits» of extreme 24h rainfall events such split.

Consequently, a series of Rx from a single station is not an ideal indicator for possible trends in extreme rainfall. Conclusions concerning regional trends of daily precipitation extremes should therefore be based on trend studies from a dense network of stations, or on other indicators.

7. Trends in frequencies of «extraordinary» 1-day precipitation

One way of answering the question of IPCC *«Has the climate become more extreme»* (cf. chapter 1), is to study the regional occurrences of «extraordinary» events. For the insurance industry in Norway, a precipitation event is characterised as «extraordinary» in a flooding context if the return period of the event is higher than 5-10 years. Whether these extraordinary 1-day rainfalls result in flooding, depends on the weather situation (ground frost, combination with snow melt, short duration high rainfall intensity, preceding heavy precipitation, etc.). For calculating return period values of 1-day precipitation, the Gumbel distribution is the most commonly used method world-wide (WMO, 1981). The Gumbel method is described in chapter 3.4, and a survey of 5 year return period values are displayed in Figure 3.5.

For each of the 85 REWARD-series of Rx, the number of occurrences of «extraordinary» 1-day rainfall events (i.e. events with a return period exceeding 5 years) were calculated on a decadal basis. The results are presented in Table 7.1 and Figures 7.1. and 7.2. For countries and regions, only decades with a data coverage of more than 50% were included. (The Norwegian Arctic stations and Tórshavn at the Faeroes are not included in the analysis).

Table 7.1 Number of extraordinary 1-day rainfall events per station and decade

Country	*No.*	*1880-89*	*1890-99*	*1900-09*	*1910-19*	*1920-29*	*1930-39*	*1940-49*	*1950-59*	*1960-69*	*1970-79*	*1980-89*	*1990-96*
DENMARK	5	-	1.80	0.80	1.80	1.80	3.40	2.00	2.00	1.80	0.60	3.20	2.00
GREENLAND	7	-	0.83	3.33	2.33	0.75	3.50	2.17	1.43	2.14	1.71	2.27	1.92
ICELAND	5	-	1.43	1.15	0.80	1.11	2.29	1.80	1.60	2.40	1.80	2.00	1.14
FINLAND	18	-	1.61	1.55	1.58	1.40	2.70	1.25	1.17	2.29	1.94	2.06	2.62
NORWAY	26	-	2.98	2.65	1.29	1.51	2.50	1.73	1.65	1.62	1.56	2.23	2.64
SWEDEN	20	1.10	1.81	1.50	1.95	1.75	2.50	2.05	1.85	1.80	1.60	2.35	1.36
Regions *													
FINLAND-N	5	-	-	-	1.04	1.40	3.60	1.04	1.80	2.00	1.20	1.60	2.57
FINLAND-S	13	-	1.41	1.70	1.78	1.40	2.34	1.33	0.92	2.40	2.23	2.23	2.64
NORWAY-N	6	-	2.73	3.05	2.00	0.50	2.67	1.25	0.83	1.67	2.17	2.67	2.38
NORWAY-C	6	-	3.13	4.00	0.59	1.83	2.33	2.50	2.17	1.17	1.38	2.33	2.38
NORWAY-W	6	-	-	1.84	2.00	1.36	1.83	1.86	1.50	1.33	1.33	2.33	3.81
NORWAY-E	8	-	2.83	2.00	0.75	2.13	3.00	1.38	2.00	2.13	1.39	1.75	2.14
SWEDEN-N	7	1.43	2.17	0.86	1.57	1.57	2.43	2.00	1.71	2.43	1.71	2.57	0.82
SWEDEN-S	13	0.92	1.62	1.85	2.15	1.85	2.54	2.08	1.92	1.46	1.54	2.23	1.65

* Stations (cf. Figure 2.1): Finland-S: 0304-4601, Finland-N: 5404-7501, Norway-N: 82290-99450, Norway-C:15660, 16740, 60800-69100, Norway-W: 47020- 54900, Norway-E:01230-39220, Sweden-S: 5343-12402, Sweden-N: 12738-19283

Table 7.1 and Figure 7.1 shows that in most of the Nordic countries the highest frequencies of extraordinary rainfalls occurred in the 1930's and after 1980. In Denmark there were in average more than 3 extraordinary rainfalls per station during the 1930's and 1980's, and just 0.6-0.8 in the periods 1910-19 and 1970-79.

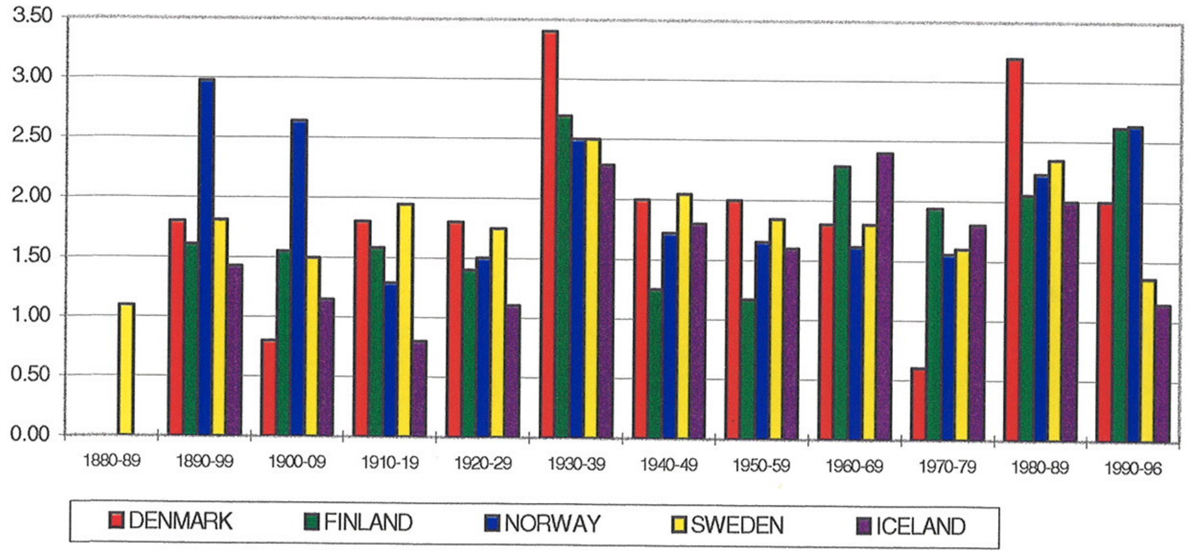


Figure 7.1 Number of extraordinary 1-day rainfall events per station and decade in the Nordic countries

Figure 7.2 shows that there are regional variations in the frequencies of Rx>M5. The rather high frequencies in Norway before 1910 are mostly due to high values in the northern and central regions. In western Norway the frequencies were below 2.0 for every decade until 1980, but during the last two decades the frequencies has increased substantially.

The analyses show that except for the western parts, the highest frequencies of «extraordinary» rainfall events in Fennoscandia occurred in the 1930's and in the two latest decades. This part of the Nordic region usually experience extreme Rx-values in weather situations with convective cells during the warm season (cf. section 3.3), and the decades with maximum frequencies of extraordinary rainfall coincides with decades with high regional summer temperatures (Tuomenvirta et al. (1998)).

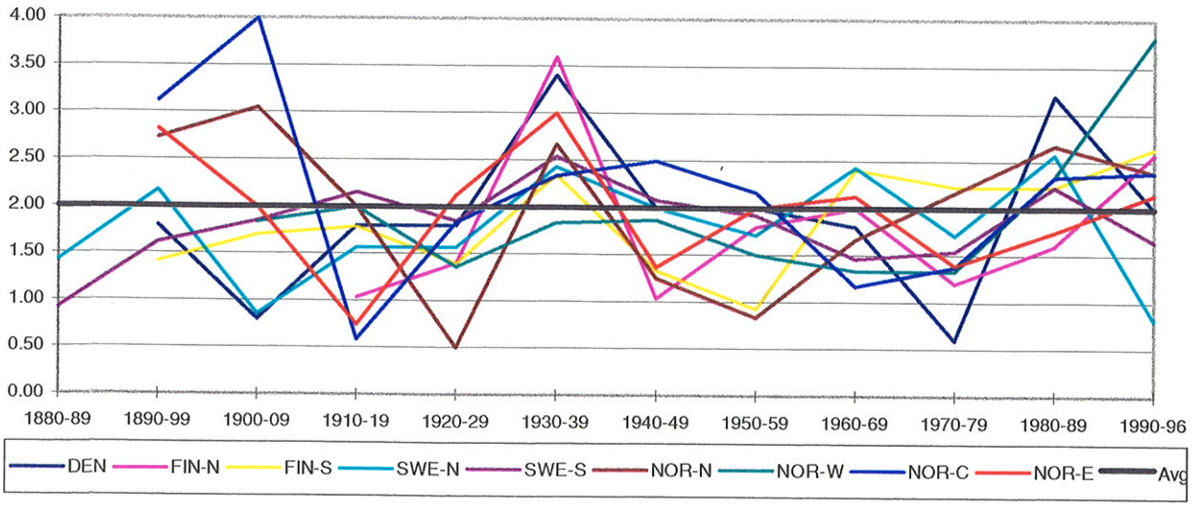


Figure 7.2 Number of extraordinary 1-day rainfall events per station and decade in Nordic regions

For western Norway where there is no summer maximum in frequencies of Rx (cf. Figure 3.3), there was no local maximum in the 1930's. In this area the two latest decades have evidently had the highest number of extraordinary rainfall events. During this period, western Norway has experienced a substantial increase in orographic precipitation during autumn, winter and spring (Førland et al., 1996a).

Even the frequency of maximum 1 day precipitation larger than threshold values is no unique indicator of changes in rainfall intensity. It is e.g. possible that in some years there are several events (even several within a month) with Rx values higher than the absolute highest Rx in other years. Thus even by using the highest monthly values of Rx it is not granted that one will get a complete survey of frequencies of extraordinary rainfalls.

As just a few digitised series of daily rainfall were available, it was considered whether the printed climatological surveys of number of days with precipitation exceeding 10 mm (RD10) could be an alternative indicator of long-term changes in extreme precipitation. However, neither this element is an ideal indicator of *heavy* rainfall trends in the Nordic countries: Certainly at some stations daily precipitation of more than 10 mm occur rather seldom, and may be classified as «heavy precipitation». E.g. at 15660 Sjåk at the leeward side of the Norwegian mountains RD10 is less than 5 days/year. But in areas with orographical enhanced precipitation in Greenland, Iceland, Faeroes and Norway 10 mm/day is in no way any extreme daily precipitation amount. E.g. 50350 Samnanger in western Norway has an average RD10=115 days/year, and during September-December in average every second day (i.e. 15 days/month) has 1-day precipitation exceeding 10 mm.

The ultimate way to study changes in frequencies of extreme precipitation, is probably by using daily records. By studying the distribution of daily precipitation, Karl et al. (1995) found that as precipitation has increased in the United States, a statistically significant increase in extreme precipitation (> 50 mm/day), had accompanied this increase. Similarly for tropical Australia, Suppiah & Hennesy (1996) show significant increases for the higher percentiles; e.g. the 90th percentile. For western Norway, Groisman et al. (1997), found that during this century the average linear trends of days with heavy rainfall (>25.4 mm) was +1.4 % per decade. For the leeward part of Norway a decreasing trend of 2.0% per decade was found.

8. Summary and conclusions.

Heavy 1-day precipitation plays a crucial role for flooding in small watersheds and in urban areas. To evaluate the hydrological consequences of the enhanced annual and seasonal precipitation experienced in parts of the Nordic region, it is important to know whether there is a similar increase in precipitation extremes. As stated in the latest IPCC report, even small changes in the mean climate or climate variability can produce relatively large changes in the frequency of extreme events. A small change in the rainfall variability has a stronger hydrological effect than a similar change in the mean. The majority of climate change investigations has been dealing with average climate, and little is known whether the precipitation increase in parts of northern Europe is accompanied by an increase in daily precipitation extremes.

Analysis of the 85 long-term series of maximum 1-day precipitation (Rx) in the REWARD-dataset demonstrated that the Nordic countries comprise a complex region for extreme 1-day precipitation amounts,- both concerning geographical distribution of absolute values, seasons for extreme Rx-values, for long-term trends and for weather situations favourable for high Rx-values.

The highest observed Rx-values are 200-250 mm/day in both Finland, Iceland, Norway and Sweden. The regional gradients are large; - several stations with 100 year long records never have experienced 1-day rainfalls exceeding 50 mm. The highest Rx-values generally are found at the southern and western coasts of Norway and in southern parts of Iceland. In Arctic areas and northern, continental parts of Finland, Norway and Sweden 1-day rainfall larger than 50 mm rarely occur. In eastern parts of the Nordic region most of the highest annual Rx-values are recorded during the summer and early autumn. At the more maritime influenced stations in Greenland, Iceland, Faeroes and western Scandinavia, the occurrence of the highest annual Rx-values are more evenly distributed throughout the year.

The 100-year return period values of Rx are in the interval 50-75 mm in large parts of the Nordic region. Exceptions are a small area at the Baltic coast of Sweden, and stations in eastern Norway and southern Iceland with 100 year estimates exceeding 100 mm/day.

The high 1-day precipitation may be caused by frontal, convective or orographic processes, or as a combination of these processes. By using a multiple linear regression model, it was found that the Rx-values show significant correlations with circulation characteristics. The model had some success especially for orographic precipitation enhancement, i.e. when strong winds from specific directions favour large precipitation amounts.

By mapping the ratios of mean Rx-values for specific periods, it was possible to depict areas with distinct changes in Rx-values. E.g. the Rx-values for the latest 15 years (1982-1996) are 5-15% higher than the long-term mean values (1890-1996) for large parts of Denmark, southern Norway, Finland and Iceland. But for all chosen periods there are no uniform positive or negative tendencies for the entire Nordic area.

The Rx-series were smoothed by a low-pass Gaussian filter. The trend curves for individual stations differed substantially,- even for neighbouring stations belonging to the same climatic region. It is concluded that the annual series of Rx from single stations are no ideal indicators for revealing trends in extreme 1-day rainfall, and possible reasons for this are discussed in section 6. However, by grouping all national series it is found that for all Nordic countries there is a maximum in the 1930s and a tendency of increasing Rx values during the latest two decades. Only for Denmark there is a significant, positive trend during the whole 100 year period.

The same trend tendencies are found by analysing the frequency of «extraordinary» precipitation events, i.e. 1-day rainfall larger than the 5 year return period value. Regional analyses show that except for the western parts, the highest frequencies of «extraordinary» precipitation events in Fennoscandia occurred in the 1930s and in the latest two decades. This part of the Nordic region usually experience extreme Rx-values in weather situations with convective cells during the warm season, and the decades with maximum frequencies of extraordinary rainfall coincides with decades with high regional summer temperatures.

For western Norway where there is no summer maximum in the frequencies of Rx, there was no local maximum in the 1930's. In this area the two latest decades have evidently had the highest number of extraordinary rainfall events. During this period, western Norway has experienced a substantial increase in orographic precipitation during autumn, winter and spring.

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APPENDIX A: Survey of REWARD Rx-series

							Highest observed Rx -values (mm)				
St.nr.nat.	Name	Country	St.nr. WMO	Lat.	Long.	Period	Spring	Summer	Autumn	Winter	Annual
6193	Hammerodde Fyr	DK	6193	55.3	14.78	1890-1995	44.5	69.8	49.1	43.6	69.8
21100	Vestervig	DK		56.77	8.32	1890-1995	32.4	56.4	59.9	34.6	59.9
25140	Nordby	DK	25140	55.43	8.4	1890-1995	43.3	94.4	59.0	37.2	94.4
27080	Tranebjerg	DK	27080	55.85	10.6	1890-1995	38.2	92.3	58.0	32.0	92.3
30380	København	DK	30380	55.68	12.53	1890-1995	38.2	76.8	61.2	32.7	76.8
304	Helsinki	FIN	2978	60.17	24.95	1882-1996	37.5	79.3	53.9	39.6	79.3
1101	Turku	FIN	2972	60.52	22.27	1891-1996	32.6	82.1	44.3	32.6	82.1
1103	Huittinen Lauttakylä	FIN		61.17	22.78	1894-1996	32.0	66.5	47.5	36.4	66.5
1202	Tampere	FIN		61.47	23.75	1891-1996	32.7	55.6	38.5	27.6	55.6
1601	Virolahti	FIN	1601	60.53	27.55	1894-1996	47.1	86.0	94.8	41.5	94.8
1701	Lappeenranta	FIN	2958	61.08	28.15	1886-1996	45.0	88.1	33.0	45.0	88.1
2104	Lavia	FIN	2104	61.62	22.55	1903-1996	41.2	66.7	41.6	34.5	66.7
2211	Virrat	FIN	2211	61.22	23.83	1909-1996	43.6	72.0	41.9	19.6	72.0
2306	Orivesi	FIN	2306	61.55	24.53	1909-1996	25.9	57.0	46.2	20.7	57.0
2425	Jyväskylä	FIN		62.2	25.72	1891-1996	45.0	86.2	63.6	30.0	86.2
3602	Kuopio	FIN		62.9	27.68	1891-1996	37.0	118.0	38.6	25.7	118.0
4509	Kestilä	FIN	4509	64.35	26.28	1909-1996	27.2	54.8	35.9	24.8	54.8
4601	Kajaani	FIN	2897	64.28	27.67	1886-1996	41.0	95.0	45.4	22.0	95.0
5404	Oulu	FIN		65.03	25.48	1891-1996	29.8	85.4	42.0	22.2	85.4
5407	Yli-Ii	FIN	5407	65.37	25.85	1912-1996	40.3	71.0	38.8	21.8	71.0
5605	Pudasjärvi Korpis.	FIN	5605	65.1	27.53	1909-1996	33.5	73.3	48.5	22.2	73.3
2896	Kuusamo	FIN	2896	65.98	29.22	1908-1996	36.0	61.0	40.5	21.7	61.0
2836	Sodankylä	FIN	2836	67.37	26.65	1907-1996	31.8	48.2	35.6	21.4	48.2
6011	Torshavn	FR	6011	62.02	-6.77	1890-1995	53.0	55.1	77.0	72.8	77.0
4210	Upernavik	G	4210	72.78	-56.17	1949-1986					
4250	Nuuk	G	4250	64.17	-51.75	1921-1995	114.1	101.0	81.9	114.1	114.1
4270	Narsarsuaq	G	4270	61.18	-45.42	1890-1995					
4320	Danmarkshavn	G	4320	76.77	-18.77	1949-1995					
4339	Ittoqqortoormiit	G	4339	70.48	-22	1949-1995					
4360	Tasilaq	G	4360	65.6	-37.63	1897-1995					
4013	Stykkisholmur	IC	4013	65.08	-22.73	1890-1996	56.6	52.6	69.0	68.0	69.0
4030	Reykjavik	IC	4030	64.13	-21.9	1924-1996	56.7	42.4	49.2	56.7	56.7
4013	Vestmannaeyjar	IC	4048	63.4	-20.28	1890-1996	92.0	75.4	145.9	92.0	145.9
4063	Akureyri	IC	4063	65.68	-18.08	1925-1996	41.3	52.0	91.8	41.3	91.8
4048	Teigarhorn	IC	4092	64.68	-14.35	1890-1996	117.1	155.7	92.9	117.1	155.7
1230	Halden	N		59.12	11.38	1895-1996	41.0	73.0	55.0	62.0	73.0
5350	Nord-Odal	N		60.38	11.55	1895-1996	52.9	68.8	60.3	33.6	68.8
15660	Skjåk	N		61.9	8.17	1896-1996	28.5	41.0	37.5	35.3	41.0
16740	Kjøremsgrendi	N	1235	62.1	9.05	1890-1996	28.8	62.8	72.0	49.8	72.0
18700	Oslo-Blindern	N	1492	59.95	10.72	1890-1996	43.0	59.8	58.7	35.5	59.8
22840	Reinli	N		60.83	9.5	1895-1996	39.0	61.0	59.0	33.0	61.0
24880	Nesbyen	N	1372	60.57	9.12	1897-1996	50.0	62.7	55.7	18.2	62.7
27500	Ferder Fyr	N	1482	59.03	10.53	1890-1996	51.5	71.4	53.9	38.6	71.4
39100	Oksøy Fyr	N	1448	58.07	8.05	1890-1996	62.0	74.2	110.5	83.6	110.5
39220	Mestad	N		58.22	7.9	1900-1996	88.1	92.7	151.4	128.7	151.4
47020	Nedstrand	N		59.35	5.8	1895-1996	82.8	129.0	124.2	104.0	129.0
47300	Utsira Fyr	N	1403	59.3	4.88	1920-1996	37.6	77.2	81.3	46.4	81.3
50350	Samnanger	N		60.47	5.9	1901-1996	172.8	143.0	195.0	172.8	195.0
50540	Bergen-Florida	N	1317	60.38	5.33	1890-1996	116.4	88.3	122.3	116.4	122.3
54130	Lærdal	N	1355	61.07	7.52	1890-1996	38.9	45.2	55.0	48.6	55.0
54900	Vetti	N	61	7.02	1895-1996	63.0	54.0	57.0	90.0	90.0	

Appendix A ctd

St.nr.nat.	Name	Country	St.nr. WMO	Lat.	Long.	Period	Highest observed Rx -values (mm)				
							Spring	Summer	Autumn	Winter	Annual
60800	Ørskog	N		62.48	6.82	1895-1996	85.0	86.0	116.0	106.5	116.0
62480	Ona	N	1212	62.87	6.53	1919-1996	68.8	78.2	72.5	71.5	78.2
68330	Lien i Selbu	N		63.22	11.12	1895-1996	63.4	52.2	51.1	63.4	63.4
69100	Værnes/Trondheim	N	1271	63.47	10.93	1890-1996	65.0	87.6	81.0	65.0	87.6
82290	Bodø	N	1152	67.27	14.43	1890-1996	72.8	65.0	74.0	72.8	74.0
83500	Kråkmo	N		67.8	15.98	1895-1996	115.3	85.3	117.9	171.7	171.7
90450	Tromsø	N	1026	69.65	18.93	1890-1996	42.6	64.0	63.5	63.0	64.0
97250	Karasjok	N	1065	69.47	25.52	1890-1996	24.6	50.7	36.1	40.0	50.7
98550	Vardø	N	1098	70.37	31.08	1893-1996	43.6	55.0	34.0	50.0	55.0
99450	Bjørnsund	N		69.45	30.07	1895-1996	25.0	46.0	41.6	22.0	46.0
99710	Bjørnøya	N	1028	74.52	19.02	1926-1996	40.5	30.8	34.0	41.5	41.5
99840	Svalbard Airport	N	1008	78.25	15.47	1957-1996	34.0	43.2	13.7	38.2	43.2
99950	Jan Mayen	N	1001	70.93	-8.67	1922-1996	51.0	87.0	68.5	60.0	87.0
5343	Lund	S		55.7	13.2	1885-1996	53.8	81.2	46.6	40.2	81.2
6240	Halmstad	S		56.67	12.92	1885-1996	33.0	81.4	79.2	34.5	81.4
6452	Växjö	S	2640	56.87	14.8	1885-1996	56.0	141.0	54.9	55.9	141.0
6641	Kalmar	S	2672	56.72	16.28	1885-1996	44.9	70.4	51.0	40.6	70.4
7147	Göteborg	S	2516	57.77	11.88	1885-1996	37.9	69.9	54.1	46.4	69.9
7647	Västervik	S	2559	57.72	16.47	1885-1996	54.1	112.9	83.7	36.0	112.9
7840	Visby	S	2592	57.67	18.33	1885-1996	38.0	85.7	52.0	28.8	85.7
8524	Linköping	S	2582	58.4	15.53	1885-1996	35.6	80.8	52.5	40.8	80.8
9322	Karlstad	S	2584	59.35	13.47	1885-1996	61.6	67.0	40.9	36.3	67.0
9635	Västerås	S	2418	59.58	16.62	1885-1996	40.0	92.5	47.4	32.0	92.5
9821	Stockholm	S	2485	59.33	18.05	1885-1996	46.3	68.3	44.4	32.5	68.3
10537	Falun	S	2433	60.62	15.62	1885-1996	39.0	64.8	62.3	26.1	64.8
12402	Sveg	S	2324	62.02	14.35	1885-1996	33.8	61.3	47.7	40.3	61.3
12738	Härnösand	S		62.62	17.93	1885-1996	78.0	187.3	64.8	52.9	187.3
13411	Östersund	S	2226	63.18	14.48	1885-1996	34.3	66.8	50.1	23.6	66.8
15772	Stensele	S		65.07	17.15	1885-1996	35.8	66.2	44.3	21.3	66.2
16179	Piteå	S		65.32	21.48	1885-1996	36.5	74.5	52.8	31.6	74.5
16395	Haparanda	S	2196	65.82	24.13	1885-1996	37.3	49.5	53.0	29.9	53.0
16988	Jokkmokk	S	2142	66.62	19.63	1885-1996	28.2	49.0	47.0	21.9	49.0
19283	Karesuando	S	2080	68.43	22.48	1885-1996	26.0	50.2	50.1	19.4	50.2

Longitude and latitude are given as decimal degrees. A comprehensive and complete list describing stations and elements in the REWARD-dataset is given by Drebs et. al 1998.